ECONOMICAL PARTICLEBOARD PRODUCTION USING HARWOOD SAWMILL RESIDUES

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DECLARATION

I certify that except where due acknowledgement has been made, the work is that of the author alone; the work has not been submitted previously, in whole or in part, to qualify for any other academic award; the content of the thesis is the result of work which had been carried out since the official commencement date of the approved research program; and, any editorial work, paid or unpaid, carried out by a third party is acknowledge.

Nirdosha Gamage

19th November 2007

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ABSTRACT

Particleboard often represents the lowest cost option amongst a range of suitable wood panel products. Particleboard consumption in the world is approximately 57% of total wood panel consumption and the demand is growing at 2 – 3% per year. This demand required more and more wood chipping to supply the raw materials as particleboards are traditionally made using custom flaked softwood particles. Hardwood sawmill residues have traditionally not been favoured by the particleboard industry (or indeed other forest product industries) owing to their high density and high extractive content. Throughout Australia considerable quantities of hardwood saw mill residues are produced as solid waste. In Victoria alone, over a million cubic metres of saw logs are converted annually into sawn timber, producing in excess of 200,000 tonnes of hardwood sawdust. In recent years, the re-growth and plantation timber industry in Australia has been producing hardwood sawmill residues with lower extractive contents and lower densities.

The work presented here is aimed at developing an economical methodology for making particleboard using 100% hardwood sawmills waste. A comprehensive literature review indicated that a similar attempt has not been conducted to date. Through the literature review, major parameters which would influence particleboard made of sawmill waste were established. Subsequently, in consultation with the softwood particleboard industry, a preliminary process of making particleboards in the laboratory was developed. This method was trialled and modified until an acceptable particleboard could be produced.

A systematic experimental investigation was then performed incorporating a design of experiments method (DOE) and analysis of variance (ANOVA) to investigate the behaviour of single-layer and three-layer particleboard properties separately with processing parameters. Seven processing parameters were studied for three-layer boards while six parameters were studied for single-layer boards. The particleboard testing was performed according to the Australian and New Zealand standards for reconstituted wood-based panels. It was found that three-layer particleboards can be produced using 100% hardwood sawmill residues as the major raw material to meet the standards for general purpose particleboard. This hardwood particleboard uses a slightly higher amount of resin and moisture for its surface layer than conventional softwood particleboards.

To understand the effect of processing parameters on the particleboard properties, further analysis was conducted. Based on this analysis, process models were developed to predict the most critical particleboard properties (modulus of elasticity, modulus of rupture and the vertical density profile) with respect to processing parameters. These models can be used to optimise properties of hardwood particleboard with regard to processing parameters. Also, these models can be used to produce particleboards in the laboratory with required design properties.

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5. Nirdosha, G., Setunge, S. Jollands, M. and Hague, J. 'Properties of hardwood sawmill residue-based particleboards as affected by processing parameters'. International Journal of Industrial Crops and Products (Accepted).

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LIST OF SYMBOLS AND ABBREVIATIONS

t_1	thickness of the test piece before immersion in water
t_2	thickness of the test sample after immersion in water
ΔS	deflection of a particleboard specimen with the load ΔW
ΔW	Increment in load in N
a	Higher level of the factor A
A	Variable or Factor A
‘A’	Effect of factor A
‘B’	Effect of factor B
‘C’	Effect of factor C
‘D’	Effect of factor D
‘E’	Effect of factor E
‘F’	Effect of factor F
‘G’	Effect of factor G
A	Target density of single-layer particleboard (*Chapter 6*)
A	Moisture content in the surface layer of three-layer particleboard
ANOVA	Analysis of variance
b	Higher level of the factor B
B	Variable or Factor B
b	Mean width of test specimen (mm)
B	Moisture content in single-layer particleboard (*Chapter 6*)
B	Moisture content in the core layer of three-layer particleboard
C	Variable or Factor C
c	Higher level of the factor C
C	Resin load in a single-layer particleboard (*Chapter 6*)
C	Resin load in the surface layer of three-layer particleboard
D	Variable or Factor D
D	Hardener content in single-layer particleboard (*Chapter 6*)
D	Resin load in the core layer of three-layer particleboard
d	Higher level of the factor D
DF	Degree of freedom
DOE	Design of experiments
E	Variable or Factor E

E	Pressing time for single-layer particleboard production (*Chapter 6*)
E	Hardener content in the core layer in three-layer particleboard
e	Higher level of the factor E
F	Press temperature for single-layer particleboard production (*Chapter 6*)
F	Pressing time for three-layer particleboard production
f	Higher level of the factor F
G	Press temperature for three-layer particleboard
g	Higher level of the factor G
G_t	Swelling in thickness
HB	Hard board
IB	Internal bond strength
k	Number of parameters
L	Span between supports (When a specimen is tested for MOE/ MOR)
MDI	Di-phenyl methane di-isocyanate
MF	Melamine formaldehyde
MOE	Modulus of elasticity (MPa)
MOR	Modulus of rupture
OSB	Oriental strand board
t	Mean thickness of particleboard specimen (mm)
P	pressure at temperature T’
T’	relaxation time
P_0	Initial pressure
PF	Phenol formaldehyde
λ	Factor depending on density, species, particle geometry, moisture content
RSM	Response surface methodology
SS	Sum of squares
MS	Mean squares
SSA or SS_A	Sum of squares of factor A
SSE or SS_E	Sum of squares of error component
SSR	Sum of squares of the regressions
SST	Sum of squares of test statistical values
MSE	Mean squares of errors
MSR	Mean squares of regressions
T	Test statistical value

UF	Urea formaldehyde
VDP	Vertical density profile
W	Ultimate failure load (N)
y	Selected response (Chapter 8)
P	Probability of null hypothesis
$a_0 \ldots a_m$	Regression coefficients
$x_1 \ldots x_7$	Factors being studied
R^2	Pearson correlation coefficients
α	probability of null hypothesis
MS	Mean squares (Chapter 8)
SS	Sum of squares (Chapter 8)
MPa	Mega Pascal
kPa	Kilo Pascals
G_t	Swelling in thickness of each test piece
t_1	Initial thickness of the test sample (Chapter 10)
t_2	Thickness of the sample after immersion (Chapter 10)
F	Maximum flexure load (N) (Chapter 10)
B	Test sample before immersion (mm) (Chapter 10)
t	Test sample thickness before immersion (mm) (Chapter 10)
l_1	Span between support (mm) (Chapter 10)

CHAPTER 1

INTRODUCTION

1.1 Rationale

Within the 'family' of wood-based panels, particleboard is a mature and established product. Particleboards are generally made in Australia, using custom flaked soft woods. According to Drake (1995; 1997), particleboard consumption in the world represents 57% of the total volume of solid wood panel product consumption. Worldwide demand for particleboard has been growing steadily at a rate between 2 to 5% per annum. According to current Australian forest statistics, particleboard consumption in Australia increased by 7% during the year 2001 (ANU 2002). Raw material costs can constitute at least 50% of total production costs, whilst the properties of the wood raw material feedstock significantly influence the properties of the finished product. The particleboard industry has started to include smaller quantities of softwood sawmill residues into custom flaked softwood particles to produce particleboards with the required quality without significantly affecting the final particleboard properties. However, communication with the particleboard industry in Australia has indicated that more than 10% inclusion of these softwood residues into wood flakes creates adverse effects on particleboard properties.

Throughout Australia considerable quantities of hardwood saw mill residues are produced annually (Kim, 2001). In Victoria alone, over a million cubic metres of saw logs are converted annually into sawn timber, producing in excess of 200,000 tonnes of hardwood sawdust. This sawdust is mainly considered as solid waste. According to the industry sponsor of this project, Dormit Pty Ltd. of Dandenong, Victoria, numerous attempts have been made to find a solution for the growing problem of disposing of nearly 50,000 tonnes of sawdust collected at its sawmill in Swifts Creek at Central Gippsland. Such attempts have included burning of sawdust to generate energy, burning of sawdust and using the heat to convert some of the residue to briquettes and using sawdust as fertiliser. Due to the high moisture content of this green sawdust, none of the above alternatives were found to be satisfactory.

To date, hardwood residues have typically not been favoured by the particleboard industry (or indeed other forest product industries), primarily because of the perception that they have relatively higher density (compared with softwoods) and contain high levels of undesirable extractives, which can cause other processing problems. This has limited the potential market for such residues and their market value. However, the move in recent years by the sawn-wood industry towards the harvesting and processing of re-growth and plantation resources has opened up new opportunities for both the residue generators and potential residue users such as the particleboard industry, since the residues are likely to have lower extractives content and be of a lower density. A method to use hardwood sawmill residues as a raw material for wood-based composites has been investigated at RMIT University, Australia and the research program and the outcomes are presented in this thesis.

Wood density is considered to be the most influential factor affecting particleboard properties. It influences binder consumption, mat consolidation and hence board properties (Lehmann 1959). Previous publications suggested that the increase in raw material density causes a decrease of particleboard strength properties while increasing linear expansion and thickness swelling properties, at a given board density (Liri 1960; Mitchell 1957). For the same raw material, increasing the board density increases the board properties, especially the internal bond strength and it is closely related to particle size distribution of flakes. Increasing the amount of smaller particles increases internal bond strength.

Moisture is a critical component in manufacturing wood and fibre composites due to its effect on the initial drying operation of wood substrate, press cycle manipulation, wood conformability, composite properties, spring back, and post consolidation and re-humidification (Frink and Layton 1985). Hardwood sawmill residue has a higher inherent moisture content. Processing of residue to control the moisture content was therefore an important parameter considered in this thesis.

According to the Australian standards for wood based panels (AS/NZS/1859: 2004), General purpose particleboard should mainly satisfy its strength properties on modulus of rupture (MOR), modulus of elasticity (MOE) internal bond strength (IB) and screw withdrawal strength. However, initial investigation which was done in RMIT University shows that screw withdrawal strength satisfies the AS/NZS 1859:2004 requirement (Appendix E). It further shows that MOR, MOE and IB need to be improved significantly.

Density variation along the thickness direction within the final particleboard product occurs during the pressing process with higher density at the surface and a lower density in the core of the wood panels (Mitchell 1957). This variation in density along the thickness direction of a board is called 'vertical density profile' (VDP). VDP has a significant impact on particleboard properties. Elastic and plastic properties of the layers are mainly determined by the density of the particular layer. The denser layer is the layer subjected to the most deformation and compression within that layer. The layer's stress-strain behaviour determines its compressibility and hence deformation. Being a hydroscopic material, the temperature and moisture content of the wood determine its stress-stain behaviour. VDP was found to depend on the pressing conditions, heat and moisture content and resin cure, while horizontal density profile depends on the mat formation process and the layout of the wood flakes (Suchsland 1969; Oudjehane and Frank 1998). In most composite materials, the VDP is directly related to mechanical properties. Therefore, the effect of VDP on a particleboard product developed using hardwood sawmill residue was another aspect which had to be explored.

The following sections of the chapter will discuss the aims and objectives of this investigation, followed by the outline of this thesis.

1.2 Aims

The major aim of this investigation was to develop new knowledge and technology for producing an economical particleboard product using large quantities of hardwood saw mill residues as the main raw material. This required research into innovative pressing techniques including high-moisture pressing, investigating relationships between mechanical properties and processing parameters of particleboard, understanding the VDP generated during the hot-pressing operation as well as understanding the relationship between the VDP and the panel properties.

1.2.1 Objectives

- To develop an experimental methodology for making particleboard from hardwood sawmill residues in the laboratory.

- To develop an understanding of the effect of process variables (hot press temperature, cold and hot press closure times) and material variables (mat moisture content, resin load, hardener load) on the mechanical properties of particleboards made from hard wood sawmill residues. The mechanical properties measured on the final board were MOR, MOE and IB according to AS/NZS 1859 (1997; 2004). The screw withdrawal strength is an important aspect for the properties of a particleboard. However, optimisation of screw withdrawal strength was not carried out as part of this investigation as initial investigation showed that it has satisfied AS/NZS 1859 (2004) requirement of 400 kPa (Appendix E). Measurement of the VDP was carried out to relate the board physical properties to the mechanical properties of a given particleboard.

- To develop and validate composite material models to predict the MOR and MOE of a particleboard for a given set of process variables and material composition, and to use these models to optimize MOE and MOR of a board within a given process-parameter range.

- To study the formation of VDP and to model the VDP as a function of processing parameters and validate it with experimental VDP.

- To investigate the durability/ thickness swelling properties of hardwood particleboard in order to identify possible applications of hardwood particleboard.

1.2.2 Scope

The scope of the work covered the development of the complete methodology for producing particleboard from 100% hardwood sawmill residue to satisfy AS/NZS 4266 (2004) and AS/NZS 1859 (2004) requirements. This required an experimental investigation to understand the effects of material and process variables on the properties of three-layer particleboard production using hardwood saw mill residues. An experimental design was developed using partial factorial design to investigate the relationship between process variables, material variables, and the mechanical properties of the particleboard. Process variables considered here were the pressing temperature, cold press closure time and hot press closure time.

Material variables were the mat moisture content, the resin load and hardener load. The mechanical properties of the board in terms of input variables were evaluated. Analysis of variance (ANOVA) was used to analyse the results to investigate the most important factors in particleboard production using hardwood sawmill residues. During the research program, the importance of the VDP in predicting board properties was understood and consequently a detailed analysis of VDP was carried out, leading to a model predicting the VDP as a function of process variables.

1.2.3 Potential benefits

A study of this nature is important both to expand fundamental knowledge as well as enhance industrial applications. Outcomes will be a significant contribution towards the sustainability of the Australian Timber Industry and the environment by reducing logging to produce chips for softwood particleboard as well as using waste material for a viable product. The outcome will also be a significant benefit to regional and rural communities.

1.3 Outline of the thesis

To achieve the objectives, a well planned research program was completed. The thesis which presents the research program is divided into eleven chapters. A brief description of each is outlined below.

1.3.1 Chapter 1: Introduction

Chapter 1 introduces the topic of this research, rationale background, aims and objectives of this investigation. Also, it outlines the organization of this thesis, giving a brief introduction to each chapter.

1.3.2 Chapter 2: Effects of raw materials and processing parameters on particleboard properties

Chapter 2 reviews the literature on important physical and mechanical properties of particleboard and effects of material and process variables on these physical and mechanical properties. Commonly measured physical and mechanical properties of a particleboard are final board density, thickness swelling property, flexural strength (MOE and MOR) and the tensile strength perpendicular to the surface (IB) of the particleboard. This chapter further reviews the literature on different types of resin or binder used in the particleboard industry and compares their advantages and disadvantages. Various attempts made in the past to investigate the suitability of different types of raw materials for particleboard production including agricultural residues are also discussed.

1.3.3 Chapter 3: Review of simulation models to predict the formation of vertical density profile (VDP)

Chapter 3 discusses the literature on analytical, numerical and empirical models to simulate VDP of a particleboard. The applicability of various mathematical, numerical and experimental models for various conditions and their limitations are highlighted.

1.3.4 Chapter 4: General procedure for producing particleboards in the laboratory and methods of testing

Chapter 4 begins with the illustration of the apparatus used in the laboratory to produce particleboards and relevant Australian standards used to test their properties. It also presents the methods and procedures which were adopted in the laboratory to manufacture particleboards using hardwood saw mill residues.

1.3.5 Chapter 5: Design of Experiments (DOE)

Theories of design of experiments (DOE) were used to organize experiments to identify the most significant parameters involving hardwood particleboards. Therefore Chapter 5 discusses methods of DOE and analysis techniques used for this research. The advantage of using experimental design based on a factorial design, instead of changing two variables at a time is highlighted. In addition, it will elaborate the analytical techniques used to analyse data, such as ANOVA.

1.3.6 Chapter 6: Significant parameters influencing the properties of *single-layer* particleboards

At the beginning of this investigation, single-layer particleboards were manufactured in the laboratory before producing conventional three-layer particleboards. Chapter 6 describes the procedure followed to identify significant parameters influencing the properties of a single-layer particleboard using hardwood sawmill residues. Once these results were analysed, the most influential parameters on the properties of single-layer particleboards were identified.

1.3.7 Chapter 7: Significant parameters influencing the properties of *three-layer* particleboard

Chapter 7 investigates the significant parameters influencing the properties of three-layer hardwood particleboard using sawmill residues. Three-layer particleboards were prepared in the laboratory by changing the mix proportions for both surface and core layers of a particleboard to identify the significant parameters on the board properties. This chapter explains the experimental parameters and procedures adopted to produce three-layer particleboards. Analysis of the experimental results to identify the most important parameters for three-layer particleboard production using hardwood sawmills residues is also discussed.

1.3.8 Chapter 8: Formulation and process modelling of particleboard production using hardwood sawmill residues

Chapter 8 presents the development of polynomial regression models to predict the MOE and the MOR of a hardwood particleboard as functions of processing parameters. The validation of these models using further experiments is also discussed in this chapter. These models were used to optimize the MOR and MOE of a particleboard.

1.3.9 Chapter 9: Development of composite process models to predict the vertical density profile (VDP) of a particleboard

Chapter 9 discusses the attempt to model the VDP of a particleboard with respect to the processing variables which were studied in this work. A process model clearly shows the relationship between the raw materials and processing parameters with the density at different locations along the thickness of the board. This chapter illustrates the modelling of VDP with regard to the actual processing parameters used. The usability as well as advantages of the model for the improvement of final particleboard properties are discussed.

1.3.10 Chapter 10: Possible applications of Hardwood particleboard (Reference to AS/NZS: 1859)

Chapter 10 presents an investigation into the thickness swelling property of a particleboard as that has a significant effect on the stability of the particleboard as well as on the bond durability. This is an important property to be explored to identify possible applications for hardwood particleboard.

1.3.11 Chapter 11: Conclusions and recommendations

Chapter 11 summarizes the general conclusions of the work reported in the thesis. Further, it illustrates recommendations for future work in the area of the research.

CHAPTER 2

EFFECTS OF RAW MATERIALS AND PROCESSING PARAMETERS ON PARTICLEBOARD PROPERTIES

2.1 Introduction

Particleboard is a low cost alternative to solid wood panels and is 57% of the total wood panel consumption in the world (Drake 1995). The demand grew 3.5% annually for 15 years until 1995 and is still growing (Drake 1995). Figure 2.1 shows the spread of total wood panel consumption in the world, indicating that North America, Europe and Asia each consume a little under one-third of the panels produced in the world. Russia takes about 8% and the rest of the world consumes the balance.

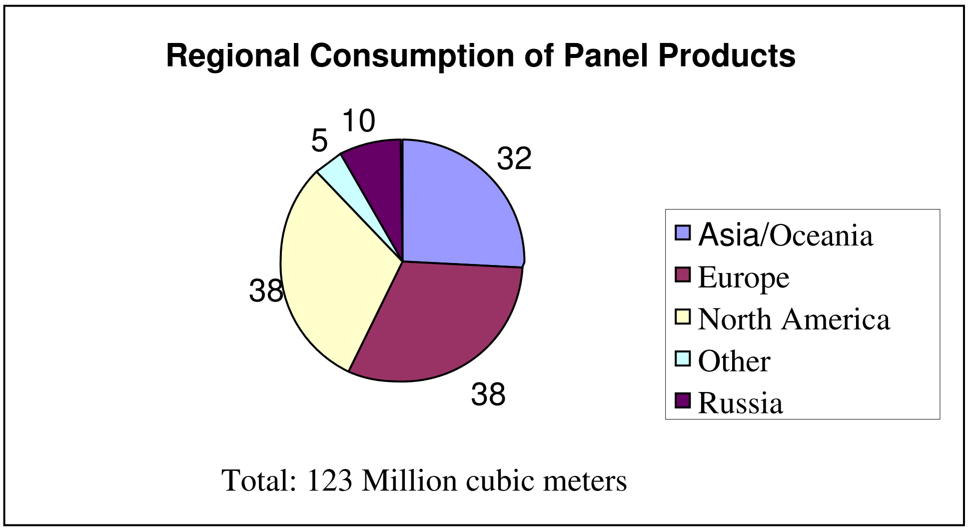


Figure 2.1: Regional consumption of panel products (Drake, 2005)

Further, Drake (1995) analysed and reported (Figure 2.2) that the growth rate for total wood panel consumption is 3 to 4% per year and the predicted total wood panel consumption could be around 210 to 225 million cubic meters by 2010. He indicated that this growth would require a further 100 million cubic meters of wood panels by 2010 compared to the consumption in 1990. Since in recent years the rate of increase in plywood consumption has declined or remained static at about 25% of total wood panel consumption, a significant increase in particleboard consumption has been observed and it will be around 60% of total wood panel consumption by the year 2010 (Drake 1995).

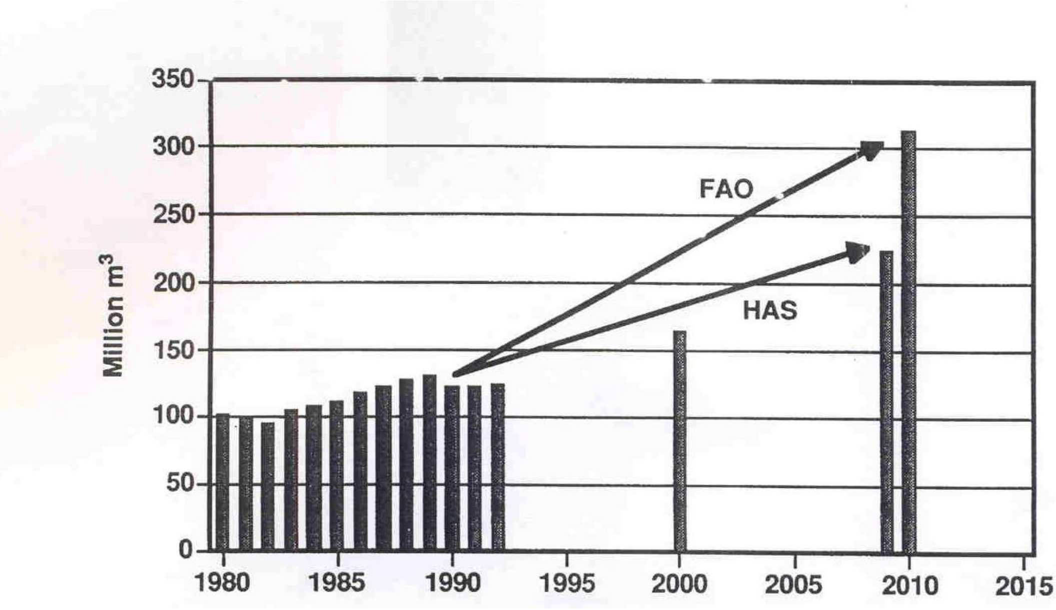


Figure 2.2: Wood-based panel consumption worldwide growth projection (FAO = Food and Agriculture Organization and HAS = H.A. Simpsons, Ltd.) after Drake 2005

Kozlowski and Helwig (1998) reported that the particleboard industry supplied a significant portion of total wood consumption in the world, which was 0.36 billion cubic meters and expected to reach 0.47 billion cubic meters by the year 2010. According to Drake (1995; 1997), the level of utilization of the current wood harvest is estimated to be around 50% of the volume that is felled and the rest is being left in the forest unused. Improved utilization practices and new manufacturing technologies could improve the amount of raw wood required by the wood panel industry.

As observed by Alma et al. (2004), the world population currently consumes over 3.5 billion tons of green wood annually. If the consumption rate of wood fibre and the rate of population growth (approximately 90 million people per year) stay constant, the demand for wood fibre will increase by over 60 million tonnes each year. That would significantly increase deforestation, creating a huge negative impact on the environment (Zheng et al. 2006). Therefore, it is vital to explore different raw materials to meet that demand. Particleboard and other wood composite researchers have been interested in the use of different raw materials such as agricultural wood wastes. The work presented here deals with the investigation of the use of hardwood sawmill residues as particleboard raw material. Therefore, it is vital to have a general understanding of important properties of particleboard as a building or construction material. A thorough knowledge of the particleboard production process, processing parameters and the relationship between processing parameters and particleboard properties will be extremely helpful.

This chapter discusses the important physical and mechanical properties of particleboard and the effects of material and process variables on these properties. Commonly measured physical and mechanical properties of particleboard are final board density, thickness swelling property, flexural strength and the tensile strength perpendicular to the surface of the particleboard. This chapter further reviews the literature on different types of resin or binder used in the particleboard industry and compares their advantages and disadvantages. Various attempts made in the past to investigate the suitability of different types of raw material including agricultural residues are also discussed.

2.2 Wood-based panels and their usability

Based on the physical configuration of the wood particles which are used to manufacture wood-based composite panel products, wood-based panel products can be categorized into four main types (Wood Handbook 1999). They are plywood, oriented strand board (OSB), particleboard and fibreboard. The similarities or variations between each type of these panels are discussed in following subsections.

2.2.1 Plywood

Plywood is a flat panel built up of sheets of veneer called plies. These plies are bonded in layers by using a bonding agent between plies to create a panel. These plies are laminated together such that their grain directions are parallel to each other. A layer can consist of one or two or odd or even numbers of plies. However, the plywood panel is always made up using odd numbers of layers in such a way that the grain directions of adjacent layers are oriented perpendicular to one another. This alternating grain direction in the adjacent plies between layers provides the dimensional stability of the plywood. Plywood can be made of either softwood or hardwood (Wood Handbook 1999).

2.2.2 Oriented strand board (OSB)

Oriented strand board is an engineered structural-use panel manufactured from thin wood strands united together with waterproof resin using hot pressing. Thin strands are normally prepared using debarked wood logs from pine or birch-type woods. These strands are dried and blended with resin and wax to form a loosely consolidated mat. The mat is then hot-pressed to produce OSB. The applications of OSB are mainly for roof, wall and floor sheathing in both industrial and commercial use.

2.2.3 Particleboard

Particleboards are generally made of three layers using custom-made softwood flake, blended with resin. Particleboard production is mainly a dry process as sketched in Figure 2.3. Particleboard includes different panel types called chipboard, flake board, strand board or wafer board depending on the size and shape of the wood particles used (Wood Handbook 1999). Particleboard has a specific gravity of between 0.6 and 0.8 and is usually produced from softwoods such as Douglas fir, southern pines or other low-value wood sources (Maloney 1993). This chapter will extensively discuss the production methods, materials and properties of particleboards.

2.2.4 Fibreboard

Fibreboard mainly includes hardboard, medium-density fibreboard (MDF) and insulation boards. Fibreboard exploits the inherent fibre strength of wood by means of wet processing. Fibreboard can be produced using a wet process or a dry process. Fibreboard production using the dry process is very similar to particleboard production except for the pressing procedure. Wet forming fibreboard is significantly different from the dry forming process. The wet process is really an extension of the paper manufacturing process (Wood Handbook 1999).

In addition, the schematic diagram in Figure 2.3 shows the different types of panels and methods used to manufacture them, particle size and average panel density (Suchsland and Woodson 1986).

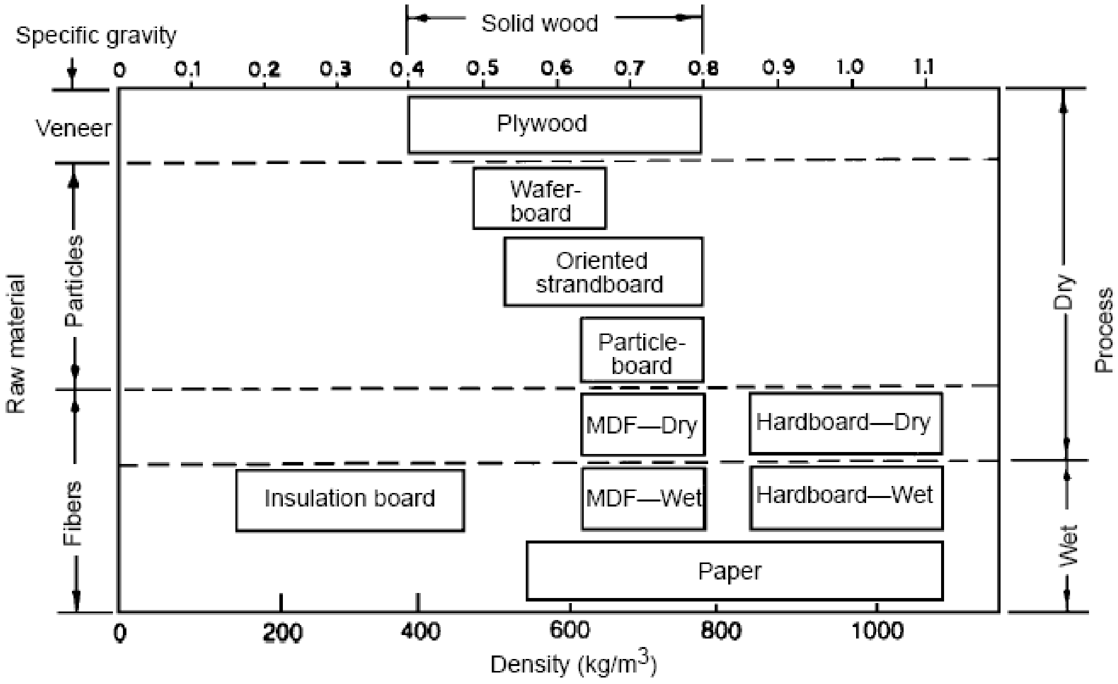


Figure 2.3: Classification of wood composite boards by particle size, density and process type (Suchsland and Woodson 1986)

Wood-based panels are used extensively in the commercial and domestic construction industry. Major uses are for roof and wall sheathing, floor decking, exterior siding and interior decorative walls. In addition, wood-based panels particularly particleboards are used for making furniture, cabinets and bathroom and kitchen cabinets and shelving (Marcin 1987). Softwood plywood has become the dominant material used in roof sheathing in residential construction. According to Marcin (1987), in USA 86% of roof sheathing used plywood and the rest used lumber sheathing of spaced panels. Further, he reported that structural particleboards and veneer composites would have gained some share of the roof sheathing market.

Exterior wall sheathing uses wood-based panes, gypsum boards or lumber boards as well as plastic foam sheathing and aluminium-foil-faced sheathing. Selecting the type of material may change depending on the structural requirements, insulation requirements and cost. Floor decking is another major use of wood panel products. This market is primarily served by particleboard, plywood, wafer board and also with new types of structural panels (Marcin 1987; ANU 2002). According to the Australian National University (ANU 2002), structural particleboard has taken the major share of floor panel consumption with its lower cost (A$

11.00 – 12.00 per square meter in 2002) compared to pine wood floor panels (A$ 21.00-22.00 per square meter in 2002). In addition to the cost, depending on the end user's requirements, particleboards or most of the other panels can be manufactured for specialized termite resistance, fire and moisture resistance and with special thicknesses and sizes.

2.3 General procedure for manufacturing particleboard

In understanding the properties of particleboards, it is important to understand the basic manufacturing procedure of particleboards. Chapter 4 discusses the laboratory procedure adopted for the purposes of this study to manufacture particleboards. This section outlines the general methodology followed by both the particleboard industry as well as particleboard researchers. Standard grade particleboards are made in Australia using custom-flaked softwood fibre as the major raw material. Boards are usually made of three-layers with finer material bonded with about 10% resin in the surface layers and coarse flaky particles bonded with a lower proportion (8%) of resin in the core (Figure 2.4).

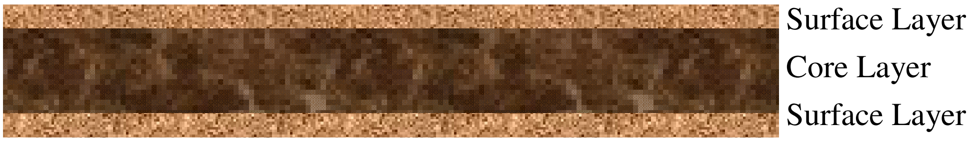


Figure 2.4: Typical cross section of a three-layer particleboard

However, single-layer or five-layer particleboards are manufactured occasionally for mainly research purposes. Figure 2.5 below depicts the general procedure of particleboard production practised by the particleboard industry. The important steps highlighted are:

- Custom flaked wood chips, also called custom flaked wood furnish, are prepared either on-site or off-site of the particleboard factory. Softwood forests are normally cut and milled to prepare the wood chips. The commercial particleboard industry uses two different types of wood chips for the core layer and for the surface layer of three-layer particleboard.

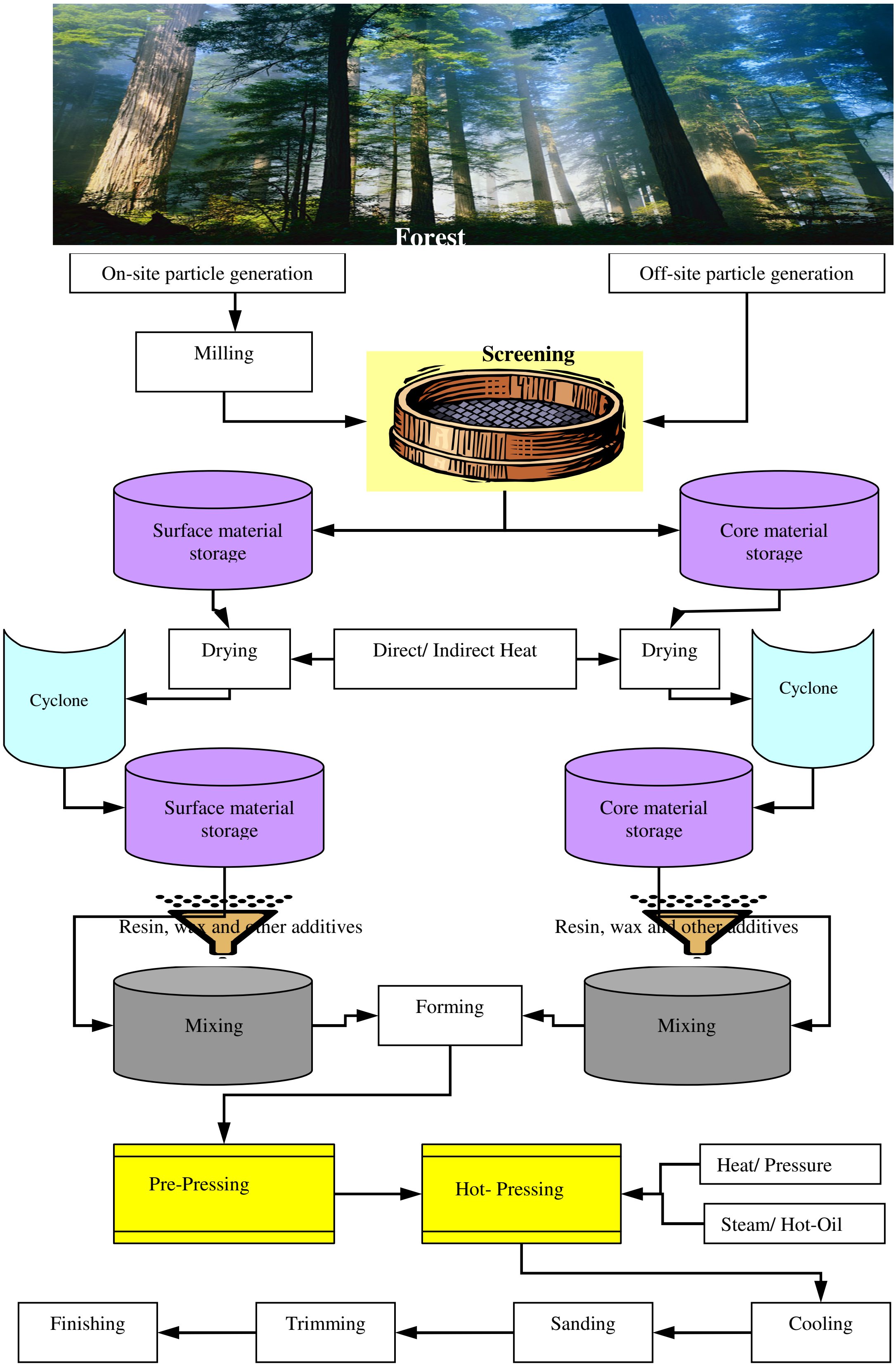


Figure 2.5: Particleboard manufacturing process (Prepared by the Author)

- These chips are classified using screening to separate surface and core layer materials for three-layer particleboards. The surface layer uses smaller sized wood chips while the core layer uses bigger particles. These custom flaked wood chips have a specific but broad particle size distribution to achieve proper compaction during the production process.
- The materials are dried to remove moisture entrapped between particles before mixing with other additives.
- Wood particles are blended while being spayed with a mix of water, resin and other additives such as hardener and wax to prepare the wood pulp. Surface and core materials are blended separately as they use two different recipes.
- The pulp is formed in three layers to prepare the particleboard mat for pressing.
- The particleboard mat is pre-pressed, followed by hot pressing. The commercial particleboard industry generally trims the edges of the wood mat before hot pressing.
- Hot pressing is done at a specific temperature for a specific time to complete the process.
- The final particleboard is left for cooling before being finished by sanding and trimming.

Up to about 5% of sawmill residue from softwood sawmills is incorporated in making particleboard without a significant reduction in mechanical properties (Nemli et al. 2006). Unlike custom flaked wood chips, sawmill residue does not have a specific particle size distribution. Therefore, using more saw dust would interfere with compaction during the production process. Use of hardwood residue, especially finer particles, has not yet been accepted nor explored in detail by the mature particleboard industry due to its inherent properties such as higher density, high extractive content and particle size distribution.

2.4 Physical and mechanical properties of a particleboard

According to wood handbook (1999) successful manufacturing of any wood composite needs a good control over raw materials used. If raw materials are uniform, consistent and predictable, the final product properties can be predicted. However, wood does not offer this uniformity but varies significantly from species to species. Size reduction during the production process and the shape of individual lignocellulosic components will depend on application. Therefore, physical and mechanical properties of a particleboard are controlled by the properties of the raw material (mainly wood furnish and resin type) used as well as processing parameters controlled during the manufacturing process. Unlike fibreboard, frbrous nature of lignocellulosics in not exploited. That is because converting wood into particles requires less energy compares with converting into fibres. Therefore, the main raw material properties which control the final properties of a particleboard are the furnish density, size, and shape. The initial moisture content of the mixture and the amount of adhesive used have significant influence on the final properties of the particleboard. The key processing parameters are the hot pressing time and the press temperature as they link with the cross-linking temperature of the resin and temperature and time taken for moisture to escape from the board (Dunky 1998; Hawke et al. 1992).

2.4.1 Density of the board

The initial pressing operation consolidates the particle mat into the desired thickness by reducing and eliminating voids between particles. Then, the curing of the resin creates the bond between particles and that ensures the retention of the consolidated mat at the desired thickness. Two stoppers placed either side of the mat enable the manufacture to attain the ultimate thickness of the particleboard or the amount of mat consolidation by closing the platens against the stoppers during the pressing process. The platens stop at the stopper which is made of an incompressible material subject to maximum applied press or the maximum capacity of the press as maximum pressing capacity is employed during the hot pressing.

The ultimate density of the particleboard is dependent upon the amount of furnish used to make the particleboard at a given thickness and the density of the wood furnish. In addition, it depends on the resin load and the amount of other additives such as hardener or wax load. However, the final board density is independent of the press capacity, press closure time or press temperature as long as they are sufficient for resin curing and evaporation of excess moisture trapped inside the mat. The VDP of the board is mainly governed by press capacity, pressing time and temperature (Oudjehane and Lam 1998). The literature on the formation of VDP and its effect on particleboard properties is reported in Chapter 3.

The densities of the raw materials used as well as the compaction of the mat during the pressing operations mainly control the density of the particleboard. Particleboards with the same average density, achieved by higher raw material density or by higher compaction do not show the same physical or mechanical properties. Larmore (1959) investigated the flexural strength of particleboard with constant specific gravity (0.73 at a temperature of 24°C and relative humidity of 65%) from different species. He found higher MOR values from particleboards made from aspen furnish (specific gravity 0.37) than those particleboards made from yellow birch (specific gravity 0.65). Further he reported that particleboards with specific gravity lower than the specific gravity of the furnish produced very low MOR. The properties of particleboard depend on both density of furnish used as well as processing parameters.

Suchsland (1959) developed a statistical model for the degree of densification of a particleboard mat with respect to particle geometry, wood species density and relative air volume. Since the total particle thickness varies in a mat, the area with greater total particle thickness experiences higher compaction than the area with low total particle thickness in order to maintain a uniform thickness during the compression. He added that the relative compression area is a significant factor to determine the bending strength of a flake-board-type particleboard. Further, he stated that narrower and thicker flakes require higher pressing capacity to attain a desired specific gravity than wider and thinner flakes.

Increase in the board density increases inter-locking between particles that enhances the development of stronger glue-bonds between particles. However, this inter-locking could be increased up to a certain point to allow moisture which is vital for heat transfer to travel from the surface to the core and then to escape from the edge of the board (Kelly 1977).

2.4.2 Bending strength of a particleboard

Bending strength of a particleboard is a very important property that determines the applicability of a particleboard for structural bending elements such as floorboards. The MOR or the ultimate bending strength and the MOE or the stiffness of the board are directly related to the bending strength. This section of the chapter mainly reviews the MOR and the MOE of particleboard with respect to wood furnish properties. These properties will further be reviewed later in the chapter under the processing condition and parameters in Section 2.6.

2.4.2.1 Modulus of rupture of a particleboard (MOR)

The MOR, defined as the ultimate bending strength of the particleboard, is normally determined after a static bending test. The MOR is very important property that controls the usability of a particleboard as a structural building element. The MOR of a particleboard is dependent on various factors including material type, size and processing conditions. This section reviews the factors which are important for MOR of particleboard as well as similar types of composite panel products.

Hse (1975) stated that the board density, divided by the wood furnish density, is the compaction ratio, which highly influences the final bending strength of softwood particleboard. Further, previous researchers indicated that the compaction ratio of the particleboard increases the MOR of the final board (Hse 1975; Howard 1974; Vital 1973). However, particleboards with the same compaction ratio from different furnish densities do not produce constant MOR values (Vital 1973). Stewart and Lehmann (1973) reported that while increase in panel density increased the MOR for panels from four different hardwood species, an increase in species density decreased the MOR. This finding is similar to the observations made by Stegmann and Durst (1965) for softwood particleboards. Therefore, it is common to both softwood and hardwood that the increase in panel density increases the MOR.

Research has found that the vertical density gradient significantly influences MOR of the particleboard, as bending stresses are higher at the surfaces (Rice 1960; Lehmann 1965). Lehmann (1965 and 1970) further explained that the increase in surface moisture content up to 16% increased the surface density and MOR, and further increase in moisture reduced the MOR due to excess of moisture trapped in the middle of the board. Suchsland (1974), Beech (1975) and Nemli et al. (2006; 2007) explained that higher moisture in the middle of the board after the hot-pressing leads to non-reversible spring-back of the particleboard. This lowers the MOR of the particleboard. Heebink et al. (1972) also found that the surface densification and MOR increased with increase in press closing speed. The formation of VDP and the effects of its variations on the board properties are discussed in Chapter 3.

Various attempts have been made in the past to investigate the effect of particle size and shape on particleboard properties for both hardwood and softwood materials (Turner 1954;

Post 1958; Brumbaugh 1960; Heebink and Hann 1959; Lehmann and Geimer 1974). According to these reports, the increase in flake length up to 5 cm while maintaining the flake thickness and other processing conditions increased the MOR however, further increase in length started to decrease the rate of increase. However, increase in flake thickness above 0.26 mm started decreasing the MOR for all flake lengths.

Brumbaugh (1960) indicated that the length/thickness ratio of the flake was a better indicator of the MOR, when increasing the length/thickness ratio up to 400 for Douglas fir particleboard. He reported that the best length/thickness ratio is 250 for optimum properties. In a similar investigation, Kimoto (1964) found the optimum MOR with a length/thickness ratio of flake at 100 by increasing it from 10 to 100. Heebink (1974) investigated the variation of MOR by changing particle length and thickness while maintaining the length/thickness ratio. He concluded that increasing the particle thickness from 0.5mm to 0.75mm had a more detrimental effect than decreasing particle length from 75mm to 50mm. Lehmann (1974) and Gatchell et al. (1966) reported that the increase in flake thickness has a negative effect on MOR when phenol formaldehyde is used as the binder. However, Stewart and Lehmann (1973) indicated that if the flake thickness was in a range of 0.15mm to 0.45 mm, the MOR did not change significantly. Suchsland (1959) reported the most appropriate particle configuration for softwood three-layered particleboard was narrow thick particles for the core and short square particles for the surface. Kusian (1968) indicated that short smooth particles at the surface produced a smooth surface.

Research on particleboard properties of hardwood sawmill residues was not found by the author. Nemli et al. (2006) once reported that finer particles such as softwood sawdust (particle size < 0.25mm) up to 5% could be incorporated for particleboard production without much variation to MOR. However, any further increase started decreasing MOR as more and more short fibre affects the bending strength (Maloney 1970; Brumbaugh 1960).

2.4.2.2 Modulus of Elasticity (MOE)

The modulus of elasticity is an important parameter that determines the stiffness or the resistance to bending of the particleboard. Generally, both MOE and MOR are calculated after a three-point bending test as per AS/NZS 4266.5 (2004). In most situations, both MOE and MOR have similar trends with respect to processing parameters such as board density and species density. Hse (1975) reported that by decreasing the hardwood species density, the MOE value for the same density particleboards can be increased as MOE increases with the increase in the compaction ratio. An increase in board density while maintaining other process parameters steady, significantly increases the MOE for both hardwood and softwood particleboards (Lehmann 1970; Kelly 1977). Various attempts have been made to show the influence of VDP and press closing time on the MOE. It has been reported that high density surfaces significantly improve the MOE even with the same mean density for softwood particleboard (Geimer et al.1975; Heebink et al. 1972). That may be due to the bending strength being mainly dependent on the surface of a beam element.

Similar to MOR, MOE could be increased by increasing the particle length/thickness ratio. MOE increases with an increase in flake length and decrease in particle thickness (Lehmann 1974; Heebink et al. 1964). Addition of fine particles such as saw dust decreases the MOE of a softwood particleboard due to low amounts of woody cells and short fibres (Nemli et al. 2006; Maloney 1970; Brumbaugh 1960). However, both Nemli (2006) and Maloney (1996) recommend that up to 5% of softwood sawdust could be included in particleboard raw material with minimum effect on MOE.

In summary, it can be concluded that both MOR and MOE of a particleboard can be improved by increasing the compaction ratio (defined as the ratio of particleboard density to the particle raw material density) as well as by increasing the length/thickness ratio for the same wood species. The optimum MOR or MOE of a particleboard can be produced with a length/thickness ratio of around 250. The MOR and MOE of a particleboard with the same mean density increase with the decrease in the density of the wood species. Therefore, our main challenge in the work proposed here is the utilization of hardwood sawmill residue as particleboard raw material without compromising MOR or MOE.

2.4.3 Internal bond strength of a particleboard

Internal bond (IB) strength is measured as the tensile strength perpendicular to the board surface. When a tensile stress is applied perpendicular to the surface, the particleboard normally fails close to the middle of the board where density is low. The lowest inter-particle contact and lower consolidation is found in the centre of a particleboard at the lowest density region.

Previous investigators indicated that the lower density core decreases the IB strength of particleboard or fibreboard and that higher density surface increases MOE and MOR (Strickler 1959; Geimer et al. 1975). According to Strickler (1959) the lower density in the core of a particleboard is a result of a lower press cycle which results in excessive moisture in the core. During the hot pressing process, the transportation of moisture from surface to core is the main medium that carries heat from the hot platen to the core of the board. That is vital to chemical reactions leading to resin cure (Lehmann 1970; Hart and Rice 1963; Heebink et al. 1972). However, if the press cycle is not sufficient to heat up the core moisture to evaporate the excessive moisture from the particleboard, this moisture may be trapped inside the particleboard even after the hot pressing. The trapping of excessive moisture leads to spring-back of the board breaking inter-particle bonds and creating a lower density core. Hse (1975) reported that an increase in compaction ratio increased the IB for particleboards from nine different hardwood species.

Similar to MOR and MOE, particle configuration has a significant effect on IB. Changing the particle configuration from long wide flakes to planer shavings or slivers improves the IB significantly (Childs 1956; Suchsland 1959; Brumbaugh 1960;d Lehmann and Geimer 1974). The research further explaines that particle configuration should be maintained in order to produce homogeneous particleboard. Flake particles for the surface and coarse particles for the core would optimize MOR, MOE and IB in the same particleboard (Kelwerth 1958; Suchsland 1960). Nemli et al. (2006), who investigated particleboard properties with respect to manufacturing parameters, reported that IB improved with increasing amounts of wood dust (particles < 0.2mm) up to 20% and then started decreasing. Smaller particles increased the contact between blended material (resin) filling the gap inside the core and increased the resistance to tension perpendicular to the surface. Further increase in dust required more and more resin to wet the whole surface until then eventually ran out of resin, producing weaker board. They observed that IB increased with resin load. The observed reduction of IB with the increase of the surface moisture from 9% to 13% was explained as due to excessive moisture being trapped inside the board after hot pressing.

Researchers have investigated the effects of adding wax during particleboard production on the IB strength of particleboard. Talbott and Maloney (1957) found a significant improvement in IB by adding 0.75% wax into phenol-formaldehyde-bonded particleboard with controlled specific gravity and particle size. Hann et al. (1962) reported similar observations for UF-bonded particleboard with 1% wax. However, Heebink and Hann (1959) observed no changes to IB strength after adding 1% wax into UF-bonded particleboard. Later they found that an increase in wax above 2% reduced the IB strength of a particleboard (Stegmann and Durst 1965; Gatchell et al. 1966). Little evidence is available to confirm the relationship between wax and IB or to explain the chemical attraction between wax and wood particles. The addition of wax is required to improve liquid water resistance of a particleboard. However, excessive wax would hinder bond formation.

Ayrilmis (2006) investigated the IB and bond durability of phenol-bonded particleboard by adding different quantities of boric acid, borax, mono-ammonium phosphate and di-ammonium phosphate, which were known to improve the fire retardant and biodegradation properties of wood and wood products. However, as almost all the fire retardants used appeared to interfere with the glue line strength development for phenolic resin, a reduction in IB was observed.

It is clear that IB is a very important property in a particleboard that depends highly on glue line strength. IB reduces with the reduction in core density since the compaction ratio is low. IB can be improved by adding extra resin into the core, however excessive addition of water resistance such as wax or addition of fire retardant such as boric acid or borax reduces the IB. Also, it is noted that the addition of excessive amounts of smaller particles such as sawdust would decrease the IB. These findings are very important for the present study as it is dealing with a new hardwood material which contains excessive amounts of sawdust.

2.4.4 Durability

Bond durability is the major issue in particleboard when it is exposed to the environment with different moisture conditions, temperature levels etc. Similar to solid wood, particleboard is hydroscopic and can become dimensionally unstable by absorbing moisture from a high humidity environment. However, the dimensional change in thickness direction is much greater for conventional flat press particleboard due to the release of compressive stress incorporated into the board during pressing operations (Kelly 1977). The thickness swelling due to absorption of moisture is not entirely reversible even after the board is subsequently dried. This irreversible thickness swelling is a result of moisture penetration into the board which leads to bond failure. Irreversible thickness swelling is a very disturbing characteristic in a particleboard since it occurs unevenly and is therefore aesthetically unappealing.

Thickness swelling normally occurs close to the edges of the board leading to swollen edges. Swollen edges absorb more and more moisture resulting in paint failure and panel decay.

Research has found that the manufacturing process of particleboards contributes to board thickness swelling. Halligan and Schniewind (1972) observed an increase in thickness swelling as board density increased when the moisture content was 10% or higher, for a series of particleboards made with three different resin levels. When moisture content was less than 10%, boards showed little influence on the change in thickness swell. This finding was confirmed by several other reports (Vital et al. 1974; Hse 1975; Gertjejansen et al. 1973). The application of high pressure during the pressing operation required to attain an adequate inter-particle contact for proper glue bonding (Dai and Stainer 1994; Suchsland and Xu 1989). These high pressures would contribute to wood cell wall buckling, creating plastic hinges or fractures depending on the viscous-elastic state of the polymers. The elastic buckling of wood cell walls during hot pressing may recover if exposed to moisture by absorbing water, ultimately contributing to the thickness swelling (Wolcott et al. 1989; 1990). Researchers have found that cell wall recovery from deformation is higher than solid wood of the same species (Wu and Piao 1999; Kelly 1977). This viscoelastic recovery of the collapsed cell wall as a spring back or non-recoverable thickness swells could be up to 75% of the total thickness swell. Adcock and Irle (1997) reported that the cells which have undergone a greater compression could have a greater potential of thickness swelling than those that were slightly compressed.

Stewart and Lehmann (1973) studied the effect of hardwood species on particleboard properties. They investigated four different hardwood species: basswood, yellow poplar, red oak and hickory. The density of those four species was reported as 593 kg/m^3, 785 kg/m^3, 993 kg/m^3 and 1073 kg/m^3 respectively. They found an increase in board stability with reduced thickness swelling when the particleboard density was increased for all the four hardwood species. They also found that neither low-density panels nor low-density species always produced the most stable board. As reported earlier, the shape of the particles is important for particleboard compaction. Also, increase in particleboard density increases particleboard compaction, hence inter-particle bonding increases, leading to increased particleboard properties.

Suchsland (1973) reported no relationship between thickness swell and board thickness for ten commercial particleboards under cyclic relative humidity and water soak exposure.

However, he too observed the highest thickness swell from the particleboards with highest densities. However, particleboard made with phenol formaldehyde resin showed no relationship between thicknesses swell and board density (Lehmann and Geimer 1974; Gertjejansen et al. 1973). Kelly (1977) explained that there was no consistent and reproducible relationship between particleboard density and linear expansion.

Some research have indicated that particle thickness has a significant effect on the stability of the particleboard and hence thickness swelling (Lehmann 1974; Brumbaugh 1960; Post 1958). Post (1961) added that flake length has no relationship with board stability or thickness swelling if the particle thickness is less than 0.3 mm. Particleboard made with thinner particles was more stable compared to that made with thick particles. Having thinner particles with lower wood mass in each particle increases the number of inter-particle contacts, facilitating better dispersion of hydroscopic swelling into microscopic inter-particle voids (Kelly 1977). Because of this swelling into microscopic voids, the creation of internal swelling within the wood particles is reduced, which results in less thickness swelling.

Further research has shown that increasing the resin content improves the thickness stability of a particleboard with both urea formaldehyde resin and phenol formaldehyde resin (Hann et al. 1963, Lehmann and Hefty 1973; Gatchell et al. 1966). It may be expected that increasing the resin content in a given particleboard will result in improved inter-particle bonding, which should improve board stability.

Paraffin wax is normally added into the mixture during particleboard production to reduce short-term moisture penetration into the board to improve durability. Many researchers have observed that wax-treated particleboard has a large or moderate reduction in both water absorption and thickness swelling in the 24-hour water soak test (Stegmann and Durst 1965; Maku et al. 1959; Heebink and Hann 1959). However, increasing the wax content to more than 1% of wax solids in oven-dry wood interferes with adhesive bonding, eventually reducing the strength properties (Kelly 1977). In contrast to the above claims, when wax-treated particleboard was exposed to water vapour for a long term, there was no reduction in either moisture content or dimensional changes (Gatchell 1966; Heebink and Hann, 1959).

Some researchers have reported that the dimensional stability of a particleboard could be improved by post-steaming of the final board or heating the unbounded particles (Heebink et al. 1972; Hujanen 1973). These methods would reduce hydroscopic thickness swelling and consequently improve dimensional stability Kelly (1977). However, reported that the industry has not accepted those methods due to excessive costs in processing.

Various types of inorganic salts such as phosphoric acid, mono-ammonium phosphate, di-ammonium phosphate, ammonium sulphate, nitrogen or boron compounds such as boron, borax and boric acid can be added to improve fire-retardant properties and biodegradation (Ayrilmis 2006; Tsunoda 2001). However, adding fire-retarding chemicals during particleboard production can cause effects on pH level, resin viscosity and reduction in the number of hydroxyl groups available for hydrogen bonding ultimately resulting in reduced bond strength (Boggio and Gertjejansen 1982). Ayrilmis (2006) observed a significant reduction in IB and aged IB by adding fire-retarding chemicals. A greater strength reduction was found with an increase in boron compounds levels or organic acid levels, since the change in pH significantly affects bond durability.

The durability of a particleboard can therefore be improved by improving the stability. Increasing the resin content in a particleboard reduces the thickness swelling as well as spring back, although high moisture content has the opposite effect. Releasing the pressure after hot pressing should be carefully maintained to reduce spring back. Increasing the pressing time also assists. Additives such as paraffin wax are added to the particleboard to reduce water adsorption in order to reduce the thickness swell. Similarly, addition of fire retardants such as borax is important for the durability of a particleboard. However, the amount of these additives should be maintained carefully as they may have an effect on the resin curing. The stability of hardwood particleboard, specially spring back and thickness swell, with respect to processing parameters will be discussed in Chapters 7 and 10 respectively.

2.5 Wood parameters

2.5.1 Wood species density

The effect of wood species density on particleboard density is interdependent such that if the final board density is less than the species density, an unsatisfactory board is produced (Suchsland 1967; Hse 1975). The final board density should be higher than the initial wood furnishing density to attain better inter-particle contact and hence sufficient bond between particles by maximizing usage of resin. Otherwise, most of the resin will polymerize at the void spaces resulting in poor inter-particle bonding. Therefore, research has suggested the need to compress the wood furnish to a higher specific gravity than their original to obtain sufficient inter-particle contact in order to improve resin efficiency.

In the case of high-density woods, generally hardwood, the inherent strength and stiffness of the wood elements is greater than that for lower density species. Therefore, a greater compressive force is required to attain a similar degree of inter-particle contact, and the magnitude of internal stress is increased (Hse 1975). Stewart and Lehmann (1973) investigated particleboard properties with cross-grained knife-planed hardwood flaked with nominal chip thickness of 0.006 (0.15 mm), 0.012 (0.30mm) and 0.018 (0.45mm) inches. A factorial design was carried out for four types of species, three panel densities and flake geometries. These researchers used a constant amount of resin, 8% of urea formaldehyde for all the experiments with pH at 3.5. The amount of catalyst needed for the resin was determined experimentally. Similar to Larmore (1959), Stewart and Lehmann (1973), Liri (1960) and Mitchel (1957) also found that the higher the species density, the lower the modulus of rupture and elasticity. With the increase of board density, the MOR and the MOE increase linearly, and the strongest board was produced from 0.006-inch (0.15 mm) flakes. Increasing the board density increases the internal bond strength and they suggested that it is closely related to particle size distribution of flakes. In addition, a higher proportion of smaller particles increase IB. However, IB does not have any relationship with the species density. Further, Stewart and Lehmann (1973) reported that the boards produced from cross-grain planer flakes were extremely stable in different room humidity conditions. Boards produced from low-density cross-grain flakes were more stable than those produced from higher density species.

Haygreen and Gartjejansen (1971) investigated the use of five tropical hardwoods with medium to low density (Aceituna, Banak, Jogo, Gallina and Aspen) on the properties of flake-type particleboards with a normal density of 721 kg/m^3 using UF resin. They observed superior bending properties in the boards made from the species with lower densities, compared to those made from the higher density species. The founding was explained as furnish from lower density species could attain better compaction and inter-particle contact than the higher density species when producing particleboard with the same normal density.

Vital et al. (1974) investigated the relationship between board density on particleboard properties using four exotic hardwood species (kiri, virola, limba and afrormosia). They produced three-layer particleboard using wood furnish from either one species or mixed species. They measured the pH-value of furnish, in order to maintain the amount of catalyst used for urea formaldehyde resin. They found that the boards pressed with a higher compression capacity (board density: species density = 1.6: 1.0) had a higher bending strength than the boards with a low compression capacity. Boards with the same compaction ratio produced the same average MOE and MOR values irrespective of whether they were made from single specie or a mix of species.

It is clear from the literature that the final board density of a particleboard should always be higher than the wood species density to attain better inter-particle contact to produce satisfactory board. This observation will be very important in the work reported here to develop a satisfactory particleboard product using hardwood sawmill residue.

2.6 Processing Conditions and Parameters

The press cycle plays an important role in particleboard production. Pressing is generally the bottleneck in particleboard production and determines plant capacity. In addition, resin efficiency; resin type and level consume a considerable portion of the total manufacturing expenses. Press time and resin consumption (which will be discussed later in this chapter) therefore directly determine the economy of the particleboard manufacturing operation.

During the pressing operation, several physical, chemical and interacting activities are happening such as the formation of the VDP and resin curing. These activities directly influence the final properties of the particleboard. At the initial stage of the hot pressing, the moisture closer to the surface of the mat evaporates as the temperature increases rapidly. As the generated vapour increases the vapour pressure at the surface, vapour moves towards the colder core of the mat, where it may condense. However, with the increase in the core temperature due to heat and mass transfer from the surface to the core by thermal conductivity, diffusivity or permeability, the moisture in the core also vaporizes. Then this vapour drives transversely to the edge of the mat and exits from the structure. Zombort et al (2001) reported that the transient void volume, which is comprised of gaps between particles, plays the major role by providing pathways for heat and mass transport during mat consolidation. According to previous researchers (Humphrey and Bolten 1989; Kamke and Wolcott 1990), reduction in void volume and wood densification that occur during compression affect heat and mass transfer during the hot-pressing process.

2.6.1 Moisture Content

Mat moisture content is a critical parameter for developing the VDP and a very significant parameter for particleboard production. However, excessive moisture when migrated to the particleboard core requires additional pressing time to exit through the edges of the board to prevent de-lamination and spring-back the pressure release due to the press opening. Excessive moisture may cause rapid densification of the surface and loose core, resulting in poor internal bond strength and poor screw withdrawal strength of the final board. In addition, excessive moisture may interface with the polymerization of resin.

In addressing the above issues, the particleboard industry generally uses a non-uniform distribution of moisture through the thickness, with high moisture for the surface and less moisture for the core. Therefore, the higher amount of moisture in the surface than the core accelerates heat transfer to the core without unnecessarily lengthening the press cycle results in increased VDP. Heebink (1977) observed improved board strength when he used non-uniform moisture content (15 percent for surface and 5 percent for core) instead of using uniform moisture content (12 percent) for three-layer particleboard.

The continuous increase in surface moisture content improves the particleboard properties until they reach their optimum levels. Then, these properties start decreasing with further increase in the moisture (Strickler 1959; Rice 1960). However, Lehmann (1960), Strickler (1959) and Rice (1960) observed an increase in dimensional stability and a reduction in water absorption with the increase in surface moisture content. The pressing time reduces with the increase in surface moisture content in faster heating of the core (Strickler 1959). When the surface moisture increases above 15 percent with core moisture at 9 percent, MOE, MOR and IB reduced (Strickler 1959). The same observations were made by Lehmann (1960), who reported that an increase in surface moisture from 13.2 to 16.5 percent increases the MOR and IB and then a further increase in moisture from 16.5 to 20 percent reduces the MOR and IB. Therefore, the literature suggests that mat moisture content should be changed only within a limited range.

Smith (1980) reported that moisture dissipation in the form of steam from the edges of the board depends on the particle geometry of the board. Flat particles, which are normally used in flake boards, provide a channel for the steam transport. However, particleboard and medium density fibreboard required a longer pressing time as steam dissipation was slow.

$$P = P_0.e^{-\lambda T'} \qquad \text{Equation 2.1}$$

Where,

P pressure at temperature T

P_0 initial pressure

T' relaxation time

λ a factor depending on board density, species type, particle geometry and the moisture content

The release of the pressure when the moisture content in the middle is higher leads to spring back and non-reversible excessive dimensional changes of the board (Suchsland 1974; Beech 1975). The spring back leads to bond line failures result in poor strength properties in a particleboard. Therefore, stress relief or the opening of the press after hot pressing, should be addressed. Deppe and Ernst (1964) reported that the pressure relaxation due to press open after completing the hot press has an exponential relationship as in Equation 2.1. It shows that relaxation pressure has e^{-T} relationship with relation time. Therefore, if shorter the relaxation time, higher the spring back will be due to high relaxation pressure. If relaxation time is increased, spring back would reduce due to low relaxation pressure. Therefore, press opening after hot pressing should carefully maintain to control the spring back.

2.6.2 Press closing time and press capacity

Generally, the final board thickness of a particleboard is achieved by placing two stoppers with a thickness equal to the required board thickness at either side of the mat and allowing the press to close until the upper platen reaches those stoppers. Press closing time, which is different to the total pressing time (explained in Section 2.5.3), is the time taken for the upper platen to meet the stopper. Press closing speed influences the properties of a particleboard and needs to be optimized to achieve the desired properties of the board. However, adjustments have to be made within narrow boundaries limited by resin curing and press capacity (Kelly 1977).

Rice (1960) and Bismarck (1974) observed improved MOE and MOR when increasing the press-closing rate by reducing the time. However, Heebink et al. (1972) and Bismarck (1974) observed a reverse relationship between press closing time and IB. They found that the IB increases with the increase in press closing time. Press closure time is important for heat and mass transfer to the core to create stable inter-particle bonding in the core, hence an increase in IB. In addition, press closure time helps to release excessive moisture from the core to prevent spring-back and breakage of inter-particle bonds. Similarly, Geimer et al. (1975) and Heebink et al. (1972) reported that reduction of the press closing speed increases core density and IB. During the hot-pressing process, resins in the surface layers of the particleboard mat start to cure as soon as the hot platens touch the particleboard mat surfaces. Faster press closing will subject the particleboard mat surfaces to platen heat and faster compression and curing at the surface before the core has warmed sufficiently. This results in a higher density surface and a lower density core. Therefore, increasing the press closing speed increases the MOE and MOR as they are mainly dependent on the surface, while reducing the IB which is dependent on the core. Reducing the press closing speed allows surface layers to cure while leaving the uncured core, resulting in dense surface and loose core and lower core density. However, the IB, thickness swelling and spring back were independent of the press closing time (Rice 1960).

According to Liri (1969), the maximum pressure required for mat consolidation decreases with increase in press closing time. He explained that when the mat was exposed to elevated temperature for a longer time, the extent of wood plasticization was higher and that reduced the pressure required. In addition, press capacity should be sufficient to consolidate the particleboard mat to a desired thickness while influencing moisture migration from the core to the edges of the board, especially in commercial production with larger-sized board (Lehmann 1959).

2.6.3 Pressing time

Pressing time is the total time taken from when the upper pattern first touches the wood mat until it leaves it. Pressing time should be sufficient to consolidate the particle mat into the desired thickness as well as the polymerization of resin into cross-linked solid polymer to hold the mat in a compacted form even after removal from the press. Pressing time together with press temperature is extremely important in particleboard production to ensure the core temperature reaches a sufficient level for resin curing as well as to evaporate the moisture from the core.

Lehmann (1960) reported a significant decrease in particleboard thickness even after removing the press if he used higher pressing time (20 to 45 minutes) with three different platen temperatures (105 ^{0}C, 152 ^{0}C, 173.3 ^{0}C). He explained that result as being due to the increased drying and subsequently higher shrinkage of furnish. A three-layer board, which is subjected to high initial pressures with short press closure time, can achieve a sandwich effect (Suchsland 1967). The effective modulus of elasticity of the board E_e is expressed as in Equation 2.2. Raw material variables that are favourable for sandwich characteristics are shown in the Table 2.1.

$$E_e = E_f - (1- \lambda)\, 3(E_f-E_c) \qquad \text{Equation 2.2}$$

Where,

E_e effective modulus of elasticity of the board

E_f modulus of elasticity of the face

E_c modulus of elasticity of the core

Table 2.1: Potential material variables (Suchsland 1967)

Material	**Species**	**Particle geometry**	**Moisture content**	**Glue content**
Face	Low compressive strength	Small void volume	High	High
Core	High compressive strength	Large void volume	Low	Low

2.6.4 Press temperature

During the pressing, a loose mat of particles transforms into a solid board with pre-determined thickness. Adequate contact between particles and heat and mass transfer into the mat to increase the temperature in the gullies for curing of the resin occurs during the pressing. Suchsland (1967) suggested that fast heat transfer to the centre of the board is therefore the key to a short press time. The final thickness of the board is achieved during the mat compression, which should occur quickly to avoid pre-curing of resins near the platens, before the densification has completed and maximum contact developed.

The importance of the processing conditions, the parameters of mat formation, consolidation as well as on the resin curing is clear from the literature. Pressing time, press temperature and the moisture content are the most important parameters, which should be carefully maintained for efficient glue bonding while achieving the proper consolidation. In this study, since we are dealing with a new raw material for particleboard production, the processing conditions and parameters need to be investigated thoroughly. Chapter 5 discusses the experimental procedures and the analytical steps which were used to identify optimum processing conditions and parameters for this work. Chapters 6 and 7 discuss the results of properties of particleboard with respect to processing parameters which were investigated in this study.

2.7 Resin or Adhesives

During the particleboard production process, resin or adhesives are normally sprayed into the wood furnish which has been continuously blending inside a blender or mixer. This continuous blending action enhances the rubbing action between particles that increases the possibility of transferring adhesive from one particle with excessive adhesive to another with less or no adhesive. The physical and strength properties of a particleboard increase as the droplet size decreases and the dispersion of the adhesive solution increases, because the finer the nozzle spray, the better the coverage of particle surfaces (Carroll and McVey 1962; Lehmann 1970, Kehr et al. 1964; Dunky 1998). Meinecke and Klauditz (1962) showed that the increase in the resin droplet size for the same resin content from 35 µm to 100 µm reduces the tensile strength, both parallel and perpendicular to the surface. They observed that increase in droplet size causes resin to stagnate in particular areas of the wood mat and not spread evenly. This reduces tensile strength. However, further decrease in the droplet size did not increase the tensile strength and this was not further explained in the research (Figure 2.6). In addition, most industrial blenders operate with droplet diameter of around 80 µm and consequently, improved board properties could be obtained by reducing the droplet size.

Carroll and McVey (1962) found that laboratory boards have higher internal bond strength and modulus of rupture than identical industrial boards, although, laboratory blended mix was pressed in the industrial press producing a board with laboratory strength. That may be due to the use of industrial blender which has bigger droplet size and therefore does not blend wood furnish and resin in the same way as laboratory blender (Meinecke and Klauditz 1962).

