EXPERIMENTAL DESIGN ON ENGINEERED WOOD: LAMINATED VENEER LUMBER (LVL) REINFORCED COMPOSITES

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A Thesis Submitted in Partial Fulfillment of the Requirements of the Degree of Master of Engineering in Polymer Engineering

Suranaree University of Technology

Academic Year 2009

การศึกษากระบวนการผลิตไม้วิศวกรรมชนิดไม้ท่อนวีเนียร์ซ้อนทับเสริมแรงด้วยวัสดุเส้นใยผ้าเสริมแรง

นางสาวยุมาทร มิ่งมงคล

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิศวกรรมมหาบัณฑิต
สาขาวิชาวิศวกรรมพอลิเมอร์
มหาวิทยาลัยเทคโนโลยีสุรนารี
ปีการศึกษา 2552

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Suranaree University of Technology has approved this thesis submitted in partial fulfillment of the requirements for a Master's Degree.

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โดยใช้พื้นฐานทางด้านคุณสมบัติเชิงกลและการยืนยันโดยการวิเคราะห์ทางสถิติ (ANOVA) ในขั้นแรกได้ออกแบบการทดลองเพื่อหาตัวแปรที่มีผลกระทบของวัตถุดิบที่ใช้ พบว่า ชนิดของกาว ชนิดของไม้ อัตรกิริยาระหว่างชนิดของไม้กับชนิดของกาว และอัตรกิริยาระหว่างชนิดของไม้กับชนิดของเส้นใยผ้าเสริมแรงมีผลอย่างมีนัยสำคัญต่อค่าโมดูลัสของการกดอัด โดยที่ชนิดของไม้มีผลมากที่สุด รองลงคือชนิดของกาว และที่มีผลน้อยที่สุดคือชนิดของเส้นใยผ้าเสริมแรง จากการประเมินชี้ให้เห็นว่าไม้ยางพารา กาวชนิดที่แข็งตัวที่อุณหภูมิห้องและเส้นใยคาร์บอนให้ค่าคุณสมบัติที่ดีขึ้น จากผลของการศึกษาอิทธิพลของปริมาณไซเลนและการทรีทเมนต์ที่ผิวหน้าของไม้โดยวิธีการรมควันและใช้น้ำยากันปลวกแสดงให้เห็นว่าอัตรกิริยาระหว่างปริมาณไซเลนกับไม้ที่ใช้น้ำยากันปลวกจะส่งผลต่อค่าความแข็งแรงอย่างมีนัยสำคัญ อัตรกิริยาระหว่างปริมาณไซเลนกับไม้ที่ได้ผ่านการทรีทเมนต์ก็จะส่งผลต่อค่าโมดูลัสด้วย นอกจากนี้อัตรกิริยาระหว่างไม้ที่ผ่านการรมควันกับไม้ที่ทาด้วยน้ำยากันปลวกและอัตรกิริยาระหว่างปริมาณไซเลนกับไม้ที่ผ่านการรมควันก็ยังมีผลต่อค่าความเหนียวอย่างมีนัยสำคัญเช่นกัน ดังนั้นจึงต้องใช้ไซเลนในปริมาณมากคือ 15% โดยน้ำหนักผสมในน้ำยาทำแข็งและใช้ไม้ที่ผ่านการรมควันเท่านั้นเพื่อให้ได้ค่าคุณสมบัติเชิงกลที่ดีที่สุด โดยที่สภาวะของการแข็งตัวที่ดีที่สุดคือที่อุณหภูมิ 70°C โดยใช้แรงกดอัดที่ 15 บาร์เป็นเวลา 60 นาที และจากการพิจารณาพารามิเตอร์ในกระบวนการแข็งตัวพบว่าแรงกดอัดจะมีผลอย่างมีนัยสำคัญที่สุด การที่จะเพิ่มคุณสมบัติเชิงกลให้ดีขึ้นจะต้องลดแรงกดอัดให้น้อยลง นอกจากนี้ยังพบว่าเวลาที่ใช้ในการกดอัดก็มีผลอย่างมีนัยสำคัญด้วยเช่นกันคือคุณสมบัติเชิงกลจะมีค่าเพิ่มขึ้นเมื่อใช้เวลาในการกดอัดนานขึ้น และจากการทดสอบคุณสมบัติความทนทานของไม้ท่อนวีเนียร์ซ้อนทับเปรียบเทียบกับไม้ท่อน 3 ชนิดคือ ไม้สัก ไม้ยางพาราและไม้ยูคาลิปตัส พบว่าไม้ท่อนธรรมดา (ยกเว้นไม้ยูคาลิปตัส) มีความทนทานต่อการดูดซึมของน้ำน้อยกว่าไม้ท่อนวีเนียร์ซ้อนทับและนอกจากนี้ยังพบว่าไม้ท่อนธรรมดา (ยกเว้นไม้สัก) จะมีความทนทานต่อการกัดกินของปลวกน้อยกว่าไม้ท่อนวีเนียร์ซ้อนทับ ยิ่งไปกว่านั้นยังพบว่าค่าความแข็งแรงที่ทนต่อแรงยึดสกรูของไม้ท่อนวีเนียร์ซ้อนทับมีค่ามากกว่าไม้ท่อนธรรมดา

สาขาวิชาวิศวกรรมพอลิเมอร์ | ลายมือชื่อนักศึกษา ยุมาทร มิ่งมงคล

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YUMATORN MINGMONGKOL : EXPERIMENTAL DESIGN ON ENGINEERED WOOD: LAMINATED VENEER LUMBER (LVL) REINFORCED COMPOSITES. THESIS ADVISOR : ASST. PROF. UTAI MEEKUM, Ph.D., 157 PP.

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The mechanical properties justification and also confirmed by the statistical analyses (ANOVA), first step of the 2^k DOE on the effect of raw materials, it was found that adhesive type, wood species, interaction between wood species and fiber type, and interaction between wood species and adhesive type had the significant effects on the flexural modulus. The most significant effect corresponding to the modulus was adhesive followed by wood species vice versa the fiber type. The rubber wood, room temperature cure adhesive, and carbon fiber gave rise to the better properties. The influence of the silane contents and wood surface treatments by mean of smoking and applying the anti termite treatment indicated that the interaction between silane quantity and anti termite application were significant influence on the flexural strength of the LVL composites. The interaction between silane and both wood surface treatments were also significant effect on the modulus properties. The interaction between smoked wood and applying anti termite on wood surface, interaction between silane quantity and smoked wood were also significant effects on the toughness properties. High quantity of silane, 15% w/w, addition to curing agent and only smoked wood should be employed to achieve the maximum properties in the production of LVL reinforced composites. The optimal curing condition was achieved at low pressure, 15 bar, low temperature, 70°C, and long curing time, 60 mins. Pressure was the most significant negative effect on the product properties. Improve in the mechanical properties was related to decreased pressure. Beside, press time was also the significant positive effect. The mechanical properties were increase with increasing press time in curing process. The durability test results of the LVL composite compared to the solid woods, teak, rubber wood and eucalyptus, suggested that the solid woods, except eucalyptus, had low water absorption resistance compared to LVL reinforced. Also solid woods, except teak, had low resistance to termite attack. In addition, the withdrawal strength of LVL reinforce composite was higher than the solid woods.

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Academic Year 2009 Advisor's Signature ______

ACKNOWLEDGMENTS

This thesis could not have been finished without a great help from Asst. Prof. Dr. Utai Meekum, my thesis advisor. I am grateful to him for all of his supporting information and useful advice, which helped me pass through my difficult times. I also thank him for his hard-working effort in correcting my thesis and encouraging me to complete my work.

I am grateful thanks and sincere appreciations to the chairperson, Asst. Prof. Dr. Pranee Chumsamrong and special thanks go to the committeeman is Assoc. Prof. Dr. Sitthichai Seangatith for his valuable suggestions and encouragements me towards end of this thesis.

I am also special thanks to all the faculty and staff members of the school of Polymer Engineering and colleagues for their hospitality and assistance throughout the period of this study.

Most importantly, I would like to express my deepest gratitude to my parents and members of family for their love, understanding, supports and encouragements. In addition, I am really appreciate The Center of Excellent for Petroleum, Petrochemical and Advanced materials, for the sponsorship throughout my course of study at Suranaree University of Technology.

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SYMBOLS AND ABBREVIATIONS

%	=	Percent
kPa	=	Kilo Pascal
MPa	=	Mega Pascal
cm	=	Centimeter
mm	=	Millimeter
kJ	=	Kilo Joule
hrs	=	Hours
mins	=	Minutes
H_0	=	Null Hypothesis
H_1	=	Alternative Hypothesis
N	=	Newton
phr	=	Parts per Hundred Parts of Resin

CHAPTER I

INTRODUCTION

1.1 General Background

Wood is one of the oldest known materials used in construction, and it is the renewable building material. For many centuries, wood has been a natural construction material for homes and other structure including bridges, waterfront structures, electric and telephone lines poles, and many other uses (Faherty and Williamson, 1997). As a number of advantages such as simplicity in fabrication, lightness, reusability, and environmental compatibility have made this material one of the most popular in the lightweight construction. However, the fracture of wood in buildings may be caused by a function of age, environment or poor design. Moreover, moisture related expansion and shrinkage of timber warps and twists wood, lowering its strength and introduces localised stress concentrations within the structure. Also mould growth, and attacking of rot and insect breaks down the internal structure of wood in historic buildings thereby its mechanical functionality is reduced. However, nowadays, wood remains important to the engineer, the architect, and the builder by mean of improving in material technology. Modern technology has increased the durability and improved fastness with greater load-carrying capacity of wood, spurred a host of new wood products that called engineered wood.

Engineered wood product is also commonly called composite wood product, "man made wood" or "manufactured wood". It is combined by a range of derivative wood products. The engineered wood is normally manufactured by bonding the strands, particles, lumbers, veneers, or other forms of wood with gules or adhesives. It also includes wood bonds with non-wood materials or reinforcing wood. There are several types of engineered wood products. The performances of engineered wood products have greatly been expanded into many applications such as structural and industrial works. The engineer wood products can be typically divided into two groups; structural and non-structural engineered wood. The structural is a term used for a load-bearing member or element of a building. It is classified into four general subgroups: structural wood panel, glued laminated timber (glulam), structural composite lumber (SCL), and wood I-joists. Structural wood panels are the most commonly used engineered wood. It also have industrial applications such as concrete forming, pallets, crates, bins, transportation equipment, furniture, and boats. The major types of structural wood panels are plywood and oriented strand board (OSB) as illustrated in Figure 1.1.

(a) (b)

Figure 1.1 Structural wood panels: (a) plywood and (b) OSB.

Plywood is the original structural wood panel. It is manufactured from thin sheets of wood or veneers bonding together with adhesive. Veneers are arranged in alternately perpendicular layers that makes its excellent strength, stiffness and dimensional stability. For plywood, there are usually an odd number of layers, with the grain of the face layers, typically oriented parallel to the long dimension of the panel.

OSB is produced from rectangular shaped wood strands bonded with adhesives to form a mat. The wood strands of three to four inches in length are directionally oriented and the mats are pressed into the boards. Like the veneer in plywood, the layers of the mat are oriented perpendicular to each other for maximum strength, stiffness and stability.

Structural composite lumber (SCL) is an engineered wood product manufactured to substitute for sawn lumber. It is created by layering dried wood veneers or strands with adhesive into blocks of material known as billets. The orientation of each layer runs in the same direction, rather than cross-laminated as in structural wood panels. One important benefit of SCL is that the veneering and gluing process enables large timbers, which previously required large trees, to be made from relatively small trees of many species, thereby providing for efficient utilization of wood fiber resources. The types of SCL include; laminated veneer lumber (LVL), parallel strand lumber (PSL), and oriented strand lumber (OSL). LVL, PSL, and OSL are shown in Figure 1.2.

(a) (b) (c)

Figure 1.2 Structural composite lumber: (a) LVL, (b) PSL, and (c) OSL.

LVL is produced by bonding thin or thick wood veneers together into a larger billet so that the grain of all veneers is parallel to the long direction. The LVL billet is then sawn into desired dimensions depending on the construction application. LVL is the most widely used of the structural composite lumber products, particularly in header and beam applications. It has the potential to be used in structural and non-structural applications such as construction and furniture industries, material for flooring and numerous other areas (Eckelman, 1993, Hayashi and Oshiumi, 1993, Wong, Razali, and Kawai, 1996, and Ozarska, 1999). LVL is stronger in bending strength than lumber of equivalent size by a factor of two or more.

PSL is manufactured from long veneer strands laid in parallel and bonded together with an adhesive to form the finished structural section. Like LVL and GLULAM, it is used for beam and header applications where high bending strength is needed. PSL is also frequently used as load bearing columns.

OSL, similar to PSL, is made from flaked wood strands that have a high length-to-thickness ratio and it must longer than their thickness. Combined with an adhesive, the strands are oriented and formed into a large mat or billet and pressed. OSL is used in a variety of applications from studs to millwork components.

Glulam is created by bonding together the individual layers of lumber having a thickness of two inches (50 mm) or less. Individual pieces of lumber in these layers are finger-jointed together to create long lengths referred to as laminations. These laminations are then bonded together along their lengths to create the finished product. It can be shaped into forms ranging from straight beams to complex curved members, and is used in a wide variety of residential and nonresidential building construction applications. Some of the largest wood structures in the world have been framed using glulam components. Glulam and their finger-jointed studs are shown in Figure 1.3.

Figure 1.3 Glulam and finger-jointed studs.

Wood I-joists are comprised of two horizontal components called flanges and a vertical called a web illustrate in Figure 1.4. These products are manufactured by using sawn or structural composite lumber as flanges and structural panel as webs, bonded together with exterior exposure adhesives, forming an "I" cross-sectional shape. The I configuration provides high bending strength and stiffness characteristics. As I-shape takes advantage of the fact that most of a beam's stress is along the top and bottom edges. Since much material towards the center of the beam is unnecessary, it can be removed, saving weight and resources without sacrificing strength. I-joists require 50 percent less wood to make than a solid wood beam of the same strength. Wood I-joists are structural, load-carrying engineered wood products designed for long span applications. They are also used primarily as floor joists.

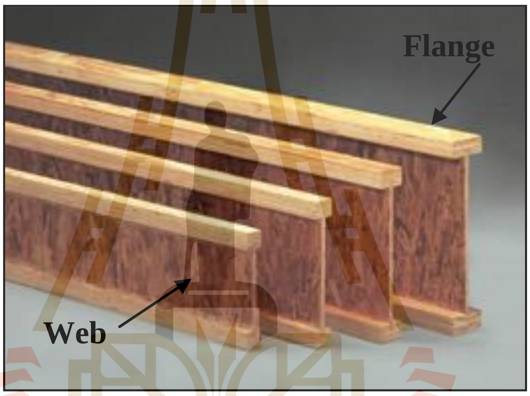


Figure 1.4 Wood I-joists.

Engineered wood products are getting popular in various applications, construction, furniture units, and indoor decorations. They are much more consistently reliable than solid wood and extremely stiff and strong, cost-effective, easy to use, and their predictable qualities lead to less rework. Besides, these products utilized what might previously have been wood waste, small pieces of wood, and wood that has defects, can be used in especially particle and fiber-based boards. They also have advantages being more dimensionally stable, less prone to humidity induced warping, and better looking than those of manufactured from solid wood. However, there are several factors affect to engineered wood properties. One of those is raw material used. In addition, bonding process is generally effect on product properties.

In this research work was focused on the raw materials used; wood species, adhesive and fiber types, which were used to manufacture the engineered wood, LVL reinforced composites, for outdoor furniture and perhaps construction materials. The effect of wood treatment such as smoking and anti termite incorporation, quantity of silane addition to enhance bond ability, and processing parameters were also interested. Expectedly, the outcome of this study could bring the clear understanding about the influence on those composite constituents and processing parameters required for the industrial scale manufacturing.

1.2 Research Objectives

The main objective of this research is to evaluate the influence of composite constituents and processing parameters on the performance properties of the LVL reinforced composites. An experimental design method was used to verify those parameters. The prime objectives of the research work could be categorized as follow;

(1) To study the effect of wood species, fiber and adhesive types on the mechanical properties of LVL reinforced composite.

(2) To evaluate the effect of silane quantity and wood surface treatments on the mechanical properties of the product.

(3) To investigate the influence of processing parameters on the final properties in order to optimize the properties of the final product.

1.3 Scope and Limitation of the Study

The main study of this research was to produce the engineered wood, LVL reinforced composite, for outdoor furniture and construction material applications. The purpose of this study was to investigate the effect of raw materials including wood species of veneer, fiber and adhesive types, silane quantity, wood surface treatments, and process parameters on the LVL reinforced composite properties. The mechanical properties by mean of flexural test of the product were measured. Also withdrawal strength of screw nail, water absorption and termite resistance testing were performed in order to certify the durability of the product. Teak, rubber wood, and eucalyptus veneers were used in this study. They were obtained from native economic farm forest. The glass and carbon woven fiber were used as reinforcement. Two adhesive systems, room temperature cure and prepreg epoxy system, were employed.

CHAPTER II

LITERATURE REVIEW

2.1 General Background

The engineered wood is one of the reliable materials. It has been successfully used in a variety of applications. Normally, they are produced from wood, adhesive and fiber reinforcement that are bonded together by pressure and heat. Thus, the properties of the product are depended on raw materials, wood, adhesive, and fiber reinforcement, and processing conditions.

In this chapter, the previous related to the engineered wood works are briefly discussed.

2.2 Engineered wood publications

According to the TISI, Thai industrial standards institute, TIS 178-2549, the standard for veneer plywood, the flexural strength and modulus of veneer plywood were reported in Table 2.1.

Table 2.1 Flexural strength and flexural modulus of veneer plywood.

Thickness (mm)	Flexural Strength (N/m^2)	Flexural modulus (N/m^2)
2.0 - 9.0	34	4500
9.0-12.0	26	4000
More than 12.0	24	3850

However, flexural strength and modulus value depend on standard of testing employed, the materials used and product structure. For example, plywood panels using poplar veneer and urea formaldehyde adhesive with three plies and having 6 mm thickness were evaluated according to the EN 310 standard having flexural strength and modulus at 58 MPa and 4812 MPa, respectively (Aydin, Colakoglu, Colak, and Demirkir, 2006).

The flexural strength at magnitude of 98.4 MPa of LVL was obtained from phenol formaldehyde adhesive and spruce veneer with 9 layers having dimension of 300 mm length, 20 mm width, and 16 mm thickness. Meanwhile the spruce solid wood itself showed the flexural strength at 88 MPa. All tests were performed according to refer DIN 52186 (Colak, Colakoglu, and Aydin, 2007).

The LVL was produced from beech and alder veneer having flexural strength at 100 MPa and 79 MPa, respectively. Melamine urea formaldehyde adhesive was employed and DIN 52186 was adopted (Toksoy, Colakoglu, and Aydin, 2006). They reported the modulus value at 7862 MPa and 6499 MPa from LVL using beech and alder veneer, respectively.

There are several research works to achieve the optimal properties that conduct the study on wood species, adhesive and fiber types which are mainly used as raw material for engineered wood. The processing conditions are also included in their works. They will be summarized in this report.

2.2.1 Veneer or peel woods

Most wood species can be utilized in engineered wood manufacturing. However, selection of wood species is important especially as raw material for general, structural and decorative industries. Due to difference species of wood have its own difference in characteristic such as mechanical properties and density. For example, a modulus of rupture at 12% moisture content of 19.3 MPa for balsa and 156 MPa for lapacho, both are South American wood species. Among the woods grown in the United States, there are also differences in mechanical properties but the difference are not great, coast Douglas fir show a modulus of rupture at 12% moisture content of 85.5 MPa, loblolly pine a value of 88.3 MPa and eastern hemlock a value of 64.3 MPa. Thus woods from different species are adaptable to various to use, depending on their mechanical and other properties (Faherty and Williamson, 1997).

Toksoy, Colakoglu, and Aydin (2006) studied the effect of alder veneer compare with beech veneer for plywood and LVL manufacturing by using MUF (melamine-urea-formaldehyde) adhesive. Beech logs were steamed for 20 hours before cutting due to it is hard to peel without steaming, whereas alder logs were not. The result of ANOVA proved that the effect of wood species of veneer on bending strength, modulus of elasticity and shear strength was significant. The mechanical values of plywood and LVL panels manufactured from beech veneer were higher than those manufactured from alder veneer. One of the reasons for this can be the higher specific gravity value of beech wood (0.68 g/cm^3) compared to alder wood (0.49 g/cm^3). However wood wettability and surface roughness also have significant effect on the shear strength of plywood (Aydin, 2004).

Celebi and Kilic (2007) evaluated screw and nail withdrawal strength properties of LVL manufactured from poplar (Populus nigra) and beech (Fagus orientalis L.) using two types of resins, PVAc (polyvinyl acetate emulsions) and PU (polyurethane). The results were found that layer thickness did not influence the withdrawal strength in transverse direction but strength values increased with increasing specific gravity of the samples in this direction.

A variety of low-grade plantation species has been studied for the production of LVL (Feng, Bao, and Fu, 1999). Thin veneers of three low density wood species, namely silver maple, yellow poplar and aspen, were used to evaluate in density, water absorption, thickness swelling, surface hardness and strength values. As the results, LVL of silver maple veneers showed an improving in properties as compared to yellow poplar and aspen. Silver maple can be used suitably in laminated veneer flooring.

Beside, where considerable proportions of juvenile material were presented in softwood, more significant shrinkage in the longitudinal direction had been experienced in comparison to that in mature wood.

2.2.2 Adhesives

There are several types of wood adhesives. The largest amounts of adhesives are used in the construction and building materials industry. They can be divided into two broad groups; natural adhesives and synthetic adhesives.

Natural adhesives are derived from natural sources rather than produced synthetically. They had widely used prior to World War II, but have been generally replaced by synthetic adhesives. The casein is still be used at present (Faherty and Williamson, 1997). The first wood adhesives based on synthetic polymers were produced commercially during the 1930s (Blomquist and Vick, 1977). These adhesives could not only be stronger, more rigid, and more durable than wood, but also have much greater resistance to water than adhesives from natural polymers.

Whether the base polymer is thermoplastic or thermosetting, it has a major influence on how an adhesive will perform in service.

Thermoplastics are long-chain polymers that soften and flow on heating, then harden again by cooling. They generally have less resistance to heat, moisture, and long-term static loading than thermosetting polymers. Common wood adhesives that are based on thermoplastic include polyvinyl acetate emulsions (PVAc), elastomerics, and hot-melts polymers.

Thermosetting polymers make excellent structural adhesives because they undergo irreversible chemical change on reheating. They do not soften and flow again. They form cross-linked polymers that have high strength, resist to moisture and other chemicals, and rigid enough to support high and long-term static loads without deforming. Phenolic, resorcinolic, melamine, polyurethane, urea, and epoxy are examples of these types of wood adhesives that based on thermosetting polymers.

Types of wood adhesive, along with their strength and durability, preparation, characteristics, and typical applications, are showed in Table 2.2 and 2.3 for natural and synthetic adhesive, respectively (Blomquist and Vick, 1977).

Table 2.2 Properties of typical uses in natural adhesives.

Type	Form and color	Preparation and application	Strength properties	Typical uses
Animal, protein	Solid and liquid; brown to white bond line	Solid form added to water, soaked, and melted; adhesive kept warm during application; liquid form applied directly; both pressed at room temperature; bonding process must be adjusted for small changes in temperature	High dry strength; low resistance to water and damp atmosphere	Assembly of furniture and stringed instruments; repairs of antique furniture
Blood, protein	Solid and partially dried whole blood; dark red to black bond line	Mixed with cold water, lime, caustic soda, and other chemicals; applied at room temperature; pressed either at room temperature or 120^{o}C (250^{o}F) and higher	High dry strength; moderate resistance to water and damp atmosphere and to microorganisms	Interior-type softwood plywood, some times in combination with soybean adhesive; mostly replaced by phenolic adhesive
Casein, protein	Powder with added chemicals; white to tan bond line	Mixed with water; applied and pressed at room temperature	High dry strength; moderate resistance to water, damp atmospheres, and intermediate temperatures; not suitable for exterior	Interior doors; discontinued use in laminated timber
Soybean, protein	Powder with added chemicals; white to tan, similar color in bond line	Mixed with cold water, lime, caustic soda, and other chemicals; applied and pressed at room temperatures, but more frequently hot pressed when blended with blood adhesive	Moderate to low dry strength; moderate to low resistance to water and damp atmospheres; moderate resistance to intermediate temperatures	Softwood plywood for interior use, now replaced by phenolic adhesive. New fast-setting resorcinol-soybean adhesives for finger jointing of lumber being developed

Table 2.2 Properties of typical uses in natural adhesives (Continued).

Type	Form and color	Preparation and application	Strength properties	Typical uses
Lignocellulosic residues and extracts	Powder or liquid; may be blended with phenolic adhesive; dark brown bond line	Blended with extender and filler by user; adhesive cured in hot-press 130°C to 150°C (266°F to 300°F) similar to phenolic adhesive	Good dry strength; moderate to good wet strength; durability improved by blending with phenolic adhesive	Partial replacement for phenolic adhesive in composite and plywood panel products

Table 2.3 Properties of typical uses in synthetic adhesives.

Type	Form and color	Preparation and application	Strength properties	Typical uses
Cross-linked polyvinyl acetate emulsion	Liquid, similar PVA emulsion but includes copolymers capable of cross-linking ; white to tan with colorless bond line	Liquid emulsion mixed with catalyst; cure at room temperature or at elevated temperature in hot press and radio-frequency press	High dry strength; improved resistance to moisture and elevated temperatures, particularly long-term performance in moisture	Interior and exterior doors; molding and architectural woodwork; cellulosic overlays
Elastomeric contact	Viscous liquid, typically neoprene or styrene-butadiene elastomers in organic solvent or water emulsion; tan to yellow	Liquid applied directly to both surfaces, partially dried after spreading and before pressing; roller-pressing at room temperature produces instant bonding	Strength develops immediately upon pressing, increase slowly over a period of weeks; dry strengths much lower than conventional adhesives; low water resistance	On-the-job bonding of decorative tops to kitchen counters; factory lamination of wood, paper, metal, and plastic sheet materials
Elastomeric mastic (construction adhesive)	Putty like consistency, synthetic or natural elastomers in organic solvent or latex emulsions; tan, yellow, gray	Mastic extruded in bead to framing members by caulking gun or like pressure equipment; nailing required to hold materials in place during setting and service	Strength develops slowly over several weeks; dry strength lower than conventional wood adhesives; resistant to water and moist atmospheres.	Lumber to plywood in floor and wall systems; laminate gypsum board and rigid foam insulating; assembly of panel system in manufactured homes

Table 2.3 Properties of typical uses in synthetic adhesives (Continued).

Type	Form and color	Preparation and application	Strength properties	Typical uses
Emulsion polymer/ isocyanate	Liquid emulsion and separate isocyanate hardener; white with hardener; colorless bond line	Emulsion and hardener mixed by user; reactive on mixing with controllable pot-life and curing time; cured at room and elevated temperatures; radio-frequency curable; high pressure required	High dry and wet strength; very resistant to water and damp atmosphere; very resistant to prolonged and repeated wetting and drying; adheres to metals and plastics	Laminated beams for interior and exterior use; lamination of plywood to steel metals and plastics; doors and architectural materials
Epoxy	Liquid resin and hardener supplied as two parts; completely reactive leaving no free solvent; clear to amber; colorless bond line	Resin and hardener mixed by user; reactive with limited pot-life; cured at room or elevated temperatures; only low pressure required for bond development	High dry and wet strength to wood, metal, glass, and plastic; formulations for wood resist water and damp atmospheres; eliminate with repeated wetting and drying; gap-filling	Laminating veneer and lumber in cold-molded wood boat hulls; assembly of wood in aircraft; lamination of architectural railings and posts; and for repairing laminated components
Hot melt	Solid blocks, pellets, ribbons, rods, or films; solvent-free; white to tan; near colorless bond line	Solid form melted for spreading; bond formed on solidification; requires special application equipment for controlling melt flow	Develops strength quickly on cooling; lower strength than conventional wood adhesives; moderate resistance to moisture.	Edge-banding of panels; plastic lamination; patching; film and paper overlays; furniture assembly
Isocyanate	Liquid contained isomers and oligomers of methylene diphenyl diisocyanate; light brown liquid and clear bond line	Adhesive applied directly by spray; reactive with water; requires high temperature and high pressure for best bond development in flake boards	High dry and wet strength; very resistant to water and damp atmosphere; adheres to metals and plastics	Flake boards; strand-wood products

Table 2.3 Properties of typical uses in synthetic adhesives (Continued).

Type	Form and color	Preparation and application	Strength properties	Typical uses
Melamine and melamine-urea	Powder with blended catalyst; may be blended up to 40% with urea; white to tan; colorless bond line	Mixed with water; cured in hot press at 120°C to 150°C (250°F to 300°F); particularly suited for fast curing in high-frequency presses	High dry and wet strength; very resistant to water and damp atmospheres	Primary adhesive for durable bonds in hardwood plywood; end-jointing of lumber; and scarf joining
Phenolic	Liquid, powder, and dry film; dark red bond line	Liquid blended with extenders and fillers by user; film inserted directly between laminates; powder applied directly to flakes in composites; all formulations cured in hot press at 120°C to 150°C (250°F to 300°F) up to 200°C (392°F) in flake board	High dry and wet strength; very resistant to water and damp atmospheres; more resistant than wood to high emperatures and chemical aging	Primary adhesive for exterior softwood plywood, flake board, and hardboard
Polyvinyl acetate emulsion	Liquid ready to use; often polymerized with other polymers; white to tan to yellow; colorless bond line	Liquid applied directly; pressed at room temperatures and in high-frequency press	High dry strength; low resistance to moisture and elevated temperatures; joints yield under continued stress	Furniture; flush doors; plastic laminates; panelized floor and wall systems in manufactured housing
Polyurethane	Low viscosity liquid to high viscositymastic; supplied as one part; two-part systems completely reactive; color varies from clear to brown; colorless bond line	Adhesive applied directly to one surface, preferably to water-misted surface; reactive with moisture on surface and in air; cures at room temperature; high pressure required, but only pressure from nailing	High dry and wet strength; resistant to water and damp atmosphere; limited resistance to prolonged and repeated wetting and drying; gap-filling	Construction adhesive for panelized floor and wall systems; laminating plywood to metal and plastic sheet materials; specialty laminates; installation of gypsum board

Table 2.3 Properties of typical uses in synthetic adhesives (Continued).

Type	**Form and color**	**Preparation and application**	**Strength properties**	**Typical uses**
Resorcinol and phenol-resorcinol	Liquid resin and powdered hardener (two parts); phenol may be copolymerized with resorcinol; dark red bond line	Liquid mixed with powdered or liquid hardener; resorcinol adhesives cure at room temperatures; phenol-resorcinols cure at temperatures from 21°C to 66°C (70°F to 150°F)	High dry and wet strength; very resistant to moisture and damp atmosphere; more resistant than wood to high temperature and chemical aging.	Primary adhesives for laminated timbers and assembly joints that must withstand severe service conditions
Urea	Powder and liquid forms; may be blended with melamine or other more durable resins; white to tan resin with colorless bond line	Powder mixed with water, hardener, filler, and extender by user; some formulations cure at room temperatures, others require hot pressing at 120°C (250°F); curable with high frequency heating	High dry and wet strength; moderately durable under damp atmospheres; moderate to low resistance to temperatures in excess of 50°C (122°F)	Hardwood plywood; furniture; fiberboard; particleboard; underlayment; flush doors; furniture cores

Due to adhesives can effectively transfer and distribute stresses, thereby increasing the strength and stiffness of the composite. Therefore, wood adhesive has played an essential role in the development and growth of the forest products industry and has been a key factor in the efficient utilization of timber resource. Consequently, adhesive selection is essential to desire product properties due to there are many types of wood adhesive.

Regarding to health hazards in formaldehyde emissions from formaldehyde based adhesives, there is growing interest in the usage of PVAc based composites in furniture, residential construction, paper, textile and other adhesive industries (Kim, S. and Kim, H.J., 2006). In order to improve the performance in adverse climatic conditions, PVAc adhesives are generally modified with cross-linking agents such as polymeric diphenylmethane isocyanate (pMDI) and other vinyl monomers during polymerization (Qiao, Easteal, and Bolt, 2000). Cross-linked PVAc is rigid, better heat and moisture resistant.

Uysal (2005) studied the effect of adhesives on shear strength and dimensional stabilization of LVL after being exposed to steam. LVLs were manufactured from Pine (Pinus sylvestris L) and Black sea fir (Abies nordmanniana). Four different types of adhesive, PF, PVAc, PU and UF were used. As a result, the highest shear strength at magnitude of 5.36N/mm^2 was obtained in pine control samples with PU adhesive.

Nadir, Candan, and Hiziroglu (2008) evaluated the bond line strength of the cardboard substrate panels overlaid with beech (Fagus orientalis Lipsky) veneer. By using four types of liquid synthetic adhesives, UF (urea-formaldehyde), PF (phenol-formaldehyde), MUF, and polyurethane(diphenylmethane-4,4-di-isocyanate), bonded the veneer sheets to the cardboards. The cardboard panels were produced from recycled food and beverage carton containers which were shredded into 5 mm particles then spread into sheets to a desired thickness. The results were found that the cardboard specimens overlaid with veneer using polyurethane adhesive had better mechanical properties and water resistance than those of the specimens made with other three types of adhesives.

According to adhesive bonding is widely recognized as an effective method for uniformly transferring the shear stresses between structural materials, and is generally considered for bonding FRP and wood to form a hybrid member. Due to moisture absorption in FRP materials is significantly lower than wood. Then higher stresses are induced in moisture cycled of FRP wood specimens compared to wood/wood bonded specimens because of the varying behavior of the dissimilar materials. In this case can succeed in weakening the adhesively bonded interface and in some circumstances can lead to failure of the hybrid material. So, careful adhesive selection is important requirements to maintain the integrity of the FRP–wood composite element (Adams, Comyn, and Wake, 1997).

Raftery, Harte, and Rodd (2009) worked on the effect of moisture cycling on the bond quality of wood adhesives when bonding FRP to Irish grown Sitka Spruce to produce the FRP reinforced glulam beam. Five wood adhesives were selected for the study, two phenol resorcinol formaldehydes (PRFs) with difference hardener ratio, MUF, PU and an emulsion polymer isocyanate (EPI). The pultruded E-glass FRPs, namely GFRP, which using a vinyl ester as matrix and Fulcrum using an engineered thermoplastic polyurethane, were used in the study. From the results show that the FRP wood specimen using MUF adhesive had the lowest shear strength for moisture cycled conditioning. For the glulam using PU and EPI adhesive showed higher shear strength.

For epoxy adhesives remain the primary choice of adhesive to form the bond to fiber reinforced plastics (Mays and Hutchinson, 1992) and are the generally accepted adhesives in bonded FRP wood connections. Advantages of using epoxy adhesives in comparison to other common wood laminating adhesives are their gap filling qualities and the low clamping pressures that are required. Consequently, because of these qualities, epoxy adhesives are an appropriate selection for applications involving bonded in rods and bars in the upgrade or repair of timber members (Broughton and Hutchinson, 2001). However, epoxy adhesives have been applied to timber in only recent years, therefore; only limited knowledge is available on the bond quality formed.

2.2.3 Fiber reinforcements

Problems related to low efficiency of structural elements increased overload and degradation by aging is common in the wood construction materials. This problem has driven the development of new structural reinforcement; *e.g.* reinforced wood with stronger material. The main purpose of reinforced wood is not only to increase the load capacity but also to recover or repair wood for renewed use.

Materials explored for reinforcing wood in the past include aluminum, bulk or wire steel, glass fibers, carbon fiber, ceramic fibers and natural and synthetic fibers (Bulleit, 1984).

The flexural properties of strength spruce beams have been compared to the flexural properties of the same beams repaired with bonded-in reinforcements in the form of steel or three of composite pultruded rods; carbon fiber reinforced plastic (CFRP), glass fiber reinforced plastic (GFRP), and glass fiber reinforced thermoplastic polyurethane (FULCRUM). Alam, Ansell, and Smedley (2009) investigated by routing out grooves on the beam faces and bonding with reinforcement in the form of steel or composite pultrusions. They had found that the steel and CFRP reinforcements are most effective in restoring the flexural strength which often exceeds its original value. These reinforcements were also effective in enhancing flexural strength but the CFRP reinforcement endows the greatest transformed flexural strength.

In the last few years, a few studies have focused on fibers reinforced polymer (FRP) material for reinforcing wood. FRP material have high strength, low weight, corrosion resistance and electromagnetic neutrality that make it suitable candidate in many applications. It includes rehabilitation and strengthening as well as the development of new wood members. Thus, the commercialization of an FRP reinforced glulam structural product has taken place. For example, solid beams of wood were experimentally appraised, reinforced with woven unidirectional of carbon fiber and fastened with sticker epoxy, with thickness varying from 0.55 to 0.75 mm. They had an increase of about 20 to 40% in the capacity of load of the reinforced structural piece (Triantafillou and Deskovic, 1992).

Johns and Lacroix (2000) used GFPR and carbon fiber reinforced plastics (CFRP) sheets to reinforce the tension side of sawn timber beams. They observed that CFRP provided a bigger improvement in flexural strength than GFRP.

Fiorelli and Dias (2003) evaluated on the bending stiffness of timber beams reinforced with woven unidirectional of glass fiber at 1% or 3% by volume, and carbon fiber of 0.4% by volume. As the results shown that the stiffness was increased ranged from 15 to 30% in beams reinforced with 1.0% of glass fiber and/or with 0.4% of carbon fiber. In the case of beam was reinforced with 3.0% of glass fiber, the increase in stiffness was significant, approximately 60%.

