STUDIES OF NATURAL FIBER / POLYMER COMPOSITES FROM BAMBOO *(BAMBUSA BLUMEANA* SCHULT*)*

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A THESIS SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENT FOR THE DEGREE OF
MASTER OF SCIENCE IN APPLIED CHEMISTRY
SCHOOL OF GRADUATE STUDIES
KING MONGKUT'S INSTITUTE OF TECHNOLOGY LADKRABANG
1998

ISBN 974-622-332-1

หัวข้อวิทยานิพนธ์	การศึกษาพอลิเมอร์คอมโพสิตเส้นใยธรรมชาติจากไผ่ (ไผ่สีสุก)
นักศึกษา	นางสาวปิยะวัน ตังควรรณวานิช
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บทคัดย่อ

งานวิจัยนี้ เป็นการศึกษา พอลิเมอร์คอมโพสิตจากเส้นใยธรรมชาติ (ไผ่สีสุก) กับเอบีเอสที่มีการปรับปรุงพื้นผิวเส้นใยไผ่ โดยการสกัดด้วยตัวทำละลาย (Acetone, methanol : benzene, and sodium hydroxide) และการต่อกิ่งด้วยพอลิเมทิลเมทาไครเลท (PMMA) โดยการฉายรังสีแกมมาที่ปริมาณการฉายรังสีรวม 0 - 20 kGy และทำการศึกษาปริมาณการต่อกิ่งที่เหมาะสม เพื่อปรับปรุงสมบัติการยึดติดระหว่างเส้นใยกับพอลิเมอร์เมทริกซ์ และสมบัติเชิงกลต่าง ๆ เช่น ความแข็งแรงแรงดึง ความทนทานต่อแรงกระแทก ความแข็ง เปอร์เซ็นต์การดูดซับน้ำและเปอร์เซ็นต์ความชื้นในคอมโพสิต เป็นต้น โดยทำการศึกษาในแนวเปรียบเทียบระหว่างพอลิเมอร์คอมโพสิตของเส้นใยก่อนและหลังการปรับปรุง

เมื่อทำการผสมเส้นใยไผ่ (0 - 40 phr) กับ เอบีเอส โดยใช้เครื่องผสมหลอมเหลวระบบปิดแบบเกลียวหนอนคู่และขึ้นรูปด้วยวิธี Injection molding พบว่า พอลิเมอร์คอมโพสิตมีสมบัติเชิงกลดีขึ้นเมื่อเพิ่มปริมาณเส้นใยในคอมโพสิต จากการศึกษาการสกัดเส้นใยไผ่ด้วยตัวทำละลาย พบว่า พอลิเมอร์คอมโพสิตมีสมบัติเชิงกลเพิ่มขึ้น แต่การดูดซับน้ำเพิ่มขึ้นเล็กน้อย

เมื่อทำการต่อกิ่งด้วยพอลิเมทิลเมทาไครเลท (PMMA) บนเส้นใยไผ่ โดยใช้รังสีแกมมาแบบขั้นตอนเดียว (Simultaneous method) ที่ปริมาณการฉายรังสีรวม 5 - 20 kGy พบว่า พอลิเมอร์คอมโพสิตมีสมบัติเชิงกลเพิ่มขึ้นและการดูดซับน้ำลดลง เปอร์เซ็นต์การต่อกิ่งของพอลิเมทิลเมทาไครเลทสูงสุดที่ปริมาณการฉายรังสีรวม 15 kGy โดยพบว่า เส้นใยที่มีการสกัดด้วยตัวทำละลายจะมีเปอร์เซ็นต์การต่อกิ่งสูงกว่าเส้นใยที่ไม่มีการสกัดด้วยตัวทำละลาย