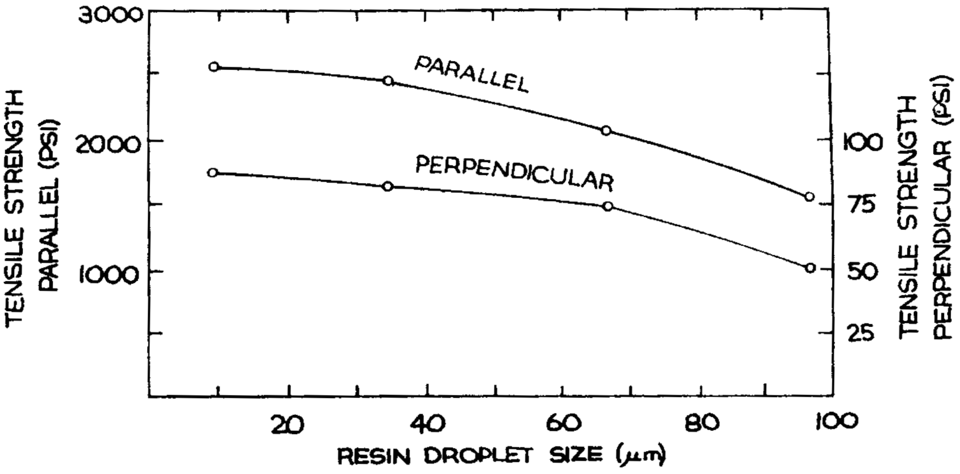


Figure 2.6: Influence of resin droplet size on tensile strength perpendicular and parallel to particleboard surface (Meinecke and Klauditz 1962)

Christensen and Robertschek (1974) and Kehr et al. (1968) reported that resin transfer during blending contributes to improved particleboard properties, especially IB. However, in a similar study, Carroll and McVey (1962) found that increase in mixing time only slightly improves particleboard properties. They explained that proper blending using smaller droplets is more effective than post-blending. Lehmann (1965) maintained a uniform distribution of resin using fine atomization to optimize board properties. He was able to improve particleboard properties by decreasing the droplet size for urea formaldehyde resin (UF). Decreasing the droplet size resulted in a uniform distribution of resin and subsequently increased particleboard properties. However, Burrows (1961),using phenolic resin that does not have high flow properties like UF resin, found that modulus rupture is independent of atomization level. However, the cause for this observation was not explained.

Carroll and McVey (1962) observed that resin efficiency could increase the coating of the particles with resin while keeping total solids lower. This is achieved by having less resin solids in one droplet but adding more droplets to one single particle area. In a similar observation, Meinecke and Klauditz (1962) found that continuous resin film is important for particleboard production. However, the increase in throughput per nozzle decreases the dimensional stability and strength properties of particleboard (Kehr et al. 1964). The lower the throughput per nozzle, the better the properties of flake board which can achieved. This is attributed to a uniform distribution of resin.

Lehman (1968; 1970) added fluorescent dye to urea formaldehyde (with three different resin contents: 2, 4, 6 percent of oven dry weight of wood furnish) and phenol formaldehyde resin using two atomization levels (fine and coarse) to investigate inter-particle bonding. The location and distribution of the adhesive in the finished board was determined by photomicrographs under ultra-violet (UV) light. Better particleboard properties could be obtained with finer atomization level than the same resin with coarse atomization level. His microphotographs revealed that continuous glue lines could be obtained with 6 percent UF resin and almost continuous with 4 percent UF resin when fine atomization was used. He further micro-photographed boards made with diluted, low viscosity. UF resin as a fine spray and no penetration of resin into the particles was observed. The fine atomization of resin improved the strength properties as well as dimensional stability of the board more effectively than the spraying method or varying the spraying temperature or the solid content of the resin (Lehmann 1965).

The amount of resin consumed for particleboard has a relationship with the particle size distribution of the wood sample. Turner (1954) reported that most of the time the amount of resin used for particleboard manufacturing is normally calculated as the amount of resin solid as a percentage of the oven-dry weight of wood. Post (1958; 1961) studied the surface areas of wood particles as the basis of oven-dry weight of the wood to optimum resin load in a controlled particle size. He observed a moderate increase in bending strength when resin solid level was increased from 3.27 g to 13.07 g for a square meter of particle surface. In another attempt, Istrate et al. (1964) showed that the particles with high slenderness coefficient (length/thickness) require less resin to glue the particleboard than ones with small slenderness ratio.

For hardwood particleboard, about 30% longer press times are required compared with softwood for curing of phenolic resins (Pizzi 1983). He explained that hardwood required higher press capacity to compact the particleboard mat compared to softwood mat. In addition, phenolic resin has a longer flow rate compared to UF resin. Pre-pressing is therefore helpful to reduce pre-curing closer to the hot platens during hot pressing.

The literature clearly shows that the smaller the droplet size, the higher the resin efficiency is. Therefore, smaller droplet size was maintained in this research to improve resin efficiency. However, this work investigated the effect of resin content on board properties to optimise the mix design.

2.7.1 Resin type

There are a number of different types of resin used in the particleboard industry. Resin type is vital for particleboard production as it directly contributes to the production cost. Urea-formaldehyde (UF) resin, melamine formaldehyde (MF) resin, phenol-formaldehyde (PF) resin and di-phenyl methane di-isocyanate (MDI) polymer are the most commonly used resins in the particleboard industry. UF resin is the most widely used resin considering its basic properties such as water solubility, thermal properties, high reactivity and most importantly lower cost compared to any other resin type. However, MF is often used in combination with UF resin to improve the strength of UF-bonded boards to achieve improved water resistance and reduction in formaldehyde emission while retaining bond strength and to speed up the curing rate of UF resin (Products 2001). PF resin is mainly used in the OSB or hardboard (HB) industry due to its superior quality in bond strength and higher retention of bond strength after soaking for a few hours. MDI bonding is superior to the other three resin types in both dry conditions as well as wet conditions. The advantage of MDI is its ability to work with higher moisture content compared to the other resins.

Urea formaldehyde resin was used as the binder in our investigation to produce three-layer particleboard using hardwood sawmill residue. Therefore, this section of the chapter critically reviews the suitability of urea formaldehyde as the resin type in the production process and its thermal properties. However, other resin types and their usage are mentioned.

Hse (1974; 1989) investigated UF resin with various ureas to formaldehyde molar ratios at different temperatures under various alkaline and acidic conditions. Resin with higher methylol content produced board with higher internal bond and modulus of rupture values. He changed the methylolation pH from 7 to 10 and polymerization pH from 3.8 to 5.8 and found that the resin with methylolation under neutral or slightly alkaline conditions produced particleboard with higher internal bond. Optimum properties were found with polymerization at pH 5.8 following a neutral methylolation reaction.

Temperature and pressing time are very important process parameters in particleboard production as they directly relate to resin curing. The press cycle should be long enough for the heat to migrate from platens to the mat centre to increase the core temperature to cure the resin. PF resin is not as reactive as UF resin, requiring higher pressing temperature and press cycle compared to UF resin (Carroll 1963; Lehmann et al 1973). Roffael and Rauch (1972) reported that raising the core temperature to 220°C improved the dimensional stability and internal bond strength of Scotch pine particleboard.

The durability of a particleboard could improve with an increase in the resin level of either PF resin or UF resin (Hann et al 1963; Lehmann 1974). Several researchers manufactured particleboards using particles which were dipped into aqueous solutions of resin or sprayed with resin solutions before being sprayed with conventional resin solution. This method is called the impregnation of resin. Phenolic impregnation of resin in particles to improve particleboard properties has been reported by several researchers (Browne et al. 1966; Haygreen and Gartjejansen 1971; Kajita and Imamura 1991). They observed a significant improvement to spring-back and thickness swelling as well as board properties. Browne et al. (1966) used phenolic impregnated resin in particleboard made with both UF resin as well as PF resin. They reported that impregnation reduced the irreversible thickness swelling. However, the cost of this method limits its applicability.

Deppe and Earnst (1971) found that particleboard with the same MOR could be produced with less MDI resin than PF. They also found that the amount of pressing time was much shorter compared to phenol formaldehyde resin.

In recent years, the demand for environmentally-friendly adhesives has increased to replace UF or PF resins to reduce formaldehyde emissions. Soybean protein has been investigated as an alternative petroleum polymer in manufacturing various binders due to its inherent advantages in renewability, biodegradability and feasibility (Mo et al. 2001; Kuo et al. 1998). The performance of protein adhesives is dependent on the dispersion and unfolding of the protein in solution. Mo et al. (2001) reported that the bond strength of soy protein-based adhesives could be increased by adding alkaline to promote unfolding. In further investigations, Mo et al. (2003) found that diphenyl di-isocyanate resin produces particleboard with superior properties than particleboard made with UF or soy protein-based resin. However, soy protein-based resin could produce particleboard suitable for standard general purposes such as interior furniture and shelves.

Acacia mernsii is an easily-grown tree in most parts of the world especially in South Africa and is a main supplier of tannin. Since the structure of the tannin is so close to the structure of phenol's structure, researchers in the wood industry started to investigate the possibility of using tannin as a natural adhesive (Plomley 1966). Improved tannin adhesives could be used for co-condensation with UF to improve swelling properties (reduce the swelling) of particleboard. However, since tannin does not flow like phenolic resin, it requires higher moisture content (25% is the norm) to improve workability. Since tannin does not shrink during curing, it produces very strong bonds between particles with very little or no destruction of the wood. In addition, when pressing at high moisture contents, spring-back of the board is very rare with tannin (Plomley 1966).

2.7.2 Urea Formaldehyde resin

Urea-formaldehyde (UF) is the most important amino-plastic resin in the wood-working industry due to its high reactivity, water solubility and the reversibility of the amino-methylene link, which also explains the low resistance of UF resins against the influence of water and moisture, especially at higher temperatures. Approximately 6 billion tonnes are produced per annum worldwide, based on a usual solid content of 66% (Dunky 1998). UF resin is based on two monomers, urea and formaldehyde.

UF resins are thermosetting duromers and consist of linear or branched oligomeric and polymeric molecules, which always contain some amount of monomer. Non-reacted urea is often beneficial to achieve better stability during storage. Formaldehyde is necessary to induce the hardening reaction; however formaldehyde emission during pressing is unpleasant.

2.7.2.1 Formation of Urea Formaldehyde

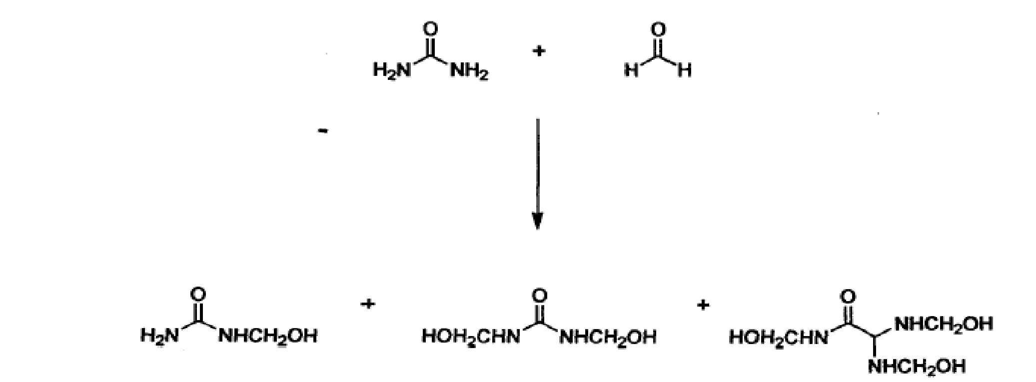


Figure 2.7: Formation of mono-, di-, and tri-methylolurea by the addition of formaldehyde to urea. (Conner 1996)

The reaction of urea and formaldehyde is a two-step process: usually an alkaline methylolation followed by an acid condensation (Dunky 1998 and Conner 1996). Methylolation refers to the addition of up to three molecules of the bi-functional formaldehyde to one molecule of urea to give the so-called methylolureas (Figure 2.7). The formation of tetra-methylolurea has not been observed experimentally. The reversibility of this reaction is one of the most important features of UF resins, and is responsible for both the low resistance against hydrolysis caused by the attack of moisture or water and subsequent formaldehyde emission.

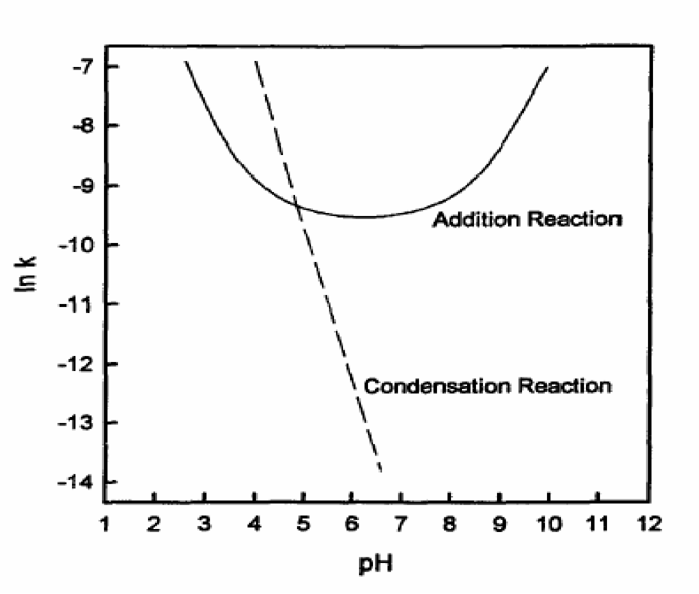


Figure 2.8: Influence of pH on the rate constant (k) for addition and condensation reactions of urea and formaldehyde (Pizzi 1983)

During the second stage, methylolureas condense into low molecular weight polymers. The type of bond between the urea molecules depends on the conditions used: low temperatures and only slightly acidic pH favour the formation of methylene ether bridges (-CH2-O-CH2-), while higher temperatures and lower pH values lead to the more stable methylene (-CH2-) bridges (Figure 2.8). Therefore, the condensation process is carried out in an acidic environment, with pH of about 5.0 until a desired viscosity is reached. After the mixture is cooled and neutralized, the extra water is removed using a vacuum distillation method to produce resin with the desired solid content. The most widely used solid content is around 60-65%.

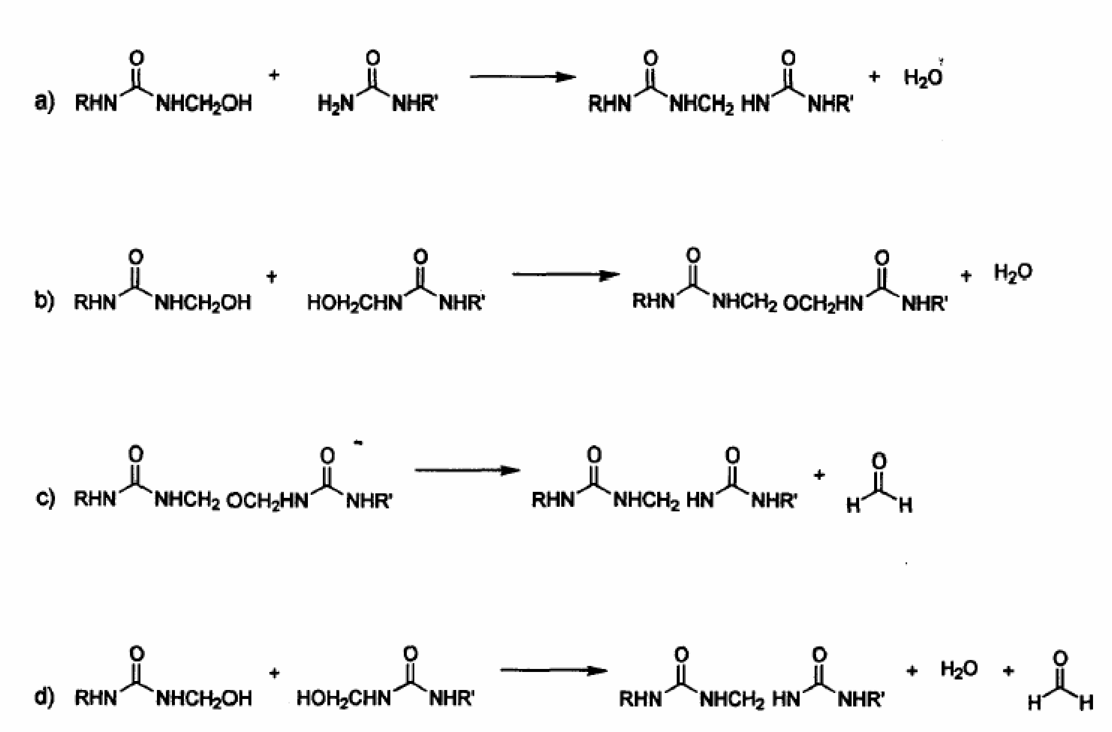


Figure 2.9: Condensation reaction of methylolureas (Conner 1996)

Conner (1996) explains the formation of the methelene bridges in four steps as in Figure 2.9 above.

1. methelene bridges between amino nitrogens by the reaction of methylol and amino groups on reacting molecules
2. methylene ether linkages by the reaction of two methylol groups.
3. mehtylene linkages by the splitting out of formaldehyde.
4. methylene linkages by the reaction of methylol groups splitting out water and formaldehyde in the process.

It is very important to control the molecular size of the UF resins during the production process as their properties change continuously as the molecular size grows larger. The molecular weight can vary from a few hundred to a few thousand with a wide range of molecular size (Pizzi 1983). The most perceptible change is the viscosity.

The addition of urea into formaldehyde is done in two stages to control the formaldehyde to urea ratio. First in the formation of methylolurea, the ratio of urea to formaldehyde is maintained at around 2.0 -1.6. In the condensation step, urea is added into methylolurea to maintain the final U/F ratio at a desirable level. In this second stage an extra amount of urea is added to consume the excess formaldehyde. The pH value of the final product is adjusted to maintain the required storage life.

2.7.2.2 Curing of Urea Formaldehyde Resin

During the curing process, UF resin forms into three-dimensional networks that are no longer thermo-formable and insoluble. Similar to the condensation process of producing UF resin, the curing of the UF resin has to be done in an acidic environment. This acidic condition is achieved by addition of direct acids or latent hardener. Ammonium sulphate or ammonium chloride is widely used as a latent acid in the particleboard industry. However ammonium chloride has not been widely used as the formation of hydrochloric acid (Equation 2.3) during the combustion of wood-based panels accelerates corrosion, and is suspected of producing dioxins (Dunky 1998).

$$4NH_4Cl + 6HCHO \rightarrow 4HCl + (CH_2)_6N_4 + 6H_2O \qquad \text{Equation 2.3}$$

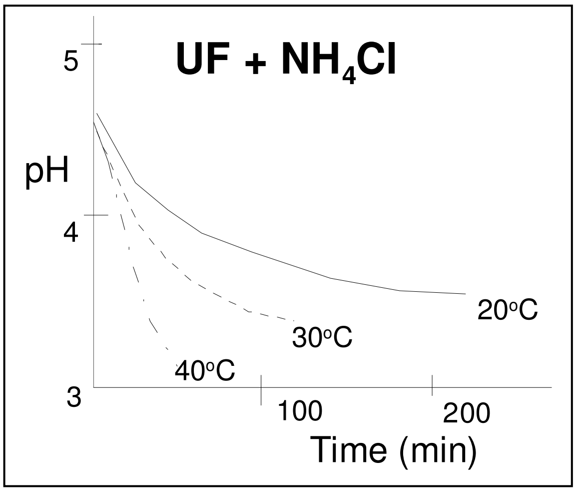


Figure 2.10: pH change of UF resin with NH_4Cl hardener as a function of temperature and time (Pizzi 1983)

Hardener reacts with free formaldehyde in the resins to generate acid. The capacity of the hardeners depends on their ability to release acid, thereby decreasing the pH of resin to accelerate the curing. The speed of the reaction depends on the amount of available free formaldehyde and ammonium salt, which is dependent on the temperature and the time (Figure 2.10). NH_4Cl (a weak acid) is said to be a better hardener than HCl (strong acid) as the latter produces weaker inter-particle-bonds (Pizzi 1983).

2.7.2.3 Testing methods for UF resin

It is important to understand the quality and the performance of the resin for quality control of the system. Solid content, refractive index, density, viscosity, pH and reactivity are usually measured in the laboratory, which produces the resins and in particleboard factories as part of their quality control system (Dunky 1998).

Gel time is one of the most important resin parameters that determines curing reactions as well as its applications. The test will yield not only the time during which the resin gels but also extra information such as whether resin gels sharply within 1-2 seconds or spans to about 10 seconds. If the time extends to more than 10 seconds, the resin will have a character of slow generating of bonding strength (Siimer et al. 2003).

2.7.2.4 Advantages and Disadvantages of UF

The main disadvantage in UF is that it is not stable at higher relative humidifies especially at elevated temperatures, since the amino-methylene linkage is susceptible to hydrolysis and is therefore not stable (Yamagushi et al. 1980). In addition, UF-bonded board lacks resistance to moisture, especially in combination with heat, compared to a board produced using PF resin or MDI resin (Conner 1996). Water also causes degradation of UF resin. Dunky (1998) has suggested the incorporation of melamine into UF resin (M-UF, MF-UF) or phenol and/or melamine into UF resin (M-U-PF, P-M-UF) to improve resistance to moisture or humidity. However, this may change the characteristics of the resin as well as the cost of the resin.

Papadopoulos and Hill (2001) reported that a board made using MDI had superior board properties compared to a board made with UF resin. They found that the amount of MDI resin required to produce a board with the same properties is considerably lower, compared with

UF resin. The bonding efficiency can be significantly increased by adding 1% wax to both UF and MDI resin. Although the mat moisture content and platen temperature have an influence on the bonding efficiency in UF bonded board, they do not have a significant effect on the bonding efficiency of MDI board.

Weather durability of a glue line is an important property, which should be maintained in particleboard. Durability is essentially dependent on cyclic stresses generated due to swelling and shrinkage of joints, as well as hydraulic attacks on the chemical bonds. Dunky (1998) reported that weather durability can be increased by the addition of hydrophobic chains into the hardened network. That can be achieved by incorporating urea-capped di- and tri-functional amines which contain aliphatic chains into the resin structure, and using the hydrochloride derivates of some of these amines as a curing agent (Ebewele et al. 1991a; 1991b; 1993; 1994).

Adding more hardener to the resin does not increase the curing reaction. Instead, it leaves residues of acids or acid compounds in the glue-lines and contributes to the brittleness of the cured resin. This will initiate hydrolysis of the wood cell wall adjacent to glue-lines as well as acid-catalysed resin degradation, which decreases bond durability (Myers 1984). Therefore, it is important to maintain the amount of hardener to create neutral glue-lines which show a distinctly improved resistance to hydrolysis.

Having reviewed the different types of resins used in the particleboard industry, UF resins were recognized as the most suitable resin for this work. Its inherent properties, such as high reactivity and water solubility, as well as low cost compared to other resin types, promote it to be the ideal candidate for this research. Press temperature and pressing time are important parameters for complete curing of resin. In addition, it is important to maintain an acidic environment for resin curing. However, literature on the amount of hardener (acid) required to create an acidic medium for UF resin curing with respect to hardwood particleboard is not available. Therefore, optimum resin content, hardener content, optimum pressing time and temperature for resin curing were investigated in this research will be discussed in Chapter 6 and Chapter 7.

2.8 Particleboards from different types of raw materials

Particleboard properties depend significantly on the properties of the raw material used. The quality of the wood furnish is affected by its properties such as density, acidity, extractive content and machinability. This section of the chapter discusses the effects of the widely-used wood species and other lingo-cellulostic material used for manufacturing particleboard on the properties of the final board. As mentioned earlier in the chapter, final board density should be higher than the wood species density to achieve proper compaction and bond between particles.

Softwood flake is the most common raw material used in particleboard production. However, research has shown that other lingo-cellulostic materials such as root wood (Howard 1974), forest residue (Heebink 1974; Lehmann and Geimer 1974)), wood bark (Dost 1971; Gertjejansen and Haygreen 1974; Anderson et al. 1974), urban wood wastes and different types of agricultural residues (Nami et al. 2001) have been investigated as potential particleboard raw materials.

2.8.1 Particleboard from softwood sawmill residue

Heebink (1974) and Lehmann and Geimer (1974) investigated phenolic-bonded particleboard produced from wood residues from lodge-pole pine and Douglas fir respectively. Heebink reported that a mixture of live and dead lodge-pole pine residue would produce particleboard with properties acceptable to the industry.

Heebink et al. (1974) compared the quality of particleboard produced from planer shavings produced from different planer settings. They found that longer and thinner flakes produced stronger, stiffer and more dimensionally stable particleboards.

2.8.2 Hardwood as Particleboard Raw Material

Vital et al. (1974) produced three-layer particleboards by combining four species of exotic hardwood species. The manufactured particleboard combined one, two, three or all four types of species at each of 1.2 and 1.6 compaction ratios. They found that the properties of the final boards were dependent on the average of the mix density. MOR and MOE had a direct relationship with the compaction ratio for boards with equal density and could be explained by the better compaction and resulting better inter-particle contact which created better bond between particles.

Hse (1975) used phenol formaldehyde resin to produce three-layer particleboards for three different densities using nine different species of hardwood with large flake size (76.2 mm x 9.525 mm x 0.4 mm). He found that if final boards need to be used in exterior applications, they should be compacted to at least 1.25 (board density / wood density). Thus, low-medium density boards from lower density species and high-density boards from high-density boards are suitable. However, thickness stability is inversely related to the board density.

Stayton et al (1971) investigated the suitability of a mixture of high-density birch and low density aspen flakes that were 12.5 mm long. They reported that particleboards with acceptable properties could be produced using 8 percent urea formaldehyde resin and 6 percent phenol formaldehyde resin with an average density 720 kg/m^3 and 737 kg/m^3 respectively. They added that the all-aspen boards were superior to board made with a mixture of birch, and adding birch adversely affected the surface quality of the final product. However, all-birch particleboard could retain at least 80 percent of all-aspen board properties.

2.8.3 Wood Bark as Particleboard Raw Material

Nemli et al. (2006) attempted to impregnate pinus brutal bark into particle to produce three-layer particleboards bonded with UF resin. They also found that increasing the extractive content in particles reduced MOR, MOE, and IB. They explained this as being possibly due to a decrease in pH value of the particles due to the presence of reactive material such as the tannin in the bark. The curing rates of formaldehyde-based resins depend on the pH. If the pH is low, then pre-cure may happen before compression of the particles. When the press closes, the pre-cured resin bonds are broken, reducing MOE, MOR and IB. However they observed the decay resistance could be increased. This may have been due to high amounts of poly-phenolic extractives, which are toxic to fungi and insects.

A substantial amount of wood bark is produced by the wood industry as 10-15% of each wood log is bark. A considerable amount of this remains unused (Nemli et al. 2006). Therefore, the use of wood bark as particleboard raw material has been investigated from time to time. Post (1971) used redwood bark as a raw material to prepare three-layer particleboard using urea formaldehyde resin. He used three levels of resin incorporating 0, 10, 20 and 30 percent redwood bark. A significant decrease in MOE, MOR and IB was observed with increase in the percentage of bark. Gertjejansen and Haygreen (1973) incorporated aspen bark into furnish of wafer and flake-type particleboard using phenol formaldehyde resin. They used 3 percent resin for wafer and 8 percent for flake boards and reported that the entire tree trunk could be used in making particleboard if the bark was removed from the but log. As explained by Nemli (2006), higher pH value in bark interferes with UF resin to pre-cure. These pre-cured resin bonds would have broken during the compression, decreasing MOE, MOR and IB.

2.8.4 Urban Wood Waste as Raw material for Particleboard

Environmental issues restrict the available timber harvest for the particleboard industry. Therefore, it needs to look beyond the traditional resources of raw materials such as planer shaving, plywood trim or sawdust as raw material. Utilizing urban wood waste that is a good source for particleboard manufacturing as well as recycling wood waste to produce particleboard is excellent for the environment.

Urban wood waste however is contaminated with foreign materials such as plastics, rubber, metals, chemicals (as preservatives), which is a concern for manufacturing plants, end-use customers, employee safety, product quality anf the tool life.

Chromated copper arsenate (CCA) is currently a major commercial wood preservative for many applications in the world. Recycling of treated wood waste into wood-based composites is a relatively low-cost alternative compared to disposal into the environment. Extraction of the CCA elements from the wood fibre can increase recycling opportunities for the remaining pulp. One novel method for recycling CCA-treated wood fibre would be to modify it by removing all or much of the heavy metal, which could be reclaimed. Acid extraction is one option for removal of copper, chromium, and arsenic from treated wood fibre, which has been explored by several researchers using different acids (Kartal and Clausen 2001). Oxalic acid (OA) is used in the extraction of contaminants such as copper, chromium, and arsenic from CCA-treated wood waste and pH reduction of wood substrate.

Bacterial fermentation is another possible method for the removal of heavy metals from treated wood, since some bacteria are extremely tolerant of toxic metals. In this method, CCA in treated wood can be first converted to its water-soluble form and then copper, chromium and arsenic can be removed from the wood through a washing process. Bacillus licheniformis isolated on CCA-treated wood had great potential to remove toxic metals when treated wood sawdust was exposed to this organism in liquid culture (Crawford and Clausen 1999).

In order to investigate the effect on the mechanical properties of particleboard due to the interference of OA on UF resin, Nami et al. (2001) compared the effect of OA on UF resin by remediating CCA-treated wood waste using OA as well as bioremediation using B. locheniformis. They further evaluated three other particles; 1). Untreated southern pine particles (SYP), 2). SYP particles treated to 6.4 kgm^3 with CCA-type C and 3). SYP particles treated to 6.4 kgm^3 with CCA-type C followed by an OA-extraction. They found that the particleboard made from CCA-treated wood particles using UF complies with the strength properties as well as thickness swelling and fungal resistance. However, leaching of arsenic is relatively high, which is not desirable either in use or in disposal. They suggest a thorough removal of CCA from treated waste prior to particleboard manufacturing. Then, they were able to produce particleboard which is even desirable for the indoor use.

2.8.5 Agricultural residue

Agricultural residues such as wheat straw and flax fibre as lignocellulose material are becoming popular alternative raw materials in the particleboard industry to supplement wood chips. Wheat straw as particleboard raw material has been investigated in recent years. Mo et al. (2003) investigated the suitability of different resin types as a binder for wheat straw particleboard. They found that MDI resin was the best resin to use with wheat straw to produce particleboards that satisfied the thickness-swelling property. As MDI facilitates working with higher moisture content than other resin types, this could effectively wet the surface of the straw, enhancing proper chemical bonding through both hydrogen bonding and covalent bonding (Dalen and Shoram 1996; Mo et al. 2003). In contrast, water-based resin such as UF or soybean-based resin, could not effectively wet the straw surface due to the hydrophobic wax and silica found on the surface of wheat straw (Hague et al. 1998). However, treating straw with bleach or modifying UF with silane coupling could improve the properties of wheat straw particleboard produced using UF as the binder (Hann el al. 1998; Mo et al. 2003).

Joss tall wheatgrass (JTW), Agropyron elongatum, has been used as pasture or "standing hay" for cattle and upland game cover or to manage saline subsurface drainage water in arid land irrigated agriculture (Zheng et al. 2006). Zheng et al. (2006) have investigated the properties of JTW particleboard made using different resin types with different MC and board density. They manufactured particleboard using UF resin and PMDI resin with and without NaOH treatment (soaking with NaOH solution followed by soaking with distilled water at 50 ^{o}C). They reported that high quality particleboard can be manufactured using PMDI resin with a board density of 730 kg/m^3 and those properties could be further increased by increasing particleboard density. 8% moisture was found most suitable for particleboard by experimenting with MC from 2% to 10% of the particles with PMDI-bonded boards. However, UF resin is not suitable for JTW particleboard with or without NaOH treatment. Similar to wheat straw, JTW contains high concentrations of extractives such as wax on the surface of JTW straw, and therefore UF would not be suitable as the binder (Vick 1999; Zheng et al. 2006).

In recent years, flax fibre have been considered as raw material by not only the particleboard industry but also by other composite industries due its inherent properties such as low density, high specific stiffness, recycle ability and low cost (Troger et al. 1998; Baley 2002; Papadopoulos and Hague 2003). Flax (Linum usitatissimum) has been identified as a potential alternative source of lignocellulose raw material which could supplement wood from natural and plantation forests for particleboard raw material (Papadopoulos and Hague 2003). They investigated the possibility of using flax particles by partially substituting flax shive with wood chips bonded with UF resin to make single-layer particleboard and mixing its strength properties. According to the report, 30% substitution of flax could produce single-layer particleboard with the strength and physical properties required by the industry standard for interior use.

Kenaf (Hibiscus cannabinus L.) stalks are another good cellulostic fibre which has been investigated by many researchers for use in particleboard, textiles or recycled plastics (Webber and Bledsoe 1993; 1999; Kalaycioglu and Nemli 2006). In an attempt to manufacture three-layer particleboards using UF as the binder, Kalaycioglu and Nemli (2006) found that Kenaf stalks could be considered as a potential raw material for particleboard production.

Athel tree is a fast growing plant widely used in the US for soil and water remediation as it is tolerant of alkaline and saline soils. Zeng et al. (2006; 2007) manufactured particleboards using Athel with UF or PMDI resin, considering that its high content of silica, phenol and oxidant would be beneficial for particleboard properties. They found that Athel with 7 – 16% UF could produce particleboards that satisfy ANSI/A208.1. However, they found that more stable particleboard could be manufactured using 5% PMDI resin.

Alma et al. (2005) investigated the suitability of cotton carpel chips as particleboard raw material using UF and melamine UF (MUF) as the binder. They found that particleboard that meets the minimum standard for particleboard and MUF-bonded board had better strength properties than UF-bonded particleboard. However, most produced board did not satisfy the screw withdrawal test perpendicular to the board.

2.9 Summary and Conclusions

A review of the published work assisted in gaining state of the art knowledge of manufacturing particleboard using a range of raw materials. Particleboards are mainly manufactured using softwood. However, hardwood flake, agricultural residues and treated timber have also been investigated at different times. In most instances, important physical and mechanical properties of a particleboard were measured and effects of material and process variables on the physical and mechanical properties of a particleboard were studied. Commonly measured physical and mechanical properties of a particleboard are final board density, thickness swelling property, flexural strength and the tensile strength perpendicular to the surface of the particleboard. The following major points are found to be important for the work undertaken in the present study.

- Final particleboard density is an important parameter. Increase in final particleboard density with the same final board thickness increases the internal pressure of the board. This increases the interlocking between particles, enhancing stronger chemical bond between particles and adhesives. However, this inter-locking could be increased up to a certain point to allow moisture which is vital for heat transfer to travel from surface to core and then to escape from the edges of the board.

- Both MOR and MOE of a particleboard can be improved by increasing the compaction ratio as well as by increasing the length/thickness ratio for the same wood species. The optimum MOR or MOE of a particleboard can be produced with a length/thickness ratio around 250.

- The MOR and MOE of a particleboard with the same mean density increase with decrease in the density of the wood species.

- IB is a very important property in particleboard, which is highly dependent on glue line strength. IB reduces with the reduction in core density since the compaction ratio is low. IB can be improved by adding extra resin into the core. However, excessive addition of water-resistant chemicals such as wax or the addition of fire retardants such as boric acid or borax reduces the IB. In addition, excessive amounts of smaller particles such as saw dust decrease the IB.

- The durability of a particleboard can be improved by improving its stability and resistance to fire or fungus. Board stability is dependent on properties such as thickness swelling or spring-back. Increasing the resin content in a particleboard reduces the thickness swelling as well as spring-back, although high moisture content does the opposite. After hot pressing, releasing the pressure slowly and carefully or increasing the pressing time reduce spring-back.

- Additives such as paraffin wax are added into the particleboard to reduce water adsorption in order to reduce the thickness swell. The addition of fire retardants such as borax is important for the durability of a particleboard. However, the amount of these additives should be carefully be monitored as they may affect resin curing.

- Spraying the resin into raw material should be done carefully as the smaller the droplet size, the higher the resin efficiency.

- UF resin was recognized as the most suitable resin for this study. Its inherent properties such as high reactivity and water solubility as well as low cost compared to other resin types make it the ideal candidate for this research.

- It is important to maintain an acidic environment for UF resin curing. However, literature on the amount of hardener (acid) required to create an acidic medium for UF resin curing with respect to hardwood particleboard is not available.

The importance of the processing conditions and the parameters on the mat-formation and consolidation as well as on resin curing is clear from the literature review. Pressing time, press temperature and the moisture content are the most important parameters, which should be carefully monitored for efficient glue bonding while achieving proper consolidation. In this study, since we are dealing with a new raw material for particleboard production, the processing conditions and parameters need to be investigated thoroughly. Chapter 6 discusses the experimental procedures and the analytical steps used to identify optimum processing conditions and parameters for this work.

Prior to establishing the experimental procedures, a review of literature covering simulation models for predicting the VDP of particleboard was undertaken. This study is reported in Chapter 3. This study was required since the success of the laboratory process developed was measured against the expected density profiles of three-layer particleboard.

CHAPTER 3

REVIEW OF SIMULATION MODELS TO PREDICT THE FORMATION OF VERTICLE DENSITY PROFILE

3.1 Introduction

The density of a particleboard is not uniform along its direction of thickness. This variation of density along the thickness direction of a particleboard is referred to as vertical density profile (VDP) vertical density gradient. The VDP in a particleboard significantly influences most of the mechanical properties of a particleboard including MOR, MOE and IB. The MOR and MOE of a board are mainly dependent on the surface layers of the board, while IB is dependent on the core. Therefore, commercial particleboard producers use VDP as a benchmark for quality control purposes. The purpose of this chapter is to examine previous studies on the formation of VDP and to investigate parameters that influence the formation of VDP. Further, the chapter will report on analytical, numerical and empirical studies used in the past to model the formation of VDP, discuss the significance of those models and outline their limitations. Chapter 9 will further examine the formation of VDP of a particleboard that was produced from hardwood sawmill residue, which is the main raw material used in this investigation.

3.2 Density Profile

The VDP forms due to the nature of the interactions of heat and mass transfer with the rheological properties of furnish and resin during the production of particleboards. It also depends on the rate of press closing, moisture distribution in the mat and the hot-press temperature (Kelly 1977; Humphrey 1982). Particle configuration, wood type and resin type also influence the formation of the density gradient of a particleboard. The VDP in a particleboard significantly influences most of the mechanical properties of a particleboard including MOR, MOE and IB. Therefore, considering the critical property of the final practical applications of the end product, the modification of the pressing operation may be important to enhance or restrict the formation of this VDP (Kelly 1977).

There are two common methods used in practice to determine the VDP. They are the gravimetric method and the x-ray scanning method. The gravimetric method uses mass/volume method to measure the density profile. In this method first the initial mass and volume of a sample is measured. Then, a layer of the sample is shaved and the mass and the volume of the sample are measured again. The reduced mass and the reduced volume are then used to calculate the density of the shaved layer. This process is repeated after shaving each layer from the sample and the density of each layer is calculated accordingly to obtain the final VDP of the sample. In the x-ray scanning method, smaller specimens from panels are used to test the density of the panel. During the scanning, an x-ray beam, parallel to the plane of the panel, is passed across the thickness of the specimen. Then it averages the in-plane density of the panel to produce the VDP (Wang et al. 2006).

3.2.1 Formation of the VDP

Suchsland (1967) explained the formation of the density profile as being due to the influence of moisture and temperature on the compressive stress of a wood perpendicular to the grain. The combination of heat and moisture severely reduces the compressive stress of the wood. However density profile in a particleboard forms due to the unequal distribution of heat and moisture content and the differences in the stress-strain relationship of all particles during the hot pressing process. When the heat and moisture transfer through the mat, their effects on the compressive strength of the wood component develop the VDP in a particleboard mat which originally had homogeneous properties.

During the hot-pressing of a particleboard, the time required for the upper platen of the hot-press to reach the stoppers is directly related to the initial pressure inside the board. If the press reaches the stoppers and has developed a pressure that exceeds the compressive strengths of inner layers, a compressive failure would occur close to two surfaces. This may result in high-density face regions and low-density core regions providing a sharp density gradient (Suchsland 1967; Stickler 1959). Although press closure time can be used to control the VDP, a VDP caused by the large pressure would not lead to desirable board properties. As soon as hot platens touch the particleboard mat, polymerization of cross-linked polymer begins, even before having sufficient inter-particle contact. Further increase in press closing time starts to break these already cured particle bonds (pre-cured bonds). Therefore, a pre-cured surface severely reduces the bending strength of a particleboard (Kelly 1977).

3.3 Effects of the moisture content, temperature and pressing time on the formation of the density profile

Strickler (1959) reported how the press cycle, moisture content and moisture distribution affected the properties of Douglas fir flake-board during the pressing operation. When the press temperature controlled the rate of heat conduction from the top and the bottom platens to board surfaces, moisture plasticizes the wood particles and improves the compaction, producing higher layer densities. A rapid press closing speed generates higher initial pressure in the mat, consequently allowing a shorter time period for heat and moisture transfer into the mat. Rapid pressing only allows maximum compression of wood closer to the surface and less compression in the core layer, which results in higher surface density and lower core density. Both Strickler (1959) and Maku (1959) reported that heat transfer into the core layer was mainly controlled by the mat moisture content in the form of steam transfer from the surface to the core. Also, the heat flow to the core is mostly by steam rather than entire heat transfer due to conduction. The increase in surface moisture content is vital for rapid heat transfer to the core and mat compaction, hence on the formation of the VDP.

Therefore, the ‘steam shock’ treatment method is widely used by the particleboard industry to control the VDP. The method uses steam to heat the mat interior quickly to reduce the wood compressive strength allowing mat consolidation to occur at lower pressure (Strickler 1959; Kelly 1977). Strickler (1959) and Maku et al. (1959) studied the heat transfer from the hot platens to the mat as well as the effect of this unsteady state heating process on moisture distribution and movement across the mat thickness. They reported that the maximum temperature reached by the core was a function of the moisture content of furnish in the early stage of the hot pressing. During the press closing time, when heat and moisture had transferred into the mat, wood compression occurred to allow consolidation of the mat to the desired thickness, during which time the VDP is established.

Research has shown that the initial temperature rise in the core of a flake-type particleboard mat could reach higher than the boiling point of water (100 ^{o}C) and start decreasing as moisture starts to evaporate from the edges of the mat releasing the heat (Strickler 1959; Maku 1959; Kelly 1977). However, the initial core temperature for granular type particles did not rise above the boiling point of water, irrespective of the mat moisture content observed from 1% to 30%. That may be due to the porosity of the particles, which may be high enough to evaporate moisture from the mat surface area to the edges to escape (Maku 1959). However, the rate of the initial temperature rise in the core was observed to be approximately the same for both flake-type and granular-type mats at the same moisture content (Strickler 1959; Maku 1959). The rate of evaporation was found to be related to the core temperature though more water may evaporate form the edges, which would result in evaporative cooling in the core at a given time period. Strickler (1959) further showed that the higher surface moisture content has a substantial influence on increasing the surface density as well as the intermediate layer density, while decreasing the inner-most layer density.

Geimer (1975) observed steeper VDP from thicker particleboards with a constant average density and constant press closing speed because heat and moisture would not reduce the internal compressive strength quickly enough to allow the compressive failure to be equally distributed across a large portion of the total thickness. Maloney (1970) reported that the higher surface resin content increased the surface density of the particleboard when he maintained other processing parameters as constant.

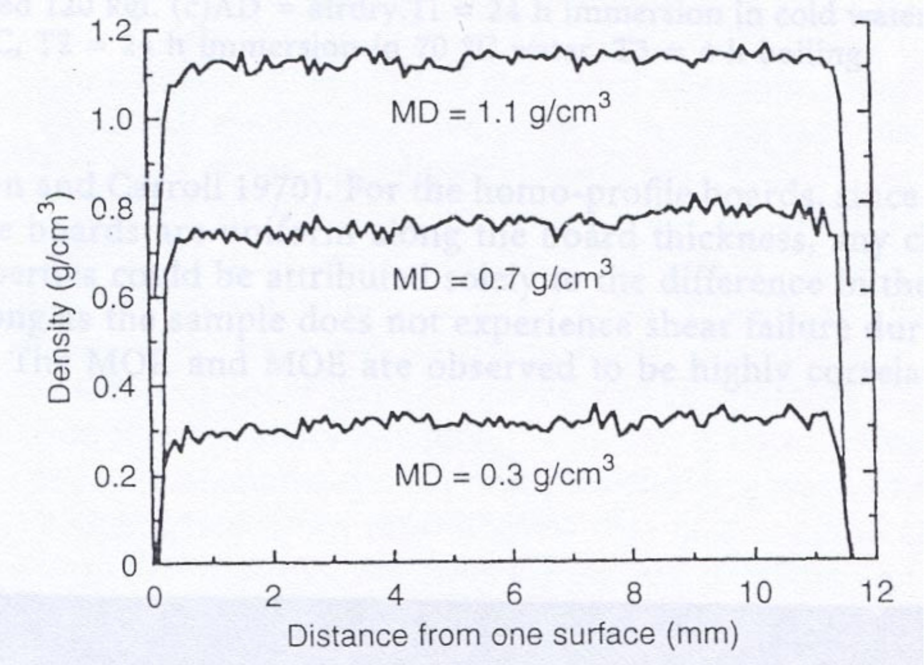


Figure 3.1: Homo-profile particleboard with uniform VDPs (Wong et al. 1998)

Wong et al. (1998; 1999) reported that the formation of a VDP was due to the effects of the mat moisture content and press closing speed. They observed and compared the board properties of homo-profile particleboard with conventional particleboard and reported that a uniform density profile has been observed for homo-profile board (Figure 3.1), while a 'U' shape density profile has been observed for conventional particleboard (Figure 3.2).

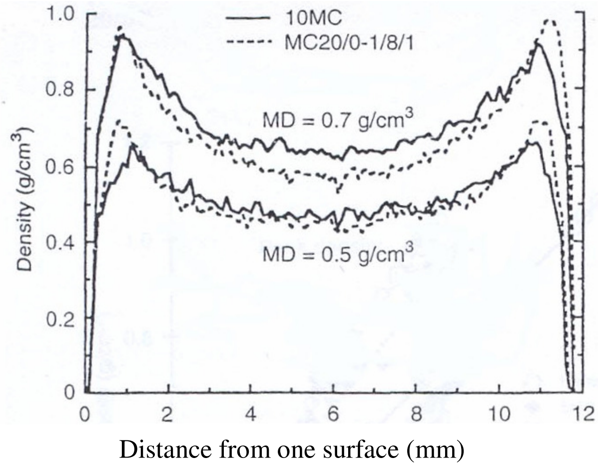


Figure 3.2: Conventional 'U'-shape density profile (Wong at el, 1998)

Wong et al. (1988; 1999) added that for the homo-profile boards (Figure 3.1), the MOE, MOR, IB and the screw withdrawal strength highly correlated with the board mean density. A conventional particleboard with the same mean density as a homo-profile board has a higher MOR and a higher MOE compared to those of homo-profile boards. This was explained as being due to a higher density closer to the surface increasing the flexural strength. However, the reverse was true for the internal bond strength due to lower density being found in the core of a conventional three-layer particleboard. Particleboards made with higher moisture content for the surface and lower moisture content for the core could increase the peak density of the board with slightly reduced density at the core. Higher press closing speed reduces the peak density of the board by increasing the density profile gradient towards the core having a minimum effect on the core density. High initial pressure with a short closing time during the hot pressing resulted in higher face density with low core density (Strickler 1959). A board with a lower initial pressure with a longer press closure time produced a relatively uniform VDP. Smith (1980; 1982) made similar observations to Strickler (1959), and reported that the press closure time can alter the shape of the density profile. Fast press closing produces a U shaped density profile, while slow press closing produces an M shaped density profile.

However, previous investigations on homogeneous particleboards observed that pressing at various press closing speeds (time taken for the upper platen to reach to stoppers) to a constant final thickness produced different VDPs (Strickler 1959; Wong et al. 1998; Miyamoto et al. 2002). This was clearly shown by Miyamoto et al. (2002) as in the Figure 3.3. It was further clarified that the time-dependent nature of the heat and moisture transfer through the mat and their resultant effect on the compressive strength of the various particle layers produce different vertical density gradients (Suchsland 1962). He further reported that with a faster press closing speed, a higher VDP could be attained, whereas with a slower press closing speed, a lower VDP is attained. A longer press closing speed helps increase stress relaxation in a board before final thickness is achieved. This affects heat and moisture transfers as well as resin cure (Miyamoto 2002). However, using longer press closing time will cause the adhesive coatings in particles next to the top and bottom platens to polymerize before sufficient inter-particle contact has occurred inside the board. This ‘pre-cured’ condition drastically reduces the bonding between particles close to the surfaces (Kelly 1977).

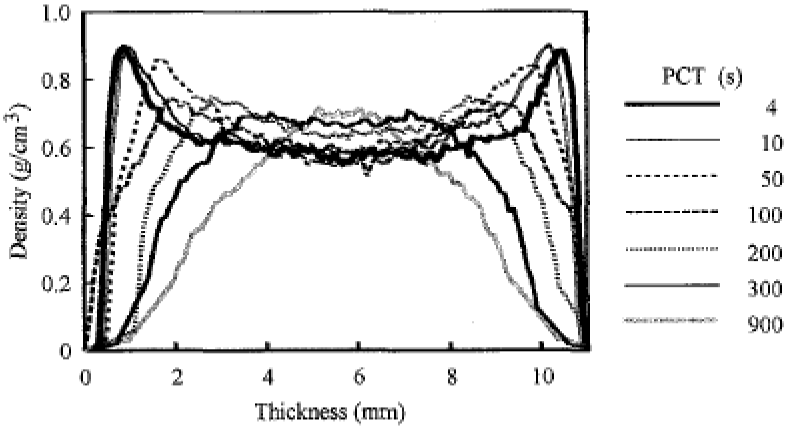


Figure 3.3 Effect of press closing temperature (PCT) on the density profile (Miyamoto et al. 2002)

Schulte and Grunwald (1996) observed that for a medium density fibreboard, the failures of the internal bond test happened at the outer part of the specimen irrespective whether the absolute minimum of the density profile is located in the centre of the specimen or of the glue type or the glue content. They observed that whether the density profile had very high maxima closer to the surface or smooth density profile or sharp relative minima in the outer parts of the specimen, failure occurred in the outer layers. They described this failure type was as being a result of the outer part of the board heating up first during the hot pressing.

Therefore, it started plasticization, densification and hardening first. At the later part of the hot pressing, the inner part of the board started to plasticize. During this time, the already cured surface layer glue bonds might have failed. Pressing conditions, heat, moisture conditions, and the curing of resins govern the vertical density profile (Suchsland 1967). However the horizontal density distribution is found to be dependent on the mat formation process and the layout of the wood strands of flakes (Dai et al. 1997).

3.4 Modelling of the VDP

Various attempts have made in the past to understand and predict the compaction of wood mat during hot pressing and formation of VDP using engineering fundamentals (Suchsland 1967; Harless et al 1987; Suo and Bowyer 1994; Dai and Steiner 1993; 1994; 1997; Length and Kamke 1996; Zombort et al. 2001; Zombort 2001; Carvalho et al. 2001). In most of these investigations, the formation of VDP is related to particle size and shape, mat formations, mat consolidation, heat and mass transfer during hot pressing. This section of the chapter discusses various attempts made in the past to model mat formation, consolidation and formation of VDP of a custom flaked softwood particleboard.

3.4.1 Modelling the mat formation

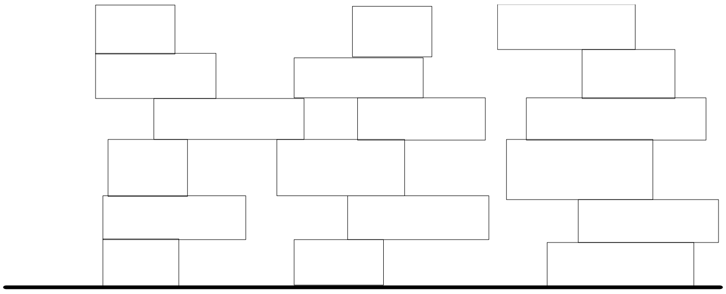


Figure 3.4: Schematic illustration of particle mat structure (Suchsland 1967)

Suchsland (1967) was one of the first to model the formation of a particleboard mat. He suggested that a mat may have identical square flakes arranged in a manner similar to the way in which bricks are combined in a brick wall (Figure 3.4). He illustrated that a mat formed layer by layer having a certain amount of wood substance with void spaces distributed within each layer can be assumed to be in a binomial distribution. However, mat structure from layer to layer could be different. The relative void space of each layer would be the same for a mat for a given type of particle. During hot pressing the amount of void space would reduce and total area of contact would increase. However, other important aspects such as the mechanism for heat and mass transfer has not illustrated in the model.

Dai and Steiner (1993; 1994; 1997) have developed a probability-based model to explain a randomly-packed, short-fibre-type wood flake composite. In this model the mat structure was viewed as a system of horizontally arranged flake columns with infinitely small cross-sectional area. When pressure is applied to the wood mat, it is primarily resisted by the transverse compression of flakes in those columns with total solid-flake thickness higher than the current mat thickness. The flake count in a column was assumed as randomly distributed by Poisson distribution. The mat compression was predicted based on the compression behaviours of the flakes. The randomly-formed flake networks are random variables essentially characterized by Poisson and exponential distribution of number of flake centres per unit area of a layer, flake area coverage, free flake length and the void size. Using this model, they tried to investigate how localized material properties in a single flake column could affect overall panel behaviour.

Zombort et al (2001) developed a model using Monte-Carlo simulation to describe mat formation in the manufacturing process and their model can produce the structure and property relationships for oriental strand boards (OSB). The model investigated mat formation, including the three-dimensional spatial geometry, orientation and density of the strands. Each of these physical characteristics was assumed to be a stochastic variable. They used data collected on industrial strands using image analysis techniques to develop probability distributions for each physical characteristic. Then the model was super-imposed on a grid on the simulated mat. Thus, this model was capable of computing the number of strands as well as the thickness and density of the mat at each grid point. The model could calculate the void volume fractions and strand contact areas which directly influence heat and mass transport properties (thermal conductivity, diffusivity and permeability) of the mat during consolidation. It was very important to know the initial sizes of particles to predict the void volumes to use this model accurately for OSB. Although the model was developed to predict the mat formation of OSB, it also successfully predicted the mat formation of random softwood fibre network.

Lenth and Kamke (1996: 1; 1996: 2) reported an investigation of flake-type mat formation for OSB. The method used is a computer image analysis technique to study the cross-sectional images of narrow mat sections. They used computer image analysis techniques to quantify the cellular structure of a flake board mat with respect to percentage area of the mat, void size and shape. The results from this investigation were used to analyse mat consolidation using theories of cellular solids.

Most of the studies discussed earlier were carried out to obtain a fundamental understanding of material behaviour during the hot-pressing process. However, most of these models have concentrated on particular types of custom-flaked softwood or custom-flaked wood materials used in the particleboard industry. The applicability of these models for prediction of mat formation of new materials with different particle shapes, particle sizes or material types is limited.

3.4.2 Modelling the consolidation and the formation of VDP

Various researchers (Suchsland 1967; Jones 1963) have considered the consolidation mechanisms of wood-based composites from different angles. Suchsland (1967) identified that the transverse compression mainly affects the consolidation of wood-fibre composite. However Jones (1963) reported that this occurs due to fibre slippage, bending at contact points, or deformation of wood fibre. Some other researchers (Dai and Stainer 1993; Wolcott et al. 1990; Length and Kamke 1996) have also modelled the behaviour of a wood-based composite, during the consolidation process. These researchers have assumed wood flake as a cellular material and used theories for cellular solids to model the consolidation of wood mat during the mat consolidation. Englund et al. (2002) developed a model to predict the compression of wood/thermoplastic fibre mat during consolidation. They concluded that the stress-strain behaviour of wood/thermoplastic fibrous material during consolidation is similar to that of granular materials. Therefore they adopted the method which is mostly used in powder compaction research. Once the material type and its behaviour were assumed, they tried to predict the formation of the vertical density profile during consolidation.

Zombort (2000) considered most possible parameters that could be incorporated into modelling the formation of VDP during the hot-pressing of particleboard. In his modelling he considered heat generation or loss at the platen and at edges due to the latent heat of water.

Also he separately modelled heat transfer due to diffusion, conduction and mass transfer due to permeability, diffusivity etc. Then he incorporated all the individual models into a numerical model to predict the formation of the density profile both vertically and horizontally.

These numerical or mathematical models assist to gain fundamental general understandings of mat formation, mat consolidation and heat-mass transfer of particleboard during the production. However, these models were developed for custom flaked softwood particleboard where particles are flake in shape. Also, these models could not be used to understand or predict the VDP of material where material properties and shape were significantly variable.

A number of other researchers used experimental design to study and then predict the formation of VDP. Kelly (1977) reported various researches on the prediction of the formation of VDP using experimental methods. Stickler (1959) and Maku et al. (1959) tried to identify the pattern of formation of VDP using experimental design. The general trend of final VDP was successfully predicted with regard to process variables such as platen temperature and moisture content. Using these models, board properties could be successfully optimized with regard to VDP.

Park et al (1999) used the theories of experimental design incorporated with response surface to study the formation of temperature profile and VDP of MDF board with regard to pressing parameters (pressing temperature, press closing time and pressure). The objective of their study was to optimize the performance of MDF with regard to its mechanical properties (MOE, MOR and IB) with regard to selected pressing parameters (moisture content, platen position and press closing time). The study showed that the VDP was highly influenced by the moisture content and platen position. However, ignoring other important parameters such as pressing time and press temperature made this study incomplete, since moisture movement is mainly controlled by temperature and time to form the VDP.

Similar to Park et al (1999), Suzuki and Miyamoto (1998) studied the formation of VDP for homogeneous particleboards using knife-ring-flaky type particles with respect to manufacturing parameters. They observed high density layers formed approximately 1 mm inside the board. The location of this high density layer was observed to influence the elastic properties of the board. Wong et al (1998; 1999) reported similar results in a similar study.

They further analysed density profile data to calculate the mean density and peak density of each board. Wong et al (1999) used these density data to predict board properties with respect to mean density and peak density using regression analysis. In addition, they studied the relationship between mean density and peak density with process parameters. The study showed that higher density near the surface was important for the mechanical properties of a particleboard while core density was important for the IB, especially for lower density boards.

Investigating the VDP with respect to processing parameters using experimental methods is attractive due to its simplicity and more appropriate prediction for practical applications. Also, it provide successful predicting capability for a given process environment such as particular laboratory or particular particleboard factory. Also, the literature shows that this method has been widely used when investigating new products, new materials or processes since inherently complex interactions are unknown. Therefore, this method is more appropriate for this investigation to find a particleboard product using hardwood sawmill residue. However, the main disadvantage of these models is that they can only successfully predict the VDP within the range of testing conditions. Since particleboard production using hardwood sawmill residues has been neither investigated nor been reported before, in this investigation, regression analyses accompanied by experimental design were used to investigate the formation of VDP. Chapter 9 investigates the formation of the VDP of three-layer particleboard produced using hardwood sawmills residues with regard to processing parameters.

3.5 Summary and conclusions

This chapter reviewed the formation of VDP and its effect on properties of particleboards. Various attempts made in the past to model the formation of VDP were reviewed. Significant findings on the formation of VDP and different types of models available to predict VDP are summarized below:

- The VDP of a particleboard forms due to the interactions of heat and mass transfer with the rheological properties of furnish and resin used during the production process.

- VDP gives an indication of the effect of processing parameters on board properties. Therefore measuring/observing VDP can be used to understand the appropriate levels of hot-pressing and optimise the pressing process.

- A number of analytical, numerical and empirical models have been developed to predict the VDP of softwood particleboard. However, these models cannot be used for particleboard made with hardwood residue.

- Most of the analytical models developed in the past considered particular material types, particle shape or size. Heat and mass transfer during hot pressing was then incorporated into modelling to predict the final VDP. Therefore, the applicability of these models in predicting the VDP of a particleboard produced from new material is limited.

- Theories of experimental design or response surface design were used in the past to study the VDP of particleboard that was manufactured using new material. However, these types of models can only be used for the range of testing conditions considered in the study.

CHAPTER 4

GENERAL PROCEDURE FOR PRODUCING PARTICLEBOARDS IN THE LABORATORY AND METHODS OF TESTING

4.1 Introduction

The objective of this research work was to investigate the possibility of developing a methodology to produce particleboard using hardwood saw-mill residue. This chapter describes the procedures, materials and equipment used for this work in the laboratory to manufacture particleboards. Further, the chapter illustrates the testing methods adopted to investigate the physical and mechanical properties of the boards produced. Single-layer and three-layer particleboards were manufactured in the laboratory with a target density 680- 720 kg/m^3 using various mix proportions derived from experimental designs with a number of variables. These variables included resin load for surface layer, resin load for core layer, moisture content for surface layer, moisture content for core layer, hardener load for core layer, pressing time and press temperature for three-layer particleboard. In addition, wax was considered to improve the moisture resistance of the particleboards at the later stages of the work. The experimental design used to perform the experiments is discussed extensively in the Chapter 5. Processing parameters and their effect on single-layer and three-layer particleboards are discussed in Chapters 6 and 7 respectively.

4.2 Materials used

4.2.1 Hardwood sawmill residues

Particleboards are traditionally made using custom-flaked softwood as the major raw material. Whilst use of softwood chips in the production of particleboard flooring is well documented, there is very little information on the use of hardwood residue in producing particleboards (Bhagwat 1993; Nirdosha et al. 2005). The worldwide demand for particleboard is growing at between 2 and 5% per annum (Drake 1995). The demand for raw materials for particleboard is continuously increasing. In Australia, considerable quantities of hardwood residues are produced annually (Kim 2001). In Victoria alone, over a million cubic meters of saw logs are converted annually, producing in excess of 200,000 tones of sawdust. Other value-adding industries such as fencing and furniture manufacturing produce a significant additional residue streams. To date, hardwood residues have typically not been favoured by the particleboard industry (or indeed other forest products industries), primarily because of the perception that they are relatively high density (compared with softwoods) and contain high levels of undesirable extractives which can cause other processing problems. This has limited the potential market for such residues and their market value.

However, the move in recent years by the sawn-wood industry towards the harvesting and processing of re-growth and plantation timber has started producing residues which are likely to have lower extractive content and be of a lower density. This potentially opens up new opportunities for both the residue generators and potential residue users such as the particleboard industry. Therefore the usability of hardwood sawmill residue as particleboard raw material was investigated.

Figure 4.1: Saw mill residue type 1: Mulch (Bigger particles)

Hardwood sawmill residues were obtained from a hardwood sawmill located in Dandenong, Victoria, Australia. Sawmill residues come in two types. Figure 4.1 shows residue type 1: Mulch (bigger particles including both cubical and flake shape particles). Figure 4.2 shows residue type 2: Fine (saw dust with smaller particles mainly cubical in shape). A Sieve analysis was done for each particle type to observe the particle size distribution (Figure 4.3).

The figure 4.3 shows that 95% of the mulch contains particles bigger than 5 mm, whilst 90% of the fine residue contains particles smaller than 5 mm.

Figure 4.2: Saw mill residue type 2: Fine (Smaller particles)

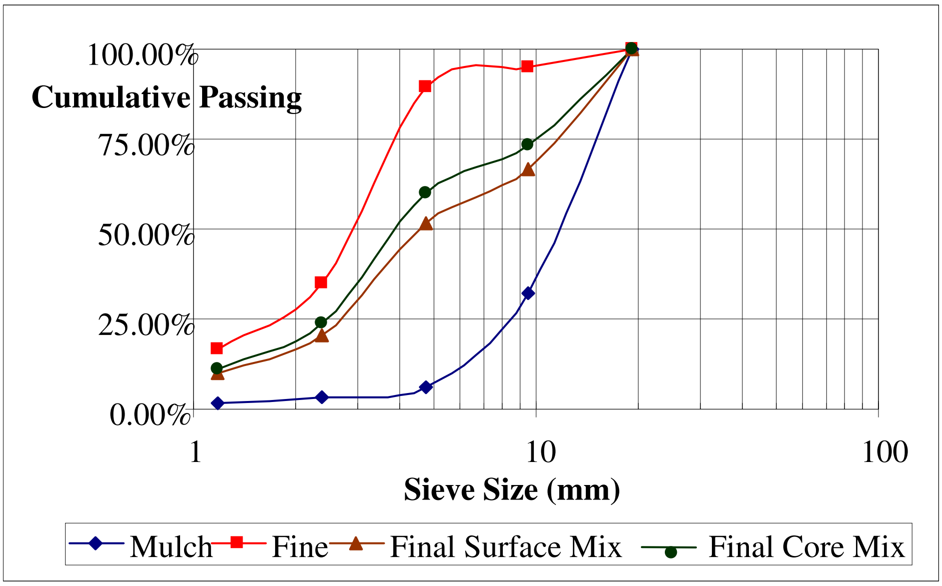


Figure 4.3: Sieve analysis curves for Mulch, Fine and final layer's mix

The particle size distribution is important in order to obtain proper compaction. Therefore, fine and mulch were mixed in different proportions for the surface layer and core layer and tested for their grading (sieve analysis). It was identified that mixing 45% Mulch with 55% Fine would provide relatively uniform particle size distribution, which was suitable as the core layer raw material. Mixing 35% Mulch with 65% Fine that contains higher amount of smaller particles was suitable for the surface layer. The softwood particleboard industry generally uses smaller particles for the surface layer and bigger particles for the core layer. This proportioning process optimises the economy of utilisation of saw mill residue in making particleboard, since no elaborate pre-processing is needed.

The mulch and fine residues were oven dried at 105°C for approximately 48 hrs to remove the moisture. Then these two types of particles were mixed separately according to the mix proportions identified for the surface and for the core.

4.2.2 Resin, hardener and wax

Urea formaldehyde (UF) was used as the resin, considering its basic characteristics at molecular level such as their high reactivity and water solubility, which renders it ideal for the wood industry. The chemical division of Orica (Australia) Pty Ltd provided the Urea formaldehyde resin (E1 resin) in liquid form. Particleboards were made in the laboratory using urea formaldehyde resin with 63-65% solids, and viscosity in the range of 115-220 cPs at 25°C. The amount of resin required for a layer of a three-layer particleboard was determined by its resin solid weight and was calculated as proportionate to the oven dry weight of the wood particles required for the layer (Appendix B).

The softwood particleboard industry uses hardener for the core layer to accelerate the curing of UF resin. The softwood particleboard industry generally uses 1 -2 % hardener for the core layer when manufacturing three-layer particleboards. Therefore, NH_4Cl was used as the hardener for the core layer to accelerate resin curing. NH_4Cl which was used in this investigation came as a crystalline salt in which 25% of NH_4Cl solid and the rest was moisture. The amount of hardener required for this work was investigated. The hardener load was calculated as the solid weight of NH_4Cl that is proportionate with the resin solid used for the core layer.

In addition, the softwood particleboard industry uses paraffin wax when manufacturing particleboards to increase short term moisture resistance. Technimul/ VivaShield Emulsion: EXP 486 was used as the Wax for this work to investigate the amount of wax required for this study to improve moisture resistant property. The VivaShield Emulsion wax came as a liquid form with 60% solid wax weight. The amount of wax added for a layer was calculated as a proportion of the solid wax weight with the dry weight to the wood particles used in that layer (surface layer or core layer).

4.3 Apparatuses and procedures used to manufacture particleboards in the labs

This section outlines the major equipments used to produce particleboards in the School of Civil and Chemical Engineering laboratories at RMIT University. Section 4.3.1 details the manufacturing apparatus used for this work. Section 4.3.2 explains the procedure used to manufacture particleboards in the laboratory. Section 4.3.3 describes the test methods and testing equipment used for this work.

4.3.1 Manufacturing Apparatuses

4.3.1.1 Mixer

A normal concrete mixer with a lid was used for mixing raw materials (Figure 4.4). The lid was designed to have a hole with a diameter of 8 cm which was used to spray the binding materials. The capacity of the mixture was 2.2 cubic foot (~ 0.062 m^3) and the rotating speed was 1250 rpm.

Figure 4.4: Mixing drum

A spray gun together with a high pressure pot was used to spray the mixture of water resin into the residue which was placed inside the rotating mixer (Figure 4.5). The capacity of the pressure pot was 1 cubic foot ($0.028m^3$). The maximum allowable pressure capacity in the pressure pot was 100 kPa (80 PSI). The pressure gun had a nozzle size of 1.5 mm and had the facility to maintain the path of the spray in either vertical, horizontal or circular directions. The blue colour which carried the mix of water-resin and the red tube carried the high pressure air.

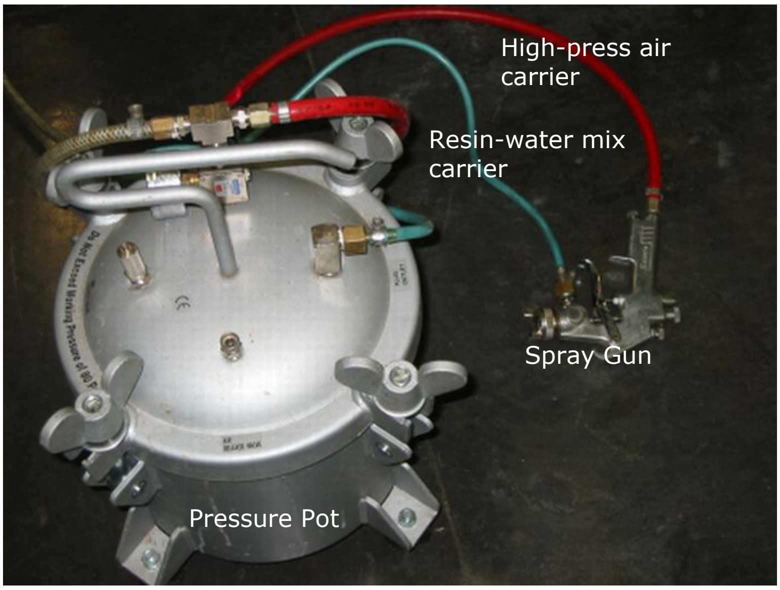


Figure 4.5: Pressure Pot and the Spray Gun

A small container (250 ml) with the mix of resin and water was kept inside the pressure pot. The end of the tube which carried the mixture was inserted into the container, to allow the transportation of the mixture to the pressure gun. Using a smaller container to hold the resin-water mix reduced wastage as well as assisted cleaning the containers quickly in order to switch from one mixing to another as soon as possible. A constant pressure capacity of 80 kPa was maintained during all the mixings although the allowable pressure capacity in the pressure pot was 100kPa.

4.3.1.2 Mould

A mould with dimensions 300 mm X 400 mm and 120 mm was used for casting particleboards before pressing. The mould could also be adjusted to prepare particleboards with the size of 400 mm X 400 mm (Figure 4.6). Horizontal lines were grooved along the perimeter of the mould at each 1cm along the depth, to facilitate spreading the pulp evenly. Teflon foils were introduced to either side (top and bottom) of the wood pulp during the moulding to stop adherence of the top and bottom of final board to aluminium plates after the hot pressing.

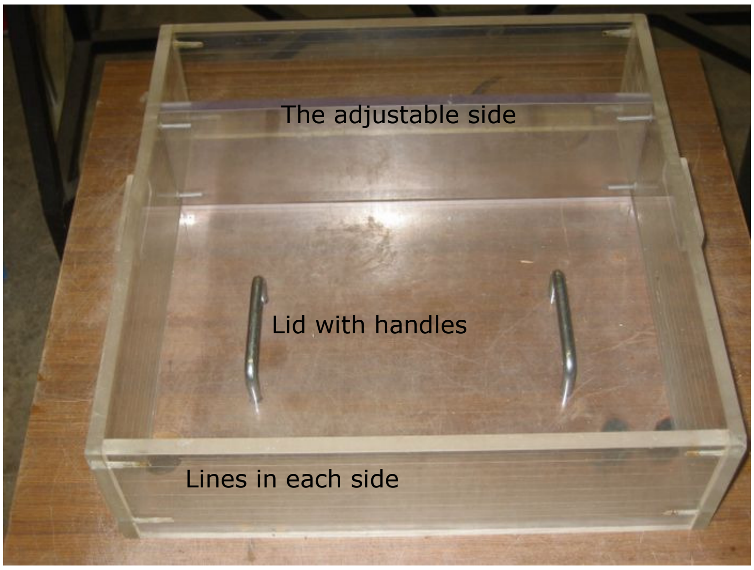


Figure 4.6: The Mould

4.3.1.3 Cold pressing and hot pressing apparatus

Figure 4.7: Cold Press

'Wabash' hot pressing equipment was used for manufacturing particleboards in the laboratory (Figure 4.8). It has facilities for both cold pressing and hot pressing. However, it takes approximately 1hr to reach 190° C and its cooling system takes nearly ½ hr to cool to room temperature (25° C). Therefore, the Wabash pressing equipment was used only for hot pressing.