Pirvu, Gardner, and Lopez-Anido (2004) worked to evaluate the reinforcement for laminated beam. Two types of fiber reinforcements were used in the study: (i) carbon fabric and (ii) a E-glass fabric, using vinyl ester as matrix. Four southern yellow pine laminated billets were reinforced with 22 layers of carbon/vinyl ester composite sheets and another four with 30 layers of E-glass/vinyl ester composites sheets. The results showed that the carbon/vinyl ester wood interface properties were superior to E-glass/vinyl ester wood interface properties.

Despite higher modulus of elasticity and lower strain to failure, carbon fiber reinforcement is not used as extensively as glass fiber reinforcement and because of higher costs. Most of the recent research on FRP reinforced wood composites has focused on glass fiber based reinforcements. Many of the researchers used glass fiber reinforced plastic (GFRP) in their respective studies. Strength improvement ranged from 20% to 100% depending on the reinforcement ratio. For stiffness properties, the improvement was lower with a maximum value of 37% observed from these studies (Dagher, Kimball, and Shaller, 1996; Gentile, 2000; Gilfillang, Gilbert, and Patrick, 2000; Fiorelli and Dias, 2003; Svecova and Eden, 2004; Borri, Corradi, and Grazini, 2005).

Galloway, Fostad, and Dolan (1996) reinforced southern pine glulam timber beams through the use of non-stressed and pre-stressed Kevlar reinforced plastic composite layers. It was observed that although pre-stressing of the reinforcement composite strengthened the beam in flexure, the presence of defects such as knots and finger joints undermined this increase.

The three types of fibers, glass, carbon and Kevlar are widely used in the above reinforcement composites. They are among the strongest materials available with tensile strength in the range of 2000-3000 MPa. As a result, the costs of these fiber reinforced composites are relatively high, limiting their use to specialty applications such as bridges.

In recent years, there has been interest shown by the composite industry to use natural fibers, which are generally available at a considerably lower cost than man-made fibers. A comprehensive review some properties of bast fiber in making composite materials were compared with man-made fibers in Table 2.4 (Andre, 2006 and Sparnins, 2006).

Table 2.4 Properties of some bast and man-made fibers.

Fiber	Density (g/cc)	Tensile strength (MPa)	Elastic modulus (GPa)	Price ($/kg)
Flax	1.4	800 – 1500	60 – 80	0.5 – 1.5
Hemp	1.5	550 – 900	70	0.6 – 1.5
Jute	1.3	393 – 773	27	0.35
Kenaf	1.5	350 – 600	40	0.33
Glass fiber	2.6	2000	76	1.3
Carbon fiber	1.95	2400	380	26 - 78
Aramid fiber	1.45	3000	130	26 - 45

From Table 2.4 can be noted that although the tensile strengths of the natural fibers are substantially lower than those of glass fibers but their elastic modulus values are not too inferior.

Since the allowable floor spans are often dictated by stiffness property of the joists, the use of natural fiber composite in reinforcing wood I-joist may be a considerably more cost effective option, in comparison with the use of man-made fiber composites. Noda, Ohashi, and Toda (2006) investigated on the use of natural fiber composites to reinforce the flanges of wood I-joists. This research was conducted in two phases. As the results, although the improvement in mechanical properties of reinforced wood I-joist was relatively small, 2-8%, because the reinforcement composite was thin and applied to the bottom flange only. Results from testing conducted on the developed composites have revealed that a bigger improvement in stiffness property is possible with the use of stronger and stiffer composites attached to both flanges.

2.3 Engineered wood processing

The engineered wood products manufactured practically requirement hot pressing to drive off residual moisture and establish hydrolytic bonding or reacting the adhesives. Then hot pressing processes became a truly viable candidate process for controlled heat treatment to enhance products durability. The bonding process involves a great number of factors that determine how successfully an adhesive bonding will be ultimately performance in service. Pressure, temperature and time are the main factors in bonding process.

For medium density fiberboard (MDF), the time and temperature effect was related to moisture environment by water absorption and thickness swelling (TS) It decreased progressively with increasing temperature (Van, Bhattacharyya, and Jayaraman, 2001). Also TS of particleboard decreased with an increase in the time and temperatures of post heat treatment.

As gone through the previous publications, there are not the exact works that fully manifested on the LVL engineered wood using epoxy adhesives and reinforced with engineering fiber to obtain the most durable indoor/outdoor structural wood. Moisture and foreign attack resistance and also stability is one of the important concern for outdoor applications. Hence, in this study the use of those constituents that will significantly enhance the incompetence of engineered wood will be the main concentration.

CHAPTER III

EXPERIMENTAL METHODOLOGY

3.1 General Background

The experimental design on engineered wood, laminated veneer lumber (LVL) reinforced composite, was conducted in three consequence steps. 2^k factorial experimental design was obtained to analyze the significant effect of each step on the mechanical properties of LVL reinforced composite. For each test, three factors were evaluated. Firstly, effect of raw materials, wood species of veneer, fibers and adhesives types, were evaluated. Base on the results from initial trial, suitable materials were chosen to proceed in second test. The surface modification of the wood veneer or laminated wood, smoke treatment and anti termite application, were studied. Quantity of silane addition to hardener was also evaluated in this phase. Finally, the effect of processing parameters including compression pressure, temperature and time, were observed. The mechanical properties by mean of flexural testing were measured. In order to certify the duration service, withdrawal strength of screw, water absorption and termite resistance testing were also investigated. The descriptions of the materials, experimental procedures and performance testing are given in detail as follows.

3.2 Materials and Chemical Reagents

The main materials were used in this research can be classified into 3 categories (i) the wood veneers (ii) the reinforcement materials and (iii) the adhesives, resin and hardener ingredients.

Three veneer wood species, teak, rubber wood, and eucalyptus, were employed for LVL reinforced composites in this study. Rubber wood and eucalyptus having the approximate diameter of 30 cm were locally obtained. They were roughly 20 years old tree. The thick veneers with an average thickness of 2.5 mm were industrially peeled and used as substrate panels. For young teak wood log, around 15 years old tree, was obtained from Thai Royal Forest Department. The log was boiled at temperature around 60^{o}C for a week. The veneer having average thickness of 0.5 mm was machine sliced. They were used to overlay the faces of LVL board. The moisture content of the veneers was controlled at approximately 6-14% by drying in the oven at 105^{o}C for several hours. The smoked wood was achieved in constructed smoking chamber. The rice husk was used as the source of smoke. Smoking process was prolonged for at least two days.

The reinforcements were plain woven E-glass fabric, LT800-E, and carbon fabric, GV-125 U, with area weight density of 821±3% g/m^2 and 123±5% g/m^2, respectively. The LT800-E and GV-125 U were supplied from Chrong Yi Company and G. Angloni Company, respectively.

Two adhesive systems, in house room temperature cure and prepreg epoxy matrix, were used. The resins were consisted of bisphenol A based epoxy resin and amine curing agent. For the epoxy resins, Epotec YD 115, YD 127 and YD 134 based on diglycidyl ether of bisphenol A (DGEBA) with an epoxy equivalent weight (EEW) of 198, 183 and 250 g/mol respectively, were supplied from the Aditya Birla Chemicals (Thailand) Ltd. They were used without further purification.

The curing agent ingredients were mainly comprised of dicyandiamide, amine curing agents and catalysts. Triethylene tetramine (TETA), aliphatic amine, supplied from Witco Co., Ltd. Isophorone diamine (IDPA), cycloaliphatic amine, supplied from Vantico Pte., Ltd. Ancamine 1618 and Ancamine 2165, the mixture of the cycloaliphatic (IDPA) and methylenedianiline (MDA) in benzyl alcohol at ratio approx. 80:20 and 60:40 by weight, respectively. Both were supplied from Air Products and Chemicals company. Dyhard 100 are Dicyandiamide having and average grain size of 40 µm. Dyhard 200 was used as catalyst. The Dyhard series were obtained from the Deggussa company.

Methyl ethyl ketone (MEK) was used as active solvent for prepreg formulation. This solvent was supplied from Use Well Development Company and used as received. All the chemicals were commercially supplied and they were used as received.

3.3 Experimental Procedures

3.3.1 LVL reinforced composites preparation

The LVL reinforced composites were produced to require thickness with approx. 38 mm which the same dimensional thickness of the construction frame materials. It was stacked using the thick veneers having dimension of 150x150x25 mm. 14 layers were required for the desired thickness specimen. Each layer was equivalent to 7.14% of the total layers. These percentages were used as low/high level classification in the design of experiment (DOE) method. The pre-dried Rubber wood and eucalyptus veneers were alternately layered. The woven fibers were placed between layers of wood sheet. Teak veneers were faced on both sides. The woven fibers and wood veneers were throughout impregnated with adhesive by using hand lay-up process. The LVL samples were cured at 150^{o}C for 45 minutes using compression press. Sample was placed into a rectangular preheated two plate metal mold laid by two Teflon^{TM} sheets on the top and bottom to prevent mold adhere to the machine. The pressure used during the cure was constantly at 30 bar. However, in order to study the effect of processing parameters or cure conditions on the properties of the final product, the cures were performed at designated pressure, temperature and time. After finishing cured in compression press, it was undergone post curing at 80^{o}C for 5 hours in oven. The LVL reinforced composites were cut by sawing machine into the require dimension for testing. The samples were polished using water proof sanding paper.

3.3.2 Adhesive formulations

Two adhesive systems, in house room temperature and prepreg epoxy matrix, were used for this study.

The room temperature cure adhesive was consisted of the resin, the Epotec YD 115, YD 127 and YD 134, and curing agent, TETA, Imidazole, Anacamine 2165, phenol and 3-Aminopropyl silane.

The prepreg epoxy matrix adhesive was consisted of the resin, the Epotec YD 115, YD 127, active solvent, MEK, and hardener, Dyhard 100, Dyhard 200, Isophorone diamine, Anacamine 2165 and 3-Aminopropyl silane.

The resin and curing agent mixtures of these adhesive systems were given in the previous work (Wanaporn, 2005). Due to the intellectual property protection, those formulations can not be given in this report.

Each formulation was the combination mixtures of the epoxy resin and curing agent in stiochiometric ratio, phr, based on the calculation. The stiochiometric relation between the epoxy resin and hardener was calculated by mean of active hydrogen equivalent weight (AHEW) of hardener and epoxy equivalent weight (EEW) of epoxy resin are give by the following equations;

$$\text{phr} = \frac{\text{AHEW}}{\text{EEW}} \times 100$$

$$\text{where AHEW} = \frac{\text{Molecular weight of amine (g/mol)}}{\text{Number of active hydrogen}}$$

$$\text{EEW} = \frac{\text{Molecular weight of epoxy resin (g/mol)}}{\text{Number of active epoxide group}}$$

3.3.3 Design of experiment (DOE)

There were three testing steps, as mentioned earlier, for the experimental design study on LVL reinforced composites. The 2^k factorial experimental design was used to analyze the significant effect on the mechanical properties and three factors were evaluated for all tests.

The experimental design for three tests of LVL reinforced composites in this study are summarized in Table 3.1 to 3.6.

Table 3.1 Factors and levels of test I.

Factor	**Low Level (-)***	**High Level (+)***
Wood species (A)	Eucalyptus 28.57% and Rubber wood 71.43%	Eucalyptus 71.43% and Rubber wood 28.57%
Fiber type (B)	Carbon fiber(CF) 33.33% and Glass fiber (GF) 66.67%	Carbon fiber (CF) 66.67% and Glass fiber (GF) 33.33%
Adhesive type (C)	Prepreg 33.33% and Room temperature (RT) 66.67%	Prepreg 66.67% and Room temperature (RT) 33.33%

*** *the % was corresponded to total 14 layers***

Table 3.2 The 2^k factorial design matrix for test I.

Condition	Code design matrix			Condition Detail					
	A	B	C	Wood species (A)		Fiber type (B)		Adhesive type (C)	
				Eucalyptus	Rubberwood	CF	GF	Prepreg	RT
M1	+	+	+	71.43% (10 layers)	28.57% (4 layers)	66.67% (10 layers)	33.33% (5 layers)	66.67% (10 layers)	33.33% (5 layers)
M2	+	+	-	71.43% (10 layers)	28.57% (4 layers)	66.67% (10 layers)	33.33% (5 layers)	33.33% (5 layers)	66.67% (10 layers)
M3	+	-	+	71.43% (10 layers)	28.57% (4 layers)	33.33% (5 layers)	66.67% (10 layers)	66.67% (10 layers)	33.33% (5 layers)
M4	+	-	-	71.43% (10 layers)	28.57% (4 layers)	33.33% (5 layers)	66.67% (10 layers)	33.33% (5 layers)	66.67% (10 layers)
M5	-	+	+	28.57% (4 layers)	71.43% (10 layers)	66.67% (10 layers)	33.33% (5 layers)	66.67% (10 layers)	33.33% (5 layers)
M6	-	+	-	28.57% (4 layers)	71.43% (10 layers)	66.67% (10 layers)	33.33% (5 layers)	33.33% (5 layers)	66.67% (10 layers)
M7	-	-	+	28.57% (4 layers)	71.43% (10 layers)	33.33% (5 layers)	66.67% (10 layers)	66.67% (10 layers)	33.33% (5 layers)
M8	-	-	-	28.57% (4 layers)	71.43% (10 layers)	33.33% (5 layers)	66.67% (10 layers)	33.33% (5 layers)	66.67% (10 layers)

Table 3.3 Factors and levels of test II.

Factor	Low Level (-)	High Level (+)
Silane quantity (A)*	2% and 5%	10% and 15%
Smoked wood (B)	14.29% (2 layers) and 28.57% (4 layers)	42.86% (6 layers) and 57.14% (8 layers)
Anti termite wood (C)	14.29% (2 layers) and 28.57% (4 layers)	42.86% (6 layers) and 57.14% (8 layers)

*** *corresponded to 100 g of hardener used***

Table 3.4 The 2^k factorial design matrix for test II.

Condition	Code design matrix			Condition Detail		
	A	B	C	Silane quantity (A)	Smoked wood (B)	Anti termite wood (C)
T1	+	+	+	10%	42.86% (6 layers)	42.86% (6 layers)
T2	+	+	-	15%	57.14% (8 layers)	14.29% (2 layer)
T3	+	-	+	10%	14.29% (2 layers)	57.14% (8 layers)
T4	+	-	-	15%	28.57% (4 layers)	28.57% (4 layers)
T5	-	+	+	2%	42.86% (6 layers)	42.86% (6 layers)
T6	-	+	-	5%	57.14% (8 layers)	14.29% (2 layers)
T7	-	-	+	2%	14.29% (2 layers)	57.14% (8 layers)
T8	-	-	-	5%	28.57% (4 layers)	28.57% (4 layers)

Table 3.5 Factors and levels of test III.

Factor	Low Level (-)	High Level (+)
Pressure (A)	15 and 25 bar	35 and 45 bar
Temperature (B)	70 and 80^oC	90 and 100^oC
Time (C)	30 and 40 min	50 and 60 min

Table 3.6 The 2^k factorial design matrix for test III.

Condition	Code design matrix			Condition Detail		
	A	B	C	Pressure(bars) (A)	Temperature(^oC) (B)	Time(mins) (C)
P1	+	+	+	35	90	50
P2	+	+	-	45	100	30
P3	+	-	+	35	70	60
P4	+	-	-	45	80	40
P5	-	+	+	15	90	50
P6	-	+	-	25	100	30
P7	-	-	+	15	70	60
P8	-	-	-	25	80	40

According to the conditions shown in Table 3.1 to 3.6, they can be classified into three categories of interests. The first test of the experimental designs, Table 3.1 and Table 3.2, was designed to study the influence of constituent materials, wood species, fiber and adhesive types, on mechanical properties of the LVL reinforced composites. They were assigned as Ms series. The second one, Table 3.3 and Table 3.4, was formulated to investigate the effect of silane quantity and wood surface treatment by means of smoking and anti-termite application on mechanical properties of the products. The Ts series were given. The last testing, Table 3.5 and Table 3.6, was constructed to evaluate the effect of processing parameters or cure conditions which include pressure, temperature, and time on mechanical properties of the final product. They were named as Ps series. For all of testes, two sub-levels for each factor are applied within the ranges that able to use in the production of LVL reinforced composites.

3.4 Mechanical Testing

The mechanical property by mean of flexural testing and withdrawal strength of screw were employed.

3.4.1 Flexural Testing

ASTM 790 was adapted for the apparent flexural properties of the LVL reinforced composites to investigate the bending stiffness. The three point bending configuration and Instron^{TM} 5569 universal testing machine with 50 kN load cell were employed. The LVL reinforced composites with 16 layers, including teak veneer layers, of stacked wood veneers were subjected to bending load. Flexural specimens with an average geometry of 130 mm length, 25 mm width, and 38 mm thickness were prepared and polished using sand paper. Four solid woods, teak, rubber wood, eucalyptus, and hardwood, were also prepared with same dimensions to provide the controlled samples. The experimental set up for bending test is schematically shown in Figure 3.1. The span length, L, was constantly set at 100 mm. The specimens were bended to failure under constant displacement control. The loading nose displacement rate of 5.5 mm/min was electrically controlled. Five specimens were needed for each test. The flexural strength, modulus, and toughness were calculated and reported. The typical failure modes were shear and debonding as observed in Figure 3.2.

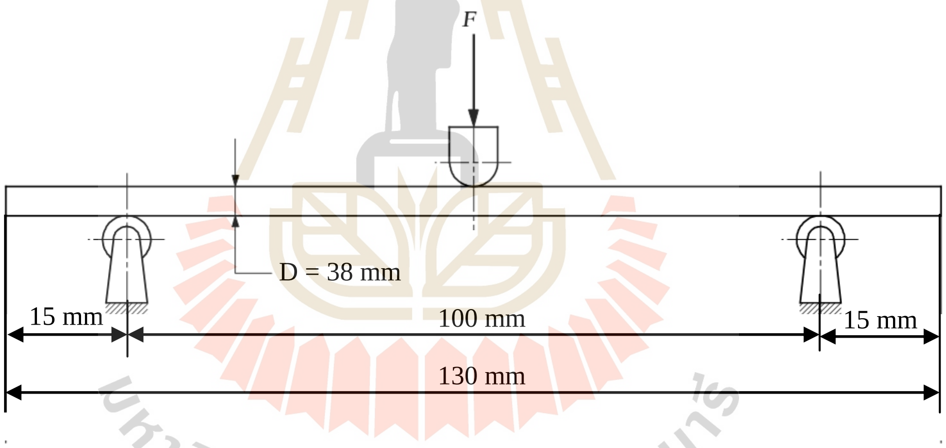


Figure 3.1 Schematic of experimental set up for three point bending test.

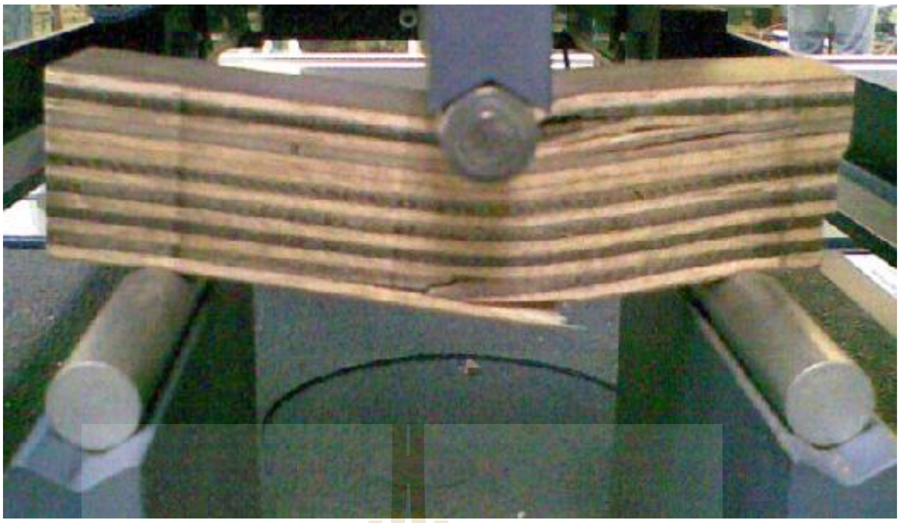


Figure 3.2 Typical failure modes of the specimen from bending test.

3.4.2 Screw Withdrawal Testing

The Instron^{TM} 5569 Universal testing machine with 50 kN load cell was used in the test. The jaw face grip with a special design adapter was used to grip and pull-out the screw nail as illustrated in Figure 3.3. According to the standard test, the LVL reinforced composites samples with an average geometry of 130 mm length, 25 mm width, and 38 mm thickness were prepared. Solid wood including teak, rubber wood, eucalyptus, and hardwood with same dimensions were also obtained to provide the reference values. The screw nail with 4.1 mm outer diameter and 50 mm in length was fitted into the pre-holed, using drills diameter of 3.3 mm, with the hole depth of 9 mm. The hole obtained was 70% of nail screw root diameter. The screw was placed in the radial direction of specimen. The screw was forced further using the screw driver until the total depth of 25 mm reached. The specimens were fixed onto the testing machine. During the test a pulling speed of 2.5 mm/min was applied until the screw were completely separated apart from specimens or until the failure of screw in some cases. For each of the test, average value obtained from 3 individual samples was recorded.

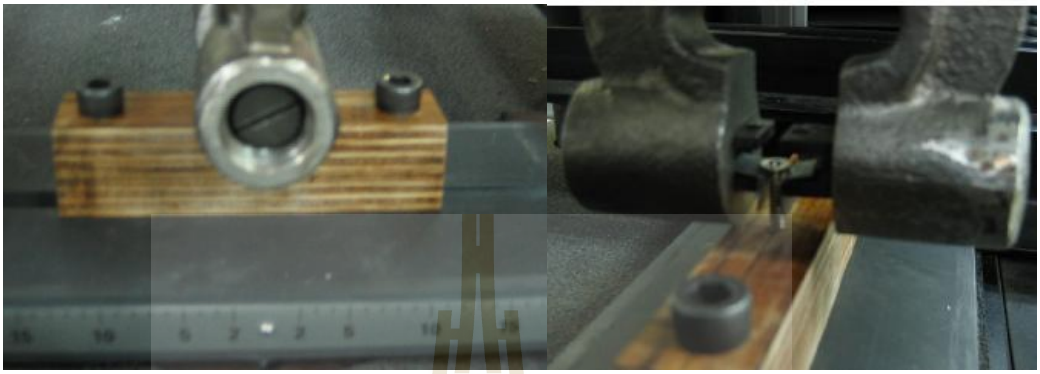


Figure 3.3 Diagram of the screw withdrawal test.

The screw withdrawal strength of the test specimen was computed according to the equation given below.

$$\sigma_s = \frac{P_{max}}{2\pi rh}$$

Where σ_s = Screw withdrawal strength, N/mm^2

P_{max} = The maximum load, N

$2\pi rh$ = The surface area of the screw exposed to friction, mm^2

3.5 Durability and Performance Testing

As target applications for this engineered wood will be used as light construction material and outdoor furniture. The durability of this material especially environmental damage will be important. Therefore, the water absorption and termite resistance testing were tested.

3.5.1 Water Absorption Testing

The water absorption of the LVL reinforced composite was evaluated by preparing three specimens with an average geometry of 65 mm in length, 25 mm in width, and 35 mm in thickness. Three solid woods, teak, rubber wood, and eucalyptus, with same dimensions were used as reference samples. The specimens were immediately weighed before submersion. In order to accelerate the water absorption process, the samples were incubated in hot water at 70^{o}C and then weighted every 24 hours until the constant measured weight were reached. For this study, 1 week of incubation was required. The excess water at the surface of specimens was removed by paper wiping weighed.

The water absorption percentage of the sample was calculated by using the following equation:

$$A = \frac{W_{1,2,3,...} - W_b}{W_b} \times 100$$

where A = Absorbed water, %

W_b = Weight before submersion, g

$W_{1,2,3,...}$ = Weight on the measurement after submersion, g

3.5.2 Termite Resistance Testing

Three specimens of the LVL reinforced composite with an average geometry of 65 mm length, 25 mm width, and 35 mm thickness were prepared. Three solid woods, teak, rubber wood, and eucalyptus with same dimensions were also used as reference. The specimens were weighed before burying in soil. The specimens were weighed every 2 weeks for 3 months to monitoring the weight loss. The testing site was located at Suranaree University of Technology where the native species of termite was abandoned and evidenced. There was no termite screen on this test.

The percentage of weight loss (WL) was calculated for each test specimen from the conditioned weight before and after testing by using the following equation. The visual observation by mean of photography on specimen before and after test was also included.

$$WL = \frac{W_b - W_{1,2,3,...}}{W_{1,2,3,...}} \times 100$$

where WL = Weight loss, %

W_b = Weight before burying in soil, g

$W_{1,2,3,...}$ = Weight on the measurement after burying in soil, g

3.6 Analysis of DOE Using Design Expert™

In order to verify the dependency of raw materials on the mechanical properties of LVL reinforced composite derived from the above constituents. The influence of wood species of veneer, fiber and adhesive type on the flexural properties of the LVL reinforced composite were performed by using the multi variance analysis (ANOVA) for the design of experiment.

In this study, the level of significant (α) was set at 0.05 or 95% confidential. The calculation of significant level of the experimental data was obtained by using Design Expert™ version 7.1.6, which is the commercial statistical software analysis to assist the statistic calculation.

According computer software calculation, the largest effect at the right side in a half-normal plot should be selected before analysis. Keep picking from right to left until the straight line is matched with the majority of the effects near zero. Notice that the Design Expert adjusts the line to exclude the chosen effects. At the point where the process should be end, this line jumps up, leaving a noticeable gap. The effect factors and their interactions that lie along the line are negligible and the rest of the effects are significant effects. The trivial effects that have no influence, fall on the straight line near zero effect level, are used to estimate the experimental error.

Pareto chart may help to visualize the magnitude of the chosen effects by displaying them on an ordered bar-chart. The vertical axis shows the t-value of the absolute effects. This is dimensionless statistic scales in terms of standard deviations. In this case, it makes no difference to the appearance of the half-normal plot. The effects that fall below the bottom limit are non significant effects. For the effects that fall above the limit are significant effects.

The significant effects from half-normal plot and Pareto chart can be also confirmed in ANOVA results. By check the probability or “P-value” for the effects which were selected. If the P-value less than 0.05, based on the statistical analysis by the ANOVA, it indicates that the effects are significant effects.

From all the significant effects on the mechanical properties of LVL reinforced composites obtained from the software. They will be used to identify the levels, low (-) / high (+) for production of LVL by using the main effects plot. The main effect plots are based on the calculated means at each point of measured respond values, for example flexural strength. The main effect plot will show the direction and extent of effect with factors. The effects of the factors are calculated by averaging the responses of each factor at the plus level and subtracting the average at the minus levels for the same factor as shown in equation 3.1. The plot having high incline or lean lines will indicate positive (+) and negative (-) effects by mean of strength to the LVL, respectively.

$$E_f = \overline{F}_{(+)} - \overline{F}_{(-)} \tag{3.1}$$

where E_f = The effect of factor

$\overline{F}_{(+)}$ = Average response at high level setting of a factor

$\overline{F}_{(-)}$ = Average response at low level setting of a factor

CHAPTER IV

RESULTS AND DISCUSSION

The main inspiration of this research work is to determine the influence of composite constituents and processing parameters on the performance properties of the engineered wood. Hence, the purpose of this work is to produce the engineered wood, LVL reinforced composite, that suitable for outdoor furniture and construction material applications. The experimental design by mean of the 2^k factorial experimental design was performed to analyze the effect of composite constituents and processing parameters on the properties of LVL reinforced composites. Three consequential steps were studied. There were the exploring an effect of raw materials, silane quantity and the wood surface treatment in order to evaluate the adhesion capability, and processing parameters on the properties of LVL reinforced composites. The flexural, withdrawal strength of screw nail, water absorption, and termite resistance testing were employed. Those results will be obtained to statistically evaluate. In this chapter, all the tested results will be presented and discussed.

4.1 Effect of Raw Materials

According to the properties of LVL reinforced composites are typically depended on the raw materials including wood species of veneers, reinforcements, and adhesives used. It is worthwhile to qualitatively verify the suitable, by mean of performance properties, of raw materials employed.

In the engineered wood industries, a great variety of wood species can be used in the production processes. The choice of the wood species used is often determined mainly by availability, legal and the price of the raw material. Eucalyptus, and rubber wood were chosen in this study due to they were easily obtained from the native economic farm forest. Young teak veneer as used as faces and decorative layers were obtained as trimmed log from Royal forest department. The young teak trees were trimmed for very 5–10 year in order to allow the remains grow bigger and taller. In bonding of engineered wood, the optimal wood moisture content is usually 6 to 14%. Lower wood moisture content can cause a quick dry out of the spread glue due to a rapid re-absorption of the water into the wood surface as well as wettability problem. The least moisture content can also lead to a high flow and an enhanced penetration into the wood, causing starved glue lines (Pizzi, 2003). High % in moisture will inhibit the curing process and also accelerate aging process of adhesive especially for ester type glue.

In addition, adhesives play a central role with in engineered wood products. The quality of bonding and the properties of the woods were determined mainly by the type and quality of adhesive. Two systems of epoxy resin adhesives, a room temperature cure and prepreg, were selected to use in this study. According to epoxy resin adhesives, they are unique characteristics including negligible shrinkage during cure, an open time equal to the usable life, excellent water and chemical resistance, ability to bond nonporous substrates, and a great versatility as gap filling qualities and the low clamping pressures. And there were not many works published on this adhesive in engineered wood applications. Woven carbon fiber and glass fiber were employed.

The mechanical properties by mean of flexural testing were measured to find out the optimal material strength of the LVL reinforced composite. The eight conditions, 2^3, with difference in raw materials, wood species of veneer, fiber and adhesive types, were designed as summarized in Table 3.2. The notation Ms series are given. The respond of the designs by mean of flexural testing were concluded in Table 4.1 to 4.2 and also plotted as presented in Figure 4.1 to 4.4.

Table 4.1 and Figure 4.1 to 4.2 show the flexural properties, flexural strength, modulus, and toughness. From the results found that the M6 test gave rise to the maximum strength and modulus values at 66.43±4.19 MPa and 1460.03±141.84 MPa, but the M1 indicates the lowest one at 33.40±7.87 MPa and 846.06±245.83 MPa, respectively. The toughness strength calculated from area under curve of the stress-strain profile was also reported. The highest toughness value was 176.79±28.32 kJ/m^2 as found in M2 followed by the M6, M3 and M4 condition. And the lowest toughness value was also again found in the M1 condition at 69.12±18.37 kJ/m^2.

The similar trends were also observed for specific flexural properties as shown in Table 4.2 and Figure 4.3 to 4.4. Again, the best of all condition in this category was found for M6 and the worst was M1. And the specific toughness results were also quite similarly trends with the toughness results.

According to the results found that the highest flexural properties were obtained at low level of eucalyptus, eucalyptus 28.57% with rubber wood 71.43%, and high CF content, CF 66.67% with GF 33.33%, and low prepreg adhesive content prepreg 33.33% with RT 66.67%, as used in M6 test. It means that the flexural properties of LVL reinforced composite is increased with lower content of eucalyptus veneer, higher content of CF and lower content of prepreg adhesive. This preliminary result suggests that the flexural properties increase with using higher content of rubber wood veneer, CF and room temperature cure adhesive.

Vice versa, the lowest values is evidenced in high content of eucalyptus, eucalyptus 71.43% with rubber wood 28.57%, 66.67% CF with 33.33% GF, and 66.67% prepreg with 33.33% RT adhesives in M1 trial. It indicates that the flexural properties value is decrease when using higher content of eucalyptus veneer and prepreg adhesive.

Taken only the effect of raw materials on the mechanical properties of LVL reinforced composites, the general conclusion could be drawn that eucalyptus veneer and prepreg adhesive in the composite decrease the mechanical properties. Vice versa, the properties will be increased by using rubber wood veneer and room temperature cured adhesive.

Table 4.1 Mechanical properties of LVL reinforced composites prepared in DOE test I using difference raw materials.

Condition	Factor			Interaction				Flexural properties		
	A (Wood species)	B (Fiber type)	C (Adhesive type)	AB	AC	BC	ABC	Strength (MPa)	Modulus (MPa)	Toughness (kJ/m^2)
M1	+	+	+	+	+	+	+	33.40±7.87	846.06±245.83	69.12±18.37
M2	+	+	-	+	-	-	-	61.69±5.31	980.69±110.45	176.79±28.32
M3	+	-	+	-	+	-	-	47.76±2.39	923.60±146.34	121.27±33.29
M4	+	-	-	-	-	+	+	37.17±1.44	1077.37±176.75	120.47±16.16
M5	-	+	+	-	-	+	-	52.46±7.79	1174.9±247.93	105.46±33.00
M6	-	+	-	-	+	-	+	66.43±4.19	1460.03±141.84	121.69±8.41
M7	-	-	+	+	-	-	+	42.37±1.92	847.11±157.23	88.32±8.85
M8	-	-	-	+	+	+	-	50.71±8.90	1197.07±184.06	93.14±21.12

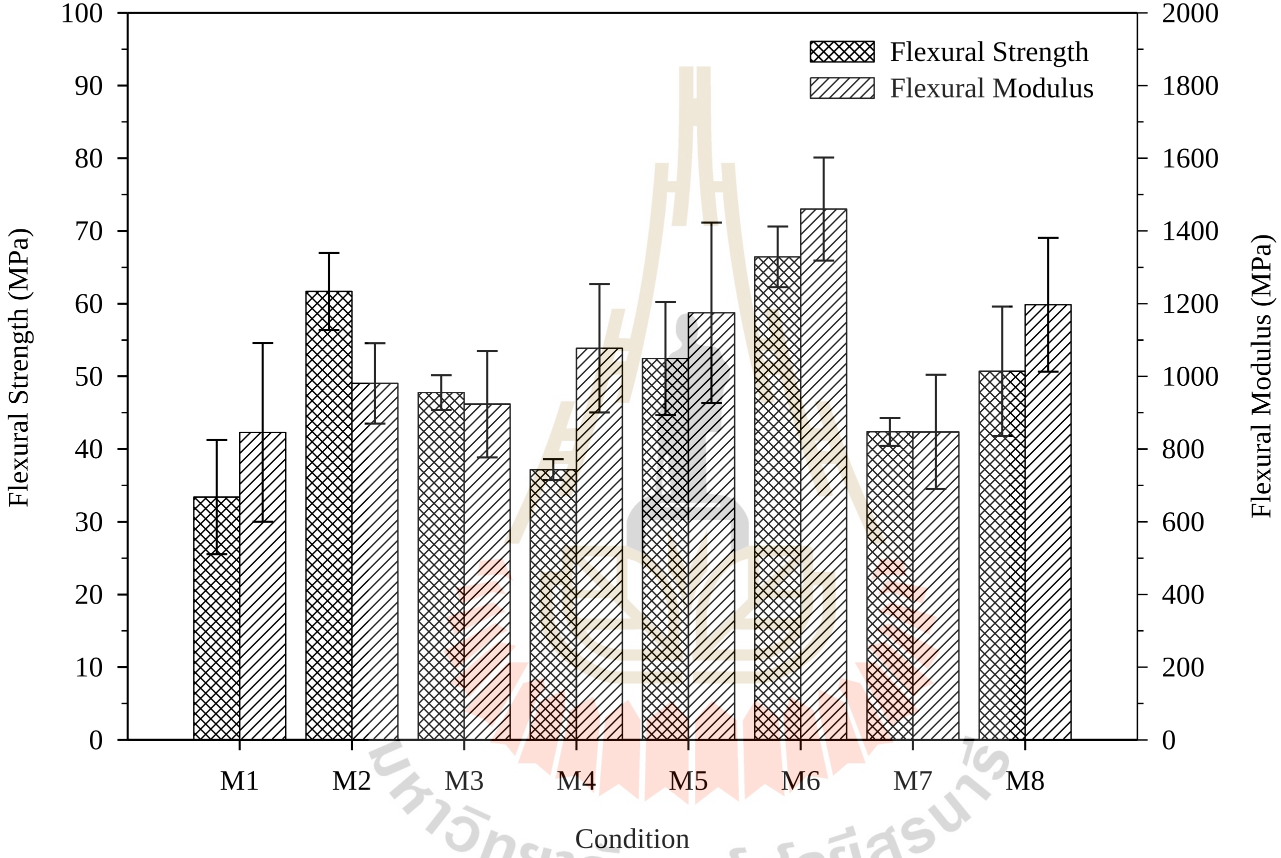


Figure 4.1 Flexural strength and flexural modulus of LVL reinforced composites prepared in DOE test I using difference raw materials.