ในการศึกษาพฤติกรรมการสลายตัวเนื่องจากความร้อนของพอลิเมอร์คอมโพสิต พบว่า พอลิเมอร์คอมโพสิตที่มีการต่อกิ่งบนเส้นใย มีอุณหภูมิการสลายตัวเหมือนกับพอลิเมอร์คอมโพสิตที่ไม่มีการต่อกิ่งแต่มีการสกัดและไม่สกัดด้วยตัวทำละลาย

จากการศึกษาสัณฐานของพอลิเมอร์คอมโพสิต โดยใช้กล้องจุลทรรศน์อิเล็กตรอน (SEM) พบว่า เส้นใยเกิดการขาดและการแตกออกเป็นเส้นเล็ก ๆ มากกว่าการหลุดออกของเส้นใยจากพอลิเมอร์คอมโพสิต เมื่อใช้เส้นใยที่มีการต่อกิ่งหรือมีการสกัด แสดงให้เห็นว่า การต่อกิ่งและการสกัดช่วยให้การยึดติดของเส้นใยกับเอบีเอสที่ผิวดีขึ้น ความยาวและลักษณะของเส้นใยที่พบหลังการขึ้นรูป โดยการสกัดเอบีเอสออกด้วยตัวทำละลาย (Methyl ethyl ketone) พบว่า ความยาวของเส้นใยลดลงจาก 2 - 3 มิลลิเมตรเหลือ 1 - 2 มิลลิเมตร และเส้นใยเกิดการเสียรูป เนื่องจากขบวนการผลิต

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Year	1998
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ABSTRACT

In this research work, natural fiber - reinforced plastic composites were prepared from bamboo fibers and acrylonitrile - butadiene - styrene (ABS) as polymer matrix. In order to improve interfacial adhesion between the fibers and the matrix, the bamboo fibers were treated by series of solvents (acetone, methanol : benzene, and sodium hydroxide) and also grafted with poly (methyl methacrylate) (PMMA) by using simultaneous γ - ray irradiation method at various total dose (0 to 20 kGy). The optimum grafting content was studied corresponding to optimum mechanical properties of the composites, such as, tensile strength, impact strength, hardness, % water absorption and moisture content, etc.. Comparative study of the untreated and treated bamboo fibers / ABS composites were carried out.

Composites of the unextracted & ungrafted bamboo fibers (0 to 40 phr) and ABS were prepared by using a brabender / twin - screw extruder and shaped by using injection molding. It was found that mechanical properties were improved with increasing the fiber loading in the composites. Contaminates, impurities, and weak layers were removed from the bamboo fibers when extracted by acetone, methanol : benzene, and sodium hydroxide aqueous solution. The extracted & ungrafted bamboo fiber / ABS composites showed improved mechanical properties compared to the unextracted & ungrafted ones, but % water absorption was slightly increased.

By simultaneous γ - ray irradiation method at various total dose of 0 to 20 kGy, grafting the bamboo fibers with methyl methacrylate (MMA) monomer could improve mechanical properties and % water absorption. % Grafting yield was highest at total dose of 15 kGy. The extracted bamboo fibers had higher % grafting yield than the unextracted bamboo fibers.

Thermal resistance of the composites was studied by TGA. It was found that the decomposition temperature of the grafted bamboo fiber / ABS composites was similar to that the ungrafted bamboo fiber / ABS composites.

Morphology of the composites was observed by SEM. It was revealed that more fiber breakage and fibrillation were found in both the grafted and extracted composites. This implied the better adhesion at the fibers / ABS interface in the grafted and extracted ones. It can be seen that the fibers were shortened to 1 to 2 millimeters in length after processing into composite form. Deformation band of the bamboo fibers was revealed by SEM.

ACKNOWLEDGEMENTS

I wishes to express my profound gratitude to my advisor, Dr. Ittipol Jangchud for constant guidance advice and encouragement throughout this study. Thanks are also to Mr. Woratham Oonjitichai, co - advisor, for valuable guidance and encouragement. I am grateful to Dr. Tongjit Kidchob, Asst. Prof. Dr. Malinee Chaisupakitsin and Mr. Manit Sonsuk for correcting and being the thesis committees.