Separate cold pressing equipment was developed and used for the cold pressing (Figure 4.7). The maximum press area for both the hot press and the cold press were equal at 500 mm x 500 mm. A high pressure hydraulic press was incorporated to develop the cold pressing equipment for the project. It has a pressing capacity of 25 tons on a 5 inch ram diameter. However, constant pressure was applied during the pressing operation until the final mat thickness reached 20 mm thickness using 20 mm stoppers. The maximum pressing capacity of the hot press was 40 tonnes on a 500 mm x 500 mm area. However, maximum pressing capacity was maintained at 37 tonnes throughout the manufacturing of particleboards in this study.

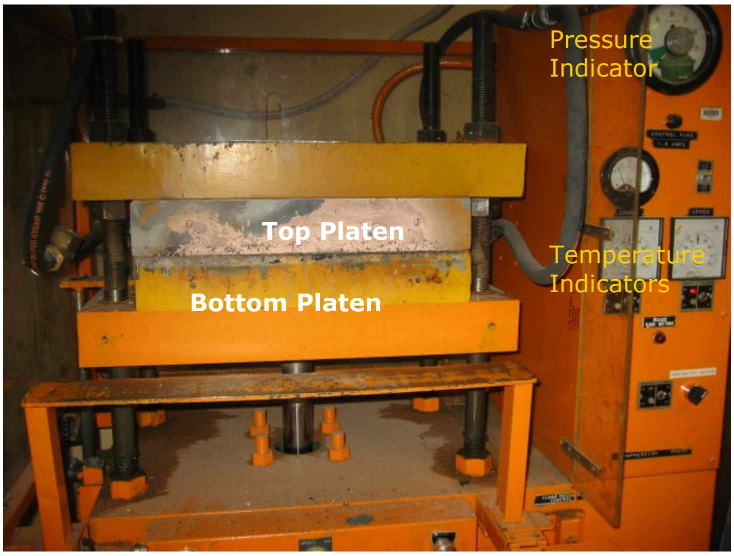


Figure 4.8: Wabash Hot Press

4.3.2 Manufacturing Procedure

This section explains the procedure adopted in this research work to manufacture particleboards using hardwood sawmill residues whereas Section 2.3 discussed the general procedure for manufacturing particleboards in industry and research contexts.

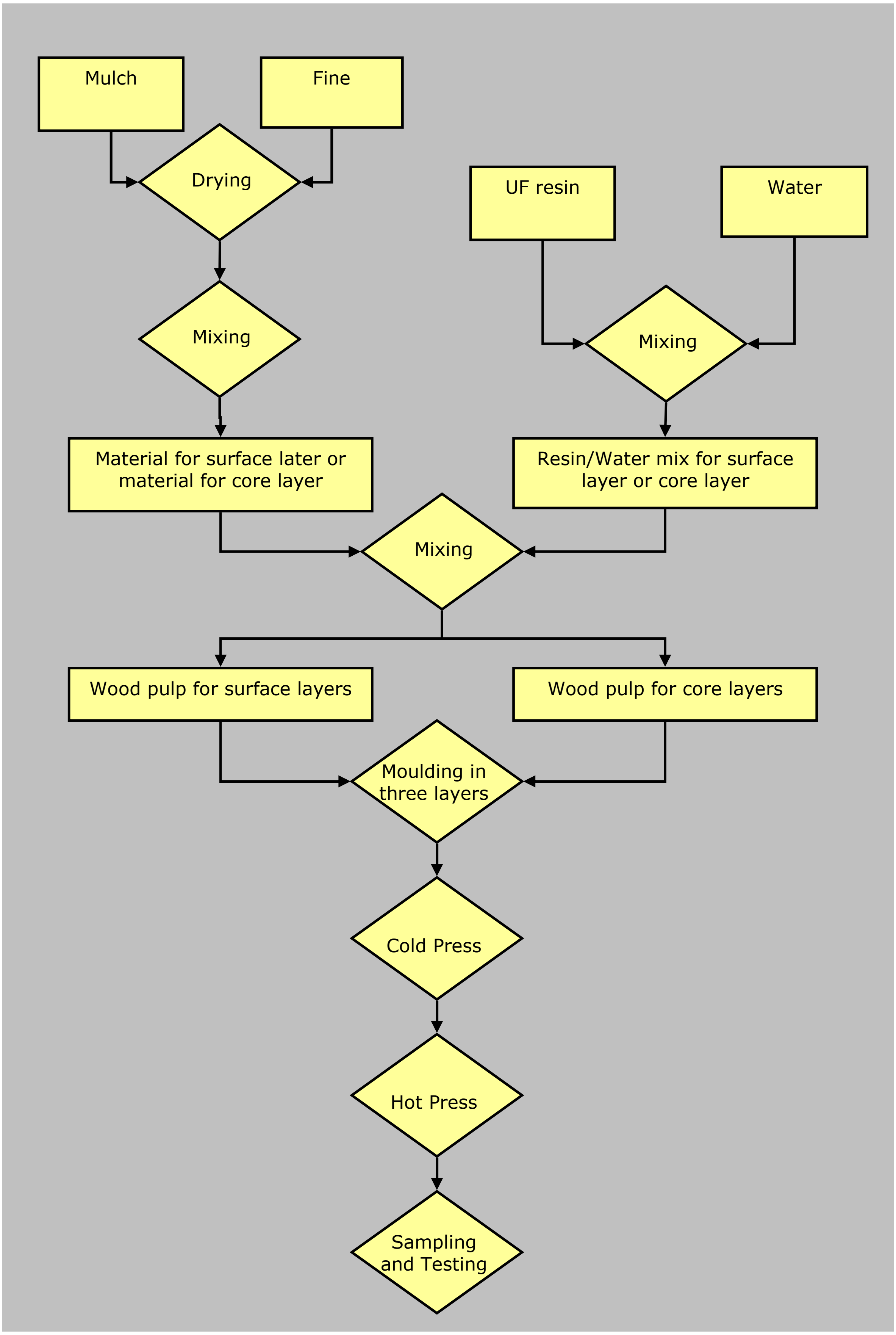


Figure 4.9: Procedure for manufacturing particleboards in the laboratory

Figure 4.9 shows the flowchart which highlights the major steps adopted in the laboratory in making particleboards. As mentioned earlier in Section 4.2.1, the hardwood sawmills residues came in two types: Mulch (bigger particles) and Fine (Smaller particles). These residues contained very high initial moisture content measured at around 80% at the saw mill when they were collected for the investigation. As this moisture content was extremely high, the residues were oven dried at a temperature of 105°C (Figure 4.10). It was of interest to investigate at the beginning, how long it would take to evaporate the moisture completely or to dry the raw material completely. The method adopted in the drying of material is given below:

- A sample of residue was left in an oven at 105°C
- The weight was measured each 6 hrs until a constant weight was achieved

It was found that residues need to be oven dried for more than 24 hrs to evaporate the surface moisture (a constant weight of residue was noted). Therefore, sawmill residues were oven dried more than 24 hrs before being used for particleboard manufacturing.

Figure 4.10: Oven drying the wood residues

The amounts of mulch, fine residue, resin and water were calculated considering the target density of the particleboard. When the target density was decided, the final board weight was calculated by multiplying the density with final board volume. The total thicknesses of two surface layers of the three layer particleboard were 40% of the total particleboard thickness. That means the final thickness of a surface layer was 20% of the final board thickness. The total weight of residue (mulch + fine) for each layer was calculated in proportion to the dry particleboard weight.

The amount of Mulch or Fine for each layer was measured considering the designed particle size distribution which was discussed in Section 4.2.1. The mulch: fine ratio for the surface layer was maintained at 35%: 65% and for the core at 45%:55% (by weight). When the calculated amount of mulch and fine were weighed for the surface layer, they were mixed inside the mixing drum for 2 minutes prior to spraying the resin mix.

Figure 4.11: Mixing the material

The proportionate amounts of resin and wax for each layer were calculated considering the solid weight of resin or the solid weight of wax with respect to the oven dry weight of the residue required for the layer. However, the solid weight of the hardener was calculated with respect to resin weight used for the same layer. The spreadsheet which incorporates a pivot table used for calculating mix proportions is attached in Appendix B. The amount of resin and water (and wax or hardener if used) required for surface layer was measured and then mixed inside a small container. Then this mix was placed inside the pressure pot and the inlet for the resin/water mix carrier of the spay gun was inserted into it. This mix was then sprayed into the mix of fine and mulch which had already been mixed for 2 minutes in the drum (Figure 4.11). After adding resin, furnish was mixed for a further 5 minutes approximately. Then this pulp was separated into two containers for the two surface layers of a particleboard.

Figure 4.12: Moulded wood mat

Figure 4.13: Manual pressing of the mat

Similar to the procedure adopted for the surface layer material, the core materials were mixed inside the mixing drum. The major difference between surface layer and core layer was the proportions of mulch and fine. The amount of mulch used for the core layer was higher than that for the surface layer. Also, the surface layer used higher amounts of resin and moisture compared to those for the core layer. When the core material was mixed, the required amount for a single core layer was measured. Then, these pulps were spread into three layers in the mould (Figure 4.12). The following steps were taken during the moulding.

- An aluminium plate was placed on the bench.
- A Teflon foil was spread on the Al plate.
- One surface layer material was spread first followed by core layer material and finished with top surface layer material.
- The thickness and the level of each layer were maintained with the help of lines in the walls of the mould.

Once the moulding was finished, the mould was closed with an aluminium plate. Then, it was manually pressed by standing on the lid (Figure 4.13). The mould was removed carefully while the researcher was still standing on the lid. Then, the researcher stepped off the wood mat cautiously. Once the mat was transferred into the cold press, the lid was carefully taken away leaving the nicely pre-pressed mat (Figure 4.14). Then another Teflon foil was placed on top of the mat followed by an aluminium plate. The aluminium plates facilitate the even distribution of pressure on the wood mat as well as even temperature distribution at the mat surface during hot pressing. The Teflon foils prevents sticking of the wood mat to the aluminium plate after the hot press.

Figure 4.14: Manually pressed wood mat (before cold press)

Constant pressure was maintained on each board during the cold pressing operations. The cold pressing time is important to remove the trapped air from the wood mat during mat consolidation. However, in this work the cold pressing time and the hot pressing time were controlled to be the same as is the usual practice in the particleboard industry. When the cold pressing and hot pressing times are kept equal, no machines are idle during the production cycle in order to maintain a low production cost of particleboard by the particleboard factory. The final thickness of the wood mat after the cold press was controlled by using two stoppers at either side of the wood mat (Figure 4.15). The thickness of each stopper was 20 mm.

Figure 4.15: Cold pressing

Figure 4.16: Hot pressing

Immediately after the cold pressing, the wood mat was inserted into the hot press (Figure 4.16). Two stoppers were used to control the final particleboard thickness. The hot press temperature and hot pressing time were maintained depending on experimental design values. The experimental design values are discussed in each chapter when the experimental design and results are discussed. The hot pressed boards were removed from the press and left to cool. Then these cooled boards were stored in a ventilated area for a week to remove the trapped air and formaldehyde before sampling and cutting (Figure 4.17). Spacers were used between these boards to facilitate ventilation.

Figure 4.17: Final particleboards (before cutting and sampling)

4.3.3 Sampling and Cutting

Samples were prepared and cut from each test board according to AS/NZS 4266.1 (2004). The thickness of the particleboard was measured and its symmetry compared about its central axes. Then, the sizes for the test pieces were marked on the cutting side of the particleboard after trimming the edges of the test particleboards. A Steel-fast chain-saw was used for cutting the samples as it gives a smooth cutting surface (Figure 4.18). Once the samples were prepared, they were left in a humidity cabinet (Figures 4.19 a and 4.19 b) at a temperature of 20°C and 65% humidity until a constant mass was achieved (AS/NZS 4266.1 2004).

Figure 4.18: The Chainsaw

Figure 4.19a: Humidity cabinet

Figure 4.19b: Samples in the humidity cabinet

4.3.4 Testing Apparatus and test methods

Each particleboard was tested for its mechanical properties (MOR, MOE and IB). In addition, particleboards from selected test groups were tested for their density profiles and thickness swelling. The MOE and MOR of a sample were tested according to three point bending test using an Instron universal testing machine. The IB of a sample was measured using a Hounsfield tensiometer.

4.3.4.1 Testing modulus of elasticity (MOE) and modulus of rupture (MOR)

A universal testing machine manufactured by Instron was used to test the MOE and MOR of a test sample using three-point bending test (Figure 4.20). The maximum loading capacity of 2 kN was used. The equipment comes with software that can be used to program the equipment to tun as required, recording the data into a computer file, as well as calculating basic properties such as compressive or tensile strength. The MOE and MOR of particleboard samples were prepared and tested according to AS/NZS 4266.5 (2004).

Figure 4.20: INSTRON universal testing machine

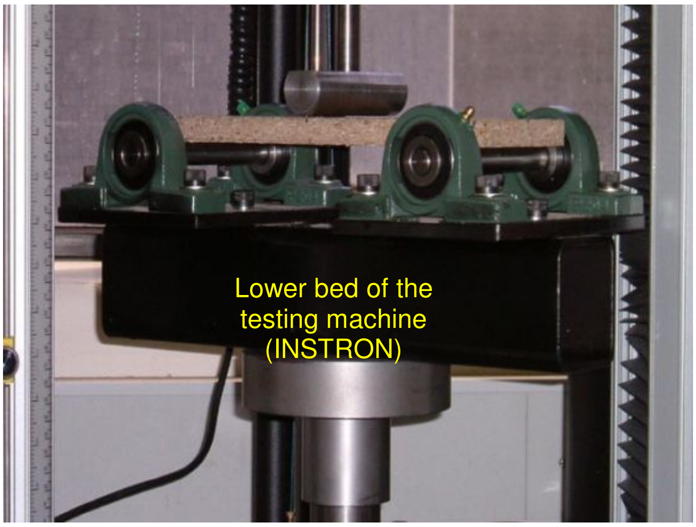


Figure 4.21: Testing of MOE and MOR

The test apparatus which was placed on the lower bed of the testing machine (Instron) in the figure 4.21 was designed by the author according to the specification given in AS/NZS 4266.5 (2004) for three-point bending test (Figure 4.21). It was then manufactured in the RMIT Civil Engineering workshop. The test piece was simply supported horizontally on parallel metal rollers with a diameter of 25 mm which were free to rotate. The centre spacing of the rollers was maintained at 250 mm. A load normal to the face of the test piece was applied at the centre of the span by means of a metal bar parallel to the supporting rollers and in contact with the test piece over its whole width, and the deflection at a given load was measured. For testing the MOR, the load was increased until sample failure occurred and the breaking load was recorded. The rate of travel of the loading bar was maintained at 5 mm/min. The MOE of the sample was calculated using equation 4.1 considering the corresponding deflection was within a load range up to one third of breaking load of the board under test. Therefore, it was programmed to consider ΔW calculated as '40% of fracture load – 10% fracture load' and the corresponding deflections to calculate the MOE. Deflection (S) was measured to the nearest 0.01 mm and load value to the nearest 5 N. The MOR of the test sample was calculated the Equation 4.2 using the ultimate fracture load.

$$MOE = \frac{L^3}{4bt^3} x \frac{\Delta W}{\Delta S} \qquad \text{Equation 4.1}$$

Where,

MOE	Modulus of elasticity, in Mega Pascal
L	Span between centres of supports, in mm
ΔW	Increment in load in N
b	mean width of test specimen, mm
t	mean thickness of specimen, mm
ΔS	deflection with the load ΔW

$$MOR = \frac{3WL}{2bt^2} \qquad \text{Equation 4.2}$$

Where,

MOR	Modulus of Rupture in MP
W	Ultimate failure load, N
L	Span between support, mm
b	mean width of test specimen, mm
t	mean thickness of test specimen, mm

4.3.4.2 Testing internal bond strength (IB)

A Hounsfield tensiometer was used with modified jaws to hold the test samples for this test (Figure 4.22). The modified jaws that can be assembled to the Hounsfield tensimeter were designed by the author according to AS/NZS 4266.6 (2004) and manufactured at the RMIT workshop. 50 mm x 50 mm samples were taken from each particleboard and processed in a humidity cabinet at 20^{o}c and 65% humidity until a constant weight was reached. Hardwood testing blocks with 70 mm x 50 mm were used, to which the test pieces were glued for IB testing. 24 hour Araldite (epoxy glue) was used to bond the test samples to the test blocks. Once the samples were glued into test blocks, they were stored for 24 hours before being returned to the humidity cabinet. The samples were stored in the humidity cabinet until testing.

Figure 4.22: Hounsfield universal testing machine

$$f_{t\perp} = \frac{F_{\max}}{ab} \qquad \text{Equation 4.3}$$

Where,

F_{max} = breaking load in newtons

a, b = length and width of the test piece, in millimetres

$f_{t\perp}$ = tensile strength perpendicular to the plane of the panel

Test blocks were assembled in the grips with modified jaws (Figure 4.23). Tension perpendicular to the surface of the test piece was determined by applying a uniformly distributed tensile force. The rate of loading was maintained so that the maximum load was achieved within 60 ± 30 seconds. The IB was determined using the maximum load in relation to the surface area of the test piece using Equation 4.3 (AS/NZS 4266.6: 2004).

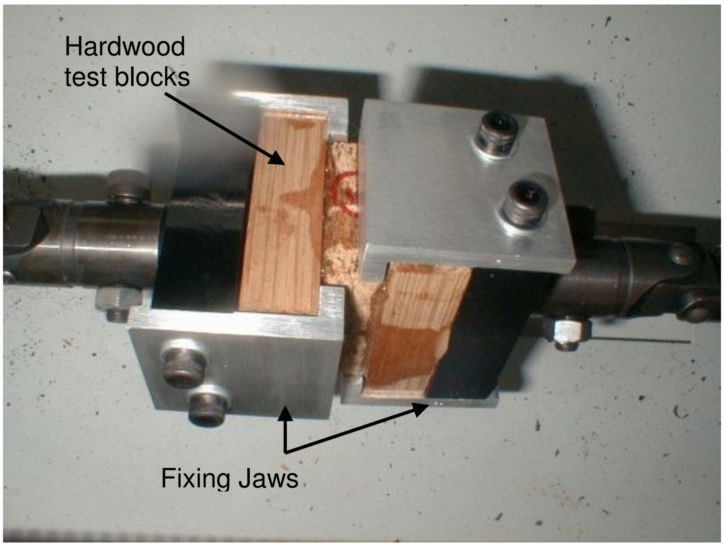


Figure 4.23: IB testing

4.3.4.3 Swelling in thickness after immersion in water (2 hour and 24 hour thickness swelling test)

Swelling in thickness of a particleboard sample was determined by measuring the increase in thickness after being immersed in water (AS/NZS 4266.8: 2004). 50 mm x 50 mm test samples were taken from particleboards and conditioned in a humidity cabinet at 20^{o}C and 65% humidity until a constant weight was reached. Then the thickness of the sample was measured with an accuracy of 0.01mm at the intersection of the diagonal (centre of the test piece). The sample was then immersed in clean, still water with pH = 7±1 and a temperature of 20^{o}C. Samples were placed with their faces vertical. The upper edges were covered by up to 25±5mm of water throughout the test. The thickness of the centre of the sample was measured after 1 hour (for the 1 hour thickness swelling test) and after 24 hours (for the 24 hour thickness swelling test). The swelling in thickness (G_t) was calculated as a percentage of initial thickness using Equation 4.4.

$$G_t = \frac{t_2 - t_1}{t_1} x100 \qquad \text{Equation 4.5}$$

Where

G$_t$ = swelling in thickness

t_1 = thickness of the test piece before immersing in water

t_2 = thickness of the test sample after immersing in water

Figure 4.24: Thickness swelling test

4.3.4.4 Wet bending strength after immersion in water at 70^o C temperature

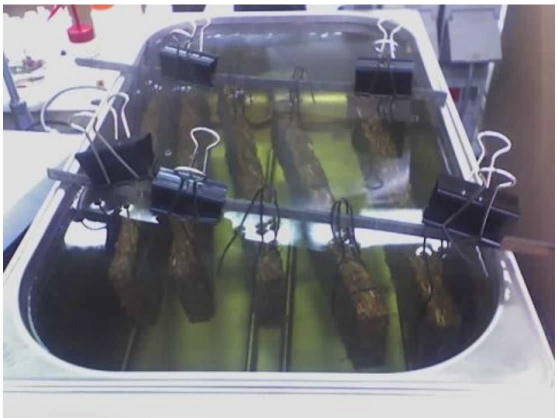


Figure 4.25a: Samples in the hot water bath

Figure 4.25b: Wet bending test

The wet bending strength of a particleboard was measured by measuring the bending strength (MOR) of a particleboard sample after being immersed in a hot water bath (AS/NZS 4266.10:2004).

4.4 Summary and Conclusions

This chapter introduced the procedure adopted in the RMIT laboratory for processing materials and manufacturing particleboards using hardwood saw mill residues. It also discussed the testing equipment used and the test methods followed to test the physical, mechanical and moisture resistance properties of particleboard. Particleboards were sampled and tested according to AS/NZS 4266:2004 on standard tests for particleboard testing.

All the equipment developed at the RMIT and the methodologies reported in this Chapter were developed entirely by the author after many trials based on findings of the preliminary literature review. These processes were further optimised using a systematic research program reported in subsequent chapters.

CHAPTER 5

DESIGN OF EXPERIMENTS (DOE)

5.1 Introduction

Experimental methods are widely used in research and development (R & D) work as well as in industrial settings for different purposes. In industrial research and development, the primary goal is to extract the maximum amount of unbiased information from the dependent variables and independent factors using a minimum number of observations in order to minimize R& D costs and optimize the process. Design of experiment (DOE) theory is a sub-set of statistics which provides the experimenter with methods for selecting the values for independent variables, so that a limited number of experiments can be performed to obtain a logical understanding of the dependent variables and independent variables. The statistical tools used to model the sensitivity in the observed data include regression analysis, analysis of variance (ANOVA) or a collective use of both techniques called response surface methodology (RSM).

The primary objectives of our research were to develop a technology for producing an economical particleboard product utilizing large quantities of hardwood saw dust and other saw mill residue (a new raw material for particleboard production), to meet AS/NZS 1859.1:1997 and to investigate the relationship of the process variables of particleboard production with the density profile of the board and its properties. DOE is a very important technique when there is a need to develop a new product using new materials if the underlying mechanism in the system to formulate a model between response variables and independent factors is unknown.

This chapter therefore discusses methods of DOE and analysing techniques used for the research. The following sections will review the advantages of DOE methods when developing a new product and process. Further, the chapter explains the method used in DOE, factorial design and fractional factorial design and how these methods have been incorporated into this research. In addition, it elaborates the analytical techniques used to analyse data, such as ANOVA (analysis of variance) tables, regression modelling and methods that can be used to check the validity of the model.

5.2 Using the Design of Experiments

DOE provides the researcher with methods for selecting the independent variable values at which a limited number of experiments can be conducted to cover a large number of independent variables. The researcher can change several factors simultaneously yet each factor is evaluated independently as though factors were varied independently. Since this research is to evaluate the suitability of hardwood saw mill residue as particleboard raw material, the challenge is that there are a lot of unknowns about how best to design the product. The theory is unknown or inadequate, risk is very high and some people are not convinced about the new product. Using DOE can turn unknowns into estimates of the effects of variables in developing empirical relationships which adequately predict and replace theoretical models between dependent and independent variables. In order to achieve the best possible empirical relationships, tests should be carried out with:

- Randomization: Randomization is the running of test parts in random order which prevents the confounding of effects that can happen when tests are run in a standard order. For example, if temperature is a controlled design variable, it would be best not to run all the temperatures at a given level at the same time. If all test points at a given temperature are run at the same time, the effects of time can be confounded (mixed up) with ten effects of temperature (DOES 1989).

- Replication: Replication is repeating the same test for several times and get the average test results for analysis in order to monitor and minimize any human error.

The selection of ranges of controlled design variables should be done in line with the test objectives and should be clustered around the current product values. Since our objective is to develop a new product, the ranges would encompass all possible achievable values as well as the aim to develop an achievable particleboard product. Also, the increment between levels of test variables should be realistic in order to obtain good readings of the variables. Selection of the range of each factor was carried out considering actual practice in the particleboard industry. Therefore, using DOE together with factorial design was identified as a very efficient way of achieving these objectives.

5.3 Factorial design

Factorial designs are most efficient way to study the effects of two or more factors than one-factor-at-a-time experiments, when studying with experiments (Montgomery 2005; Bailey 2004). In factorial design, all the possible combinations of the levels of the factors are investigated. Also, it helps to identify the interaction between factors as well as the significance of the main effect with respect to the level of the other factors without drawing misleading conclusions. Since factorial design allows the effects of a factor to be estimated at several levels of the other factors, yielding conclusions are valid over a range of experimental conditions.

5.3.1 Factorial design

Since 2^k of experiments are performed at each replicate of the trial experiments for k number factors (independent variables), the design is called 2^k factorial design. In this method, only 2 levels for one factor are considered for the experiments. 2^k factorial design is very important at the start of the response surface methodology to identify important process or product variables for response surface design. 2^k is the building block that is used to create other response surface design. It is often used to fit a first-order response surface model to generate the factor effect required to perform the method of steepest ascent.

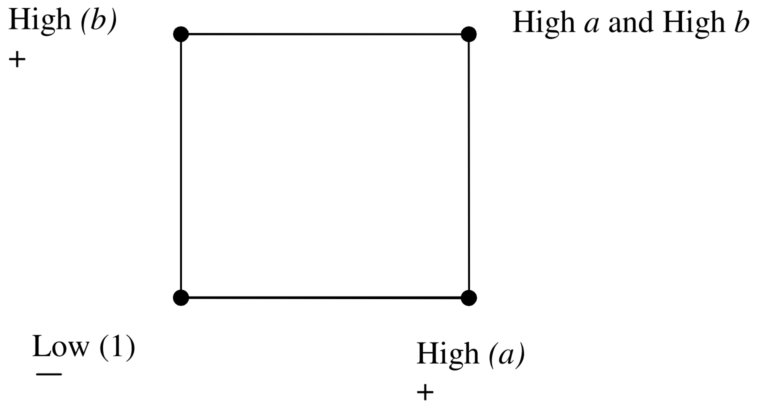


Figure 5.1: Design space for two parameters, 2 – level factorial design.

Figure 5.1 shows the two parameters, 2^k (k=2) design which contains two levels; low and high values of the parameters. These two levels may be quantitative, such as two values of temperature or time; or two values of moisture or resin; or even two values of machine or operator. In the 2^k design experiments will be conducted for at least four factor-level combinations.

Generally the effect of the factor (A) is denoted as capital letter 'A', the effect of factor B as 'B' and the interaction effect of AB as 'AB'. In the 2^k design the low and high levels of the factors A and B are denoted as '-' and '+' respectively on the A and B axes (Figure 5.1). This convention is used by the 'MINITAB' software which was used here for the design and analysis of experiments. Therefore, the same convention will be used in the following chapters for analysing and graphing the effects of factors such as 'A' for 'surface moisture content', 'B' for 'core moisture content' and 'C' for 'surface resin content' etc.

5.3.1.1 Effects

The average effect of the factor (A) on the response is an important property that is used to determine the relative strength of the effects. The totals of the response (R1) from all the replicates (n) are used to calculate the average effect. Figure 5.1 shows the total of R1 from n replicate at each four levels of the design as (1), a, b and ab. Then the average effect of the factor A on the response R1 is calculated by averaging:

- The effect of A at the low level of B [a – (1)]/n and
- The effect of A at the high level of B ([a-(1)]/n).

Therefore, the main effect of A can be calculated using Equation 5.1 which can be expanded as in Equation 5.2. Similarly, the average effect of the AB interaction on the R1 can be calculated as in Equation 5.3. Myers and Montgomery (2002) have elaborated in detail the method of calculating the effects of factors and interaction.

$$A = \bar{y}_{A^+} - \bar{y}_{A^-} \qquad \text{(Equation 5.1)}$$

$$A = \frac{ab+a}{2n} - \frac{b+(1)}{2n} = \frac{1}{2n}[ab+a-b-(1)] \qquad \text{(Equation 5.2)}$$

$$AB = \frac{ab+1}{2n} - \frac{a+b}{2n} = \frac{1}{2n}[ab+(1)-a-b]$$ (Equation 5.3)

The average effect on the response value is important for analysing experimental results as the higher the value, the greater the effect on the response. Therefore, this can be used to identify the most important factors on the response as well as to screen out the least important factors. Then, the analysis of variance (ANOVA) is generally used to confirm this. The sign of the calculated value of the effect determines whether the factor has a positive or a negative effect on the response. If the sign is '+', then the factor has positive effect on the response, otherwise the factor has a negative effect on the response.

5.3.1.2 Analysis of Variance (ANOVA)

The ANOVA Table has been used extensively to identify the most important factors and interactions on the dependent variables or response variables such as MOE or MOR in this research. The ANOVA table (Table 5.1) includes:

- Test statistical value (T),
- Test of null hypothesis (P-values),
- Degree of freedom and Error component.

It is a very important tool to determine the important factors or their interactions on the response variables as well as their level of importance. The factor effect that is not significant is normally distributed with mean zero and variance σ^2.

A variable with a significant effect will have a higher 'T' value compared to non-significant variables (Myers and Montgomery, 2002). Therefore, parameters with higher 'T' value are considered as significant variables and those with lower 'T' values are considered to have a negligible effect on that particular testing property. The level of significance of the variable considered is estimated by calculating the probability of the null hypothesis (P). MINITAB 14 can be used to calculate these statistical values. According to Myers and Montgomery (2002 page 89) the SSR value (sum of squares of the regression value) for each factor or interaction may be easily calculated from the data in Equations 5.2 and 5.3 (see Equation 5.4).

Table 5.1 Analysis of Variance for Significance of Regression in Multiple Regressions (Myers and Montgomery 2002)

Source of Variation	**Sum of Squares**	**Degree of Freedom (DF)**	**Mean Squares**	**T**	**P-Value**
Regression	SSR	k	MSR	MSR/ MSE	
Error of residuals	SSE	n-k-1	MSE		
Total	SST	n-1			

$$SS_A = \frac{[ab + a - b - (1)]^2}{4n} \qquad \text{(Equation 5.4)}$$

Where,

SS_A = Sum of squares of factor A

5.3.1.3 P-values

The experimenter should select the most significant factors which have an effect on the response while omitting unimportant factors. Adding more and more factors for the regression model may increase the sum of squares for regression. However, having unimportant factors in the model increases the mean square of error, thereby reducing the usefulness of the model (Myers and Montgomery 2002). The significant interactions should be given priority because a significant interaction will influence how the main effects are interpreted. At this point hypothesis testing is done to select the most important factors and interactions. A null hypothesis is made as ‘the particular factor does not have a significant effect on the response’ and the probability of this null hypothesis (P-value) is calculated with respect to that. The calculated P-value is then compared with α (=0.05) to conclude that the null hypothesis is true or not true. If the P-value is less than 0.05 ($P < \alpha$), it implies that the null hypothesis is not true. Therefore the factor or the interaction has a significance effect on the response with more than 95% significance. This significant tool will be extensively used for factor screening in this research.

5.3.1.4 Normal effects plot

Normal effects plot is another tool used to analyse data to identify significant effects and interactions in the particleboard production process. Normal effects plot compares the relative magnitude and the statistical significance of both main and interaction effects. The MINITAB software draws a line to indicate where the points would be expected to fall if there were no effects. Significant effects are larger and farther from the line than non-significant effects. By default, MINITAB uses ‘α-level = 0.05’ and labels any effect that is significant. These plots will be used in this analysis as they will screen the most significant process variables with 95% level of significance.

5.3.2 2^{k-p} Factorial design

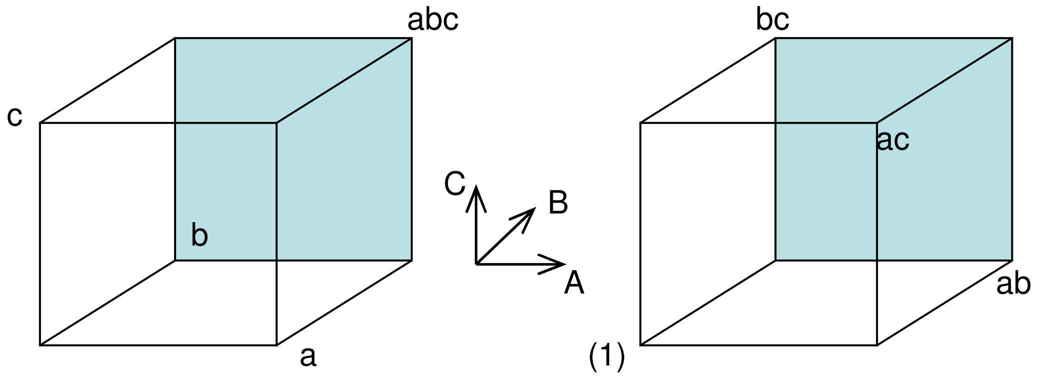
When there are many factors which are to be considered for experimentation, the number of runs required to complete a replicate of experiments is higher with 2^k full factorial design. At the beginning of our research to develop hardwood particleboard using saw mill residues, seven factors were identified as possible variables which may control the properties of the final particleboard. In order to complete a single replicate of a full 2^k design, 128 particleboards should be manufactured and tested in the lab. Due to the time and resources needed for completing such a large number of experiments, it is vital to find an alternative but efficient method to complete the task.

Fractional factorial design (2^{k-p}) was identified as it would fulfil our requirements. Fractional factorial design is a widely-used method in the industry to design for product or process or to improve an existing process by performing experiments efficiently. Also, this method significantly reduces the number of experiments by drastically minimizing costs and time. According to Montgomery (2005), the success of fractional factorial design depends on:

1. The sparsity of effects: When there are several variables, the process is likely to driven by some of the main effects and interactions.
2. The projection property: Fractional factorial design can be projected into a larger design.

3. Sequential experimentation: It is possible to combine the runs of two or more fractional factorial designs to assemble sequentially a larger design to estimate the factor effects and interactions of interest.

In case of a 2^{3-1} fractional factorial design, four experiments need to be conducted. There are two fractions to this 23-1 design: combination type (a) and (b) as in Figure 5.2. Then experiments can be conducted for either combination type (a) or (b). However, the runs for the combination (a) are normally conducted (first half of Table 5.2) with plus sign for ABC. ABC is called the generator and 'I' (the first column of Table 5.2) is called the identity column. The '—' and the '+' signs respectively represent the 'low' and the 'high' value of A, B and C factors on the A or B or C axes (Montgomery 2005; Myers and Montgomery 2002).



(a) The principal fraction, I = +ABC (b) The alternate fraction, I = -ABC

Figure 5.2: The two one-half fractions of the 2^3 design. (Myers and Montgomery 2002, p.156)

The linear combinations associated with the main effects can be calculated using equation 5.2. Since there is no replicate, the value of n becomes 'one' and the main effect of A will be as in Equation 5.5. The two factor interaction of BC can be calculated using equation 5.4 and it is formulated in Equation 5.6.

$$[A] = \frac{1}{2}(a - b - c + abc)$$ (Equation 5.5)

$$[BC] = \frac{1}{2}(a - b - c + abc)$$ (Equation 5.6)

Table 5.2: Plus and minus signs for 2^3 factorial designs.

Treatment Combination	**Factorial Effect**							
	I	**A**	**B**	**C**	**AB**	**AC**	**BC**	**ABC**
a	+	+	-	-	-	-	+	+
b	+	--	+	-	-	+	-	+
c	+	-	-	+	+	-	-	+
abc	+	+	+	+	+	+	+	+
ab	+	+	+	-	+	-	-	-
ac	+	+	-	+	-	+	-	-
bc	+	-	+	+	-	-	+	-
(1)	+	-	-	-	+	+	+	-

When Equations 5.5 and 5.6 are considered, it is clear that factor effect of A = combination effect of factor B and factor C (ei: [A] = [BC]. Similarly [B] = [AC] and [C] = [AB]. This property is called aliases. That is, factor effect of A and combining effect of BC are aliases. Therefore experiments will be performed for the fraction of these aliases; either in Figure 5.2.a or 5.2.b. When analysing a fractional factorial design, the property of aliases is taken into consideration to predict the main effects or interaction effects of the aliases. Therefore this property was used to design the experiments for designing screening tests to identify main effects and interactions on the properties of particleboard. The following section will discuss screening tests and methods used for analysis.

5.3.2.1 Screening Tests

At the initial stage of the project, a series of screening experiments was performed to identify the most important parameters and their interactions controlling the process and the final properties of the particleboard. Two series of screening tests were performed. In the first stage, single-layer particleboards were manufactured considering six variables (factors). Fractional factorial design 2^{6-3} was done with three replicates and the results are analysed and discussed in Chapter 6. In the second stage of the screening test, 2^{7-3} fractional factorial design was carried out considering 7 factors for three-layer particleboard. Sixteen (16) different treatment combinations were recognized to conduct the experiments (Table 5.3). Considering the literature and industrial practices the following seven variables were identified as having an effect the three-layer particleboards. Although pressing pressure is an important parameter with regard to particleboard production, it could not be controllable with the hot press used for this work. Also, highest pressing capacity used for this investigation was found to be 1/8 times of the industrial set-up after communication with the particleboard industry. Therefore, the maximum pressing capacity (40 tonnes on 500 mm x 500 mm area) was used for this investigation.

1. A Moisture Surface
2. B Moisture Core
3. C Resin Surface
4. D Resin Core
5. E Hardener Core
6. F Pressing Time
7. G Hot press Temperature

Table 5.3: Plus and minus signs 2^{7-3} for fractional factorial design

Runs	**A**	**B**	**C**	**D**	**E**	**F**	**G**
1	-	-	-	-	-	-	-
2	-	-	+	-	+	+	+
3	+	-	-	+	+	+	-
4	-	+	-	+	+	-	+
5	+	-	+	+	-	-	+
6	-	+	+	+	-	+	-
7	+	-	-	-	+	-	+
8	+	-	+	-	-	+	-
9	-	-	+	+	+	-	-
10	+	+	-	-	-	+	+
11	+	+	+	+	+	+	+
12	+	+	-	+	-	-	-
13	-	-	-	+	-	+	+
14	-	+	+	-	-	-	+
15	-	+	-	-	+	+	-
16	+	+	+	-	+	-	-

The software that was used for design and analysis (MINITAB release 14) produces the output for Table 5.3 as well as aliases required for folding the experiments. The sixteen aliases defined are tabulated in Table 5.4. The parameter range (low and high value) used to design experiments the results and analysis are discussed in detail in Chapter 6.

Table 5.4: The aliases structure

1	I + ABCE + ABFG + ACDG + ADEF + BCDF + BDEG + CEFG
2	A + BCE + BFG + CDG + DEF + ABCDF + ABDEG + ACEFG
3	B + ACE + AFG + CDF + DEG + ABCDG + ABDEF + BCEFG
4	C + ABE + ADG + BDF + EFG + ABCFG + ACDEF + BCDEG
5	D + ACG + AEF + BCF + BEG + ABCDE + ABDFG + CDEFG
6	E + ABC + ADF + BDG + CFG + ABEFG + ACDEG + BCDEF
7	F + ABG + ADE + BCD + CEG + ABCEF + ACDFG + BDEFG
8	G + ABF + ACD + BDE + CEF + ABCEG + ADEFG + BCDFG
9	AB + CE + FG + ACDF + ADEG + BCDG + BDEF + ABCEFG
10	AC + BE + DG + ABDF + AEFG + BCFG + CDEF + ABCDEG
11	AD + CG + EF + ABCF + ABEG + BCDE + BDFG + ACDEFG
12	AE + BC + DF + ABDG + ACFG + BEFG + CDEG + ABCDEF
13	AF + BG + DE + ABCD + ACEG + BCEF + CDFG + ABDEFG
14	AG + BF + CD + ABDE + ACEF + BCEG + DEFG + ABCDFG
15	BD + CF + EG + ABCG + ABEF + ACDE + ADFG + BCDEFG
16	ABD + ACF + AEG + BCG + BEF + CDE + DFG + ABCDEFG

Once the screening experiments are completed, the most important variables and their interactions will be identified. Since we are dealing with seven basic parameters as well as more than one response variable, it is important to study the behaviour of these responses with respect to more than one variable. That will accelerate the achievement of the objective of developing a new material while optimizing the process. Therefore, regression modelling was used to find second order regression models between response such as MOR and effects or their interactions to optimize the process. The method used will be outlined in the next section.

5.4 Developing regression models

Regression modelling is a collection of statistical techniques useful for developing important empirical models based on observed data from the process. In the case of two independent variables such as x1 and x2 and one dependent (response) variable: y, the first order regression model can be written as in Equation 5.7. A first order model sufficiently predicts the process when the experiments are performed in a confined region of independent variables (Myers and Montgomery 2002; Montgomery 2005). Therefore, it is assumed that a first order model will sufficiently predict the particleboard production process in our laboratory environments because our experiments were designed to be conducted over a relatively small region of the independent variable space. The β_0...Values are called regression coefficients and ε is the error term. These regression coefficients can be expressed in natural units such as temperature in Celsius. They can also be converted into coded variables, which are dimensionless with mean zero and standard deviation (Montgomery 2005; Myers and Montgomery 2002).

$$y = \beta 0+\beta 1x1+\beta 2x2+\beta 3x1x2 +\varepsilon \qquad \text{Equation 5.7}$$

Multiple linear regression techniques are used to calculate the regression coefficients of the model. Once the important variables and their interactions are identified using ANOVA (discussed in Section 5.3.1.2), the regression coefficients with respect to those variables and their interactions are calculated to form the regression models to predict the MOR, MOE and IB. Further, surface density, core density and the mean density of the particleboard can be predicted using the processing parameters. Chapters 6 and 7 discuss the formation of regression models to predict responses and their validations using further experiments.

A statistical method called least square estimator is used to estimate these regression coefficients after the completion of all the experiments with regard to experimental design to collect all the response data (y values) (Montgomery 2005). There are two types of regression coefficients which are calculated by slightly different methods, called coded units and un-coded units.

5.4.1 Coded versus un-coded units

By default, the MINITAB software calculates regression coefficients using coded units. Coding eliminates any spurious statistical results due to different measurement scales for the factors - for example, ‘seconds’ versus ‘degrees’. In addition, using un-coded units often leads to co-linearity among the terms in the model. This inflates the variability in the coefficient estimates and makes them difficult to interpret. Using the coded units helps eliminate this problem.

Using un-coded units provides estimated regression coefficients in the original factor scales. However, it may change the results of the statistical tests of hypotheses used to determine whether each term is a significant predictor of the response. In the light of advantages of using coded units over un-coded units, coded units will be used to develop regression models here.

5.4.1.1 Transformation into coded units

The original measurement units for experimental factors can be transformed into coded units. In this experimental study, measurement scales as diverse as Celsius (temperature), seconds (Time) or percentage (moisture content or resin load) are transformed into a common, coded scale. For each factor level measured in the original scale, the coded unit can be obtained as in equation 5.8 (Montgomery 2005; Myers and Montgomery 2002).

$$CodedUnit = \frac{\{OriginalFactorlevel - [(Max.Factorlevel + Min.Factorlevel)/2]\}}{\{(Max.Factorlevel - Min.Factorlevel)/2\}} \quad \text{Equation 5.8}$$

5.4.2 Checking model adequacy using residual analysis

The difference between actual y value and the model predicted y value is called the residual or the error (Equation 5.9). In linear regression modelling, the error term is assumed to be independently distributed with mean zero and variance σ^2. Due to this assumption, the observed y value should be independently distributed with mean $\beta_0+\Sigma\beta_j x_{ij}$ and variance σ^2 (Myers and Montgomery 2002).

$$e_i = y_i - \hat{y}_i$$ Equation 5.9

Where:

i	1, 2, 3,..n , (number of responses)
y_i	model predicted response value
$\hat{y}_i$	average of the observed response

The residual estimation can be used to examine model adequacy. If the residual versus the predicted response $\hat{y}_i$ scatter randomly, it suggests that the earlier assumption is satisfied. Standardized residuals are more informative than normal residuals. Standardized residuals can be used to check any unusual observations in the experiments and will be discussed in the next section. (Figure 5.4 displays a plot of standardized residual versus the predicted y).

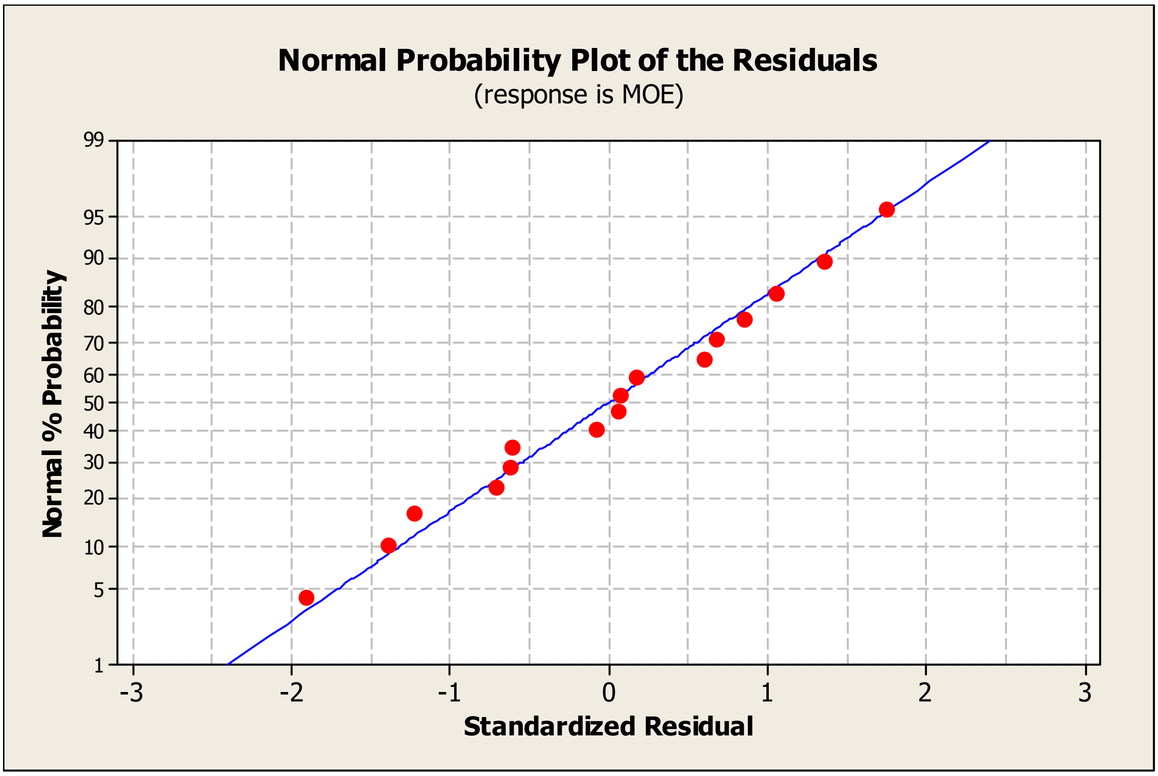


Figure 5.3: A normal probability plot of standardized residual data

A normal probability plot is another tool used to check the normality assumptions made earlier. In this plot, the normal percentage probability is plotted against the standardized residuals in a semi-log graph. If the normal probability plot of residuals is in a straight line, it indicates that there is no significant difference from the normality assumptions made earlier (Montgomery 2005). These techniques will be used in Chapters 6 and 7 to check the adequacy of regression models statistically. Figure 5.3 shows a normal probability plot with residual data. It is seen that almost all the data lie on the straight line and hence it satisfies the normality assumptions.

5.4.2.1 Standardized residual

In contrast to ordinary least square residuals, standardized residuals convey more information on the model as well as the data used to develop the model. The standardized residuals can be calculated using the ordinary residuals (e_i) and mean square of residuals (MS_E) as in Equation 5.10. The sum of the square of the errors or residuals (SS_E) needs to be calculated in order to calculate the MSE. The SS_E can be calculated from residual data using Equation 5.12.

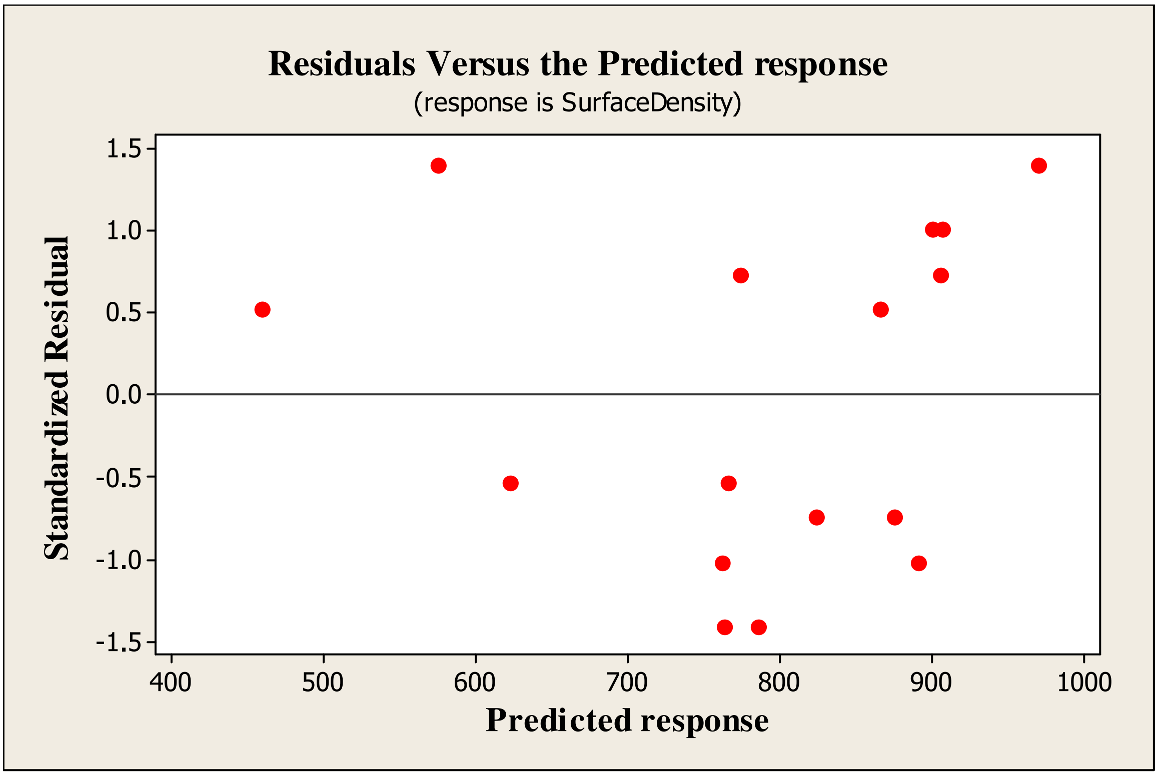


Figure 5.4: Plot of residuals versus predicted response

$$d_i = \frac{e_i}{\hat{\sigma}}$$ Equation 5.10

Where

d_i = standardized residual

e_i = ordinary residual

$\hat{\sigma} = \sqrt{MS_E}$

i = 1, 2…n

$$MS_E = \sqrt{\frac{SS_E}{n-p}} \qquad \text{Equation 5.11}$$

Where

n is the number of observations made and

p is the number of number of model parameters

$$SS_E = \sum_{i=1}^{n} (y_i - \hat{y}_i)^2 = \sum_{i=1}^{n} e_i^2 \qquad \text{Equation 5.11}$$

These standardized residuals have mean zero and approximate unit variance consequently they are useful to identify any outliers in the response data. Normally standardized residuals lie in $-3 \le d_i \le 3$ and any residual outside this range is called an unusual observation or an outlier (Montgomery 2005). Figure 5.4 shows the plot of standardized residuals versus the predicted response for the surface density of particleboards. These data are randomly distributed with a variance < 1.5. Therefore, it can be concluded that these data are reliable and they do not have any outliers.

5.4.2.2 R^2 value

R^2 value is a commonly-used technique to check the validity of a model. R^2 value is calculated using SSE and SST. This technique will be used to validate process models discussed in Chapter 6 and Chapter 7. The calculated value for R^2 value may vary from zero to one (or 0 to 100%).

$$R^2 = 1 - \frac{SS_E}{SS_T} \qquad \text{Equation 5.12}$$

R^2 is used to compare the experimental data and model predicted data. If $R^2 \rightarrow 100\%$, this implies the developed model significantly elaborates the total population of the data and hence the model is acceptable. Adding more and more variables to the model increases the R^2

significantly. Therefore, the adjusted R^2 value can be calculated to check the validity of the model further. If the adjusted R^2 value is significantly lower than the R^2, then the model does not adequately predict the process (Montgomery 2005; Myer and Montgomery 2002). The R^2 adjusted can be calculated using Equation 5.13.

$$R^2{}_{adj} = 1 - \frac{n-1}{n-p}(1-R^2) \qquad \text{Equation 5.12}$$

Where,

n is the number of observations made and

p is the number of number of model parameters

There is another way of calculating the R^2 value using adjusted SS_E and SS_T, when the population size of the data changes significantly. However, in the case of this study, this will not be important as the sizes of the population of data are always same or almost same.

5.5 Application of experimental design for developing natural composites

The DOE method or the statistical analysis techniques discussed here have been used by many researchers in the past to develop new natural composite products using new raw materials (Nelmi et al. 2003; 2006; 2007; Stewart and Lehman 1973; Okino et al. 2004). Okino et al (2004) incorporated the 2^k factorial design to investigate the physical and mechanical properties of laboratory-made particleboard and flake board using natural and acetylated particles. They investigated the properties of the boards with respect to change in two different materials. A 2^k- full factorial design was carried out to perform experiments and the effect of a factor was studied by using test of significant (calculating p-values with $\alpha = 0.05$). They did not consider investigating the effects by change in resin, moisture or pressing temperature with respect to the new raw material. Instead they kept other processing parameters as constant.

Nemli et al. (2003) used DOE and statistical methods to investigate the suitability of Kiwi prunings as particleboard raw material. In addition to the methods used by Okino et al. (2004), they used ANOVA to study the significant differences among factors and levels. Further, they used the Tukey test to identify the significant variations among factor groups. In their study, ANOVA was observed to successfully predict the significant factors, factor levels and their interactions in producing a new particleboard product using Kiwi prunings. In their investigation, they kept most of the processing parameters such as moisture content, hardener load, pressing time and temperature constant though they might have had some significant effects on the process. Karr et al. (2000) investigated the suitability of wheat straw as a particleboard raw material. They used DOE techniques to investigate the effects of processing parameters on straw particleboard quality. ANOVA was mainly used to compare and screen the most important effects with respect to the production process in the laboratory environment.

Experimental design combined with regression analysis to develop a response model has been used on many occasions to find the unknown mechanisms between response and the process or the systems (Park et al. 1999; Windon and Cook 1998; Rikards et al. 2004). Park et al. (1999) used regression modelling to model the hot pressing process of the three-layer MDF production process. First they found the most important factors with respect to internal temperature of the MDF during production. Then they utilized them to find relationships for temperature profile and density profile with respect to pressing time, press temperature and moisture content. The developed models were then used to optimize the hot pressing process of the fibre board.

In addition, the DOE method has been widely used in experimental investigations in the areas of drug production, ceramic production, material and polymer sciences (Kincl and Vrecer 2005; Ragonese et al. 2002). Box-Behnken experimental design has been used by various authors for factor screening, process modelling and optimization in various other fields. Ragonese at al. (2002) and Kincl et al. (2005) used the method for the formulation of the process and optimization of a capillary electrophoresis method for pharmaceutical research. In other situations DOE has been used to formulate the Ullmann type side production (Rozsumberszki et al. 2004). These researchers used the DOE with the response surface method to formulate a second-order polynomial equation showing the production process. Lee and Gilmore (2003) used the DOE method to formulate and model the process of developing a thermoplastic polymer using industrial wastes. In most of these investigations, either ANOVA regression analysis, or the response surface method, or combinations of these techniques have been used to produce new material, or to optimize existing products, or process.

5.6 Summary

This chapter has provided an introduction to the DOE method using factorial design and its efficiency in developing a new product using new raw materials, developing a new production process or improving an existing process or product. Further the chapter has discusses selected tools and techniques used in analysing experimental data of this research. The most important tools discussed here are:

- 2^k fractional factorial design and how it will be used to design experiments and analyses.
- ANOVA which is a very efficient tool used to identify the most important factors and their interaction for developing a new particleboard product.
- Regression analysis and calculating regression coefficients, which can be used to model particleboard properties such as MOE and MOR using processing parameters. These models are very useful to optimize particleboard properties and this optimization will be discussed in Chapter 8.
- Residual analysis (error analysis) and residual plots are important techniques to select correct data from experiments. Residual analysis and normal probability plots can further be used to check the validity of regression models.
- DOE methods have been used by various researchers in the past, to develop new materials, to develop experiments with new raw materials, or new processes or to optimize existing processes.

CHAPTER 6

SIGNIFICANT PARAMETERS INFLUENCING THE PROPERTIES OF *SINGLE-LAYER* PARTICLEBOARD

6.1 Introduction

This chapter describes the procedure followed to identify significant parameters influencing the properties of particleboard using hardwood sawmill residues. Single layer particleboards were manufactured in the laboratory before producing three layer particleboards at the start. Once these results were analysed, most influential parameters were identified for single layer particleboards. Then, these processing parameters and their upper and lower values were identified and incorporated into design of the mix proportionates for three-layer particleboards. Three layer particleboards were prepared by changing the recipe for both surface and core layers to find the significant parameters. Three layer particleboards are discussed in detail in the Chapter 7. Results, analysis and outcomes for the single-layer particleboards are discussed here.

6.2 Objectives

Particleboards are generally manufactured using softwood flakes. The ingredients as well as the production process for softwood particleboards are therefore well documented. There is a little literature available on particleboard production using hardwood materials. Particleboard production using hardwood sawmill residues have never being investigated before. Since the properties of three-layer particleboards would be a function of the three separate layers, it was decided to explore properties of single layer particleboards to establish an understanding of the properties of individual layers.

The objective of this work is to determine influence of the processing parameters on the properties of single layer hardwood particleboard. A partial factorial experimental design was carried out to study all the processing parameters and their interactions on final product. Initial investigation shows that hardwood particleboard may need higher resin content and higher moisture content compared to industrial softwood particleboard (Appendix E). Six material and process variables with three levels were experimented (Table 6.1). The last column of the Table 6.1 shows the average values for same variables use in industrial softwood particleboard for three layer particleboards (Values collected after communication with a local particleboard factory). The MOE, MOR and IB of the final particleboard product were investigated and the effect analysis with respect to these strength properties was done.

Table 6.1: Variables used in the experimental design for single layer particleboards

Variable	**Effect**	**Low Value**	**Middle Value**	**High Value**	**Industrial Softwood Particleboard**
Target Board Density (kg/m^3)	A	600	700	800	680
Moisture Content	B	9	14.5	20	11
Resin Load (% of dry wood residue load)	C	5	10	15	11
Hardener Content (% of resin load)	D	0	1	2	1.5
Pressing Time (Minutes)	E	4	6	8	3
Press Temperature (^{o} C)	F	150	195	220	190

6.3 Materials and Methodology

A local hardwood sawmill provided the hardwood sawmill residues for the project. These residues contained a mix of residues from different hardwood. However, the majority of them were from two species of eucalyptus (Regnans or Mountain Ash and Obliqua or Messmate Stringy Bark). Residues come of two types called fine and mulch. Fines consist of smaller, cubical shaped particles formed of saw dust and Mulch is bigger, flaky particles. These particles were sieved as both mulch and fine material consisted of unevenly distributed particles as well as a large amount of bigger particles, which disturb proper compaction when preparing the board. From each batch of fines and mulch residues samples with particle-size <19.00 mm were measured separately for a particular layer. Then, mixture of fines and mulches were prepared in order to obtain a better particle size distribution which is vital for better compaction of the board. In the three layer particleboard a mix of 65% fine with 35% mulch was used for the surface layer while a mix of 55 % fine with 45% mulch was used for the core layer. A mix of 65% fine with 35% mulch that is similar to the surface material in three layer board was used in the single layer particleboards. Initial particle size distributions and final mix for surface and core materials of residues are given in Figure 6.1.

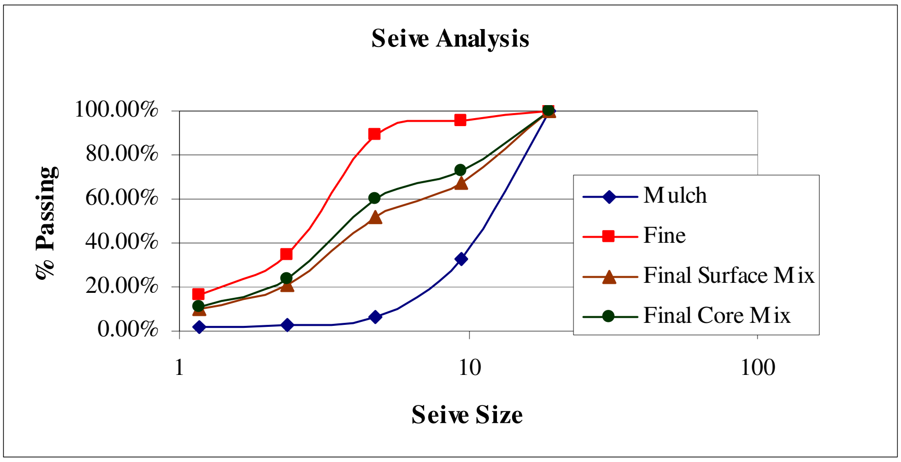


Figure 6.1: Sieve analysis data of the raw material

The initial moisture content of these residues were measured at the laboratory and established to be in 65-85% at the saw mill. Therefore, raw materials were oven dried at a temperature of 105°C to remove this excessive moisture. It was studied and found that these residues need to be oven dried for 24 hrs – 48 hrs to dry them properly.

Conventional three layer particleboards are manufactured using formaldehyde resin as the binder. In addition to the resin, hardener is used for the core layer to facilitate the resin curing. In this work, urea formaldehyde (E1 resin) was used as the binder. This resin which contained 63-64.9% solid, and viscosity in the range of 115-220cPs at 25°C, was provided by the Divisions of Adhesives and Resins of Orica Chemicals, Deer Park, Australia. The chemical composition of the resin is attached in the appendix A. Ammonium Chloride was used as the hardener (catalyst).

6.3.1 Methodology

Fine and Mulch were sieved separately. The saw mill residue was oven dried at 105°C for approximately 48 hours to remove excessive moisture intact. Fine and Mulch were measured as required by the mix proportion for a board as well as the mix proportion for the particular layer according to the Figure 6.1. Then, these Fine and Mulch were mixed inside the mixing drum. The amount of resin, hardener and water were measured separately and mixed together before spraying onto the wood residue which had already been in the mixing drum. When the pulp was ready, it was hand formed in a rectangular mould of 300 mm X 400 mm. Then it was manually pressed and then cold pressed followed by the hot press. The cold pressing time and the hot pressing time were maintained to be at equal. Then, final board was sampled and tested for its physical and mechanical properties. The complete laboratory procedure for the particleboard manufacturing was explained in the Chapter 4.

6.4 Test procedure

Finished particleboards were then kept in an open space approximately for a week to remove formaldehyde trapped inside. Then they were stored in a controlled humidity (65%) and temperature (20°C) before testing according to AS/NZS 4266.5 and AS/NZS 4266.6. MOR, MOE and IB were measured as part of testing the properties of the final board.

All boards were trimmed to obtain 200 mm x 300 mm rectangles by trimming 50 mm thick strips along the edges. Samples were cut and prepared as per AS/NZS 4266.1(2004). Thickness of the final board which was measured to calculate the IB was used to calculate the spring-back too. (Spring-back is the thickness swelling happening in a particleboard immediately after removal from the hot-pressing.) 100 mm x 300 mm samples were cut to measure the MOR and MOE. 50 mm x 50 mm samples were taken to measure the IB.

6.5 Screening test 1: Identification of significant parameters for single layer particleboard

6.5.1 Experimental design

Table 6.2: The aliases structure for 2^{6-3} design

1	A + BD + CE + BEF + CDF + ABCF + ADEF + ABCDE
2	B + AD + CF + AEF + CDE + ABCE + BDEF + ABCDF
3	C + AE + BF + ADF + BDE + ABCD + CDEF + ABCEF
4	D + AB + EF + ACF + BCE + ACDE + BCDF + ABDEF
5	E + AC + DF + ABF + BCD + ABDE + BCEF + ACDEF
6	F + BC + DE + ABE + ACD + ABDF + ACEF + BCDEF
7	AF + BE + CD + ABC + ADE + BDF + CEF + ABCDEF
8	ABD + ACE + BCF + DEF + ABEF + ACDF + BCDE

Fractional (1/8) factorial design was done using 6 factors (that is 2^{6-3} number of experiments for a single replicate) for the variables in Table 6.1. The highest and the lowest point of each factor were considered for experimentation. In addition, the centre point of the distribution was also considered to produce experimental particleboard. The alias structure for this set of experiments (as explained in the Chapter 5) is tabulated in the Table 6.2. Particleboards were manufactured for each recipe produced by the experimental design with three replicates.

6.6 Results, Analysis and Discussion

After preparing the samples for each test mentioned earlier, they were stored in a humidity cabinet with a controlled humidity (65%) and a controlled temperature (22°C) for approximately two weeks before testing. Then, they were tested for MOE, MOR and IB. Test method and equipments used were reported in the Chapter 4. Test results were then statistically analysed incorporating theories of experimental design to calculate the test statistical values (T) for each process variable and the probability of null hypothesis (P). The theories used for experimental design and analyses used in here were discussed in the Chapter 5.

6.6.1 Factors affecting the flexural strengths of a hardwood particleboard

Table 6.3 shows the calculated T and P values while Figure 6.2 and Figure 6.3 show the normal probability for standardized effect (or test statistical value considering the error term) for each variable on MOE, MOR and IB respectively. Solid line in each Figure 6.2, 6.3 and 6.4 connects the negative and positive limit of test statistical value for 95% significant level. Any parameter which has a negative effect lies left to this line where as parameter with positive effect lies right to it. The magnitude of the test statistical value of each variable is compared with this upper and lower limit in the line. If the test statistical value is higher than the upper limit (positive limit in the line) is positively significant on the tested property with 95% significance level. If the test statistical value is smaller than the lower limit (negative limit in the line) has a significant negative effect with 95% significant level.

MOE, MOR and IB are the most important strength properties which determine the suitability of particleboard as building elements. Therefore, only these properties were studies in this initial investigation with the single-layer particleboards.

Table 6.3: Estimated Effects and Coefficients for Tested Board Properties

Term	**MOE**		**MOR**		**IB**	
	T	**P**	**T**	**P**	**T**	**P**
Density (A)	-1.05	0.301	0.06	0.953	1.00	0.330
Resin Load (B)	6.78	0.000	0.81	0.429	-0.53	0.604
MC (C)	3.05	0.008	2.58	0.020	1.44	0.169
Hardener (D)	-4.48	0.000	0.85	0.406	0.35	0.730
Temperature (E)	-0.74	0.468	-0.66	0.517	0.11	0.916
Pressing Time (F)	4.56	0.000	0.05	0.958	-0.92	0.372
Density*Pressing Time(AF)	1.73	0.100	-1.33	0.202	-0.65	0.525

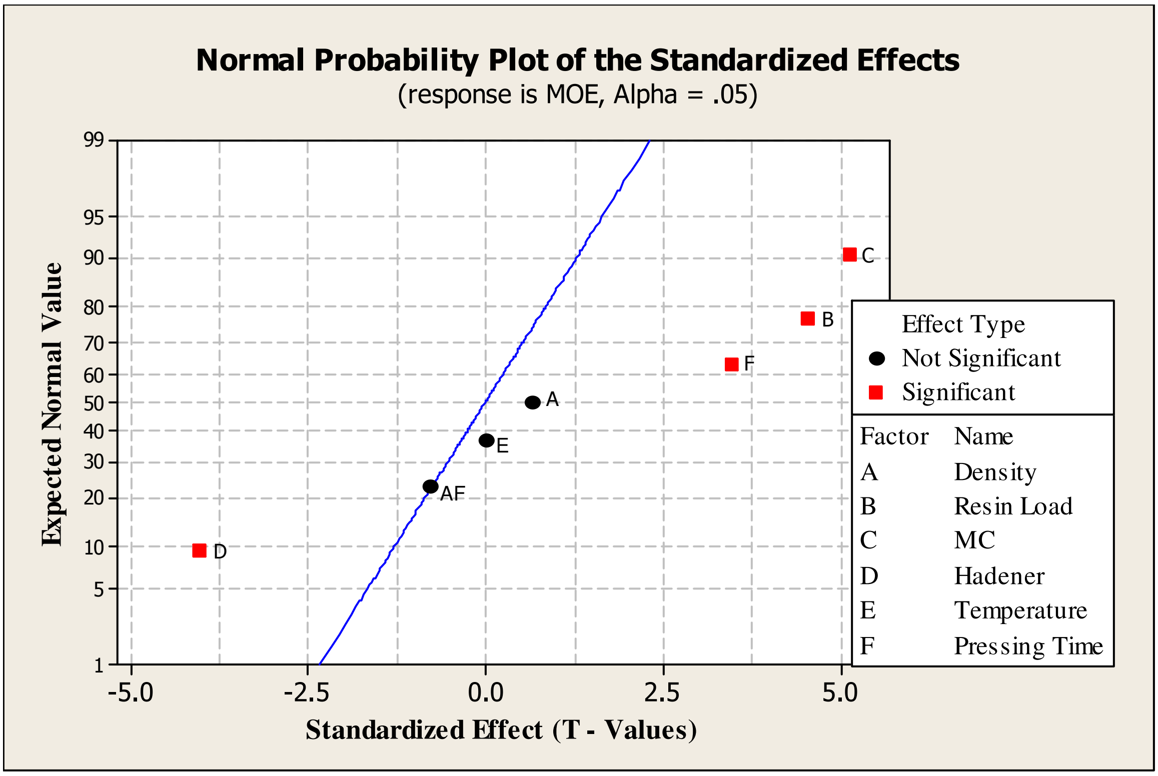


Figure 6.2: Significant factors affecting the MOE of single-layer particleboard

It can be seen from Table 6.3 that for each of the tested properties moisture content was the most significant factor with probability for null hypothesis; $P < 0.05$ for MOE and MOR. Also, the lowest P (= 0.169) for IB was found with the moisture content. In addition, Figure 6.2 and Figure 6.3 show that the moisture content has a positive effect on both MOE and MOR.