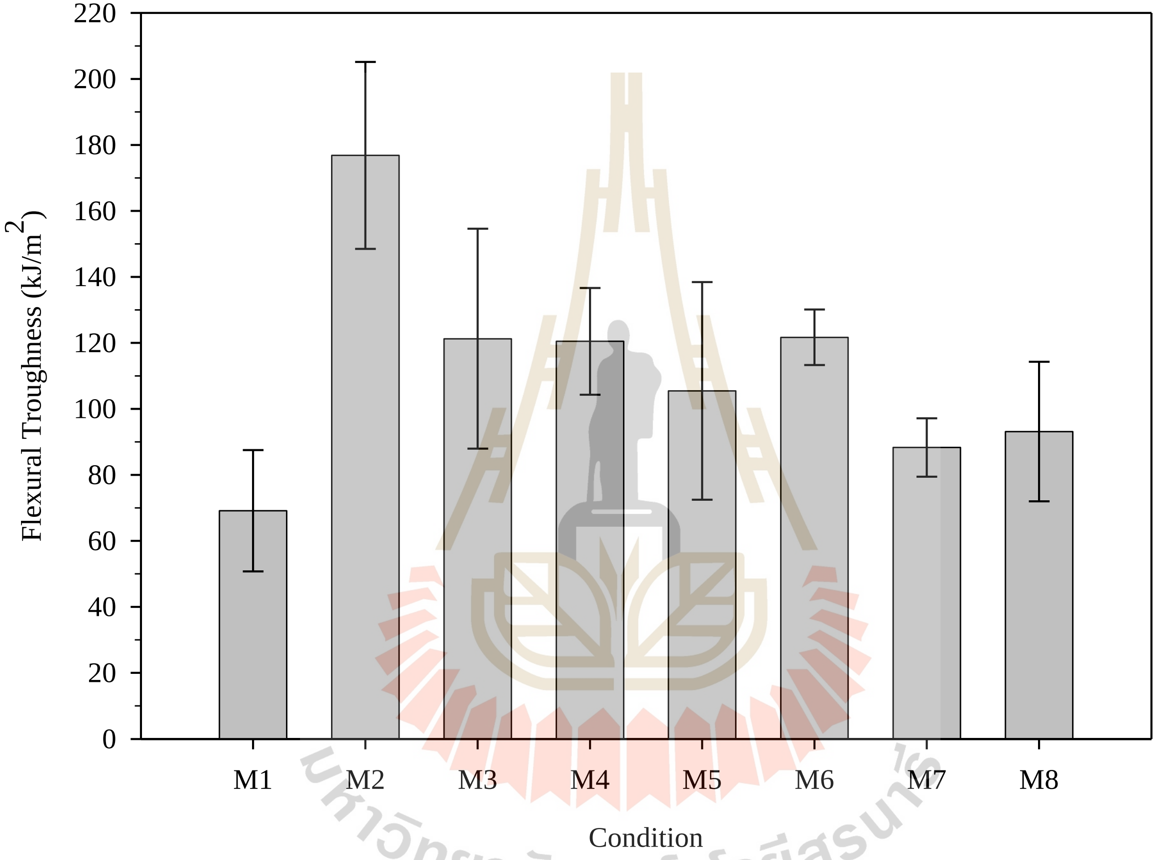


Figure 4.2 Flexural toughness of LVL reinforced composites prepared in DOE test I using difference raw materials.

Table 4.2 Specific mechanical properties of LVL reinforced composites prepared in DOE test I using difference raw materials.

Condition	Factor			Interaction				Flexural properties		
	A (Wood species)	B (Fiber type)	C (Adhesive type)	AB	AC	BC	ABC	Specific Strength $\left(\frac{kPa}{kg/m^3}\right)$	Specific Modulus $\left(\frac{kPa}{kg/m^3}\right)$	Specific Toughness $\left(\frac{(J/m^2)}{kg/m^3}\right)$
M1	+	+	+	+	+	+	+	40.34±7.45	1017.17±228.61	83.55±19.06
M2	+	+	-	+	-	-	-	66.21±3.64	1053.65±108.00	189.44±25.22
M3	+	-	+	-	+	-	-	54.87±4.31	1057.67±148.18	139.73±40.130
M4	+	-	-	-	-	+	+	40.81±3.32	1185.85±223.87	132.61±22.16
M5	-	+	+	-	-	+	-	59.80±7.85	1335.90±247.68	120.56±38.43
M6	-	+	-	-	+	-	+	74.36±5.43	1635.46±178.83	136.38±12.88
M7	-	-	+	+	-	-	+	49.29±2.47	983.82±172.39	102.68±9.91
M8	-	-	-	+	+	+	-	54.39±6.44	1284.34±107.35	99.82±18.44

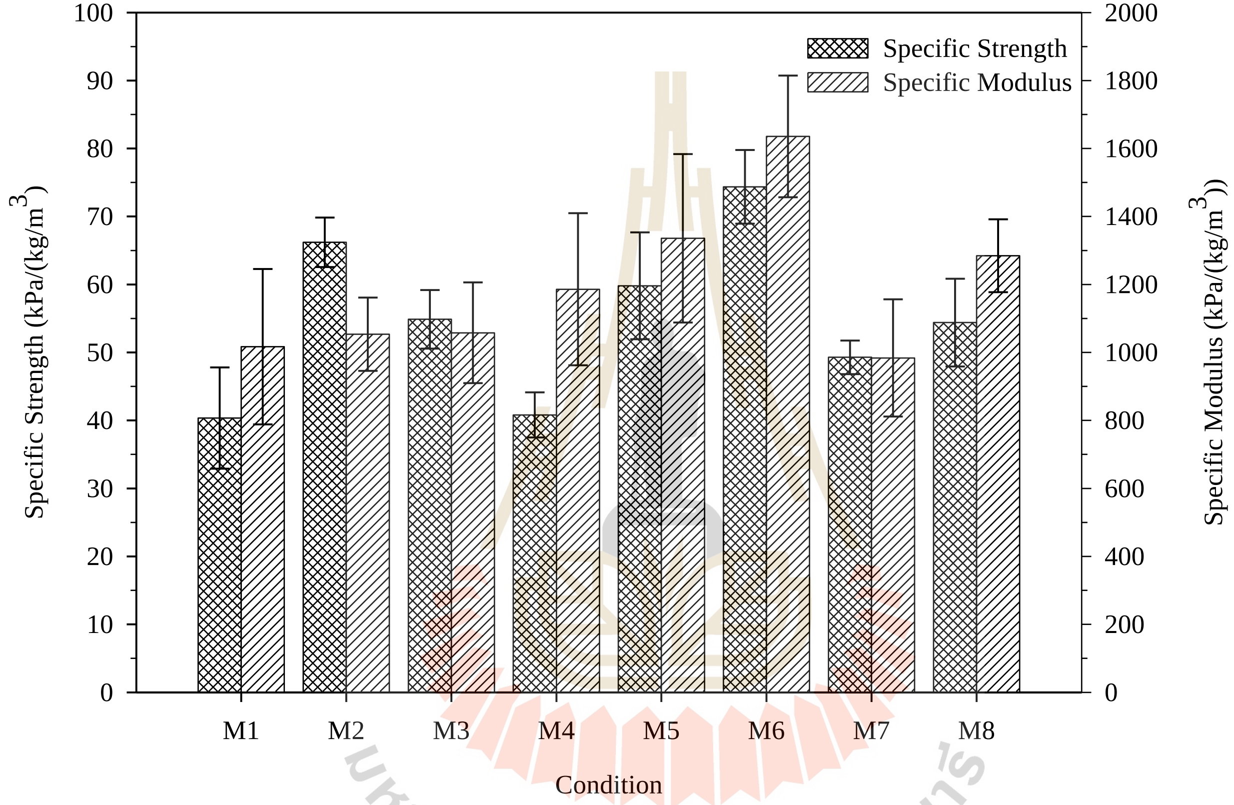


Figure 4.3 Specific strength and specific modulus of LVL reinforced composites prepared in DOE test I using difference raw materials.

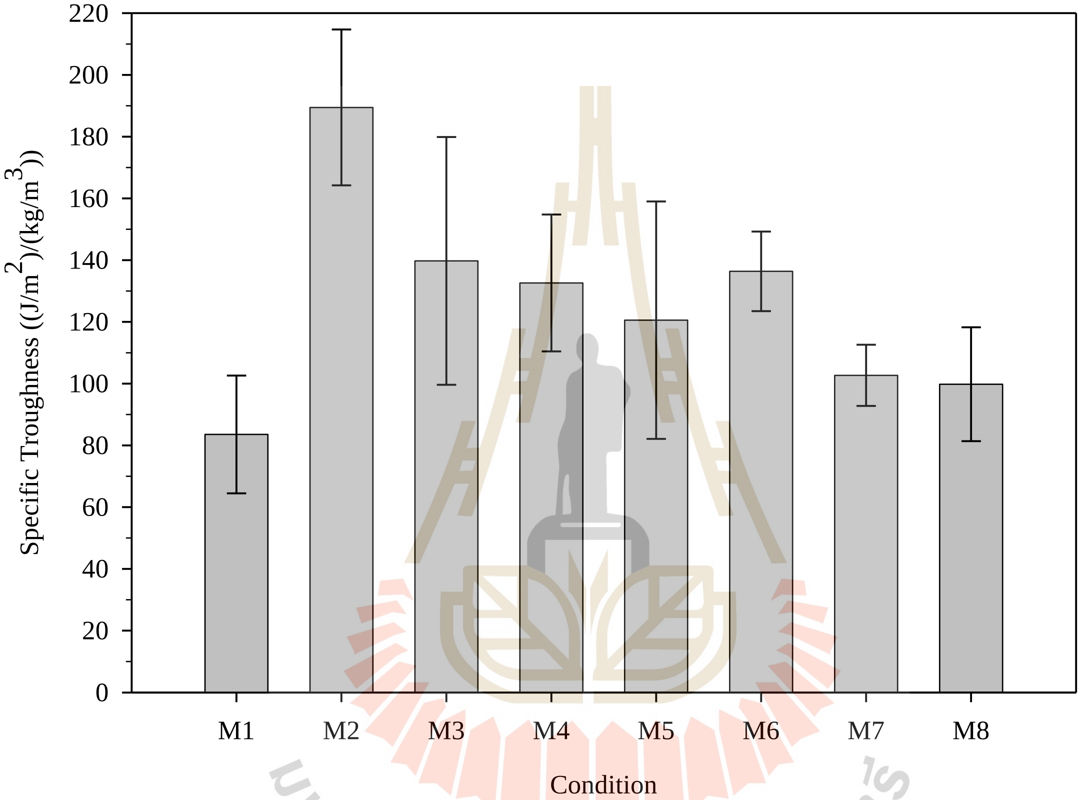


Figure 4.4 Specific toughness of LVL reinforced composites prepared in DOE test I using difference raw materials.

In order to verify the dependency of raw materials on the mechanical properties of LVL reinforced composite derived from the above constituents. The influence of wood species of veneer, fiber and adhesive type on the flexural properties of the LVL reinforced composite were performed by using the multi variance analysis (ANOVA) for the DOE using the Design Expert^{TM}.

The DOE results include the half-normal plots, ANOVA, and main effect plots as shown in Figure 4.5 to 4.10, Table 4.3 to 4.8, and Figure 4.10 respectively.

The plot shown in Figure 4.5 and 4.6 illustrate the half-normal plots of flexural strength and specific flexural strength, respectively. According to the results at least six effect including interaction ones are on the straight line but the last two, C and BC are beyond the line. However, by method of half-normal plot, these two points is considered as not obvious out of the line. Using the plot only, it can spell out that there is no obviously significant effect of materials used to prepare the LVL on both responds. The plots are also confirmed by the statistical analysis, ANOVA, results as summarized in Table 4.3 and 4.4. The ANOVA reviews that P-value of both C and BC effect are higher than the assigned significant value at 0.05 as mentioned previously.

The similar analysis was performed for flexural modulus and specific flexural modulus and the half-normal plots are shown in Figure 4.7 and 4.8. The ANOVA testing to support the normal plots are shown in Table 4.5 and 4.6. The plot results manifest that adhesive types (C), wood species of veneer (A), interaction between wood species and fiber type (AB), fiber type (B), and finally interaction between wood species and adhesive type (AC) are all significant effects due to the flexural modulus properties of LVL reinforced composite. Due to these effects are placed beyond the straight line of near zero effect level which implied that they are significant effects. Additionally, the ANOVA results are also statistically significant at level of 5%, P-value less than 0.05. Moreover, these significant effects can be also detected in the main effect plot, as shown in Figure 4.11, as they having steeper slope comparison with other effects. The maximum modulus properties was determined as low level of adhesive type (C-), prepreg-adhesive, and eucalyptus wood of veneer (A-), and high level of CF (B+). Also the interaction between wood species and adhesive type is found at low level (AC-). The interaction between wood species and fiber type is observed at high level (AB+). These factors show the better flexural modulus properties of LVL.

Figure 4.9 is the half-normal plot corresponding to flexural toughness and Table 4.7 is the ANOVA figures. Both half-normal plot and ANOVA test show that there is no significant effects on the flexural toughness of the LVL reinforced composites. The results are also confirmed by the specific flexural toughness as given in Figure 4.10 and table 4.8, respectively.

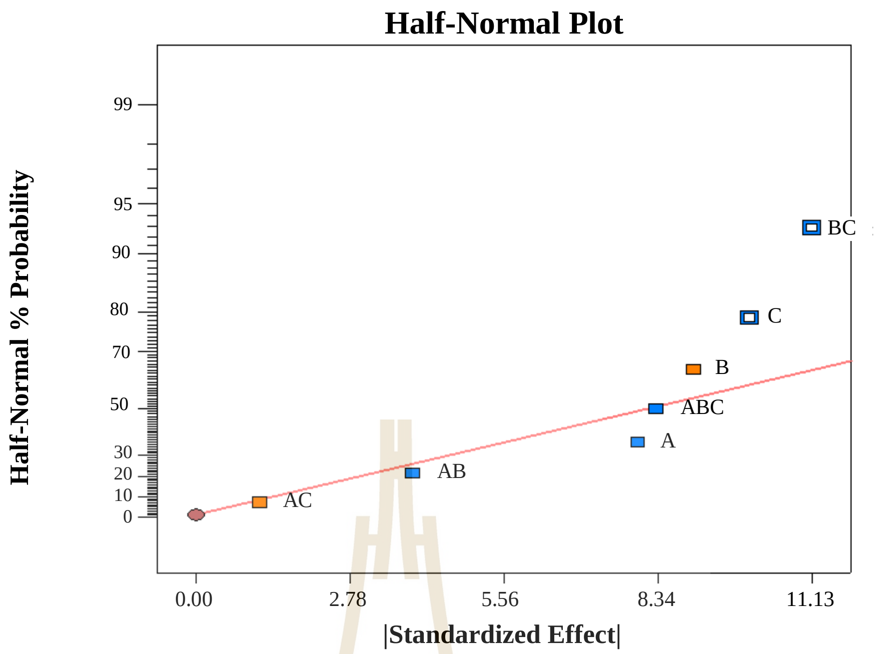
The above results conclude that the mechanical properties of LVL will decrease with increasing eucalyptus level from low to high. For example, increasing 28.57% eucalyptus to 71.43% with decreasing the rubber wood from 71.43% to 28.57%. From the results discovered, eucalyptus was negative effect due to the mechanical properties decrease as increasing eucalyptus veneer content. Vice versa, the mechanical properties will increase as decreasing this effect from high level to low level. That mean, rubber wood was positive effect due to the mechanical properties increase with increasing rubber wood veneer content. Therefore, rubber wood veneer should be employed as raw material to achieve the better properties.

Even the specific gravity value of eucalyptus is higher than rubber wood, but the mechanical properties of LVL reinforced composite made from high eucalyptus content were lower than those made from high content of rubber wood veneer. This outcome is contradicted previous works. They concluded that the mechanical properties of LVL were increased with increasing specific gravity of wood (Toksoy, Colakoglu, and Aydin, 2006). However, wood wettability and surface roughness also have significant effects on the surface adhesion of the substrates. One of the reasons for negative effect may be due to the residual oil in eucalyptus that is no favor the epoxy adhesive. This phenomenon would weaken the adhesion strength.

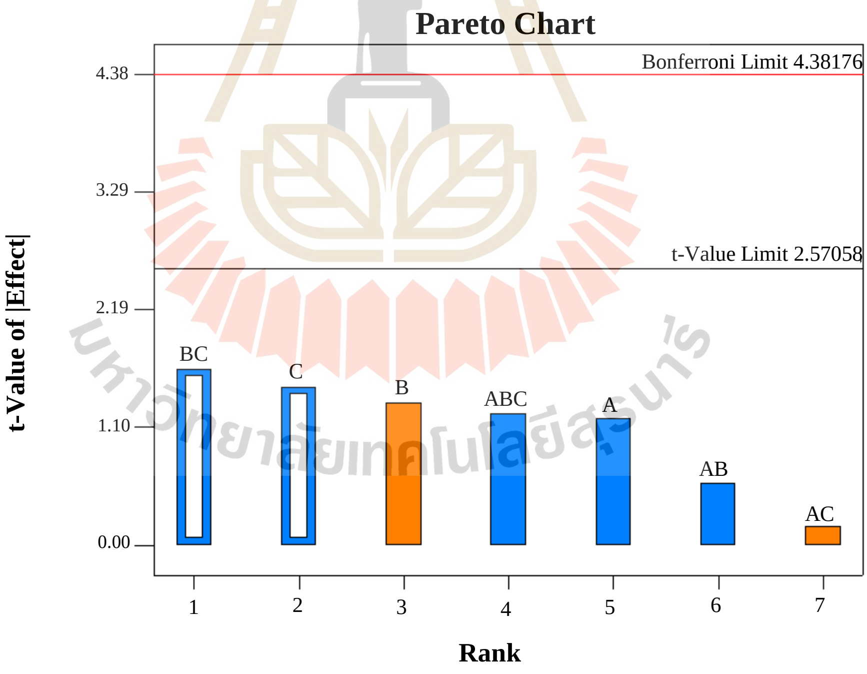
Adhesive type was strongly effect on the product properties. From the analysis in the main effect plot, they are shown that the modulus properties decrease as increasing the prepreg to RT cure from low level, 33.33% prepreg with 66.67% RT cure adhesives, to high level, 66.67% prepreg with 33.33% RT cure adhesive. It presents that the mechanical properties decrease with increasing prepeg adhesive content. Thus, prepreg adhesive is negative effect. This cause may be from the higher viscosity of prepreg adhesive than the RT one. Then, it is hard to flow and difficult to impregnate in the glue line of the wood veneer. Vice versa, room temperature cure adhesive is positive effect as the reason of its lower viscosity then it is easy to flow and more impregnable.

The mechanical properties is observed to increase with increasing fiber type, low level 33.33% CF with 66.67% GF to high level 66.67% CF with 33.33% GF. According to main effect plot results, the CF is positive effect on the product properties, but the significant order is not to pronounce as found in wood species and adhesive type. Economically, GF has lower cost that CF. Therefore, glass fiber was preferred to use instead of carbon fiber in the next test.

Base on this study, the final optimal setting to achieve the maximum mechanical values corresponding to the raw material design parameters in LVL reinforced composite are using rubber wood veneer and glass fiber with room temperature cure adhesive.



(a)



(b)

Figure 4.5 Response analysis for flexural strength in DOE test I: (a) Half-normal plot and (b) Pareto chart.

Table 4.3 ANOVA results of flexural strength in DOE test I.

Source	Sum of Squares	df	Mean Square	F-value	P-value
C	200.08	1	200.08	2.17	0.2006
BC	247.58	1	247.58	2.69	0.1621
Residual	460.68	5	92.14		
Cor Total	908.34	7			

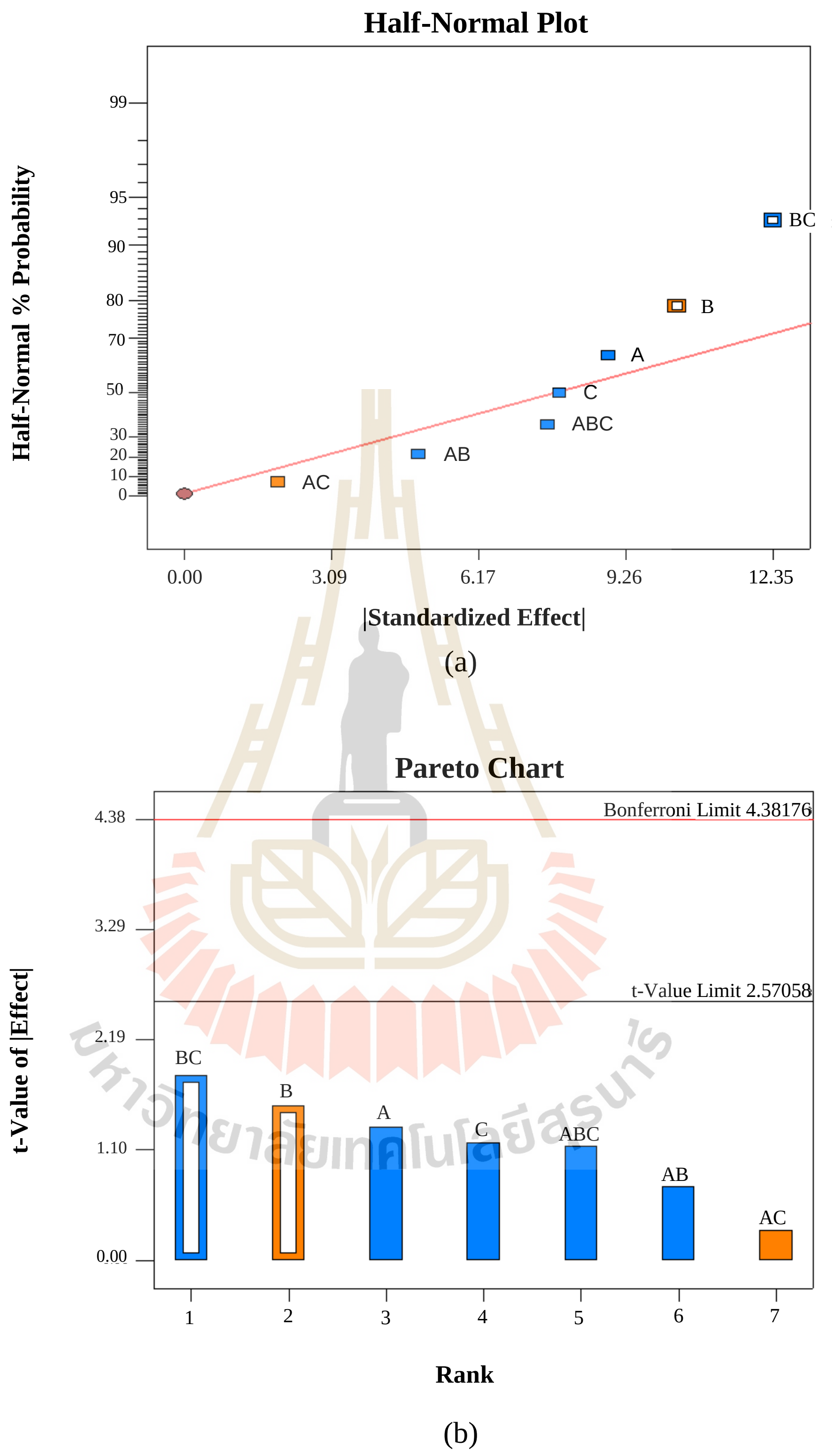
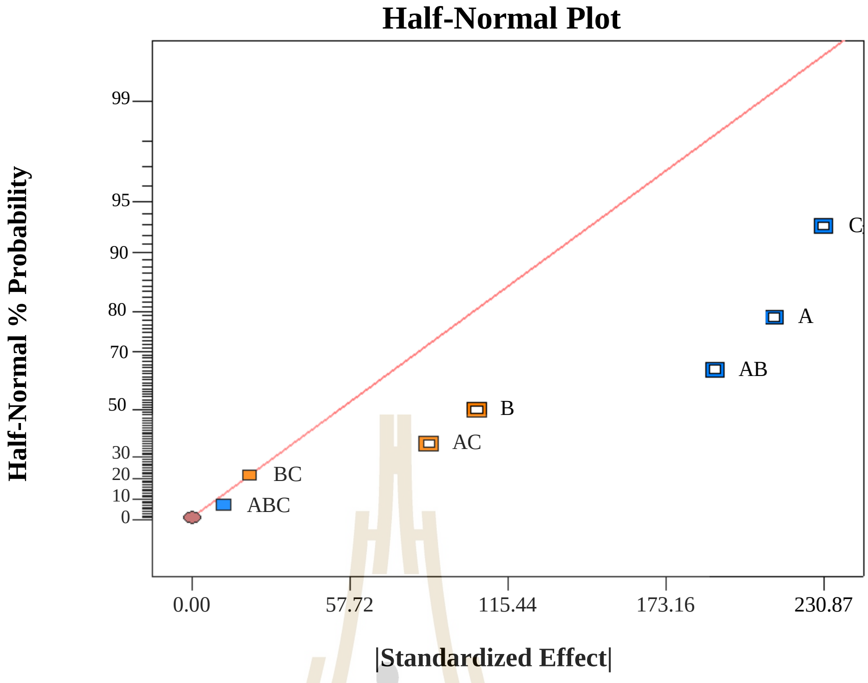


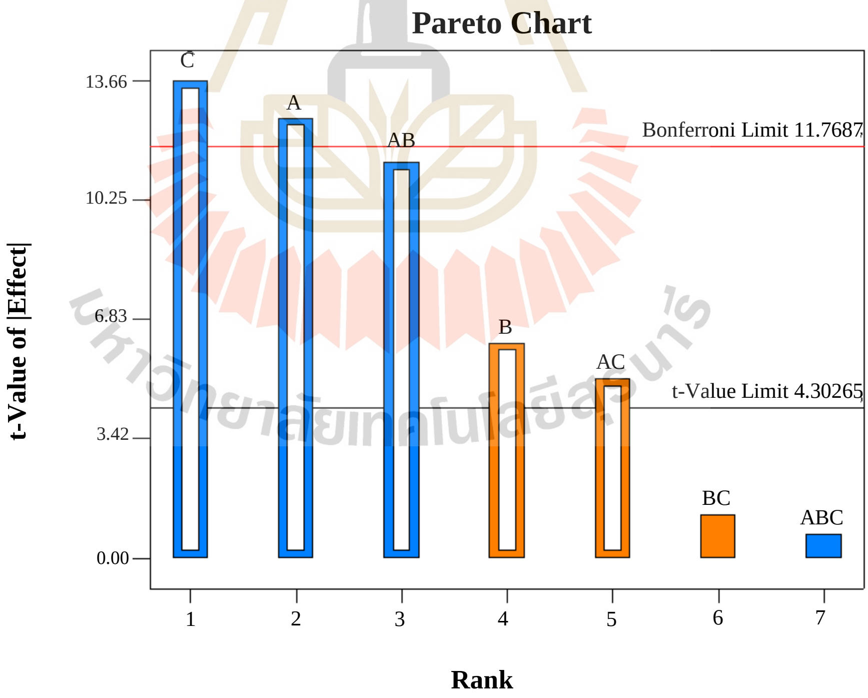
Figure 4.6 Response analysis of specific strength in DOE test I: (a) Half-normal plot and (b) Pareto chart.

Table 4.4 ANOVA results of specific strength in DOE test I.

Source	Sum of Squares	df	Mean Square	F-value	P-value
B	213.82	1	213.82	2.36	0.1855
BC	304.80	1	304.80	3.36	0.1264
Residual	453.96	5	90.79		
Cor Total	972.59	7			



(a)

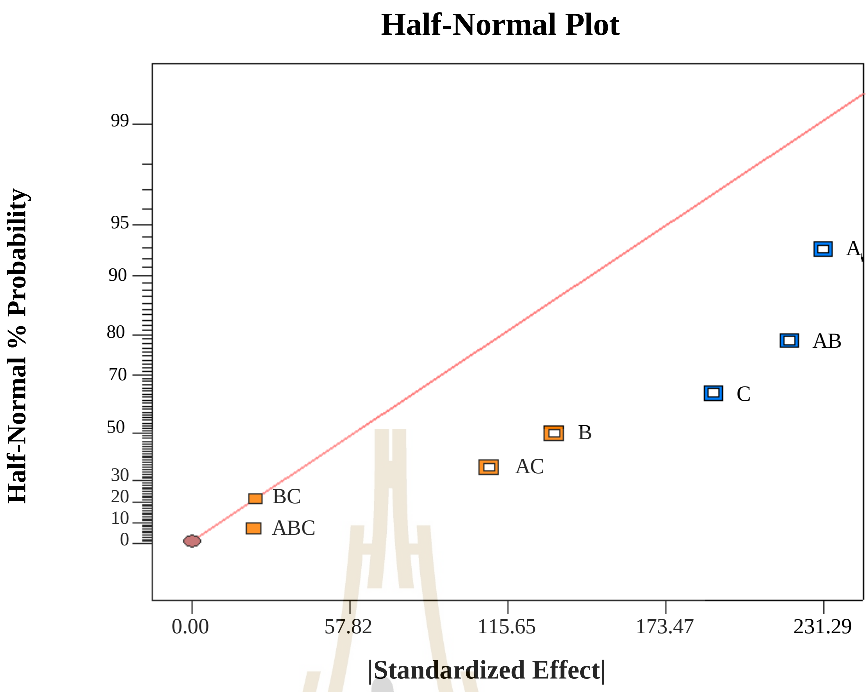


(b)

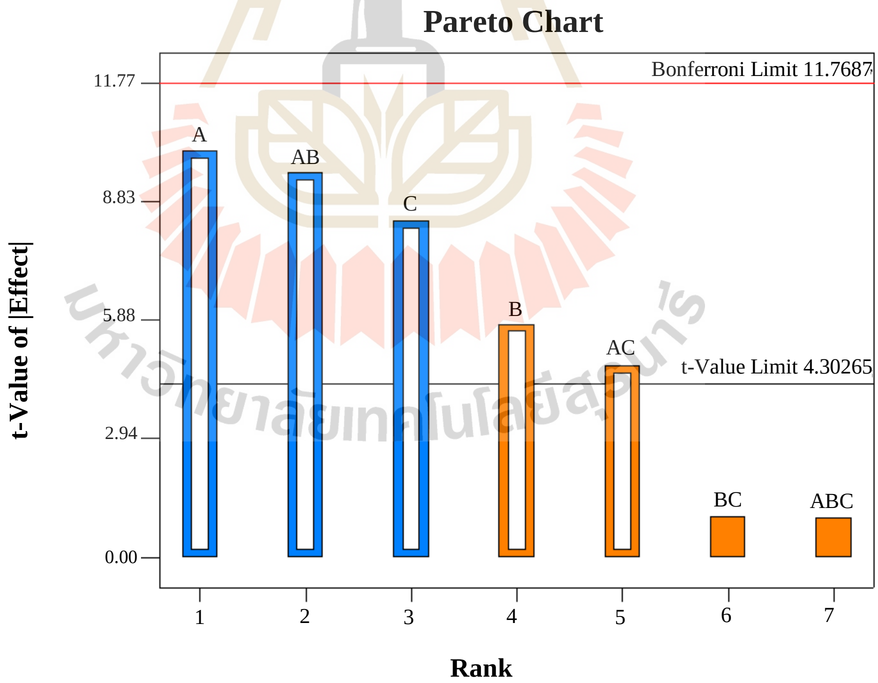
Figure 4.7 Response analysis of flexural modulus in DOE test I: (a) Half-normal plot and (b) Pareto chart.

Table 4.5 ANOVA results of flexural modulus in DOE test I.

Source	Sum of Squares	df	Mean Square	F-value	P-value
A	90607.69	1	90607.69	158.67	0.0062
B	21686.95	1	21686.95	37.98	0.0253
C	106606.30	1	106606.30	186.69	0.0053
AB	73147.77	1	73147.77	128.10	0.0077
AC	15024.85	1	15024.85	26.31	0.0360
Residual	1142.08	2	571.04		
Cor Total	308215.64	7			



(a)

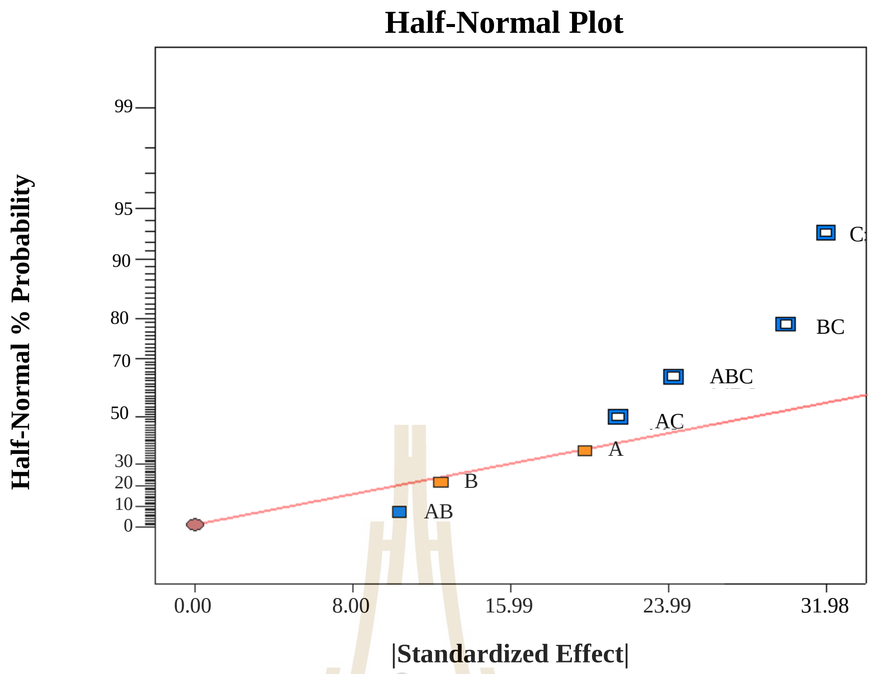


(b)

Figure 4.8 Response analysis of specific modulus in DOE test I: (a) Half-normal plot and (b) Pareto chart.

Table 4.6 ANOVA results of specific modulus in DOE test I.

Source	Sum of Squares	df	Mean Square	F-value	P-value
A	106994.07	1	106994.07	101.76	0.0097
B	35179.23	1	35179.23	33.46	0.0286
C	73101.11	1	73101.11	69.53	0.0141
AB	95900.43	1	95900.43	91.21	0.0108
AC	23698.50	1	23698.50	22.54	0.0416
Residual	2102.78	2	1051.39		
Cor Total	336976.12	7			



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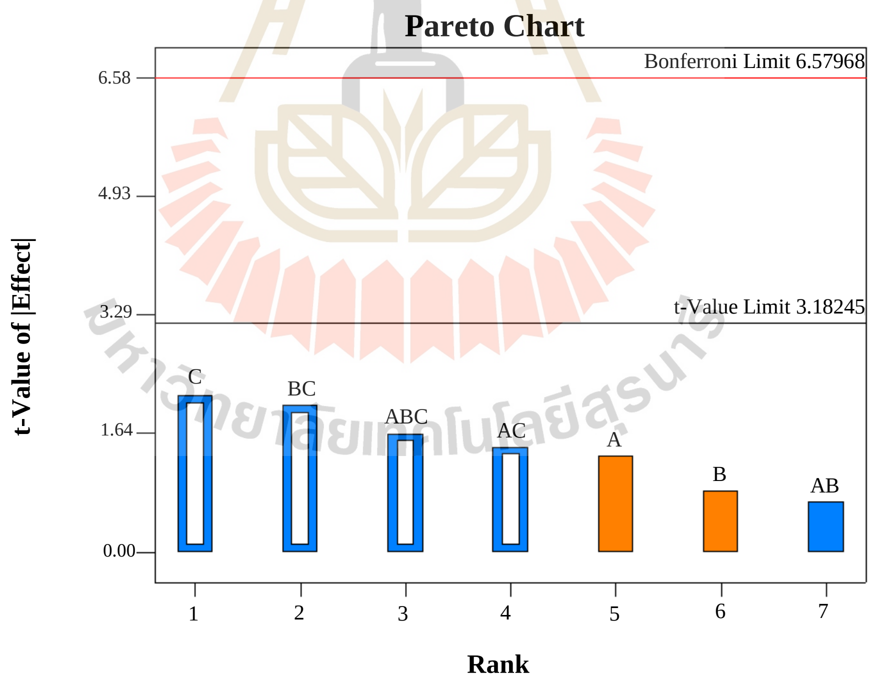
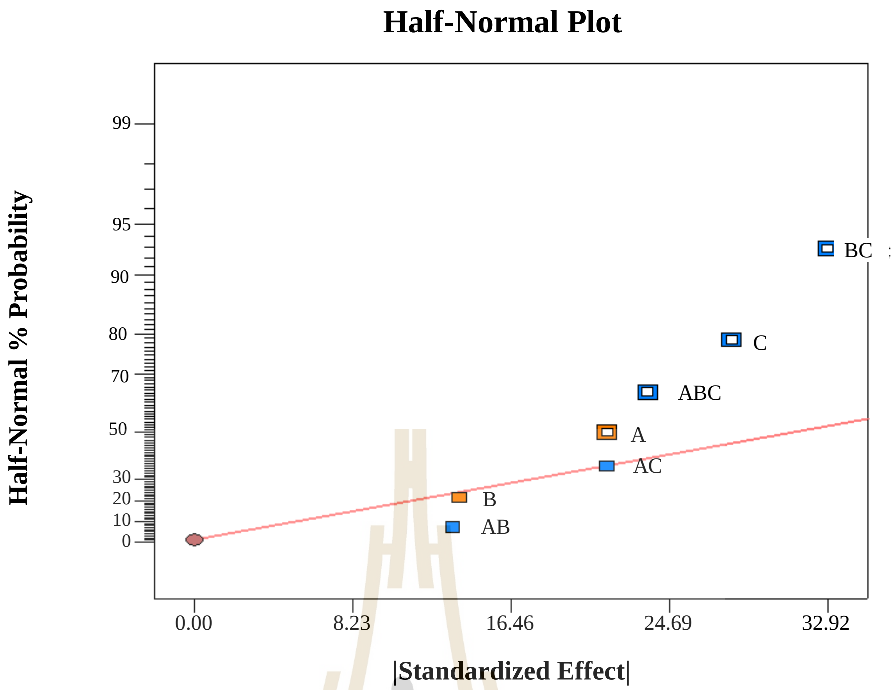


(b)

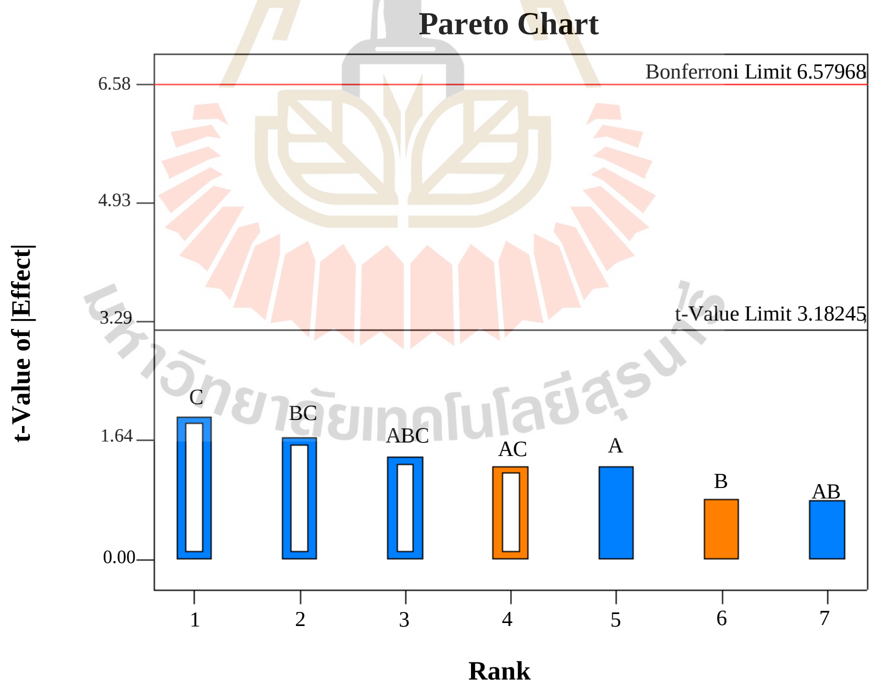
Figure 4.9 Response analysis of flexural toughness in DOE test I: (a) Half-normal plot and (b) Pareto chart.