Sincere thanks go to technicians of the Department of Chemistry, KMITL for their helps during conducting the experiment.

Most important, I would like to express my faithful thanks to my parents for their kindness and encouragement throughout the course of completing this thesis.

Piyawan Tangkawanwanit

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LIST OF ABBREVIATIONS

phr	Part (s) per hundred parts of ABS
MPa	Mega Pascal
kGy	kilo - Gray
ABS	Acrylonitrile - butadiene - styrene
PMMA	Poly (Methyl methacrylate)
MMA	Methyl methacrylate
SEM	Scanning electron microscope
FTIR	Fourier Transform Infrared Spectrophotometer
TGA	Thermogravimetric analyzer
ASTM	American Society for Testing and Materials

CHAPTER I

INTRODUCTION

In the last three decades, polymer composites have become popular as light - weight / high performance structural materials. Polymer composites have played an important role in several industries. A rapid growth in the demand of fiber reinforced polymer composites in several applications has motivated scientists and engineers to develop better performance composites. In recent years, more attention has been focused on the development of technologies for the utilization of biomass materials, such as, agricultural residue, wood fibers, etc. and in combination with synthetic materials, and also the fabrication of new products. Organic fillers, such as, residues from sawmills and agricultural operations are derived from renewable natural resources. They are plentiful, available in nature, environmental friendly, and relatively inexpensive. The attempt is to substitute synthetic fibers ,such as, glass and carbon fibers due to the high cost and high energy requirement in their productions.

Natural fibers are abundantly available as by - products and waste from agricultural industries and by nature. Recently, natural fibers have emerged as their uses in fiber - reinforced polymers and fiber - polymer composites. Some advantages of natural fibers compared to those of synthetic fibers include low density, high strength - to - weight ratio, good mechanical properties, abundant availability, relatively inexpensive, renewability, and bio - degradable. However, they have some disadvantages, i.e., high water absorption and low fiber - polymer interfacial adhesion. These problems can be relieved by treating fibers with some chemicals to enhance the properties.

1.1 Objectives of this work

This work was proposed to enhance the properties of the bamboo fibers / polyacrylonitrile - butadiene - styrene (ABS) composites by decreasing the ability of water absorption and improving the fiber - polymer interfacial adhesion. Grafting methyl methacrylate (MMA) onto the fibers using gamma - ray irradiation technique would be expected to improve the properties.

The Objectives of this study were:

1. to study the effects of PMMA grafted onto the bamboo fibers on mechanical and morphological properties of the fibers and the composites,

2. to find optimum conditions of γ - ray irradiation for grafting PMMA onto the bamboo fibers by varying total dose,
3. to study percentage of the fiber loading on physical properties of the composites,
4. to study the effects of extractives on irradiation and properties of the composites.

The ultimate goal was to find an alternative way to utilize a Thai bamboo (*Bambusa blumeana* Schult) as a high performance composite. Proposed testing techniques were water absorption, surface morphological study by SEM (Scanning electron microscopy), thermal behavior, and mechanical testing, i.e., tensile strength, % elongation at break, modulus at 3 % strain, impact strength, etc. Comparative study of untreated bamboo fibers and treated bamboo fibers would be carried out.

CHAPTER II

THEORETICAL CONSIDERATION AND LITERATURE REVIEW

2.1 Composite materials

There has been a rapid growth in the use of fiber reinforced materials in engineering applications in the last few years. The main purposes in the development of composite materials are to obtain materials with controlled properties and to find reinforcing materials and polymer matrices whose mixtures have improved properties and not attainable by the components of the composite isolately [1]. By definition, composite materials are composed of a reinforcing structure, surrounded by a continuous matrix [2].