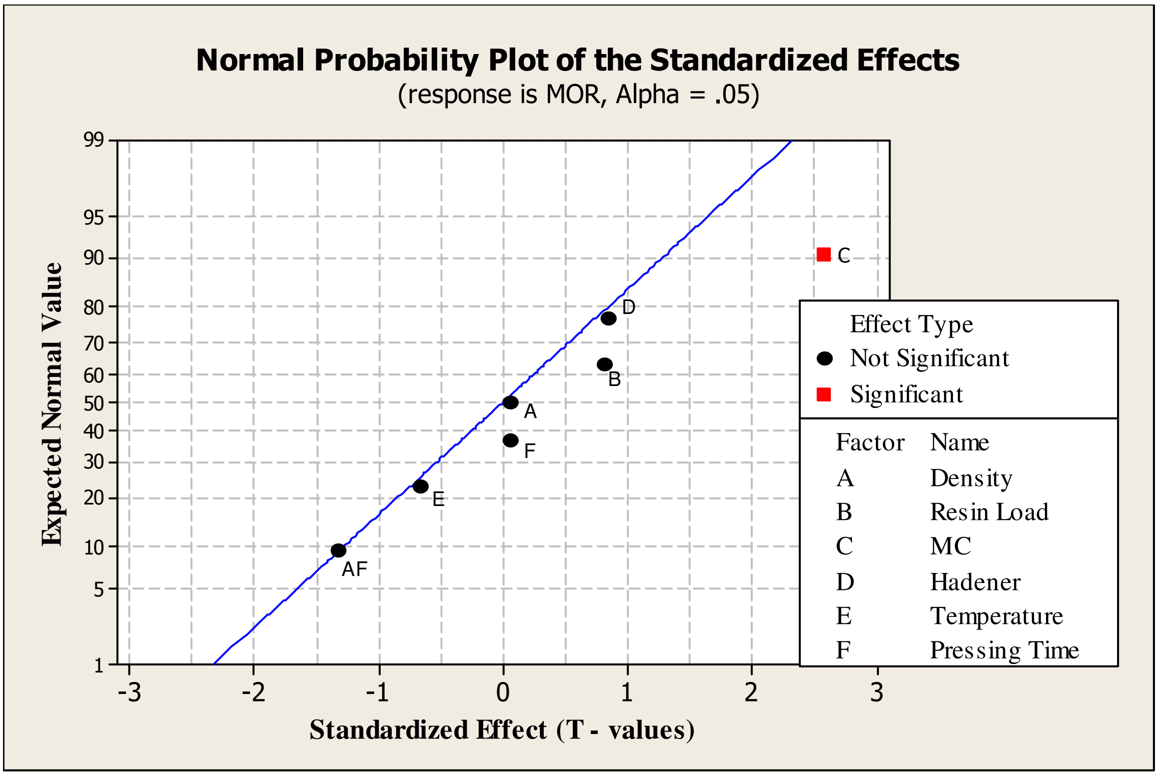


Figure 6.3: Factors affecting the MOR of single-layer particleboard

Moisture is a critical component in manufacturing wood composites and fibre composites due to its effect on the initial drying operation of wood substrate, press cycle manipulation, wood conformability, composite properties, spring back, and post consolidation, re-humidification. One method of reducing the high compressive force required during the pressing is to press at high moisture content. Raw materials with high moisture content have not been used in the past because of the excessive vapour pressure generated during the hot pressing. That would disturb the wood composite addition (Kelly, 1977). Optimum moisture content in softwood particleboard furnish has been accepted as around 8% - 10% for the core and 11%-15% for the surface material.

Preliminary results reported herein indicate that the optimum moisture content for hardwood residue can be higher than that for softwood particleboard furnish. This could be explained as the higher inherent moisture content (absorption) of hardwood compared to softwood. This observation is extremely important and needs to be explored systematically since pressing at high moisture content can lead to a reduction in the cost of production of particleboard by reducing the energy required to press as well as dry the material. Resin load and pressing time has a significant positive effect on MOE ($P < 0.05$ and T is "+"), hardener has a negative effect on that ($P < \alpha$ and T is "-" in Table 6.3 and Figure 6.2). Higher amount of resin will produce a strong and rigid composite, which also will reduce the water absorption and the thickness swell (Karr et al., 1999). In addition, pressing time provides the time required for resin curing and creation of more cross-linking sites increasing the MOE.

The purpose of having hardener in the core layer of softwood three-layer particleboard is to create an acidic medium to facilitate better curing of the urea formaldehyde resin. However, results in the Figure 6.2 indicated that the hardener has a negative impact on MOE of a single layer particleboard. Having hardener at the surface of the board accelerate the resin curing at the surface. However, when completing the total press cycle, already cured resin may have over cooked resulting in a weaker surface. The surface of the board is mainly responsible for flexural strength of a particleboard.

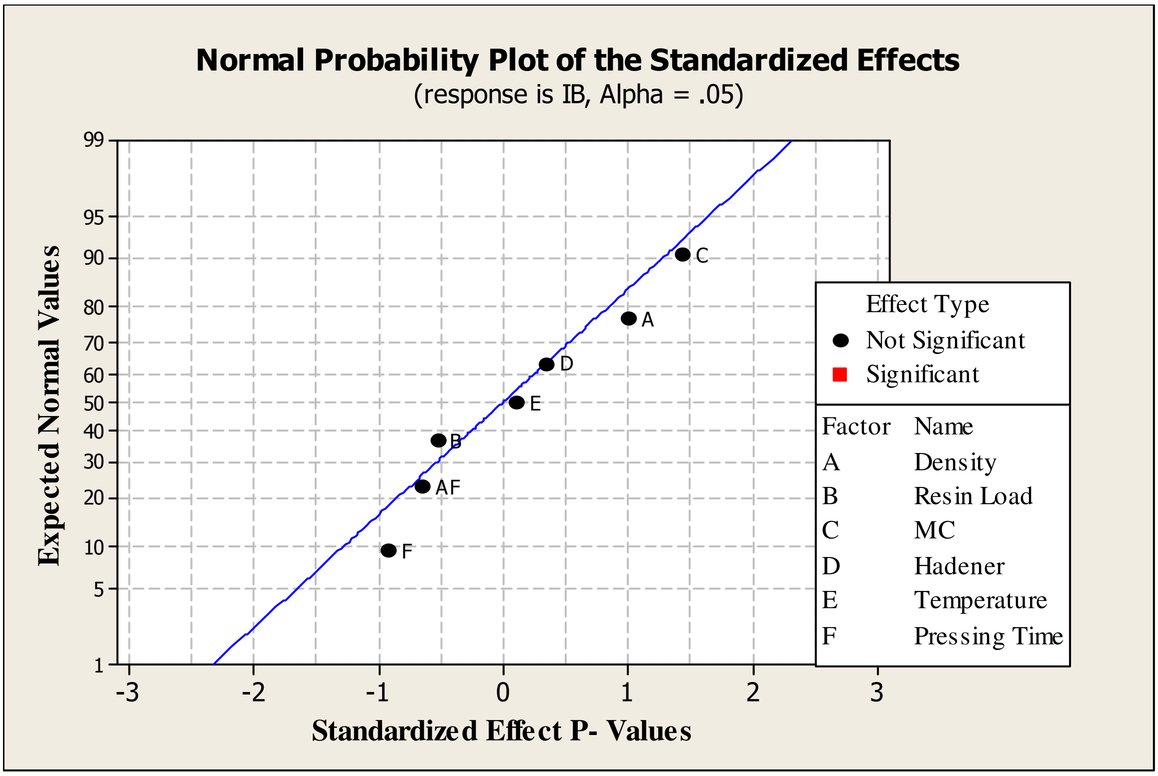


Figure 6.4: Factors Affecting IB of single-layer particleboard

Figure 6.4 represents the normal probability plot of standardised effect for IB of single layer particleboard. However, figure 6.4 does not provide much information on the significant variables or interactions. Generally, IB of a particleboard is mainly dependent on the core of the particleboard. Having same amount of resin, hardener, moisture through out of the board does not create significant variation between the surface and the core of the board. At the same time, using high moisture in the core (same as surface), increases the core moisture further when the surface moisture migrates into the core during the hot pressing. The excessive moisture creates a higher steam pressure in the core of the board. When the hot-press pressure is released, releasing this steam pressure causes the spring-back in the board. Internal glue-bonds between particles may also have been broken due to this spring-back resulting in weaker IB boards.

6.7 Summary and Conclusions

From the preliminary work presented here, following conclusions can be made.

- Moisture content is significantly affecting both MOE and MOR of hardwood single-layer particleboard. Almost all the single layer particleboards have undergone spring-back due to some of the moisture may not have beenreleased completely during the hot pressing.

- It is interesting to observe that hardwood particleboard furnish may have a higher moisture content than softwood furnish without adversely affecting the board properties. However, pressing at high moisture may have to be verified with further work on three layer boards.

- Resin load, pressing time have significant positive influence on the MOE of single layer particleboard. However, according to results, there was not any significant relationship between IB and any variable. However, this observation may not be used to predict the IB behaviour of three-layer particleboards. Further investigation need to be performed to verify this observation or identify differentiation between single layer and three layer particleboard.

Therefore, the next section, Chapter 7 will be investigating the properties of three-layer particleboard which are produced using hardwood saw mill residues.

CHAPTER 7

SIGNIFICANT PARAMETERS INFLUENCING THE PROPERTIES OF *THREE-LAYER* PARTICLEBOARD

7.1 Introduction

It is evident from the previous chapter that the significant parameters influencing the properties of three-layer particleboards may not be the same as the significant parameters for single-layer boards. Therefore, it is important to make a separate study of three-layer particleboards to evaluate the significant parameters. This chapter investigates the significant parameters influencing the properties of three-layer hardwood particleboard using saw-mill residues. Three-layer particleboards were prepared in the laboratory by changing the recipe for both surface and core layers to find the significant parameters. This chapter explains the experimental parameters and procedures adopted for manufacturing. Results, analysis and outcomes are also discussed.

7.2 Objectives

The work presented here aims at investigating the effect of material and process variables on the properties of three-layer particleboard production using hardwood saw-mill residues. The investigation has three main objectives.

- To study the effects of material variables (surface resin load, core resin load, surface moisture content, core moisture content) and process variables (pressing temperature and the press closure time) on the mechanical properties (Modulus of Rupture (MOR), Modulus of Elasticity (MOE) and Internal Bond strength (IB)) of the finished board.

- To study the effects of the material variables (resin load for surface, resin load for core, moisture content for surface, moisture content for core, hardener for core) and the process variables (pressing temperature and the press closure time) on the physical properties (the density profile) of the finished board.

- To compare the mechanical properties and the physical properties of the finished board with respect to processing parameters.

7.3 Screening test 2: Identification of significant parameters for three-layer particleboard

Similar to single-layer particleboard production discussed in the Chapter 6, both process variables and material variables were considered here in the screening test. Process variables considered are the pressing temperature and press closure time, and the material variables are the mat moisture content, the resin load and hardener for the core. Both mat moisture content and resin load were different from surface to core. Therefore, seven experimental variables were investigated in the production of particleboard using hardwood sawmill residues. Moisture content for the surface (A), moisture content for the core (B), Resin load for the surface (C), Resin load for the core (D), Hardener for the surface (E), Pressing time (F), Press temperature (G) were changed according to Table 7.1. Based on the preliminary work discussed in Chapter 6 which conforms to the published literature (Chapter 2), it was identified that higher moisture content may be required for hardwood particleboard compared to softwood particleboard.

Table 7.1: Variables used in the experimental design for three-layer particleboards

Variable	**Low Value**	**High Value**	**Units**
Surface Moisture Content (A)	11	22	% of dry wt of the board
Core Moisture Content (B)	7.5	15	% of dry wt of the board
Surface Resin Content (C)	8	20	Resin load as a % of dry wt of the board
Core Resin Content (D)	5	13	Resin load as a % of dry wt of the board
Core Hardener Content (E)	1	3	% of Resin load
Pressing Time (F)	120	300	Seconds
Press Temperature (G)	150	200	^{o}C

Therefore, moisture for the surface was considered in the range of 11% to 22% whilst moisture for the core was considered in the range of 7% to 15%. However it should be noted that the softwood particleboard industry uses approximately 11%-15% moisture for the surface and 8%-10% for the core. Similarly resin load also selected with a wider range covering industrial softwood particleboard. Industrial softwood particleboard uses surface resin in the range of 8% to 13% whereas core resin in 8% to 10%. Industrial softwood particleboard uses hardener for core layer 1.5% of resin solid use in the core. Industrial softwood particleboard is manufactured with 190 0C and 180 seconds pressing time. (These values were obtained after communication with a local particleboard factory).

7.4 Experimental design

A screening experimental series was conducted to identify the most important parameters and their interactions controlling the properties of three-layer particleboard made with hardwood sawmill residues. Seven material and process variables with two levels (low and high values) were identified and used with two replicates, as in Table 7.1. A 1/8 fractional (2^{7-3}) factorial design was carried out to investigate the effects of material variables and process variables on the mechanical and physical properties of the finished boards. Sixteen different experimental boards were produced with one replicate in our laboratories. The different treatment combinations with respect to this 2^{7-3} design were tabulated in Figure 5.3 in Chapter 5. The target board density was kept constant at 710 kg/m^3 and the target thickness was 15.2mm.

7.5 Materials and Methodology

As for single-layer particleboard production, which was discussed in Chapter 6, the same materials were used to prepare three-layer particleboard. Firstly a sieve analysis was done for the two types of particles (fine and mulch) obtained from the saw mill. As discussed in Section 6.2.1, a mix of 65% fine with 35% mulch was used for the surface layer while a mix of 55 % fine with 45% mulch was used for the core layer. Urea formaldehyde E1 resin was used with hardener (NH_4Cl) for the core layer.

7.6 Methodology

Fine and Mulch residues were sieved separately. The saw mill residues were then oven dried at 105^{o}C for approximately 48 hours to remove excessive moisture. Fine and Mulch residues were measured separately for the surface layer and mixed in the mixing drum. The amounts of resin, and water were measured separately and mixed together in a cup. The resin-water mixture was then sprayed onto the wood residue in the mixing drum. When the pulp was ready, the required amounts for two surfaces were separated. Similarly, the pulp was prepared for the core layer. Unlike for the surface layer, hardener was added into the water-resin mixture prior to spraying. When the pulp for the core layer was ready, the required amount for the core of the board was measured. Then, the pulps were hand-formed in three layers in a rectangular mould of 300 mm X 400 mm. Then it was manually pressed. The manually pressed particleboard mat was then cold pressed followed by the hot press to manufacture the final particleboard. The cold pressing time and the hot pressing time were equal. Then the completed board was sampled and tested for its physical and mechanical properties. The complete laboratory procedure for the particleboard manufacturing was explained in Chapter 4.

7.7 Test procedure

Similar to the single-layer particleboards, the finished three-layer boards were then kept in an open space for approximately one week to remove the formaldehyde trapped inside. All boards were trimmed to obtain 200 mm x 300 mm rectangles by trimming 50 mm wide strips along the edges. Samples were cut and prepared as per AS/NZS 4266.1(2004). The thickness of the final board was measured to calculate the spring-back. Then the samples were stored in a humidity cabinet with controlled humidity (65%) and temperature (20^{o}C) before testing as per AS/NZS 4266 (2004). MOR, MOE, IB, and spring-back were measured as part of testing of the properties of the final board. Mean density and the density profile of the board were also measured.

7.7.1 Testing of board's physical properties

Mean density and the density profile of each board were included in the measured physical properties. The mean density of the board was measured according to AS/NZS 4266.4(2004) by measuring the weight and the volume of a test sample. A sample with a volume of 100 mm x 300 mm x board thickness from each board was used to measure the mean density of the board. A 50 mm x 50 mm sample from each board was used to measure the vertical density profile. Then, mean surface density and mean core density of the board were calculated from the measured density profile values.

7.7.2 Testing of board's mechanical properties

After measuring the density profile, all the samples were sanded to remove the low density, loose surface before performing other tests. Then, the MOR, MOE and IB were measured to ascertain the mechanical properties of the final board. A sample of 100 mm x 300 mm was used to test the MOE and MOR, and a sample of 50 mm x 50 mm was used to test IB according to AS/NZS 4266.5(2004) and AS/NZS 4266.6(2004) respectively.

7.8 Results, analysis and discussion

Table 7.2 shows the 16 different recipes given by experimental design to manufacture particleboards. These 16 screening test boards are labelled as ST 1…16. Moisture content and resin content were calculated with respect to the oven-dried wood weight and these percentage values are tabulated in Table 7.2. However, the hardener content was calculated with respect to the resin solid. The percentage of hardener solid with respect to resin solid is given in Table 7.2. The measurement of the pressing time was commenced as soon as the top platen of the press touched the particleboard mat. The hot press time and the cold press time were maintained the same and measured in seconds. Press temperature was measured in degrees Celsius and both top and bottom platens were kept at the same temperature. The averages of the test results are also tabulated in Table 7.2. MOE and MOR are measured in mega Pascals (MPa) while IB is measured in kilo Pascals (kPa). Mean surface density and mean core density were calculated from the density profile test data and presented in the same Table 7.2.

Test results show that particleboard ST5 has MOE > 2000 MPa, MOR > 16 MPa and IB > 400 kPa. According to AS/ NZS 1859 (2004), this particular board satisfies the minimum strength property requirement for standard grade particleboard. Therefore, it is clear that particleboard can be manufactured using hardwood saw mill residues. However, it is necessary to test this board for its moisture resistance in order to use it as a standard grade particleboard. Therefore, the investigation of moisture resistance property of these particleboards has been conducted and is discussed in Chapter 10.

Table 7.2: Experimental variables and results

Board Number	**Moisture Surface** (% of oven dry weight of wood)	**Resin Surface** (% of oven dry weight of wood)	**Resin Core** (% of oven dry weight of wood)	**Hardener Load** (% of resin solids weight)	**Pressing Time (s)**	**Press Temperature**	**IB (kPa)**	**MOE (MPa)**	**MOR (MPa)**
ST 1	11	8	5	1	120	150	74.40	1253.0	6.085
ST 2	11	20	5	3	300	200	389.32	1983.0	9.659
ST 3	22	8	13	3	300	150	330.12	1801.8	8.256
ST 4	11	8	13	3	120	200	320.00	1394.0	6.687
ST 5	22	20	13	1	120	200	545.88	2419.0	12.530
ST 6	11	20	13	1	300	150	605.32	2233.0	11.600
ST 7	22	8	5	3	120	200	86.12	1480.0	6.000
ST 8	22	20	5	1	300	150	282.92	2190.0	8.970
ST 9	11	20	13	3	120	150	368.52	1464.0	8.509
ST 10	22	8	5	1	300	200	76.28	1658.0	7.518
ST 11	22	20	13	3	300	200	384.00	1990.0	10.091
ST 12	22	8	13	1	120	150	122.40	957.0	5.025
ST 13	11	8	13	1	300	200	638.92	1450.0	7.615
ST 14	11	20	5	1	120	200	415.72	1915.0	10.350
ST 15	11	8	5	3	300	150	103.20	1078.0	5.277
ST 16	22	20	5	3	120	150	17.60	829.0	3.639

On the other hand, these particleboards required extra resin and moisture for the surface layer compared to industrial softwood particleboards. Therefore, it is necessary to optimize this recipe to find optimum processing parameters. Therefore, it was decided to develop composite models for the MOE and MOR of the hardwood particleboard incorporating the effects of the processing parameters. Those models were then used to optimize particleboard mix proportions. This matter is discussed in Chapter 8.

Table 7.3: Estimated Effects and Coefficients for physical properties of a board

Term	**MOE**		**MOR**		**IB**	
	T	P	T	P	T	P
Moisture Surface (A)	-0.94	0.393	-6.37	0.003	-6.82	0.001
Moisture Core (B)	-1.23	0.274	-0.94	0.4	-4.28	0.008
Resin Surface (C)	7.74	0.001	17.57	0	8.01	0
Resin Core (D)	0.23	0.831	4.45	0.011	11.91	0
Hardener Core (E)	-4.88	0.005	-10.18	0.001	-4.86	0.005
Pressing Time (F)	2.26	0.073	4.03	0.016	5.48	0.003
Press Temperature (G)	5.53	0.003	11.17	0	6.06	0.002
Moisture Surface * Moisture Core	-2.65	0.045	-3.61	0.022	-3.94	0.011
Moisture Surface * Press Temperature	3.37	0.02	7.45	0.002	-1.74	0.142
Moisture Surface * Hardener Core	NS	NS	-2.96	0.041	NS	NS
Moisture Surface*Resin surface	NS	NS	NS	NS	NS	NS
Moisture Core*Resin Core	3.08	0.027	4.20	0.014	NS	NS
Moisture Surface*Pressing Time	NS	NS	NS	NS	NS	NS
Moisture Core*Resin Surface	NS	NS	NS	NS	NS	NS
Moisture Surface*Moisture Core*Resin Core	NS	NS	NS	NS	NS	NS
NS = Not Significant						

The results were analysed using the theories of experimental design as discussed in Chapter 5. The effects that are not significantly dependent on the testing parameters are normally distributed with mean zero and variance (σ^2), and will tend to fall along a straight line on a normal probability plot. However, a variable with significant effect will have a nonzero mean and hence does not lie on the straight line (Myers and Montgomery 2002). Therefore, effects with higher 'T' value are considered as significant variables, while those with lower 'T' values are considered to have a negligible effect on that testing property. The level of significance of a given variable is calculated assuming that there is no significant effect (null hypothesis: P) of that variable on a particular testing property. Test results were then statistically analysed incorporating theories of experimental design to calculate the test statistical values (T) for each process variable and the probability of null hypothesis (P). Using 5% significance for null hypothesis, a factor is considered to affect the tested property if $P < 0.05$. In other words, the null hypothesis is not true and the factor affects the board property with 95% significance.

Table 7.3 shows the calculated T and P values for the testing properties of particleboards discussed in this chapter. Normal probability plots and Pareto charts will be used to analyse the data to identify significant variables as well as to find the level of significance.

7.8.1 Factors affecting the mechanical properties of a board

MOE, MOR and IB values used to determine the mechanical properties of the final particleboard (Table 7.2) and their statistical analysis results (T and P values) are given in Table 7.3. Resin surface, pressing time and press temperature significantly influence all the tested properties of hardwood particleboard (Table 7.3). This is to be expected, as higher resin content would coat more surfaces thus providing better bonding between particles. Press temperature and pressing time are important as they provide the heat and time required for resin curing and creating more cross-linking sites, eventually reducing spring-back and thickness swelling (Karr 1999). Surface resin content has more effect on both MOR and MOE, while core resin has more effect on the IB and MOE. The MOR of a board is mainly dependent on the surface layer of the board though IB depends on the core layer.

7.8.1.1 Modulus of Elasticity (MOE)

T and P for each process variables with respect to MOE can be found in Table 7.3. The most significant parameters which affect MOE can be found in the table with $P < 0.05$. As explained in Chapter 5, T values are higher for the effects with P < 0.05. The higher the T value, the higher the effect on MOE. In addition, Figure 7.1 shows the normal probability plot for standardized effect for MOE. Significant parameters which control MOE are marked with red squares. The test statistical value and the effect that satisfies 95% significant margin value was calculated and found to be around (+ or -) 2.4. The blue line in Figure 7.1 connects the two positive and negative margins of the test statistical values. Effects or combinations of effects, which negatively influence MOE, stay on the negative side of the graph (That is T < -2.4 in Table 7.3). Therefore, the hardener and the combination of moisture core with moisture surface negatively influence the MOE. Resin surface, press temperature, the combination of moisture surface and press temperature and combination of moisture core with resin core have positive significant effects on MOE.

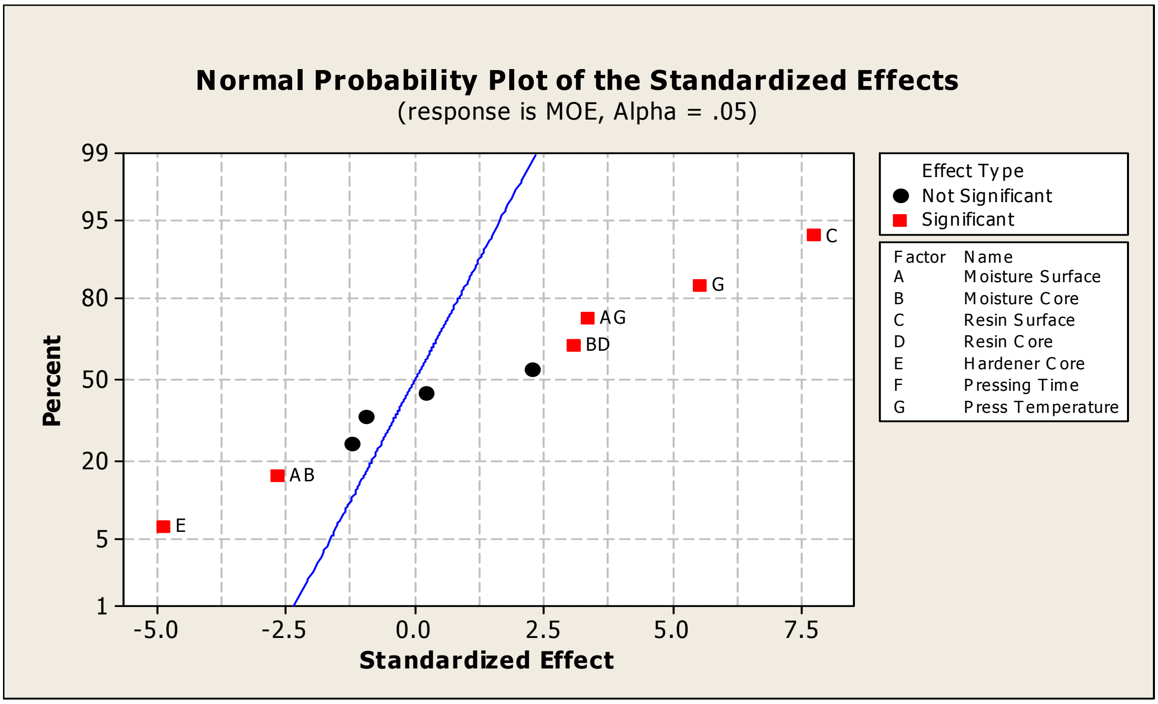


Figure 7.1: Normal probability plot for standardized effect for MOE

Figure 7.2 is the Pareto chart which highlights significant parameters with respect to MOE in a bar chart. This figure shows that the resin surface has the most significant effect on the MOE of hardwood particleboard. The amount of resin is important to create proper bonding between particles. Generally in-plane and lateral bending loads are primarily resisted by the surface materials in a structural element (Vinson 1999). Hence, having higher amount of surface resin in the surface layer is vital to create inter-particle bonding in the surface layer.

That creates a stronger surface layer in three-layer particleboard, and directly influences the MOE of particleboard.

Figure 7.2 show that press temperature has the second highest effect on MOE. Press temperature is important for heat and mass transfer to the core of the board for curing of resin and to release the excessive moisture from the final board. Also, fast heat transfer is a key to a short press cycle (Suchsland 1967).

According to Figure 7.2, hardener has the third highest effect on MOE. However, Figure 7.1 shows the hardener negatively affects the MOE. Hardener is a normal ingredient in three-layer softwood particleboards. In softwood particleboards, hardener is added into the core layer to create an acidic medium to accelerate the resin curing, since UF resin prefers an acidic medium. However, hardener may not be required for this task. It was hypothesised that hardwood saw mill residue is acidic in nature. That hypothesis was finally confirmed by measuring the pH value of sawmill residues which were found to be acidic. The testing of the acidity of sawmill residue is discussed later in this chapter.

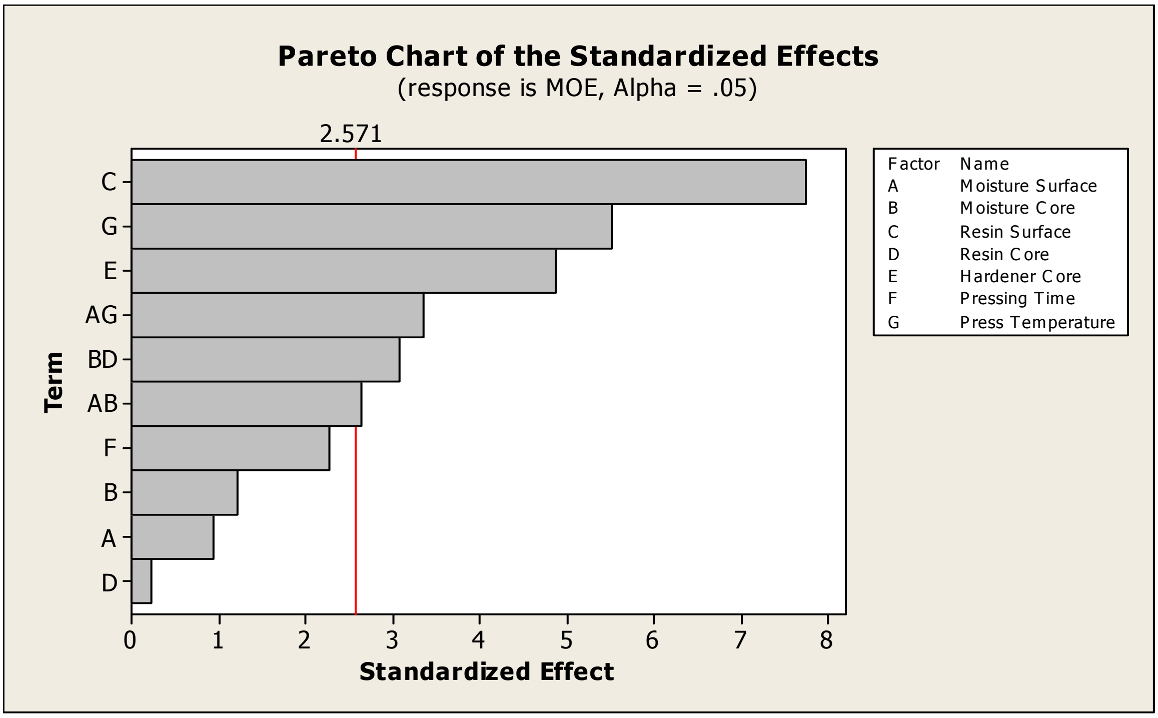


Figure 7.2: Pareto chart for standardized effect MOE

Moisture surface combined with press temperature is the next significant factor for hardwood particleboard. Moisture surface and press temperature directly influence the heat and mass transfer to the core. Further, the increase in moisture surface reduces the hardness of the wood mat and provides better compaction of the mat before resin curing. In addition, the combination of these factors may provide enough steam to carry heat from the surface to the core that is essential for resin curing. This ultimately increases the stiffness of the board. However, moisture surface combined with moisture core negatively influence the MOE, possibly because the excessive moisture that may be trapped inside the board, creates excessive steam pressure inside the board. Releasing the hot press allows steam pressure to relax, leading to thickness swelling in the board, resulting in inter-particle bond failures. In addition, moisture core combined with resin core positively affect the MOE. These individual factor effects or combinations of factor effects were further studied using contour plots. Contour plots show the behaviour of the MOE with respect to two variables, while other processing parameters are considered as steady at their middle levels.

The advantage of drawing a contour plot is that response surface is viewed in a two dimensional plane in the plot where the constant responses are connected to produce contour lines. In a contour plot, change in the response with respect to change in two variables (whilst others are kept constant) is presented and that is very useful for establishing the desirable response values and mixture blends for this work.

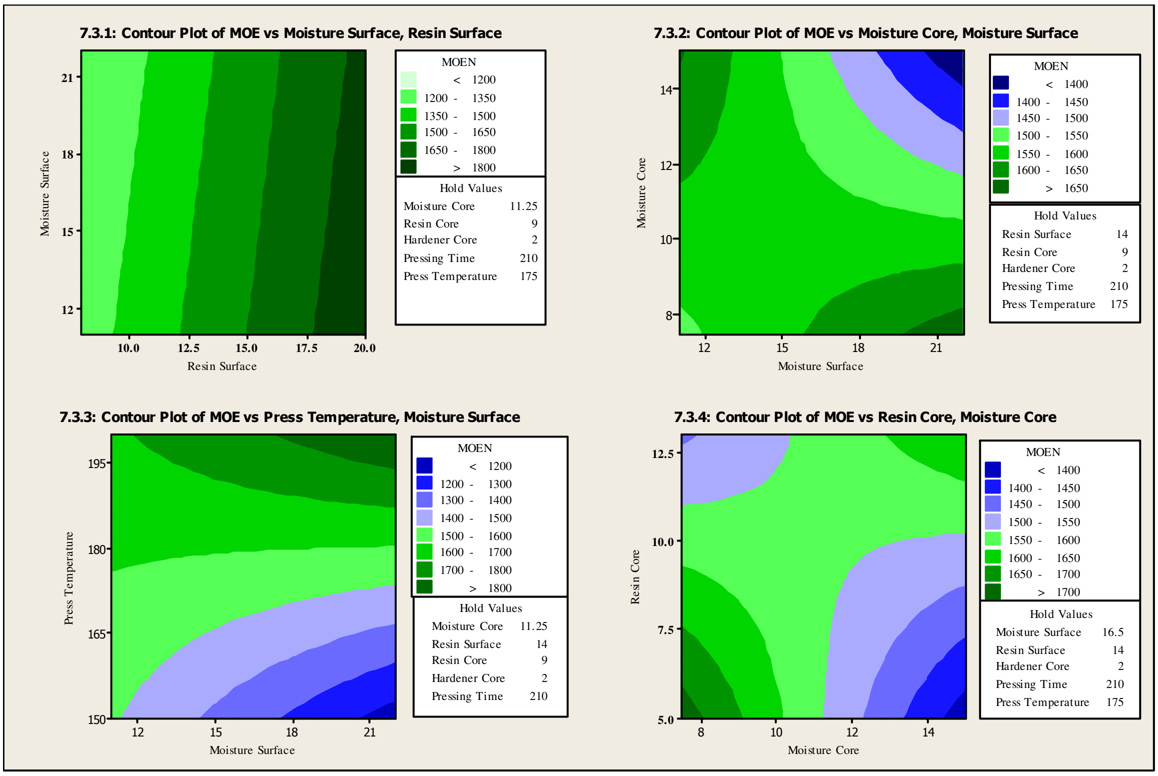


Figure 7.3: Contour plots of MOE with respect to most significant effects

Figure 7.3 shows the contour plots of MOE with respect to most significant factors. Figure 7.3.1 shows the resultant MOE when moisture surface and resin surface are changed. It indicates that increasing the surface resin by keeping moisture surface constant leads to a steady increase of MOE. However, increasing the moisture surface, while keeping the resin surface constant, does not change MOE significantly, reflecting that resin surface is the dominant factor for particleboard MOE.

Figure 7.3.2 is the contour plot for MOE when moisture core and moisture surface are changed. It shows that increasing both surface and core moisture initially increases the MOE then significantly reduces it. There is a saddle in the middle of the graph, implying that both the surface and core moisture can be changed by a certain amount while achieving a constant MOE. It also shows that a very low core moisture (approximately 8%) with higher surface moisture (15% or higher) will give the highest achievable MOE (dark green area of the graph). This combination of moisture is a critical finding for this product, as using a high core moisture has a negative effect on most of the properties of particleboard. However, it was noted earlier as well as being reported in previous work (Chapter 2) that surface moisture is very important for heat transfer to the particleboard core and for mat consolidation during production to achieve better properties. Heebink (1974) observed that higher strength properties were found in softwood particleboards when he used 15% surface moisture and 5% core moisture, when other parameters were constant.

Increasing press temperature when moisture surface is high can produce boards with high MOE (Figure 7.3.3). However the surface moisture content can only be increased up to a certain maximum value, as it may eventually contribute to thickness swelling. Figure 7.3.4 shows that both resin core and moisture can be maintained at their minimum values if other parameters are at their middle values (of the tested parameter range) to produce particleboards with higher MOE (MOE > 1700 MPa). Therefore, it may be possible that moisture core and resin core can be kept at their lower limits when the above variables are increased in producing particleboards with higher MOE values.

Therefore, considering the effects, interaction and contour plots of significant parameters on the MOE, better MOE values may be found if particleboards are produced with the following approximate mix proportions:

- Surface moisture - 15% or higher

- Core moisture – 8%
- Resin surface – 15 % or higher
- Resin core – 10%
- Press Temperature – approximately 190 °C

When the pressing time is at its middle value (Pressing Time – 210 seconds)

These mix proportions need to be compared with other particleboard properties to produce optimised particleboards. This is discussed in Chapter 8.

7.8.1.2 Modulus of Rupture (MOR)

Similar to MOE, T and P for each process variable and important interactions with respect to MOR can be read in Table 7.3. Most significant parameters and their interactions have $P < 0.05$ and have higher T values in the table. As explained in Chapter 5, T values are higher for the effects with $P < 0.05$. The higher the T value, the higher the effect on MOR. In addition, Figure 7.4 shows the normal probability plot for standardized effect for MOR. The method of calculating effects was discussed in Chapter 5.3. Significant parameters which control MOR are marked with red squares. The test statistical value for the effect that satisfies 95% significant level is calculated to be around (+ or -) 2.5. That is marked in blue line in Figure 7.4. The parameters which have positive effect on the MOR can be found right of the blue line, whereas, the effects and interactions with negative influence on MOR lie left of the blue line. Therefore, resin surface, resin core, pressing time and press temperature are the parameters which have a positive influence on MOR. Moisture core, hardener, moisture surface combined with moisture core, moisture surface combined with hardener and moisture surface combined with moisture core and resin core have a negative effect on MOR.

Figure 7.5 shows these significant effects in a bar chart. It shows that resin core and resin surface have the most significant effects on MOR out of all the others. Similar to MOE discussed earlier, resin is the most important ingredient in particleboard manufacturing to create strong inter-particle bonding. Unlike MOE, core resin is also very important for MOR. This suggests that, both stronger surface and stronger core are important for optimum bending strength in three-layer particleboard made using sawmill residues. Moisture core and moisture surface combined with moisture core have the next most significant effect on MOR (Figure 7.5). Similar to MOE, these have a negative effect on MOR.

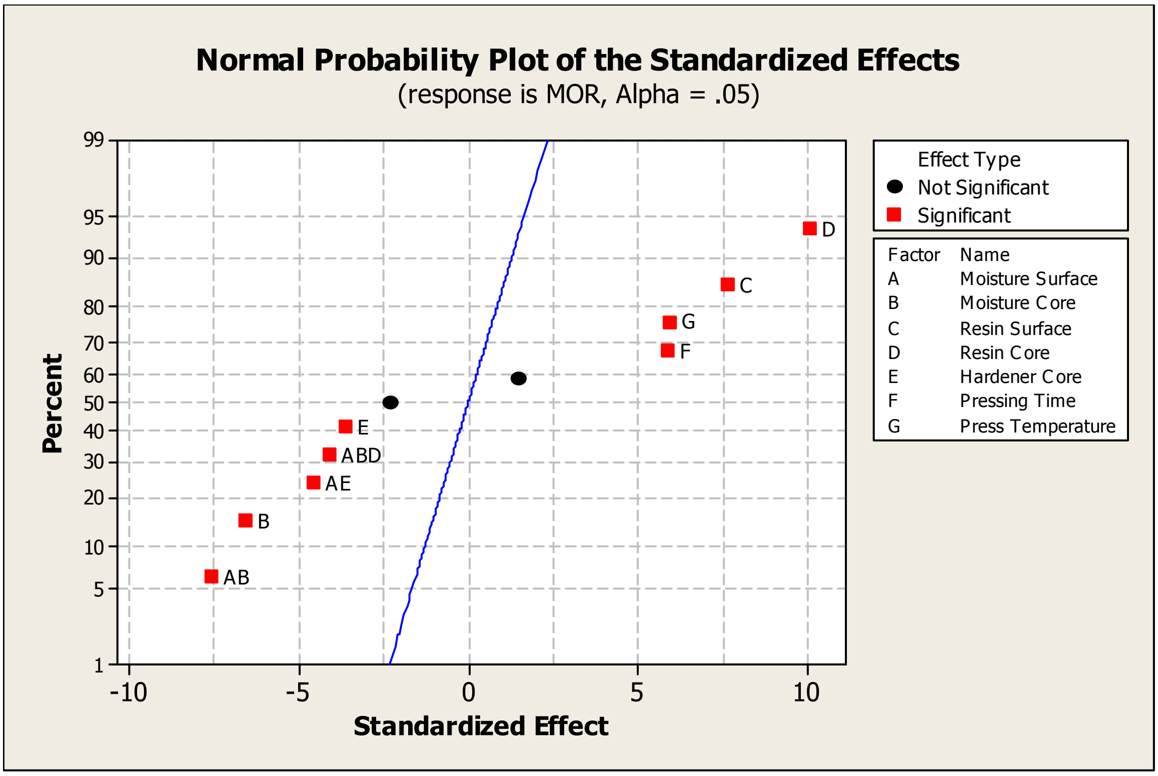


Figure 7.4: Normal probability plot for standardized effect for MOR

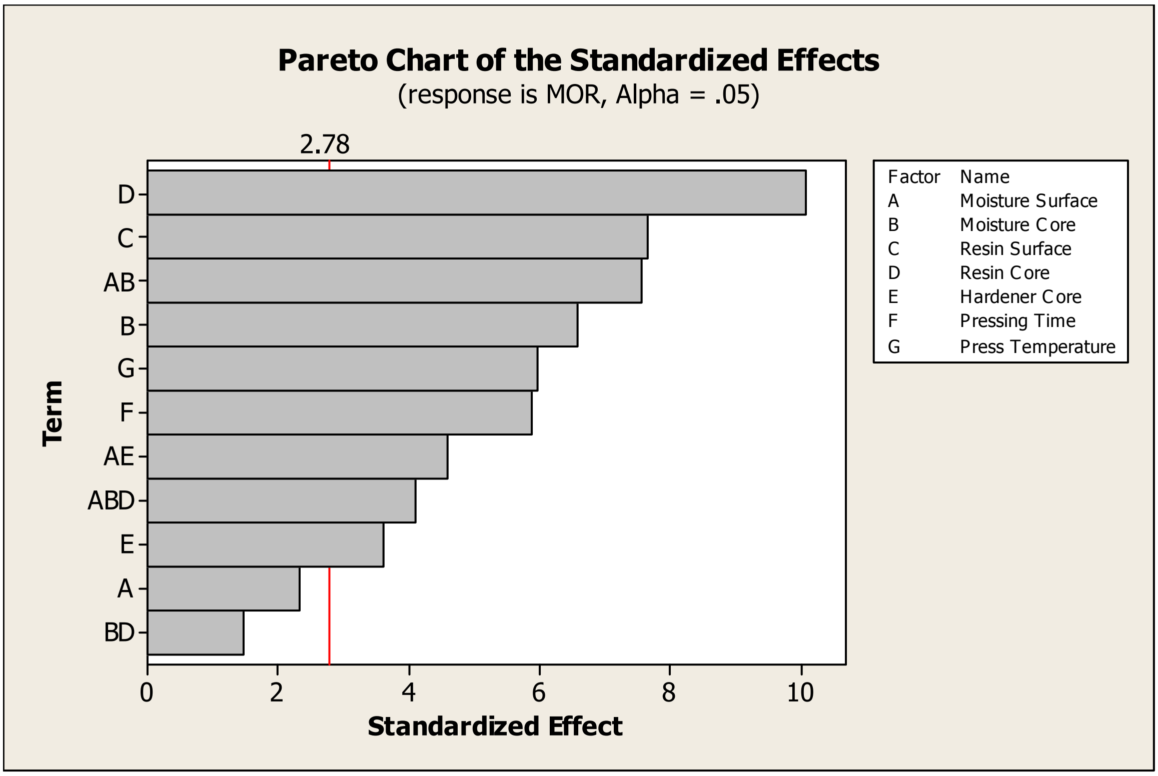


Figure 7.5: Pareto chart for standardized effect MOR

Although moisture is important for heat and mass transfer to the core for resin curing, excessive moisture disturbs particleboard properties. Press temperature and pressing time have the next most significant effects on MOR. Both press temperature and pressing time are required for heat and mass transfer and resin curing as well as evaporating excessive moisture from the sides of the board during hot pressing.

Similar to MOE, hardener negatively affects the MOR of the particleboard. However, the behaviour of MOR with respect to change in moisture surface and hardener has not been studied before or could not be found in any of the literature cited here. Since hardener accelerates resin curing, this will cause curing of resin before moisture exits from the board completely. The excessive moisture trapped inside the board may have created steam pressure. Releasing this high steam pressure causes spring-back which results in breaking some of the glue-bonds. This ultimately reduces the MOR of the particleboard.

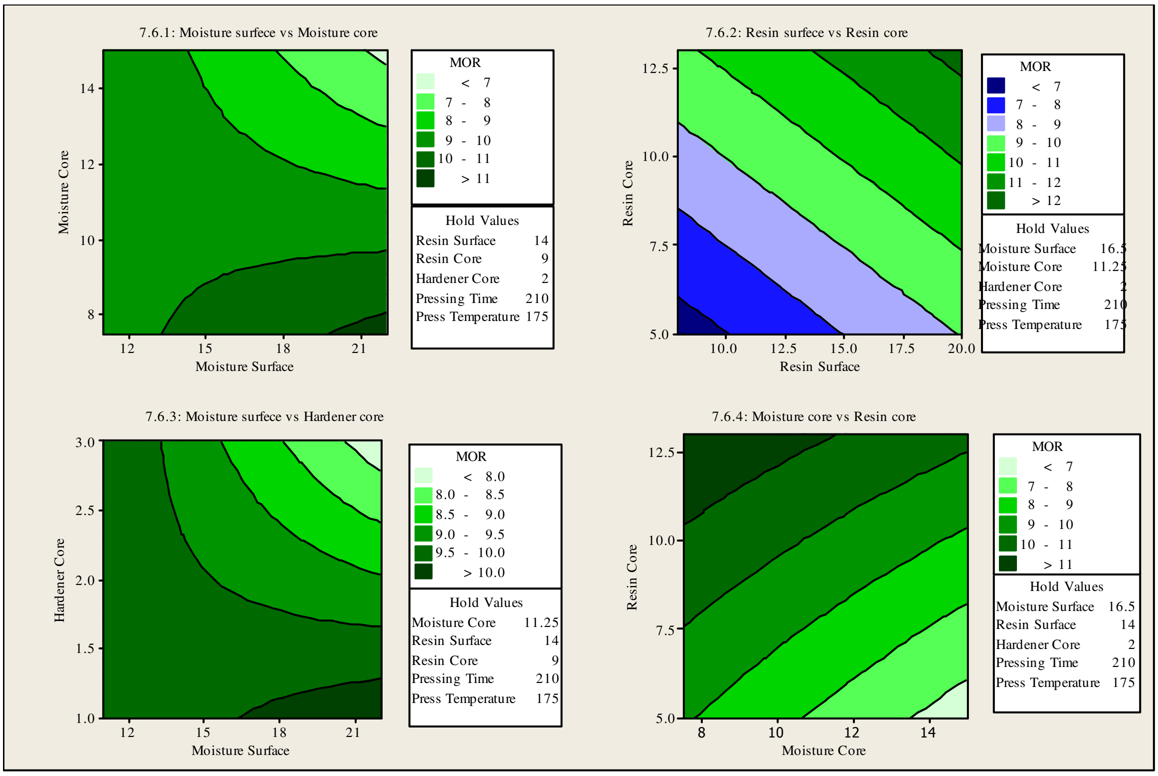


Figure 7.6: Contour plots of MOR with respect to most significant effects

These data were further analysed using contour plots to find the best combination of the significant effects with respect to MOR. In a contour plot for MOR, two parameters are changed at a time by keeping other parameters constant at the middle of their parameter range. Figure 7.6 shows the contour plots of MOR with respect to selected significant parameters. Figure 7.6.1 shows how MOR changes with respect to change in moisture surface and moisture core simultaneously. Increasing both surface moisture and core moisture decreases the MOR, showing that MOR does not change much if the core moisture is increased while surface moisture is at a lower level. Instead, similar to MOE, MOR increases when surface moisture is increased while keeping the core moisture at the lowest limit. A higher level of surface moisture is required for the other properties, hence surface moisture should be kept at a higher value and the core moisture should be reduced. Similar to the MOE, the optimum MOR value may be achieved if core moisture is kept at the lower level (approximately 8 – 9%) when a higher level of surface moisture is maintained (13% or higher).

Figure 7.6.2 shows that increasing the resin surface and resin core simultaneously increases the MOR steadily. The highest MOR can be found by combining the highest surface resin and highest core resin. That indicates that both the surface and core resin are important to have a satisfactory MOR in particleboard. However, resin is one of the main components that control the cost of the production. Therefore, an optimum combination between surface resin and core resin should be found without compromising the strength properties. As discussed earlier, increasing surface resin by keeping core resin at a lower value (approximately 10%) would increase the MOE. Therefore, core resin should be kept at its lowest value whilst increasing the surface resin.

Figure 7.6.3 shows the behaviour of MOR with respect to change in moisture surface and hardener-core. It can be seen that keeping the moisture surface at its lower level while increasing hardener does not make much difference to the MOR of particleboards. However, increasing both these parameters simultaneously drastically reduces the MOR of the final product. It also shows that by keeping the hardener level at its minimum while increasing the moisture surface, better MOR properties can be achieved. It was also explained earlier that, combining moisture surface with the hardener core negatively affects the MOR. This observation may be due to the fact that hardener may not be required since hardwood sawmill residue is acidic. Therefore, the addition of extra acid may weaken glue line bonding.

According to figure 7.6.4, increasing the resin core while keeping the moisture core at its minimum, is important for MOR. It shows that MOR > 11 MPa can be achieved when resin core is approximately 10% or higher and moisture core is at 8 % when other parameters are at their middle level in the designed experimental range. This observation also supports that core resin and core moisture can be maintained at a lower level similar to softwood particleboard in achieving particleboard with higher flexural properties. Reducing core moisture should also reduce spring-back during particleboard production.

Therefore, the following predictions can be made from the observations made on the response plots. With the increase in resin surface with resin core, MOR is increased and the opposite is true for moisture surface with moisture core. Hardener should be kept to its minimum or should be avoided completely in order to achieve better MOR. Therefore, better MOR values may be found if particleboards are produced using the following mix proportions:

- Surface moisture content – 13% or higher
- Core moisture content – 8% - 9%
- Resin surface – 15% or higher
- Core resin – approximately 10%

where as pressing time and press temperature are at their middle values (Press temperature – 175 ^{o}C and Pressing time – 210 seconds).

7.8.1.3 Internal Bond Strength (IB)

Internal bond strength is measured as the tensile strength perpendicular to the board surface. IB of a particleboard is mainly controlled by the inter-particle bonding in the particleboard. Inter-particle bonding in a particleboard is provided by glue-line bonding between particles. As part of measuring the mechanical properties of the product, IB was measured for each particleboard. Experimental observations showed that most of the test samples split close to the core of the board, when they were tested for their IB. Similar to MOE and MOR discussed earlier, T and P values of each important effect with regard to IB were calculated and tabulated in Table 7.3. It is seen from Table 7.3 that all the individual parameters studied here are significantly important, to different degrees on the IB of the final particleboard product (with $P < 0.05$). In addition, the interaction of moisture surface and the moisture core is an important effect with respect to the IB.

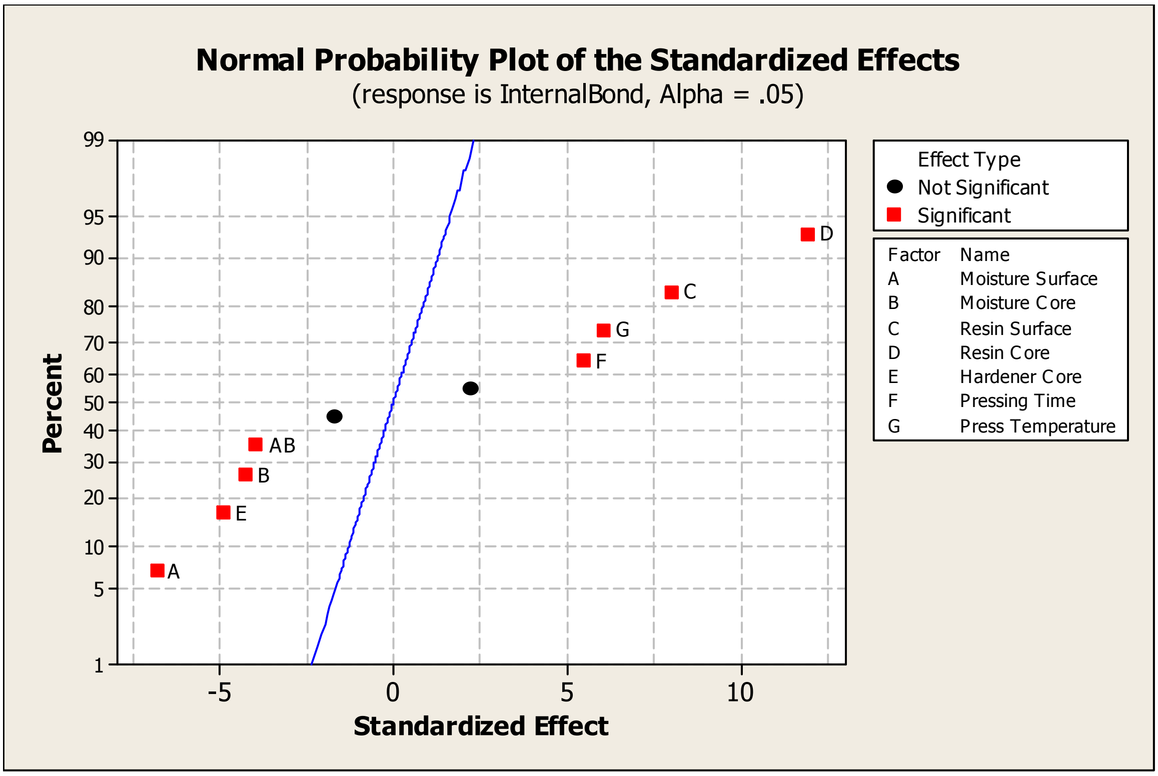


Figure 7.7: Normal probability plot of standardized effect for IB

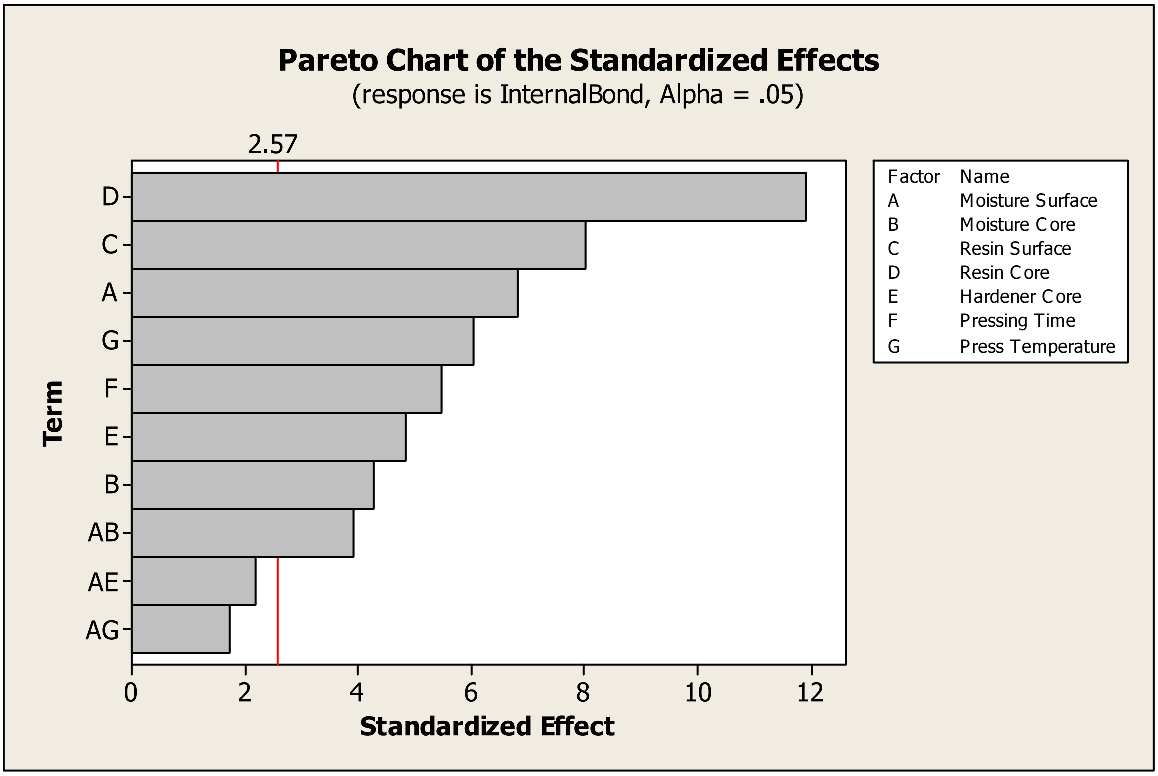


Figure 7.8: Pareto chart of standardized effect for IB

Figure 7.7 shows the normal probability plot of standardized effect for IB. Parameters which have positive effects on IB stay on the positive side of the graph, while ones with negative effects stay on the negative side. Therefore, while resin surface and resin core with pressing time and press temperature have positive effects on IB, moisture surface and core with hardener have negative effects. Excessive moisture always has a negative effect on the mechanical properties as moisture trapped inside the board after hot pressing could cause spring-back. Press temperature and pressing time affect the IB as they provide the heat and time required for resin curing and creating more cross-linking sites in the core.

The Pareto chart of standardized effects for IB is plotted in Figure 7.8, which shows that the resin core is the most significant effect on IB of this product. This is to be expected, as the IB strength of a particleboard is mainly dependent on the inter-particle bonding of the core. Core resin is thus very important to create good inter-particle bonds in the core. Surface resin is also important for IB, as the IB test may otherwise fail close to the surface.

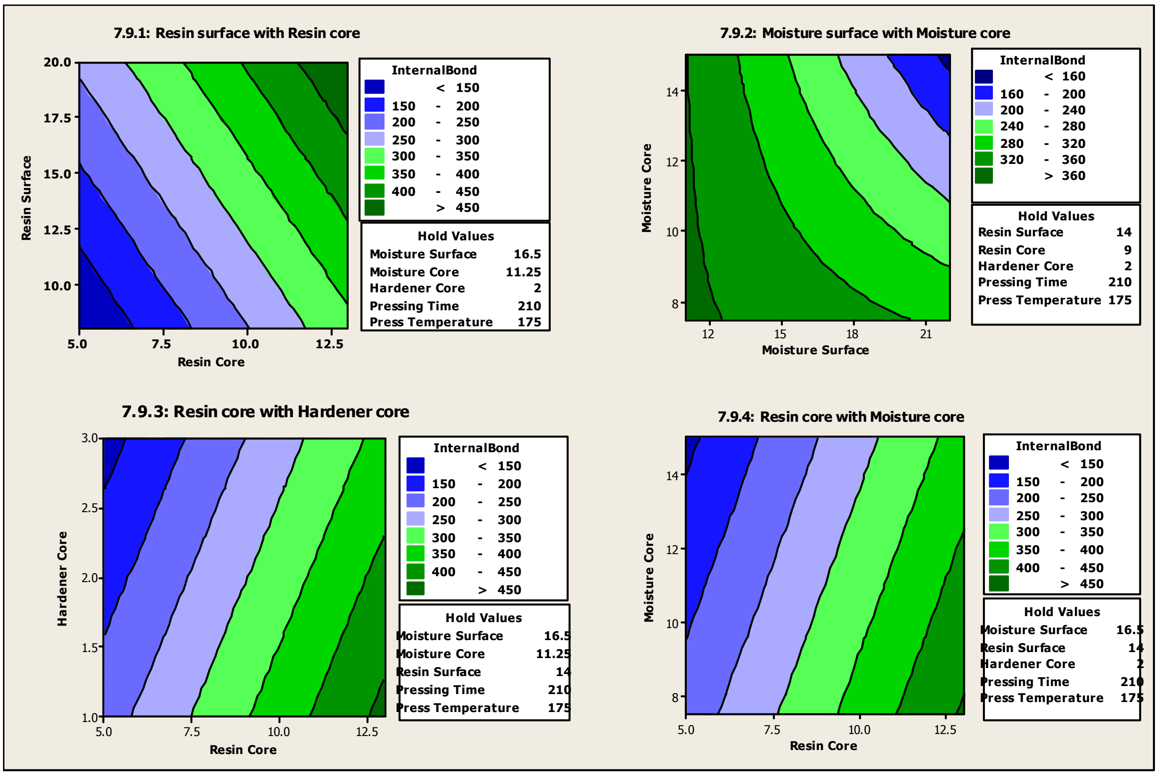


Figure 7.9: Contour plots of IB with respect to most significant effects

Figure 7.9 shows the contour plots of IB with respect to selected significant effects. Figure 7.9.1 shows that both resin core and resin surface are important to produce a particleboard that satisfies the AS/NSZ 1859 (2004). According to AS/NZS 1859 (2004), IB of a standard general purpose particleboard should be higher than 300 kPa. It was seen in Table 7.2 that most particleboards satisfy the IB required by the AS/NZS 1859 (2004). As explained earlier the surface resin content is critical for both MOE and MOR. However, core resin is more important for the core. This is because, MOR and MOE of particleboard mainly dependent on inter-particle bonding of surface layers whereas IB is dependent on inter-particle bonding of the core.

When observing Figure 7.9.1, it can be seen that any IB value which is in the green area in the graph satisfies AS/NZS 1859 (2004). Therefore, the core resin content can be reduced as much as possible despite the surface resin without failing the IB as per AS/NZS 1859 (2004).

Figure 7.9.2 shows that increasing both moisture surface and moisture core simultaneously reduces the IB. However, as discussed earlier, moisture surface combined with press temperature is important for most properties to provide heat transfer from surface to core through steam for resin curing. Therefore, moisture surface could not be reduced as it affects chemical reactions of resin. However, it was noted earlier that the moisture core has a negative effect on most parameters. Also, it was also suggested earlier that moisture core should be kept at its lowest to have better MOE and MOR. It has been observed that excessive steam pressure after hot pressing causes spring-back results in breaking inter-particle bond. Therefore moisture core should be reduced as much as possible without compromising IB.

Figure 7.9.3 shows how the IB changes with respect to the change in hardener core and resin core. It shows that increasing the hardener reduces the IB even if resin core is kept constant. The optimum IB can be achieved with minimum hardener and maximum core resin. Therefore, as suggested earlier for MOR, a minimum amount of hardener or zero level of hardener should be used to achieve better IB. Therefore, it is clear from Figure 7.9.3 that industry grade IB can be found with core resin at 8% or higher if the hardener is at its minimum. Figure 7.9.4 show the behaviour of IB with respect to changes in moisture core and resin core. Similar to the hardener core, increasing the moisture core reduces the IB even if resin core is kept constant. Therefore, minimum moisture core should be suitable for this product as moisture core disturbs most of the properties discussed so far.

From the study on the factors affecting the mechanical properties of hardwood particleboard it was found that moisture is a critical variable that needs to be controlled carefully for better compaction of the wood mat. Also moisture is the main medium that transports heat from the surface to the core of the board. The interaction of surface moisture with press temperature increase board flexural strengths (MOE and MOR) as they are vital for the heat transfer from surface to core required for resin curing. The fast transfer of heat from the mat surfaces to the core is also essential in short press cycles. However, the interaction of moisture surface with moisture core has a negative effect on the MOE, MOR and IB.

Moisture core has a negative effect on the rigidity of the board (MOE), flexural strength (MOR) as well as IB. In the tested parameter range, hardener has a significant negative impact on all the tested mechanical properties of hardwood particleboard ($P < 0.05$ and T is negative in Table 2). Hardener decreases the IB when increasing the resin or moisture in the core of hardwood particleboard. In addition, the combination of surface moisture with hardener core has a negative impact on MOR. The purpose of having hardener in the core layer of softwood particleboard is to create an acidic medium to facilitate better curing of the resin. However, it is evident that the hardener may not be required for this. That may be further tested as described in Chapter 8 by manufacturing and testing particleboard without the hardener. Considering the factor effect, interactions and contour plots discussed in this section, it can be suggested that particleboard having the following mix proportions may produce higher MOE, MOR and IB:

- Surface moisture – 13% or higher
- Core moisture – approximately 8%
- Resin surface – 15% or higher
- Resin core – 8 % or higher
- Press Temperature – approximately 190 ^{o}C
- Pressing Time - approximately 210 seconds.

7.8.2 Factors affecting the physical Properties of a hardwood particleboard

As part of the investigation, the physical properties of the final particleboards were measured. Their behaviours with respect to manufacturing parameters were studied and results are reported in this section. The mean density of the final particleboard has also been measured as that can be different from the predicted board density due to the process conditions. Density profiles of the final particleboards were measured using a density profile meter. The density profile data were used to calculate the mean surface density and mean core density. The thickness of the final board was measured as change in thickness is an important gauge of spring-back.

Table 7.4 shows the experimental variables and test results for mean density, mean surface density, mean core density and board thickness. The estimated effects and coefficients for those tested physical properties are compiled in Table 7.5. Resin core, pressing time, press temperature have significant positive impacts on all the tested properties. As quoted earlier, press temperature and pressing time are important for heat and mass transfer during the hot pressing. Similar to mechanical properties, the combination of moisture surface with moisture core has a negative impact on all the physical properties measured.

7.8.2.1 Mean Density, Mean Surface Density and Mean Core Density

7.8.2.1.1 Mean density

Mean density of a particleboard is measured in this study as it is the main factor directly related to the weight of the final board. If the particleboard is too heavy, it may not be suitable for some applications. Therefore, it is important to limit the mean density of a board while maintaining the strength properties at a standard level. The mean density was measured using the weight/volume method, while mean surface density and mean core density of the particleboard were calculated from density profile data. The density profiles were measured using the x-ray scanning method.

Resin core (D), Pressing Temperature (G) and the Pressing time (F) are the most significant individual variables affecting the particleboard mean density but moisture core has a negative effect on it. Although moisture surface has a positive impact on particleboard mean density with increased pressing time, it has a negative impact when combined with higher core moisture or with increase in moisture core and core resin. In addition, the ANOVA table suggests that mean density has a second order relationship with the process variables. The normal probability plot of standardized effect for mean density is shown in Figure 7.10.

Table 7.4: Experimental Variables and Tested Physical Properties

Board Number	**Moisture Surface**	**Resin Surface**	**Resin Core**	**Hardener Load**	**Pressing Time (s)**	**Press Temperature**	**Thickness**	**Mean Density**	**Mean Surface Density**	**Mean Core Density**
ST 1	11	8	5	1	120	150	16.92	679.870	605	494
ST 2	11	20	5	3	300	200	15.20	713.374	904	676
ST 3	22	8	13	3	300	150	15.64	750.733	911	679
ST 4	11	8	13	3	120	200	16.40	708.058	873	655
ST 5	22	20	13	1	120	200	15.52	723.797	985	665
ST 6	11	20	13	1	300	150	15.62	740.845	866	690
ST 7	22	8	5	3	120	200	16.52	690.377	737	578
ST 8	22	20	5	1	300	150	15.40	716.508	887	624
ST 9	11	20	13	3	120	150	16.74	668.346	759	583
ST 10	22	8	5	1	300	200	15.74	711.330	812	555
ST 11	22	20	13	3	300	200	15.20	717.140	915	677
ST 12	22	8	13	1	120	150	19.52	603.000	611	512
ST 13	11	8	13	1	300	200	15.10	713.267	756	611
ST 14	11	20	5	1	120	200	16.28	698.083	760	553
ST 15	11	8	5	3	300	150	17.46	637.610	792	668
ST 16	22	20	5	3	120	150	19.40	608.162	493	462

Table 7.5: Estimated Effects and Coefficients for Physical properties of a particleboard

	Thickness		**Mean Density**		**Surface Density**		**Core Density**	
	T	**P**	**T**	**P**	**T**	**P**	**T**	**P**
Moisture Surface	2.81	0.038	-0.67	0.537	0.07	0.948	-4.98	0.04
Moisture Core	7.34	0.001	-4.07	0.015	-1.96	0.145	-3.78	0.063
Resin Surface	-3.42	0.019	1.62	0.181	2	0.139	4.88	0.04
Resin Core	-2.6	0.048	2.98	0.041	3.13	0.052	12.66	0.006
Hardener Core	2	0.102	-1.63	0.178	0.36	0.74	7.51	0.017
Pressing Time	-10.18	0	5.64	0.005	4.61	0.019	18.58	0.003
Press Temperature	-9.17	0	4.75	0.009	3.71	0.034	7.07	0.019
Moisture Surface * Moisture Core	4.13	0.009	-4.42	0.012	-4.32	0.023	-14.85	0.005
Moisture Surface * Press Temperature	-2.64	0.046	NS	NS	1.31	0.281	3.78	0.063
Moisture Surface * Hardener Core	NS	NS	NS	NS	-2.66	0.076	-5.32	0.034
Moisture Surface*Resin Core	NS	NS	NS	NS	NS	NS	4.55	0.045
Moisture Core*Resin Core	NS	NS	NS	NS	0.66	0.554	3.56	0.071
Moisture Surface*Pressing Time	-5.01	0.004	3.86	0.018	1.76	0.176	NS	NS
Moisture Core*Resin Surface	NS	NS	2.05	0.11	NS	NS	NS	NS
Moisture Surface*Moisture Core*Resin Core	NS	NS	-3.37	0.028	NS	NS	-1.92	0.195
# NS = Not Significant								

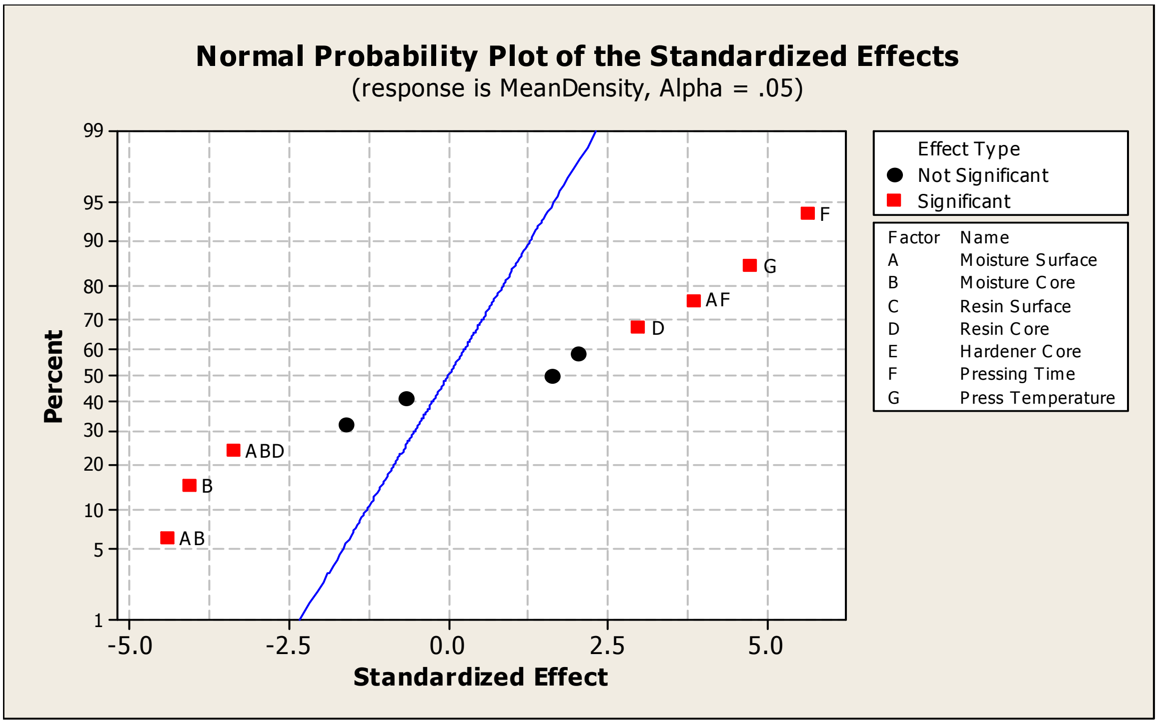


Figure 7.10: Normal probability plot of standardized effect for mean density

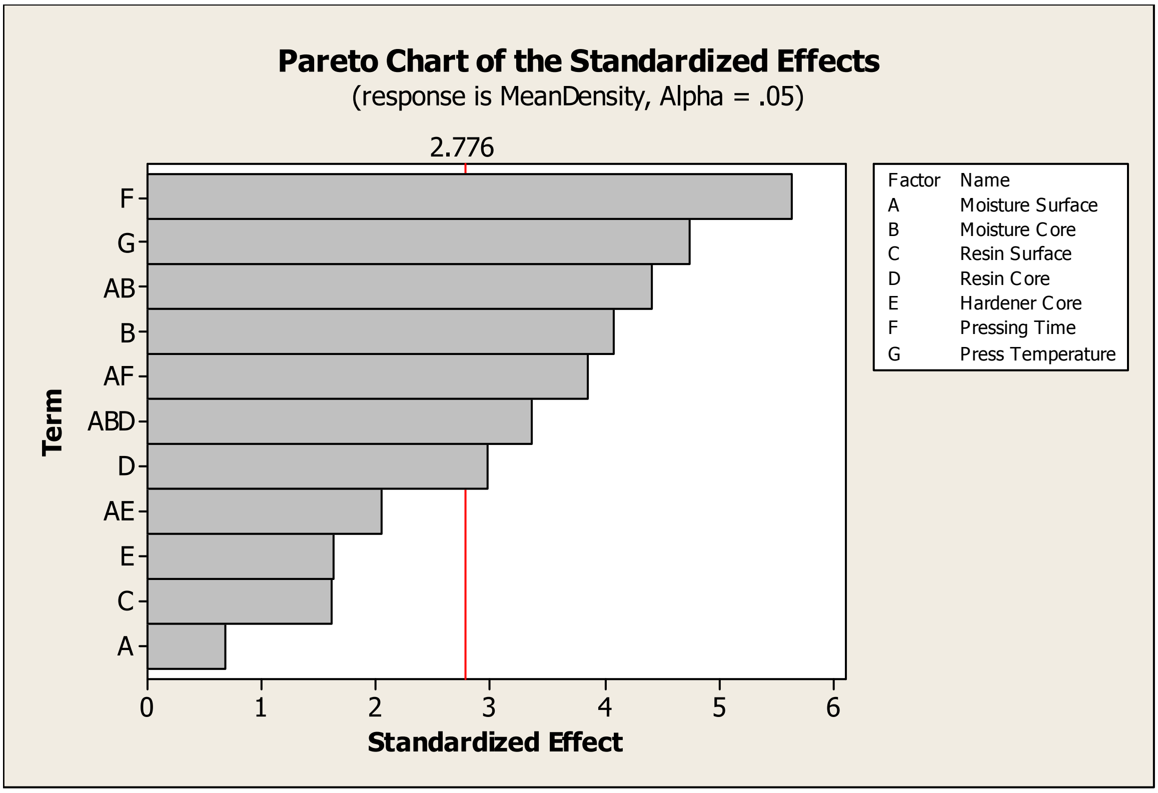


Figure 7.11: Pareto chart of standardized effects for mean density

Effects which have a positive influence on the mean density can be found on the right of the straight line. Therefore, pressing time, press temperature, resin core and the combination of moisture surface with pressing time have significant positive effects on mean density. Moisture surface with pressing time is important for mat consolidation, which leads to a better mean density. Resin core and pressing time are important for internal inter-particle bonding in the core. Similar to most of the parameters discussed earlier, moisture core and combination of moisture surface with moisture core significantly reduce the mean surface density. In addition, moisture surface and moisture core combined with resin core have negative effects on the mean density. That may be due to excessive moisture trapped inside the particleboard causing spring-back leading to lower mean density.