Table 4.7 ANOVA results of flexural toughness in DOE test I.

Source	Sum of Squares	df	Mean Square	F-value	P-value
C	2045.86	1	2045.86	4.69	0.1188
AC	920.57	1	920.57	2.11	0.2421
BC	1796.24	1	1796.24	4.12	0.1353
ABC	1177.48	1	1177.48	2.70	0.1988
Residual	1307.59	3	435.86		
Cor Total	7247.73	7			



(a)



(b)

Figure 4.10 Response analysis of specific toughness in DOE test I: (a) Half-normal plot and (b) Pareto chart.

Table 4.8 ANOVA results of specific toughness in DOE test I.

Source	Sum of Squares	df	Mean Square	F-value	P-value
A	921.98	1	921.98	1.67	0.2874
C	1560.26	1	1560.26	2.82	0.1918
BC	2167.45	1	2167.45	3.91	0.1423
ABC	1112.02	1	1112.02	2.01	0.2514
Residual	1661.16	3	553.72		
Cor Total	7422.87	7			

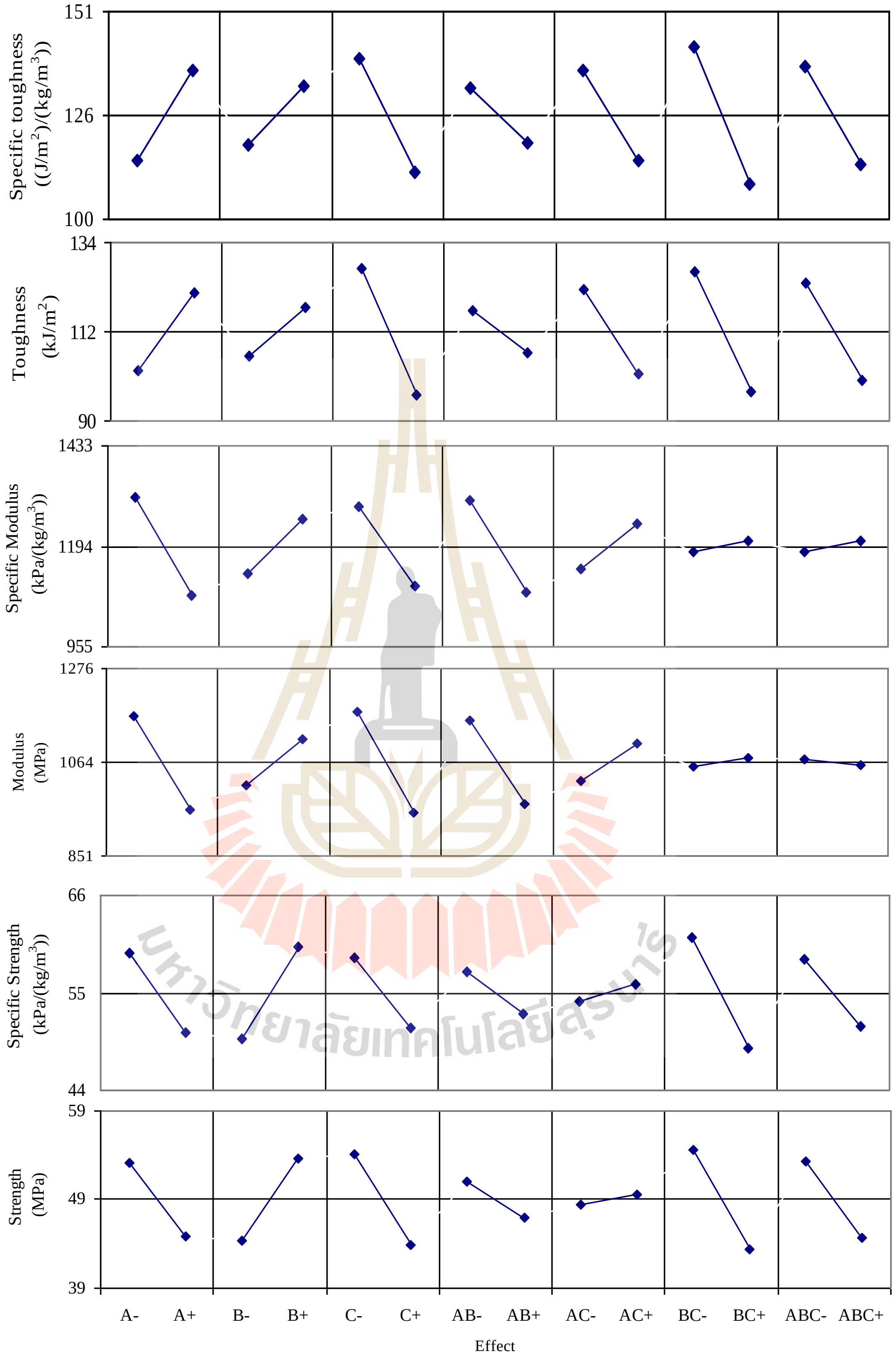


Figure 4.11 Main effect plot for DOE test I.

In order to fine tune the influence of woods content in the LVL composites, the only ratio of eucalyptus and rubber wood were varied and the flexural properties were measured. The %, by number of layers, of the eucalyptus with respect to rubber wood veneer were 0, 14.29, 28.57 and 50%. The test results are summarized in Table 4.9 and also graphically presented in Figure 4.12 to 4.14.

The results show that the mechanical properties are generally decreased with increasing eucalyptus ratio 0% to 50% except at 28.57% where the value is out of trend. As expected that increasing in the eucalyptus ratio would decrease the properties of the composites as discussed in DOE analysis.

Table 4.9 Summary of the mechanical properties of the LVL reinforced composites prepared by using difference wood species content.

Eucalyptus content	Flexural properties			Flexural specific properties		
	Strength (MPa)	Modulus (MPa)	Toughness (kJ/m^2)	Specific Strength $\left(\frac{kPa}{kg/m^3}\right)$	Specific Modulus $\left(\frac{kPa}{kg/m^3}\right)$	Specific Toughness $\left(\frac{(J/m^2)}{kg/m^3}\right)$
0% (0 layer)	58.67±4.59	1155.81±71.74	156.84±28.77	68.76±4.49	1355.13±75.02	183.72±32.26
14.29% (2 layer)	56.46±2.78	920.63±49.08	122.91±1.96	61.72±4.15	1005.03±31.87	134.28±3.27
28.57% (4 layer)	61.00±3.13	890.10±70.44	144.45±21.17	67.63±2.75	986.91±73.12	160.25±23.66
50.00% (7 layer)	34.25±7.09	711.62±132.57	78.35±22.98	35.83±6.36	745.47±126.55	82.41±24.78

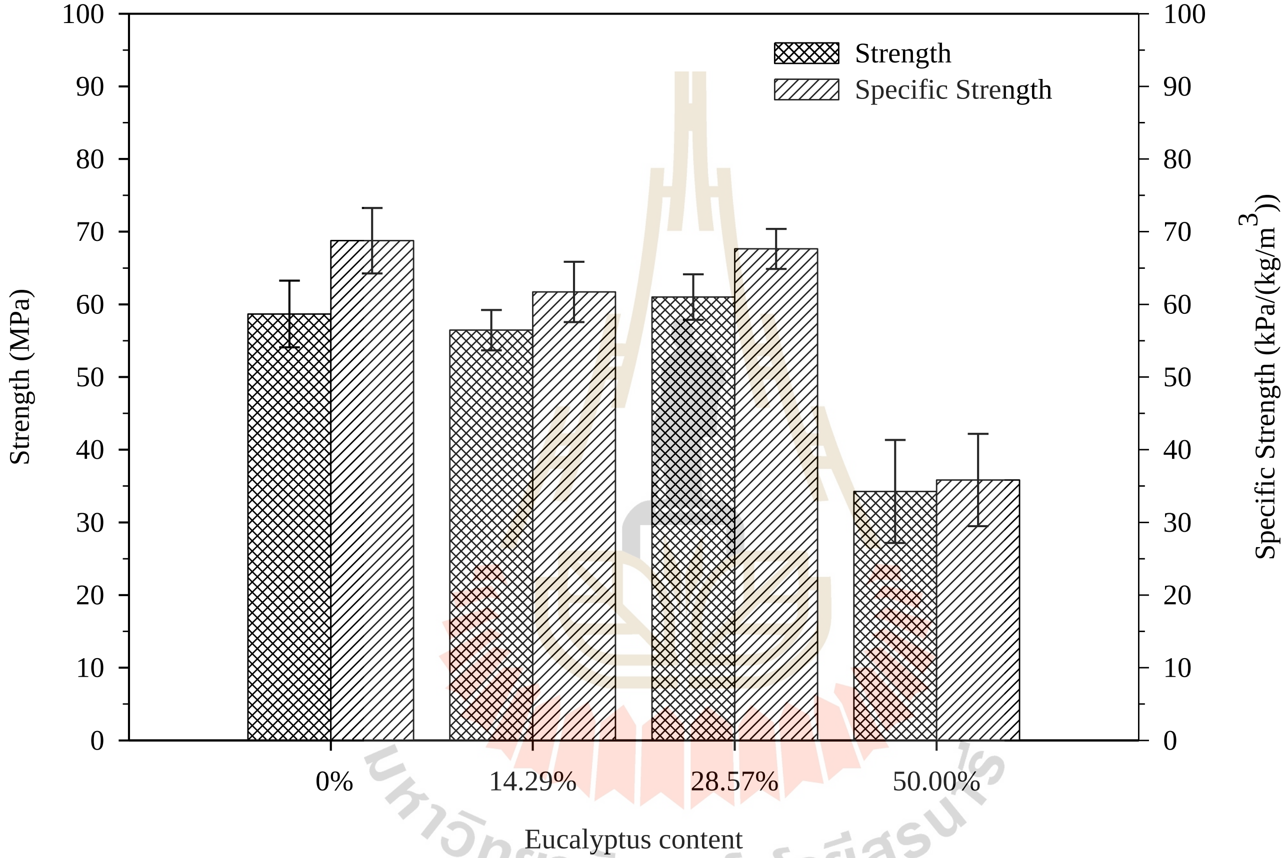


Figure 4.12 Flexural strength of the LVL reinforced composites prepared by using difference wood species content.

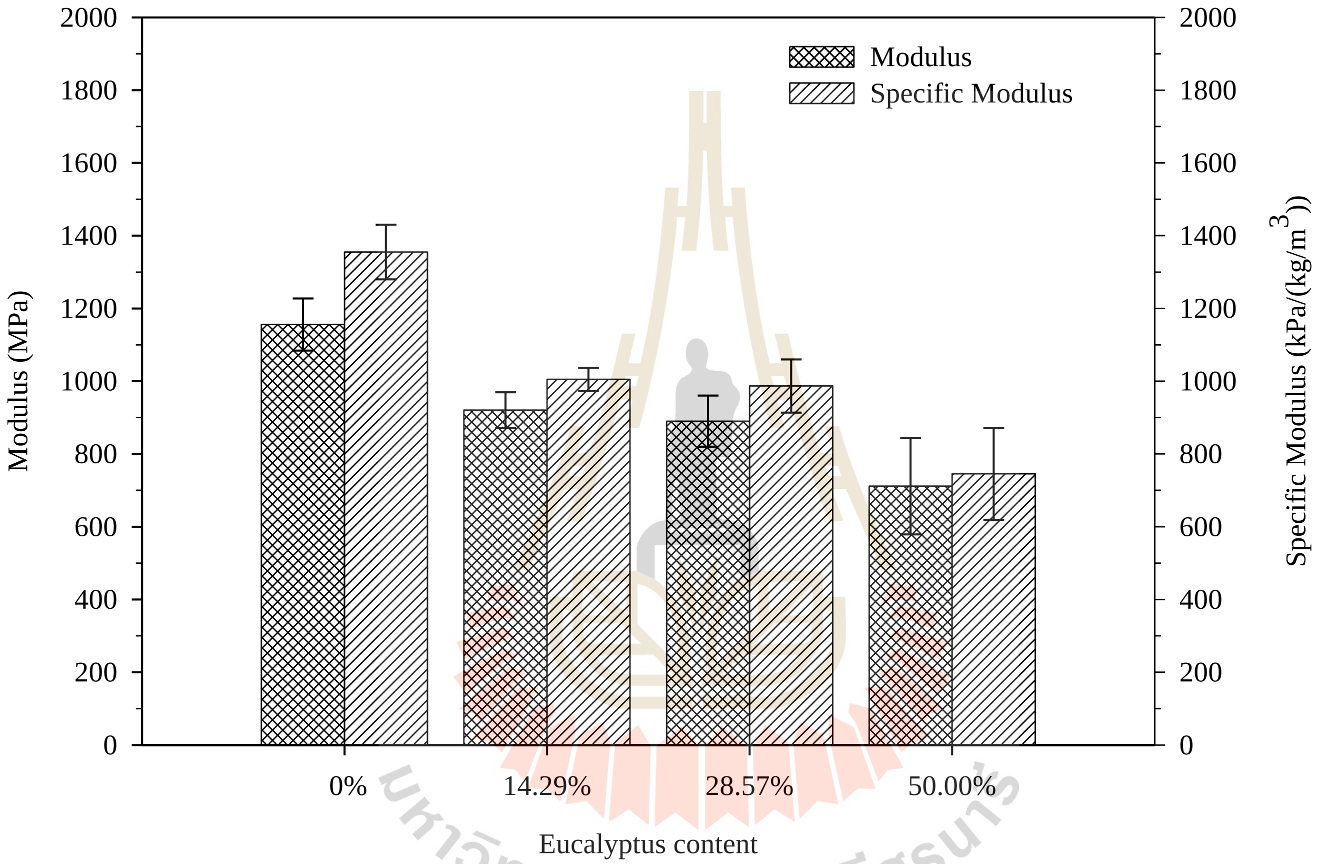


Figure 4.13 Flexural modulus of the LVL reinforced composites prepared by using difference wood species content.

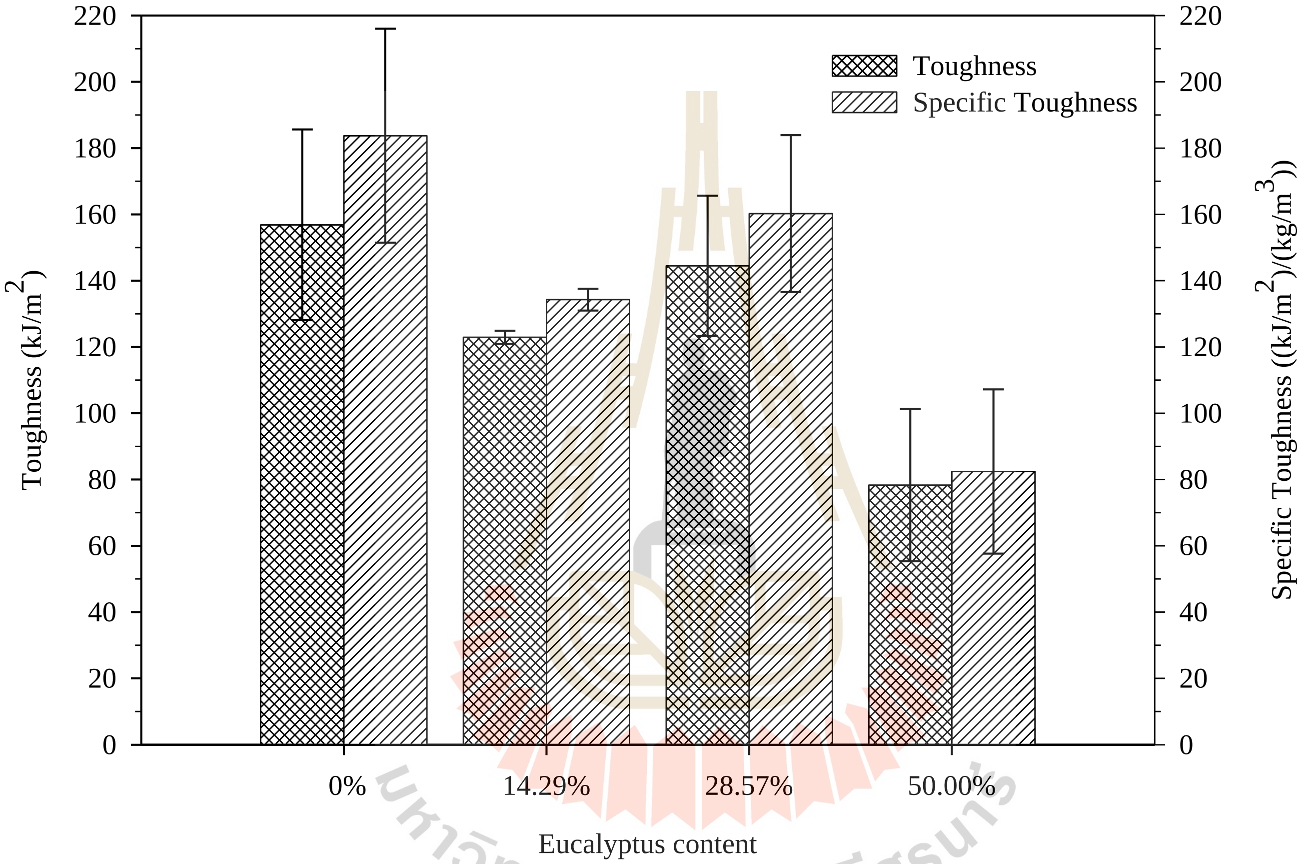


Figure 4.14 Flexural toughness of the LVL reinforced composites prepared by using difference wood species content.

Moreover, the single factor analysis of variance or one-way ANOVA test is applied to verify the dependency of wood species ratio on the mechanical properties of the LVL composites. Typically, two statistical hypothesizes, null (H_0) and alternative (H_1) are identified as show below;

H_0 : the wood content can not be differentiated by means value of the properties

H_1 : one way or another the wood content can be differentiated by means value of properties

If H_0 is accepted, it means that the property of the LVL reinforced composite does not depend on the content. Vice versa, accepting H_1 means that the property of the composite depends on the ratio between those two wood veneers.

In this study, the level of significant (α) for accept H_0 is set at 0.05 or 95% confidential. According one-way ANOVA, if F-value is less than F-critical, at the given level of significant (P-value), 0.05, then the hypothesis H_0 will be accepted. Vice versa, H_0 would be rejected and the hypothesis H_1 will be accepted.

Table 4.10 summarizes the one-way ANOVA results for flexural strength, modulus, and toughness properties obtained from the veneer ratios experiment. The statistical test figures show that all the F-value are higher than F-critical. Hence all H_1 are accepted. Consequently, it can conclude that the mechanical properties of the LVL reinforced composites are influenced by the ratio of veneer used. The eucalyptus is inferior the properties.

Table 4.10 Summary of one-way ANOVA of the mechanical properties of the LVL reinforced composites prepared by using difference wood species content.

Test properties	Source	Sum of Squares	df	Mean Square	F Value	F Critical	P-value	Conclusion
	Content	2295.35	3	765.12				
Strength	Pure Error	339.76	16	21.24	36.03	36.03	< 0.0001	H_1 Accepted
	Cor Total	2635.11	19					
	Content	3564.52	3	1188.17				
Specific strength	Pure Error	307.08	16	19.19	61.91	61.91	< 0.0001	H_1 Accepted
	Cor Total	3871.59	19					
	Content	499608.94	3	166536.31				
Modulus	Pure Error	115554.92	16	7222.18	23.06	23.06	< 0.0001	H_1 Accepted
	Cor Total	615163.86	19					
	Content	944778.67	3	314926.22				
Specific Modulus	Pure Error	109996.11	16	6874.76	45.81	45.81	< 0.0001	H_1 Accepted
	Cor Total	1054774.78	19					
	Content	17856.28	3	5952.09				
Toughness	Pure Error	7224.41	16	451.53	13.18	13.18	0.0001	H_1 Accepted
	Cor Total	25080.70	19					
	Content	28351.56	3	9450.52				
Specific Toughness	Pure Error	8879.29	16	554.96	17.03	17.03	< 0.0001	H_1 Accepted
	Cor Total	37230.85	19					

The ratio of those two fibers, CF and GF, were also redefined by mean of flexural testing for the LVL composites. The percentages by layers of CF with respect to GF were designed at 0, 13.33, 40, 66.67 and 100%, respectively. The test results are summarized in Table 4.11 and plotted as presented in Figure 4.15 to 4.17

As expected, the flexural strength and modulus values are slightly increased with increasing of percent CF ratio. On the other hand, the toughness properties are ambiguously decreasing with increasing CF ratio, except at 13.33% CF content where the measured value is observably out of the line.

Table 4.11 Summary of the mechanical properties of the LVL reinforced composites prepared by using difference fiber reinforcement content.

CF content	Flexural properties			Specific flexural properties		
	Strength (MPa)	Modulus (MPa)	Toughness (kJ/m^2)	Specific Strength $\left(\frac{kPa}{kg/m^3}\right)$	Specific Modulus $\left(\frac{kPa}{kg/m^3}\right)$	Specific Toughness $\left(\frac{(J/m^2)}{kg/m^3}\right)$
0% (0 layer)	76.73±3.74	859.90±34.01	293.34±56.33	89.24±5.26	999.5±32.26	341.49±68.95
13.33% (2 layer)	79.08±3.84	1065.30±60.48	243.68±58.48	89.01±2.74	1199.56±66.88	273.44±58.96
40.00% (6 layer)	84.00±4.18	1059.86±39.01	286.10±26.47	93.98±3.45	1185.93±29.36	320.25±29.68
66.67% (10 layer)	82.62±4.35	1132.08±27.11	252.23±46.95	95.81±5.30	1312.63±29.11	292.64±55.21
100.00% (15 layer)	86.44±4.87	1167.29±47.48	276.78±52.19	95.12±4.56	1284.71±42.79	304.42±55.87

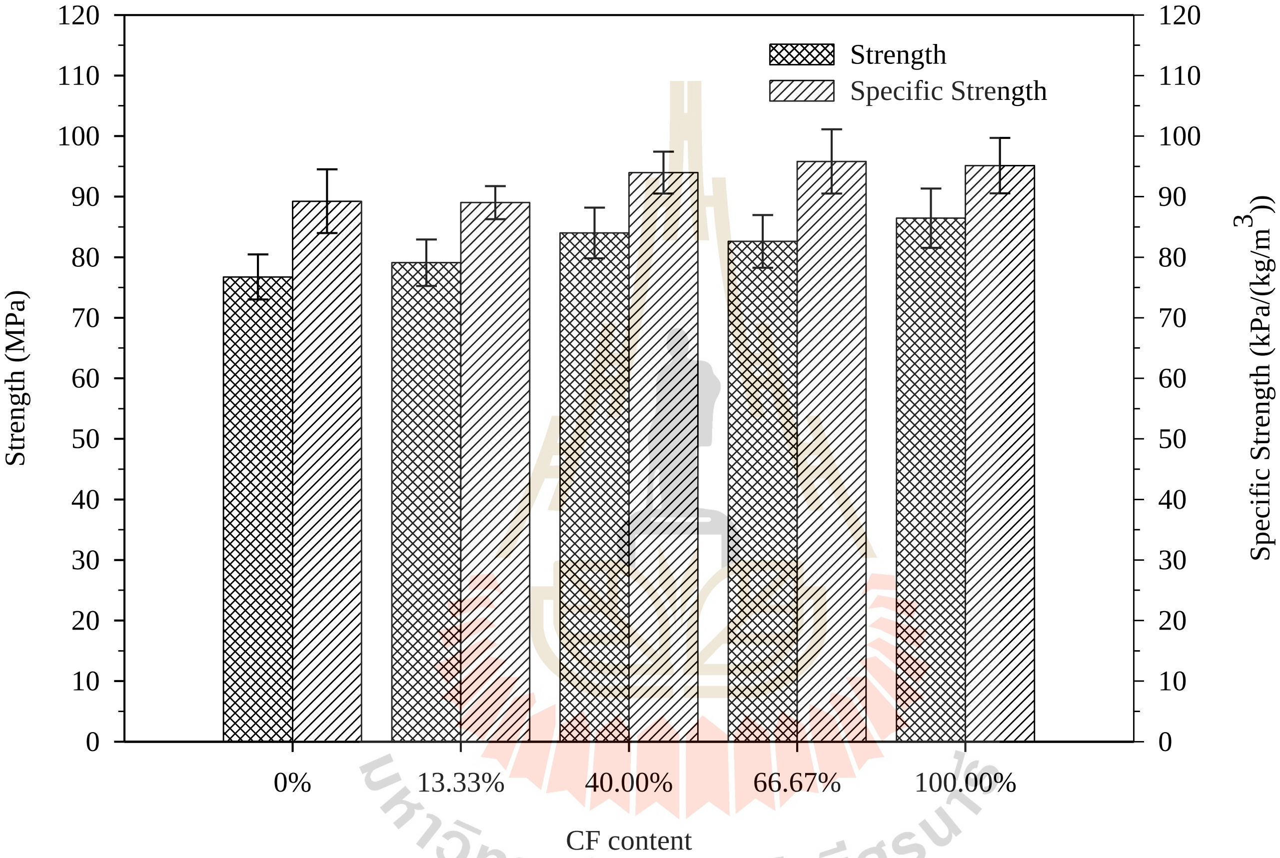


Figure 4.15 Flexural strength of LVL reinforced composites prepared by using difference fiber reinforcement content.

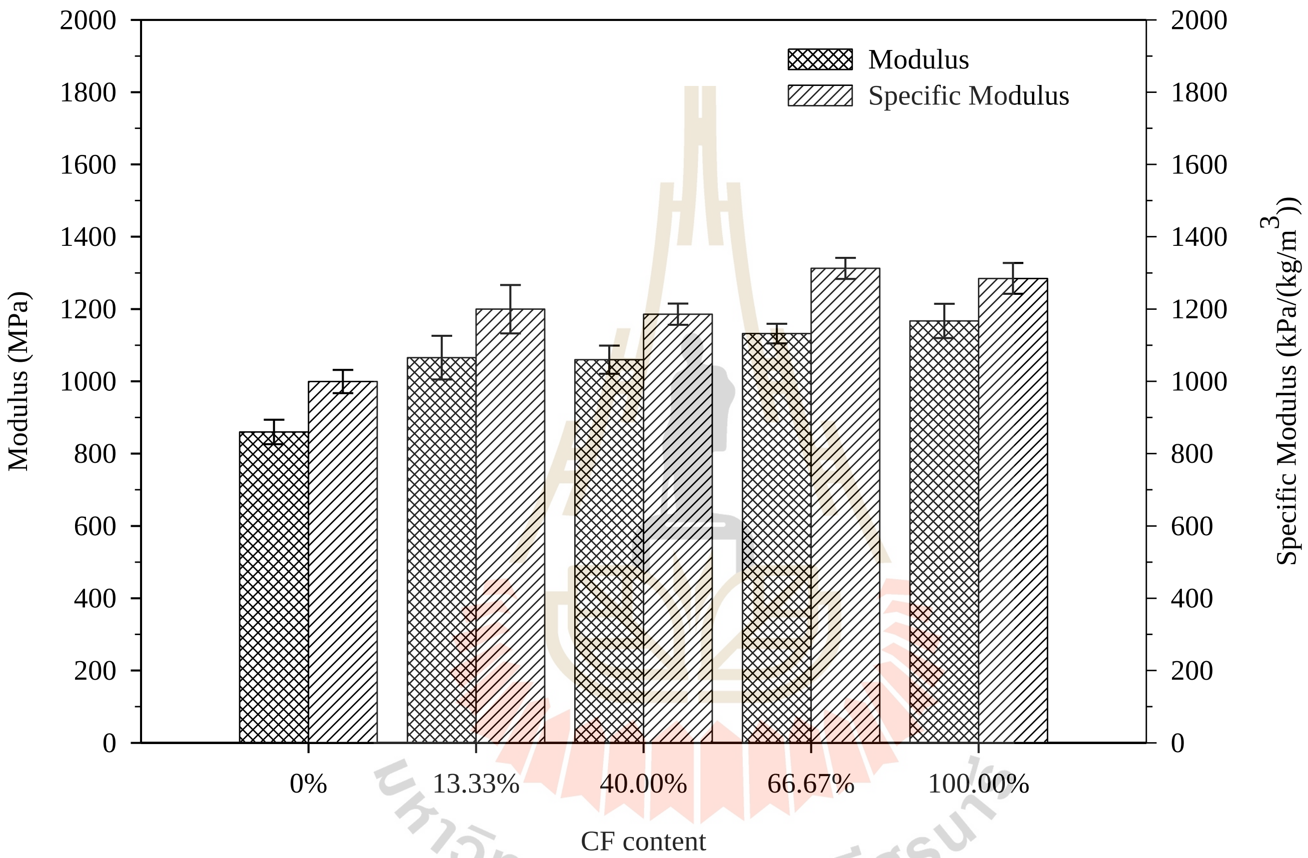


Figure 4.16 Flexural modulus of LVL reinforced composites prepared by using difference fiber reinforcement content.

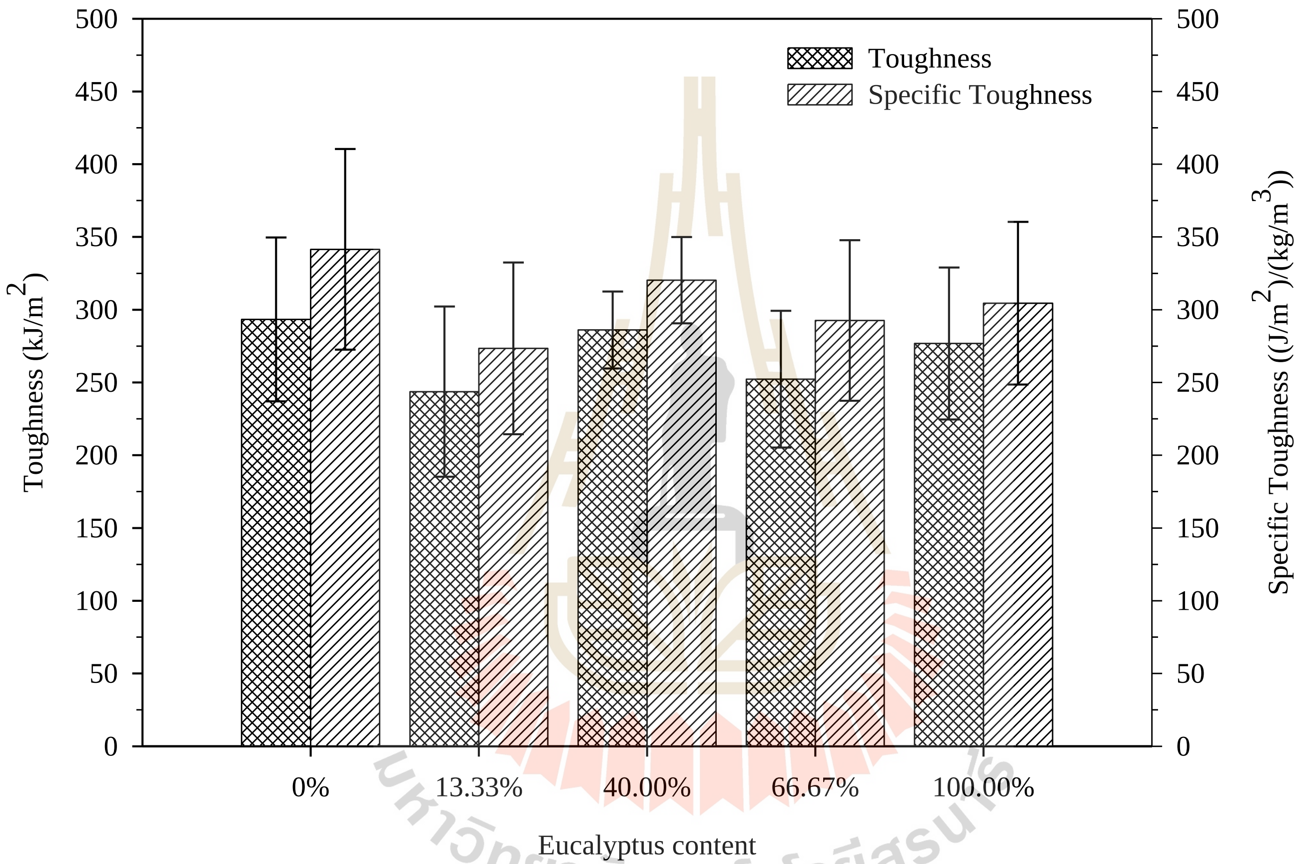


Figure 4.17 Flexural toughness of LVL reinforced composites prepared by using difference fiber reinforcement content.

The one-way ANOVA verification on the mechanical properties of LVL reinforced composites obtained from those the experimental results are performed and summarized in Table 4.12. It is seen that the statistical conclusions are not inconsistency. Both H_0 and H_1 are accepted with respect to the test responds. It is difficult to draw only one conclusion, as found in case of wood content, for the contribution of CF content on the mechanical properties. However in general speaking, the CF is play the important role in the strength but GF has the great influence on toughness. One thing should be bare in mind that CF has low density but high cost, contradicted, GF has higher density and lower cost.

Taken both experimental results from the 2^k DOE and one-way ANOVA, the arguable conclusion for the dependency of the wood species and fiber types on the mechanical properties of the manufactured LVL composites is influenced by the content of those constituents. However, the fiber type does not obviously have an affect on the mechanical properties of the LVL where wood species do.

Table 4.12 Summary of one-way ANOVA of the mechanical properties of the LVL reinforced composites prepared by using difference fibers content.

Test properties	Source	Sum of Squares	df	Mean Square	F Value	F Critical	P-value	Conclusion
Strength	CF Content	300.38	4	75.10	4.22	2.87	0.0123	H_1 Accepted
	Pure Error	355.85	20	17.79				
	Cor Total	656.23	24					
Specific strength	CF Content	213.37	4	53.34	2.78	2.87	0.0550	H_0 Accepted
	Pure Error	383.90	20	19.20				
	Cor Total	597.28	24					
Modulus	CF Content	283627.75	4	70906.94	38.02	2.87	< 0.0001	H_1 Accepted
	Pure Error	37301.22	20	1865.06				
	Cor Total	320928.97	24					
Specific Modulus	CF Content	300998.01	4	75249.50	41.56	2.87	< 0.0001	H_1 Accepted
	Pure Error	36216.30	20	1810.82				
	Cor Total	337214.31	24					
Toughness	CF Content	9288.31	4	2322.08	0.95	2.87	0.4561	H_0 Accepted
	Pure Error	48894.04	20	2444.70				
	Cor Total	58182.36	24					
Specific Toughness	CF Content	13513.90	4	3378.48	1.11	2.87	0.3814	H_0 Accepted
	Pure Error	61125.83	20	3056.29				
	Cor Total	74639.74	24					

4.2 Surface Enhancement

It is known that one of the vital properties of adhesives to bond two substrates is chemical interaction between the two. Moreover, substrates such as wood, other chemicals are needed to apply both pre and post production to enhance the durability accomplishment. One of the common treatments found in wood industries is anti termite application. In this present work, the commercial available anti-termite liquid, Chindrite^{TM}, was applied on the surface of the veneer. Smoked treatment of the wood veneer is not only change the surface properties such as increase the acidity but it is also acted as naturally coloring. Silane compounds are well-known for improving the bonding strength between substrates. The silane molecules are bifunctional, containing polar silanol groups and organofunctional groups capable of reaction with polymer. They are generally employed to improve the adhesion between the constituent materials that strongly affects the mechanical properties. In this research task, well quantify silane was added into curing agent.

In this study, the effects of parameters that possibly improve the adhesion strength between the LVL components, namely silane content in curing agent and wood surface treatments as mention earlier, on the wood composite were examined. There were eight designed test runs as presented in Table 3.4 and they were assigned as T's series.

Table 4.13 summarized the test figures of flexural properties including the strength, modulus, and toughness of LVL reinforced composites correspondence to the DOE given in Table 3.4. The results are also graphically presented in Figure 4.18 and 4.19. Based on the measured figures, it is found that the T4 condition provided the maximum strength and modulus at 54.01±7.75 MPa and 1286.36±73.75 MPa, respectively. The lowest values at 31.81±6.37 and 636.99±134.30 are observed for the T1.

The flexural toughness is also calculated. The series figures, from high and low, are T7, T3, T2, T4, T8, T1, T6 and T5, respectively. The maximum and minimum values are 143.15±31.75 and 92.65±14.28 kJ/m^2.

The same trend is also found for the specific figures as illustrated in Table 4.14 and, in Figure 4.20 and 4.21. Again, the results show that the promising condition in term of the strength is T4 and the incompetence condition is T1. Accordingly, the specific flexural toughness is flowed the same tendency.

Due to T4 is shown an outstanding condition among this category. Close observation, it is found that high quantity of silane, 15% w/w, low content of wood surface treatment by both smoked wood and anti termite application, 28%. It indicates that the flexural properties of LVL reinforced composite is increased with employing higher quantity of silane but lower content of wood surface treatments. Contradictorily, the inferior flexural properties are observed by using combination of high quantity of silane and high anti termite surface treatment. As expected that the treatment interferes bonding integrity of adhesive to wood substrates. Therefore, the boding strength will be decreased.