Generally, properties of composites depend on :

1. Properties of fibers and matrices
2. Fiber volume fraction (V_f) and fiber orientation
3. Flaws and voids
4. Interfacial bonding between fibers and matrices

2.1.1 Advantages and disadvantages of composites [3]

The advantages of composites include :

1. Weight reduction (high strength - or modulus - to - weight ratio)
2. Longer life (less corrosion)
3. Lower manufacturing costs because of lower part count
4. Inherent damping property
5. Increased (or decreased) thermal or electric conductivity

The disadvantages include :

1. Cost of raw materials and fabrication
2. Environmental degradation of matrix
3. Difficulty in attaching (e.g.welding)
4. Difficulty with analysis

Composite structural elements are now used in a variety of components for automotive, aerospace, marine, and architectural structures in addition to consumer products, such as, skis, golf clubs, tennis rackets, I - beam, channel section, and other structural elements used in building.

2.1.2 Fabrication processes

A summary of fabrication processes used for polymer composites with various types of fiber reinforcement was given in Tables 2.1 and 2.2 .

Table 2.1 Fabrication processes for polymer - matrix composites [4]

Process	Type of fiber reinforcement			
	Continuous	Chopped	Woven	Hybrid
Open mold				
Hand lay - up		X	X	
Spray - up		X		
Autoclave	X		X	
Compression molding	X	X	X	X
Filament winding	X			
Pultrusion	X			
RRIM	X			
Thermoplastic molding	X	X	X	X
RTM	X	X	X	X
Structural reaction injection molding (SRIM)	X	X	X	X

Table 2.2 Manufacturing routes for fiber reinforced plastic products [5]

Manufacturing route	Outline of fabrication and processing methods
Open mold processes	
1. Hand lay - up [6]	Resin and reinforcement are brought together on a molding tool and consolidated into a form curable by heat or chemical action.
2. Spray - up	Spray - up is similar to the hand lay - up process. Chopped rovings and resin are sprayed simultaneously into a prepared mold and rolled before the resin cures.

Table 2.2 (continued)

Manufacturing route	Outline of fabrication and processing methods
3. Centrifugal casting	Mixtures of the fibers and resin are introduced into a rotating mold and allowed to cure *in situ.*
4. Vacuum bag, pressure bag, autoclave	Layers of fibers, usually unidirectional sheets, are pre-impregnated with resin and partially cured (β - staged) to form a pre - preg.
5. Filament winding	Continuous rovings or strands of fibers are fed over rollers and guides through a bath of resin and then wound, using a programmer controlled machine, onto a mandrel at pre - determined angles. The resin is partially or completely cured before removing the component from the mandrel.
Closed mold processes	
6. Pultrusion	A continuous feed of fibers, in pre – selected orientation, is impregnated with resin and pulled through a heated die to give the shape of the final section.
7. Hot press molding, compression molding	Heated matched dies or tools are loaded with raw material (SMC, DMC, cloth or unidirectional pre – preg) pressed to the shape of the cavity and cured.
8. Reinforced reaction injection molding (RRIM)	Fibers are either placed in the closed mold before resin is injected or added as short chopped fibers to one of the resin components to form a slurry before injection.
9. Injection molding, transfer molding	Molten or plasticized polymer mixed with short fibers is injected, usually at high pressure, into the cavity of a split mold and allowed to solidify or cure. The mold is opened and the fabricated part is ejected. The cycle of operation is then repeated [6].

2.1.3 Fiber – reinforced composites

The most common example of composites is the fibrous composite consisting of reinforcing fibers embedded in a binder or matrix material [4]. Fibrous reinforcement is so effective because many materials are much stronger and stiffer in fiber form than they are in bulk form. Fiber - reinforced composite materials consist of fibers of high strength and modulus embedded in or bonded to a matrix with distinct interfaces (boundaries) between them [7]. In general, the fibers are the principal load - carrying members, whereas the surrounding matrix keeps and protects them from environmental damages due to elevated temperature or humidity.