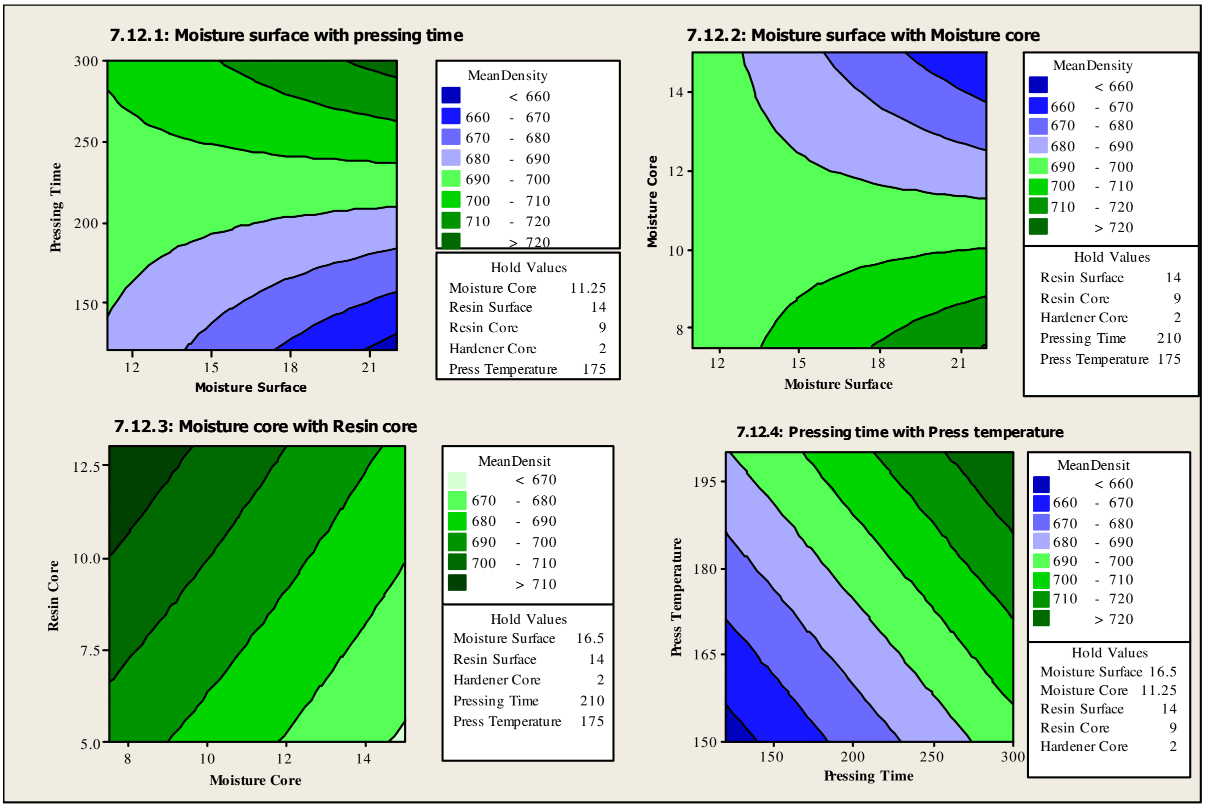


Figure 7.12: Contour plots of Mean density with respect to most significant effects

The Pareto chart of standardized effects for mean density is plotted in Figure 7.11. It shows that the pressing time is the main effect that controls mean density. Substantial pressing time is required for mat consolidation to increase the mean density. Similar to the study of mechanical properties discussed earlier, the interacting effects of the significant parameters on the mean density were plotted as contour plots and are shown in figure 7.12. The interacting contour plots were drawn considering the most important parameters with regard to particleboard mean density.

The expected mean density for the final board was approximately 700 kg/m^3 and particleboards with that mean density stay in the light green areas of the graphs. Figure 7.12.1 shows how the mean density changes when moisture surface and pressing time are changed. It shows that particleboard with mean density around 700 kg/m^3 can be produced with pressing time of 240 seconds. The moisture surface could be reduced to as low as 12%. Since moisture surface is very significant for almost all the properties discussed earlier, the moisture surface should be maintained around 15% at least, to produce a satisfactory particleboard. Although moisture is important for mat consolidation, the effect of moisture core on particleboard mean density is negative. Since moisture core causes spring-back, it reduces the mean density. Therefore, core moisture should be maintained at its minimum because the designed board density can be achieved with 15-18% moisture surface and with minimum core moisture (Figure 7.12.2).

Figure 7.12.3 shows that resin core significantly improves the particleboard mean density whilst the opposite is true for the moisture core. It also shows that moisture core can be kept at its minimum without any effect on the expected mean density. Both pressing time and press temperature should be increased to achieve the designed mean density since they are important for resin curing to create proper inter-particle bonding (Figure 7.12.4). Therefore, in order to produce particleboard with a mean density equal to 700 kg/m^3, the following factors should be maintained the following approximate figures:

- Moisture surface – 15% or higher
- Moisture core or resin core – approximately 8%
- Press Temperature – 190°C
- Pressing time 240 seconds
- Resin surface – approximately 14% or more

7.8.2.1.2 Mean surface density

The behaviour of the mean surface density was studied carefully as flexural properties (MOE and MOR) of the particleboard are mainly dependent on the surface layers. The effects of processing parameters on surface density are discussed here, and the relationship between surface density and mechanical properties will be discussed later in the chapter. The T and P values with respect to particleboard surface density were calculated and tabulated in Table 7.5. It can be seen in Table 7.5 that resin core, pressing time, press temperature, combination of moisture surface with moisture core and the combination of moisture surface with hardener core have significant influence on particleboard mean density, with $P < 0.05$.

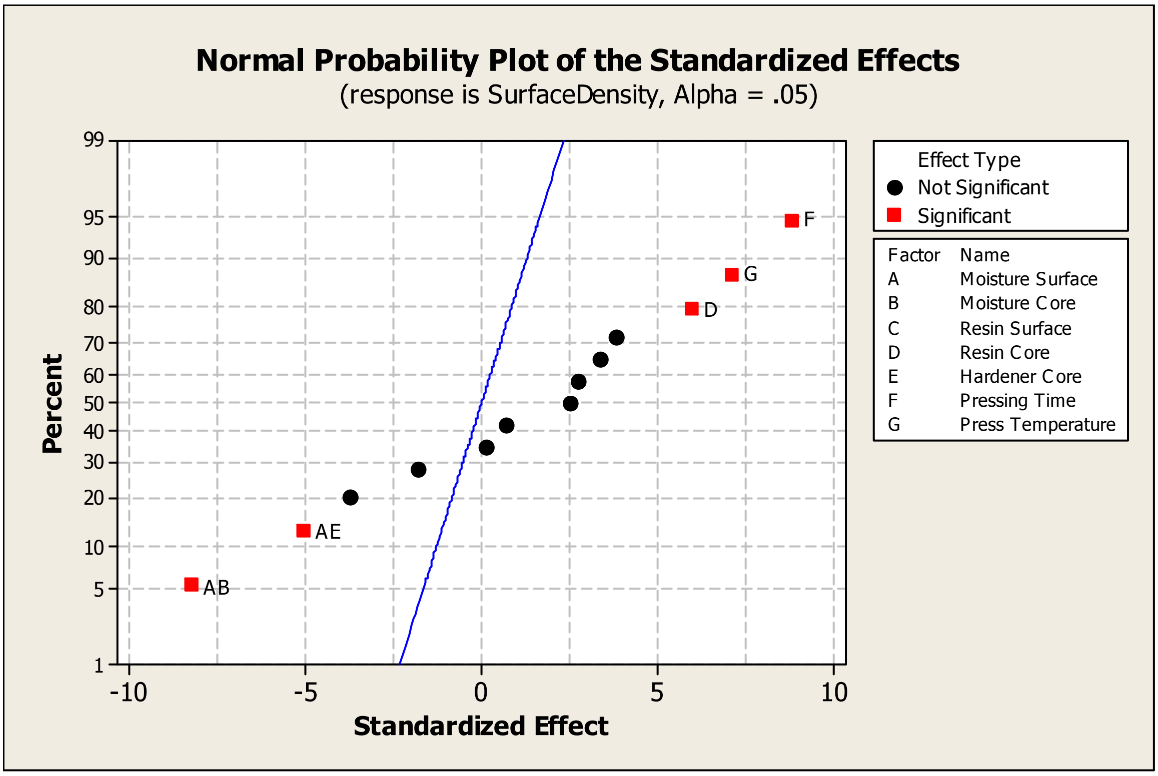


Figure 7.13: Normal probability plot of standardized effect for mean surface density

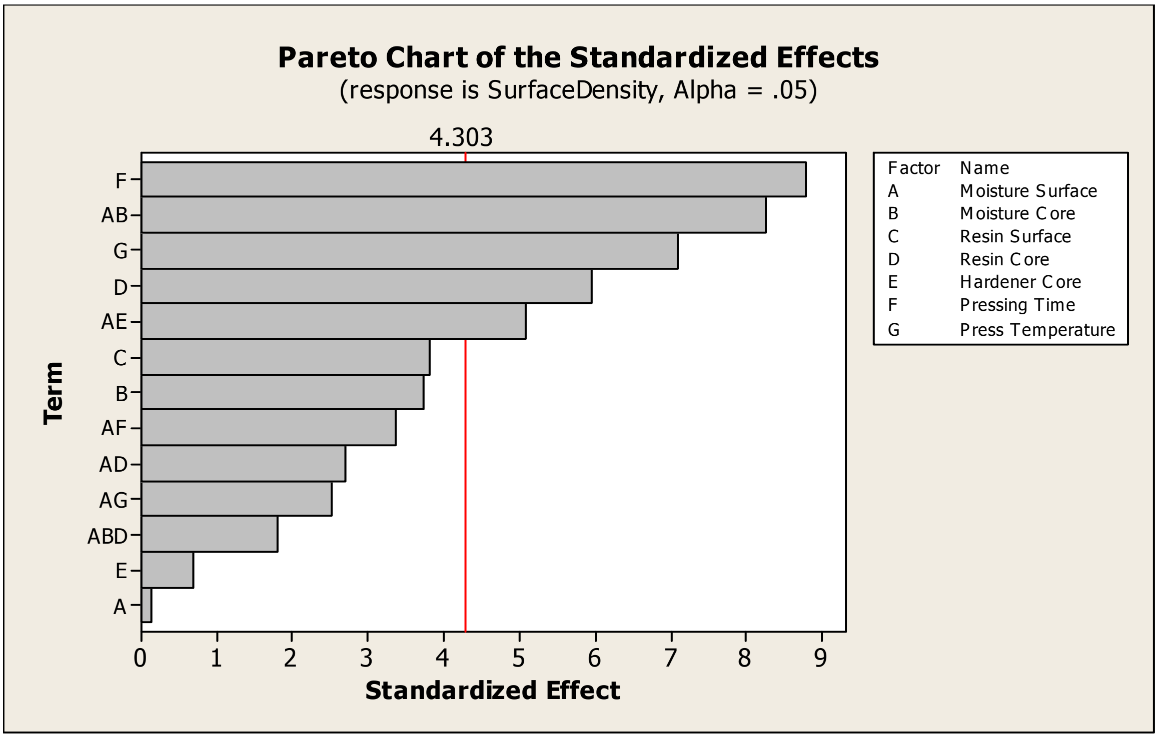


Figure 7.14: Pareto chart of standardized effects for Surface density

Figure 7.13 is the normal probability plot for standardized effect for mean surface density. Similar to MOR, Figure 7.13 shows that the pressing time, press temperature and the resin core have significant positive impacts on the particleboard mean surface density. Similar to MOR, the effect of combined moisture surface with moisture core and the effect of combined moisture surface with hardener core have a negative impact on particleboard mean surface density. Therefore, particleboard mean density may also be vital for board MOR.

Figure 7.14 shows the significant effects on surface density in a bar chart. The pressing time is the most important factor affecting mean surface density. Similar to mean density and MOR, the resin core and the press temperature are significant for the mean surface density. The second most important effect is combining surface moisture with the core moisture. This combined effect is a negative effect.

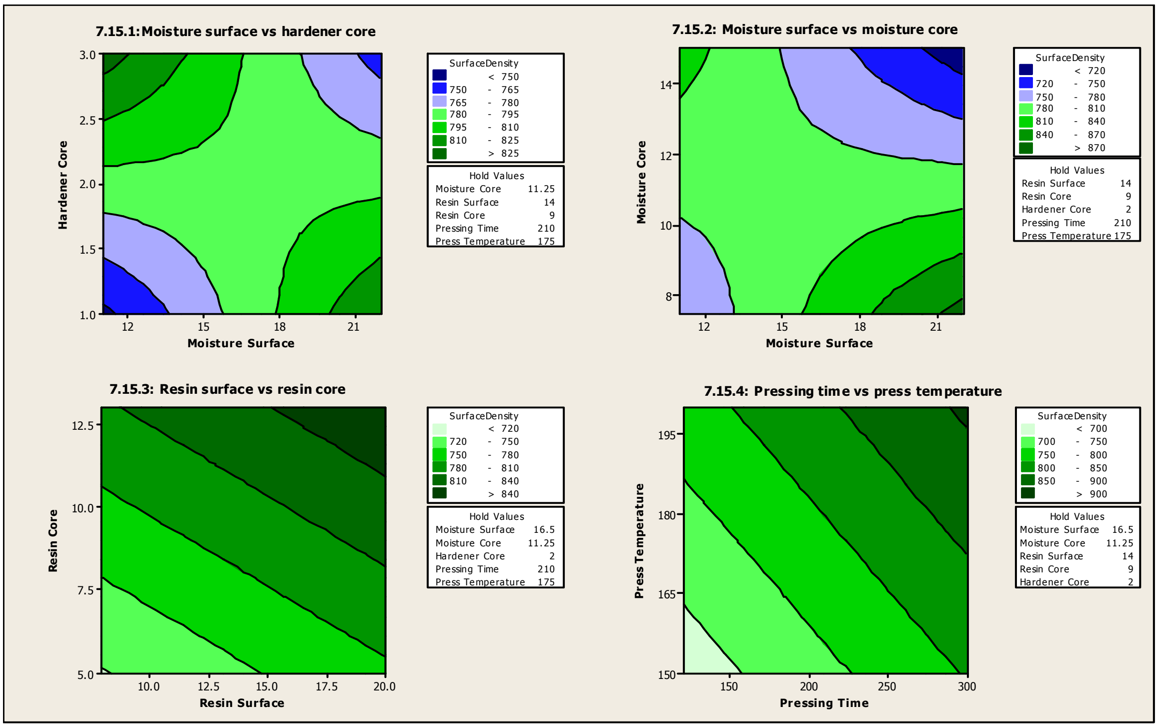


Figure 7.15: Contour plot for Surface density with respect to most significant effects

That combination has been shown to have a significant negative impact on almost all the parameters discussed so far. Similar to MOR, the combination of moisture surface with hardener core has a negative effect on particleboard mean surface density. Therefore, it is clear that most effects and inter-active effects on particleboard mean surface density are common with the significant effects for MOR.

Figure 7.15 shows the contour plots for surface density with respect to the most significant effects. The effect of moisture surface and hardener core on the mean surface density has a saddle in the middle (Figure 7.15.1). Increasing moisture surface if hardener core is unchanged produces higher surface density. Although higher hardener with less surface moisture can produce higher mean surface density, the use of hardener should be avoided as hardener has a negative effect on most of the properties tested. However, surface moisture does not always have negative effects. Similar behaviour was found in Figure 7.15.2 for the change in surface density with regard to moisture surface and moisture core. Since moisture core has a negative impact on most of the tested properties, higher surface moisture with lower core moisture should be the better combination to achieve a compact surface.

Increasing both resin surface and resin core increases surface density (Figure 7.15.3). Since resin mainly affects production cost, the best combination which satisfies the required particleboard properties should be selected. Therefore, the combination of higher surface resin with low core resin is suggested as the best combination which produces a compact surface with better mechanical properties. Figure 7.15.4 shows that mean surface density increases with increasing both pressing time and the press temperature. Therefore similar values of the factors which were suggested earlier to achieve the mean density of 700 g/m^3 would produce the compact surface. They are approximately as follows:

- Moisture surface – 15% or higher
- Moisture core or resin core – approximately 8%
- Press Temperature – 190^{o}C
- Pressing time – 240 seconds
- Resin surface – approximately 14% or more

7.8.2.1.3 Mean core density

The IB of particleboard is mainly dependent on the core layers. Therefore, the mean core density is important and was calculated from density profile data. The relationship between mean core density and the processing parameters was investigated. Table 7.4 shows the results of mean core density with respect to processing parameters and Table 7.5 includes the test statistical values (T) and probability of null hypotheses values (P) with respect to mean core density. The normal probability plot of the standardised effect (Figure 7.16) and the Pareto chart of the standardised effects (Figure 7.17) were plotted using these data. Positively significant effects can be found right of the blue line and negative effects left of the blue line (Figure 7.16). The effects with their level of significance can be read in bar charts in Figure 7.17.

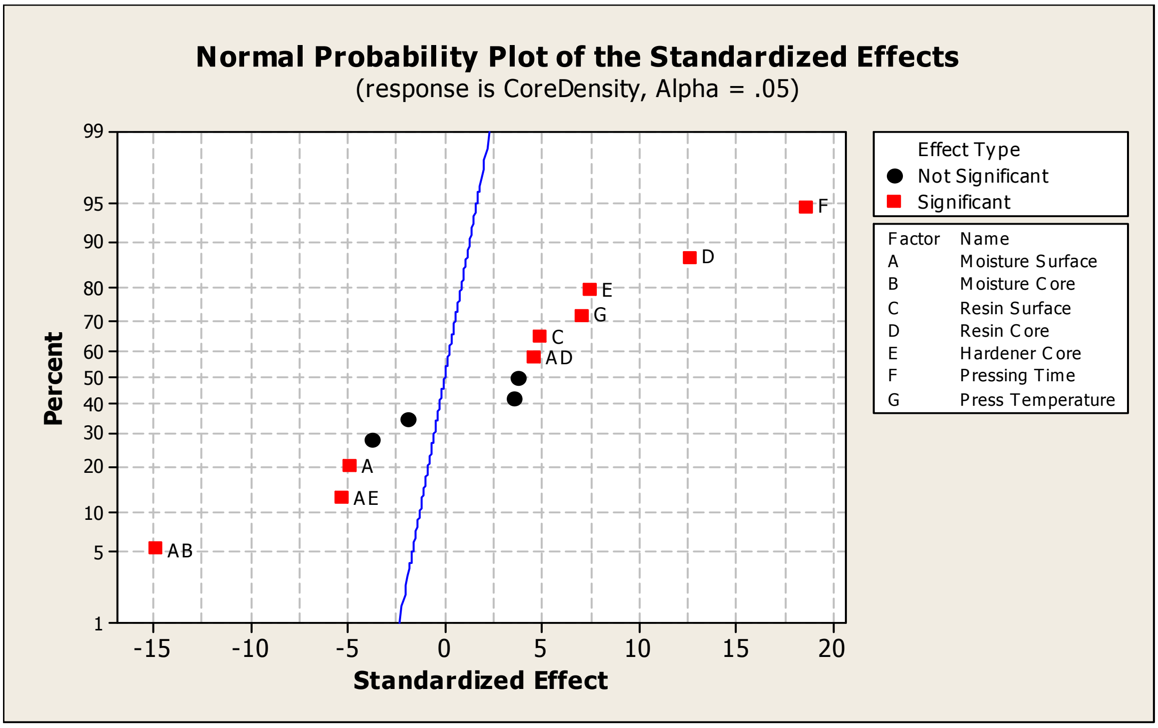


Figure 7.16: Normal probability plot of standardized effect for mean core density

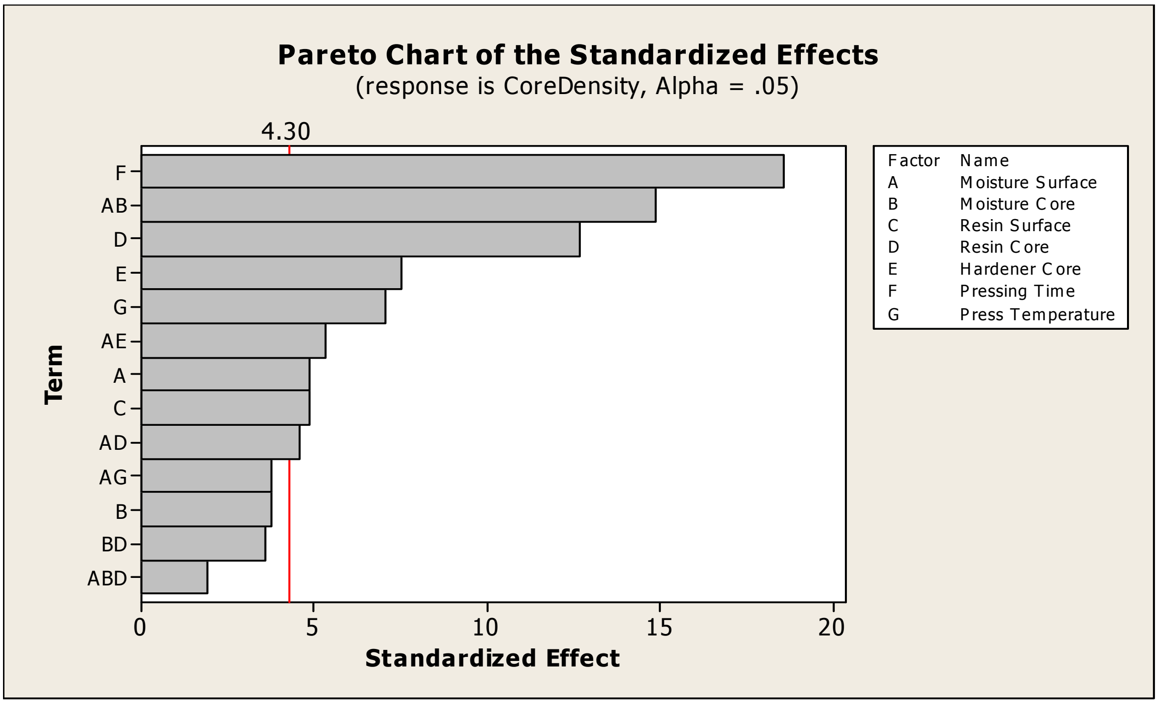


Figure 7.17: Normal probability plot of standardized effect for mean core density

It can be seen from Table 7.5 that most of the variables studied here are affect mean core density ($P<0.05$). Similar to the effects on the surface density, pressing time is the most positively significant parameter (Figure 7.16) as well as the most significant parameter (Figure 7.17) on core density. In addition, Figure 7.16 shows that both resin surface and resin core are significant for improving core density. Also, moisture surface combined with resin core and the press temperature significantly improve core density. Moisture surface is important for mat consolidation as well as heat transfer to the core. Press temperature is vital for resin curing. Therefore, moisture surface facilitates wood compaction as well as heat transfer which are vital for resin curing in the core to increase the core density.

Unlike all the parameters discussed earlier, hardener core has a positive impact on particleboard core density (Figure 7.16). Hardener may accelerate the resin curing in the core to increase inter-particle bonds in the core to increase core density. However, Figure 7.17 shows that hardener combined with moisture surface has a significant negative impact on the mean core density. Extra surface moisture transported into the core and trapped inside during the hot-pressing creates higher steam pressure in already bonded core (due to hardener). When releasing the hot-press, spring-back occurs due to this trapped steam, resulting in reduced core density. Similar to most properties discussed earlier, combining moisture surface with moisture core has a significant negative impact on core density. Therefore, it is clear that moisture surface alone or combined with core moisture or hardener has a negative effect on core density.

Figure 7.18 shows the contour plots of mean core density with respect to selected significant parameters. The relationship between surface moisture and core moisture on the core density was studied further because surface moisture is also important for particleboard mechanical properties. Although moisture surface alone or in combination with core moisture or hardener core has a negative impact on core density, an optimum amount for surface moisture could be established using Figure 7.18.1. Figure 7.18.1 has a saddle at the middle with a reasonable higher core density (> 600 kg/m^3). Therefore, core moisture may be kept at its minimum while having optimum surface moisture as reasoned earlier.

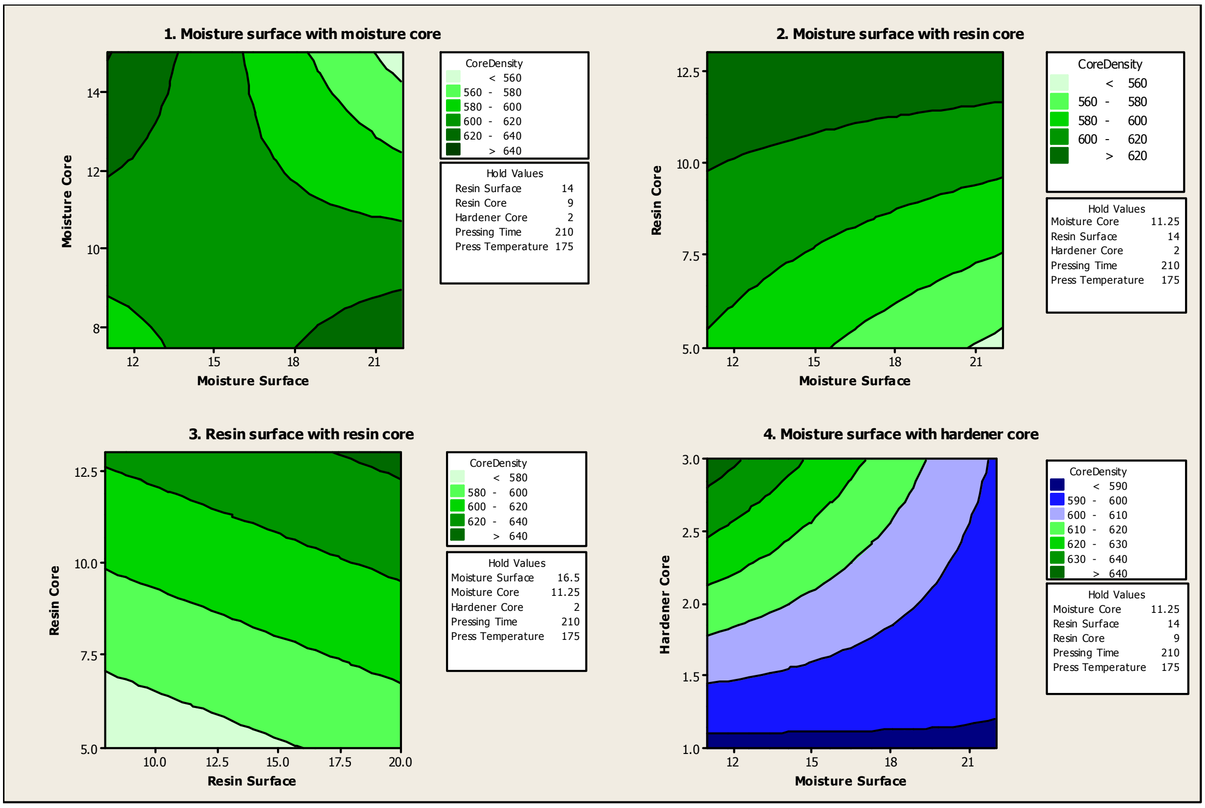


Figure 7.18: Contour plot for mean core density with respect to most significant effects

Resin core is dominant for particleboard core density compared with surface moisture (Figure 7.18.2). This is expected as core resin creates stronger inter-particle bonds in the core, whereas extra moisture may cause spring-back to reduce the core density. However, Figure 7.18.3 shows that both increases in the resin surface and the resin core increase core density. Therefore, a suitable minimum amount of core resin with a higher amount of surface resin should be selected without compromising core density as surface resin is critical for most particleboard properties. However, the average core density in each graph is higher than 500 kg/m^3. Figure 7.18.4 shows that hardener is more important compared to surface moisture for the particleboard core density. However, hardener negatively affects most of the properties studied earlier.

The relationship between particleboard mechanical properties and density profile has further been investigated and results are reported later in this chapter. Increases in both surface and core density increase the mean density of the board. Increase in mean density increases the weight of the final particleboard and that affects the handling of the board in practical applications. Therefore, minimum core density with sufficient strength has been studied to achieve an efficient particleboard product.

7.8.2.2 Particleboard Thickness

Maintaining a constant particleboard thickness is important for its use as a wood panel. However, particleboard thickness may change due to various factors discussed in Section 2.4.4. Particleboard thickness just after manufacturing was measured and its variation, with respect to processing parameters is discussed in this section. Table 7.4 shows the results of particleboard thickness values, and Table 7.5 includes the test statistical values (T) and probability of null hypotheses values (P) with respect to the thickness. Increase in the particleboard thickness after the hot pressing is defined as spring-back. Spring-back normally happens just after hot-pressing due to the relaxation of internal pressure due to hot-pressing. Optimum spring-back was found in board ST16 which has the highest moisture level and highest resin level (Table 7.4).

Similar to the investigation earlier, the normal probability plot of the standardised effect (Figure 7.19) and the Pareto chart of the standardised effects (Figure 7.20) were plotted using the data presented in Table 7.5. Figure 7.19 shows that moisture in both surface and core has significant positive impact on increasing board thickness. In other words, moisture is the main cause of spring-back.

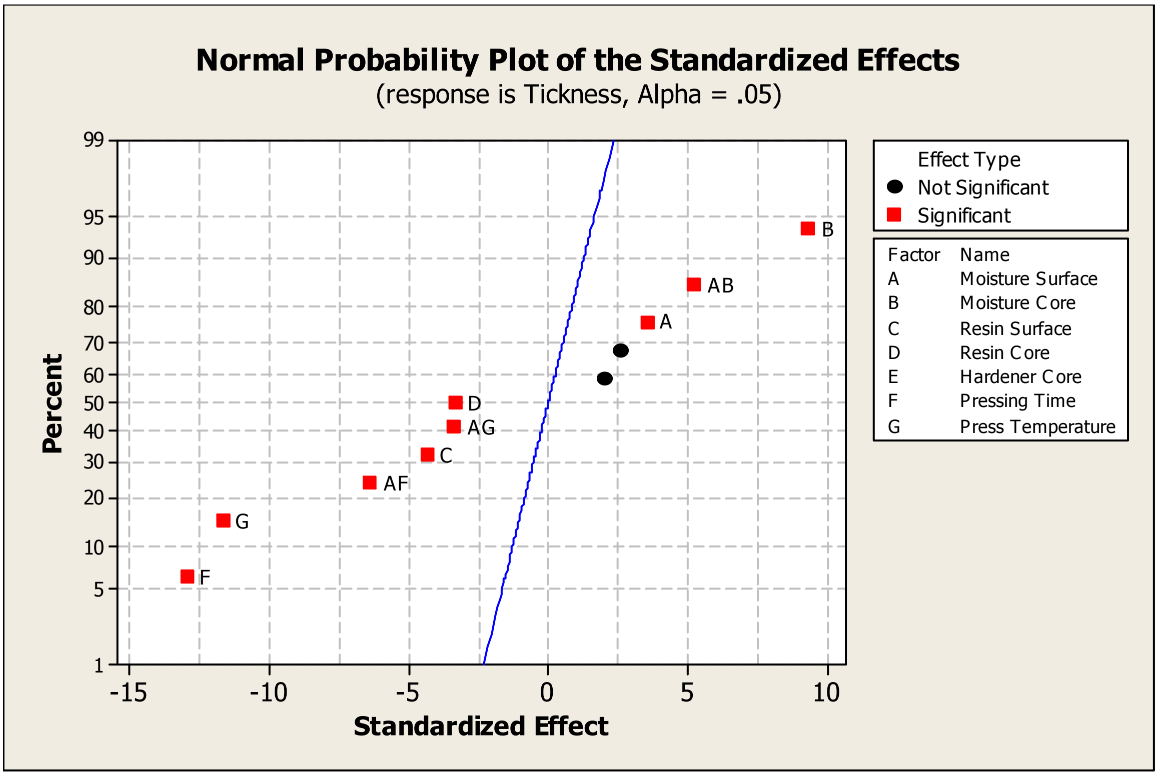


Figure 7.19: Normal probability plot of standardized effect for particleboard thickness

The excessive moisture that may be trapped inside the board after hot pressing can create weaker bonds that result in spring-back. This has been explained by previous researchers (Beech 1975; Suchsland 1969) as the result of releasing the pressure after hot pressing. Higher moisture content in the middle may lead to spring-back and non-reversible excessive dimensional changes of the board. Also, Deppe and Ernst (1964) reported that releasing the pressure after completing the hot pressing, has an exponential relationship as in Equation 7.1.

$P = P_0 e^{-\lambda T'}$ Equation 7.1

Where,

P = pressure at the time T

P_0 = initial pressure

T' = relaxation time

λ = a factor depending on density, species, particle geometry, moisture content

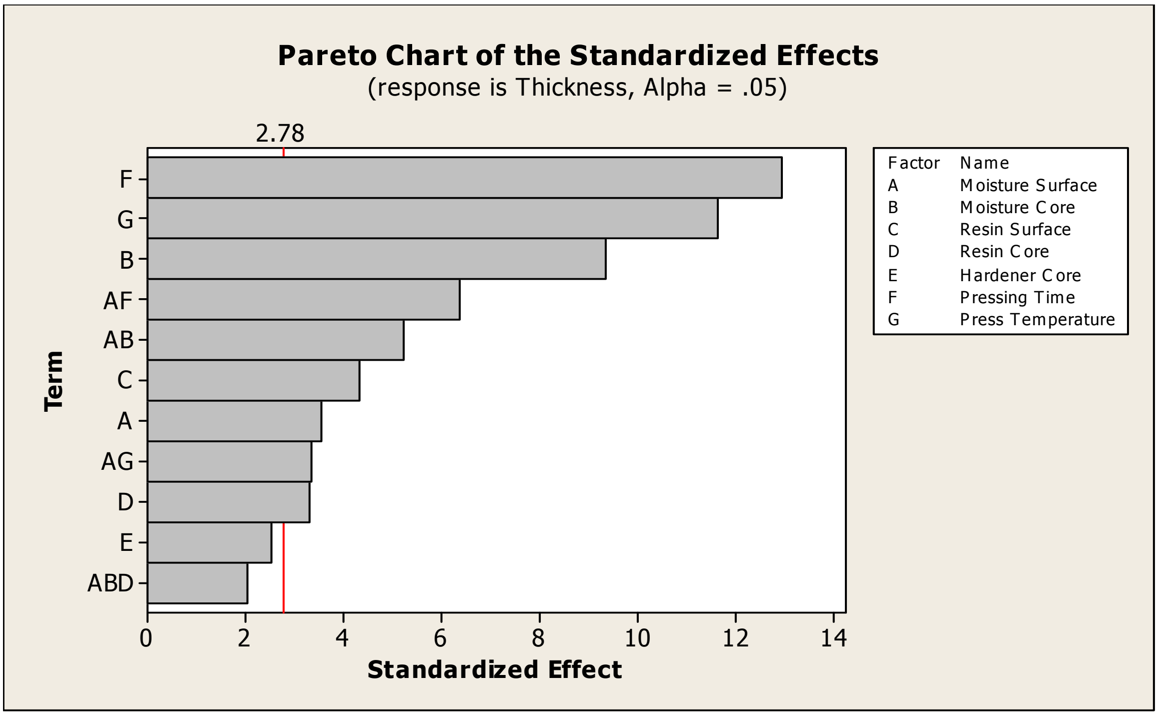


Figure 7.20: Pareto chart for standardized effect on the thickness

Pressing time and press temperature have the most significant negative effects on increasing thickness to control spring-back (Figures 7.19 and 7.20). However, resin surface, resin core, moisture surface combined with press temperature or pressing time have negative effects on thickness-increase or spring-back.

Moisture surface combined with temperature or pressing time are required for heat transfer to the core of the board to improve resin curing. When resin has properly cured by creating more and more cross linking sites, it reduces spring-back due to the release of the press. Increasing the pressing time or press temperature gives moisture enough time and temperature to become steam and to exit from the board.

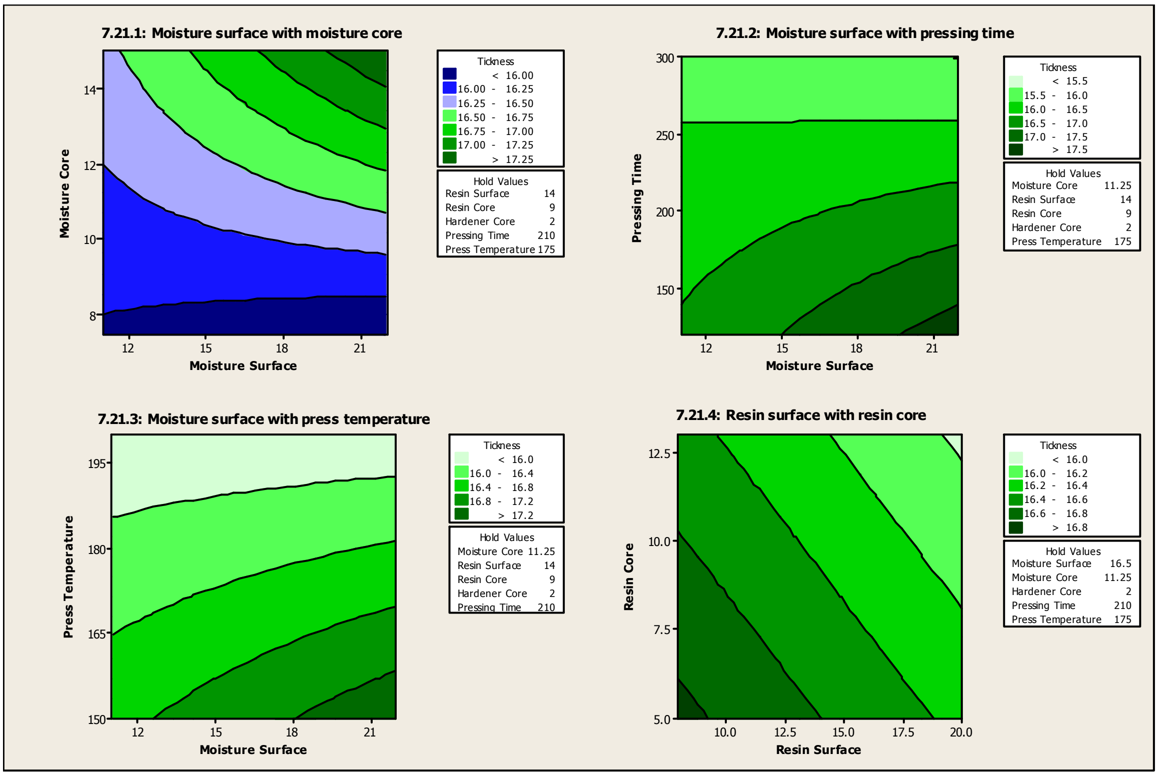


Figure 7.21: Contour plot for the particleboard thickness with respect to the most significant effects

In order to find the best combination of the effects to control particleboard thickness, contour plots were plotted considering the most significants effects with respect to the thickness. Figure 7.21.1 shows that moisture core is the most dominant factor that increases particleboard thickness. Therefore, moisture core should be controlled to its minimum possible level (< 10%) while increasing the moisture surface as required by most properties (Figure 7.21.1). By increasing the pressing time or press temperature with constant surface moisture, increase in thickness or spring-back can be controlled (Figure 7.21.2 and Figure 7.21.3). The minimum increase in thickness can be found above the horizontal contour of Figure 7.21.2 and Figure 7.21.3 (with pressing time > 250 seconds and press temperature > 180^{o}C). Resin surface and resin core are equally important to control particleboard thickness to minimise spring-back (figure 7.21.4). Therefore particleboard with the designed thickness (15.2 mm) may be produced with the following figures:

- Moisture core < 10% (then the moisture core can be changed anywhere within the range)
- Pressing Time – approximately 250 seconds
- Press Temperature > 185°C
- Resin core – 10%
- Resin Surface > 15%

In the tested parameter range, moisture is a critical variable that needs to be controlled carefully for better compaction of the wood mat. Also, moisture is the main medium that transports heat from the surface to the core of the board. Moisture has a negative effect on physical properties such as mean density and thickness of board. Interaction of moisture surface with moisture core reduces all the tested properties.

In the tested parameter range, hardener has a significant negative impact on all the tested properties of hardwood particleboard except core density. The purpose of having hardener in the core layer of softwood particleboard is to create an acidic medium to facilitate better curing of the resin. It was hypothesized that hardwood residues already have a higher acidity, and hardener is not required in the core to create an acidic medium to facilitate faster cross-linking. This hypothesis was proven to be true when the pH value of hardwood residue was measured in acidic range. Adding more hardener to the resin does not increase the curing reaction, and instead leaves residues of acids or acid compounds in the glue-lines. These acidic compounds may also contribute to the brittleness of the cured resin. This will initiate hydrolysis of the wood cell wall adjacent to the glue-lines as well as acid-catalysed resin degradation which, decreases bond durability (Myers, 1984). Therefore, an alternative catalyst/ hardener will need to be investigated to accelerate the curing of the core layer or an alkaline used to decrease the curing of the surface layer to match the curing of the surface and core layers.

7.8.3 Board density profile and mechanical properties

In sections 7.8.1 and 7.8.2 the effects of processing parameters on the physical and mechanical properties of particleboard were discussed. MOR, MOE and IB were studied under mechanical properties and particleboard density (mean density, surface density and core density) and thickness were studied under physical properties. This section evaluates how mechanical properties can be dependent on these physical properties. Therefore this section compares the patterns of density profile data with the actual mechanical properties of the same particleboard.

Figures 7.22, 7.23 and 7.24 show the density profiles of final boards. In each board, density at the surface of the board is very low. Then it increases dramatically to provide the highest density at 1 to 2 mm from the surface. Then it reduces to a constant value along the core layer. The reason for lower density at the surface may be due to over-curing of the resin at the surface of the board, which may have broken the bonds between particles providing loose particles at the surface. Figure 7.22 displays vertical density profiles of particleboards that have relatively uniformly shaped density profiles, better mechanical properties and lower thickness swelling compared to those boards in Figures 7.23 and 7.24. Board ST 5 which had 120 seconds pressing time has a sharp peak close to the surface, whereas numbers ST2, ST6, ST8 and ST13 which had 300 seconds pressing time have a blunt peak (Table 7.2 and Figure 7.22).

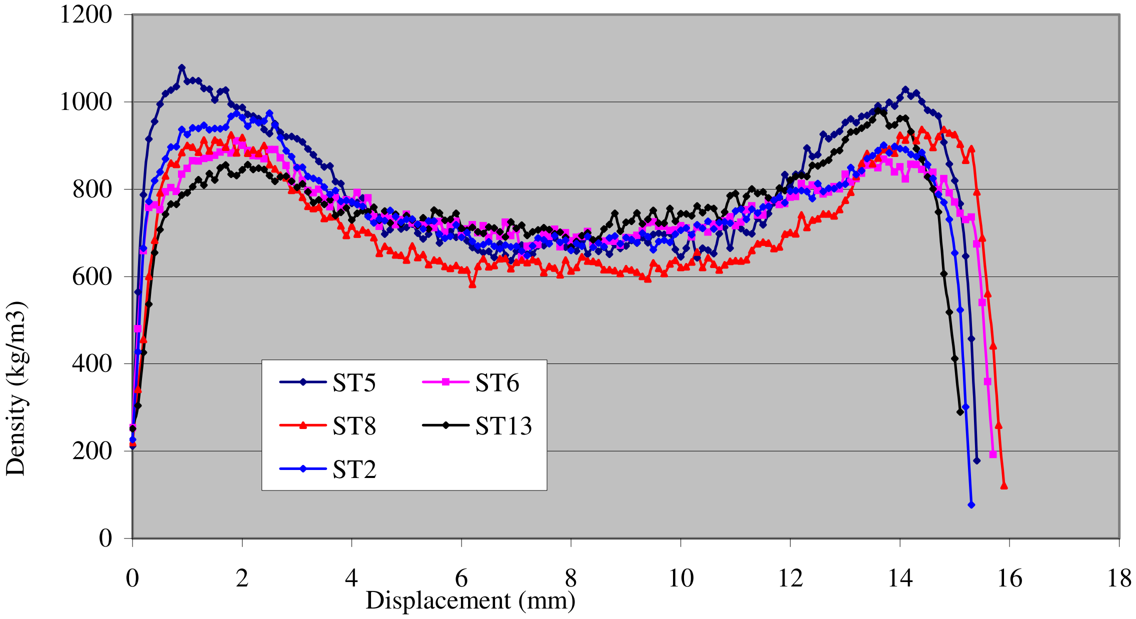


Figure 7.22: Density profiles of boards with the best mechanical properties

The highest MOE and MOR were found in ST 5 (Figure 7.22) and that set also has a higher IB which complies with the mechanical properties required by AS/NZS 1859 (2004). Board ST5 has the highest peak density close to the surface layer and also consistent core density that higher than 700 kg/m^3 (Figure 7.22). Boards which have relatively high MOE and MOR have both peak density higher than 900 kg/m3 and mean core density higher than 600kg/m^3. In addition, boards with lower pressing time have their peak surface density closer to the surface of the board, whereas increased pressing time moves the peak surface density towards the core. This observation was confirmed by board density profiles plotted in Figures 7.23 and 7.24.

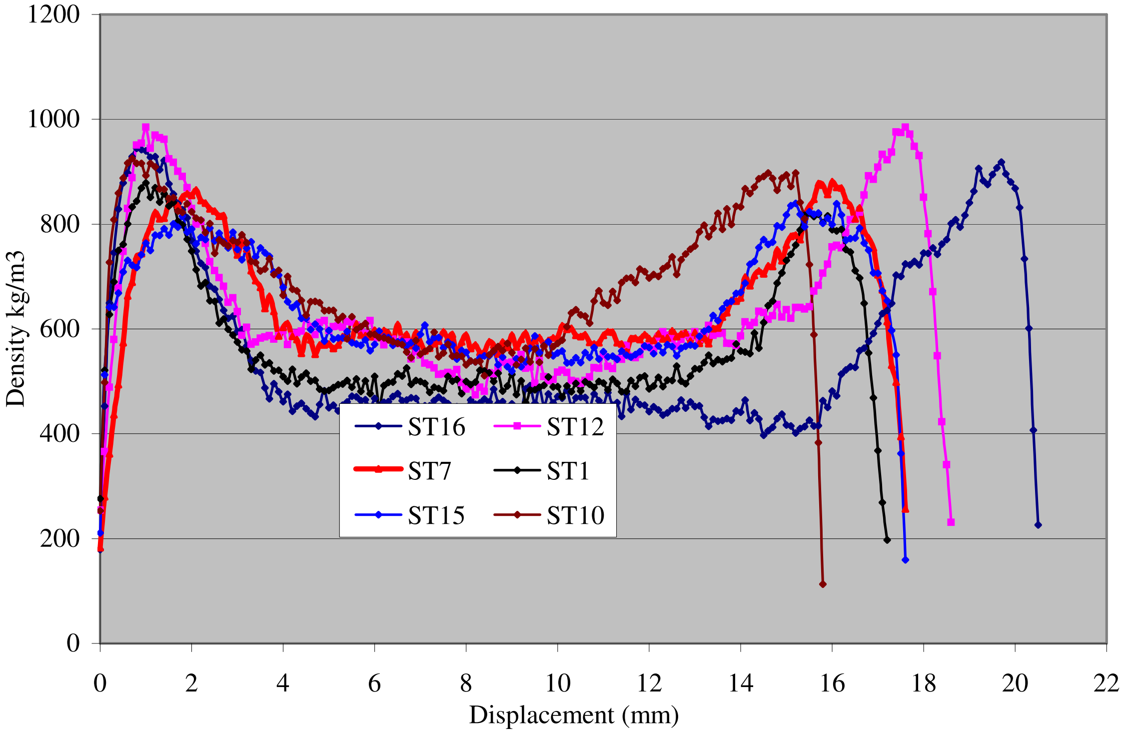


Figure 7.23: Density profiles of boards with medium mechanical properties

In addition, boards with lower pressing time have their peak surface density closer to the surface of the board, whereas increased pressing time moves the peak surface density towards the core. Similar observations have been reported by previous researchers, it is clear that high initial pressure with short closing time during the hot pressing results in higher face density with low core density, and a board with lower initial pressure with longer press closure time, shows relatively uniform vertical density (Strickler 1959; Wong 1998). Smith (1980) also made a similar observation to those reported by Strickler (1959), and reported that press closure time can alter the shape of the density profile. Fast press closing produces a U shaped density profile while, slow press closing produces an M shaped density profile.

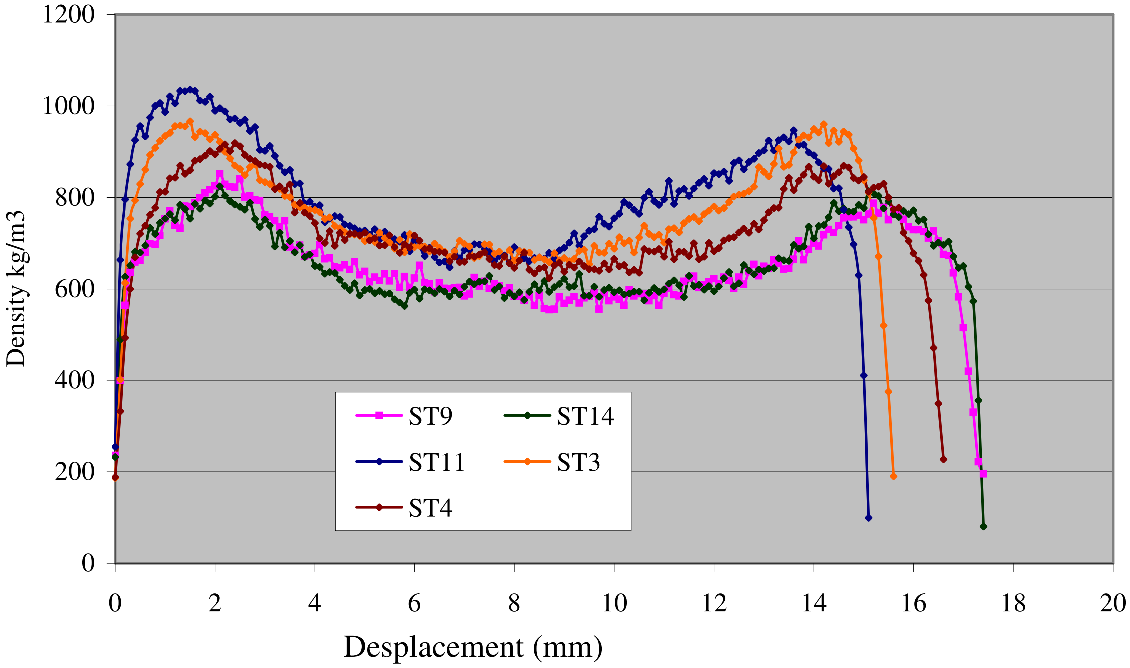


Figure 7.24: Density profiles of boards with the weakest mechanical properties

Boards ST2, ST5, ST11 and ST13 have higher mean surface and mean core density, which produced better mechanical properties than those of boards ST1, ST4, ST10 and ST13 respectively. However, this observation is not true for boards ST14, ST15, ST2, ST3 and ST6. That may be explained by the hypothesis that boards with high density may not necessarily have better inter-particle bonding than boards with lower density. The density profile forms due to the interactions of heat and mass transfer with the rheological properties of furnish and resin during the production of particleboard and that depends on the pressing time and the temperature (Humphrey 1982; Suchsland 1969). The shape of the density profile describes the change in density along the mat thickness.

According to Schulte and Fruhwald (1996), for a medium density fibre-board, the failure of the internal bond test happens at the outer part of the specimen, irrespective whether the absolute minimum of the density profile is located in the centre of the specimen, or the glue type or the glue content. They observed the same behaviour with all specimens: whether the density profile had very high maxima closer to the surface or smooth density profile or sharp relative minima in the outer parts of the specimen. This failure type is explained by them, as a result of the outer part of the board starting heating up first during the hot pressing, which cause that it starts plasticization, densification and hardening first. At the latter part of the hot pressing, the inner part of the board starts plasticizing and densification. During this time, already cured surface layer glue bonds could have failed. Therefore, the density profile may not always correctly predict particleboard properties.

Wong et al. (1998; 1999) observed that the high moisture content (MC) on the faces enhances plasticizing of the wood particles, in addition to retarding the occurrence of pre-cure, giving rise to tight and hard faces near the surfaces. Theoretically, moisture on the mat faces would change into steam, then move into the core upon hot pressing, hence facilitating the transference of heat to the core. Consequently, while faces are plasticized and set at higher density, the core would still be resisting the pressure. When sufficient heat finally reaches the core, most of the wood particles would have been compressed and set near the faces. As a result, a wide and low density zone forms in the core. It has been estimated that about 12% MC needs to be converted to steam in order to fill all the voids in the particleboard during hot pressing (Strickler, 1959).

7.9 Testing the acidity of sawmill residues

The acidity of saw mill residue was tested according to the method adopted by Stewart and Lehmann (1973) for cross-grain, knife-planed hardwood flakes. Fifteen grams (15 g) of saw dust (fine material) was measured into a clean glass container. A hundred and fifty millilitres (150 ml) of boiling water was added to the residue meal. Then, the wood meal was left at room temperature for 30 minutes to cool it to room temperature (24^{o}C) before the liquid was filtered. A fifty millilitre (50ml) sample was taken from the filtered liquid to test for its pH.

The same procedure was repeated for testing the pH value for the mulch sample. Custom-flaked soft wood samples used in the particleboard industry (at H R Henderson's Pty Ltd., Victoria, Australia) for surface and core material were also tested as benchmarks to compare their pH value with hardwood residues.

Table 7.6: Test results of the pH values of wood samples

Sample	**pH Value**
Distilled water used in the laboratory	7.00
Mulch (Wood residue)	6.46
Fine (Wood residue)	5.13
Soft wood flake – Core material	6.73
Soft wood flake – Surface material	6.74

The pH test results showed that soft wood flakes can be considered as slightly acidic or rather neutral in nature as the pH is similar to the distilled water used in the lab. Results revealed that the pH of wood residues (both mulch and fine) is acidic in nature as pH < 7.0 (the pH of distilled water).

Therefore, hardwood residue may not require additional additives to create an acidic medium for accelerating UF resin curing. Adding additional additives may leave acidic residues between inter-particle bonds resulting in brittleness of cured resin. This will initiate hydrolysis of the wood cell-wall adjacent to the glue-lines as well as acid-catalysed resin degradation which decreases bond durability (Myers 1984). Therefore, in the experimental work performed after this finding hardener was deliberately not used in and attempt to optimise particleboard properties without using hardener.

7.10 Summary and Conclusions

This chapter has reported on the physical and mechanical properties of hardwood particleboard with regard to processing parameters. Three-layer particleboards were manufactured in the laboratory by changing seven manufacturing parameters. The manufacturing parameters which were studied here are surface resin load, core resin load, surface moisture content, core moisture content, pressing temperature and press closure time. Modulus of Rupture (MOR), Modulus of Elasticity (MOE) and Internal Bond strength (IB) of the finished board were studied as well as the physical properties of the final particleboard. The tested physical properties were mean density, surface density, core density, thickness and density profiles. These board properties with respect to the manufacturing parameters were analysed and the results are summarised below.

- Moisture is a critical variable that needs to be controlled carefully for better compaction of the wood mat. Moisture is also the main medium that transports heat from the surface to the core of the board. The fast transfer of heat from the mat faces to the core is essential in short press cycles that control the cost of production. However, moisture as an individual variable has a negative effect on the rigidity of the board (MOE) as well as IB. However, the interaction of surface moisture with press temperature increases board flexural strength as well as physical properties.

- Interaction of moisture surface with moisture core has a negative impact on all the tested parameters. Using higher amounts of moisture for both surface and core may leave some moisture trapped inside the particleboard just after releasing the hot press. Therefore, this trapped moisture may have caused steam pressure inside the board after hot pressing could which cause spring-back by breaking already set inter-particle bonds.

- In the tested parameter range, hardener has a significant negative impact on almost all tested mechanical properties of hardwood particleboard. Hardener decreases the IB when increasing the resin or moisture in the core of hardwood particleboard. In addition the combination of surface moisture with hardener core has a negative impact on MOR. The purpose of having hardener in the core layer of softwood particleboard is to create an acidic medium to accelerate resin curing in the core. It was found that hardwood sawmill residue is already acidic and therefore, hardener may not be required. This will be further tested in Chapter 8 by manufacturing and testing particleboard without hardener.

- Results of the laboratory studies indicate that resin surface and pressing time significantly influence both mechanical and physical properties of hardwood particleboard. Resin is the main ingredient that creates permanent inter-particle bonds in the particleboard. Therefore, an adequate pressing time is vital for mat consolidation as well as heat transfer from surface to core for resin curing.

- Hardwood particleboard had better mechanical and physical properties when the surface resin content and pressing time were higher. These particleboards used greater amount of surface resin compared to softwood board. It helped to make more inter-particle bonds in the surface to increase mechanical properties.

- While pressing time and pressing temperature significantly reduce thickness-swell, moisture core increases it drastically. Pressing temperature significantly affects MOR, MOE and the thickness, but it has only a small effect on the other properties. Although resin core significantly increases both IB and MOR of the board, resin surface is very important for all the properties tested. Therefore, resin core needs to be reduced without compromising IB or MOR while keeping the resin surface at a higher value.

- Relationships between MOE with processing parameters and MOR with significant processing parameters were studied further to predict MOE and MOR with respect to processing parameters. The results are reported in the next chapter.

- Density profile alone cannot predict board mechanical properties. Inter-particle bond has a significant influence on strength properties. However, results show that particleboards that have a surface density 900kg/m^3 and core density > 600kg/m^3 produce MOE and MOR, which satisfy the AS/NZS 1859(2004) standards for general purpose particleboard.

CHAPTER 8

FORMULATION AND PROCESS MODELLING OF PARTICLEBOARD PRODUCTION USING HARDWOOD SAWMILL RESIDUES

8.1 Significance of Process Modelling

As discussed in earlier chapters, factorial design is a very efficient method widely used in experiments involving several variables. Chapter 6 and Chapter 7 respectively discussed how factor screening is done to obtain the most important factors for single-layer and three-layer particleboards. In addition, using this method, important variables and combined effects were investigated. Process modelling using experimental design is another important tool that can be used to develop a new product, to formulate a new process or to improve an existing product or process. Process modelling is an empirical method of developing a process model based on observed data from the process considering the response surface. The underlying response surface is typically driven by a combination of some unknown physical mechanisms and known chemical reactions. The multiple regressions are a collection of statistical techniques used for this model building.

It is a well recognized method in chemical and polymer science, pharmaceutical research and drug development as it is an efficient and an economical tool that can be used for mix designs for almost any product considering the production variables. Since the process model clearly explains the relationships between raw materials and processing parameters with final board properties, it can be used to do quantitative and qualitative analyses of hardwood particleboard production. In addition, the model can be used to optimize particleboard properties and to develop the recipe to produce hardwood particleboard with expected properties.

When the most significant parameters were found for the properties of three-layer particleboards (Chapter 7), the relationships between those significant parameters with respect to particleboard properties can be found using linear regression techniques as discussed in Chapter 5. The experimental results for three-layer particleboard shown in the Table 7.2 show that only one particleboard (ST5) has the flexural strength properties (MOE and MOR) which comply with the AS.NZS 1859 (2004) requirements. Also, the recipe for this particular particleboard indicates that it uses the optimum resin content for both surface and core. Further, MOE and MOR are not only dependent on resin but also on some other process parameters (Chapter 7). Therefore, it is important to develop process models for MOE and MOR considering the most important effects with respect to each other using regression analysis. Then these models can be used to optimise the respective property. This chapter therefore explains the methodology used to develop process models for MOR and MOE. In addition the developed models will be validated using further experiments.

8.2 Methodology

8.2.1 Composite process models

Composite process models discussed here are empirical models which are developed using multiple regression analysis. Multiple regressions are a collection of statistical techniques used for model building. The method is suitable for the exploration of response surfaces and to develop second order polynomial models, thus helping optimization of the process by using a smaller number of experimental runs (Myers and Montgomery 2002). Myers and Montgomery (2002) added that second order polynomial models work well in solving true response surface problems. As observed in Chapter 7, tested parameters (responses) for this investigation behaved in true responses surfaces with respect to process variables. Therefore, a polynomial function may explain the behaviour of responses with regard to process variables. That suitability will be tested by calculating regression coefficients. The generated model contains quadratic terms with two-factor interaction effects of individual terms. The second order polynomial models are of the following form:

$$Y = a_0 + a_1x_1 + a_2x_2 + a_3x_3 + \ldots\ldots + a_8x_1x_2 + a_9x_1x_3 + \ldots\ldots a_nx_1^2 \ldots\ldots + a_mx_7^2 + E \qquad \text{Equation 8.1}$$

Where,

Y is the selected response,

$a_0 \ldots a_m$ are the regression coefficients,

$x_1 \ldots x_7$ are the factors being studied and

E is the error term.

In this investigation, it was observed that multiple linear models excluding 2nd order effects provide a reasonable prediction of particleboard properties.

8.2.2 Method of developing composite process models

Factorial experimental design was carried out considering seven process and material variables with their two levels and the centre point in planning experiments (Table 7.1). Then, the most important effects and interactions were identified by observing and analysing the final board properties (Chapter 7). As discussed in Chapter 7, final particleboards were tested and final results were statistically analysed. Subsequently, significant parameters affecting each different properties were identified (Table 7.2). Test statistical values for significant parameters are relatively higher than those which are non-significant. In addition, the probability of null hypothesis is less than 0.05 (α). Then, the partial regression coefficients which are required to develop a polynomial function (equation 8.1) relating the tested property with significant parameters were estimated using the least square regression method discussed in Chapter 5. Minitab (release 14) was used to calculate these coefficients incorporating design of experimental theories.

Once models were developed, the reliability of those models was estimated statistically before testing experimentally. ANOVA is one method used to estimate the significance of the selected model type: whether a linear model or a polynomial model is required. Further, Pearson correlation coefficients (R^2) that compare and explain the reliability of the experimental data with predicted data were used to explain the validity of the model. When both of the above were satisfactory for the predicted model, further experiments were performed and their results against predicted results by the model were compared.

8.3 Predicting MOR with respect to processing parameters

As discussed in Chapter 7, nine factors or interactions are significant for MOR. Those are the effects which have $P< 0.05$ in the Table 7.3 and are reproduced in Table 8.1. In addition, effects which generally have significant effects on most properties were also considered for model development. Sometimes parameters with a less significant effect on MOR may have a higher effect on another parameter. Therefore, during the process optimisation, those effects become a variable. Therefore, the effects with minor effect on MOR ($P < 0.15$) were also considered for the MOR model. However, adding minor effects or non-significant variables may decrease the validity of the model by increasing the error. Therefore, R^2 and the R^2 adjusted were calculated using the method explained in Chapter 5. If R^2 is close to 100% it is a reflection of the reliability of the model. If the model has significant errors due to the inclusion of non-significant parameters, a significant variation of R^2 and the R^2 adjusted can be found (Myer and Montgomery 2002).

Table 8.1: Lower and Upper limit of each variable

Variable	**Lower Limit**	**Upper Limit**
Surface Moisture Content (A)	11	22
Core Moisture Content (B)	7.5	15
Surface Resin Content (C)	8	20
Core Resin Content (D)	5	13
Core Hardener Content (E)	1	3 % of Resin load
Pressing Time (F)	120	300 Seconds
Press Temperature (G)	150	200 ^{o} C

Table 8.2: Test statistical and coefficient used for MOR model

Term	**Co-eff**	**T**	**P**
Constant	11.429	210.70	0.003
Moisture Surface	-0.476	-8.39	0.075
Moisture Core	-1.067	-23.84	0.027
Resin Surface	1.541	27.72	0.023
Resin Core	1.634	36.51	0.017
Hardener Core	-0.584	-13.04	0.049
Pressing Time	0.952	21.27	0.030
Press Temperature	0.967	21.60	0.029
Moisture Surface*Moisture Core	-1.228	-27.43	0.023
Moisture Surface*Resin Surface	0.191	4.27	0.147
Moisture Surface*Hardener Core	-0.742	-16.58	0.038
Moisture Surface*Pressing Time	-0.198	-4.42	0.142
Moisture Surface*Press Temperature	0.165	3.69	0.168
Moisture Core*Resin Core	0.238	5.33	0.118
Moisture Surface*Moisture Core* Resin Core	-0.667	-14.91	0.043

The regression method used in this calculation was discussed in detail in the section 5.4 of the Chapter 5. The validity of the second order polynomial function for this investigation was explained in section 8.2.1. The MINITAB software calculates the regression for coded variables as well as un-coded variables. The model presented here was developed using coded variables and should use only coded variables as factors. If the model is developed using the un-coded variables, that model can be used with variables with the same units. Since this work uses the Celsius temperature scale, un-coded models cannot be used for data with Fahrenheit temperature scale. If the model is developed for coded data, then it is not dependent on the unit of the parameter but only on the parameter range. The difference between coded and un-coded variables was explained in Chapter 5.

$$MOR = 11.429 - 0.476*A - 1.067*B + 1.541*C + 1.634*D - 0.584*E + 0.952*F + 0.967*G - 1.228*A*B + 0.191*A*C - 0.742*A*E - 0.198*A*F + 0.165*A*G + 0.238*B*D - 0.667*A3*B3*D3$$

Equation 8.2

Where:

A = Surface moisture content
B = Core moisture content
C = Surface resin load (with respect to dry residue wt)
D = Core resin (with respect to dry residue wt)
E = Hardener (core- with respect to resin load)
F = Pressing time
G = Press temperature (Note: all the variables are in coded units.)

The coded variables and the method of calculating them were explained in Chapter 5. The upper and the lower limit used to calculate the coded unit are given in Table 8.1. Results used for regression analysis was Tabulated in Table 7.2. The calculated regression coefficients for significant factors (Regressor variables) with respect to the MOR model are given in Table 8.2. These coefficients are calculated considering the coded variables. The P and T values for those major effects are also tabulated in the same table. Incorporating these regression coefficients, the process model for MOR can be compiled as in Equation 8.2. The regression method used in this calculation was discussed in detail in the section 5.4 of the Chapter 5. The validity of the second order polynomial function for this investigation was explained in section 8.2.1.