Table 4.13 Mechanical properties of LVL reinforced composites prepared in DOE test II using difference silane quantity and wood surface treatment.

Condition	Factor			Interaction				Flexural properties		
	A (Silane quantity)	B (Smoked wood)	C (Anti termite wood)	AB	AC	BC	ABC	Strength (MPa)	Modulus (MPa)	Toughness (kJ/m^2)
T1	+	+	+	+	+	+	+	31.81±6.37	636.99±134.30	92.65±14.28
T2	+	+	-	+	-	-	-	45.55±5.26	873.87±68.68	125.10±13.65
T3	+	-	+	-	+	-	-	41.69±8.03	890.00±106.91	128.29±35.18
T4	+	-	-	-	-	+	+	54.01±7.75	1286.36±73.75	119.83±28.92
T5	-	+	+	-	-	+	-	44.53±5.73	1160.83±84.95	70.52±7.84
T6	-	+	-	-	+	-	+	52.46±8.45	1003.37±134.68	91.83±40.83
T7	-	-	+	+	-	-	+	48.66±9.92	966.83±75.44	143.15±31.75
T8	-	-	-	+	+	+	-	45.50±3.64	934.01±128.13	111.01±19.31

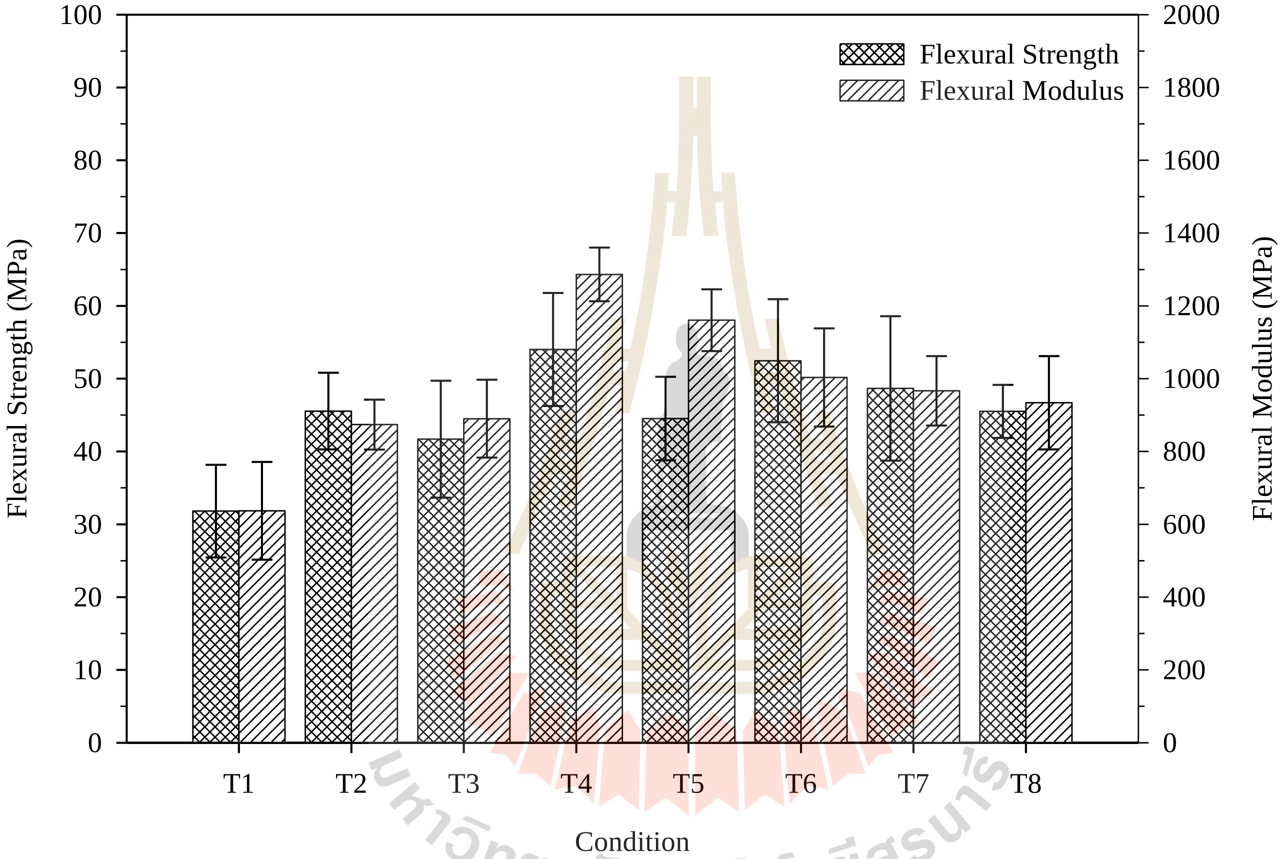


Figure 4.18 Flexural strength and flexural modulus of LVL reinforced composites prepared in DOE test II using difference silane quantity and wood surface treatment.

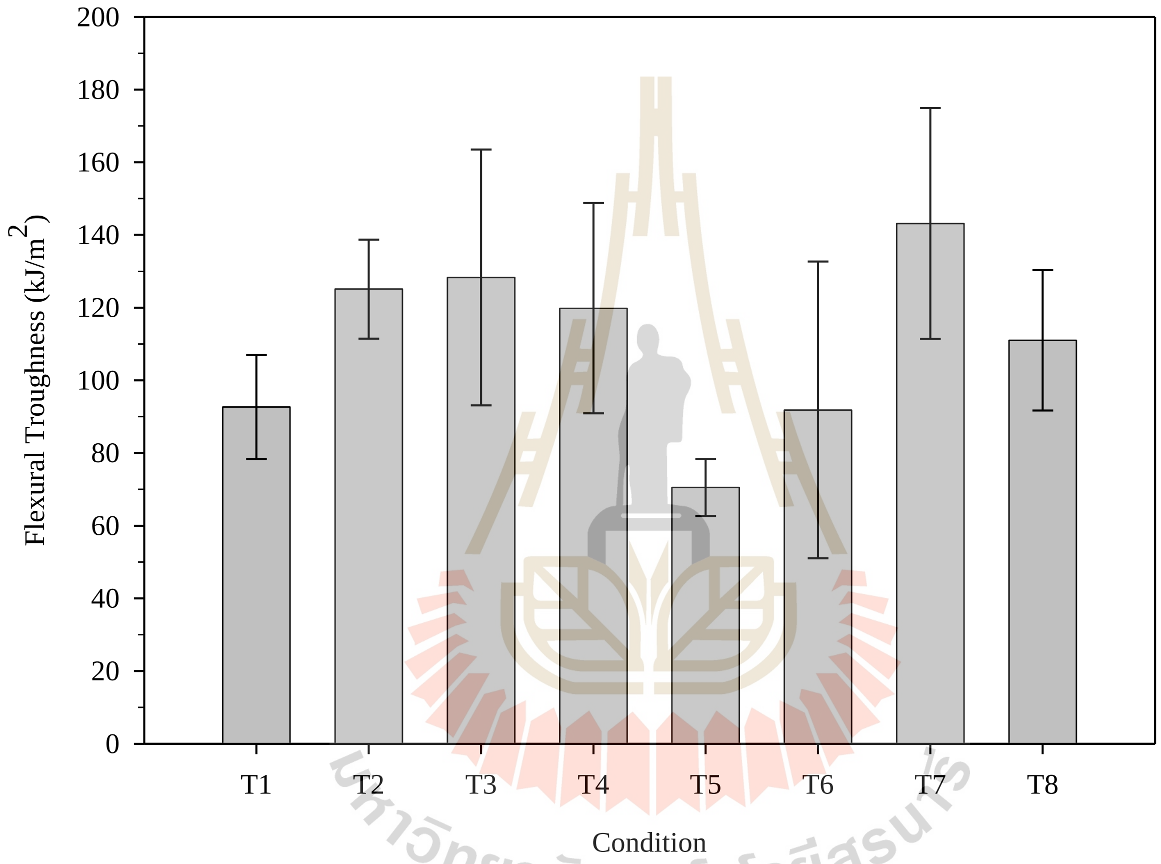


Figure 4.19 Flexural toughness of LVL reinforced composite prepared in DOE test II using difference silane quantity and wood surface treatment.

Table 4.14 Specific mechanical properties of the LVL reinforced composites prepared in DOE test II using difference silane quantity and wood surface treatment.

Condition	Factor			Interaction				Flexural properties		
	A (Silane quantity)	B (Smoked wood)	C (Anti termite wood)	AB	AC	BC	ABC	Specific Strength $\left(\frac{kPa}{kg/m^3}\right)$	Specific Modulus $\left(\frac{kPa}{kg/m^3}\right)$	Specific Toughness $\left(\frac{J/m^2}{kg/m^3}\right)$
T1	+	+	+	+	+	+	+	36.48±6.94	730.91±149.57	106.46±16.86
T2	+	+	-	+	-	-	-	53.09±7.10	1018.21±101.25	145.57±15.41
T3	+	-	+	-	+	-	-	47.05±8.67	1004.43±106.97	144.53±37.58
T4	+	-	-	-	-	+	+	57.50±6.81	1371.74±50.26	127.67±28.89
T5	-	+	+	-	-	+	-	50.28±6.22	1311.34±94.08	79.56±7.42
T6	-	+	-	-	+	-	+	50.54±10.08	1047.58±104.56	95.42±41.26
T7	-	-	+	+	-	-	+	57.20±3.45	1041.95±90.14	154.01±31.81
T8	-	-	-	+	+	+	-	50.22±4.83	1031.57±155.64	122.56±22.56

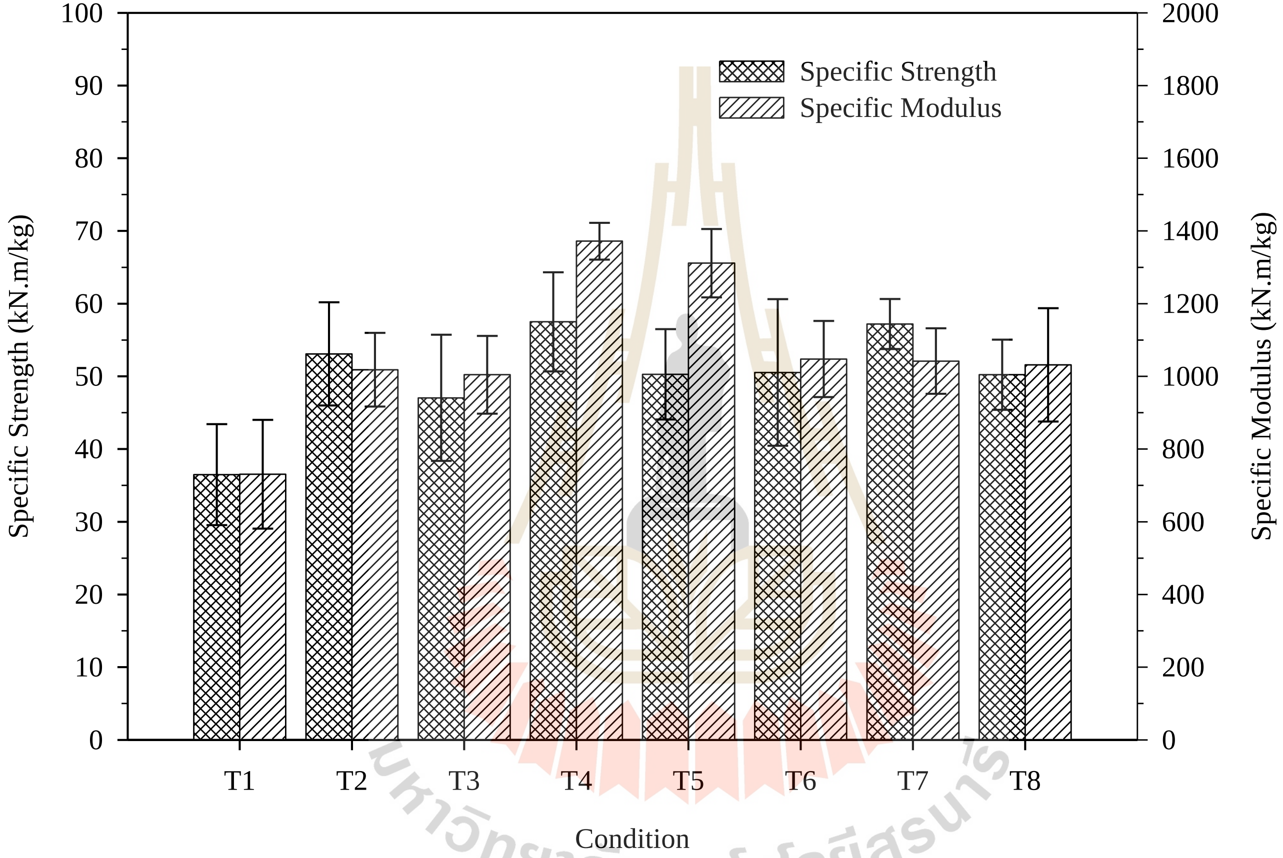


Figure 4.20 Specific strength and specific modulus of LVL reinforced composite prepared in DOE test II using difference silane quantity and wood surface treatment.

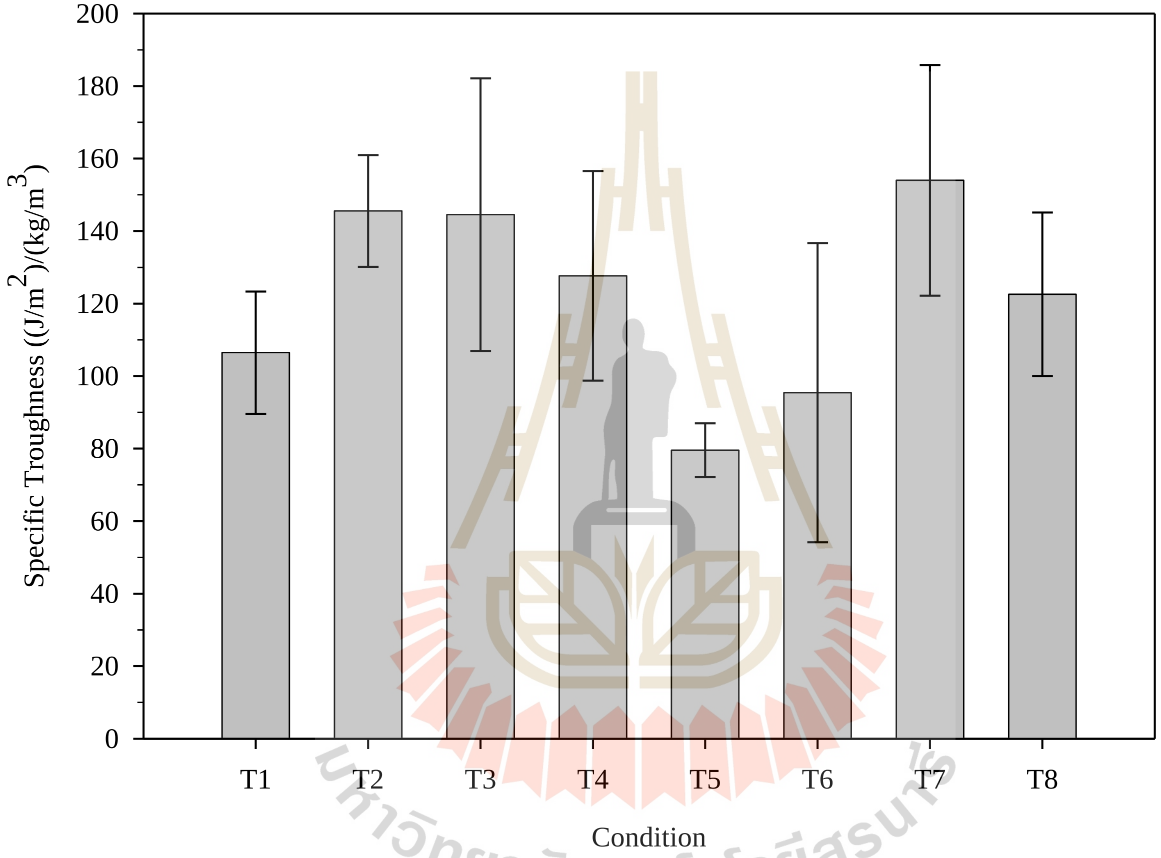


Figure 4.21 Specific toughness of LVL reinforced composite prepared in DOE test II using difference silane quantity and wood surface treatment.

The response value of flexural properties in half-normal plot and the ANOVA tests to validate the effect of parameters for enhancing surface bonding are shown in Figure 4.22 to 4.27 and summarized in Table 4.15 to 4.20, respectively.

Taking only flexural strength into consideration as presented in Figure 4.22 and Table 4.15, it is noticed that there are no significant effects on flexural strength of LVL composites within P-value more than 0.05. However, the results review that interaction between silane quantity and anti-termite treatment (AC) is most significant effect on the specific strength of the composites as indicated in the ANOVA output shown in Table 4.16 where P-value is 0.0344. This figure is less than the set value at 0.05.

The ANOVA results in Table 4.17 and 4.18, the interaction between silane quantity and smoked wood treatment (AB) are significant effect on the modulus and specific modulus. Beside, the interaction between silane content and anti termite treatment (AC) is significant effect on only the specific modulus as the P-value less than 0.05.

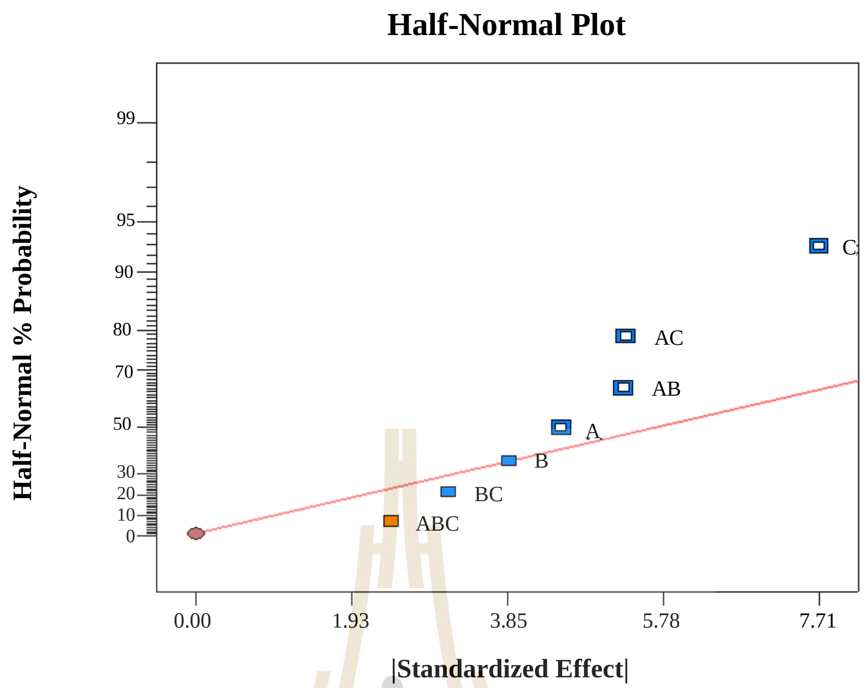
The significant effects on toughness and specific toughness are shown in Figure 4.26 and Table 4.19, and Figure 4.27 and Table 4.20, respectively. The analysis by both the half-normal plot and ANOVA are found that interaction between smoked wood and anti termite treatment (BC) and silane quantity and smoked wood treatment (AC), and the effect of smoked treatment (B), and silane (A) are significantly effect on the toughness properties of LVL reinforced composites.

Also those significant effects can be detected in the main effect plots, Figure 4.30, as they show high slope. These numbers reinforce the results obtained from the above statistical analyses.

Based on this research work, the interaction between silane quantity and anti termite treatment at high level (AC+) is given rise to minimal specific strength. So, it is the negative effect. Therefore, the strengths of the wood composite will decrease as setting this interaction effect at high level (+). There are another two mathematically possibilities that make this output is a positive sign. They are high silane quantity (+) multiply by high anti termite treatment level (+) or low silane quantity (-) multiply by low anti termite treatment (-). Vice versa, the strength will increase if the AC interaction is kept at low level, negative sign. They are using low silane quantity (-) with high anti termite treatment (+) or using high silane quantity (+) with low anti termite treatment (-). In conclusion to silane quantity as it is significant positive effect on toughness as shown in the main effect plot. It indicates that the toughness of the wood increase with increasing silane quantity. Therefore, high silane quantity with low anti termite must be selected to get the over all better properties. As expected that wood surface treatment interferes to the bond integrity of adhesive wood substrates and silane can be used to improve the adhesion between the constituent materials that strongly affects the mechanical properties.

In addition, the interaction between smoked wood and anti termite treatment is strongly effect on the toughness properties. It is the negative effect because it exhibits the minimum toughness values if this interaction is set at high level. Meaning that toughness properties will be decreased with increasing this interaction from low level to high level. Vice versa, the figures will be increased with changing this interaction from high level (BC+) to low level (BC-). The possibility can be algebraically done by using high content of smoked wood (+) with low content of anti termite treatment (-) or using low content of smoked wood (-) with high content of anti termite treatment (+), consequently. As mentioned earlier, anti-termite should be maintained at low level (-). Therefore, high content of smoked wood with low content of anti termite treatment must be employed to achieve the optimal properties. Considering the interaction between the silane and smoked wood is shown the significantly effect on the toughness properties as the positive effect. The maximum toughness is obtained with increasing this interaction from low level (AB-) to high level (AB+). It again can be achieved by using either high silane quantity (+) with high content of smoked wood (+) or using low silane quantity (-) with low content of smoked wood (-). In this case, high silane quantity with high content of smoked wood must be selected to obtain the best toughness properties because anti termite must be used at low level then smoked wood should be used at high level.

As discussed above, the final optimal settings for the significant effects in this test is that setting silane quantity at high level, smoked wood at high level, and anti termite at low level. According to the purpose of both wood surface treatments, smoking and anti termite application, was in different directions. Thus, only smoked wood treatment was performed in next step with high silane quantity, 15% w/w, added in curing agent.



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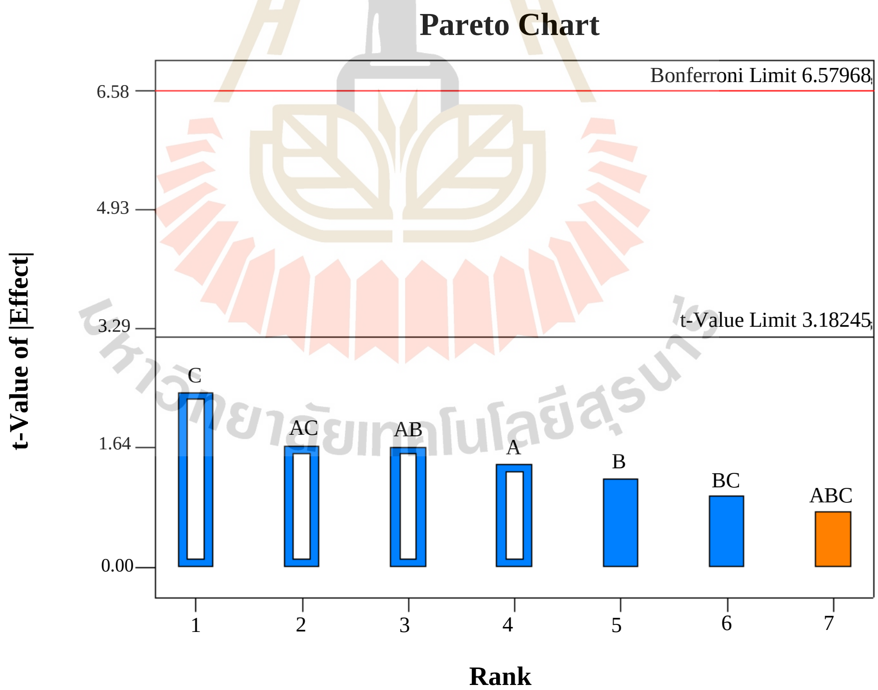
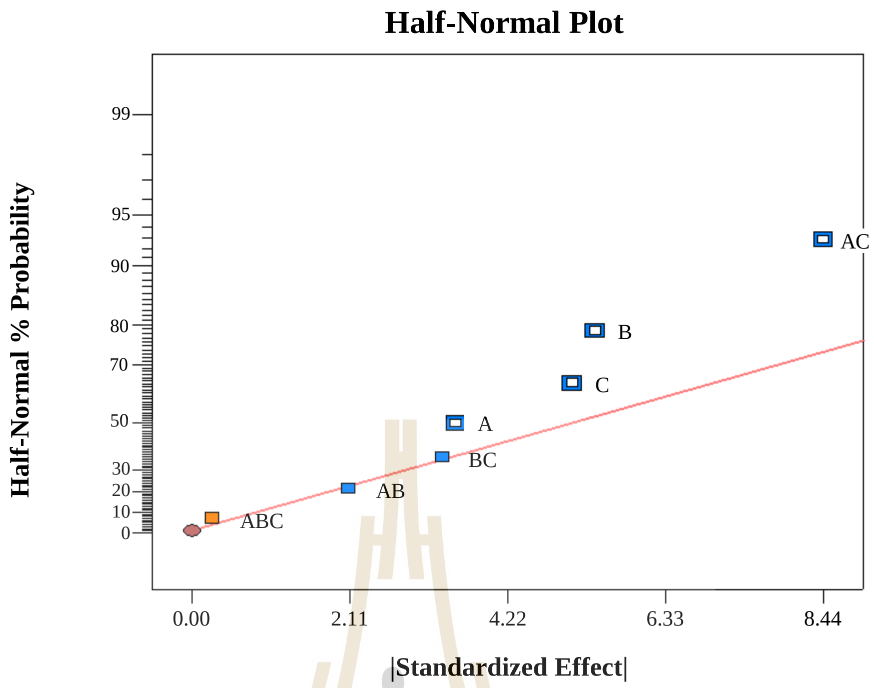


(b)

Figure 4.22 Response analysis for flexural strength in DOE test II: (a) Half-normal plot and (b) Pareto chart.

Table 4.15 ANOVA results of flexural strength in DOE test II.

Source	Sum of Squares	df	Mean Square	F-value	P-value
A	40.88	1	40.88	2.00	0.2520
C	118.87	1	118.87	5.82	0.0948
AB	56.04	1	56.04	2.74	0.1962
AC	56.64	1	56.64	2.77	0.1944
Residual	61.26	3	20.42		
Cor Total	333.69	7			



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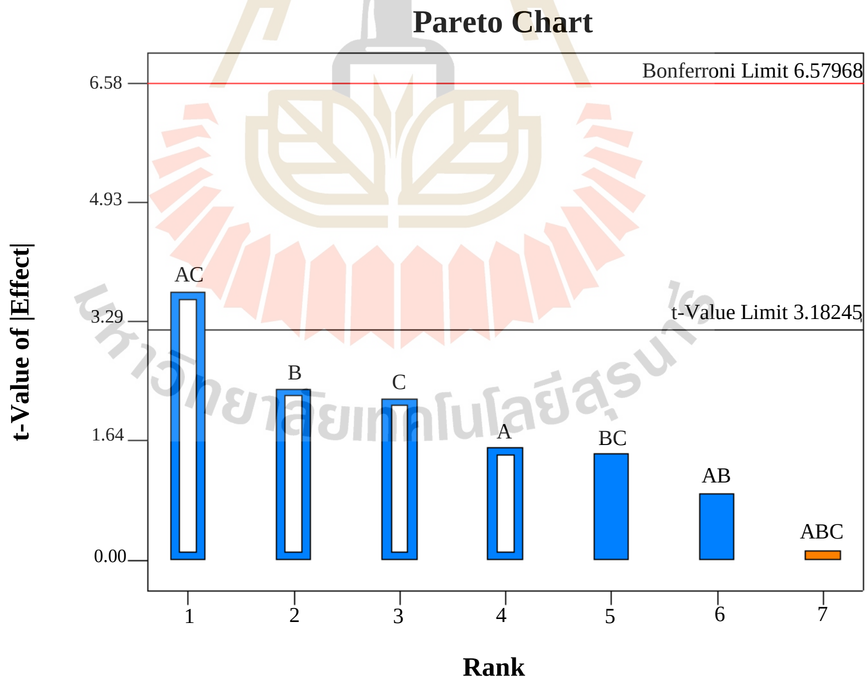
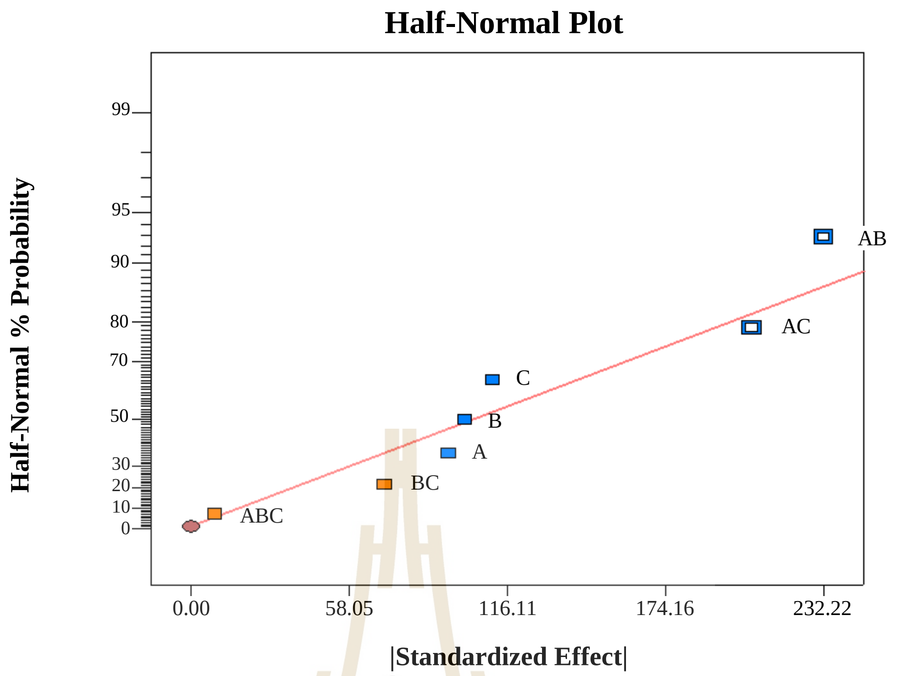


(b)

Figure 4.23 Response analysis for specific strength in DOE test II: (a) Half-normal plot and (b) Pareto chart

Table 4.16 ANOVA results of specific strength in DOE test II.

Source	Sum of Squares	df	Mean Square	F-value	P-value
A	24.97	1	24.97	2.39	0.2200
B	58.16	1	58.16	5.56	0.0995
C	51.71	1	51.71	4.95	0.1126
AC	142.59	1	142.59	13.64	0.0344
Residual	31.37	3	10.46		
Cor Total	308.80	7			



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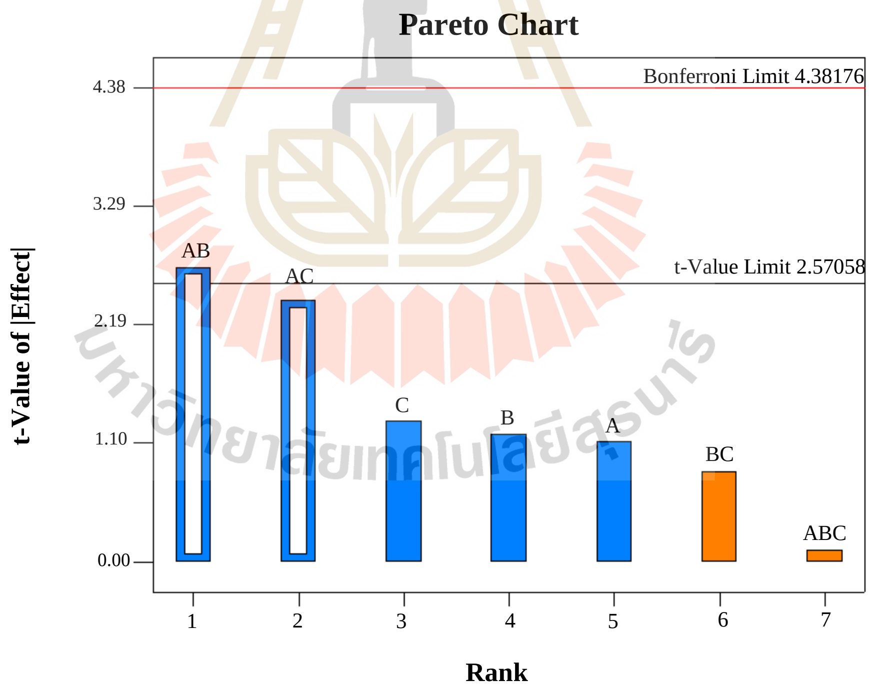
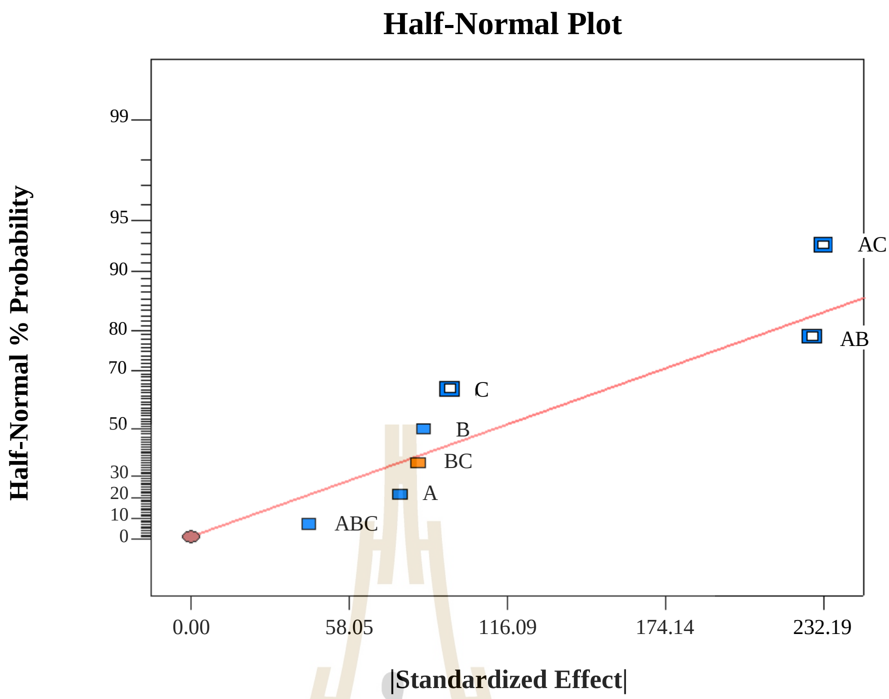


(b)

Figure 4.24 Response analysis for flexural modulus in DOE test II: (a) Half-normal plot and (b) Pareto chart.

Table 4.17 ANOVA results of flexural modulus in DOE test II.

Source	Sum of Squares	df	Mean Square	F-value	P-value
AB	107848.85	1	107848.85	7.40	0.0417
AC	84772.87	1	84772.87	5.82	0.0607
Residual	72830.49	5	14566.10		
Cor Total	265452.21	7			



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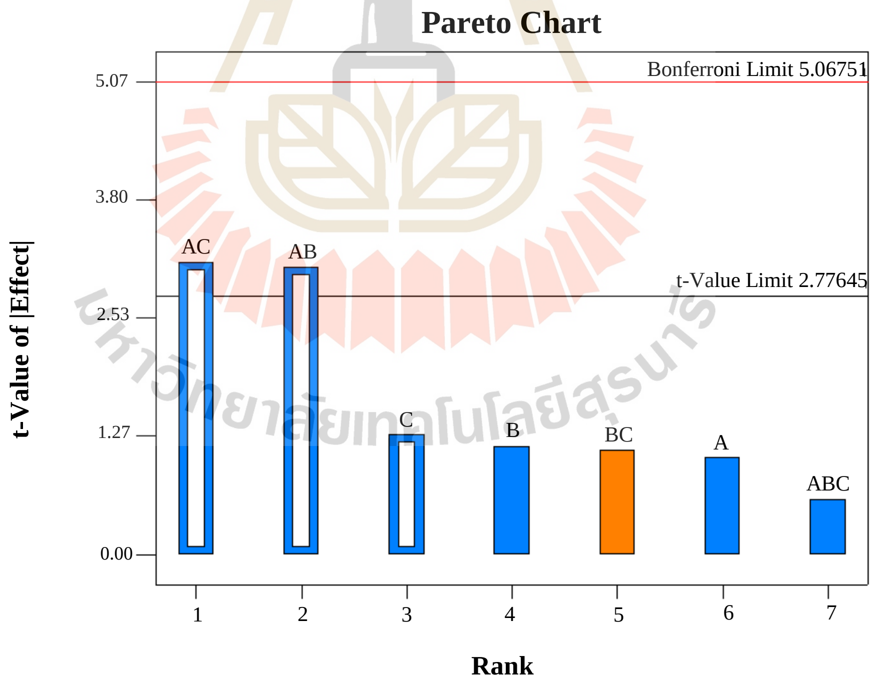
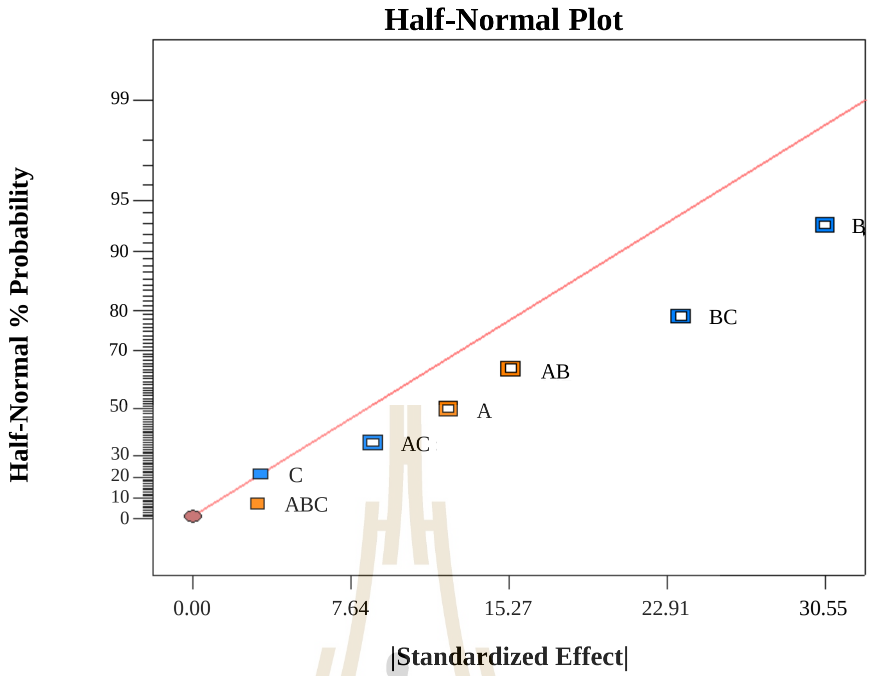


(b)

Figure 4.25 Response analysis for specific modulus in DOE test II: (a) Half-normal plot and (b) Pareto chart.