8.3.1 Significance of the developed model

For estimation of the significance of the model, ANOVA was calculated (Table 8.3). It shows that the main effects and three-way interactions are the most important effects on MOR with $P<0.05$. The two-way interactions which are considered here are very significant with $P < 0.05$. The model has fifteen degrees of freedom (DF = 15) which includes main effects, two-way interactions, three-way interactions and the error term. Table 8.3 shows that the sum of squares (SS) of mean squares (MS) of the error term is negligible compared to those for main effects or interactions which are considered in the MOR model. Therefore, the error term can be ignored into the model. In addition, R^2 was calculated with regard to the model. R^2 measures the amount of reduction in the variability of y obtained by using the regression variables (Equation 5.12). It was found that the calculated R^2 >99.00% and the adjusted R^2 > 99.98%. As discussed in Chapter 5, there is no significant variation between R^2 and the adjusted R^2. Therefore, it can be suggested that this model will adequately predict the MOR of final particleboard using the current production process. However, a large value of R^2 does not necessarily imply that the developed regression model is a good one which predicts the process correctly unless it is tested with further experiments. Therefore, the next section describes the experimental validation of the model and the method used to select the processing parameters to prepare the test boards. In the meantime, this model will be used to optimise the MOR of the board.

Table 8.3: Analysis of Variance for MOR (coded units)

Source	**DF**	**SS**	**MS**	**F**	**P**
Main Effects	7	122.698	17.5283	547.06	0.033
2-Way Interactions	6	35.482	5.9137	184.57	0.056
3-Way Interactions	1	7.124	7.1236	222.33	0.043
Residual Error	1	0.032	0.0320		
Total	15	165.336			
Where: SS = sum of squares MS = mean squares					

Table 8.4: Manufacturing variables and corresponding coded values

Board Numb	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**A**	**B**	**C**	**D**	**E**	**F**	**G**
1	17.5	9	20	11	0	180	195	0.1818	-0.6	1	0.5	-2	-0.333	0.8
2	13	9	17.5	11	0	300	195	-0.636	-0.6	0.5833	0.5	-2	1	0.8
3	22	9	17.5	11	0	300	195	1	-0.6	0.5833	0.5	-2	1	0.8
4	17.5	9	20	11	0	300	195	0.1818	-0.6	1	0.5	-2	1	0.8
5	13	9	20	11	0	240	195	-0.636	-0.6	1	0.5	-2	0.3333	0.8
6	22	9	15	11	0	240	195	1	-0.6	0.1666	0.5	-2	0.3333	0.8
7	22	9	20	11	0	240	195	1	-0.6	1	0.5	-2	0.3333	0.8
8	17.5	9	17.5	11	0	240	195	0.1818	-0.6	0.5833	0.5	-2	0.3333	0.8
9	13	9	17.5	11	0	180	195	-0.636	-0.6	0.5833	0.5	-2	-0.333	0.8
10	17.5	9	17.5	11	0	240	195	0.1818	-0.6	0.5833	0.5	-2	0.3333	0.8
11	17.5	9	15	11	0	300	195	0.1818	-0.6	0.1666	0.5	-2	1	0.8
12	13	9	15	11	0	240	195	-0.636	-0.6	0.1666	0.5	-2	0.3333	0.8
13	22	9	17.5	11	0	180	195	1	-0.6	0.5833	0.5	-2	-0.333	0.8
14	17.5	9	15	11	0	180	195	0.1818	-0.6	0.1666	0.5	-2	-0.333	0.8
15	17.5	9	17.5	11	0	240	195	0.1818	-0.6	0.5833	0.5	-2	0.3333	0.8
16	19	9	20	11	1	300	200	0.4545	-0.6	1	0.5	-1	1	1
17	18	9	20	13	1	210	200	0.2727	-0.6	1	1	-1	0	1
18	19	9	20	11	1	240	190	0.4545	-0.6	1	0.5	-1	0.3333	0.6

Table 8.5: Actual and Model predicted values for MOR and MOE

Board Number	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**MOR**	**MOR model-1**	**Error % model-1**	**MOR model-2**	**Error % model-2**	**MOE**	**MOE(model)**	**Error**
1	17.5	9	20	11	0	180	195	17.84	16.42	7.95	16.33	8.44	2994.98	2781.359	7.13%
2	13	9	17.5	11	0	300	195	14.62	15.28	-4.49	15.37	-5.13	2534.57	2692.03	-6.21%
3	22	9	17.5	11	0	300	195	16.91	18.69	-10.57	18.55	-9.71	2952.87	3156.16	-6.88%
4	17.5	9	20	11	0	300	195	19.49	17.64	9.47	17.60	9.68	3118.6	3022.765	3.07%
5	13	9	20	11	0	240	195	16.54	15.15	8.40	15.38	7.03	2724.93	2731.082	-0.23%
6	22	9	15	11	0	240	195	15.74	17.47	-11.0	17.27	-9.76	2897.63	2913.543	-0.55%
7	22	9	20	11	0	240	195	17.24	18.92	-9.73	18.56	-7.65	2991.38	3073.043	-2.73%
8	17.5	9	17.5	11	0	240	195	18.39	16.38	10.95	16.33	11.22	2648.58	2803.392	-5.85%
9	13	9	17.5	11	0	180	195	16.24	13.84	14.78	14.10	13.18	2728.3	2534.951	7.09%
10	17.5	9	17.5	11	0	240	195	15.11	16.38	-8.38	16.33	-8.05	2720.88	2803.392	-3.03%
11	17.5	9	15	11	0	300	195	17.71	16.33	7.79	16.32	7.86	2878.52	2825.425	1.84%
12	13	9	15	11	0	240	195	15.27	13.97	8.53	14.093	7.71	2554.87	2495.9	2.31%
13	22	9	17.5	11	0	180	195	18.08	17.69	2.14	17.283	4.41	2990.65	2830.427	5.36%
14	17.5	9	15	11	0	180	195	14.63	15.11	-3.28	15.05	-2.87	2671.91	2584.018	3.29%
15	17.5	9	17.5	11	0	240	195	16.56	16.37	1.11	16.33	1.41	2606.79	2803.392	-7.54%
16	19	9	20	11	1	300	200	16.83	17.52	-4.10	17.40	-3.40	2890.00	3002.454	-3.89%
17	18	9	20	13	1	210	200	18.53	17.16	7.39	17.03	8.07	3070.63	2801.036	8.78%
18	19	9	20	11	1	240	190	15.68	16.53	-5.41	16.38	-4.47	2822.87	2793.616	1.04%

8.3.2 Validating the MOR

After generating the model equations to relate the dependent and independent variables, the validity of the model was checked with further experiments. Several particleboards were manufactured in the laboratory in order to validate the model and to improve the MOR simultaneously, considering the developed model. Also, the developed particleboard recipe shows that it requires higher amounts of resin and moisture for the surface layer of three-layer particleboard compared to the industrial recipe for softwood particleboards (Chapter 7).

As discussed in Chapter 7, moisture is a critical variable that needs to be controlled carefully for better compaction of the wood mat. In addition, moisture is the main medium that transports heat from the surface to the core of the board. However, moisture as an individual variable has a negative effect on the rigidity of the board (MOE). Also, the findings in Chapter 7 indicated that the surface layer should use higher amounts of moisture and resin and the core layer should use lower moisture and resin amounts while keeping other parameters constant to optimise properties. Therefore, further particleboards were manufactured with reduced moisture and resin for the core layer while using higher amounts of moisture and resin for the surface layer. Further, the resultant MOR of these boards will be used to compare with the model's predicted MOR. As stated in Chapter 7, hardener has a significant negative impact on almost all the tested mechanical properties of hardwood particleboard. In addition, the combination of surface moisture with hardener core has a negative impact on MOR. Hence, new boards were manufactured with and without adding hardener to the core to check the behaviour of the final particleboards.

The manufacturing parameters were selected in order to optimise particleboard properties considering the above factors. The final optimal experimental parameters were calculated using the developed model for MOR, which allows comparison and negotiation of the response (MOR) with the processing parameters and the combination of them to optimise the response. Further, it was checked whether these factor levels would produce particleboards with higher MOE. The selected manufacturing variables and the coded values for the actual values for the variables are tabulated in Table 8.4. When these particleboards were manufactured, their MOR values were tested and tabulated in Table 8.4. The predicted MOR values by Equation 8.2 are labelled as 'MOR (model 1)' data in the Table 8.5.

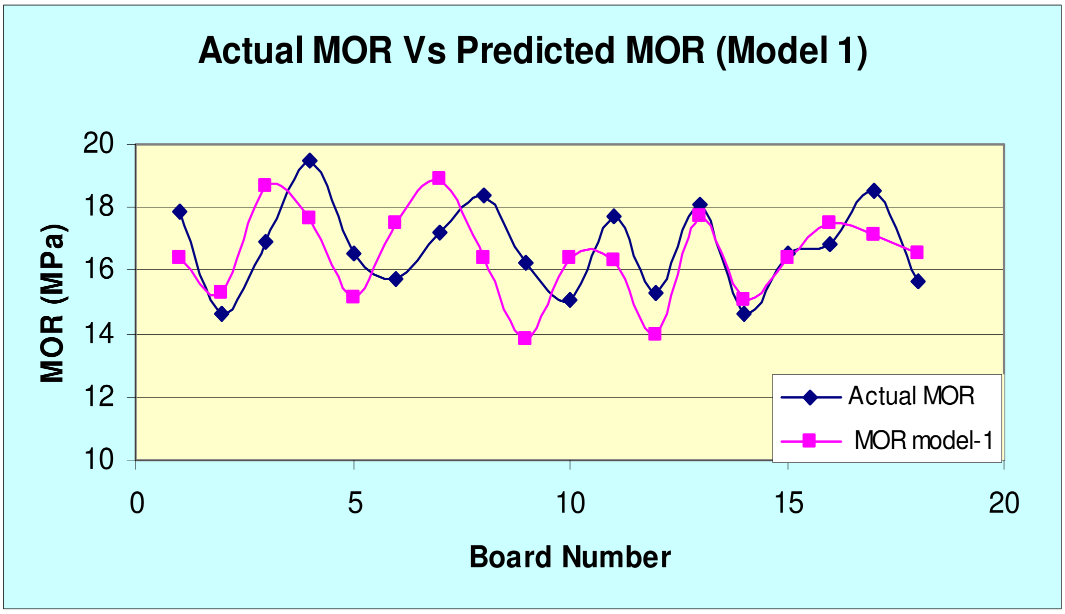


Figure 8.1: Actual MOR Vs Predicted MOR (model 1) as predicted by Equation 8.2

Figure 8.1 compares the actual MOR values for the manufactured boards with the model predicted values. It shows that the process model represented by Equation 8.2 closely predicted the actual MOR of a particleboard. Also, Table 8.5 shows that Equation 8.2 predicts the actual MOR with less than 15% variation. Experimental and predicted values of 80% of the boards differ less than 10% (Board numbers 3, 6, 8 and 10 in the Table 8.5). That variation could be due to an error in the model. As stated earlier it was hypothesised that selecting less significant effects may have added some error to the model. Therefore, it may be reasonable to remove some of the less significant effects from the model. This removal was done one by from least significant effect until achieving best possible prediction. It was found that removing 'Moisture surface * Press Temperature' and 'Moisture surface * Pressing Time' from the model, had increased the model accuracy. Further removal of less significant factors such as 'moisture core * resin core' did not affect the model accuracy or decrease the accuracy. Therefore that hypothesis was included in reducing the number of factor effects to develop the MOR - model 2 given in Equation 8.3. The sensitivity of the model was tested by calculating R^2 and R^2 adjusted and found to be at 99%. Therefore, the model 2 also should accurately predict the MOR.

The predicted MOR values with respect to the same variables are also tabulated in Table 8.5 labelled 'MOR model-2'. The margins of errors are also tabulated in the same table, labelled with 'error model 2'. It shows that the margin of error has reduced when less significant effects were avoided in the model. It also shows that the MOR model-2 predicts the actual MOR values correctly, with more than 87% accuracy.

$$MOR = 11.429 - 0.476*A - 1.067*B + 1.541*C + 1.634*D - 0.584*E + 0.952*F + 0.967*G - 1.228*A*B - 0.742*A*E + 0.238*B*D - 0.667*A*B*D \quad \text{Equation 8.3}$$

Where:

A = Surface moisture content
B = Core moisture content
C = Surface resin load (with respect to dry residue wt)
D = Core resin (with respect to dry residue wt)
E = Hardener (core- with respect to resin load)
F = Pressing time
G = Press temperature (Note: all the variables are in coded units.)

8.4 Predicting MOE with respect to processing parameters

Similar to the process model development for MOR, the significant effects regarding the particleboard MOE were identified. As discussed in Chapter 7, MOE is mainly dependent on six effects which have $P < 0.05$ in Table 7.3. In addition, effects which generally have significant effect on most properties were also considered. Any effect with less significant effect on MOE, may have a higher effect on another parameter. Therefore, during the process optimisation, those effects become a variable. Therefore, effects with minor effect on MOE ($P < 0.15$) were also considered for MOE model building. However, adding minor effects or non-significant variables may decrease the validity of the model by increasing the error term as discussed earlier. The R^2 and the R^2 adjusted was calculated and compared to check the variation as discussed in Chapter 5. If $R^2 >> R^2$ adjusted, it warns that those non-significant effects would create a significant error in the model. The effects that were considered for the model and their regression coefficients are tabulated in Table 8.6.

Table 8.6: Estimated Effects and Coefficients for MOE (coded units)

Term	**Co-eff**	**T**	**P**
Constant	2080.9	136.48	0.005
Moisture Surface	34.7	2.90	0.211
Moisture Core	-124.2	-0.39	0.061
Resin Surface	246.9	20.67	0.031
Resin Core	82.7	6.92	0.091
Hardener Core	-128.4	-0.75	0.059
Pressing Time	167.0	13.98	0.045
Press Temperature	155.2	12.99	0.049
Moisture Surface*Moisture Core	-182.9	-5.31	0.042
Moisture Surface*Resin Surface	-55.5	-4.65	0.135
Moisture Surface*Resin Core	43.7	.65	0.170
Moisture Surface*Pressing Time	77.3	.47	0.098
Moisture Surface*Press Temperature	66.0	.52	0.114
Moisture Core*Resin Core	54.1	.53	0.138
Moisture Surface*Moisture Core* Resin Core	-65.4	-5.47	0.115

$$MOE = 2080.9 + 34.7*A - 124.2*B + 246.9*C + 82.7*D - 128.4*E + 167*F + 155.2*G - 182.9*A*B - 55.5*A*C + 43.7*A*D + 77.3*A*F + 66*A*G + 54.1*B*D - 65.4*A*B*D$$

Equation 8.4

Where:

A = Surface moisture content
B = Core moisture content
C = Surface resin load (with respect to dry residue wt)
D = Core resin (with respect to dry residue wt)
E = Hardener (core- with respect to resin load)
F = Pressing time
G = Press temperature (Note: all the variables are in coded units.)

The Upper and Lower limits used to calculate the coded unit for the MOE model are given in Table 8.1. Results used for this analysis was included in Table 7.2. The calculated regression coefficients for significant factors (Regressor variables) with respect to the MOE model are given in Table 8.6. These coefficients are calculated considering the coded variables. The P and T values for those major effects are also tabulated in the same table. Incorporating these regression coefficients, the process model for MOE can be presented as in equation 8.4. The regression method used in this calculation was discussed in detail in the section 5.4 of the Chapter 5. The validity of the second order polynomial function for this investigation was explained in section 8.2.1.

8.4.1 Significance of the developed model

For estimation of the significance of the model, the ANOVA was calculated (Table 8.7). It shows that the main effects and two-way interactions are the most important effects on MOR with $P<0.1$. One variable with a three-way interaction is considered although its' $P > 0.1$. The model has fifteen degrees of freedom (DF=15) which include main effects, two-way interactions, three-way interactions and the error term. Table 8.7 shows that the SS of MS of the error term is negligible compared to those for main effects or interactions which are considered in the MOE model. Therefore, the error term was ignored in the model. In addition, R^2 was calculated with regard to the model.

Table 8.7: Analysis of Variance for MOE (coded units)

Source	**DF**	**SS**	**MS**	**F**	**P**
Main Effects	7	2446934	349562	152.99	0.062
2-Way Interactions	6	827259	13786	60.34	0.098
3-Way Interactions	1	68487	68487	29.97	0.115
Residual Error	1	2285	2285		
Total	15	3344965			
SS = sum of squares		MS = mean squares			

The calculated $R^2 > 99.93\%$ as well as the adjusted $R^2 > 98.98\%$ were found. As discussed in Chapter 5, there is no significant variation to R^2 if the adjusted R^2 is calculated. Therefore, it can be suggested that this model will adequately predict the MOE of final particleboard using the current production process. As discussed earlier, a large value of R^2 does not necessarily imply that the developed regression model is a good one which predicts the process correctly unless it is tested with further experiments.

8.4.2 Validating the MOE

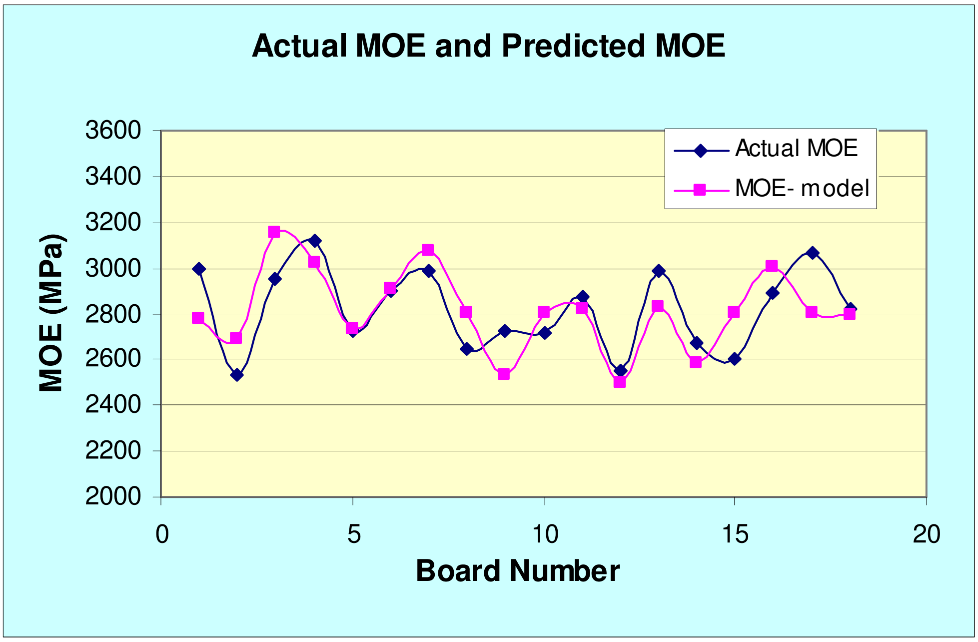


Figure 8.2: Actual MOE vs Predicted MOE

After generating the MOE model equation to predict the MOE of a particleboard, the validity of the model was checked with further experiments. The same experimental data used to validate MOR model were used to check the MOE model. Table 8.5 shows the resulting MOE values of the particleboards as well as the predicted MOE values from Equation 8.4 and the error. It shows that Equation 8.4 sufficiently predicts the MOE of a particleboard with less than 9% variation. Figure 8.2 shows actual and predicted MOE values against the board number. As the variation is very minor, this model should not require any corrections and can be used as it is to predict the MOE.

8.5 Optimising the MOE and MOR

The other objective of this study is to optimise the MOE and MOR values of a particleboard using the process model. As stated in Section 8.3.2, particleboard recipes were selected here considering the developed models with the intention of optimising the particleboard properties. According to AS/NZS 1859 (2004), standard general purpose particleboards need to satisfy three main properties. They are, MOR, IB and thickness-swelling.

Therefore, the equation 8.2 was used to find the best of all possible solutions for MOR in the feasible region which was recognized for these experimentations. Also, resin and pressing time are the main process parameters which contribute for the production cost. Therefore, objective of this optimization was to obtain higher MOR and MOE value by controlling the production cost. This optimization was base on experimental design. As explain in Chapter 7, hardener has a negative impact on most of the particleboard properties. Therefore, it was looked what the efficient amount of hardener could be used when obtains higher MOR and MOE. Considering these factors, experiments were design as in Table 8.5 and resultant board properties are tabulated in Table 8.8.

Table 8.8: Particleboard properties and AS/NZS 1859 (2004)

Board No	**MOR (MPa)**	**MOE (MPa)**	**IB (kPa)**
1	17.84	2994.98	828.41
2	14.62	2534.57	1162.90
3	16.91	2952.87	861.14
4	19.49	3118.60	1298.94
5	16.54	2724.93	1198.31
6	15.74	2897.63	1239.10
7	17.24	2991.38	1038.87
8	18.39	2648.58	1302.58
9	16.24	2728.30	1256.58
10	15.11	2720.88	1058.97
11	17.71	2878.52	1368.25
12	15.27	2554.87	708.66
13	18.08	2990.65	908.38
14	14.63	2671.91	1220.61
15	16.56	2606.79	1157.96
Mean Strength	16.69	2801.03	1107.31
AS/NZS1859 (2004) for High Performance Particleboards	16.00	2400.00	400.00
AS/NZS1859 (2004) for General Purpose Particleboards	12.00	Not a requirement	300.00

Table 8.8 shows the properties of particleboards with respect to board numbers (The processing parameters for these relevant boards were tabulated in Table 8.5), mean of each property as well as the minimum requirements set by the AS/NZS 1859 (2004) for general purpose particleboard and high performance particleboard. Table 8.8 shows that hardwood particleboards can be developed in our laboratory set-up using hardwood sawmill wastes. It shows that the MOE data for the developed particleboards were always higher than 2500 MPa. According to AS/NZS 1859 (2004), MOE is not a significant property for standard general purpose particleboards, but it is an important property for high performance particleboard and the expected value is 2400 MPa. MOR data for the developed particleboards are also higher than the AS/NZS 1859 (2004) requirements for general purpose particleboards with minimum MOR > 12MPa and mean MOR (= 16.43 MPa for those 15 boards) is higher than 16 MPa.

According to AS/NZS 1859 (2004), particleboards need to be tested for IB and moisture resistance. Therefore, the boards were tested for their IB and the results are tabulated in Table 8.8, which shows that the mean IB for those boards is higher than 300 kPa which is the AS/NZS requirements for general purpose particleboard. Also, mean of IB is higher than 400 kPa which is the requirement for high performance particleboard. The results of these optimised particleboards show that the MOR, MOE and IB of these boards easily satisfy the strength properties for general purpose particleboard and is an achievable target for high performance particleboards. However, the AS/NZS 1859 standards state that particleboard needs to be sufficiently moisture resistant in order for use as a general purpose board. Therefore, Chapter 10 explores the performance of these particleboards under different moisture conditions.

The formation of the VDP with respect to processing parameters was studied as part of this investigation. Chapter 9 discusses the variation of particleboard density along its thickness direction due to the variation of process variable. This variation in density in the thickness direction was used to predict the formation of VDP with regard to processing parameters and results are reported in Chapter 9.

8.6 Summary and Conclusions

Theories of experimental design and analysis were used for this product and process development. This methodology is a very efficient tool for extracting the maximum amount of complex information with the minimum number of experiments. Therefore, it reduces the material required for experiments and the time for experiment and analysis significantly.

Particleboards were tested for modulus of elasticity (MOE) and modulus of rupture (MOR) and results were statistically analysed using MINITAB 14. First, the significant process variables with respect to particleboard mechanical properties were found. Then process models for mechanical properties of the hardwood particleboard were developed considering the relationships between board properties and significant process variables. The reliability of the models was statistically tested it was and found that both models are very satisfactory. Further, the models for MOE and MOR successfully predict MOE and MOR respectively for both within the model developed range as well as in a robust data range.

CHAPTER 9

DEVELOPMENT OF COMPOSITE PROCESS MODELS TO PREDICT THE VERTICLE DENSITY PROFILE (VDP) OF A PARTICLEBOARD

9.1 Introduction

The density of a particleboard is not uniform along its thickness direction. This variation of density along the thickness direction of a particleboard is called the vertical density gradient or the vertical density profile (VDP). Kelly (1977) reported from previous research that the VDP of a particleboard is highly dependent upon particle configuration, moisture distribution in the mat, press closing speed, hot pressing temperature, and reactivity of the resin used and compressive strength of the wood component. As explained in Chapter 3 on the formation of the VDP, it influences many mechanical properties including MOE, MOR and IB as well as the dimensional stability of a particleboard. These properties are critical, depending upon the application of the final particleboard. Therefore, it is important to enhance or restrict the formation of the VDP by altering the above-mentioned processing variables to achieve the most critical property of the board. As explained in Chapter 3, there are number of stochastic and deterministic models available to predict the vertical density profile (Suchsland 1967; Dai at el 1997; Wolcott et al 1990; Length and Kamke 1995; Zombort 2001). Most of these models were formulated using fundamental engineering principles considering key interacting variables. Also, most of these models were developed for flake-type materials mainly from softwood particles. However, the material used in this study, was waste from hardwood timber and mainly contained particles with granular or cubical shapes. During the hot pressing, in granular type particles, the rates of temperature transfer from the surface to the centre as well as from the centre to the edges of the board were different to those of flake-type particles (Maku et al 1959). Therefore, the type of particle directly influences the formation of VDP.

As discussed earlier in Chapters 6, 7 and 8, process modelling using factorial experimental design was recognised to be useful to study the new material as well as for the variation of VDP of the final board. In this study, an attempt was made to model the VDP of a particleboard with respect to the processing variables. A process model clearly shows the relationship between the variation of density at different locations along the thickness of the board with the raw materials and processing parameters used. This chapter discusses the modelling of VDP with regard to the actual processing parameters which were used in this study. The usability of the model and its advantages for the improvement of final particleboard properties are discussed.

9.2 Methodology

Initially, particleboard thickness was divided into thin layers with a layer thickness as 10% of the final board thickness. Densities at each of these layers were investigated. In addition to the density at 10% length from the surface, density at a 5% length was investigated, because the density closer to the surface of a three-layer particleboard changes significantly near the surface (Figure 9.1). It was assumed that the VDP of a particleboard is symmetric about the centre of the particleboard. Therefore, the VDP of one half of the board was modelled initially and the other half was predicted considering the symmetry.

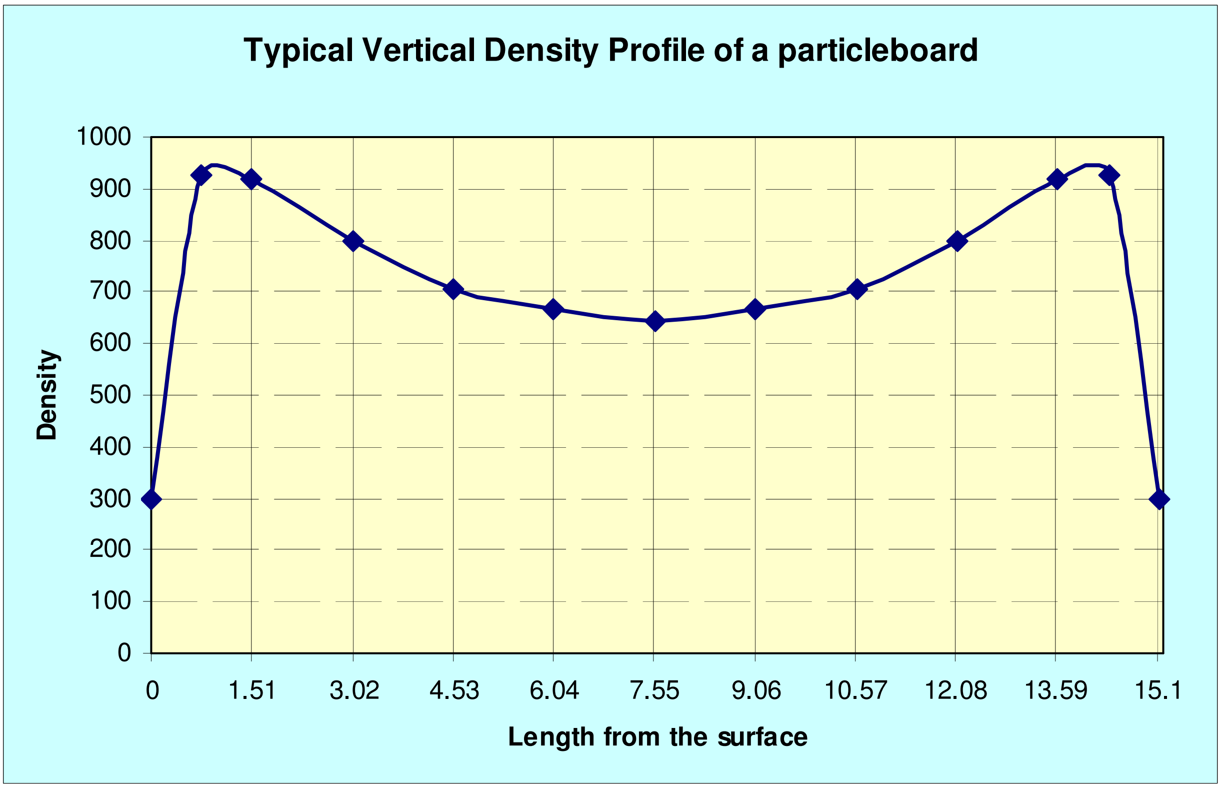


Figure 9.1: VDP along the thickness of a particleboard

The same experimental design as in Chapters 7 and 8 was used to collect the data for this study (Table 7.1). Once the particleboards were manufactured from the experimental design in Table 7.2, samples were prepared from each board to measure the VDP using a density profile-meter. The density profile-meter uses X-ray scanning to measure the density along the thickness of the test sample and stores the data as text files. From these data (Appendix C), the density of each layer was measured. These measured data against processing parameters for each board was tabulated and attached in Appendix F. Then, the most significant process variables with regard to layer density were identified using ANOVA, as was illustrated in Chapter 5 and used in Chapters 8. Then, regression coefficients were calculated for significant parameters to develop polynomial regression function to relate processing parameters to the density in the layer.

9.3 Identification of most significant parameters with regard to density along the thickness

Once the experimental density data for each layer were identified, they were analysed against processing variables to identify the most significant effect on the density of each layer. MINITAB software was used to calculate the T and P for each factor effect. As discussed in Chapter 5, any factor which has a significant effect on the testing property has a higher T value as well as a lower P value. Factors or interactions of factors with $P < 0.05$ have significant effects on the density. Table 9.1 shows the P values for significant factors on the density of each layer. It was assumed that second order polynomial function may describe the behaviour of density against processing parameters. This assumption will be tested by calculating regression coefficient for each model. If the coefficient is close to 100%, then model is sufficiently predicting the density for that layer, else second order polynomial function may not suitable for this prediction. As discussed in Chapter 5, a second order polynomial composite model should contain all the significant individual factors, interactions and a constant to predict the selected variable (Equation 9.1). It is clear from the data in Table 9.1 that adding a constant is significant for the model with $P \geq 0$.

In addition, densities for all the inner layers (where distance is higher than 10% of the thickness) were significantly affected by resin core, pressing time and the press temperature. These three factors are important for inter-particle bonding in the inner layers to increase the density. In addition, the interaction of moisture surface with moisture core significantly changes the density in internal layers of the board. By observing only the P, it is not possible to confirm whether this effect is positive or a negative. Therefore, Pareto charts were used to identify the type of effect on these variables and as explained in the following sections.

Table 9.1: The probability of null hypothesis (P) for significant parameters

Term	**P**						
Distance from the surface (% of thickness)	**5%**	**10%**	**20%**	**30%**	**40%**	**50%**	**Thick-ness**
Constant	0.001	0.000	0.000	0.000	0.000	0.000	0.000
Moisture Surface	0.016	0.006	0.884	0.010	0.001	0.011	0.023
Moisture Core	0.191	0.012	0.093	0.002	0.000	0.001	0.001
Resin Surface	0.107	0.109	0.026	0.092	0.001	0.002	0.012
Resin Core	0.059	0.006	0.002	0.000	0.000	0.000	0.030
Hardener Core	0.046	0.992	0.509	0.012	0.321	0.024	0.064
Pressing Time	0.061	0.008	0.001	0.000	0.000	0.001	0.000
Press Temperature	0.207	0.012	0.001	0.000	0.000	0.001	0.006
Moisture Surface*Moisture Core	0.042	0.048	0.006	0.025	0.000	0.001	0.003
Moisture Surface*Resin Surface	0.060	0.075	NS	NS	0.024	0.066	NS
Moisture Surface*Resin Core	0.041	0.017	0.069	0.222	NS	0.017	NS
Moisture Surface*Hardener Core	0.090	0.079	0.023	0.234	NS	0.014	NS
Moisture Core*Resin Core	0.053	0.021	0.200	0.154	0.001	0.01	NS
Moisture Surface * Pressing Time	NS	NS	NS	NS	NS	NS	0.003
Moisture Surface *Press Temperature	0.082	NS	0.072	0.006	0.007	0.003	0.028
Moisture Surface*Moisture Core* Resin Core	0.043	0.085	NS	NS	0.032	NS	0.113

9.3.1 Modelling the density at 10% x thickness from the board surface

Table 9.1 shows the factors significant for the density at 10% x thickness from the surface of the board. Those factors which have $P < 0.05$ have 95% probability of affecting the density at the point. The Pareto chart of those significant factors and their test statistical values are given in Figure 9.2. The test statistical value for 95% probability level is shown in red line with a value 4.3. Therefore, moisture surface (A), resin core (D), pressing time (F), moisture core (B), as well as interactions of moisture surface with resin core (AD), moisture core with resin core (BD), moisture surface with moisture core (AB) are significant for this layer density. Figure 9.3 shows the normal probability plot for these significant effects. It shows that moisture core and the interaction of moisture core with moisture surface have negative effects on the density, while the others have positive effects.

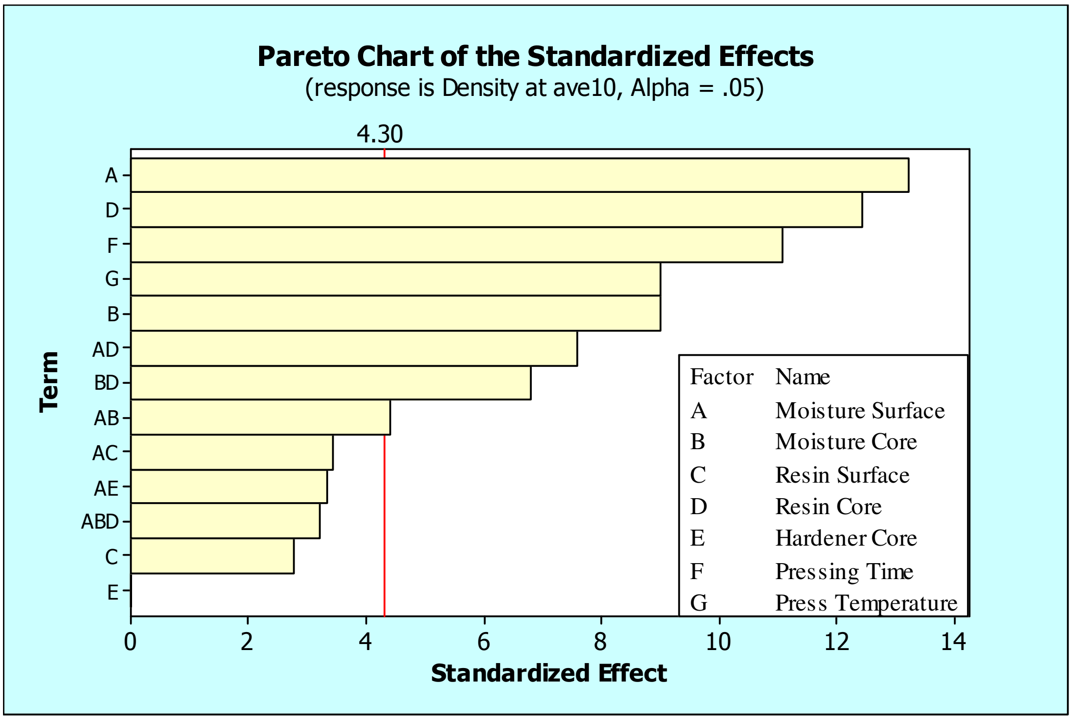


Figure 9.2: Pareto Chart of the Standardized effects

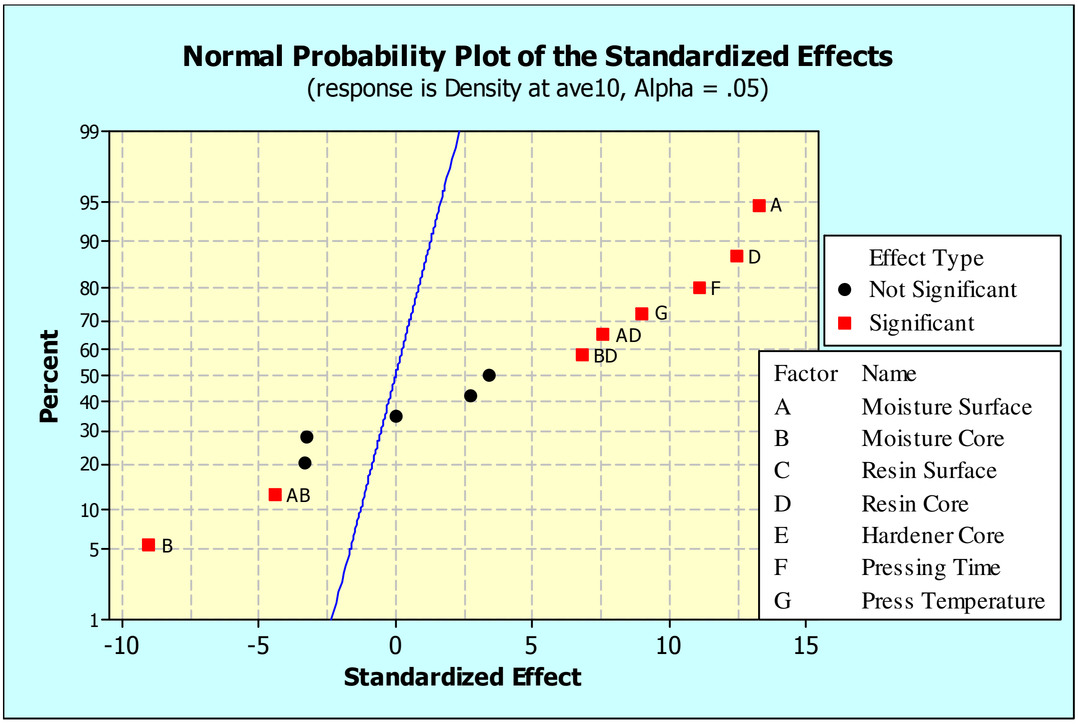


Figure 9.3: Normal probability plot of the Standardized effects

Once the most important factors affecting the density at 10% depth from the surface were identified, regression coefficients for these factors were calculated using MINITAB 14. These regression coefficients were calculated for coded variables as explained in Chapter 5 in order to make them independent of the dimension of the variable. Then, a model to predict the layer density from 10% x thickness from the surface was developed using these coded regression coefficients (Equation 9.1.).

$$\text{Density at 10\% x thickness from the surface} = 866.41 + 34.17*A - 23.26*B + 7.15*C + 32.13*D - 0.03*E + 28.58*F + 23.26*G - 11.36*A*C + 8.89*A*C + 19.56*A*D - 8.62*A*E + 17.54*B*D - 8.29*A*B*D \qquad \text{Equation 9.1}$$

Where:

A = Surface moisture content
B = Core moisture content
C = Surface resin load (with respect to dry residue wt)
D = Core resin (with respect to dry residue wt)
E = Hardener (core- with respect to resin load)
F = Pressing time
G = Press temperature (Note: all the variables are in coded units.)

9.3.1.1 Significance of the developed model

The ANOVA was calculated for the developed model to estimate its significance (Table 9.2). It shows that main effects and two-way interactions are more important with $P < 0.05$, and three-way interactions with $P < 0.10$. In addition, R^2 which measures the reduction in the variability of y which was obtained by regression variables was calculated with regard to the model. It was shown that $R^2 = 99.74\%$ and adjusted $R^2 = 98.08\%$. There is not a significant variation between R^2 and the adjusted R^2. Thus, as discussed in Chapter 5, it is concluded that the model will be adequately predict the density at the point. Therefore it can be suggested that equation 9.2 will adequately predict the density at 10% x thickness distance from the surface of the board under the current processing conditions. Also, second order multiple regression model appropriates for modelling the density at this depth of the particleboard.

After generating the model equation, its usability was tested against further experimental data. Density profile data from several particleboards were compared against actual density and results are shown in Figure 9.4 as well as in Table 9.3. These data have proven that the developed model can adequately predict the density at '10% x thickness from the surface' with less than 13% variation when the processing parameters are known.

Table 9.2: Analysis of Variance for Density at 10% thickness (coded units)

Source	**DF**	**SS**	**MS**	**F**	**P**
Main Effects	7	66400.2	9485.7	89.00	0.011
2-Way Interactions	5	15566.5	3113.3	29.21	0.033
3-Way Interactions	1	1100.0	1100.0	10.32	0.085
Residual Error	2	213.2	106.6		
SS = Sum of Squares	MS = Mean square				

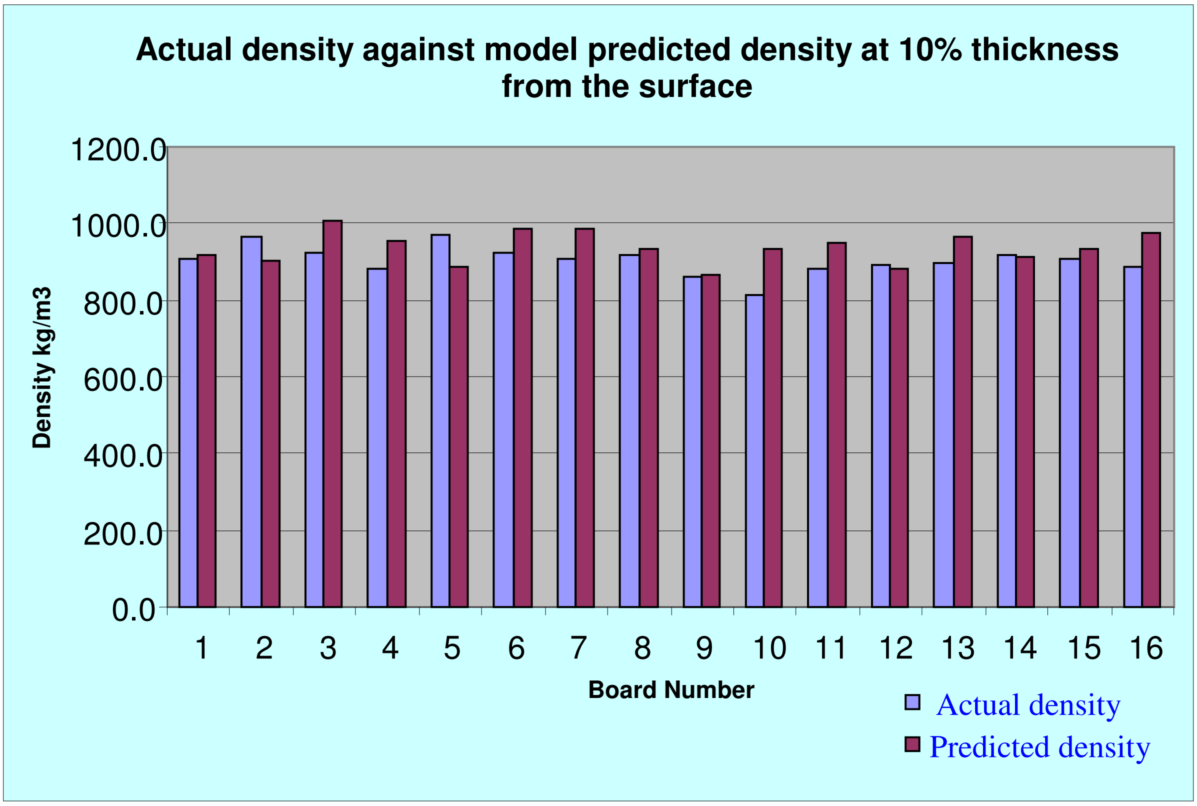


Figure 9.4: Actual density versus predicted density at '10% x thickness' distance from the surface

9.3.2 Modelling the density at '20% x thickness' distance from the board surface'

The same steps as in Section 9.3.1 were adopted to develop a model to predict at '20% x thickness' distance from the surface of the board. Table 9.1 shows the important parameters which affect the density at this layer with $P < 0.05$. Resin surface, resin core, press temperature, pressing time, a combination of moisture surface with moisture core, and a combination of moisture surface with hardener significantly influence the density at 20% x thickness distance (with $P < 0.05$). In addition to these six variables, a combination of moisture surface with press temperature, and of moisture surface with resin core were also considered for the model development because they too have smaller P values. Out of these important parameters, pressing time is the most significant factor followed by press temperature for the density at this level (Figure 9.5). However, a combination of moisture surface with moisture core and a combination of moisture surface with hardener core have significant negative effects on the density at this level (Figure 9.6) whereas pressing time, press temperature, resin core and resin surface have positive effects.

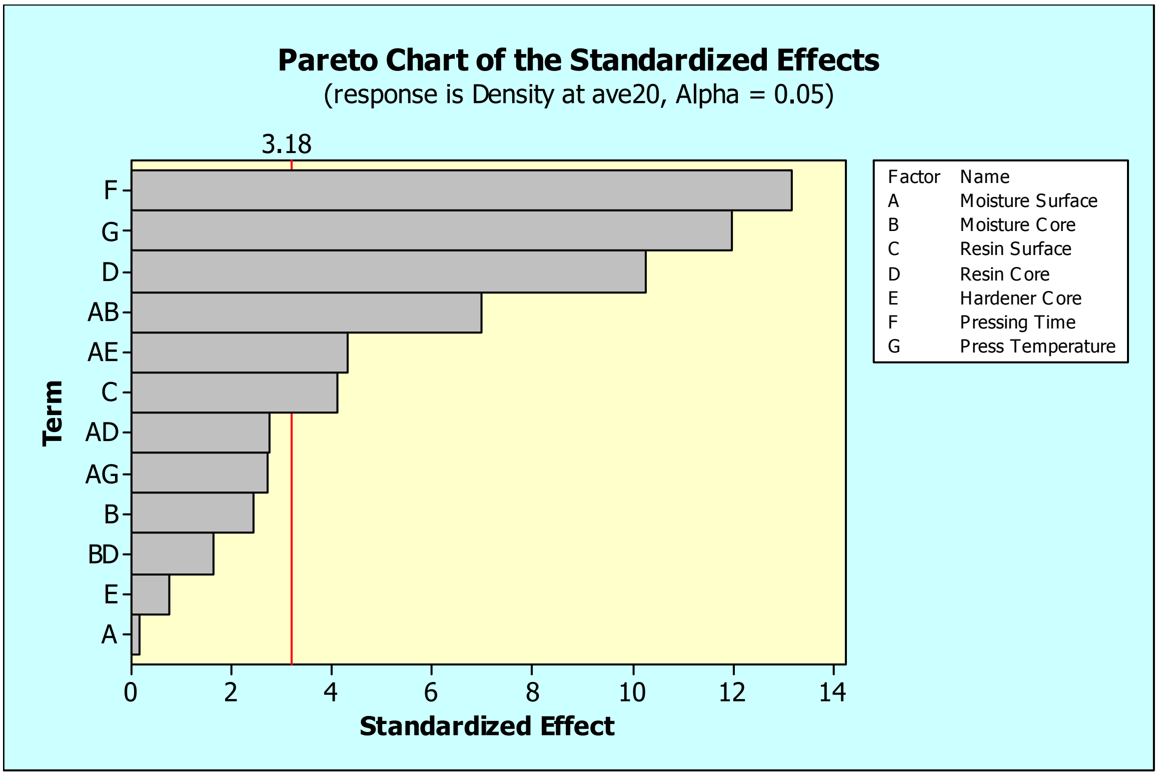


Figure 9.5: Pareto chart of the significant parameters for the density at 20% x thickness

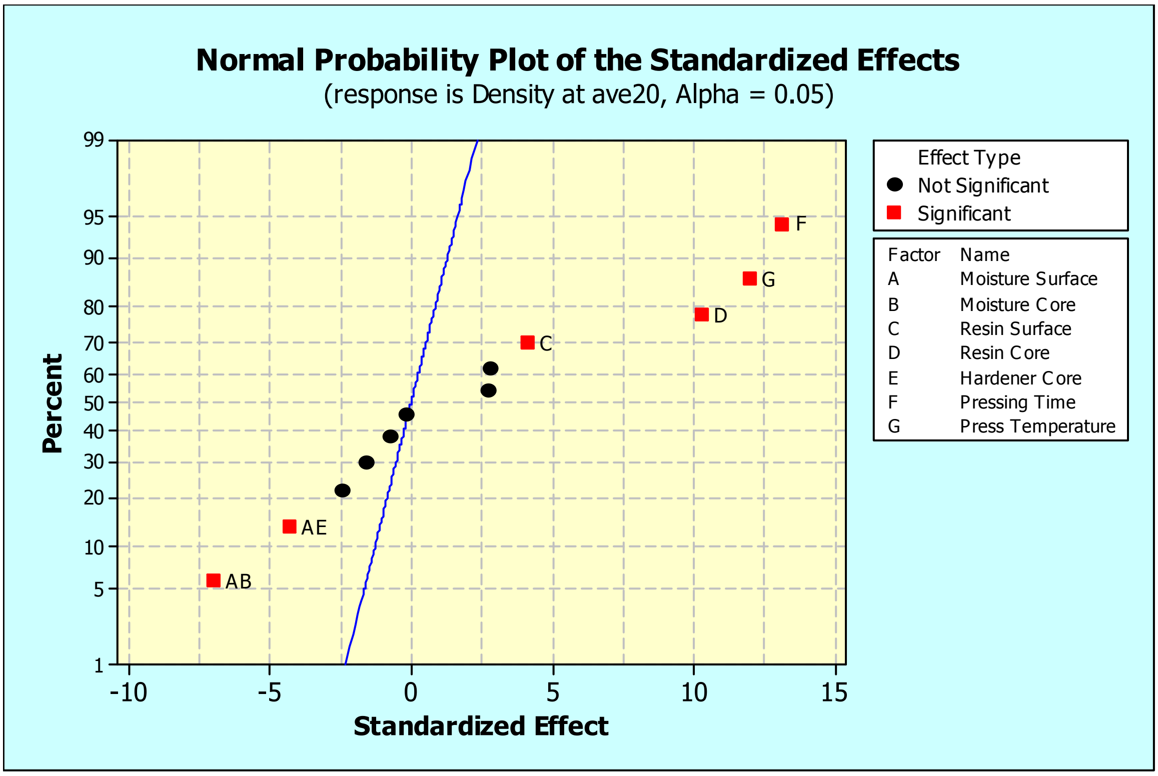


Figure 9.6: Normal probability plot of standardized effects for the density at 20% x thickness

After finding the important variables as well as their significance on density at '20% x thickness' distance from the surface, a polynomial regression model was developed incorporating these variables similar to Section 9.3.1 to predict the density at '20% x thickness' of the particleboard.

*Density at 20% x thickness from the surface = 701.11 - 0.76*A - 11.62*B + 19.57*C + 49.07*D - 3.51*E + 62.87*F + 57.14*G - 33.47*A*B + 13.25*A*D - 20.64*A*E + 5.64*A*F + 13.02*A*G - 7.81*B*D* Equation 9.2

Where:

A = Surface moisture content

B = Core moisture content

C = Surface resin load (with respect to dry residue wt)

D = Core resin (with respect to dry residue wt)

E = Hardener (core- with respect to resin load)

F = Pressing time

G = Press temperature (Note: all the variables are in the coded units.)

Table 9.3: Comparison of actual density and predicted density at each layer

Board Number	***Actual 5%**	**#Pred. 5%**	**Error**	**Actual 10%**	**Pred. 10%**	**Error**	**Actual 20%**	**Pred. 20%**	**Error**	**Actual 30%**	**Pred. 30%**	**Error**	**Actual 40%**	**Pred. 40%**	**Error**	**Actual 50%**	**Pred. 50%**	**Error**
1.0	939.6	926.2	-1.4	909.9	918.6	0.9	808.3	800.1	-1.0	715.4	705.4	-1.4	671.8	666.7	-0.8	669.1	642.2	-4.2
2.0	967.8	880.0	-10.0	963.9	903.0	-6.7	826.4	809.0	-2.2	744.3	784.9	5.2	681.6	722.8	5.7	681.4	712.5	4.4
3.0	916.0	996.5	8.1	924.1	1004.8	8.0	823.5	945.3	12.9	729.9	765.2	4.6	683.9	715.9	4.5	681.0	644.6	-5.7
4.0	942.8	943.3	0.1	880.0	956.7	8.0	808.7	885.3	8.6	700.0	776.9	9.9	659.3	724.5	9.0	614.6	686.7	10.5
5.0	1001.1	860.8	-16.3	972.9	887.6	-9.6	859.3	777.6	-10.5	738.4	751.0	1.7	705.6	700.3	-0.8	692.1	697.4	0.8
6.0	970.5	987.3	1.7	924.8	983.8	6.0	831.7	891.4	6.7	719.4	727.7	1.1	683.4	683.0	-0.1	676.7	613.1	-10.4
7.0	908.6	1008.7	9.9	908.3	987.7	8.0	796.4	907.7	12.3	728.1	731.3	0.4	693.8	690.9	-0.4	685.8	631.5	-8.6
8.0	908.6	929.7	2.3	918.4	934.9	1.8	806.4	834.5	3.4	708.5	739.3	4.2	694.3	690.4	-0.6	697.7	656.3	-6.3
9.0	816.5	842.7	3.1	861.5	864.9	0.4	781.0	729.9	-7.0	743.2	713.4	-4.2	684.9	665.0	-3.0	672.6	667.9	-0.7
10.0	751.4	929.7	19.2	816.2	934.9	12.7	798.4	834.5	4.3	709.5	739.3	4.0	662.8	690.4	4.0	657.2	656.3	-0.1
11.0	854.9	933.2	8.4	880.8	951.1	7.4	791.6	869.0	8.9	711.7	773.2	8.0	705.5	714.2	1.2	704.0	670.4	-5.0
12.0	899.3	861.9	-4.3	890.4	880.3	-1.2	834.1	761.3	-9.6	784.9	747.3	-5.0	702.3	687.6	-2.1	680.3	683.1	0.4
13.0	843.6	999.6	15.6	897.1	966.7	7.2	812.8	853.9	4.8	741.8	693.8	-6.9	704.7	658.1	-7.1	670.7	600.0	-11.8
14.0	931.3	916.1	-1.7	915.8	913.0	-0.3	800.1	783.8	-2.1	720.0	701.8	-2.6	681.4	656.4	-3.8	661.0	625.8	-5.6
15.0	851.6	929.7	8.4	908.8	934.9	2.8	826.1	834.5	1.0	745.2	739.3	-0.8	727.3	690.4	-5.3	728.2	656.3	-11.0
16.0	840.5	938.2	10.4	886.8	974.1	9.0	793.5	907.7	12.6	705.0	771.5	8.6	670.8	730.3	8.1	648.6	667.8	2.9

* Actual – Actual density # Pred. – Predicted density

9.3.2.1 Significance of the developed model

Table 9.4 Analysis of Variance for Density at 20% thickness (coded units)

Source	**DF**	**SS**	**MS**	**F**	**P**
Main Effects	7	162522	23217.4	63.64	0.003
2-Way Interactions	5	31238	6247.5	17.13	0.021
Residual Error	3	1094	364.8		
Total	15	194854			
SS = Sum of Squares	MS = Mean square				

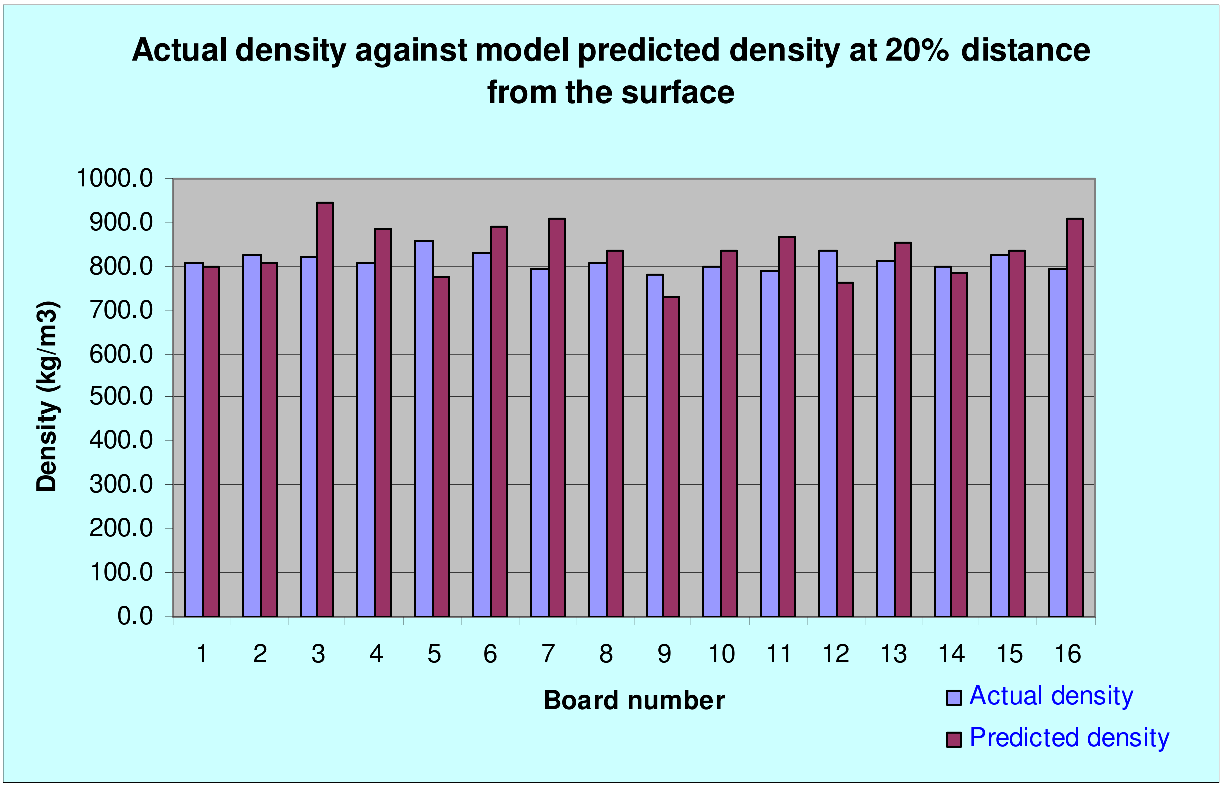


Figure 9.7: Actual density against the predicted density at 20% thickness level

Once the model was developed to predict the density at ‘20% x thickness distance from the surface’, the ANOVA for the model was calculated to test its significance (Table 9.4). It shows that main effects and two-way interactions are very significant for the model with $P < 0.05$. In addition, R^2 and R^2 adjusted were calculated to estimate the variability of the predicted density. Results show that $R^2 = 99.44\%$ and R^2 adjusted = 97.19%. Since there is not much variation between R^2 and the R^2 adjusted, this model adequately predicts the density at 20 % x thickness level of the particleboard. Then, the model was tested using the experimental results as shown in Table 9.3 and Figure 9.7. Figure 9.7 shows that the model closely predicts the density at this level of the particleboard with less than 13% variation (Table 9.2).

9.3.3 Modelling the density at '30% x thickness' distance from the board surface'

Similar to the factor screening discussed earlier, it was found moisture surface, moisture core, resin core, hardener core, press temperature, a combination of moisture surface with moisture core and a combination of moisture core with press temperature are significant for the density at 30% x thickness distance from the surface of a particleboard (Table 9.1 with $P < 0.05$). Of these variables, resin core is the most significant, followed by pressing time and press temperature for the density at this level (Figure 9.8). Figure 9.9 shows that these three variables have significant positive effect on the density at this depth of the board. Figure 9.9 shows that all the other variables; moisture core, moisture surface, hardener core, combining moisture surface with moisture core and combining moisture surface with press temperature have negative effects on the density at this level.

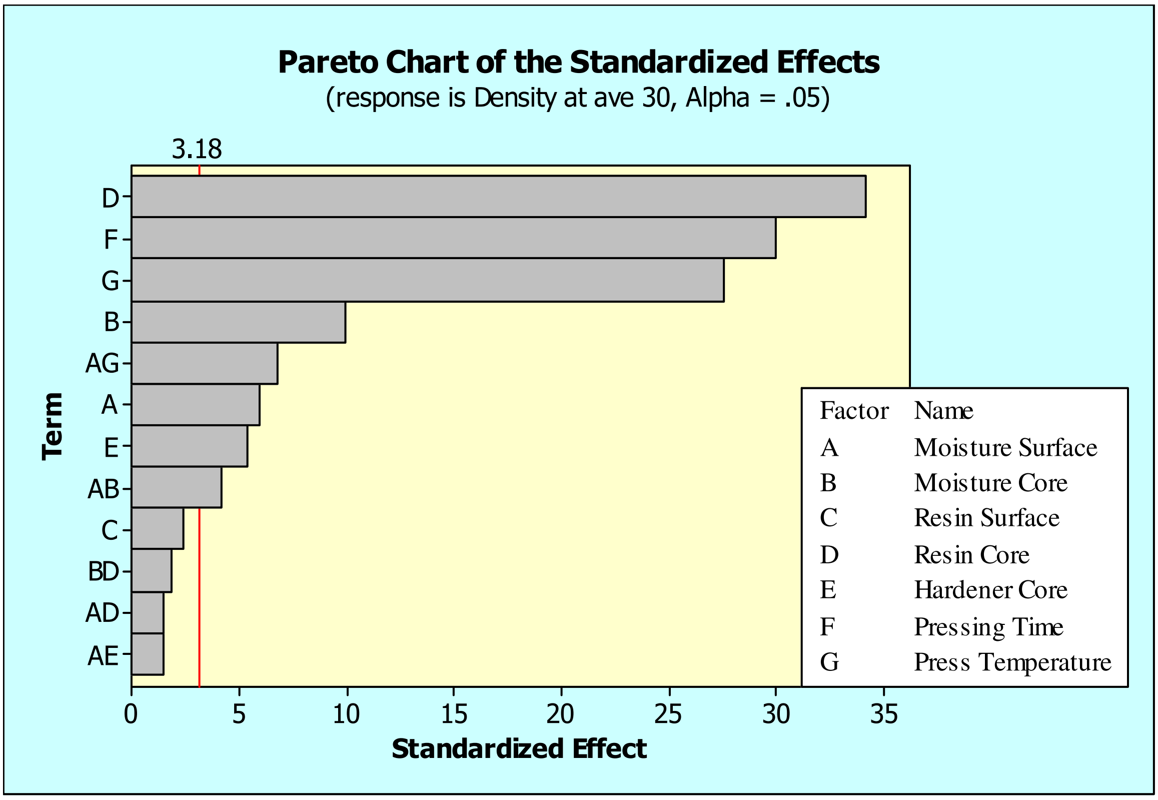


Figure 9.8: Pareto chart of the standardized effects on the density at 30% distance

Above variables have over 95% significance on the density at this depth. Figure 9.8 shows that resin surface, combining moisture core with resin core, moisture surface with resin core, moisture surface with hardener core have some effect on the density. Therefore, these variables were also considered for developing the Equation 9.3.

*Density at 30% from the surface = =620 - 10.61*A - 17.75*B+4.36*C + 61.11*D - 9.65*E + 53.58*F + 49.22*G - 7.41*A*B - 2.71*A*D - 2.63*A*E - 12.17*A*G + 3.4*B5*B5*

Equation 9.3

Where:

A = Surface moisture content
B = Core moisture content
C = Surface resin load (with respect to dry residue wt)
D = Core resin (with respect to dry residue wt)
E = Hardener (core- with respect to resin load)
F = Pressing time
G = Press temperature (Note: all the variables are in the coded units.)

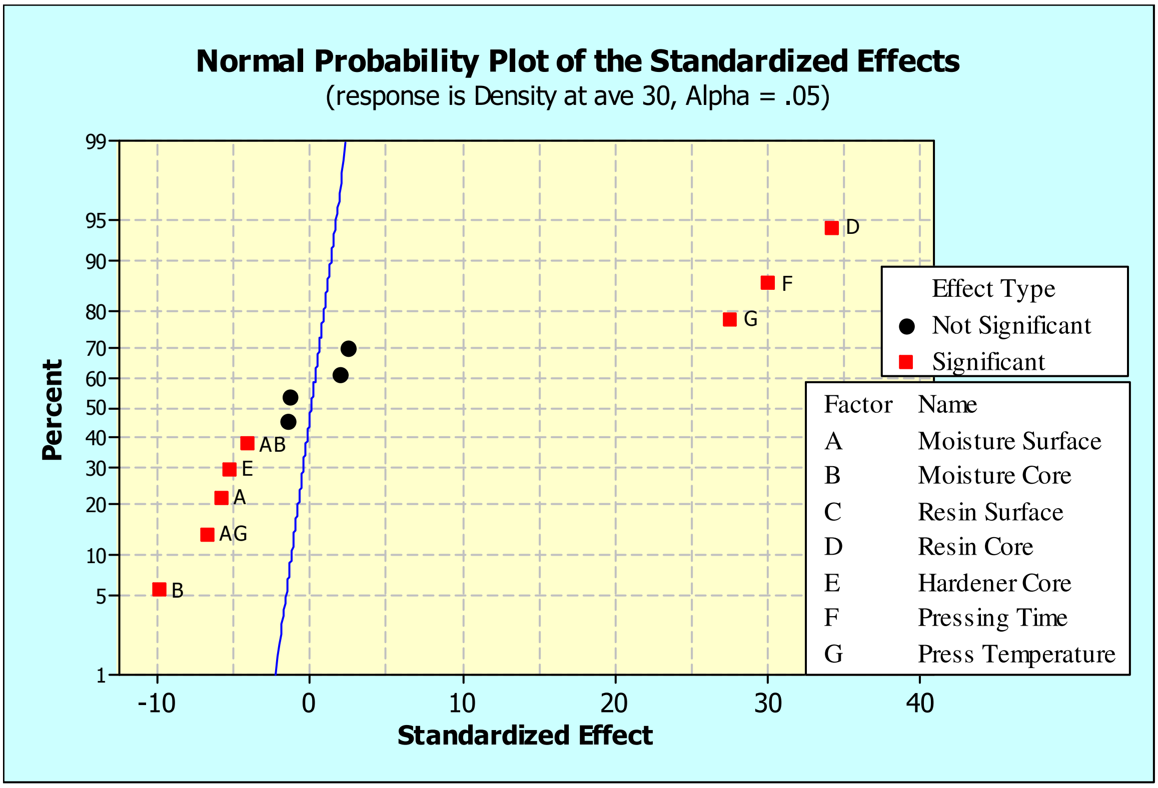


Figure 9.9: Normal probability plot of the standardized effects on the density at 30% distance

Therefore, both these negative as well as positive variables were considered for developing a regression model for the density. Similar to the work discussed earlier, regression coefficients were calculated with regard to these variables to develop the regression model in Equation 9.3.

9.3.3.1 Significance of the developed model

Similar to the work discussed earlier, ANOVA was calculated for the developed model to estimate its level of significance. It revealed that the model needs to consider the seven main effects, four two-way interactions and one three-way interaction effect to develop the model to predict the actual density precisely (Table 9.5). Table 9.5 shows that each of these variables has a $P < 0.05$. Therefore, the level of significance of these variables is more than 95%. Further, R^2 and R^2 adjusted were calculated for the model. For this model, $R^2 = 99.97\%$ and R^2 adjusted = 99.83%. This indicates that the model would adequately predict the density in a layer at '30% x thickness' level.

The reliability of the model was tested by comparing the density data predicted by the model with experimental data. As shown in Table 9.2 and Figure 9.10 the model accurately predicts the density at this level with less than 10% variation.

Table 9.5: Analysis of Variance for Density at 30% thickness (coded units)

Source	**DF**	**SS**	**MS**	**F**	**P**
Main Effects	7	153072	21867.4	427.79	0.000
2-Way Interactions	5	3665	733.0	14.34	0.026
Residual Error	3	153	51.1		
Total	15	156890			
SS = Sum of Squares	MS = Mean square				

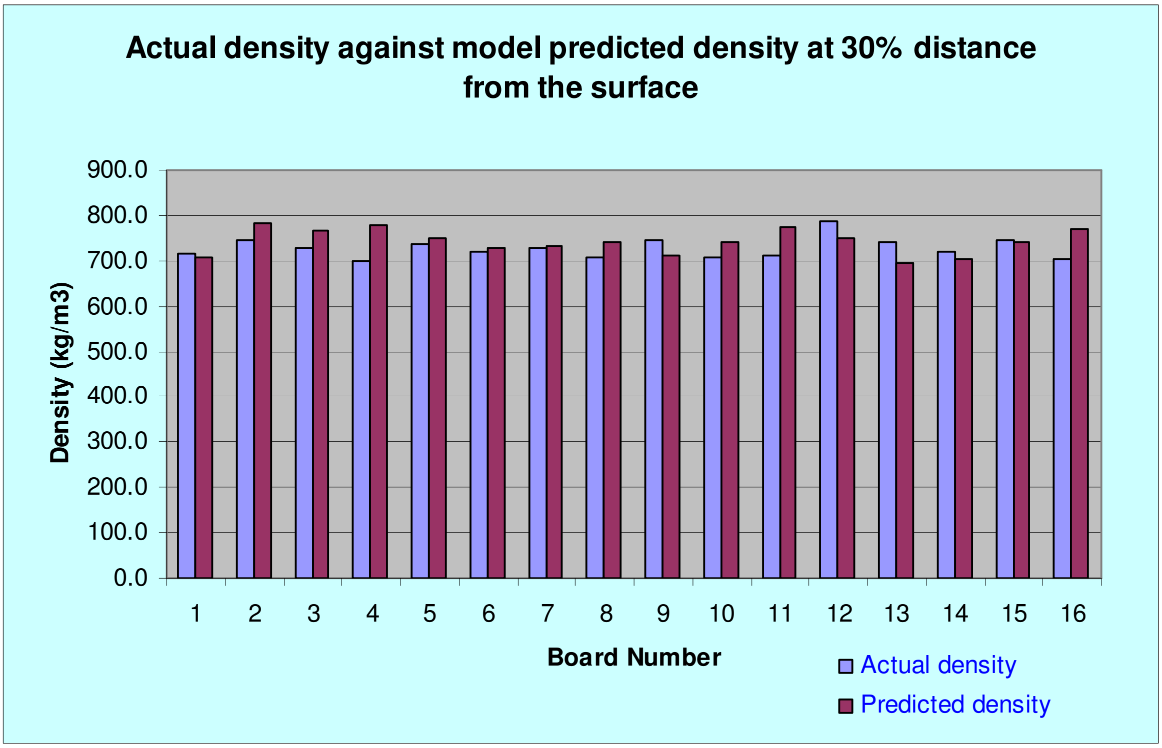


Figure 9.10: Actual versus predicted density at '30%xthickness' distance from the surface

9.3.4 Modelling the density at '40% x thickness' distance from the board surface

The significant factors for the density at '40% x thickness' distance from the surface of the particleboard were found to be resin core, pressing time, press temperature, moisture core, resin surface, moisture surface, a combination of moisture surface with moisture core, a combination of moisture core with resin core, a combination of moisture surface with press temperature, a combination of moisture surface with resin surface and a combination of moisture surface, moisture core and resin core (Figure 9.11 and Table 9.1 with $P < 0.05$).