Table 4.18 ANOVA results of specific modulus in DOE test II.

Source	Sum of Squares	df	Mean Square	F-value	P-value
C	18094.96	1	18094.96	1.64	0.2691
AB	104073.09	1	104073.09	9.45	0.0371
AC	107824.24	1	107824.24	9.79	0.0352
Residual	44035.55	4	11008.89		
Cor Total	274027.85	7			



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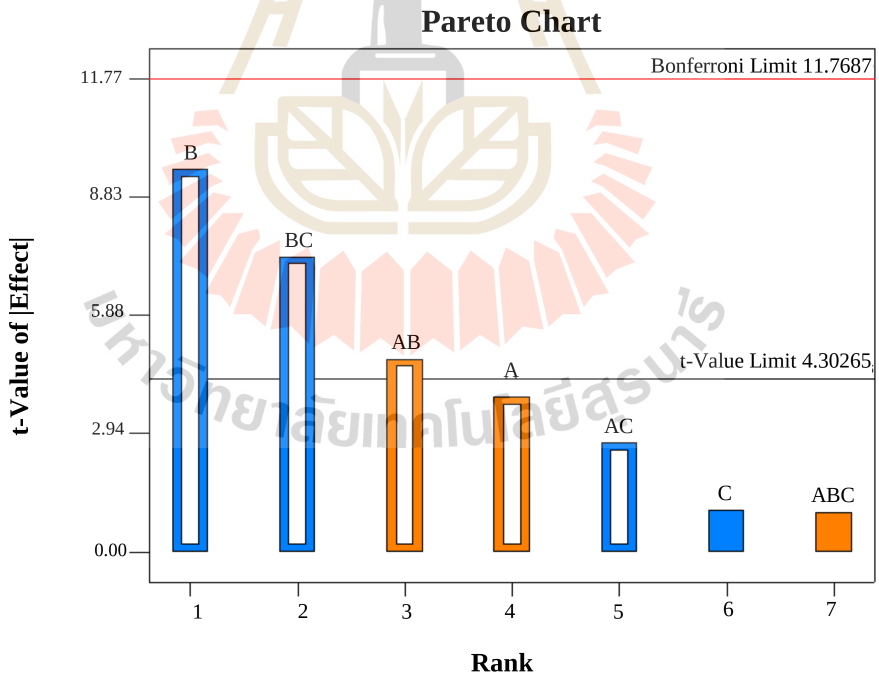
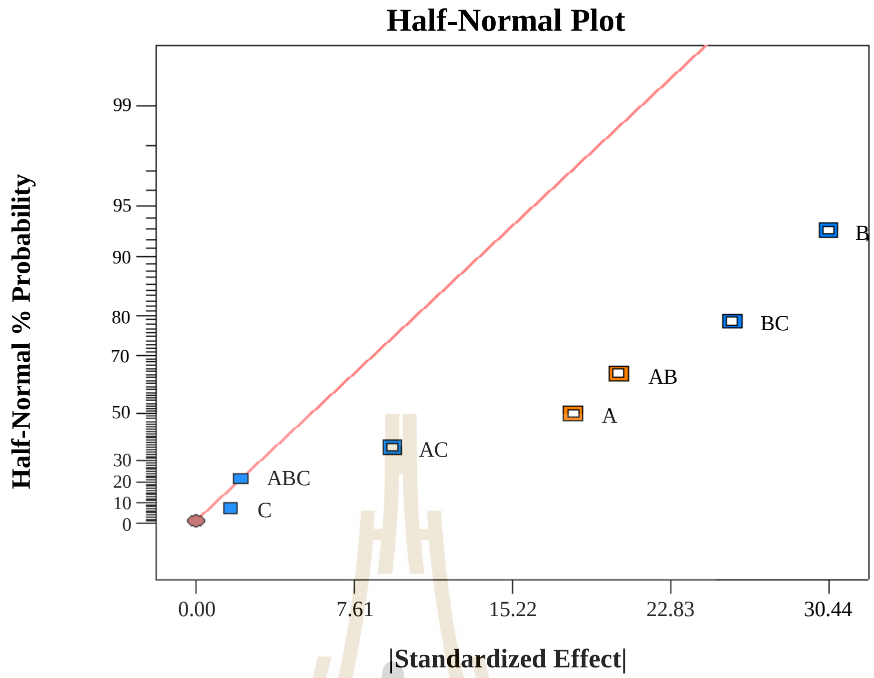


(b)

Figure 4.26 Response analysis for flexural toughness in DOE test II: (a) Half-normal plot and (b) Pareto chart.

Table 4.19 ANOVA results of flexural toughness in DOE test II.

Source	Sum of Squares	df	Mean Square	F-value	P-value
A	304.64	1	304.64	14.77	0.0615
B	1866.39	1	1866.39	90.46	0.0109
AB	472.04	1	472.04	22.88	0.0410
AC	151.52	1	151.52	7.34	0.1135
BC	1113.06	1	1113.06	53.95	0.0180
Residual	41.27	2	20.63		
Cor Total	3948.91	7			



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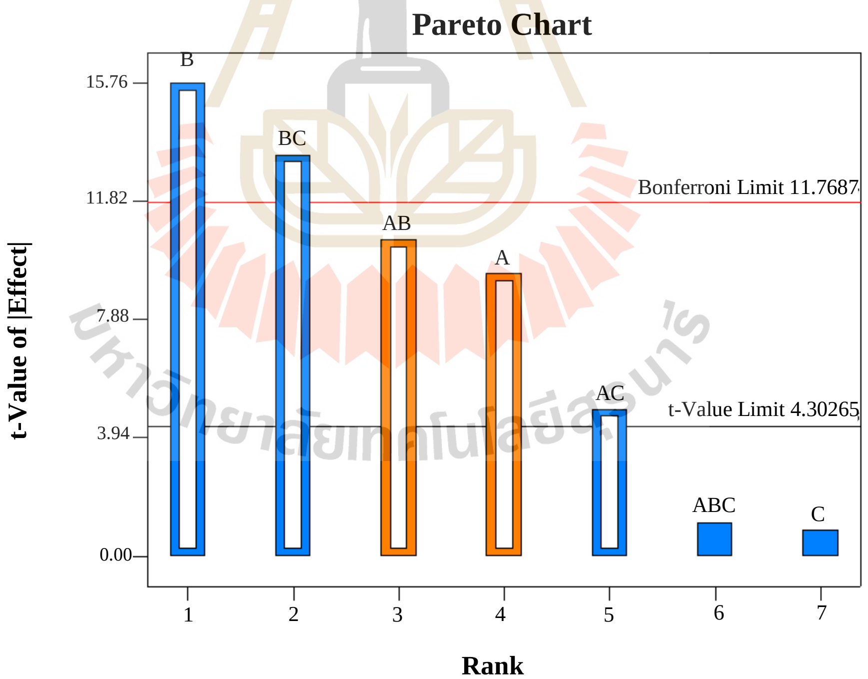


(b)

Figure 4.27 Response analysis for specific toughness in DOE test II: (a) Half-normal plot and (b) Pareto chart.

Table 4.20 ANOVA results of specific toughness in DOE test II.

Source	Sum of Squares	df	Mean Square	F-value	P-value
A	660.22	1	660.22	88.48	0.0111
B	1853.09	1	1853.09	248.35	0.0040
AB	828.51	1	828.51	111.03	0.0089
AC	178.87	1	178.87	23.97	0.0393
BC	1333.09	1	1333.09	178.66	0.0056
Residual	14.92	2	7.46		
Cor Total	4868.69	7			

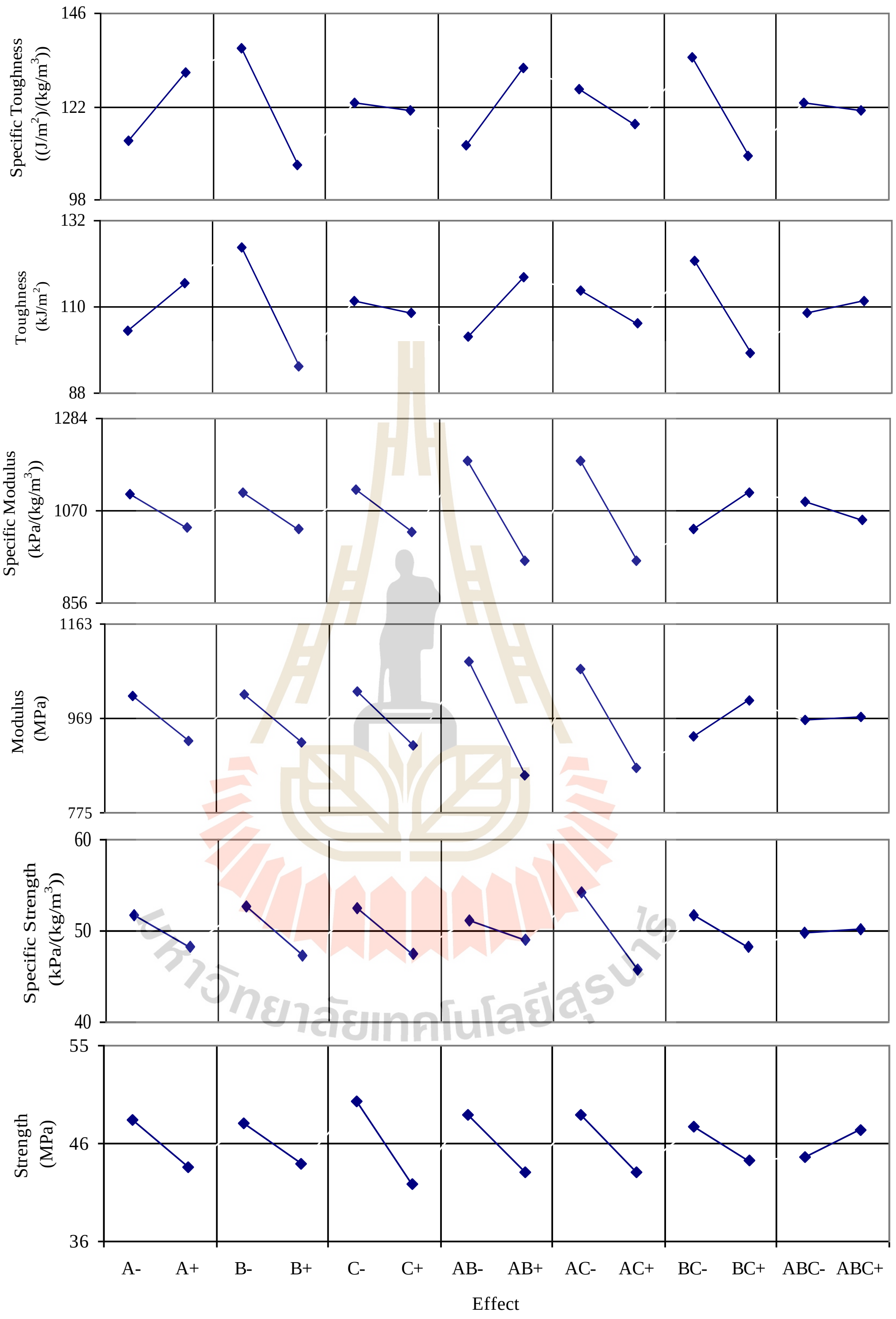


Figure 4.28 Main effect plot of test II.

4.3 Effect of Processing Parameters

During the hot press process the hardening of the resin and possible reaction of adhesive with the veneer and fiber substance is taken place. Therefore, the processing condition applied during curing stage can play a major role in the final properties of the products. The processing parameters are particularly pressure, temperature, and time. These variables must be optimized to produce acceptable and/or outstanding products.

Table 4.21 presented the flexural strength, modulus and toughness results of LVL reinforced composites derived from difference processing parameters, pressure, temperature and time as designed by 2^k DOE. There were eight conditions, given by P1 to P8, as shown in Table 3.6. Figure 4.29 and Figure 4.30 showed the plots of flexural strength and modulus, and toughness, respectively. From the results, it is found that the maximum strength at 58.81±3.51 MPa is observed in the P7 condition. The lowest strength, 34.05±2.39 MPa is seen in the P2.

The P5 and the P4 conditions reveal the maximum and minimum modulus at 944.62±85.59 MPa and 557.32±293.46, respectively. Within the standard deviation, the P5 and P1 indicate the maximum and minimum toughness strength at 144.00±39.93 kJ/m^2 and 81.02±11.03 kJ/m^2, respectively.

The similar trend is also resumed for the specific values as concluded in Table 4.22 and graphically presented in Figure 4.31 and 4.32.

Roughly speaking, the most promisingly processing condition is P7 where the highest strength value is obtained. The setting is low pressure and temperature with long pressing time in curing process. Even though modulus and toughness of the composites derived from this condition is slightly lower than the P5, low pressure, high temperature and long press time, the P7 would be better candidate because the temperature is lowered which mean less energy consumed in term of economic aspect.

Table 4.21 Mechanical properties of LVL reinforced composites prepared in DOE test III using difference processing condition.

Condition	Factor			Interaction				Flexural properties		
	A (Pressure)	B (Temperature)	C (Time)	AB	AC	BC	ABC	Strength (MPa)	Modulus (MPa)	Toughness (kJ/m^2)
P1	+	+	+	+	+	+	+	38.01±4.16	742.09±43.41	81.02±11.03
P2	+	+	-	+	-	-	-	34.05±2.39	812.79±50.60	94.21±34.32
P3	+	-	+	-	+	-	-	43.12±14.81	689.61±144.76	109.65±57.93
P4	+	-	-	-	-	+	+	35.73±13.81	557.32±293.46	114.37±39.93
P5	-	+	+	-	-	+	-	54.45±5.95	944.62±85.59	144.00±39.93
P6	-	+	-	-	+	-	+	51.21±8.48	791.66±47.10	109.16±22.25
P7	-	-	+	+	-	-	+	58.81±3.51	906.08±35.13	141.71±13.59
P8	-	-	-	+	+	+	-	46.69±13.26	688.59±84.91	129.94±51.56

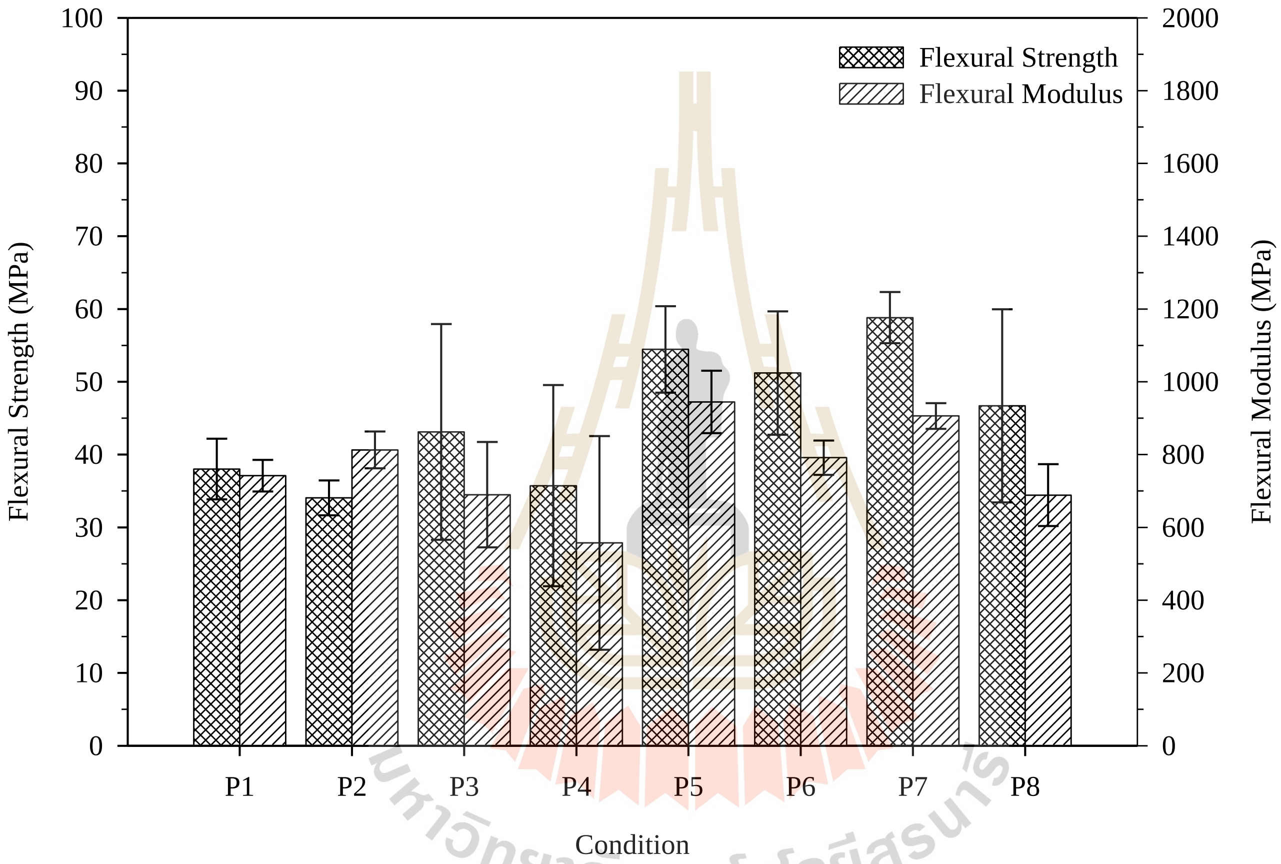


Figure 4.29 Flexural strength and flexural modulus of LVL reinforced composite prepared in DOE test III using difference processing condition.

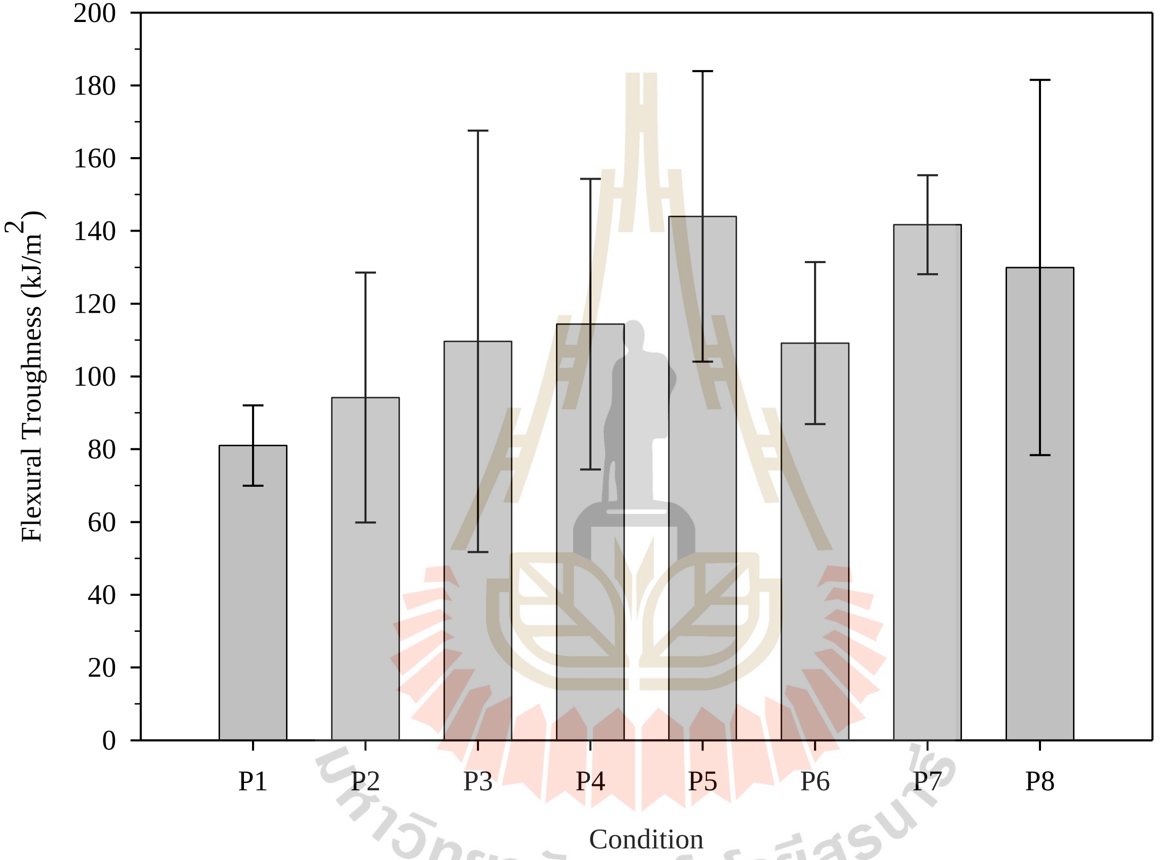


Figure 4.30 Flexural toughness of LVL reinforced composite prepared in DOE test III using difference processing condition.

Table 4.22 Specific mechanical properties of LVL reinforced composites prepared in DOE test III using difference processing condition.

Condition	Factor			Interaction				Flexural properties		
	A (Pressure)	B (Temperature)	C (Time)	AB	AC	BC	ABC	Specific Strength $\left(\frac{kPa}{kg/m^3}\right)$	Specific Modulus $\left(\frac{kPa}{kg/m^3}\right)$	Specific Toughness $\left(\frac{(J/m^2)}{kg/m^3}\right)$
P1	+	+	+	+	+	+	+	42.35±5.52	824.63±34.10	90.30±14.29
P2	+	+	-	+	-	-	-	37.75±2.89	901.15±62.34	104.31±37.88
P3	+	-	+	-	+	-	-	46.47±15.82	741.82±142.98	118.92±63.72
P4	+	-	-	-	-	+	+	39.42±14.11	612.85±306.19	126.96±44.11
P5	-	+	+	-	-	+	-	59.56±4.93	1033.89±67.55	157.57±21.19
P6	-	+	-	-	+	-	+	59.42±8.49	920.74±43.10	126.58±22.48
P7	-	-	+	+	-	-	+	65.20±4.10	1004.90±52.12	156.92±12.77
P8	-	-	-	+	+	+	-	52.11±15.25	768.21±109.97	144.99±58.68

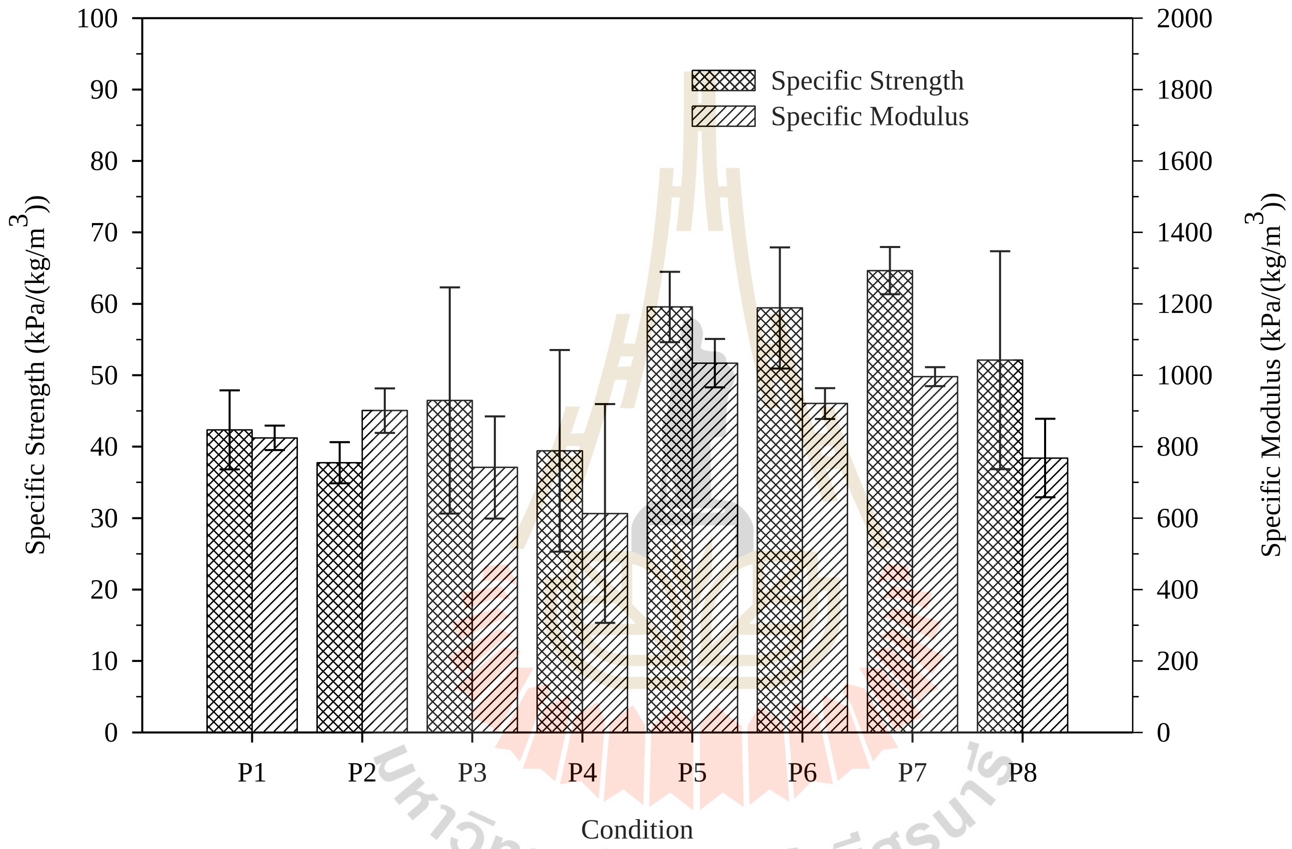


Figure 4.31 Specific strength and specific modulus of LVL reinforced composite prepared in DOE test III using difference processing condition.

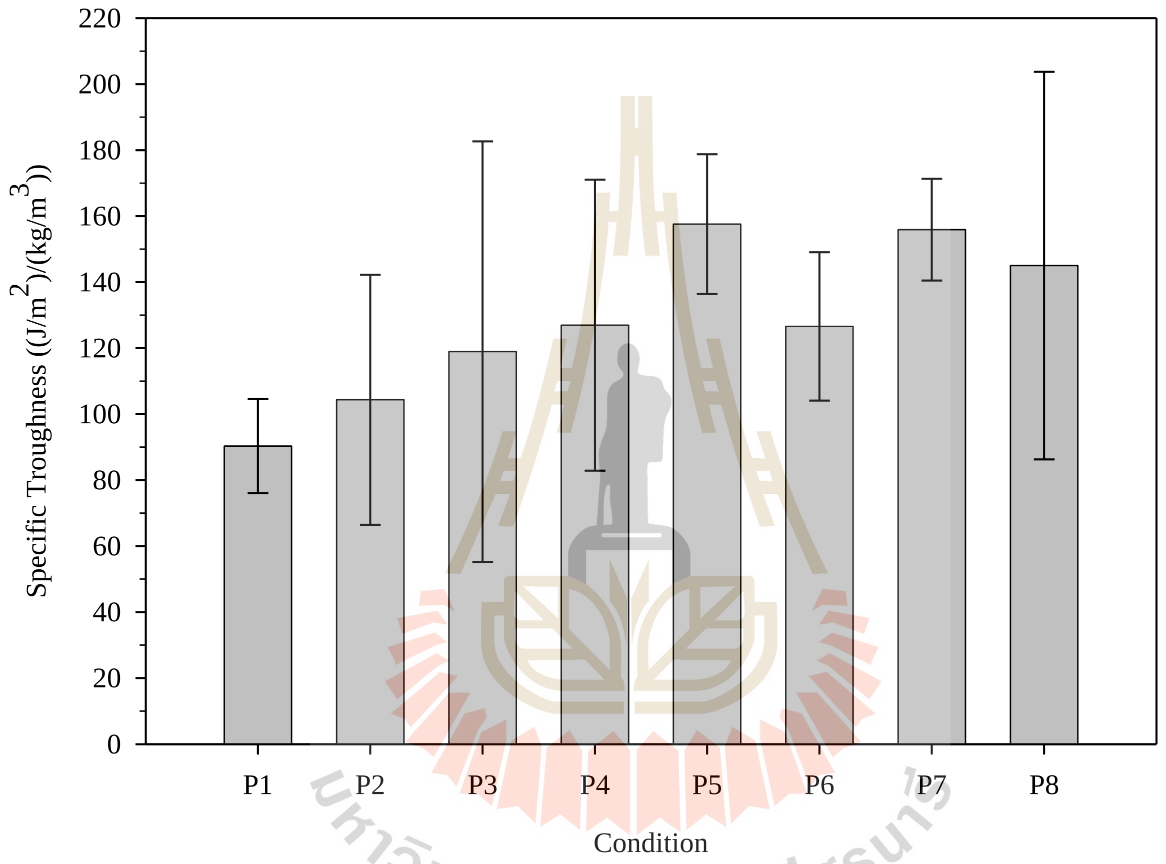


Figure 4.32 Specific toughness of LVL reinforced composite prepared in DOE test III using difference processing condition.

The three factors DOE, pressure, temperature and time and its analysis of the response values in respect to flexural properties by half-normal plot and ANOVA, are illustrated in Figure 4.33 to 4.38 and Table 4.23 to 4.28 respectively.

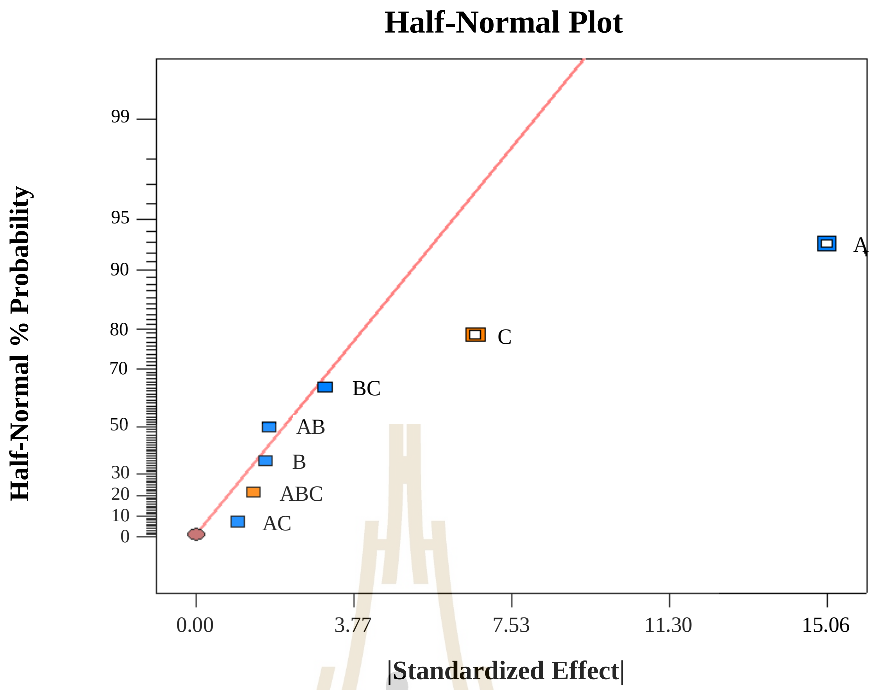
According to the variance analysis outcome, the effects of pressure (A) and time (C) on the flexural strength and specific flexural strength is statistically significant. This is illustrated in Table 4.23 and 4.24 as the calculated P-value less than 0.05. The highest values, strength and the specific, are obtained where pressure set at low level (A-) and the time at high level (C+) as show main factor plots in Figure 4.39. It indicates that using low pressure and long period of time in curing reaction will increase the strength. Vice versa, the inferior properties is obviously seen when the pressure is increased to high magnitude and time is minimized. Therefore, pressure was negative effect (-) and time was positive effect (+).

Based on the statistical testing, using the ANOVA, on modulus figures reported in Figure 4.35-4.36 and Table 4.25-4.26, there is no significant effect from processing factors.

Again, pressure, factor A, is the most significantly effect on the toughness properties as the obtained P-value is less than 0.05, shown in Table 4.27 and 4.28. From the main effect plot, Figure 4.39, shows that pressure at low level provide the highest toughness and specific toughness values. In contrast, the toughness properties will dramatically decrease when increasing the pressing pressure.

Pressure is negative effect on the mechanical properties meaning that the inferior properties are seen when using too high pressing pressure. It can be explained that pressure is required to hold the composite laminate in place, force liquid matrix to penetrate into fiber and drive off the bubble from specimen. Applying too high pressure will cause the reverse phenomenon. The liquid adhesive will be driven out from the fiber by excessive high pressure force. There will not be enough. The process time is positive effect on the strength properties. As increasing the period of reaction time, the better strength properties are obtained. Due to fully cure, on the other word, high degree of cure will be achieved. Further increasing period of curing time will be done with carefully monitoring, especially at high temperature and thick specimen. The longer the processing time at higher press temperature, the more rapid chain degradation will be observed. Hence, the properties of the sample will be diminished.

To conclude the process parameters setting which maximize the mechanical properties of LVL reinforced composites, the optimal setting are given at low level pressure, 15 bar, low level temperature, 70^{o}C, and high level of time, 60 mins.



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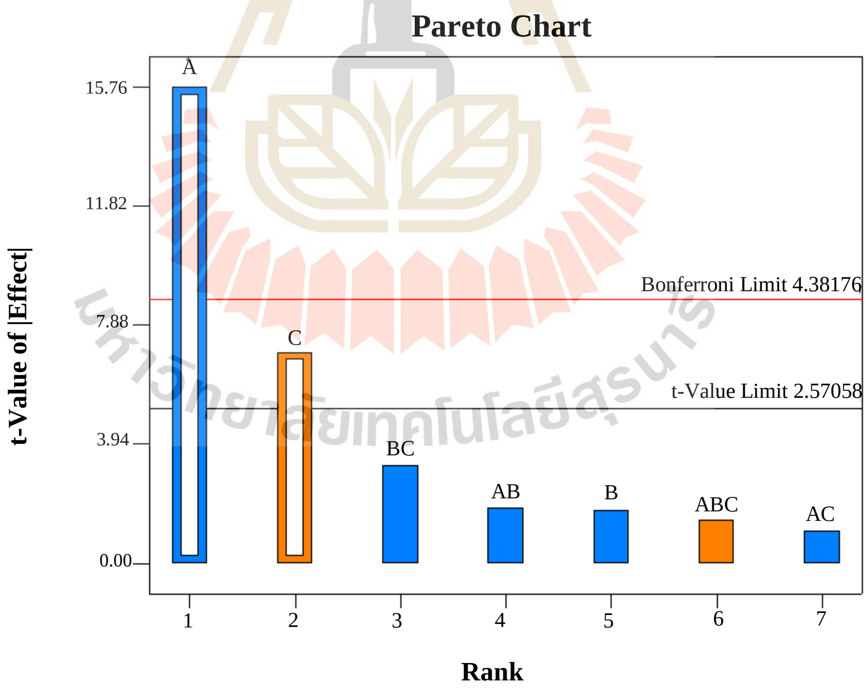
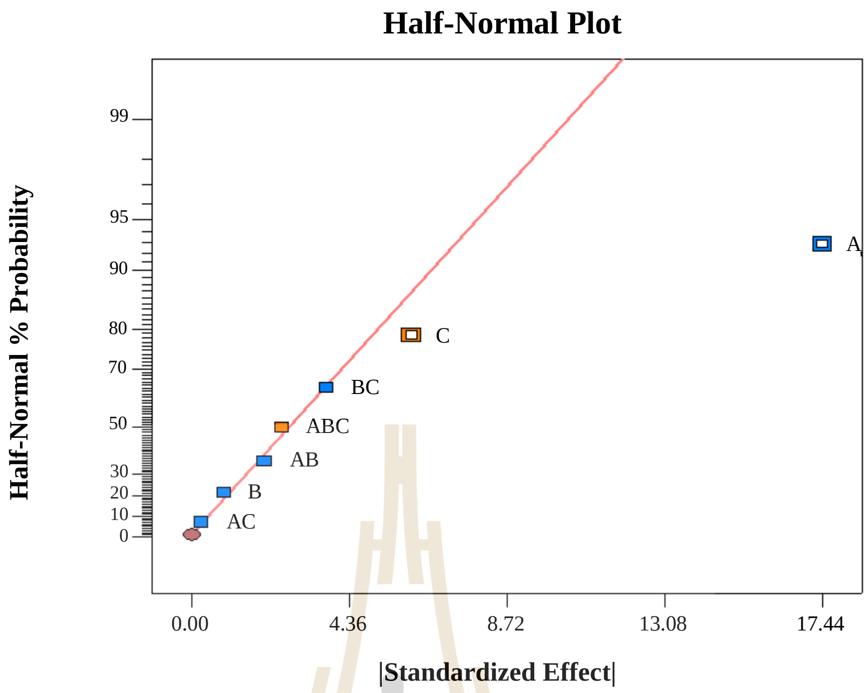


(b)

Figure 4.33 Response analysis for flexural strength in DOE test III: (a) Half-normal plot and (b) Pareto chart.