Figure 9.12 shows that resin core, pressing time, press temperature, resin surface and a combination of moisture core with resin core have positive effects on the density at this level, while other variables have negative effect. Therefore, these variables and their effects were considered for the development of the polynomial equation to predict the density. MITAB was used to calculate regression coefficients with regard to these variables at 95% significant level. Equation 9.4 presents the polynomial regression equation developed to predict the density at this level of the particleboard.

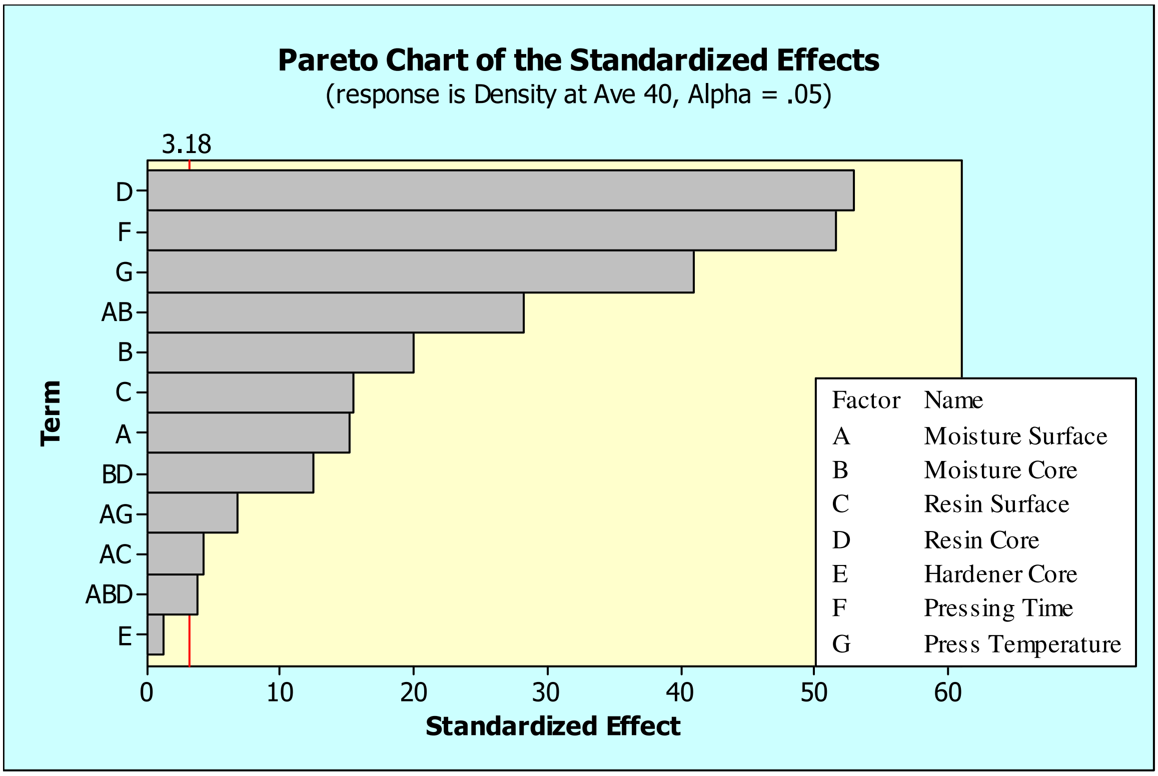


Figure 9.11: Pareto chart of the significant parameters for the density at 40% x thickness

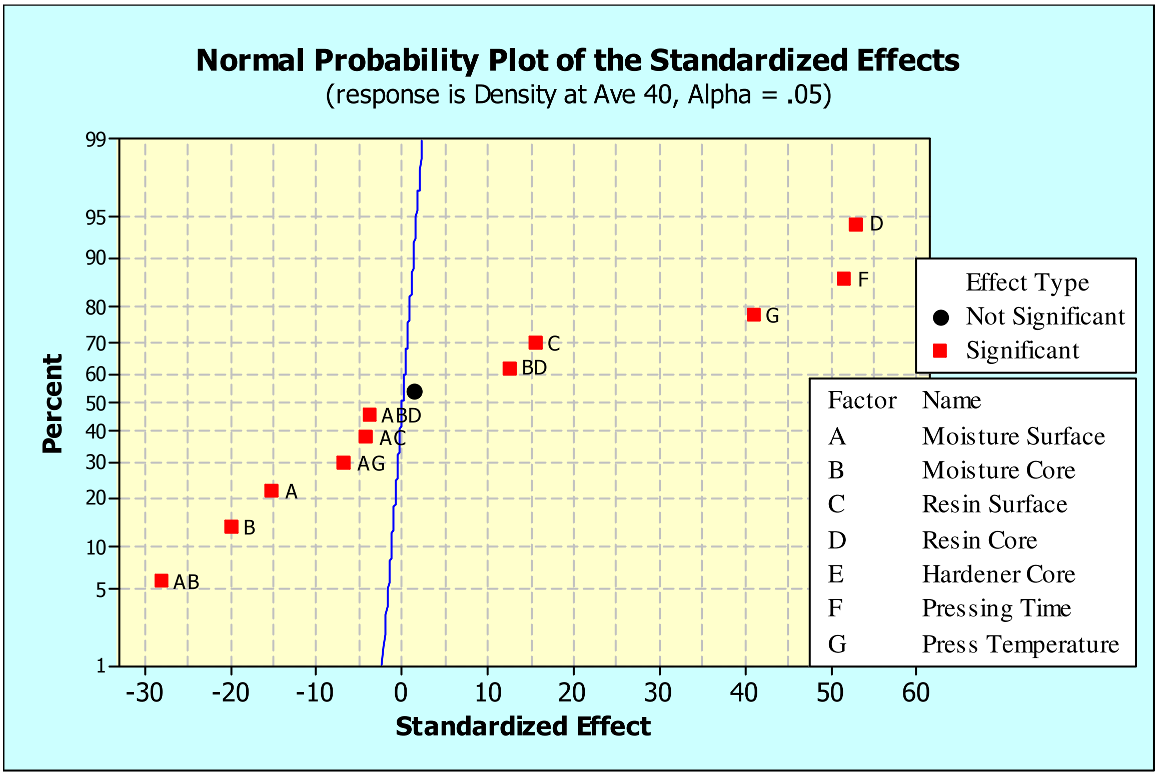


Figure 9.12: Normal probability plot of standardized effects for the density at 40% x thickness

*Density at 40% from the surface = =614.59 - 12.75*A - 16.75*B + 13*C + 44.35*D + 0.99*E + 43.32*F + 34.35*G - 23.64*A*B - 3.54*A*C - 5.7*A*G + 10.42*B*D - 3.19*A*B*D* Equation 9.4

Where:

A = Surface moisture content
B = Core moisture content
C = Surface resin load (with respect to dry residue wt)
D = Core resin (with respect to dry residue wt)
E = Hardener (core- with respect to resin load)
F = Pressing time
G = Press temperature (Note: all the variables are in the coded units.)

9.3.4.1 Significance of the developed model

Table 9.6: Analysis of Variance for Density at 40% thickness (coded units)

Source	**DF**	**SS**	**MS**	**F**	**P**
Main Effects	7	90175	12882.2	1145.4	0.000
2-Way Interactions	4	11401	850.3	253.42	0.000
3-Way Interactions	1	163	163.3	14.52	0.032
Residual Error	3	34	11.2		
Total	15	101774			
SS = Sum of Squares MS = Mean square					

Table 9.6 represents the ANOVA calculated for factors in the developed model (equation 9.4) to test its significance. It shows that all the seven main effects and four number of two-way interactions are important for the model ($P < 0.05$). In addition, one three-way interaction effect is important for the model development.

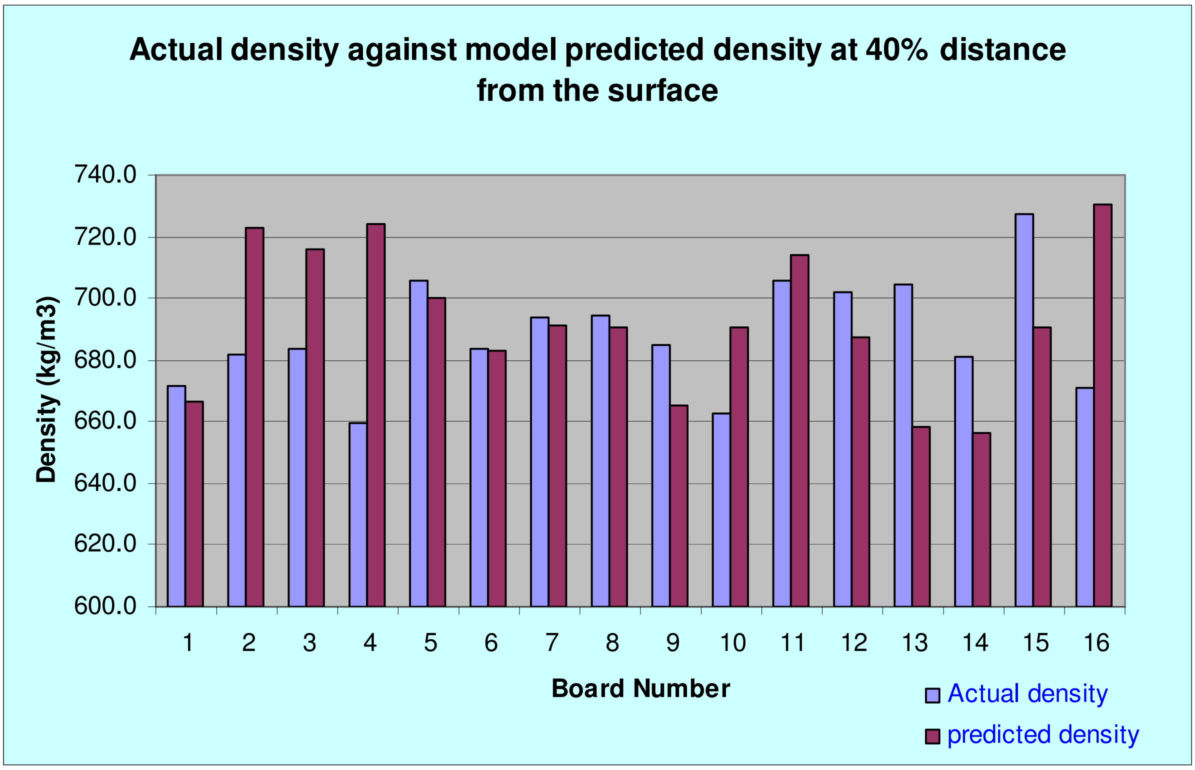


Figure 9.13: Actual versus predicted density at '40% x thickness' distance from the surface

As initially suggested, the model has considered twelve effects. Also, R^2 and R^2 adjusted were calculated for the model and both were above 99.8%. Therefore, this model should adequately predict the density at '40% x thickness' distance from the surface of the particleboard. Then the model was tested using experimental density profile data as presented in the Table 9.2 and Figure 9.13. The results in Table 9.2 show that equation 9.4 can accurately predict the density in the particleboard at '40% x thickness' distance from the surface with less than 9 % variation.

9.3.5 Modelling the density at the centre layer ('50% x thickness' distance from the board surface)

Similar to the steps followed earlier, the important parameters that affect the density at the centre of the particleboard were explored. It was found that all the main effects are significant for the density at the centre of the particleboard (Table 9.1 and Figure 9.14).

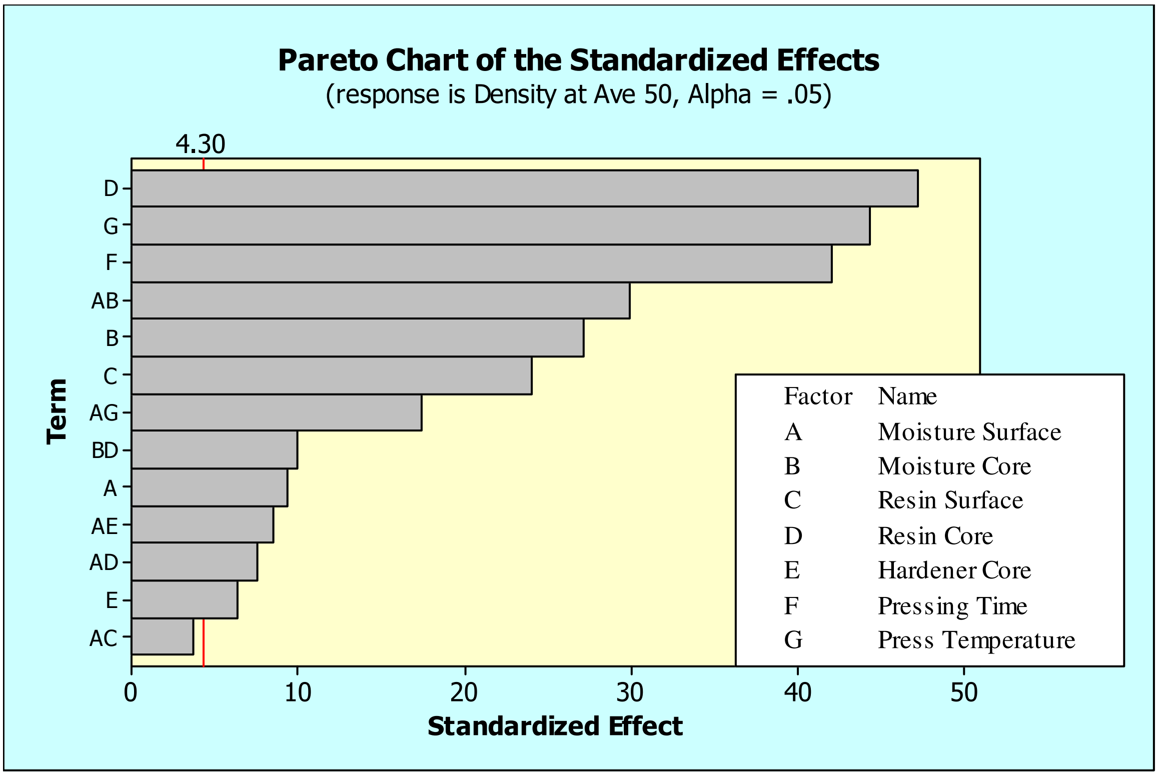


Figure 9.14: Pareto chart of the significant effects for density at the centre (50% x thickness)

In addition to the main effects, combinations of moisture surface with moisture core, an interaction of moisture surface with press temperature, an interaction of moisture core with resin core, an interaction of moisture surface with hardener and an interaction of moisture surface with resin core are significant for the density at the centre of the particleboard. Therefore, regression coefficients were calculated for these parameters to develop the polynomial equation to predict the density at the centre (equation 9.5). Of these variables, hardener, moisture surface, moisture core, interacting moisture surface with press temperature and interacting moisture surface with moisture core have negative effects on the density at the centre of the board, while all the other parameters have positive effects on the density at the centre of the board (Figure 9.15).

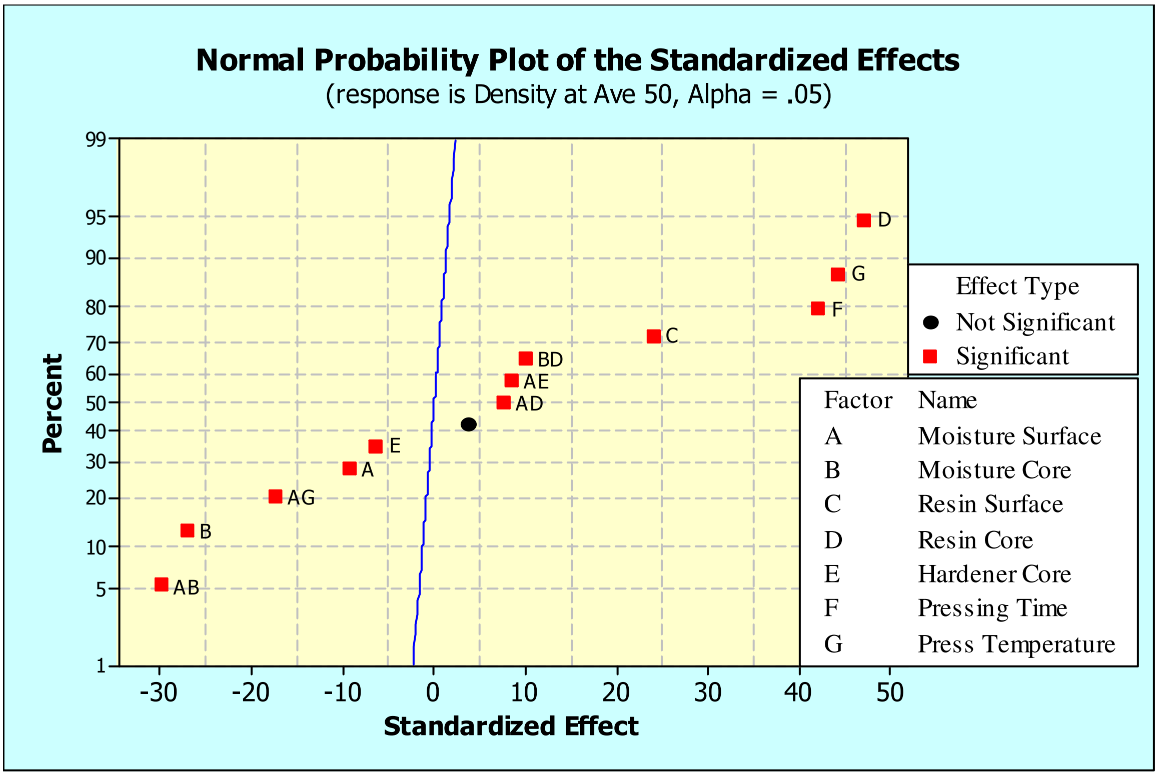


Figure 9.15: Normal probability plot of standardized effects for the density at the centre (50% x thickness)

Density at the centre of the board $= 618.85 - 7.45*A - 21.53*B + 19.09*C + 37.49*D - 5.03*E + 33.44*F - 23.79*G - 23.79*A*B + 2.93*A*C + 6*A*D + 6.73*A*E - 13.8*A*G + 7.94*B*D$ Equation 9.5

Where:

A = Surface moisture content

B = Core moisture content

C = Surface resin load (with respect to dry residue wt)

D = Core resin (with respect to dry residue wt)

E = Hardener (core- with respect to resin load)

F = Pressing time

G = Press temperature (Note: all the variables are in the coded units.)

9.3.6 Significance of the developed model

The ANOVA was calculated for the parameters in the developed model in equation 9.5. It also highlighted that all the seven variables and six interactions which were considered for the model development are vital with $P < 0.05$ (Table 9.7). The calculated R^2 was 99.98% and R^2 adjusted was 99.83%, indicating that this model should adequately predict the density at the centre of the board. The model equation was experimentally tested as shown in Table 9.2, which shows that model can predict the actual density at the centre of the board with less than 10% variation. The comparison of actual and predicted density at the centre is plotted in Figure 9.16.

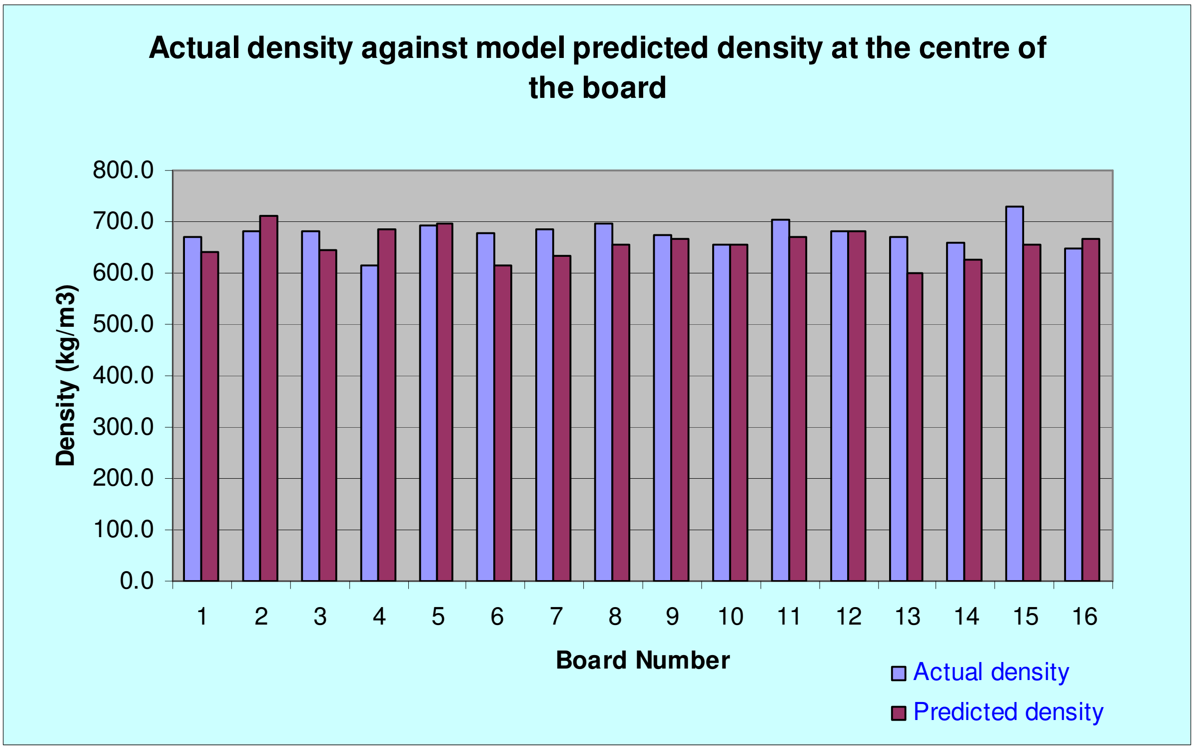


Figure 9.16: Actual versus predicted density at the centre of the particleboard

Table 9.7: Analysis of Variance for Density at the centre of the board (coded units)

Source	**DF**	**SS**	**MS**	**F**	**P**
Main Effects	7	74774.1	10682.0	1057.88	0.001
2-Way Interactions	6	14546.8	2424.5	240.11	0.004
Residual Error	2	20.2	10.1		
Total	15	89341.1			
SS = Sum of Squares	MS = Mean square				

9.3.7 Modelling the density at '5% x thickness' distance from the board surface

When the actual vertical density profiles of a three-layer particleboard were considered in Chapter 7 (Figures 7. 21 – 7.23), it was clear that the density closer to the surface of the particleboard changed significantly in a three-layer particleboard. Therefore, in addition to modelling the density at each 10% x thickness levels, the density at '5% x thickness' from the surface level was also studied to achieve smooth VDP closer to the board surface.

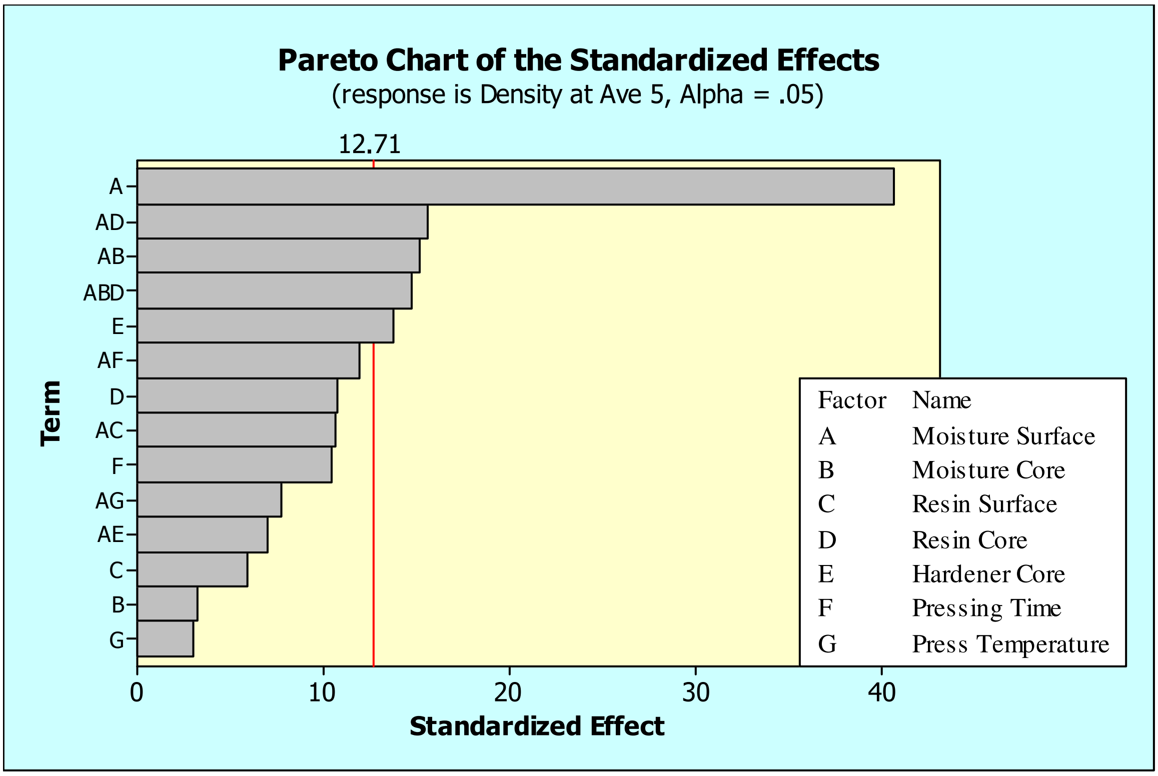


Figure 9.17: Pareto chart of the standardized effects

It was found that moisture surface, hardener core, interaction of moisture surface with resin core, interaction of moisture surface with moisture core, and interaction of moisture surface with moisture core and resin core have significant effects on the density closure to the surface (at 5% x thickness distance from the surface). Of these variables, moisture surface is extremely important for compaction hence density close to the surface (Figure 9.17). Figure 9.18 shows that the moisture surface, an interaction of moisture surface with moisture core and an interaction of moisture surface with resin core have positive effects on the density. Hardener core and the interaction of moisture surface, moisture core and the resin core have negative effects on the density at this layer. In addition to the variables which have $P < 0.05$, variables that have some effect (as in Figure 9.17) on the density at this layer were considered to develop the regression model shown in equation 9.6.

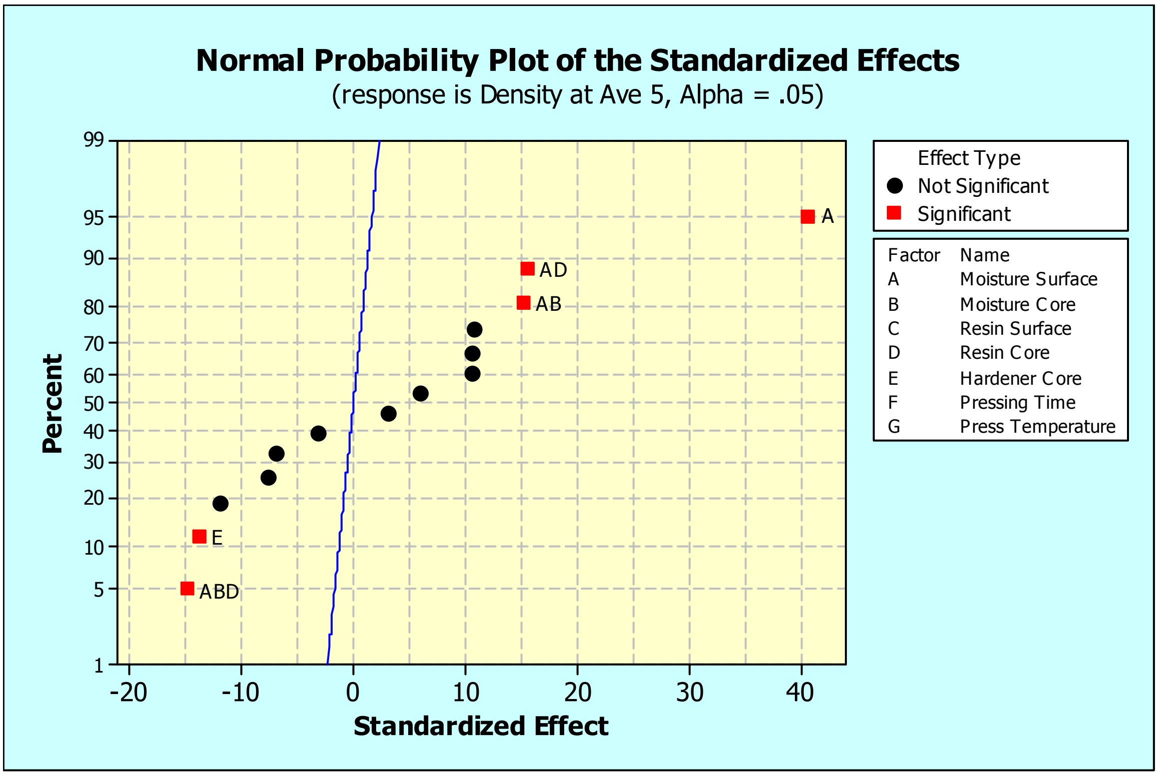


Figure 9.18: Normal probability plot of the standardized effects

Density at '5% x thickness' from the surface = $846.07 + 62.86*A - 4.98*B + 9.13*C + 16.68*D - 21.35*E + 16.18*F + 4.59*G + 23.47*A*B + 16.45*A*C + 24.11*A*D - 10.8*A*E - 18.5*A*F - 11.5*A*G - 22.84*A*B*D$ Equation 9.6

Where:

A = Surface moisture content

B = Core moisture content

C = Surface resin load (with respect to dry residue wt)

D = Core resin (with respect to dry residue wt)

E = Hardener (core- with respect to resin load)

F = Pressing time

G = Press temperature (Note: all the variables are in the coded units.)

9.3.8 Significance of the developed model

When the model was developed the ANOVA for the model was calculated to test its significance (Table 9.8). The ANOVA showed that the model needs to consider the seven basic variables, six two-way interactions and one three-way interaction with $P < 0.07$. The $R^2 = 99.97\%$ and the $R^2 = 99.53\%$ were found for the model. Therefore, the model has considered all the significant variables and it should adequately predict the density at '5% x thickness' distance from the surface. Then the model was validated using experimental data as shown in Table 9.2 and Figure 9.19. Results showed that the model closely predicts the density at this level, although one board had 19% deviation. Unlike the inner layers, the actual density close to the surface could easily be affected by experimental errors, such as over-cooking (over-curing) the surface resin. Therefore, predicted density and actual density may not be the same closer to the surface.

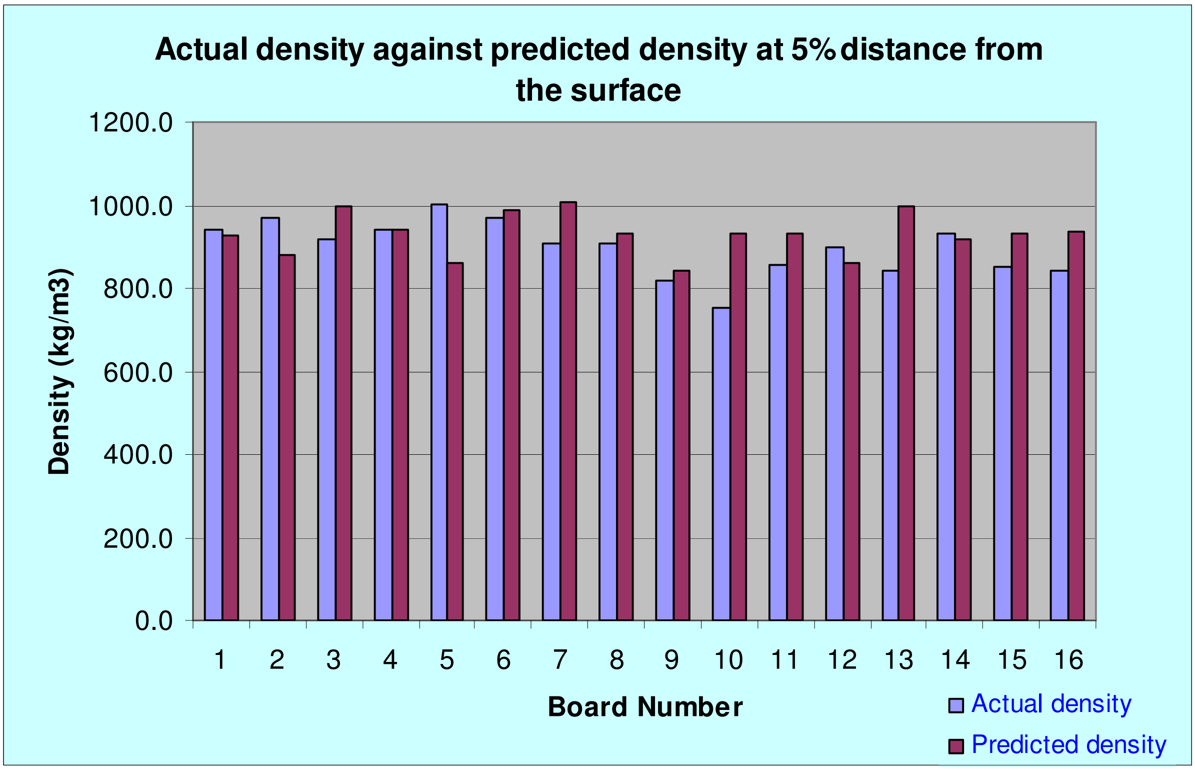


Figure 9.19: Actual versus predicted density at the centre of the particleboard

Table 9.8: Analysis of Variance for Density at 5% (coded units)

Source	**DF**	**SS**	**MS**	**F**	**P**
Main Effects	7	81227	11603.9	303.83	0.044
2-Way Interactions	6	32047	5341.1	139.85	0.065
3-Way Interactions	1	8347	8346.6	218.54	0.043
Residual Error	1	38	38.2		
Total	15	121659			
SS = Sum of Squares	MS = Mean square				

9.3.9 Modelling the thickness of a particleboard

After developing models to predict the density at each layer along the thickness, these predicted densities should be plotted against the distance (in thickness direction) to complete the VDP. Experimental results showed that the thickness of each board was different to each other due to the change in thickness caused by spring-back after hot pressing. Therefore, the thickness of each board should be predicted with respect to process variables first.

The processing variables affecting board thickness were tabulated in Table 9.1 with $P < 0.05$ and are presented in Figure 9.20. It appears that pressing time is the most important factor for the thickness. In addition, press temperature, moisture surface, moisture core, resin surface, resin core as well as interaction of moisture surface with pressing time, interaction of moisture surface with moisture core and moisture surface with press temperature are significant for the final board thickness. Of these variables, moisture surface, moisture core and the interaction of these two increased particleboard thickness (Figure 9.21). When these factors were identified, a regression model was developed using regression coefficients with respect to each process variable (Equation 9.7).

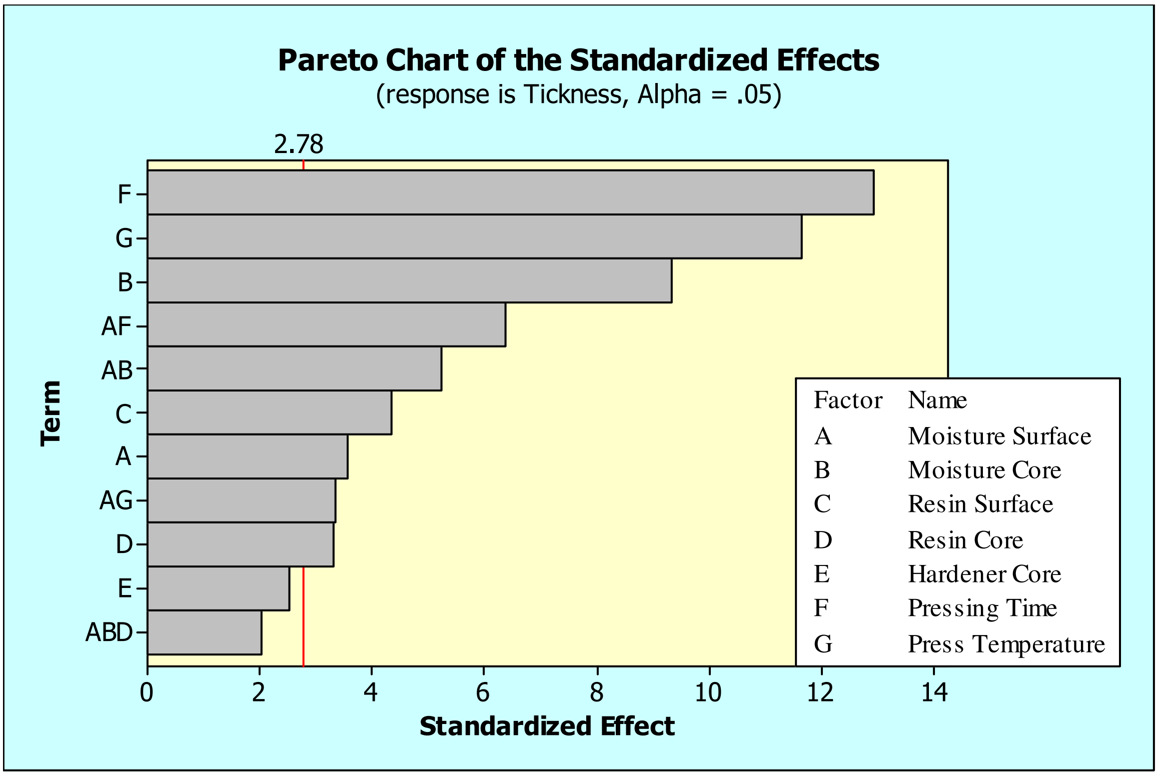


Figure 9.20: Pareto chart of standardized effects that affect particleboard thickness

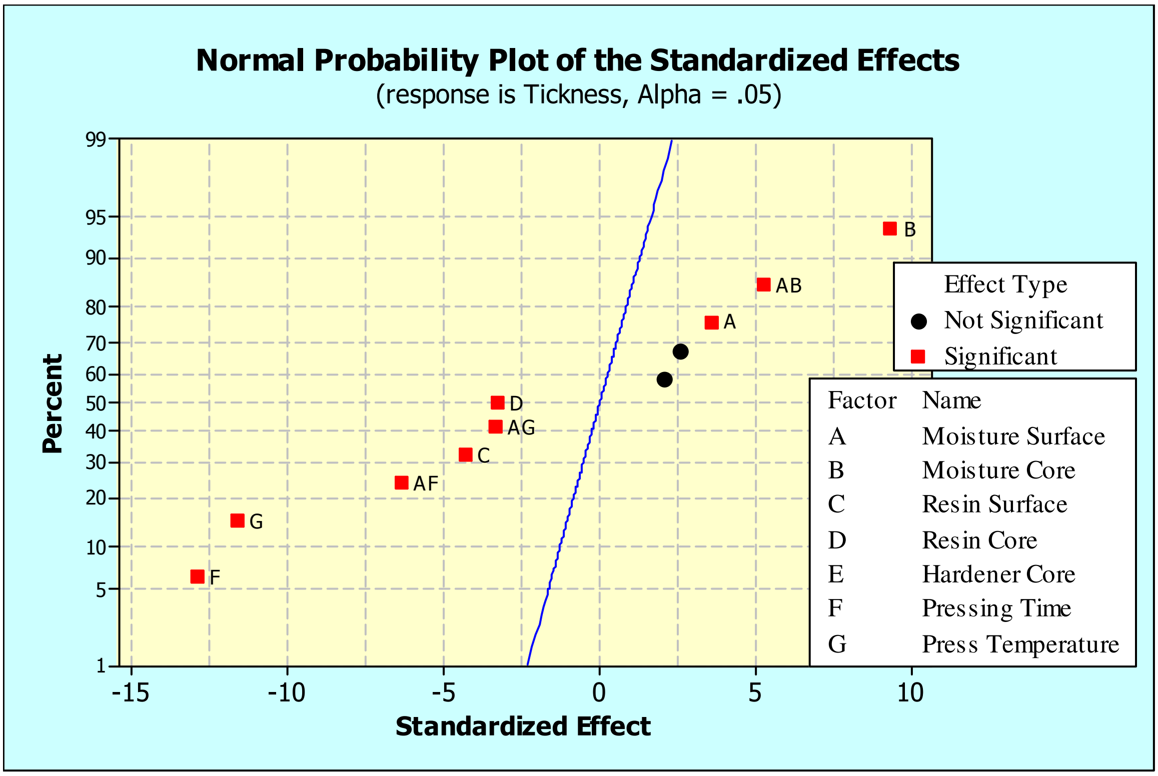


Figure 9.21: Normal probability plot of the standardized effects that affect thickness of a particleboard

$$\text{Thickness of the particleboard} = 16.41 + 0.2075*A + 0.54*B - 0.2525*C - 0.19*D + 0.14*E - 0.75*F - 0.68*G + 0.305*A*B - 0.37*A*F - 0.195*A*G \quad \text{Equation 9.7}$$

Where:

A = Surface moisture content
B = Core moisture content
C = Surface resin load (with respect to dry residue wt)
D = Core resin (with respect to dry residue wt)
E = Hardener (core- with respect to resin load)
F = Pressing time
G = Press temperature (Note: all the variables are in the coded units.)

9.3.10 Significance of the developed model

The ANOVA was calculated for the developed model to estimate its validity statistically. Table 9.9 shows that the model needs to consider all the main effects and three two-way interactions to predict the thickness successfully. In addition R^2 and R^2 adjusted were calculated to be over 97.6%. Therefore, this model should adequately predict the thickness of a board.

Table 9.9: Analysis of Variance for Thickness (coded units)

Source	**DF**	**SS**	**MS**	**F**	**P**
Main Effects	7	23.7631	3.39473	62.87	0.001
2-Way Interactions	3	4.2872	1.42907	26.46	0.004
3-Way Interactions	1	0.2209	0.22090	4.09	0.113
Residual Error	4	0.2160	0.05400		
Total	15	28.4872			
SS = Sum of Squares	MS = Mean square				

The usability of the model equation was tested using experimental data (Table 9.10). The data in Table 9.10 show that the model can predict the thickness of a particleboard with less than 10% variation under the present working conditions. These data were plotted in Figure 9.22.

Table 9.10: Actual versus predicted thickness

Board Number	**Actual Thickness**	**Predicted Thickness**	**Error (%)**
1	15.1	15.16	0.42
2	14.8	14.59	-1.45
3	15	13.77	-8.95
4	14.7	14.07	-4.45
5	14.5	14.83	2.20
6	14.5	14.62	0.82
7	14.8	14.41	-2.71
8	14.7	14.72	0.16
9	15.1	15.27	1.15
10	15.2	14.72	-3.24
11	14.9	14.28	-4.31
12	14.9	15.04	0.91
13	14.7	15.26	3.68
14	14.7	15.37	4.38
15	14.2	14.72	3.55
16	14.9	13.92	-7.02

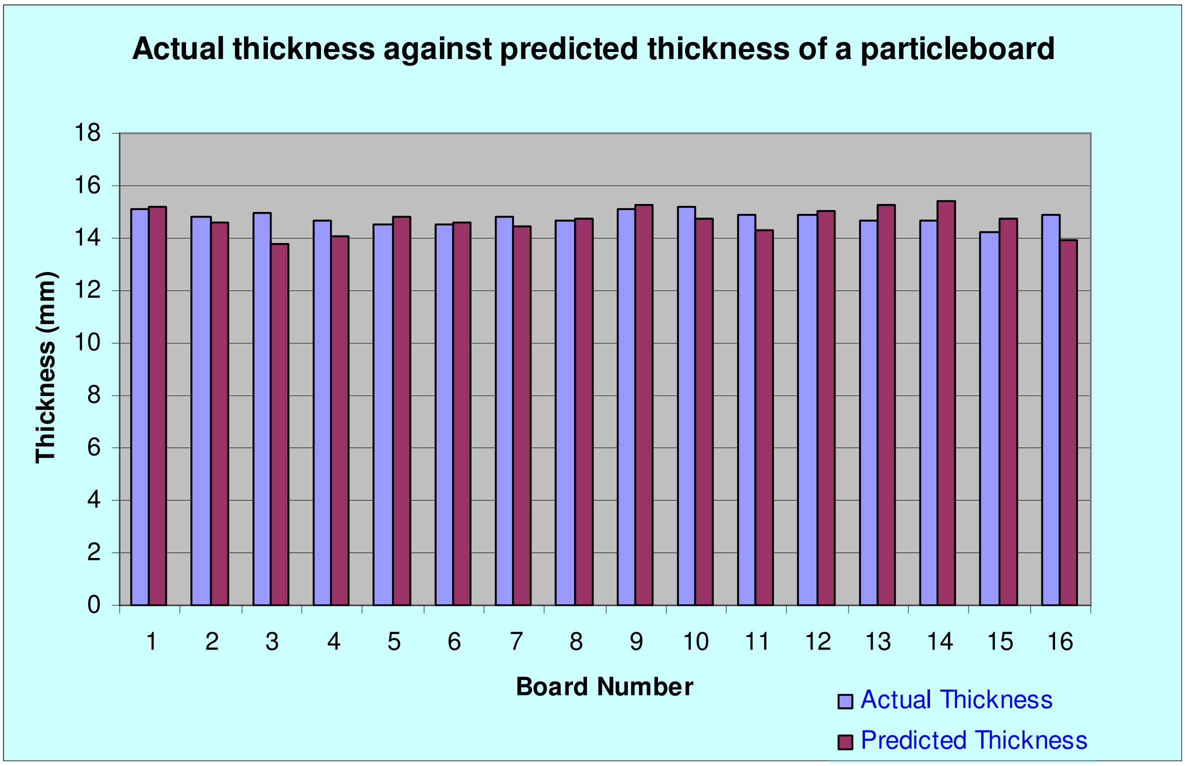


Figure 9.22: Actual thickness versus predicted thickness of a particleboard.

The ANOVA was calculated in each of the above calculations to predict density at different levels of the board or the thickness. Error terms existed in the ANOVA tables. However, the SS or MS of those error terms were negligible compared to the SS or MS of the main effects and interactions which were considered for model development. That suggests that the main effects and interactions which were considered for those models adequately explain the behaviour of the predicting variable with negligible error.

9.4 Predicting the density profile by combining thickness and layer density

Earlier sections explained how to develop process models to predict the density along the thickness of a particleboard. The density near the surface of the board could not be predicted very accurately compared to densities in the inner layers. That may possibly be due to the density near the surface being affected by external factors such as human error in handling the boards, experimental error such as over curing of resin during hot pressing, other than processing variables. Therefore, having a predicted VDP is important for quality control purposes when manufacturing boards.

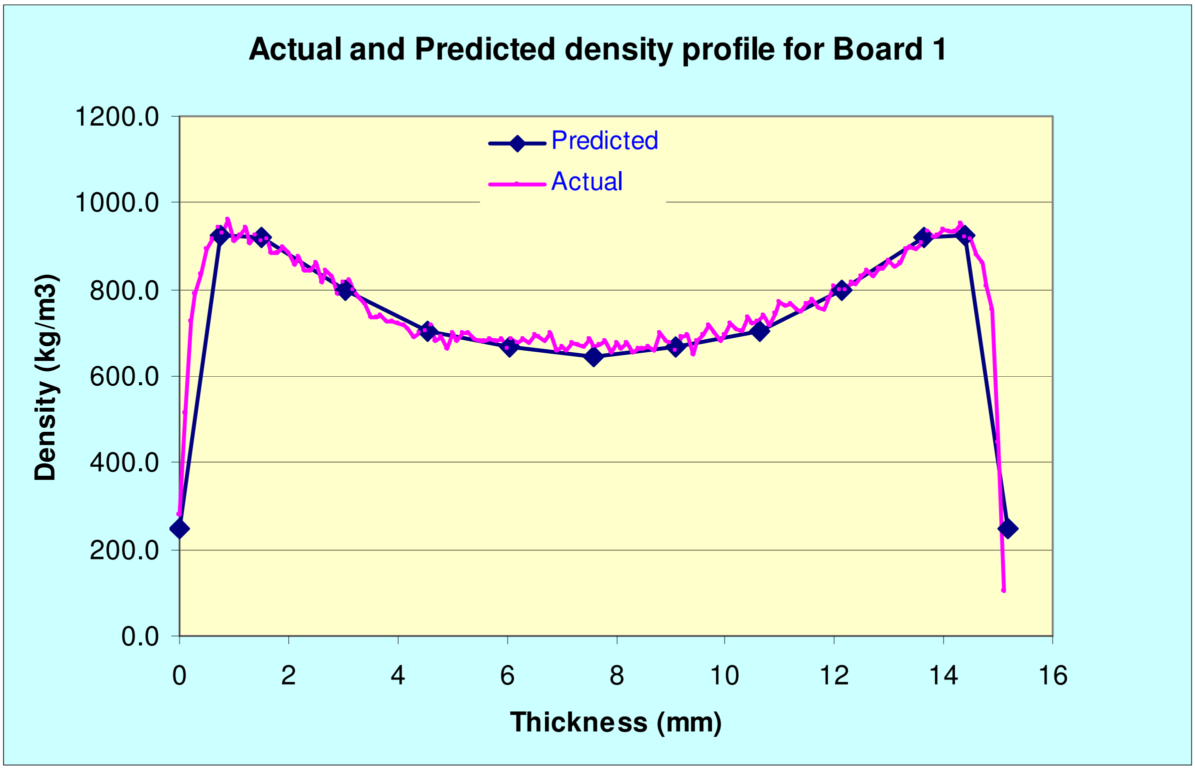


Figure 9.23: Actual density against the predicted density for particleboard 1

The experimental results showed that the actual densities near the surface of the produced particleboards were in the range of 170 kg/m3 to 350 kg/m3. Therefore, the density near the surface for each predicted VDP was assumed to be 250kg/m3. This assumption was only required for the presentation of the predicted VDP in the above plots. Then the predicted density along the thickness was plotted against the thickness in Figure 9.23.

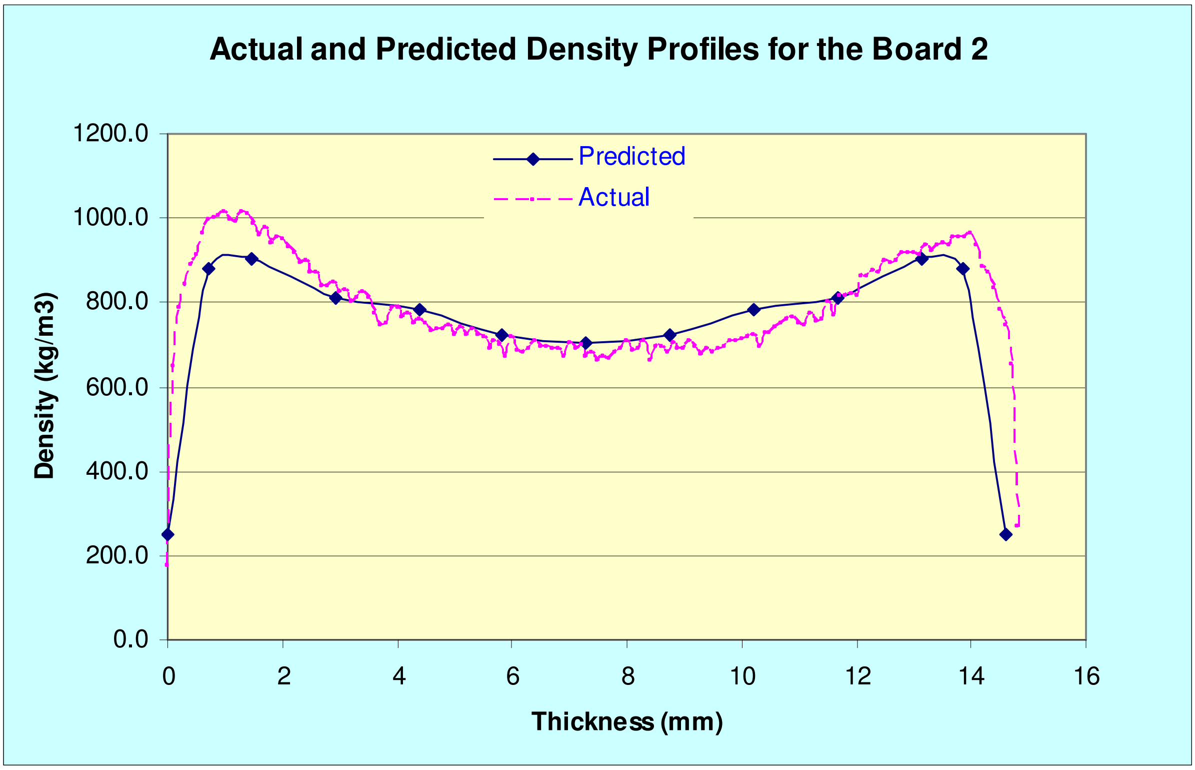


Figure 9.24: Actual density against the predicted density for particleboard 2

9.5 Summary and Conclusions

This chapter discussed the formulation of process models to predict the density at different layers of a particleboard along the thickness direction as well as to predict the thickness of the same board. The aim of predicting the density at each layer and the thickness was to incorporate them to predict the VDP of a particleboard with respect to processing parameters.

The consistency between actual VDP and model predicted VDP from several particleboards from different processing parameters validated the developed models. The results showed that these process models could predict the density with less than 15% variation along the thickness. That accuracy increased to less than 10% variation, when predicting the density closer to the core of the board.

Also, using these models it is possible to obtain better understanding of particleboard with respect to different process conditions. Therefore, they can be used to study the VDP of a particleboard, before producing it in the laboratory. By this means, a particleboard with a designed VDP could be produced. That will accelerate the experimental process to produce particleboards with optimised VDP. Hence, it will save time, material and labour required for experimentation.

Most commercial production processes use VDP as a measure of quality control. This model therefore would be extremely valuable for the progress of the research to the next stage of commercialisation.

CHAPTER 10

POSSIBLE APPLICATIONS OF HARDWOOD PARTICLEBOARD (Reference to AS/NZS: 1859)

10.1 Introduction

Using hardwood particleboard as structural or non-structural panels will be investigated in this chapter. As summarised in Chapter 8, particleboards that can be produced using sawmill residues have satisfied the strength requirements according to AS/NZS 1859(2004). However, AS/NZS (1859:2004) requires that in addition to strength properties, there are number of other physical properties that should be satisfied by the particleboard to be used as standard particleboard. These properties include surface soundness, surface water absorption and thickness swelling properties. This chapter investigates the thickness swelling property of particleboard as that has a significant effect on the stability of the particleboard as well as on the bond durability, as identified by the literature review (Chapter 2). As reported in Chapter 2, irreversible thickness swelling is recognized as a problematic characteristic in particleboard as it occurs unevenly and is thus aesthetically unappealing. In addition, irreversible thickness swell normally happens close to the edges, which results in paint failure of the board on that spot. Furthermore, Kelly et al (1977) showed that this swollen edge absorbs liquid or water to a greater degree, which in turn leads to panel decay.

The particleboard industry uses the emulsion wax (0.5 – 1.0% of the oven dry wt of the wood) to improve the stability of the particleboard by improving short term moisture resistance (Wood Handbook 1999). A wax composition has water repellent and adhesive properties, is cheap and has wide application in the manufacture and treatment of particleboard and other cellulose materials (Free Patents Online 2007). Therefore, the thickness swelling property was investigated for particleboard with and without wax. Also, the optimum amount of wax required to optimize the thickness swell property will be identified.

10.2 Materials and method

Similar to the experiments performed and discussed in earlier chapters, the same hardwood sawmill residues and resin were used for this experiment. In addition, Technimul/VivaShield Emulsion: EXP 486 was used as the wax. A multivariate experimental design was developed using a full factorial design to make three-layer hardwood particleboards in the laboratory. Previously optimized processing parameters were used to prepare boards (Chapter 8). Resin load for surface and core layer were kept constant at 18% and 10% respectively. Surface and core moisture content were also maintained at 16% and 9%. Pressing time and press temperature were controlled to be 240 seconds and 195 ^{0}C respectively.

10.2.1 Test Procedure

Finished boards were then in a ventilated area for a week to remove formaldehyde. Then, all boards were trimmed to obtain 200 mm x 300 mm rectangles by trimming 50 mm wide strips along the edges. Two 300 mm x 75 mm specimens for wet bending strength testing and six 50 mm x 50 mm specimens for thickness swelling testing were cut and prepared from each of the final boards. Then those specimens were stored in the humidifier for curing according to AS/NZS 4266.5 (2004) for at least 24 hours in a standard climate of 20 ± 2 ºC and relative humidity of 65 ± 5% before testing was performed.

10.2.2 Thickness swelling

This test was designed to provide information on the durability of the board after moisture penetration. Two types of swelling in thickness tests were measured according to AS/NZS 4266.8(2004) after immersion in water. The first test was swelling in thickness, determined after complete immersion in water for one hour. The second test was thickness swelling determined after complete immersion for 24 hours. The swelling in thickness of each test piece (G_t), expressed as a percentage of the original thickness was calculated using Equation 10.1 (AS/NZS 4266.8: 2004).

$$G_t = \frac{t_2 - t_1}{t_1} x100\% \qquad \text{Equation 10.1}$$

Where:

t_1 = initial thickness of the test sample (mm)
t_2 = thickness of the sample after immersion (mm).

10.2.3 Wet bending strength

The method used complied with AS/NZS 4266.10(2004). Test pieces were immersed in a hot water bath at a temperature of 70 ± 3 °C for 2 hours and then tested for their wet bending strength ($f_{\max}$) within 15 minutes. However, once they were removed from the water bath, they were left for a few minutes to drain off excess water before testing for $f_{\max}$. Then, the three-point bending test was performed using the Instron Universal testing machine and $f_{\max}$ was calculated for each test piece using equation 10.2.

$$f_{\max} = \frac{3Fl_1}{2bt^2} \qquad \text{Equation 10.2}$$

Where

F = maximum flexure load (N)
b = test sample before immersion (mm)
t = test sample thickness before immersion (mm)
l_1 = span between support (mm)

10.3 Results and discussion

Tests results obtained from the 1 hour and 24 hours thickness tests and the 2 hour wet bending strength test are presented in Table 10.1. These tests were designed to provide information on the durability of the board after moisture penetration.

Table 10.1: Results obtained from thickness swell tests and wet bending test

Sample Number	**Wax Surface**	**Wax Core**	**1hr Thickness swell (%)**	**24 hr Thickness Swell (%)**	**Wet bending strength (MPa)**
1	0.5	0.4	1.06	3.93	4.38
2	0.0	0.0	4.66	11.95	2.20
3	1.0	0.0	1.76	16.15	2.67
4	1.0	0.8	3.20	21.58	1.30
5	0.0	0.8	2.34	12.32	1.26
AS/NZS 1859:2004 requirements			*< 12*	*< 20*	*> 4.5*

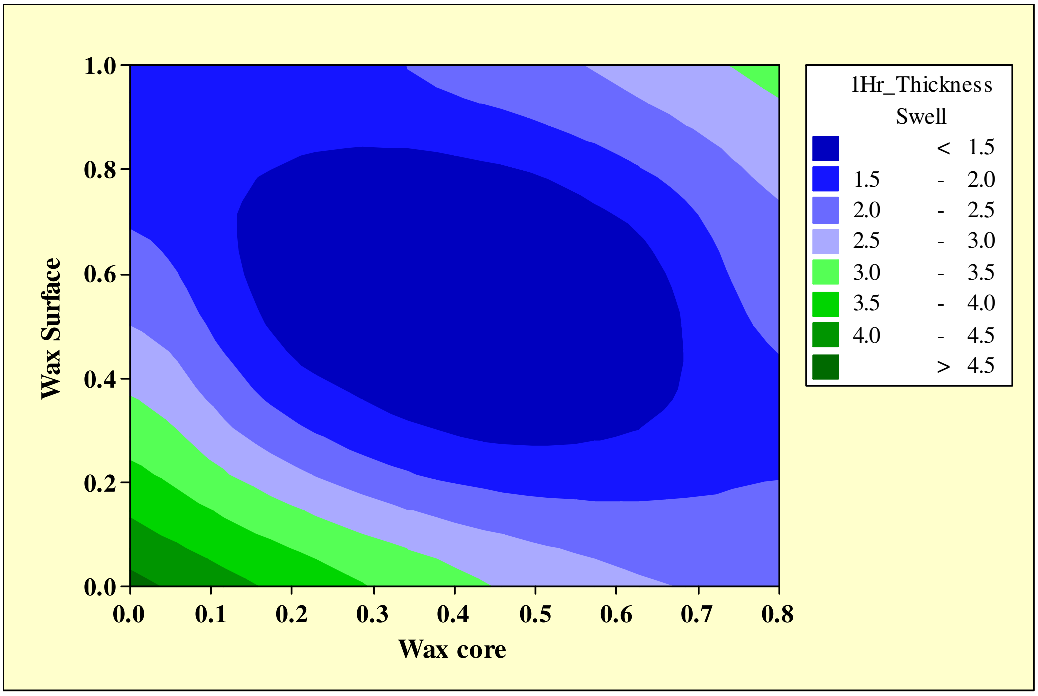


Figure 10.1: Contour plot of 1 hr thickness swell Vs Wax surface and Wax core

According to AS/NZS 1859(2004), general purpose particleboard should meet thickness swelling requirements in addition to flexural strengths (modulus of rupture (MOR > 12 MPa) and internal bond strength (IB > 300 KPa)). The MOR and IB values already complied with AS/NZS standards and the results were presented in Chapters 7 and 8. As seen in Table 10.1, all the 5 boards have 1 hour thickness swelling values less than 12 % as required by AS/NZS 1859.1(2004).

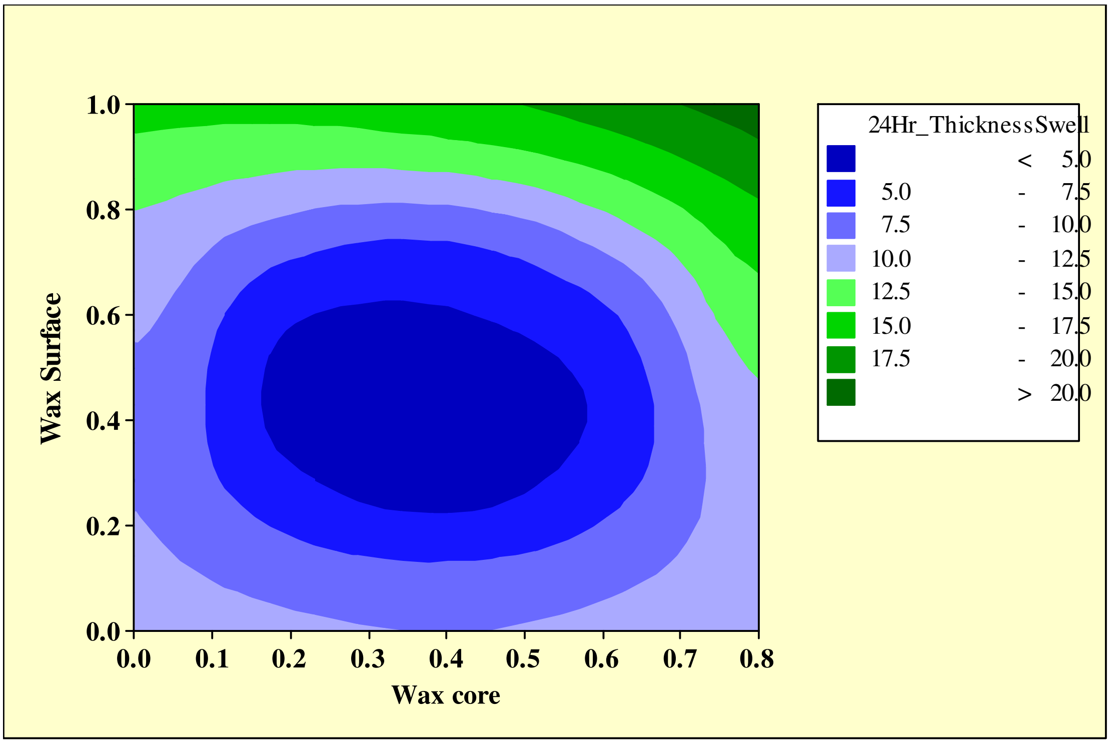


Figure 10.2: Contour plot of 24 hr thickness swell Vs Wax surface and Wax core

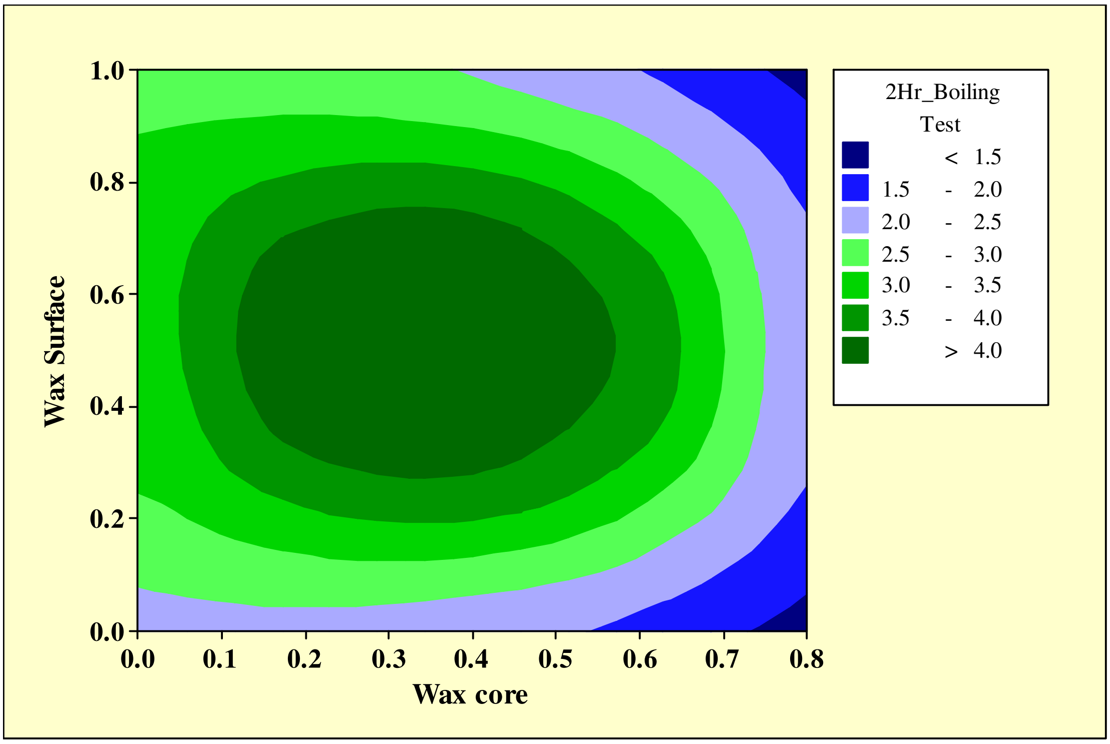


Figure 10.3: Contour plot of 2 hr wet bending strength Vs Wax surface and Wax core

In addition, results show that with the exception of board 4 these particleboards meet the AS/NZS 1859.1(2004) requirements for 24 hour thickness swell tests. Hence, it may be concluded that hardwood particleboard meets the AS/NZS 1859 requirements for standard general purpose particleboard that can be used for interior furniture.

Figures 10.1 and 10.2 explain the relationship between thickness swell with respect to wax surface and wax core. The best resistance to moisture can be attained when both surface and core wax are in the range of 0.35 % – 0.555%. That is at the middle of the contour plot (dark blue area). The addition of excessive wax does not increase the resistance to thickness swelling for hardwood particleboard. Suchsland and Woodson (1986) also indicated that the wax content for commercial fibreboard does not exceed 0.5% of fibre oven dry weight. The Wood Handbook (1999) confirms that the most appropriate amount of wax in a particleboard should be maintained between 0.5 percent to 1 percent of the oven dry weight of the wood particle. Wax has been used in the particleboard and panel industry for years to reduce capillary suction of inter-fibre voids. This reduces water absorption and thickness swell. However, Albercht (1968) indicated that an increase in the wax content beyond 1% would provide marginal improvement in the water resistance of particleboard.

In addition to testing the durability of hardwood particleboard for general purposes, tests were conducted for moisture resistance for applications such as furniture and cabinets for bathroom and kitchen areas which encounter occasional wetting. Figure 3 shows the behaviour of the bending strength of hardwood particleboard with respect to surface and core wax, in hot and wet conditions. The best results could be obtained at 0.2 – 0.5% core wax with 0.4 – 0.6% surface wax which is almost similar to the thickness swelling property.

However, the wet bending strength required little improvement to meet the AS/NZS 1859 requirement for moisture-resistant general purpose particleboard (Table 10.1). The wet bending results may be expected as the amino-methylene linkage in the UF resin is highly susceptible to hydrolysis. Therefore, bond lines are not stable at higher relative humidity, especially at elevated temperature (Dunkey 1998). Further, Dunkey (1998) indicated that the incorporation of melamine and sometimes phenol improves the low resistance of UF bonds to the influence of humidity, water and weather. However, the cost of melamine resin is much higher than UF and therefore UF is the more popular resin in the particleboard industry for manufacturing standard grade particleboard. However, it is recommended to investigate superior resins such as melamine resin for manufacturing particleboards using hardwood sawmill residues to further improve moisture resistance.

10.4 Summary and Conclusions

This chapter presented an investigation into the dimensional stability of particleboard for relevant applications.

According to AS/NZS 1859, the durability of the final product is mainly governed by its ability to resist different humidity moisture conditions. Therefore, hardwood particleboards were tested for thickness swelling after immersion in water for 1 hour and 24 hours. In addition, they were tested for wet bending after immersion in a hot water bath at temperature of 70 ^{0}C for 2 hours.

Both 1hr and 24 hour thickness swell test results satisfied AS/NZS 1859 (2004) for standard general purpose particleboard suitable for the manufacture of interior furniture and shelves. However, the wet bending test results indicated that the hardwood particleboard needs further improvement for use as moisture-resistant general purpose panels generally used in occasional wet areas such as bathrooms or kitchens. That improvement may be achieved by the use of melamine resin or phenol resin instead of UF resin, as UF resin generally is not suitable for higher moisture conditions especially at elevated temperatures.

CHAPTER 11

CONCLUSIONS AND RECOMMENDATIONS

11.1 Conclusions

A considerable quantity of hardwood sawmill residues are produced annually in Australia. These residues are typically considered as solid wastes. Hardwood sawmill residue as particleboard raw material has neither been investigated nor reported earlier. The possibility of particleboard production using hardwood sawmill residue was investigated in this study. A series of experiments was carried out in this study to investigate important parameters for the properties of both single-layer and three-layer particleboards manufactured using hardwood sawmill-residues. Further, process models were developed and validated to predict MOR, MOE and the formation of VDP of three-layer particleboards manufactured using hardwood sawmill residues. This chapter presents a consolidated body of knowledge developed through the work presented in Chapters 1 to 10.

Hardwood sawmill residue required for this investigation was supplied by Dormit Proprietary Limited (Hardwood Saw miller), from their sawmill located in Dandenong, Victoria, Australia. The Orica Proprietary Limited provided the urea formaldehyde (E1) resin for this study from their chemical division located at Deer Park, Victoria, Australia.

11.2 Conclusions of the literature review

- MOR, MOE and IB are the main strength properties which need to be achieved to satisfy industry standards for use as general purpose (softwood) particleboard. MOE and MOR of a particleboard are mainly dependent on its surface layer whereas IB is dependent on the core layer of a three-layer particleboard.