Table 4.23 ANOVA results of flexural strength in DOE test III.

Source	Sum of Squares	df	Mean Square	F-value	P-value
A	453.82	1	453.82	62.63	0.0005
C	89.10	1	89.10	12.30	0.0172
Residual	36.23	5	7.25		
Cor Total	579.15	7			



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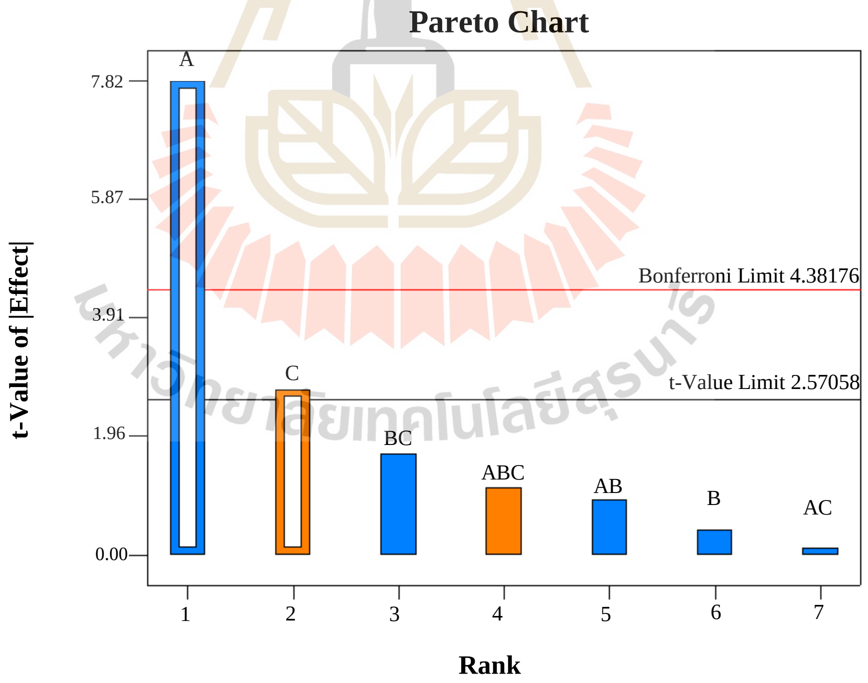
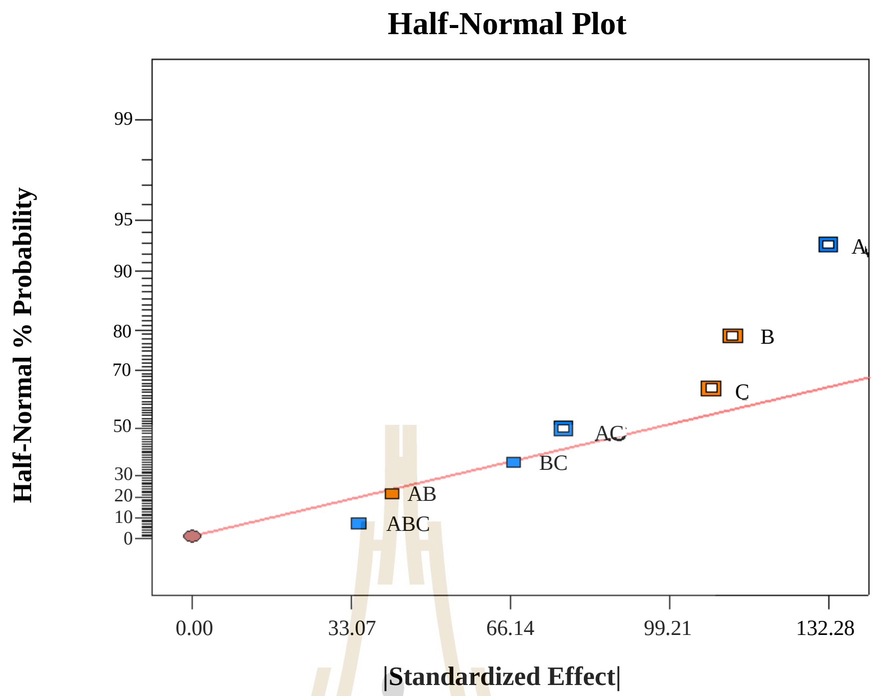


(b)

Figure 4.34 Response analysis for specific strength in DOE test III: (a) Half-normal plot and (b) Pareto chart.

Table 4.24 ANOVA results of specific strength in DOE test III.

Source	Sum of Squares	df	Mean Square	F-value	P-value
A	618.05	1	618.05	58.50	0.0006
C	77.34	1	77.34	7.32	0.0425
Residual	52.83	5	10.57		
Cor Total	748.22	7			



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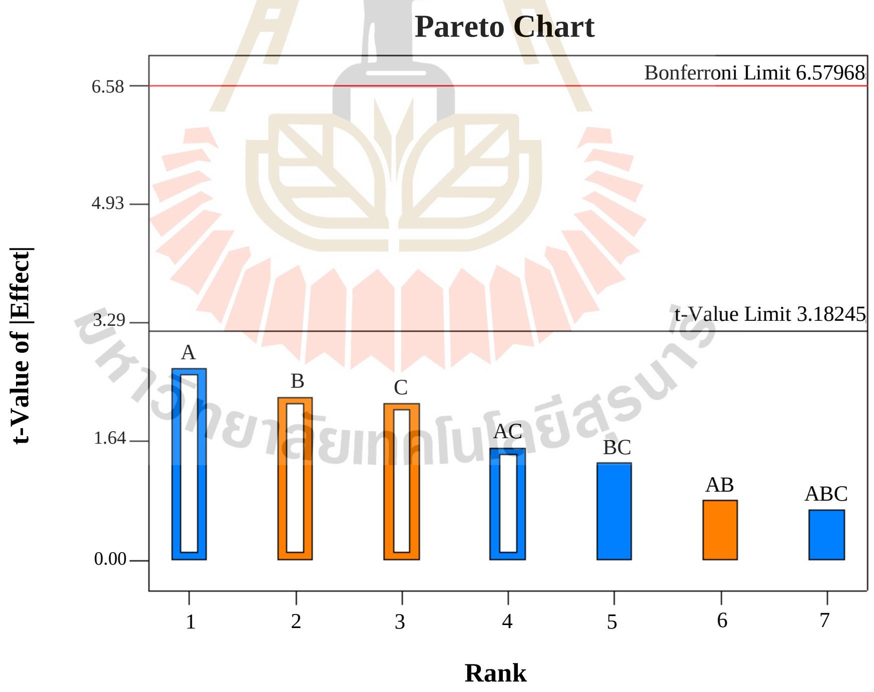


(b)

Figure 4.35 Response analysis for flexural modulus in DOE test III: (a) Half-normal plot and (b) Pareto chart.

Table 4.25 ANOVA results of flexural modulus in DOE test III.

Source	Sum of Squares	df	Mean Square	F-value	P-value
A	34997.85	1	34997.85	7.09	0.0761
B	25264.15	1	25264.15	5.12	0.1086
C	23331.24	1	23331.24	4.73	0.1179
AC	11923.54	1	11923.54	2.42	0.2179
Residual	14800.34	3	4933.45		
Cor Total	110317.11	7			

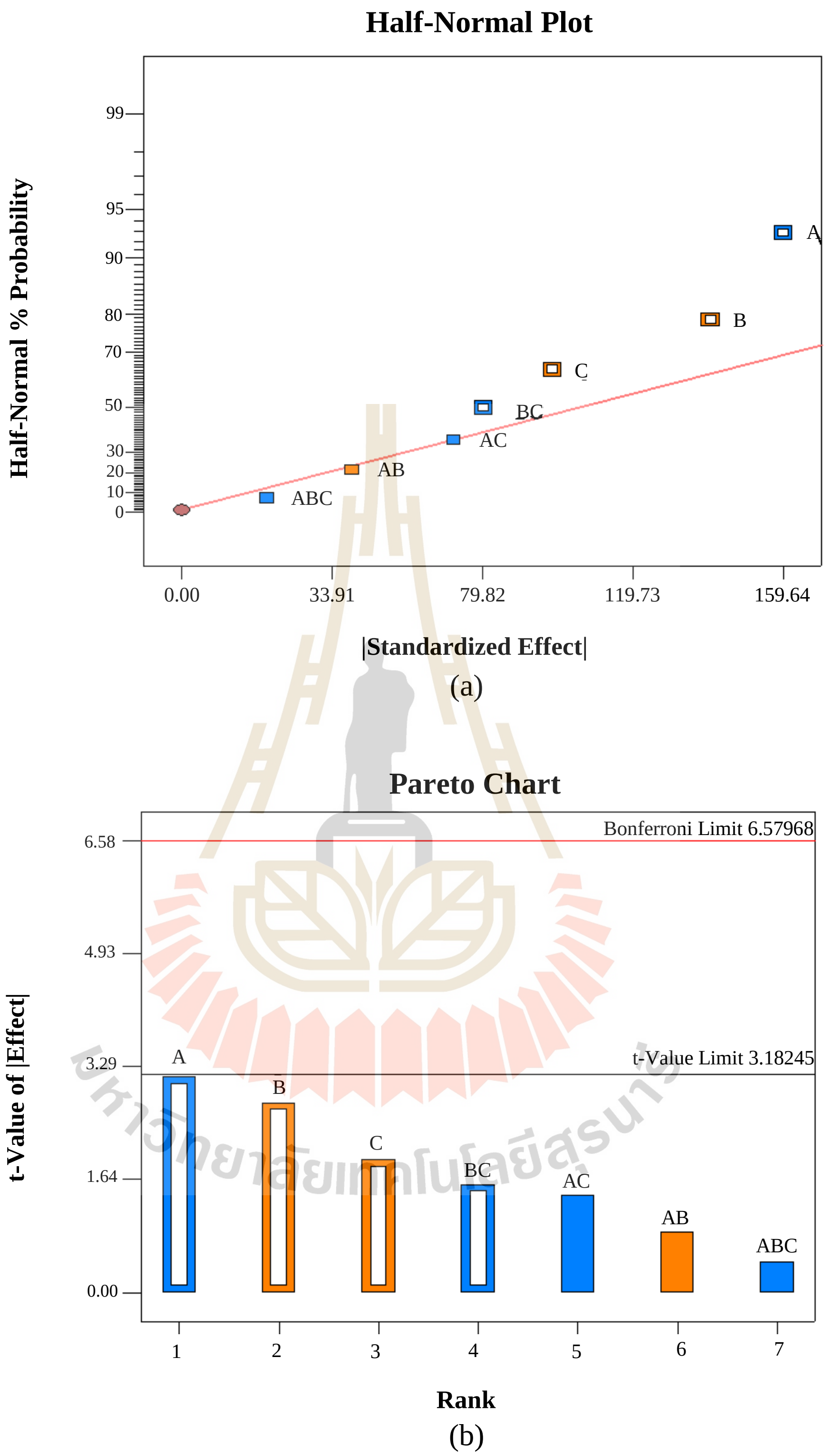
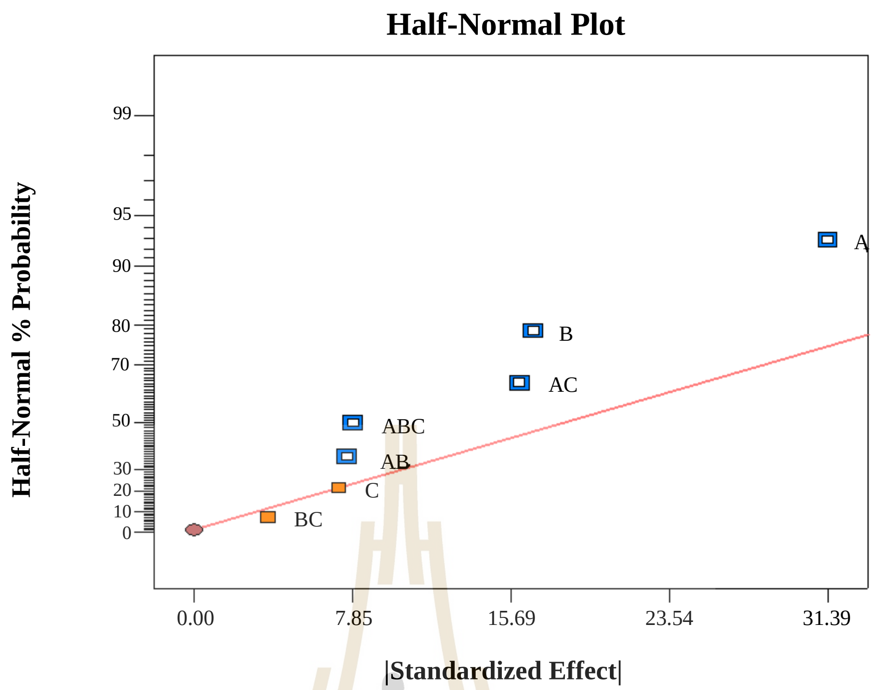


Figure 4.36 Response analysis for specific modulus in DOE test III: (a) Half-normal plot and (b) Pareto chart.

Table 4.26 ANOVA results of specific modulus in DOE test III.

Source	Sum of Squares	df	Mean Square	F-value	P-value
A	52374.63	1	52374.63	9.59	0.0534
B	38174.60	1	38174.60	6.99	0.0774
C	20230.76	1	20230.76	3.70	0.1500
BC	13532.19	1	13532.19	2.48	0.2136
Residual	16387.65	3	5462.55		
Cor Total	140699.84	7			



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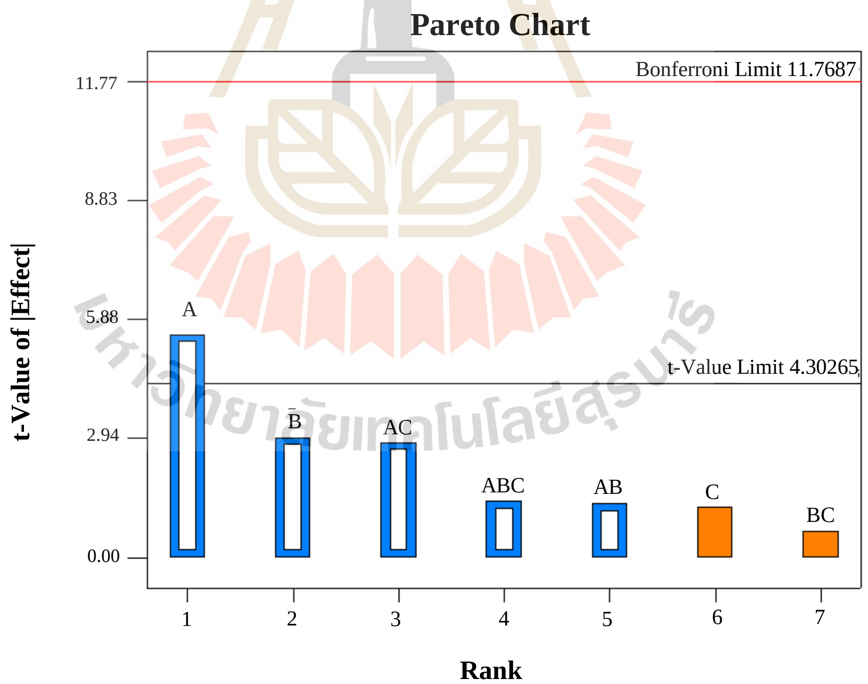
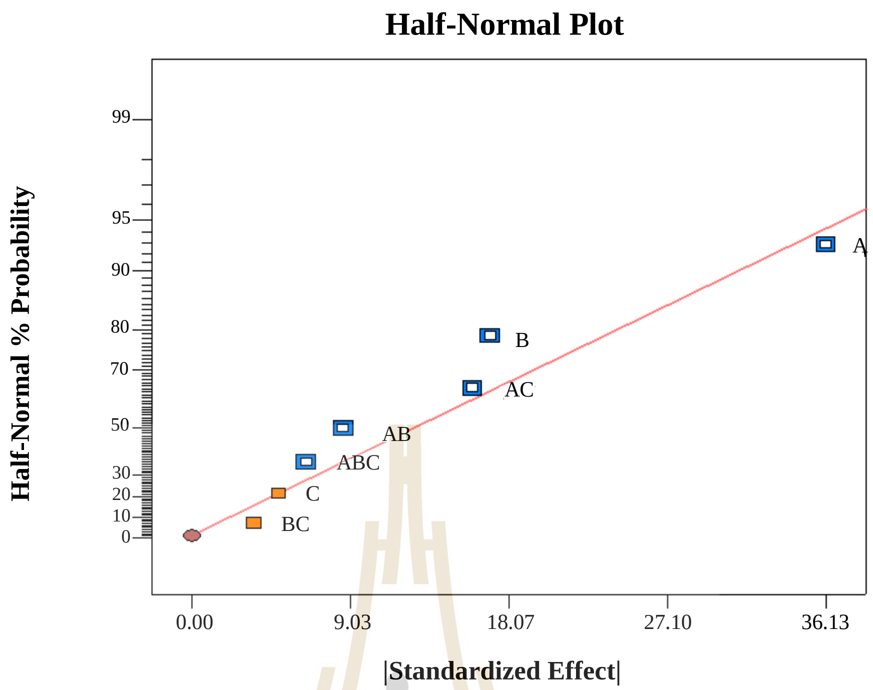


(b)

Figure 4.37 Response analysis for flexural toughness in DOE test III: (a) Half-normal plot and (b) Pareto chart.

Table 4.27 ANOVA results of flexural toughness in DOE test III.

Source	Sum of Squares	df	Mean Square	F-value	P-value
A	1970.54	1	1970.54	30.43	0.0313
B	565.90	1	565.90	8.74	0.0979
AB	114.86	1	114.86	1.77	0.3144
AC	520.46	1	520.46	8.04	0.1052
ABC	124.37	1	124.37	1.92	0.3001
Residual	129.50	2	64.75		
Cor Total	3425.64	7			



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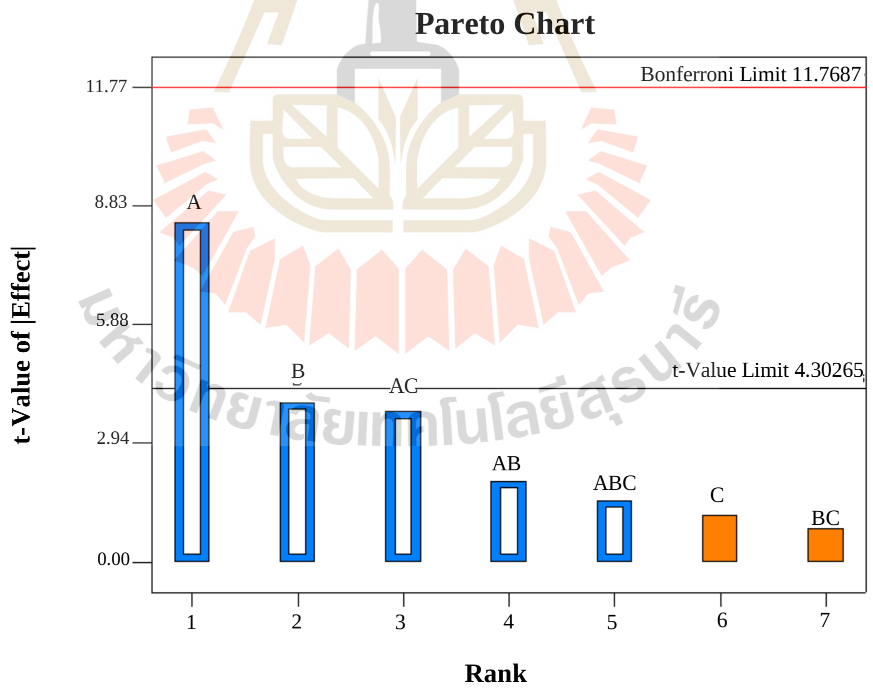


(b)

Figure 4.38 Response analysis for specific toughness in DOE test III: (a) Half-normal plot and (b) Pareto chart.

Table 4.28 ANOVA results of specific toughness in DOE test III.

Source	Sum of Squares	df	Mean Square	F-value	P-value
A	2648.22	1	2648.22	70.05	0.0140
B	595.11	1	595.11	15.74	0.0580
AB	140.16	1	140.16	3.71	0.1940
AC	528.11	1	528.11	13.97	0.0647
ABC	78.54	1	78.54	2.08	0.2862
Residual	75.61	2	37.80		
Cor Total	4065.74	7			

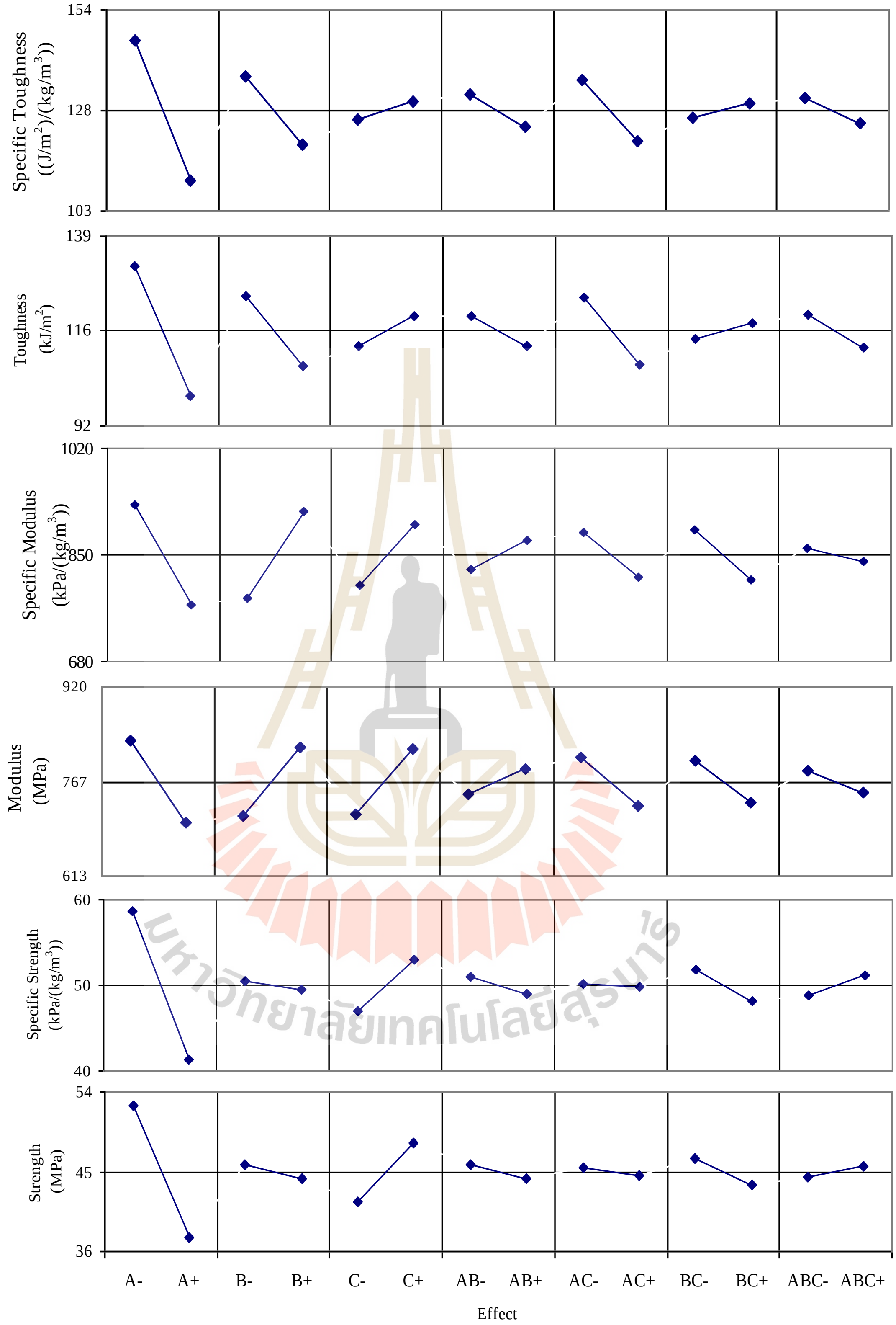


Figure 4.39 Main effect plot of test III.

As the above results in DOE test I to III, the best properties of the LVL reinforced composite are prepared by using smoked rubber wood veneer, GF and RT adhesive with high quantity of silane, 15% w/w, additional to curing agent. And they are produced in the optimal curing condition at low pressure, 15 bar, low temperature, 70^{o}C, and long curing time, 60 mins.

Table 4.29 and Figure 4.40 to 4.43 show the mechanical properties of the best LVL composite prepared by the optimal constituents and curing condition compared to solid woods including teak, rubber wood, eucalyptus and hardwood. Figure 4.44 also presented the typical stress-displacement behavior of the given woods.

From the results found that flexural modulus of the LVL composite are obviously higher than the solid woods. In case of flexural strength, it slightly higher than those of solid woods. In contras, flexural toughness of the LVL composite is found to be lower than the solid woods.

Table 4.29 Summary of the mechanical properties of the LVL reinforced composite compared to the solid woods.

Wood Type	Flexural properties			Flexural specific properties		
	Strength (MPa)	Modulus (MPa)	Toughness (kJ/m^2)	Specific Strength $\left(\frac{kPa}{kg/m^3}\right)$	Specific Modulus $\left(\frac{kPa}{kg/m^3}\right)$	Specific Toughness $\left(\frac{(J/m^2)}{kg/m^3}\right)$
Teak	56.48±4.03	336.14±57.62	382.66±26.26	79.28±3.40	468.32±29.46	542.60±95.75
Rubber wood	43.80±5.87	250.41±44.28	329.57±29.56	68.95±5.54	393.46±47.14	519.84±28.61
Eucalyptus	50.41±14.48	368.49±143.28	285.58±102.01	55.74±11.00	405.23±131.36	314.73±83.12
Hardwood	50.15±2.68	303.59±7.30	383.44±47.86	74.54±2.92	451.56±18.04	569.36±60.48
LVL composite	58.81±3.51	906.08±35.13	141.71±13.59	64.65±3.29	996.16±26.46	155.89±15.42

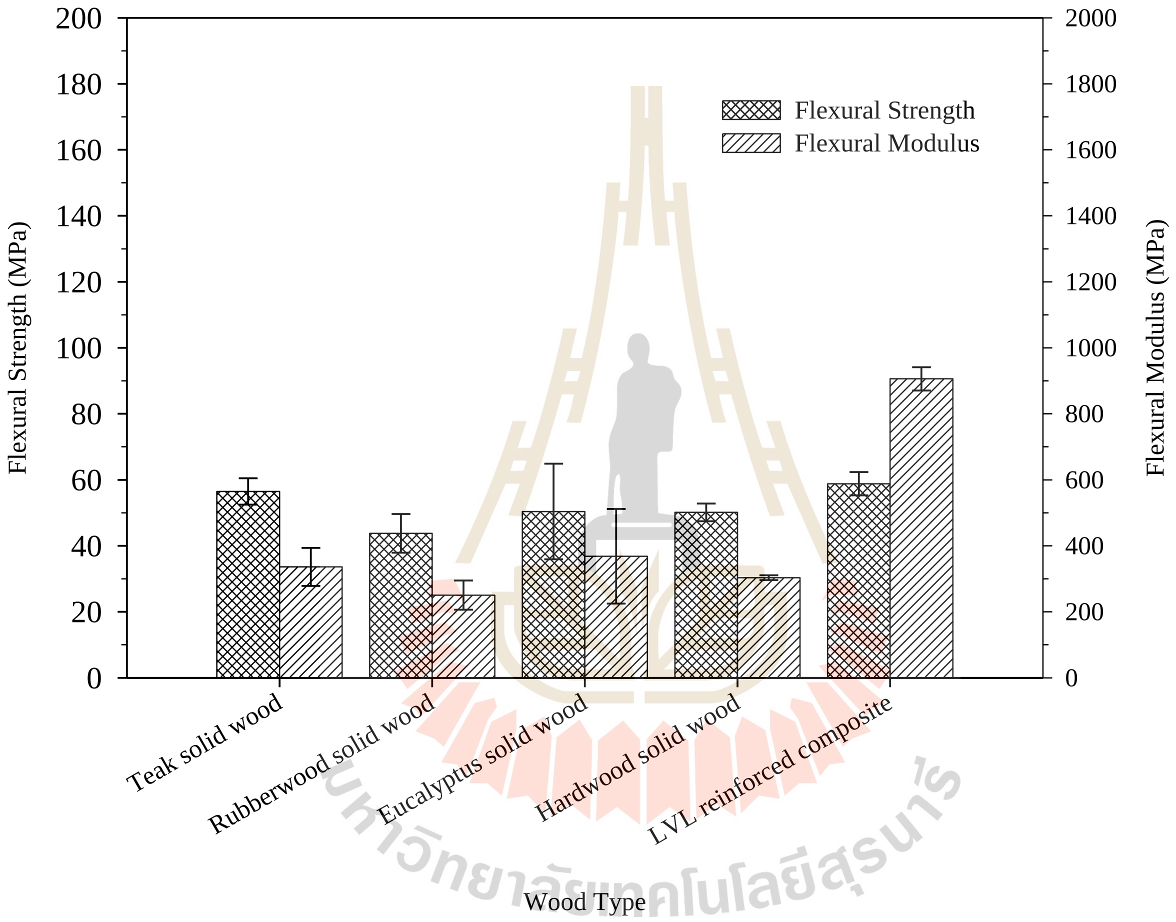


Figure 4.40 Flexural strength and flexural modulus of the woods.

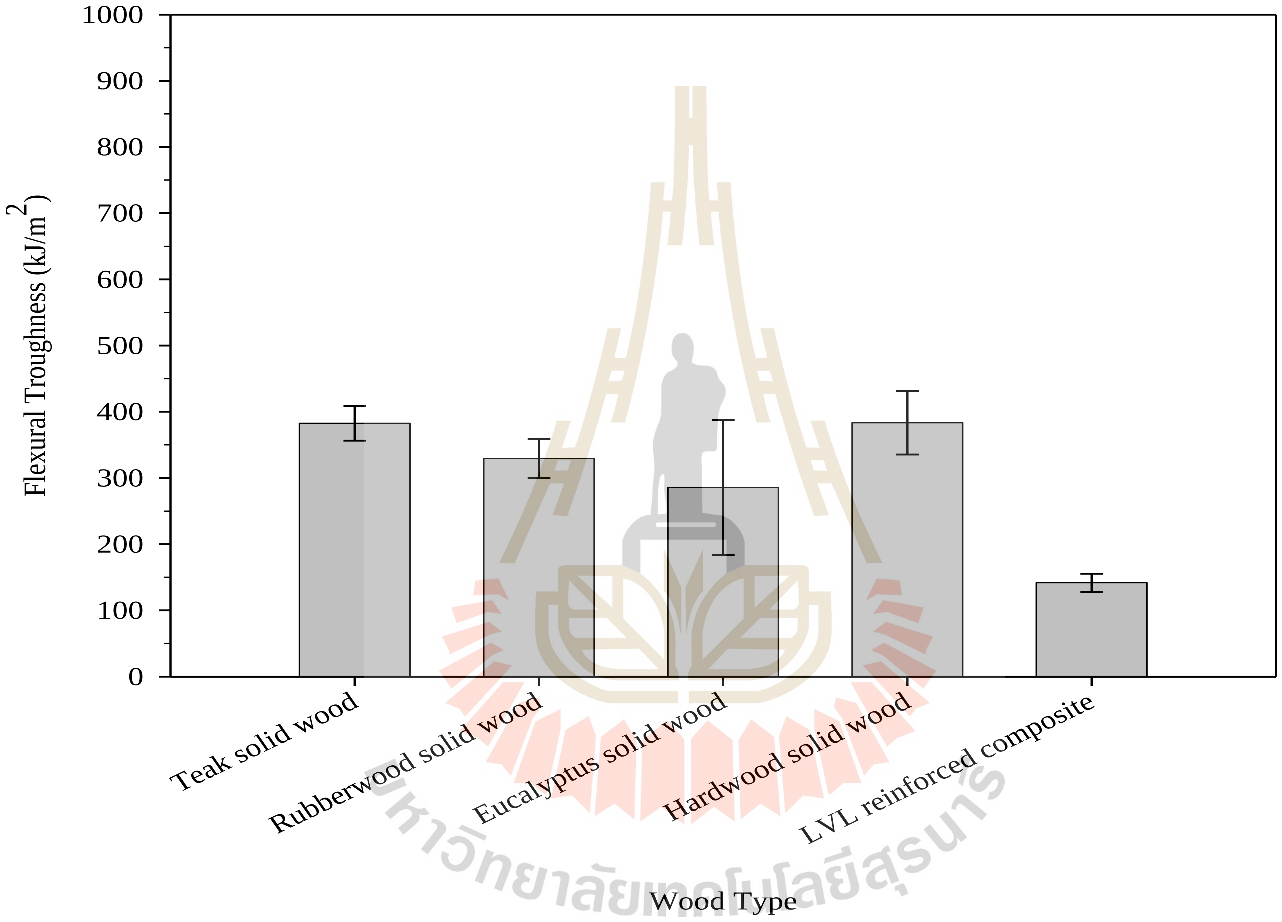


Figure 4.41 Flexural toughness of the woods.

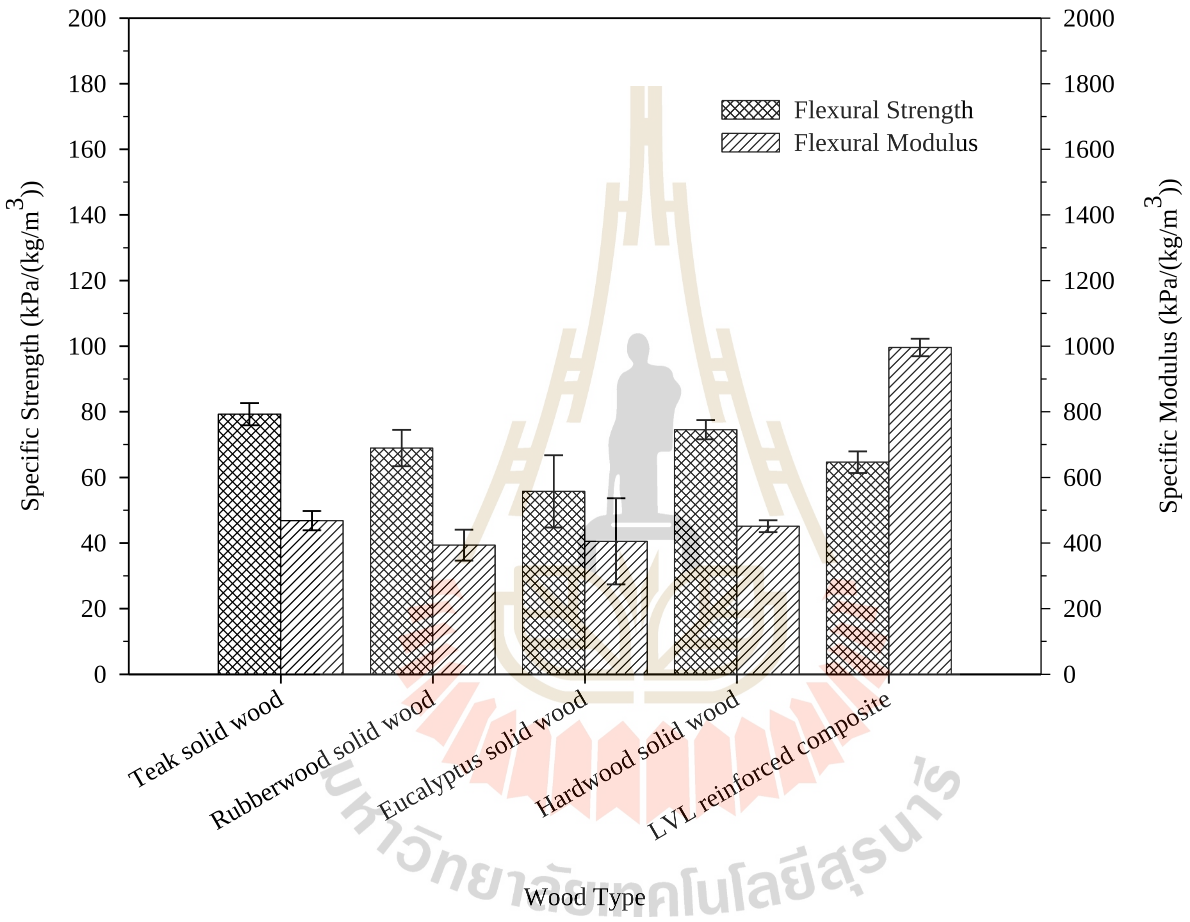


Figure 4.42 Specific strength and specific modulus of the woods.

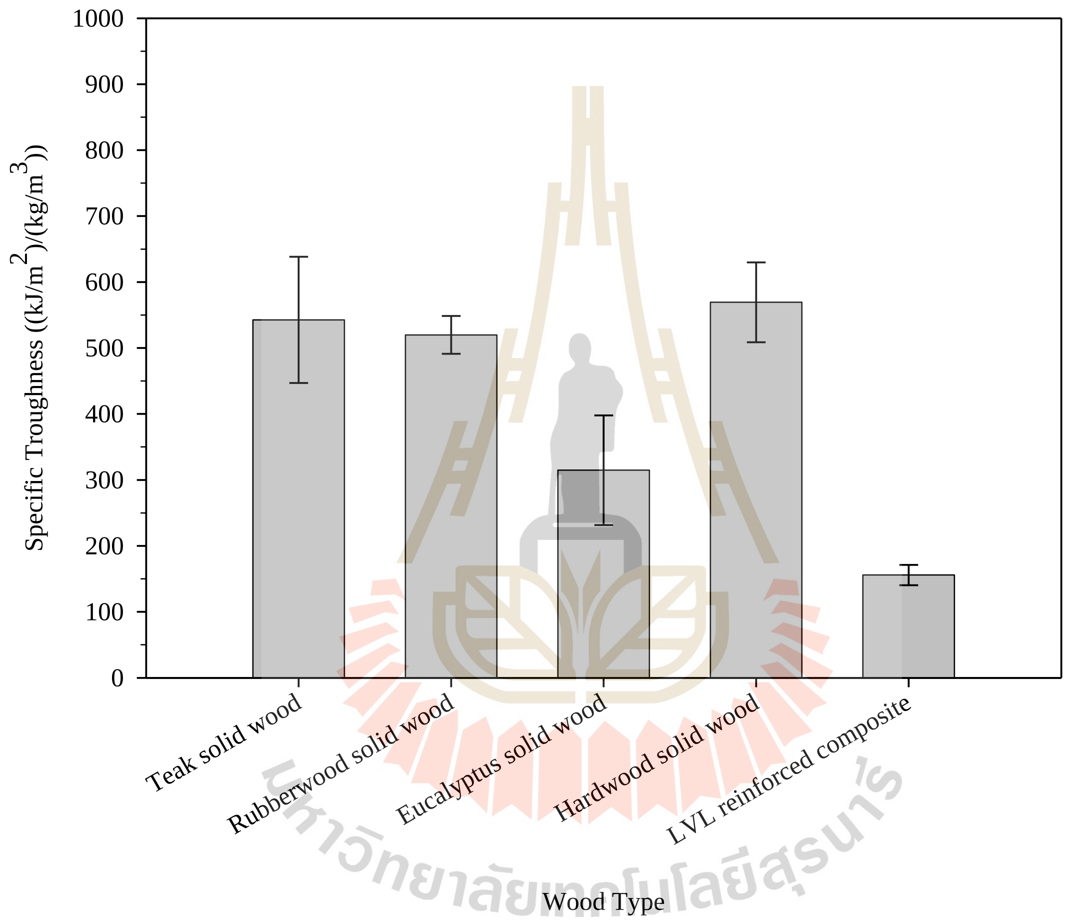


Figure 4.43 Specific toughness of the woods.

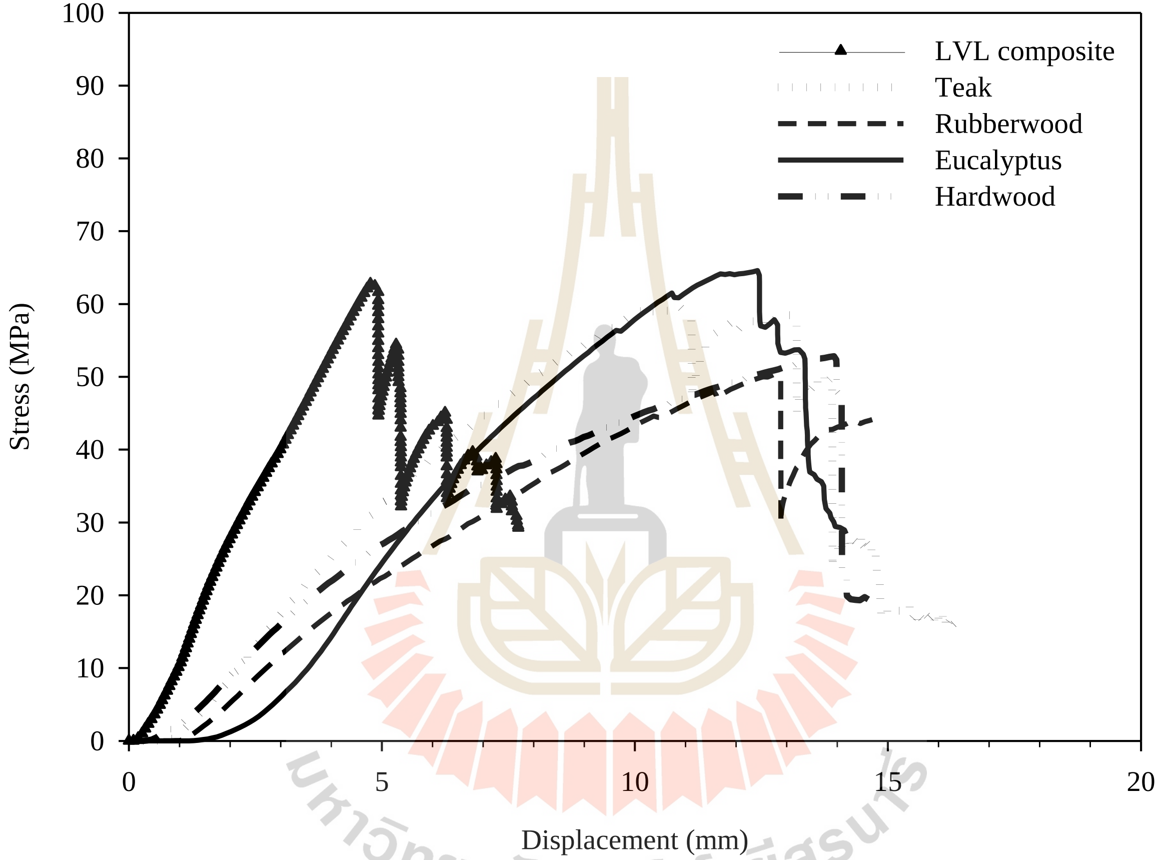


Figure 4.44 Typical stress-displacement behavior of LVL reinforced composite compare to the solid woods.

4.4 Withdrawal Strength of Screw

According to the stability of any building system, composed of interconnected components, is directly related to the performance of the fastening elements. The most widely used fastening elements found in the connections of solid wood materials are nails and screws. Therefore, knowledge of the withdrawal strength of nail and screw for wooden elements will provide useful information about the durability and stability of the whole system. Besides, it is significant to have information about withdrawal strength of nail and screw so as to achieve the efficient use of materials in the building system. In this study, the withdrawal strength of screw of the LVL reinforced composites was made in comparison with solid wood to offer possibilities and locations of usage in the building system for the laminated samples as alternative building materials. On the other hand, densities of the samples were directly calculated from the actual weight over the microscale measured volumes of the samples.

Table 4.30 presents the withdrawal strength and average density results of solid wood and LVL reinforced composite. The plot is illustrated in Figure 4.45 and Figure 4.46. During the test it was observed that the screw attached to LVL was fail before the completely withdraw process was reached. So, the figure shown is not the actual withdraw strength of LVL. The true value would be higher that the reported. As the results, the highest value at 16.48±1.09 N/mm^2 of withdrawal strength is evidenced for LVL reinforced composite. The strength for eucalyptus, hardwood, rubber wood and teak wood are consequently lower. The lowest withdrawal strength is teak and rubber wood solid wood.

LVL reinforced composite is the highest withdrawal strength as compared to solid woods. This may be because LVL reinforced composite has the higher density. Similar result was published in the literature (Ozcifci, 2009). Thus, it may has been attributed to the increase of internal bond strength. In the other study, it was found that there was a linear relationship between withdrawal strength of nail and the specific gravity. An increase in the withdrawal strength of nail was determined by increasing in specific gravity (Celebi and Kilic, 2007).

The increase in density of LVL reinforced composite contributed from the reduction of the total volume as the compression pressure was applied during the manufacture. In addition, the addition of adhesive also contributes to the increase in the density as the density of adhesive is much higher than that of the wood veneer. This had a greater effect on the total density of the LVL reinforced composite after adhesive was applied (Sulaiman et al., 2009).

By dividing the strength with the density to obtain the specific values as reported on Figure 4.45, it is observed that the specific value of Teak and rubber wood are higher that the others. However, it can not really compare with LVL wood due to the fact that the actual strength of this wood is higher that the reported number. General conclusion can be draw at this stage of work that the withdrawing strengths of LVL are probable higher than the solid woods.

Table 4.30 The test results of withdrawal strength of screw.

Materials	Density (kg/m^3)	Screw withdrawal strength (N/mm^2)
Teak solid wood	631.59±41.92	12.92±0.33
Rubber wood solid wood	581.77±50.20	12.93±0.54
Eucalyptus solid wood	849.55±62.92	15.07±1.67
Hardwood solid wood	757.68±20.45	14.21±0.45
LVL reinforced composite	855.50±23.21	16.48±1.09*

*screw were fail beyond this point.

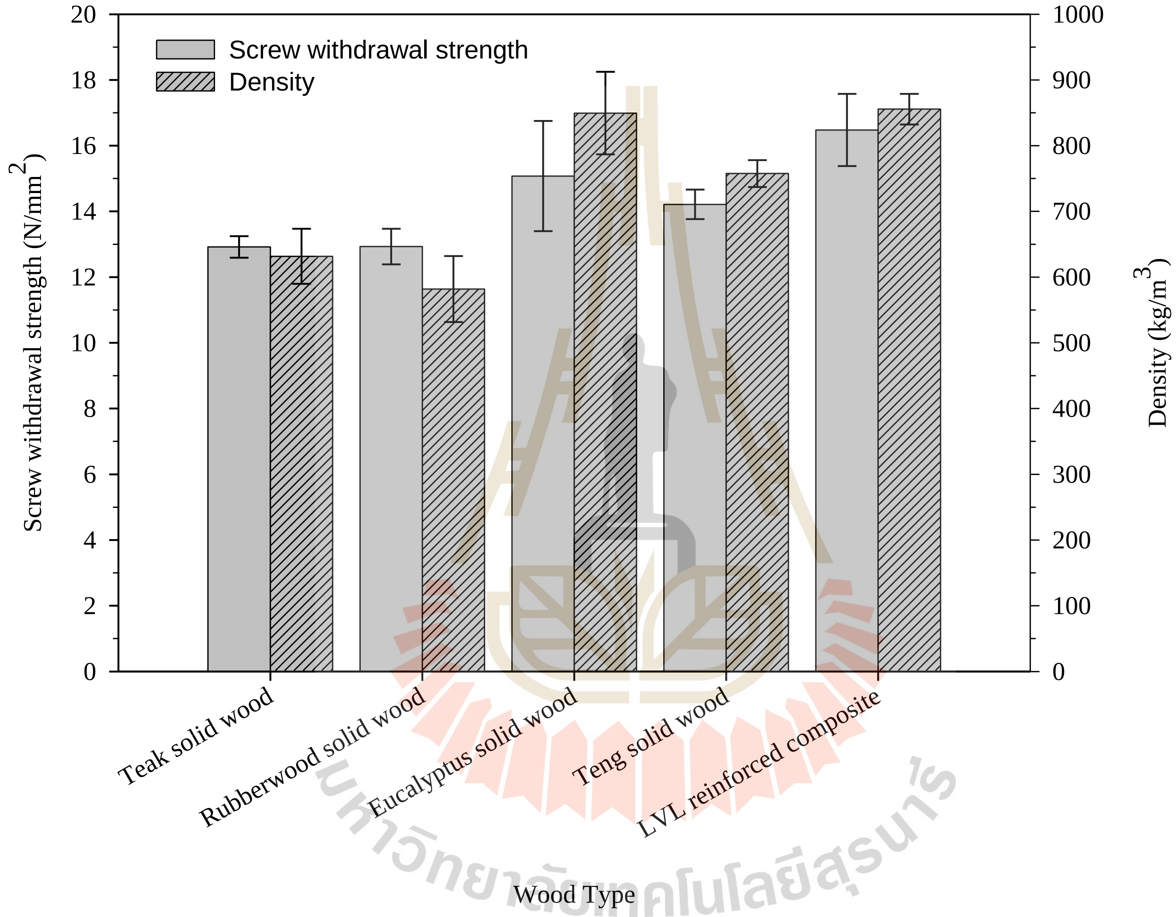


Figure 4.45 Screw withdrawal strength and density of the solid woods and LVL composite.

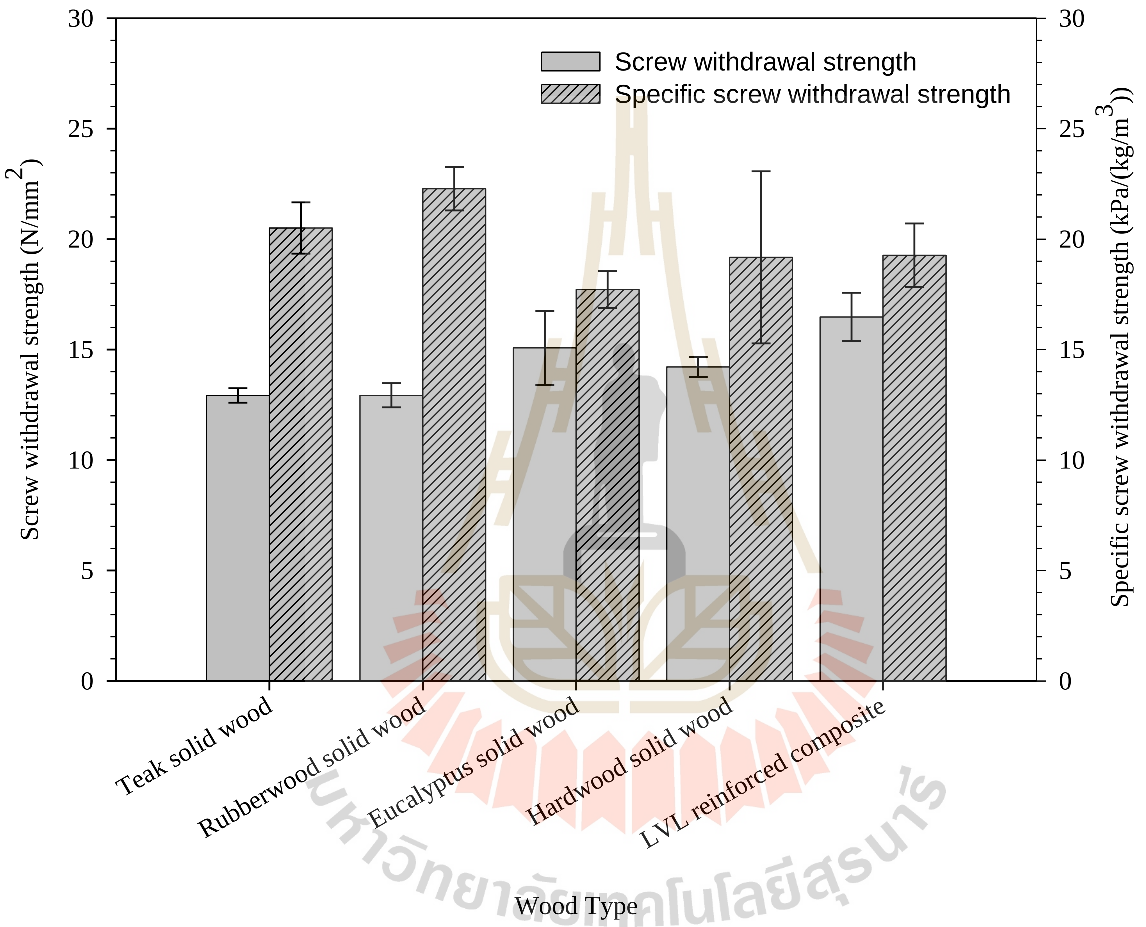


Figure 4.46 Screw withdrawal strength and the specific one of the solid woods and LVL composite.

4.5 Durability Properties

The terms of durability and/or environmental resistance are widely determined in the field of construction materials. Although a construction material may initially have suitable properties. But prolong to hazard environment may alter these properties. The alteration process, eventually leading to failure, is call degradation. The degradation is used to denote the loss of quality of the material under the influence of the environment. This quality can be mechanical, physical or chemical attack. Durability indicates how well a material resistance to degradation. In this study, durability including water absorption, and termite resistance of LVL reinforced composite were observed in comparison with solid woods.

4.5.1 Water absorption

Wood is a hygroscopic material, which loses and gains moisture easily as a result of humidity changes. The amount and direction of exchange, loss or gain, depend on the relative humidity and temperature of the air and the presence amount of water in wood. The tendency of wood to absorb moisture is very important on durability properties of wood including mechanical strength, appearance, and dimension stability. According to moisture content changing relate to expansion or shrinkage of timber warps and twists then it is lower strength. Therefore, the aim of this study is to compare the durability property by mean the water absorption of LVL reinforced composite with the solid woods.

Figure 4.47 is water absorption results of the solid woods and LVL reinforced composite conducted at 70^{o}C for a week. From the results, it is found that the lowest water absorption (%), low amount of exchange moisture, is established in LVL reinforced composite. Therefore, LVL reinforced composite exhibit the better water resistance compared to the solid woods. As expected, the water absorption value is higher for the solid woods, especially in rubber wood, compared with LVL reinforced composite. Commercially, rubber wood had it limitation for outdoor applications as it shows the highest water absorption value, on the other word, the lowest water resistance. It always twists, bends and finally cracks. In case of eucalyptus solid wood shows the lower water absorption. This may be caused from the hydrophobic oily surface of the wood.

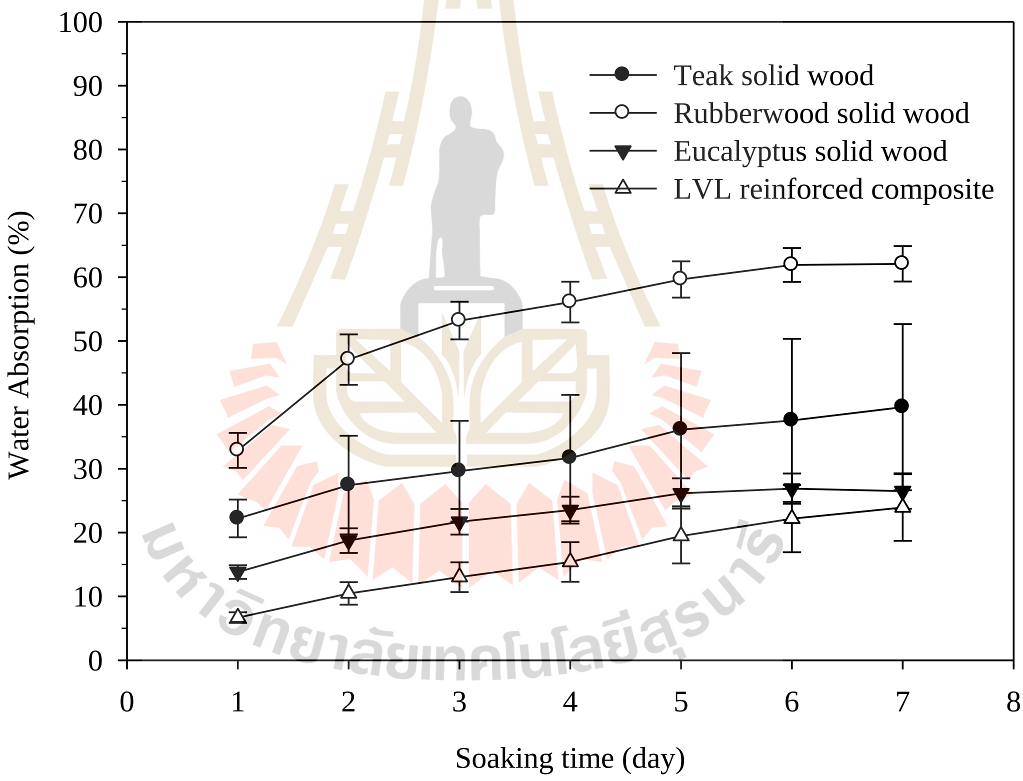


Figure 4.47 Water absorption results of the solid woods and LVL composite.

4.5.2 Termite resistance

The termites or white ants are one of the most important groups of organism known to destroy cellulosic materials especially wood. Termites breaks down the internal structure of wood in historic buildings thereby its mechanical functionality is reduced. They cause the severe damages. Not all timber species are equally susceptible to attack by termite. In this study, the termite resistance of LVL reinforced composite and three solid wood species were submersed in the natural land site and the weight loss was monitored every 2 weeks for 3 months.

Figure 4.48 presents the calculated weight loss resulted from solid woods and the LVL. As expected, the solid woods, except teak, shows rapid weight loss percentage, indicating that these solid woods were attacked or destroyed by termite. This statement is visibly evidenced in the following photographs. As typically know for its outstanding characteristic, teak solid wood shows no attack by termite within 3 months. It is certified as “national durability” or alternatively “decay resistance” wood (Eaton and Hale, 1993).

LVL reinforced composite shows lower weight loss percentage. Meaning that, it is better in termite resistance. This superior characteristic of the LVL may be explained by that the epoxy adhesive act as the protective surface of the wood from termite attack.

Moreover, the physical appearances of the samples by visual observation before and after burying in soil are firmly illustrated in Figure 4.49. It is clearly reflected that LVL reinforced composite had no termite attack. So, it has high degree of resistance, equally to teak species, compared to those solid woods.

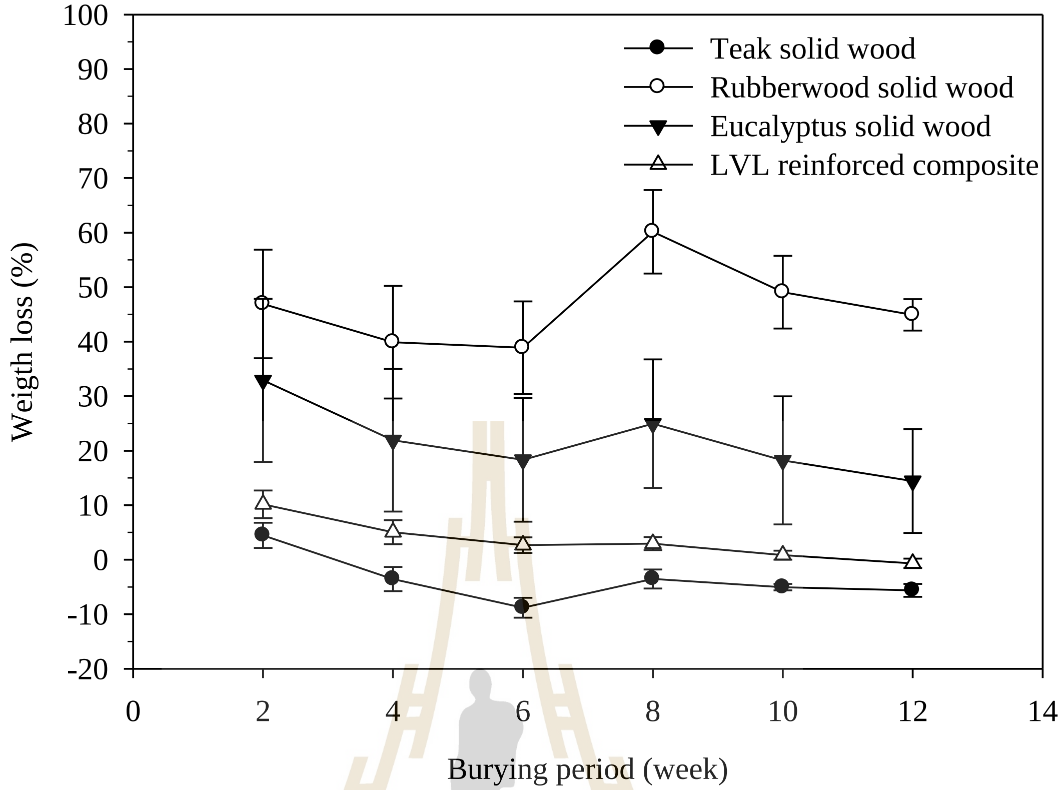


Figure 4.48 Weigh loss results of the woods.

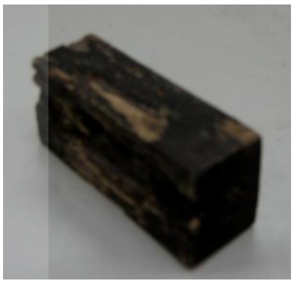
Wood Type	**Before**	**After**
Teak solid wood		
Rubber wood solid wood		
Eucalyptus solid wood		
LVL reinforced composite		

Figure 4.49 The physical appearance before and after burying in soil for 12 weeks of the solid woods and LVL composite.

CHAPTER V

CONCLUSIONS

The main objective of this work is to investigate the influence of composite constituents and processing parameters on the performance properties of LVL reinforced composites that suit for outdoor furniture and construction material applications. The 2^k factorial experimental design was used to analyze the significant effects of those factors base on flexural properties and also confirmed by the statistical testing using the ANOVA.

According to first step experimental design on the effect of raw materials, both flexural results and based on the statistical analyses (ANOVA), found that there were no individual significant effects on the flexural strength and toughness of LVL reinforced composites. However, from these results found that adhesive type, wood species of veneer, interaction between wood species and fiber type, and interaction between wood species and adhesive type were the significant effects on the flexural modulus. The most significantly effect on the modulus was adhesive type followed by wood species vice versa the fiber type. The evaluation of the mechanical properties indicated that rubber wood, room temperature cure adhesive, and carbon fiber gave rise to the better properties. Thus, rubber wood, room temperature cure adhesive, and carbon fiber could be proposed for manufacturing of LVL reinforced composites. But there were not obviously significant effects on fiber used, then glass fiber was chosen, as economic reason, for the second step of work.

Study on influence of the silane contents and wood surface treatments, smoking and anti termite treatment, the results indicated that the interaction between silane quantity and anti termite application was a significant influence on the flexural strength of LVL reinforced composites. The interaction between silane quantity and both wood surface treatments were also significant effect on the modulus properties. In addition, the interaction between smoked wood and applying anti termite on wood surface, interaction between silane quantity and smoked wood were also significant effects on the toughness properties. The better properties were provided by high level of silane, high content of smoked wood, and low content of anti termite wood treatment. Therefore, high quantity of silane addition to curing agent and only smoked wood should be employed to achieve the maximum properties in the production of LVL reinforced composites.

Investigating of the effect of processing parameters in curing on the flexural properties of LVL reinforced composites, it was discovered that pressure was the most significant effect, negative, on the product properties. Improve in the mechanical properties was related to decreased pressure. Beside, press time was also significant the positive effect. Although time was not clearly reflect from the mechanical results, but it was detected in the ANOVA results. The mechanical properties was increase with increasing press time in curing process. From the results, the optimal condition to maximize mechanical properties was assumed at low pressure, 15 bar, low temperature, 70^{o}C, and long time, 60 mins.

Within this research limitation including material used, specimen, magnitude of curing parameters and so on, the durability including withdrawal strength of screw, water absorption, and termite resistance of LVL reinforced composite were observed and compared with solid woods. It was found the withdrawal strength of LVL reinforce composite was higher than the solid woods as its density. As expected that solid woods, except eucalyptus, had low water absorption resistance as it more hygroscopic compared to LVL reinforced. Also solid woods, except teak, had low resistance to termite attack. Therefore, LVL reinforced was the best candidate by mean of durability properties compared to solid wood.

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APPENDIX A

FLEXURAL STRESS-DISPLACEMENT CURVES

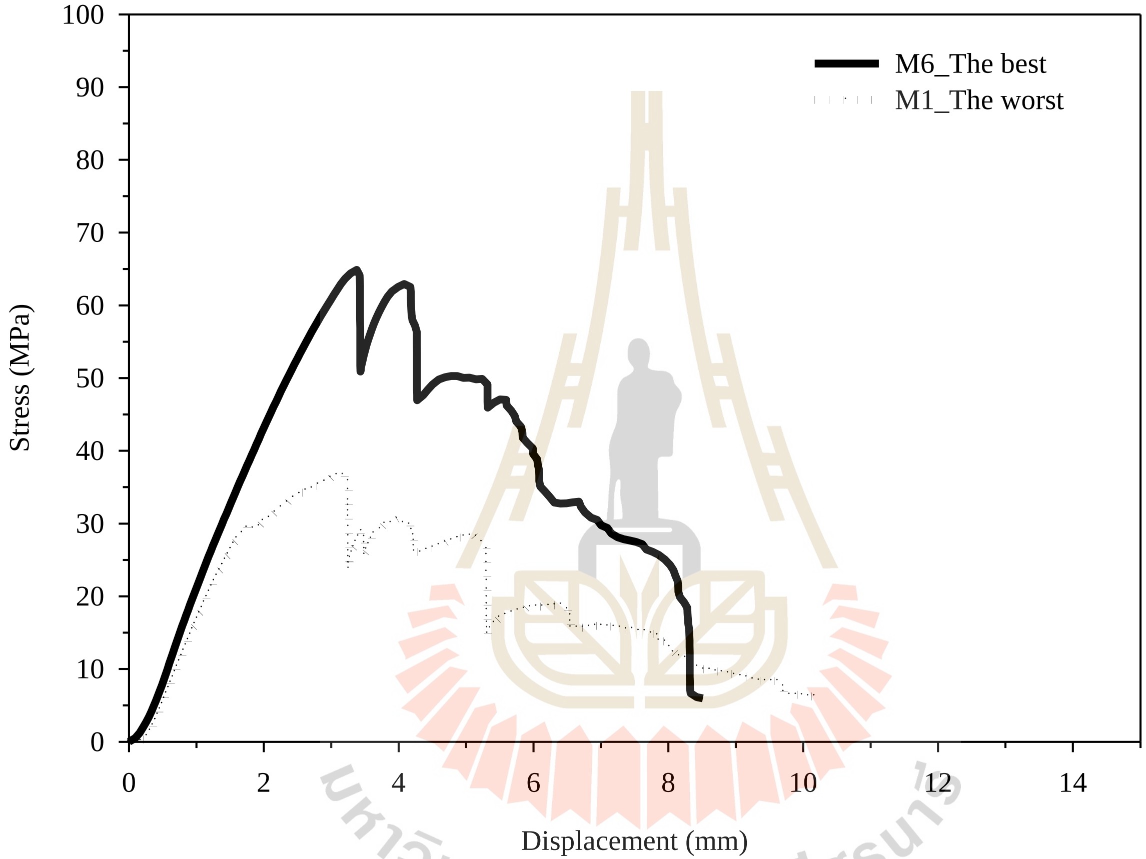

Figure A.1 Stress-displacement curves of the best and the worst properties of the LVL prepared in DOE test I.

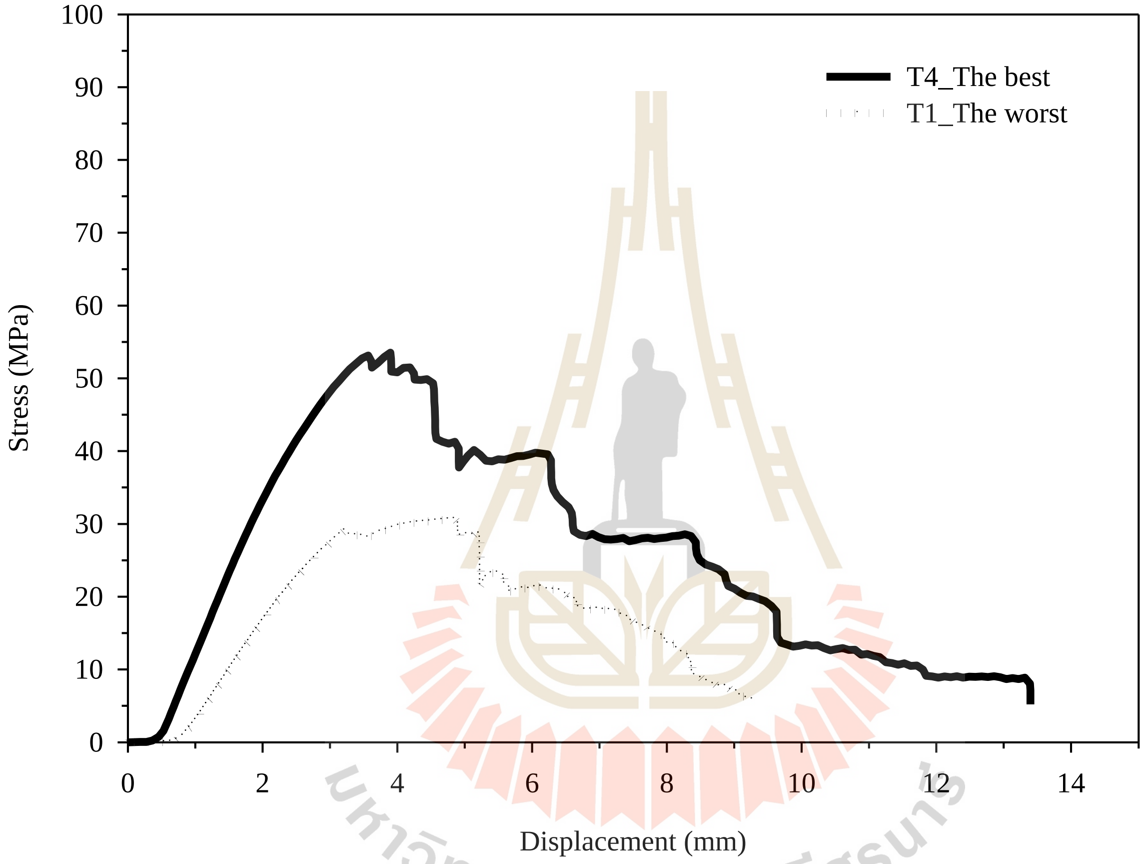

Figure A.2 Stress-displacement curves of the best and the worst properties of the LVL prepared in DOE test II.

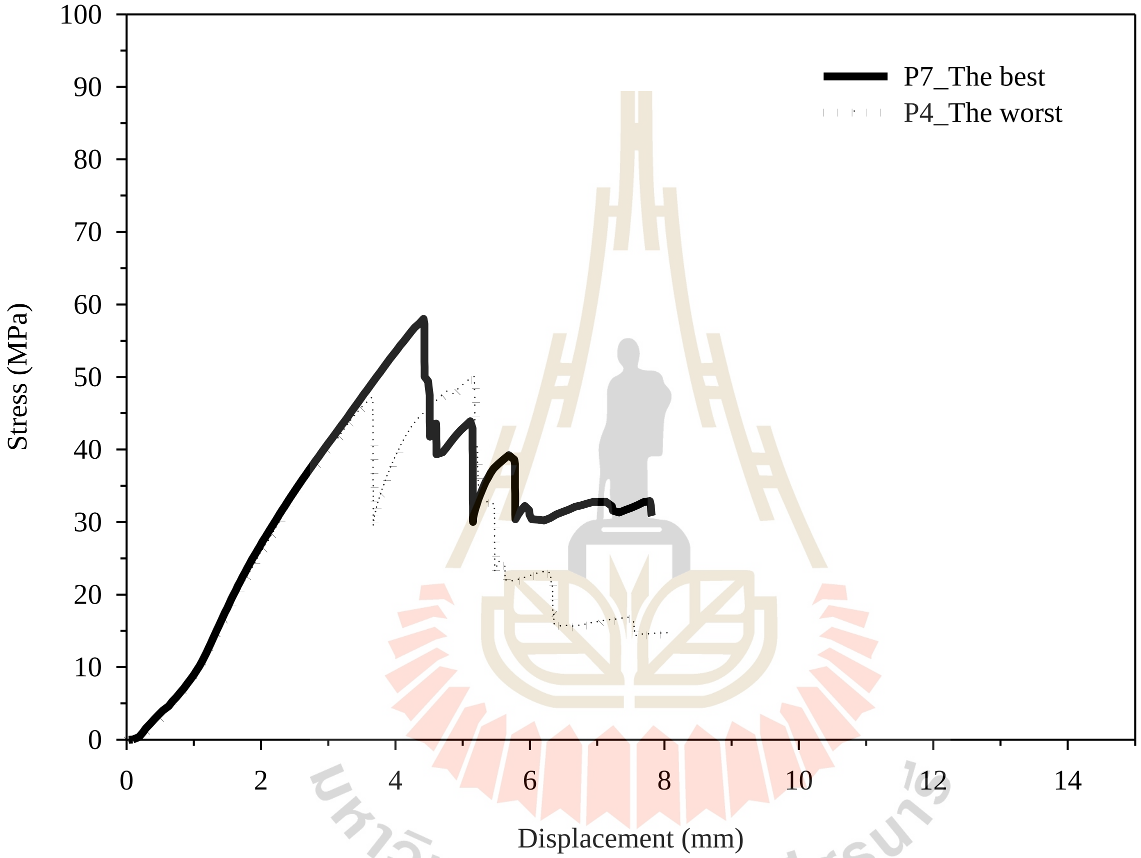

Figure A.3 Stress-displacement curves of the best and the worst properties of the LVL prepared in DOE test III.

APPENDIX B

RESEARCH PUBLICATION

Experimental Design on Engineered Wood: Laminated Veneer Lumbers(LVL) Reinforced Composites

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Engineered woods for outdoor furniture and construction materials for hazards environmental condition is the prime concern for this study. The laminated veneer lumber(LVL) derived from rubber wood and eucalyptus peeled sheet and teak veneer was prepared. All of the wood obtained from economic farm forest. The glass and carbon woven fiber reinforcement and in house room temperature and prepreg epoxy matrix were employed. 2^k factorial experimental design were used to analyze the significant effect of those constituent of the mechanical property by mean of flexural strength of the engineered wood obtained. The main experimental factors for the design include fiber, adhesive and peeled wood types. The treatment of the laminated wood such as smoking and anti termite application is also investigated. Quantity silane addition to curing agent will also evaluated. According to the preliminary experimental design results, based on the statistical analyses, it was found that adhesive types had significantly effected on flexural strength of LVL vice versa the fiber types.

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BIOGRAPHY

Yumatorn Mingmongkol was born on June 18, 1979 in Phitsanulok, Thailand. She finished high school from Mahidol Wittayanusorn school at Nakhorn Pathom and graduated bachelor degree in faculty of Industrial Engineering from Naresuan University at Phitsanulok. She has been employed under position of *Process Engineer* at PCTT CO., LTD. for 2 years, under position of *Production Engineer* at THAI NIPPON CO., LTD. for 1 year, and under position of *Manufacturing Engineer* at CELESTICA CO., LTD. for 2 years. She graduated master degree in Polymer Engineering at the state university at Nakhorn Ratchasima, Suranaree University of Technology. During graduate study she presented oral presentation entitled of "**Experimental Design on Engineered Wood: Laminated Veneer Lumber (LVL) Reinforced Composites**" in the 4th China-Europe symposium on processing and properties of reinforced polymers on June 8-12, 2009 in Guilin, China.