- Both MOR and MOE of a particleboard can be improved by increasing the compaction ratio as well as by increasing the length/thickness ratio for the same wood species. The MOR and MOE of a particleboard with the same mean density increase with the decrease in the density of the wood species.

- IB is a very important property in a particleboard that is highly dependent on the glue line strengths. IB reduces with the reduction in core density since the compaction ratio is low. IB can be improved by adding extra resin into the core.

- Board stability is dependent on properties such as thickness swelling or spring-back. Increasing the resin content in a particleboard reduces thickness swelling as well as spring-back, although high moisture content does the opposite. Additives such as paraffin wax are added to the particleboard to reduce water adsorption in order to reduce thickness swell.

- The VDP of a particleboard forms during production due to the interaction of heat and mass transfer with rheological properties of furnish and resin. The shape of the VDP of a particleboard is important as the MOE and MOR of a particleboard are dependent on the surface layers of the particleboard, while IB is dependent on the core.

11.3 Establishment of a method of making particleboards in the laboratory

- Chapter 4 explained the methods used in this study to prepare particleboards in the RMIT laboratory. Equipment needed to manufacture particleboards in the laboratory was designed and manufactured or modified. The study showed that three-layer particleboards should be cold pressed before hot pressing to achieve improved strength properties. Cold pressing equipment was developed during this study. Using the cold press, particleboard properties were improved significantly. Using a cold press compacts the wood mat to a certain thickness before hot-pressing and minimises the overcooking of the surface layer during hot-pressing.

- Tools and parts required to hold test samples before testing for (a) MOR and MOE (b) IB were designed according to AS/NZS 4266(2004) and manufactured at RMIT workshops for testing particleboard samples for this study.

11.4 Method of experimental design for product development

Design of experiments (DOE) using partial factorial design was identified as the ideal tool to organize experiments with multiple variables applicable to this investigation. Chapter 5 explained the selected tools and techniques used in analysing experimental data. The most important tools discussed were

- 2^k fractional factorial design and how it can be used to collect data and analysis for experiments with multiple variables.
- ANOVA to identify the most important parameters.
- regression models to predict important particleboard properties with respect to process variables using regression analysis.

11.5 Identification of significant parameters for *single-layer* and *three-layer* particleboards

Chapters 6 and 7 investigated the relationships between *single-layer* and *three-layer* particleboard properties with respect to their processing variables. It was found that the moisture content was very significant on both MOE and MOR of hardwood single-layer particleboard. However, using high moisture resulted in spring-back in almost all the single-layer particleboards. Also, resin load and pressing time improved the MOE of single-layer particleboard.

From the studies on three-layer particleboard, the following conclusions were drawn.

- Moisture is a critical variable that needs to be controlled carefully in three-layer particleboards to achieve better compaction as well as to transfer heat and mass to the core of the board during hot pressing. Moisture as an individual variable has a negative effect on the rigidity of the board (MOE) as well as IB. However, the interaction of surface moisture with press temperature increased board flexural strengths (MOE and MOR).
- Hardener has a negative impact on the properties of hardwood three-layer particleboards. Hardener may not be required for this product as the hardwood residues used in this study were found to be inherently acidic.

- Resin surface and pressing time significantly influence both mechanical and physical properties of hardwood particleboard. Hardwood particleboard has better mechanical and physical properties when the surface resin content and pressing time are higher.

- Although the pressing time and pressing temperature significantly reduced the thickness swell, moisture core increased it drastically. Pressing temperature significantly affected MOR, MOE and the thickness but it had only a small effect on the other properties. Although resin core significantly increased both IB and MOR of the board, resin surface was more important for all the properties tested. Therefore, resin core was reduced significantly without compromising IB or MOR while keeping the resin surface at a higher value.

- Density profile alone cannot predict the board's mechanical properties. Inter-particle bonding has a significant influence on strength properties. However, results showed that particleboards with a surface density of 900 kg/m^3 and core density > 600 kg/m^3 produce MOE and MOR which satisfy the AS/NZS 1859 (2004) standards for general purpose particleboard.

11.6 Process modelling of particleboard properties

Chapter 8 discussed the modelling of the MOR and MOE of hardwood particleboards with respect to their processing parameters and important interactions of those variables. It was concluded that the MOE and MOR of a particleboard can be predicted successfully using processing variables and interactions. The developed MOR and MOE model successfully predicted the MOR or MOE of a board with more than 90% accuracy in the designed parameter range. Also, these models can be used to optimise the MOR and MOE of particleboard with respect to processing parameters.

11.7 Predicting the VDP of a hardwood particleboard

Chapter 9 reported the formulation of process models to predict the density at different layers of a particleboard along the thickness direction as well as to predict the thickness of the same board. The aim was to predict the density at each layer and the thickness of the same layer with respect to processing parameters. Then, these densities with respect to thicknesses were incorporated to predict the final VDP of the particleboard.

The consistency between actual VDP and model predicted VDP from several particleboards from different processing parameters was observed. The density of a particleboard could be predicted with less than 10% variation of the density closer to the board surfaces. The inner densities were also predicted with less than 15% variation. The VDP models can be used to predict the VDP of particleboard if the processing variables are known. Commercial particleboard producers use VDP as a benchmark for quality control purposes. Therefore, predicting VDP would accelerate the experimental process to produce particleboards with optimised VDP, as VDP can be used as a benchmark to compare board qualities.

11.8 Durability of hardwood particleboards and their applications

According to AS/NZS 1859 (2004), the durability of the final product is mainly governed by its ability to resist different humidity conditions and moisture conditions. Chapter 10 reported on the investigation of hardwood particleboards for thickness-swelling after immersion in water for 1 hour and 24 hours. In addition, they were tested for wet bending after immersion in a hot water bath at a temperature of 70 ^{0}C for 2 hours. Only the 1hour and 24 hour thickness swell test results satisfied AS/NZS 1859 (2004). Therefore, these particleboards can be used as standard general-purpose particleboard suitable for the manufacture of interior furniture and shelves.

11.9 Recommendations for future research

- In this investigation, particleboard production using 100% hardwood sawmill residues was studied. Results showed that density of this particleboard was marginally higher than the density of conventional softwood particleboard and higher amounts of resin and moisture are needed for the surface layer to achieve the same strength properties as softwood particleboard. Therefore, further investigation on the possibilities of reducing particleboard density without compromising their strength properties is recommended.

- The flexural strength of three-layer particleboard is mainly dependent on the surface layer of the board. Mixing hardwood with softwood flakes, at least for the surface layer, is recommended for future studies, in order to examine the possibility of maintaining higher flexural strength as well as reducing the particleboard density and surface moisture and resin.

- Urea formaldehyde was the only resin used in this study due to its basic properties as well as the cost concerns. However, the use of superior resins such as melamine-urea formaldehyde resin or MDI resin may reduce the amount of resin required for the surface layer to produce particleboard with the same properties. According to the literature review, these superior resins may improve the moisture resistance of particleboard and therefore should be explored in future studies. Using melamine-urea formaldehyde resin may improve water resistance and the amount of formaldehyde emission of the end product may be reduced.

- Investigation into the efficiency of resin is essential in a future study as this product used higher amounts of resin compared to conversational softwood particleboard. A microscopic investigation of the final board product using UV-microscopes is recommended to investigate the penetration of resin into the wood for the understanding of the mechanism of glue line bonds between particles. That will help to improve resin efficiency when using hardwood sawmill residue in the production of particleboards. Such a study may also be useful to improve the particleboard production process, reduce pressing time or reduce the usage of resin. Resin consumed and pressing time directly control the production cost of the final product.

- Resin efficiency with the nozzle size of the spray gun should be studied as smaller droplet size may improve resin efficiency.

- It was found that hardwood residue is inherently acidic and conventional catalysts such as NH_4Cl are not necessary. Therefore, a suitable type of hardener should be investigated in a future study to accelerate resin curing in the core compared to the surface resin. Using an alkaline such as NH_4OH or NaOH for the surface layer instead of an acid for the core layer should be investigated as hardwood residue is inherently acidic.

- While the structural properties assessed in this thesis, namely MOR, MOE and IB are adequate, one of the main applications of particleboards is flooring. In this application the board could be in direct compression. Therefore, it would be desirable to assess the compressive strength of the new board for completeness. ASTMD 1037-93 (standard method of evaluating the properties of wood-based fibre and particleboard panel materials) provides a method for assessing the compressive strength.

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ECONOMICAL PARTICLEBOARD PRODUCTION USING HARWOOD SAWMILL RESIDUES

APPENDICES

APPENDIX A

Product Information sheet for UF resin

Orica Adhesives & Resins
Gate 3 Ballarat Road Deer Park 3023
Tel: 03 9217 8195 Fax: 03 9217 6845
Emergency: 1800 033 111 (All Hours)

PRODUCT INFORMATION SHEET

1. PRODUCT TYPE

Urea Formaldehyde (UF) liquid resin.

Safety information for this product is available on the Materials Safety Data Sheet, Substance Key 000030727965.

2. PRODUCT SPECIFICATIONS

PROPERTY

SPECIFICATION	RANGE	TEST METHOD
Viscosity(cPs @ 25°C)	115 - 220	TECH-WI-351
Solids(%)	63.1 - 64.9	TECH-WI-352
pH(25°C)	7.9 - 9.1	TECH-WI-353
Gelation Time(sec)	50 - 80	TECH-WI-339

3. TYPICAL PROPERTIES

PROPERTY	TYPICAL VALUE	TEST METHOD
SG(25°C)	1.276	TECH-WI-364
Water Dilutability(25°C)	250%	TECH-WI-355

For additional Technical Information contact Orica Adhesives Technical Centre. "All information and any advice given by Orica is as up-to-date and accurate as possible. Orica accepts no liability resulting from reliance upon same and gives no warranties other than those imposed minatorily by law".

PRODUCT INFORMATION SHEET

4. APPLICATION

The urea formaldehyde resin is formulated for use in the manufacture of standard grade particleboard. It is suitable as both a surface and core resin and has been designed to meet the E1 formaldehyde emission standard as defined in AS/NZS 1859.1:1997.

5. PRODUCT STORAGE

The useable life of formaldehyde based resins will be affected by the storage temperature.

The effect of storage temperature on the resin properties is shown in the attached graph of viscosity versus time.

Depending on the storage temperature this resin should be used within the times shown below:

Storage	Temperature
1 week	35°C
3 weeks	25°C
5 weeks	15°C

APPENDIX B

SPREAD SHEET USED FOR CALCULATING MIX PROPORTIONATES

RunOrder	16					
Pressing Time	Press Tem	Moisture C	Resin Core	Hardener Co	Moisture Surfa	Resin Surfac
120	150	15	5	3	22	20
Grand Total						
Board Properties						
Target density	710.00					
Matt area	400*300	120000				
Thickness	15.20					
Volume	1824000	cubic mm				
Total Wt	1295.04	g				
Core Wt	777.02	g	60%			
Cum surface layer Wt	518.02	g	40%			
One surface Layer Wt	259.01					
				Variables		
Material Properties	**% Solids**		density			
Wood chips (oven dried)	100.00		Moisture content			
Resin	63.10		Resin Loading			
Hardner	25.00		Hardner Loading			
Layer Properties	**Surface**	**Core**				
Gross moisture content (MC)	22.00	15.00				
Resin loading (%from dry board wt) (RC)	20.00	5.00		Resin solid wt / Dry wood residue		
Hardner loading (%on resin solids) (HC)	0.00	3.00				
Calculation for Surface		after press		add 15%for	**35%Multch**	65%Fine
	Water (g)	**Dry wt (g)**	**Gross wt (g**	**Measure Wt**		
Wood residue	0.00	431.68	431.68	496.43	173.75	322.68
Resin	50.49	86.34	136.82	157.35		
Hardner	0.00	0.00	0.00	0.00		
Water (added)	63.48	0.00	63.48	73.00		
Total wt	113.96	518.02	631.98	726.78		
Calculation for the Core						
		after press		add 10%for	45%Multch	55%Fine
	Water (g)	**Dry wt (g)**	**Gross wt (g**	**Measure Wt**		
Wood residue	0.00	738.97	738.97	812.86	365.79	447.08
Resin	21.61	36.95	58.56	64.41		
Hardner	3.33	1.11	4.43	4.88		
Water (added)	91.62		91.62	100.78		
Total wt	116.55	777.02	893.58	982.94		
Important For Calculations						
.631Wr+Wo = Dry board Wt		Wh/Wr =	0.08			
.389Wr + Wwa = Weight of Water		Wr/Wo =	0.08			
Wt of water/ Wt of solid = MC						
0.611Wr/Wo = RC		Wo =	738.97			
Wr - Wt of resin		Wr =	58.56			
Wo - Wt dry wood residue		Wh =	4.43			
Wwa - Wt of water added						

Note:

Wr = Dry weight of resin

Wo = Dry weight of wood residue

RC = Resin content (as a percentage of dry weight of wood residue)

Wwa = Extra water need to be added into the mix

Wh = Weight of hardener

APPENDIX C

Density profile data used for developing VDP

Displacement	ST1R	ST2R	ST3R	ST4R	ST5R	ST6R	ST7R	ST8R	ST9R	ST10R	ST11R	ST12R	ST13R	ST14R	ST15R	ST16R
0.00	276.06	226.65	186.69	188.19	212.13	253.81	182.59	219.72	236.05	252.79	254.87	254.11	251.49	232.20	210.59	179.20
0.10	521.24	427.48	401.41	332.54	564.41	479.84	280.02	341.59	399.74	497.88	663.30	365.72	304.00	488.84	512.44	452.86
0.20	627.68	665.05	613.17	493.59	787.51	658.79	361.91	456.13	564.25	727.12	795.62	488.80	425.89	626.49	641.49	649.30
0.30	689.95	772.05	753.49	599.58	914.94	758.28	436.07	600.15	635.87	808.26	872.47	580.07	536.81	651.43	641.39	745.27
0.40	749.73	819.36	793.58	668.61	954.88	763.69	493.44	683.30	658.68	859.19	924.78	678.30	654.89	681.15	668.27	828.54
0.50	761.56	839.61	829.47	720.90	994.83	752.81	573.54	791.69	662.01	887.59	956.14	747.98	707.07	679.12	708.65	878.46
0.60	800.32	869.73	860.84	737.88	1018.85	793.97	663.01	830.46	680.12	916.39	933.12	829.79	742.83	694.55	730.60	897.67
0.70	832.81	896.16	892.82	762.05	1026.93	803.24	689.43	859.83	698.80	925.14	975.03	888.62	765.86	733.07	721.61	928.73
0.80	843.86	897.48	907.99	777.53	1034.74	794.30	738.17	856.85	696.88	915.81	999.61	950.61	765.51	720.29	717.53	944.65
0.90	868.90	936.75	923.30	811.91	1078.43	834.06	743.59	883.69	716.63	916.13	1006.22	954.68	786.57	744.23	741.57	942.12
1.00	878.52	925.45	934.04	812.06	1046.74	847.30	773.44	900.45	753.00	892.77	986.80	985.01	791.70	753.89	763.87	939.98
1.10	850.84	940.73	941.34	841.60	1049.05	865.18	794.98	896.83	770.22	916.05	1020.68	944.41	805.75	763.50	749.47	927.77
1.20	869.29	938.93	955.77	843.17	1048.01	864.34	822.25	885.01	738.62	909.28	1005.40	969.66	821.42	750.14	779.09	928.93
1.30	841.89	946.11	957.20	870.04	1030.68	870.10	809.95	912.41	732.83	867.30	1032.81	964.54	809.50	783.50	778.69	903.40
1.40	857.54	935.93	954.98	851.59	1028.84	872.47	811.54	887.63	780.76	866.37	1031.91	961.86	835.92	774.59	791.51	921.44
1.50	834.78	938.77	966.25	859.26	1004.49	877.62	839.20	912.99	779.25	848.41	1035.69	924.36	821.14	753.44	778.87	876.61
1.60	841.09	938.34	931.80	880.52	1023.60	885.03	840.83	907.80	787.62	850.79	1032.93	917.75	848.83	786.06	800.13	857.36
1.70	805.08	941.62	944.07	883.71	1027.20	890.39	835.33	896.66	798.90	824.89	1012.02	900.54	855.80	775.15	794.15	839.67
1.80	798.68	966.56	940.31	891.51	994.78	882.45	851.50	924.27	809.41	822.14	1008.91	890.97	833.86	793.39	815.18	827.12
1.90	770.98	973.62	926.83	901.10	987.23	910.14	857.81	883.60	816.26	839.21	1020.08	869.72	831.55	786.82	784.35	812.14
2.00	748.28	963.89	937.17	893.99	987.63	900.17	854.89	918.48	825.23	823.56	989.48	829.78	844.20	801.79	790.78	768.73
2.10	713.26	944.13	921.69	906.36	971.36	888.80	865.11	882.33	851.42	811.13	995.02	799.60	855.86	824.16	762.68	748.19
2.20	682.12	959.14	899.56	915.97	967.70	876.82	844.90	890.10	828.12	808.00	988.26	804.75	844.87	804.31	774.66	725.22

Displa-cement	ST1R	ST2R	ST3R	ST4R	ST5R	ST6R	ST7R	ST8R	ST9R	ST10R	ST11R	ST12R	ST13R	ST14R	ST15R	ST16R
2.30	688.34	952.21	885.22	901.55	961.87	876.36	840.05	881.91	823.76	784.02	970.69	763.40	848.38	792.26	770.73	717.60
2.40	653.83	955.62	870.03	918.47	937.05	869.58	828.87	900.26	822.22	801.31	972.73	728.16	844.98	784.44	792.31	682.03
2.50	652.51	974.57	861.80	912.02	927.42	890.46	824.55	856.15	840.64	744.22	962.46	711.51	831.38	779.52	767.82	675.90
2.60	611.28	947.18	848.67	892.87	950.26	890.73	815.35	846.48	800.77	770.14	969.50	697.89	818.06	773.32	782.40	655.98
2.70	618.69	918.07	866.13	884.20	929.93	871.62	816.60	832.00	803.60	763.82	945.13	680.99	828.17	788.59	766.50	635.50
2.80	599.38	887.84	872.28	879.29	919.85	854.29	768.64	826.28	794.19	758.07	953.85	650.80	830.15	753.04	754.62	620.03
2.90	588.53	874.73	837.32	871.55	921.00	816.56	768.13	797.83	792.84	768.55	904.21	659.20	817.93	735.10	784.59	624.44
3.00	574.92	849.45	833.42	870.01	915.74	847.96	740.90	798.76	761.59	764.90	901.86	632.72	804.08	751.17	751.23	594.94
3.10	560.18	850.11	829.10	867.00	908.19	820.21	765.42	781.13	757.32	779.41	912.66	587.77	812.58	738.30	732.16	598.94
3.20	557.63	829.38	820.05	818.07	892.13	796.51	752.59	761.16	748.34	764.21	891.02	602.80	794.04	692.38	754.15	567.75
3.30	522.76	824.85	818.93	824.15	879.15	791.55	711.30	756.01	735.35	728.65	868.96	570.73	769.06	722.72	766.00	540.13
3.40	540.43	819.28	802.94	814.93	863.78	800.00	692.14	758.54	748.64	726.64	855.11	575.09	775.67	690.29	737.48	519.67
3.50	549.65	805.20	800.79	828.65	851.25	778.47	679.32	733.22	691.12	710.60	859.90	582.07	765.60	704.78	754.33	516.71
3.60	531.32	787.94	784.08	767.05	853.54	759.09	639.30	736.37	683.97	714.04	829.37	584.56	775.38	680.31	745.33	487.88
3.70	535.11	797.05	779.05	787.87	817.47	780.81	662.59	737.61	695.60	733.96	830.82	587.12	739.92	695.74	738.99	467.11
3.80	519.91	771.66	778.39	766.63	812.89	757.29	633.87	715.96	671.30	704.05	786.26	580.19	746.89	669.53	709.05	495.26
3.90	521.38	773.77	772.89	758.87	777.10	775.53	586.63	694.48	674.10	711.56	790.97	587.33	757.18	675.17	702.74	480.44
4.00	509.07	771.23	772.53	743.81	767.52	772.60	603.29	715.58	677.12	664.10	780.22	596.74	729.56	649.88	679.54	461.25
4.10	500.42	764.22	767.25	710.13	769.48	792.16	610.38	697.10	696.21	699.93	783.12	570.36	745.13	647.68	652.13	475.11
4.20	522.87	760.64	752.60	700.08	780.02	762.40	586.19	706.74	665.49	675.81	745.81	586.02	750.87	633.46	641.13	443.19
4.30	495.68	737.69	756.54	726.11	742.05	779.77	579.93	700.60	667.34	672.64	753.40	592.38	748.73	636.44	647.79	453.03
4.40	508.24	722.65	737.29	693.90	736.34	736.97	553.41	688.78	647.83	654.30	759.15	595.44	758.86	634.36	619.87	458.06
4.50	515.71	731.41	732.36	722.64	735.96	714.92	587.25	653.41	645.96	626.14	757.03	620.17	728.48	619.71	620.01	447.98
4.60	500.42	728.01	724.40	706.71	697.47	737.45	579.05	669.55	652.03	651.94	740.67	604.26	750.15	606.51	598.76	439.58
4.70	502.54	751.57	720.16	720.92	707.70	732.00	551.73	659.67	642.14	652.80	737.25	588.94	723.04	597.59	608.97	432.65
4.80	485.13	737.22	718.71	720.63	720.03	718.56	569.29	649.14	659.33	650.26	732.68	612.43	742.73	612.48	600.04	455.60
4.90	481.38	724.45	716.00	717.46	708.89	730.04	569.50	648.54	630.29	634.83	726.33	615.64	720.87	585.60	576.51	482.00
5.00	482.98	730.75	704.59	722.47	712.87	742.77	571.29	638.02	638.01	635.68	727.89	597.10	739.95	597.59	596.97	449.41
5.10	488.40	731.62	713.59	705.66	719.64	721.76	562.70	669.96	615.15	635.73	718.52	604.15	729.22	599.44	580.45	454.62
5.20	493.51	720.18	702.82	711.06	699.01	718.53	569.55	643.39	625.56	617.06	730.33	605.25	716.81	590.51	582.75	443.42
5.30	494.97	708.68	722.63	694.70	686.16	717.77	585.38	650.54	617.92	623.57	707.19	602.98	734.71	595.55	582.63	454.30
5.40	501.64	727.12	710.61	695.64	697.44	711.06	582.76	627.65	632.37	581.24	724.83	613.75	709.10	588.75	595.17	460.67

Displa-cement	**ST1R**	**ST2R**	**ST3R**	**ST4R**	**ST5R**	**ST6R**	**ST7R**	**ST8R**	**ST9R**	**ST10R**	**ST11R**	**ST12R**	**ST13R**	**ST14R**	**ST15R**	**ST16R**
5.50	488.60	727.04	701.96	717.02	718.82	711.89	580.28	638.08	617.29	623.42	711.79	612.62	751.74	589.53	573.92	471.72
5.60	504.92	697.23	687.52	691.15	676.34	725.66	609.85	635.98	633.18	598.93	708.66	607.09	745.50	576.92	571.09	470.40
5.70	480.86	687.91	707.49	678.82	701.52	701.00	588.36	622.75	603.45	604.23	703.00	600.22	728.70	570.26	568.74	463.35
5.80	500.92	692.33	680.31	697.93	703.69	719.16	587.42	618.55	626.69	610.37	717.95	590.82	730.71	562.60	579.20	465.14
5.90	476.65	718.24	720.19	690.71	689.66	726.25	585.60	625.47	603.45	590.12	681.96	615.65	744.49	591.03	558.30	447.99
6.00	509.54	689.77	691.26	716.58	702.82	693.77	597.41	614.76	623.67	589.73	705.46	584.13	710.46	598.30	570.60	467.19
6.10	452.65	701.03	693.85	705.54	681.85	708.58	588.71	615.35	651.55	583.58	694.02	582.67	705.93	578.32	595.45	454.39
6.20	491.85	680.38	692.57	687.30	666.17	718.68	596.92	582.07	613.44	582.90	671.54	569.39	712.27	598.62	584.81	459.96
6.30	498.25	670.01	682.53	688.20	660.66	699.74	592.03	623.14	611.48	579.19	689.74	580.68	702.61	596.76	583.66	461.49
6.40	498.87	673.09	698.90	681.57	654.88	716.54	577.25	640.39	593.43	575.75	669.61	580.33	698.43	590.26	568.80	470.97
6.50	514.46	679.57	690.17	681.09	657.63	688.95	608.64	622.60	613.05	572.43	657.42	572.03	712.94	599.71	575.78	476.49
6.60	510.10	669.31	681.32	679.30	643.29	705.39	579.34	625.23	601.30	569.90	659.81	579.54	710.78	593.71	575.91	463.03
6.70	525.26	663.70	670.50	660.18	675.17	691.88	589.44	640.92	600.57	555.83	646.94	575.53	702.22	583.39	567.43	464.49
6.80	494.39	672.37	681.94	670.19	649.00	724.39	568.15	641.56	601.95	545.06	683.17	542.75	690.23	596.06	573.55	468.69
6.90	501.74	667.50	705.08	658.44	636.58	693.38	593.15	618.31	603.24	578.12	666.81	557.27	725.16	587.57	563.21	467.14
7.00	499.70	669.39	698.43	659.08	658.16	707.48	575.54	632.93	584.31	551.49	685.27	549.69	710.15	604.52	589.32	449.72
7.10	496.22	658.60	693.01	671.87	672.36	645.25	558.56	637.87	588.14	557.10	684.80	534.64	717.31	615.74	607.19	453.31
7.20	479.14	648.37	667.23	670.49	650.86	668.96	563.10	631.61	625.04	562.51	697.77	531.87	694.54	609.97	574.90	453.28
7.30	488.87	669.85	672.07	674.95	650.59	670.49	572.20	638.12	606.26	593.67	696.83	525.18	702.37	615.66	583.53	463.11
7.40	486.34	688.45	697.60	680.13	670.18	672.87	577.04	634.88	616.35	546.64	687.21	513.17	706.69	616.14	583.35	469.72
7.50	482.32	683.71	696.75	665.20	670.58	697.70	594.56	609.44	600.63	554.43	680.52	514.35	711.71	628.47	564.19	463.68
7.60	509.72	674.96	676.80	652.28	688.41	691.05	581.93	622.75	610.67	570.50	661.47	516.96	707.65	597.69	575.25	457.42
7.70	500.11	693.33	681.76	650.10	688.16	707.82	589.54	619.49	606.85	547.91	672.02	514.57	698.06	605.44	569.58	448.67
7.80	503.56	678.03	669.90	670.80	668.87	667.90	550.04	603.80	596.31	549.06	673.07	522.27	701.26	579.89	542.29	451.32
7.90	476.31	682.86	685.27	655.93	667.27	700.42	575.32	637.91	601.42	548.06	656.12	497.10	689.51	591.08	559.01	420.57
8.00	500.05	659.38	661.80	645.60	664.01	681.92	588.60	613.17	583.32	531.74	691.36	485.10	668.12	583.32	555.39	445.88
8.10	493.75	675.75	682.72	661.75	658.28	690.01	562.55	621.24	583.01	539.04	683.20	489.89	680.63	592.94	539.19	464.66
8.20	498.41	669.52	680.59	679.11	681.80	691.09	569.32	645.04	574.87	537.11	666.72	474.23	693.11	575.71	537.26	456.67
8.30	521.12	692.19	679.16	641.58	650.65	703.24	555.47	635.79	586.36	538.18	660.38	488.56	700.36	593.46	545.04	458.82
8.40	520.05	666.89	663.17	634.02	672.69	671.64	556.50	634.56	563.10	510.70	667.71	481.10	683.98	610.25	548.84	466.25
8.50	516.21	676.91	668.59	644.28	657.42	680.55	575.30	631.72	585.60	550.41	669.13	516.07	685.55	596.86	548.59	460.59
8.60	499.56	668.84	664.54	647.11	667.19	680.82	569.17	615.57	556.62	558.17	666.34	514.34	708.99	617.05	556.61	484.83

Displa-cement	ST1R	ST2R	ST3R	ST4R	ST5R	ST6R	ST7R	ST8R	ST9R	ST10R	ST11R	ST12R	ST13R	ST14R	ST15R	ST16R
8.70	515.58	688.51	658.53	623.19	651.20	680.81	552.37	615.76	553.94	566.25	678.73	525.40	719.12	593.09	531.70	458.34
8.80	481.66	692.51	677.80	651.57	672.68	680.29	574.91	613.31	555.33	558.64	665.34	536.26	744.42	603.87	546.41	461.16
8.90	491.27	675.18	662.94	657.09	664.11	671.42	564.57	606.73	582.47	572.70	684.32	534.59	703.63	610.75	527.81	437.23
9.00	513.05	689.04	667.55	637.65	669.82	689.29	588.34	618.30	568.35	554.77	690.08	536.63	723.89	621.84	519.36	457.12
9.10	475.02	685.02	660.63	652.94	682.19	688.41	565.82	614.92	575.28	531.86	700.88	540.79	726.32	604.04	543.09	437.83
9.20	500.77	677.01	665.12	646.46	676.96	694.36	580.29	610.13	582.87	541.97	721.37	550.96	745.71	605.77	527.88	441.48
9.30	459.57	699.48	683.01	659.51	688.91	704.10	592.06	600.65	568.68	563.42	694.02	524.98	720.60	632.37	537.09	485.58
9.40	483.20	690.91	686.06	649.69	677.55	722.75	570.67	594.84	580.28	536.91	715.33	527.04	730.54	585.09	563.33	491.64
9.50	483.91	660.96	653.59	642.94	696.60	725.33	577.30	631.50	583.78	561.87	726.67	496.33	751.65	584.69	586.76	458.34
9.60	488.81	680.20	694.07	642.70	698.97	714.47	583.58	618.87	590.47	536.65	730.41	539.56	721.95	604.30	554.68	487.89
9.70	492.47	683.33	679.72	639.24	696.15	714.53	570.58	606.76	555.27	567.86	757.46	509.18	722.37	582.99	568.23	453.00
9.80	508.27	678.07	678.61	655.78	698.84	705.01	578.01	628.73	590.99	550.19	742.50	500.88	755.73	597.23	575.70	476.07
9.90	489.38	697.08	699.30	642.34	662.13	706.77	582.90	636.79	573.55	566.65	736.44	503.51	726.16	602.63	548.69	458.89
10.00	490.03	705.66	687.79	665.74	645.25	716.08	584.02	620.75	581.87	572.30	754.16	517.55	743.91	592.33	554.40	471.09
10.10	470.63	710.92	713.16	649.53	664.80	710.76	605.85	622.60	577.20	578.36	763.88	521.40	743.04	596.77	557.54	468.20
10.20	491.10	695.58	699.83	652.28	693.39	690.75	599.53	633.40	563.99	604.00	789.83	516.76	738.89	587.88	535.15	482.91
10.30	480.35	718.39	705.02	635.82	642.79	713.51	601.04	655.80	598.38	630.54	783.05	501.66	761.56	590.07	536.02	452.73
10.40	496.16	710.26	679.75	641.29	665.12	711.83	587.52	620.87	584.52	636.39	773.01	499.67	745.99	594.11	544.72	468.67
10.50	481.17	726.73	712.49	635.16	660.55	701.86	585.51	642.98	589.27	627.03	763.99	495.93	758.08	593.76	535.62	469.56
10.60	498.90	708.84	738.42	687.23	652.20	719.87	588.72	628.41	589.19	624.54	799.29	501.82	755.85	575.48	555.06	469.27
10.70	494.56	723.64	720.16	682.56	697.63	714.15	574.52	615.12	573.64	610.95	812.61	508.41	728.97	590.93	545.64	449.91
10.80	488.46	724.99	713.23	681.60	712.72	727.05	571.56	626.66	584.66	653.24	792.25	526.01	747.50	602.04	564.58	475.83
10.90	499.60	722.37	718.63	686.93	665.17	736.65	573.56	634.56	563.75	672.97	783.70	524.86	785.06	593.27	542.48	463.07
11.00	496.76	749.86	700.84	670.61	718.10	716.25	587.96	636.30	590.50	649.21	795.46	550.43	790.56	598.87	556.91	454.19
11.10	483.61	754.05	730.42	702.94	709.83	724.58	594.38	635.75	600.74	645.50	836.40	528.26	755.62	611.50	547.08	478.31
11.20	504.03	730.68	732.29	664.61	700.82	753.21	594.04	638.83	587.24	671.30	785.58	524.47	783.74	618.74	547.78	454.53
11.30	496.05	754.45	723.19	681.78	698.21	761.42	573.92	660.08	584.29	654.33	813.56	543.23	800.31	608.30	542.17	459.32
11.40	480.31	745.60	743.76	680.57	733.37	740.13	571.26	675.40	616.37	688.66	818.37	542.06	789.90	582.12	557.74	432.99
11.50	480.76	759.17	752.72	672.06	718.51	740.08	556.42	678.90	623.65	696.74	803.26	568.76	794.10	628.56	549.86	476.08
11.60	501.70	760.65	756.79	699.85	744.10	774.08	581.67	676.27	627.42	697.89	819.58	547.50	780.03	606.16	546.23	445.74
11.70	490.63	774.54	748.08	664.62	769.23	774.00	582.46	664.06	602.17	688.57	832.06	544.94	774.05	608.91	551.13	465.60
11.80	507.30	782.21	763.40	670.64	778.37	764.88	579.63	668.17	608.73	713.97	840.13	551.10	802.77	598.48	556.58	455.74

Displa-cement	ST1R	ST2R	ST3R	ST4R	ST5R	ST6R	ST7R	ST8R	ST9R	ST10R	ST11R	ST12R	ST13R	ST14R	ST15R	ST16R
11.90	510.27	768.76	771.09	700.33	833.17	767.03	588.85	697.31	615.18	709.56	825.44	565.79	797.12	606.25	567.34	454.33
12.00	485.48	795.24	780.18	682.15	804.80	781.13	581.69	700.80	622.14	697.37	852.69	567.16	820.85	594.80	564.82	442.46
12.10	490.97	796.69	771.14	689.16	834.56	782.91	578.31	697.69	611.25	703.61	850.63	561.02	829.03	605.28	552.77	451.27
12.20	507.81	797.13	776.88	705.66	836.05	812.75	590.78	740.96	625.78	700.05	856.75	584.16	831.14	623.13	567.58	445.22
12.30	490.18	794.48	789.94	710.60	894.27	799.39	581.06	712.73	618.14	714.64	835.89	594.67	828.86	636.75	554.75	435.79
12.40	502.36	778.18	801.85	712.97	874.39	809.58	582.73	729.23	600.53	720.48	875.36	587.84	854.61	605.28	570.16	440.02
12.50	501.65	812.89	806.30	723.63	878.82	796.80	596.23	732.65	625.43	737.25	881.19	580.77	853.01	612.03	566.25	447.58
12.60	528.92	794.83	808.04	731.61	926.12	788.54	585.59	743.07	610.30	703.87	861.38	567.12	859.94	652.11	548.89	447.81
12.70	500.61	802.28	813.70	722.82	915.81	793.12	590.35	743.61	637.49	732.26	877.26	580.05	866.53	640.08	563.63	464.64
12.80	495.26	801.32	823.44	742.16	924.92	805.86	592.56	738.60	653.59	743.07	884.36	589.07	885.43	632.07	567.26	448.89
12.90	510.12	808.99	865.95	730.04	932.45	800.33	577.07	753.31	628.23	752.10	897.21	585.50	888.74	642.38	569.36	460.61
13.00	524.21	811.75	855.77	750.41	953.01	833.90	593.34	774.91	649.52	758.50	902.73	594.76	913.02	638.78	567.85	451.92
13.10	523.53	849.44	846.05	767.42	960.92	816.19	572.56	793.22	644.81	785.40	924.16	580.16	931.29	644.10	585.79	453.44
13.20	535.98	833.26	873.49	776.52	952.58	823.99	584.00	829.37	663.40	797.86	902.86	592.13	932.11	645.30	595.52	431.56
13.30	549.66	842.00	906.55	777.48	967.06	836.13	571.67	859.46	655.09	775.75	925.13	606.49	940.02	666.74	599.55	414.25
13.40	534.29	869.96	867.27	818.40	969.06	855.00	600.78	881.54	643.14	792.11	931.52	587.73	947.27	662.34	625.55	427.64
13.50	541.13	877.04	870.80	842.72	977.39	855.32	601.62	858.72	644.74	820.32	922.06	590.82	959.09	661.56	615.88	424.00
13.60	537.76	888.13	898.19	816.21	990.92	848.63	622.46	871.42	664.65	790.16	946.87	592.35	979.27	696.46	638.46	425.11
13.70	542.81	900.95	926.67	836.13	980.22	868.75	631.37	890.61	704.90	828.97	914.58	572.59	974.24	688.11	649.74	428.91
13.80	544.36	883.15	935.80	849.25	999.13	862.31	654.27	892.18	663.28	799.23	915.13	572.05	945.15	692.80	652.32	426.04
13.90	571.07	898.06	931.14	867.17	990.16	839.45	653.09	882.92	686.61	833.79	898.26	568.41	946.98	736.40	667.71	443.43
14.00	557.75	892.75	949.68	845.47	1009.32	851.20	659.02	923.31	698.75	832.65	892.29	586.56	961.58	710.00	669.38	441.11
14.10	555.83	890.86	942.15	837.46	1028.56	823.00	698.90	912.43	693.75	867.90	877.07	613.47	962.37	737.43	687.31	464.06
14.20	552.83	879.72	960.02	868.50	1013.30	857.16	682.40	932.02	717.69	858.45	863.12	606.65	931.89	739.80	723.20	425.19
14.30	591.75	874.16	918.83	829.75	1020.56	856.04	701.91	911.30	730.02	870.84	861.82	612.02	892.60	756.58	728.76	439.86
14.40	563.39	883.91	946.27	846.39	1000.25	844.96	710.66	937.14	722.85	886.51	819.49	633.54	868.67	788.03	755.00	428.12
14.50	612.47	856.07	921.44	855.17	980.90	831.91	705.01	923.22	737.91	891.06	820.08	631.36	828.13	769.89	770.38	397.04
14.60	644.88	824.93	943.98	869.09	975.77	838.80	720.24	895.67	755.03	897.72	772.97	618.37	800.71	776.01	761.49	405.68
14.70	652.92	788.16	936.79	865.86	967.43	798.41	719.43	920.82	757.23	886.89	734.99	625.26	747.53	768.77	765.71	412.33
14.80	687.47	769.39	906.75	842.29	907.67	824.26	751.19	937.15	757.34	864.57	697.68	646.33	606.07	768.75	796.51	429.03
14.90	707.13	730.80	881.17	836.98	857.61	791.97	729.99	928.50	760.93	887.98	629.58	622.44	518.32	783.80	794.25	437.40
15.00	730.69	654.24	837.47	844.63	819.60	770.49	760.03	925.34	750.62	893.93	410.58	636.37	412.00	776.38	817.39	416.83

Displa-cement	**ST1R**	**ST2R**	**ST3R**	**ST4R**	**ST5R**	**ST6R**	**ST7R**	**ST8R**	**ST9R**	**ST10R**	**ST11R**	**ST12R**	**ST13R**	**ST14R**	**ST15R**	**ST16R**
15.10	742.64	523.10	811.03	812.46	766.58	745.07	776.49	902.89	763.69	872.11	99.08	620.07	289.48	813.62	835.42	414.71
15.20	760.27	301.31	754.94	821.22	646.83	730.31	779.27	866.44	786.84	897.58		640.88		809.02	839.36	401.15
15.30	788.57	77.12	670.68	823.79	457.53	735.74	770.71	893.07	765.33	841.59		640.73		803.34	818.56	409.75
15.40	816.84		520.17	829.61	178.23	674.20	814.22	793.54	778.13	810.03		637.59		775.82	794.69	413.94
15.50	821.31		375.31	800.11		540.04	834.89	688.46	750.86	722.96		642.33		791.91	823.35	425.61
15.60	814.53		190.47	773.93		359.54	847.72	560.52	772.67	589.04		672.25		762.34	818.95	415.03
15.70	818.92			777.59		192.05	877.25	441.33	763.37	383.23		683.14		756.83	820.91	415.50
15.80	802.66			723.05			874.61	259.74	752.47	113.22		706.29		770.06	801.64	463.44
15.90	815.80			704.80			856.64	121.10	735.29			723.16		763.42	811.59	450.51
16.00	789.22			678.18			880.88		729.24			756.34		771.84	799.16	481.24
16.10	786.99			661.33			869.92		729.33			759.48		748.47	838.68	472.60
16.20	789.81			630.77			868.61		724.81			754.75		751.36	817.44	513.92
16.30	751.43			574.45			845.71		710.57			783.59		719.57	769.33	521.84
16.40	746.77			471.04			835.99		726.08			808.31		694.18	772.23	527.76
16.50	710.97			348.84			810.02		705.00			808.97		701.45	773.26	526.95
16.60	697.43			227.38			830.68		675.49			822.13		696.49	792.44	558.21
16.70	648.61						787.67		672.40			855.29		703.12	763.94	563.60
16.80	554.18						773.22		634.81			891.86		671.15	750.36	575.96
16.90	468.40						754.53		582.21			885.18		645.69	707.07	591.64
17.00	368.09						703.01		514.96			908.46		649.86	706.26	610.11
17.10	268.82						674.62		419.94			932.73		604.47	672.77	629.48
17.20	197.12						614.16		330.18			922.90		573.40	653.48	635.35
17.30							531.26		222.03			937.15		356.41	596.78	649.04
17.40							498.80		195.50			975.86		80.46	550.64	702.65
17.50							394.86					974.45			362.50	700.50
17.60							256.52					985.19			159.56	724.14
17.70												971.52				722.14
17.80												948.15				728.86
17.90												930.35				722.29
18.00												851.42				744.79
18.10												781.37				744.30
18.20												670.64				754.44

Displa-cement	**ST1R**	**ST2R**	**ST3R**	**ST4R**	**ST5R**	**ST6R**	**ST7R**	**ST8R**	**ST9R**	**ST10R**	**ST11R**	**ST12R**	**ST13R**	**ST14R**	**ST15R**	**ST16R**
18.30												548.58				742.08
18.40												422.72				761.70
18.50												341.13				770.72
18.60												230.72				801.19
18.70																808.07
18.80																794.60
18.90																816.62
19.00																840.66
19.10																862.58
19.20																905.94
19.30																882.99
19.40																875.42
19.50																894.43
19.60																907.55
19.70																918.27
19.80																895.64
19.90																880.61
20.00																868.23
20.10																831.50
20.20																733.87
20.30																601.07
20.40																406.99
20.50																226.17

APPENDIX D

Density profile data used to validate VDP

Displacement	RSM1	RSM2	RSM3	RSM4	RSM5	RSM6	RSM7	RSM8	RSM9	RSM10	RSM11	RSM12	RSM13	RSM14	RSM15
0.00	280.73	175.67	149.57	167.27	171.67	226.92	214.93	200.43	232.05	223.10	143.97	251.92	201.40	217.46	164.35
0.10	515.88	647.21	539.62	508.69	511.51	398.38	481.26	361.11	338.41	377.70	441.35	539.96	627.69	615.72	443.44
0.20	728.37	789.74	801.32	749.86	630.15	569.98	684.37	548.33	426.42	497.92	629.73	680.57	731.42	719.35	613.54
0.30	789.94	844.91	910.30	896.40	663.86	736.05	820.61	663.20	530.42	653.48	728.35	750.58	808.74	736.65	673.99
0.40	836.18	889.88	933.75	919.81	734.86	823.46	866.82	719.83	637.27	724.26	795.53	770.18	844.89	776.75	699.59
0.50	892.54	914.42	957.52	980.22	773.15	894.73	889.81	766.77	678.94	770.64	836.54	781.39	889.70	838.92	731.88
0.60	914.99	962.54	967.80	1001.41	820.26	918.55	923.84	753.34	706.97	807.71	875.87	815.96	906.22	841.18	772.24
0.70	942.65	997.84	966.21	998.05	853.03	914.49	935.57	771.87	724.87	857.89	889.56	826.25	919.67	852.81	800.30
0.80	929.42	1001.37	952.28	1017.46	879.18	913.11	946.86	814.22	754.93	859.73	908.32	868.26	956.22	899.33	816.53
0.90	959.71	1006.88	954.16	984.54	899.30	928.82	937.51	822.44	772.66	890.93	910.73	888.79	948.04	902.22	847.03
1.00	909.62	1016.20	943.53	990.72	887.01	941.69	962.27	832.54	770.93	886.40	907.63	866.63	945.82	921.54	855.07
1.10	926.14	997.11	902.86	984.09	893.40	956.67	948.62	836.00	784.53	896.99	911.82	903.07	907.92	909.52	863.08
1.20	942.52	991.97	890.81	985.00	910.10	929.98	946.19	854.94	784.50	922.24	927.01	912.68	910.06	927.17	883.26
1.30	907.58	1014.00	880.46	963.46	916.04	951.18	944.40	835.56	781.09	923.96	895.04	927.43	881.66	916.56	875.52
1.40	924.24	1009.27	893.47	974.42	887.41	938.04	929.89	844.96	780.90	889.35	914.27	893.87	901.47	938.58	873.88
1.50	913.11	985.74	865.05	959.42	898.51	932.62	895.84	842.02	802.19	887.00	909.42	886.83	867.16	917.74	869.46
1.60	915.08	958.46	869.43	957.12	889.84	889.55	930.45	833.77	796.58	881.88	884.71	882.21	877.57	895.62	867.04
1.70	882.68	979.54	879.70	957.58	884.40	920.78	907.60	830.44	812.47	899.42	901.56	904.36	864.16	891.03	873.68
1.80	883.11	939.90	844.80	951.85	896.84	896.38	904.38	848.00	828.57	870.75	870.87	900.21	854.17	903.54	872.04
1.90	899.37	953.65	870.77	949.65	900.69	884.43	893.39	862.25	812.70	862.20	892.88	910.05	887.34	896.06	849.08
2.00	886.19	949.49	840.10	924.09	871.03	868.67	895.93	846.77	792.39	883.43	885.81	915.33	885.13	908.02	868.71
2.10	858.92	933.03	849.42	904.47	855.28	890.66	874.23	826.27	815.47	854.19	872.16	864.33	855.13	890.78	819.74
2.20	873.89	919.55	855.17	910.73	857.68	865.27	888.34	843.02	793.47	847.96	866.33	866.36	862.99	868.11	832.53
2.30	842.91	893.15	853.90	916.41	842.56	854.06	858.39	838.57	800.56	836.19	856.24	878.80	818.35	852.51	816.18
2.40	843.73	899.31	851.86	908.64	830.26	853.56	851.29	834.90	811.94	836.36	840.49	861.46	843.38	869.65	829.13
2.50	860.68	871.99	837.43	913.21	828.78	835.14	832.99	834.02	811.45	830.67	844.74	841.16	842.29	828.85	802.83

Displacement	**RSM1**	**RSM2**	**RSM3**	**RSM4**	**RSM5**	**RSM6**	**RSM7**	**RSM8**	**RSM9**	**RSM10**	**RSM11**	**RSM12**	**RSM13**	**RSM14**	**RSM15**
2.60	818.12	869.27	826.24	883.93	810.43	846.24	831.85	819.02	793.60	828.27	856.59	840.58	833.97	840.33	788.48
2.70	845.57	837.52	834.03	896.86	821.00	825.51	827.09	792.13	803.21	810.12	835.22	808.42	814.27	853.43	799.95
2.80	828.95	837.50	820.88	872.46	813.48	820.70	834.59	822.23	813.39	841.09	856.24	831.40	810.89	826.15	799.88
2.90	789.76	848.83	796.58	878.24	794.14	834.88	835.62	831.30	802.35	815.96	837.59	813.98	808.98	834.27	764.21
3.00	817.05	823.92	779.98	877.01	783.91	822.94	804.53	780.40	800.04	818.68	845.50	801.10	783.76	842.95	769.87
3.10	821.93	831.62	790.35	877.15	757.35	825.84	831.02	794.21	797.05	789.71	854.27	806.04	776.60	825.05	748.97
3.20	797.35	801.59	764.51	860.55	750.41	793.27	798.63	786.19	771.11	746.16	835.22	811.58	770.42	816.40	737.93
3.30	780.81	812.65	778.97	883.13	741.08	802.00	775.50	768.87	761.27	741.42	829.47	801.52	772.73	827.63	748.29
3.40	768.41	824.18	752.47	862.46	727.91	785.89	769.01	789.71	777.94	736.30	816.13	777.99	784.82	805.69	727.02
3.50	737.17	810.18	731.14	847.70	726.87	770.32	772.80	792.48	756.06	744.33	801.95	769.12	774.62	812.20	739.78
3.60	737.43	775.58	768.63	833.15	719.31	753.71	758.72	787.00	761.08	733.31	800.89	774.41	769.34	813.45	728.22
3.70	739.04	744.71	745.88	824.95	731.70	748.39	781.00	761.60	769.73	729.19	800.52	762.05	772.07	805.18	724.21
3.80	728.33	751.64	716.54	829.27	706.42	751.30	754.56	739.42	760.57	720.25	776.15	759.53	733.26	802.12	739.20
3.90	728.26	786.62	707.98	789.01	706.62	742.46	748.80	783.59	753.97	728.79	799.25	760.58	745.42	800.14	711.56
4.00	723.61	786.56	703.04	787.97	718.19	727.81	749.64	742.39	733.62	724.43	787.60	748.62	736.41	753.29	702.50
4.10	716.54	765.11	694.89	802.46	689.87	745.85	746.78	760.13	743.67	757.54	787.09	765.50	752.49	796.96	726.76
4.20	706.94	775.63	691.29	760.99	691.48	748.08	701.42	763.43	731.10	731.45	770.02	752.25	747.91	751.55	708.58
4.30	691.75	748.58	689.00	750.22	715.38	748.12	723.09	762.25	723.23	735.09	763.50	738.33	711.48	749.08	730.82
4.40	699.96	759.48	715.96	738.40	702.60	727.58	712.88	762.78	741.56	741.14	758.01	747.82	713.24	740.73	692.51
4.50	703.06	751.44	686.38	733.57	667.72	733.24	738.57	745.38	704.38	737.37	747.26	743.95	708.04	754.46	701.66
4.60	716.04	731.69	687.58	728.21	708.68	729.37	731.63	721.75	736.08	728.09	754.42	723.93	727.67	726.27	681.72
4.70	679.20	738.72	669.54	728.81	686.87	707.87	715.09	743.37	734.11	723.87	741.89	718.55	718.07	753.28	692.03
4.80	689.42	735.50	638.48	721.92	674.12	755.10	705.23	742.94	721.83	720.53	734.13	721.01	726.59	722.99	697.27
4.90	663.01	748.03	633.35	719.44	662.21	720.34	720.84	737.48	716.02	700.28	730.59	683.20	744.83	713.67	673.11
5.00	700.69	723.05	669.34	730.98	651.16	722.48	699.82	727.93	694.25	699.66	724.46	699.74	703.80	716.00	718.49
5.10	682.66	739.24	633.98	715.21	649.28	729.64	720.39	732.03	713.17	701.27	709.03	693.72	705.92	747.42	676.54
5.20	700.59	720.49	652.37	715.26	645.80	699.69	713.76	716.88	676.61	710.92	694.69	703.33	721.28	724.88	698.79
5.30	697.38	737.03	623.38	733.03	656.36	707.90	727.61	716.12	714.74	703.14	730.77	663.18	705.84	726.00	677.33
5.40	685.75	722.10	636.25	685.10	660.03	699.49	723.42	706.97	684.91	699.31	715.52	704.71	701.95	733.83	677.13
5.50	681.17	718.63	641.46	711.49	642.95	716.23	742.83	719.55	691.92	727.73	721.04	691.59	698.46	723.40	678.64
5.60	679.46	689.54	656.76	697.69	626.43	706.31	708.01	725.53	677.91	718.19	714.73	691.57	713.48	724.43	652.82
5.70	684.64	708.94	624.87	694.95	626.65	695.45	714.97	699.30	672.29	715.37	719.01	696.14	681.48	722.23	703.91
5.80	681.98	698.68	637.08	703.59	640.27	679.12	701.99	703.14	661.70	691.02	716.88	693.95	677.08	710.82	674.80

Displacement	RSM1	RSM2	RSM3	RSM4	RSM5	RSM6	RSM7	RSM8	RSM9	RSM10	RSM11	RSM12	RSM13	RSM14	RSM15
5.90	685.48	672.41	629.45	719.98	676.33	681.40	681.66	717.65	682.62	711.46	695.10	708.35	676.84	737.93	688.25
6.00	665.16	717.09	633.02	690.03	623.37	689.92	703.97	695.80	675.15	712.46	690.98	675.26	681.33	720.17	681.25
6.10	684.29	686.38	669.55	692.52	653.51	688.30	687.92	685.68	673.97	696.68	692.43	688.52	685.70	709.05	661.14
6.20	678.68	679.22	631.62	690.72	637.50	687.47	708.03	701.36	691.03	666.41	725.26	675.67	679.83	727.73	686.35
6.30	684.91	690.00	631.05	679.25	641.82	687.16	686.50	674.00	651.74	682.43	682.92	666.30	689.56	740.91	672.85
6.40	678.09	707.07	651.01	687.66	634.91	710.50	691.99	676.13	679.16	671.27	705.83	696.70	682.51	729.58	669.91
6.50	696.50	694.08	628.09	693.96	659.18	688.21	690.54	698.30	652.02	695.71	697.63	683.69	681.75	732.82	650.65
6.60	692.04	696.66	629.53	670.41	647.84	690.63	695.08	676.03	652.44	687.90	682.10	672.69	671.89	721.17	645.72
6.70	679.13	692.02	611.96	700.42	626.24	703.21	687.62	677.43	647.45	686.45	695.94	693.46	672.46	731.23	635.10
6.80	699.82	689.10	651.43	687.66	640.74	683.61	694.49	663.68	663.75	688.11	690.45	684.61	670.67	749.05	659.24
6.90	659.99	672.00	636.83	672.82	635.86	677.78	668.92	672.34	644.78	671.08	671.58	676.70	661.83	732.43	663.64
7.00	669.35	704.02	626.51	691.74	647.11	703.78	682.40	673.30	680.10	670.31	697.24	681.62	655.82	728.79	638.36
7.10	660.07	689.32	613.22	672.82	635.21	686.46	675.11	660.89	667.19	665.84	707.76	669.42	644.81	762.22	663.12
7.20	676.70	699.84	618.76	690.07	640.17	673.67	695.88	654.03	647.86	698.86	694.26	700.39	637.14	735.76	644.80
7.30	671.54	673.90	604.85	692.08	648.09	668.30	665.99	670.82	661.89	670.96	683.23	693.36	655.96	731.10	686.66
7.40	665.86	681.38	614.59	678.89	643.96	685.82	697.72	669.60	662.39	704.08	680.32	695.27	667.88	727.55	648.59
7.50	687.42	662.49	627.16	684.11	649.12	697.31	689.89	672.59	657.59	672.02	697.07	670.74	661.03	722.11	640.10
7.60	669.11	672.98	639.35	678.58	635.45	686.31	690.16	671.46	657.22	695.43	678.51	685.07	660.99	740.88	638.27
7.70	673.88	669.27	640.39	673.27	641.47	671.46	690.49	666.37	656.71	676.08	675.53	673.84	677.34	739.43	637.97
7.80	680.79	680.25	655.89	676.41	640.70	704.29	669.27	650.94	652.79	703.07	680.42	680.16	681.58	734.63	650.23
7.90	655.89	690.95	658.84	700.98	639.69	697.76	691.39	675.53	667.75	691.93	669.66	667.18	665.40	747.11	656.94
8.00	675.01	709.42	646.47	674.52	638.03	689.46	694.29	646.01	665.54	681.20	709.06	709.45	659.97	751.09	644.54
8.10	664.50	686.86	653.62	688.34	634.44	682.42	696.83	643.99	643.22	666.58	682.56	695.43	669.13	733.82	641.37
8.20	675.15	691.30	624.55	679.28	653.52	691.61	685.20	659.51	651.12	655.95	719.07	700.41	660.12	730.65	663.23
8.30	655.18	710.43	655.01	691.36	641.29	698.29	692.42	646.92	638.57	658.26	699.70	697.23	667.07	739.18	623.42
8.40	665.33	663.83	648.74	690.63	639.73	694.72	685.66	650.09	653.01	682.47	685.08	687.30	651.31	739.01	648.62
8.50	661.95	696.37	670.48	703.47	654.65	706.14	710.83	674.69	652.68	685.38	716.23	687.87	666.82	732.27	638.20
8.60	668.82	694.32	657.49	708.82	651.84	722.31	712.34	663.24	679.68	670.94	685.39	703.48	689.09	751.12	656.06
8.70	660.51	680.25	689.14	721.22	621.82	700.34	685.48	661.43	660.51	661.33	695.05	676.56	685.67	742.69	663.39
8.80	698.61	704.01	647.12	719.57	645.83	685.65	696.10	661.82	673.69	711.93	691.27	701.05	685.96	716.76	685.34
8.90	682.13	690.76	648.98	710.12	650.22	706.14	707.01	663.48	628.10	699.53	709.49	689.68	681.45	722.70	660.37
9.00	678.47	692.60	653.46	711.52	626.03	681.27	702.05	674.06	655.49	685.33	692.96	672.47	672.55	739.94	662.14
9.10	658.91	706.95	668.90	713.99	628.98	709.05	715.37	670.48	650.53	677.13	702.37	667.62	697.95	732.74	636.90

Displacement	**RSM1**	**RSM2**	**RSM3**	**RSM4**	**RSM5**	**RSM6**	**RSM7**	**RSM8**	**RSM9**	**RSM10**	**RSM11**	**RSM12**	**RSM13**	**RSM14**	**RSM15**
9.20	690.82	693.33	677.50	702.68	634.30	699.76	716.37	678.63	662.36	704.73	709.40	693.15	699.75	735.54	672.01
9.30	694.06	676.07	634.12	718.85	637.34	729.61	695.96	665.83	669.28	681.19	710.45	693.21	691.74	746.83	681.59
9.40	650.10	691.54	656.34	694.10	627.57	684.69	698.62	693.22	667.04	692.67	712.76	694.37	718.58	710.77	675.16
9.50	681.46	682.16	661.74	695.63	637.99	724.33	741.35	678.16	653.98	701.56	707.30	697.70	705.64	723.82	668.43
9.60	696.95	692.66	671.13	738.93	628.99	710.43	717.06	682.14	675.21	686.64	717.56	700.60	725.26	733.92	693.70
9.70	716.17	696.49	651.58	735.86	627.23	706.14	740.96	663.30	694.20	692.79	701.32	714.97	711.43	744.65	687.23
9.80	700.27	708.06	667.31	733.03	627.30	727.56	726.49	704.65	670.14	690.21	717.79	714.94	693.33	725.88	698.59
9.90	680.60	708.69	666.86	736.85	644.76	719.77	713.57	676.20	678.73	710.40	713.60	709.59	698.60	753.37	679.81
10.00	696.60	711.22	672.46	728.68	652.42	720.59	722.84	694.26	673.07	702.59	734.68	707.24	707.65	741.23	716.43
10.10	722.85	718.48	677.16	709.57	670.78	721.73	715.29	700.98	683.92	725.33	727.78	729.60	709.63	734.21	708.34
10.20	706.06	721.78	676.49	726.54	698.80	720.38	714.90	704.74	664.83	690.69	740.03	721.19	708.92	731.90	701.28
10.30	705.87	694.92	684.07	745.29	658.23	697.07	704.06	680.78	683.07	693.95	740.45	735.82	726.78	776.49	694.85
10.40	733.92	729.17	658.68	761.85	693.08	728.63	736.65	719.19	649.03	686.00	722.57	751.00	695.43	756.40	708.35
10.50	723.55	729.19	680.01	737.58	681.02	725.31	740.06	741.08	681.02	726.13	754.26	730.99	733.16	754.54	698.50
10.60	727.81	739.26	694.22	748.50	695.27	746.49	722.17	709.92	682.97	712.02	735.82	744.28	743.61	769.86	726.02
10.70	739.82	749.45	702.02	773.92	681.36	737.74	757.12	714.53	679.66	719.39	746.42	752.98	727.06	758.28	728.31
10.80	718.48	759.60	670.85	770.05	701.82	736.45	731.99	698.07	663.07	720.25	782.55	746.33	728.18	786.59	727.19
10.90	742.86	765.19	685.62	764.98	691.40	746.57	738.00	717.30	680.90	711.56	749.40	783.75	745.33	776.88	717.28
11.00	770.25	749.22	671.76	783.16	707.86	743.74	743.62	741.21	708.74	717.80	774.10	775.93	739.36	787.19	719.62
11.10	761.81	747.92	665.68	778.36	695.27	739.36	741.78	739.70	687.66	743.70	748.66	776.78	755.03	789.81	724.54
11.20	765.00	771.80	685.39	812.66	697.27	741.14	738.65	743.91	736.69	742.05	750.97	774.70	739.24	795.41	724.56
11.30	753.18	755.34	708.03	811.15	706.46	764.12	741.94	730.53	707.11	750.90	741.67	785.83	737.15	780.30	755.73
11.40	748.90	759.98	703.08	846.68	703.02	743.85	776.17	758.46	707.54	741.11	757.94	810.98	734.19	816.72	756.45
11.50	764.97	800.41	695.18	835.35	706.47	758.88	753.82	780.55	742.40	759.78	748.72	792.91	754.68	827.51	769.45
11.60	776.51	770.64	716.61	840.45	719.47	767.01	763.80	772.94	767.39	758.53	772.69	797.46	757.96	818.88	757.79
11.70	756.36	814.72	719.97	849.43	750.38	754.79	766.48	772.66	757.34	770.09	790.87	812.75	769.27	841.72	763.99
11.80	753.19	815.34	714.29	864.14	729.81	769.88	777.10	758.67	782.85	786.52	755.44	815.45	800.67	839.40	784.04
11.90	775.45	821.15	724.54	861.02	735.08	781.64	779.50	792.98	776.53	754.17	799.89	811.65	791.26	839.45	797.15
12.00	808.26	814.37	732.35	866.71	750.37	817.03	788.20	780.37	767.22	767.66	790.71	824.03	774.07	864.34	791.86
12.10	799.56	859.61	748.52	893.12	743.48	782.37	795.46	781.63	796.70	764.61	822.68	839.88	824.04	851.84	817.05
12.20	799.98	863.72	748.94	899.48	762.90	798.99	802.45	786.71	779.62	778.30	808.58	830.74	811.91	869.27	817.66
12.30	814.30	875.02	769.23	904.20	761.49	802.02	831.81	801.67	784.58	771.89	798.37	839.71	821.93	861.98	835.07
12.40	811.41	871.36	787.30	922.61	767.68	822.39	817.23	800.81	784.87	778.82	791.39	829.81	840.65	893.27	836.08

Displacement	**RSM1**	**RSM2**	**RSM3**	**RSM4**	**RSM5**	**RSM6**	**RSM7**	**RSM8**	**RSM9**	**RSM10**	**RSM11**	**RSM12**	**RSM13**	**RSM14**	**RSM15**
12.50	828.64	896.88	780.52	929.99	805.74	835.95	837.92	828.00	785.97	773.16	789.81	847.95	857.81	873.06	856.57
12.60	842.20	896.00	812.27	937.41	780.12	838.17	826.88	828.27	796.36	807.18	771.64	874.73	860.95	876.49	853.13
12.70	830.32	896.95	836.15	949.23	792.19	850.66	860.18	833.68	811.68	834.40	815.09	851.93	865.40	880.06	871.62
12.80	848.40	916.09	833.67	973.75	810.06	844.45	873.77	837.90	814.14	814.45	822.80	851.72	885.31	895.67	844.80
12.90	846.08	915.49	852.42	982.95	842.40	857.60	862.15	860.83	824.09	843.02	818.28	895.73	883.06	878.92	881.97
13.00	864.95	917.72	843.19	971.38	834.34	886.82	860.84	858.49	818.58	821.64	843.82	885.72	927.03	873.77	875.25
13.10	852.44	913.43	851.75	973.85	855.25	847.48	892.69	861.80	848.74	841.82	865.81	896.24	918.34	873.10	886.77
13.20	859.72	934.79	840.03	990.99	878.29	877.86	889.96	873.66	816.02	836.04	883.97	916.83	930.03	852.72	866.32
13.30	892.54	921.57	865.56	1010.46	883.30	883.90	909.36	885.39	831.23	853.52	850.24	908.30	930.05	868.81	881.41
13.40	898.14	933.89	866.82	1001.27	880.29	888.91	900.66	869.40	825.55	879.58	878.15	912.02	954.01	846.65	898.70
13.50	895.42	940.35	884.98	1001.07	893.15	917.83	905.74	881.04	830.22	874.50	871.44	913.25	968.12	850.43	906.64
13.60	906.71	936.07	890.80	1037.96	895.89	905.59	909.81	868.04	797.52	890.02	890.29	894.93	936.51	830.17	882.25
13.70	934.61	953.49	893.25	1004.21	883.46	906.55	914.04	880.25	822.49	868.75	870.36	905.19	948.80	790.83	888.82
13.80	918.59	953.18	933.71	1018.26	882.71	915.04	913.62	875.73	789.45	890.94	883.10	898.32	964.54	791.36	895.26
13.90	926.42	952.34	904.89	1010.66	904.67	891.87	886.69	898.68	794.36	875.95	913.36	895.01	941.37	742.98	919.17
14.00	938.28	962.96	919.38	989.27	882.65	920.99	881.58	886.72	784.71	878.60	874.01	860.85	942.99	705.36	894.11
14.10	933.49	937.72	916.73	993.53	882.81	865.86	880.27	865.46	807.33	850.09	890.20	798.96	932.38	657.13	891.77
14.20	932.43	885.25	883.16	949.72	854.12	833.08	852.63	833.25	767.76	852.51	871.23	776.98	915.00	418.19	880.61
14.30	949.73	871.86	868.57	763.21	844.29	774.86	791.39	818.87	766.38	824.38	863.24	741.01	841.87	61.49	860.10
14.40	922.16	833.76	810.29	530.96	815.79	661.43	677.42	802.09	747.78	817.79	821.88	701.37	796.35		845.07
14.50	914.95	783.64	680.06	328.41	790.88	557.19	509.66	790.27	718.09	794.62	798.97	660.05	732.67		808.94
14.60	881.53	744.65	423.79		736.91	399.76	330.30	738.42	727.92	777.05	756.28	637.42	674.62		754.33
14.70	860.10	652.25	242.92		704.58	285.30	144.97	717.39	724.81	663.79	713.72	434.68	369.91		715.48
14.80	806.93	269.45			400.13	128.30		646.63	692.77	548.82	643.71	94.92	24.44		704.19
14.90	753.68				42.08			531.72	610.28	371.10	507.65				558.14
15.00	445.17							396.25	518.08	291.40	310.44				179.08
15.10	104.04							198.04	391.67						
15.20									246.91						
15.30									159.35						
15.40															
15.50															
15.60															
15.70															

APPENDIX E

Results of the Preliminary (Trial) Boards made using only the hot pressing (with out using the cold press)

Press Temperature = 195 ^{o}C   Pressing time = 300 Seconds

Target Density (kg/m^3)	Actual Density (kg/m^3)	Moisture Surface (%)	Moisture Core (%)	Resin Surface (%)	Resin Core (%)	MOR (Mpa)	MOE (Mpa)	IB (kPa)	Screw Withdrawal	
									Face (kPa)	Edge (kPa)
680		15	9	10.5	8.5	3.51	526.44			
				12.5	10.5	3.97	578.26			
				15	13	6.5	1057.4			
680		15	9	10.5	8.5	2.83	389.91			
				12.5	10.5	2.83	462.73			
				15	13	3.67	564.1			
680		15	9	10.5	8.5	5.51	1343.54			
				12.5	10.5	3.96	1046.66			
				15	13	3.4	479.27			
700				15	13	6.8	1157.4			
680		15	15.7	15	13	7.61	984.75	584.14	740	988.5
720		15	15.7	15	13	6.12	1035.42			
760	815.26	15	15.7	15	13	9.03	1184.68	517.04	756.00	1187.50
800		15	15.7	15	13	9.14	1185.76		709	1112.15

Target Density (kg/m^3)	Actual Density (kg/m^3)	Moisture Surface (%)	Moisture Core (%)	Resin Surface (%)	Resin Core (%)	MOR (Mpa)	MOE (Mpa)	IB (kPa)	Screw Withdrawal	
									Face (kPa)	Edge (kPa)
680		15	17.25	15	13	9.41	1192.79		684	1053.5
720	747.29	15	17.25	15	13	6.8	1015.80		650.00	1187.00
760		15	17.25	15	13	7.78	1123.56			
800	786.26	15	17.25	15	13	8.56	1168.00	503.34	667.00	1141.50
840	843.32	15	17.25	15	13	9.86	1680.60		831	1330
800		15	15.7	15	13	9.14	1185.76	584.14	709	1112.15
800	859.55	18	15.7	15	13	12.00	1650.67	671.04	972.00	1655.00
800	783.96	21	15.7	15	13	7.91	1392.88	769.00	654.70	1078.00
800	892.52	24	15.7	15	13	11.95	1715.47	473.54	708.00	1101.00
680	748.07	15	13	15	13	5.55	785.78	394.61	648.00	1051.50
720	751.15	15	13	15	13	8.13	1195.43	565.75	524.00	892.50
760	755.39	15	13	15	13	5.39	757.58		750.70	1333.70

APPENDIX F

Density profile against process parameter used to model VDP

Board Number	Moisture Surface	Resin Surface	Resin Core	Hardener Load	Pressing Time (s)	Press Temperature	Density at 5%	Density at 10%	Density at 20%	Density at 30%	Density at 40%	Density at 50%
ST 1	11	8	5	1	120	150	810.165	803.870	542.395	495.38	491.045	499.56
ST 2	11	20	5	3	300	200	876.775	910.960	821.965	725.825	689.02	674.96
ST 3	22	8	13	3	300	150	899.785	957.965	817.7	719.395	687.79	669.9
ST 4	11	8	13	3	120	200	750.29	863.455	780.115	711.16	672.52	641.58
ST 5	22	20	13	1	120	200	1005.255	997.325	905.005	719.86	671.565	688.16
ST 6	11	20	13	1	300	150	793.135	854.015	814.895	724.125	711.245	667.91
ST 7	22	8	5	3	120	200	765.63	863.055	669.17	584.055	582.13	574.91
ST 8	22	20	5	1	300	150	891.095	922.470	749.88	644.58	627.32	637.91
ST 9	11	20	13	3	120	150	710.815	791.040	694.935	618.405	584.415	553.94
ST 10	22	8	5	1	300	200	904.87	854.620	791.64	651.005	570.53	531.74
ST 11	22	20	13	3	300	200	930.715	991.280	876.245	760.51	697.77	680.52
ST 12	22	8	13	1	120	150	963.1	862.505	611.745	600.925	529.055	524.98
ST 13	11	8	13	1	300	200	848.875	870.715	820.805	853.875	717.175	711.71
ST 14	11	20	5	1	120	200	722.84	765.990	721.105	606.82	590.84	617.05
ST 15	11	8	5	3	300	150	752.755	797.895	738.765	568.69	562.47	531.7
ST 16	22	20	5	3	120	150	910.99	755.405	501.435	454.15	448.575	471.09