2.1.3.1 Elastic properties of short fiber composites

Most fiber - reinforced composites are anisotropic and their properties in each direction are different. Discontinuous fiber - reinforced composites have lower strength and modulus than continuous fiber composites. However, with random orientation of fibers, it is possible to obtain nearly equal mechanical and physical properties in all directions in the plane of the lamina. A simplified analysis of composite materials allows the mechanical performance of a composite material to be determined from the properties of its individual components. Firstly, stress (σ), strain (ε), and modulus (E) in an article are defined as:

$$\sigma = F / A \tag{2.1}$$

Where F is the applied load, and A is the cross-sectional area of the specimen

$$\varepsilon = (l - l_0) / l_0 \tag{2.2}$$

Where l_0 is the original length and l is the length of the specimen after a certain time under a load F, and

$$E = \sigma / \varepsilon \tag{2.3}$$

For a unidirectionally aligned material containing fiber of length (l) the rule of mixtures equation (2.4) may be modified by the inclusion of a length correction factor, η_l, so that

$$E_l \text{ or } E_{//} = E_f V_f + E_m V_m \tag{2.4}$$

$$E_{//} = \eta_l E_f V_f + E_m V_m \tag{2.5}$$

Where E_f = Modulus of fiber,

E_m = Modulus of matrix,

V_f = Volume fraction of fiber,

V_m = Volume fraction of matrix

Cox [5] derived the following expression for η_l

$$\eta_l = 1 - (\tanh \tfrac{1}{2}\beta l) / \tfrac{1}{2}\beta l \qquad (2.6)$$

$$\text{Where } \beta = \frac{\left(2G_m \right)^{\frac{1}{2}}}{E_f r_f^2 \ln (R / r_f)} \qquad (2.7)$$

2R = Center - to - center distance from to its nearest neighbor ,

r = Fiber radius,

G_m = Shear modulus of matrix

If $E_f >> E_m$ the effective modulus of the short fiber material compared with continuous fiber material is

$$E\,(\text{short}) / E\,(\text{continuous}) = \eta_l \qquad (2.8)$$

An alternative form of equation (2.5), which was developed by Halpin [5] as an extension of the Halpin - Tsai equations, expressed the longitudinal Young's modulus as

$$E_{//} = \frac{E_m (1 + \xi\eta V_f)}{(1 - \eta V_f)} \qquad (2.9)$$

$$\text{Where} \quad \eta = \frac{((M_f / M_m) - 1)}{(M_f / M_m) + \xi} \qquad (2.10)$$

in which M_f the corresponding fiber modulus, M_m the corresponding matrix modulus and $\xi = 1 / r$.

2.1.3.2 Tensile strength of short fiber composites

The strength of fibrous composites relies on the transfer of stresses from the matrix to the fibers. The ultimate tensile strength of a number of fibrous - reinforced composites may be estimated as

$$Tu = V_f (1 - \frac{L_f}{2L}) T_f + V_m T_m \qquad (2.11)$$

Where Tu = Ultimate tensile strength of composite,

V_f = Volume fraction of fiber,

L_f = Critical fiber length,

L = Length of fiber,

T_f = Tensile strength of fiber,

V_m = Volume fraction of matrix,

T_m = Tensile strength of matrix

Fiber length is an important parameter in determining the stress to be transferred. This may be expressed as

$$L_f = DST_f \tag{2.12}$$

Where L_f = Critical fiber length,

D = Diameter of fiber,

S = Strength of matrix bond to fiber (approximately equal to shear strength of matrix),

T_f = Tensile strength of fiber

The factors that greatly affect the tensile strength of the composites are consisted of the perfection of packing and alignment of the fibers and imperfections, such as, voids. Points of stress concentration are caused by points of contact between different fibers which can especially damage to transverse tensile strength.

The principal applications for short fiber reinforced thermoplastics are as injection molding compounds. Short fiber reinforced thermoplastic molding materials are very widely used in industry [6]. The discontinuous fiber composites are not as strong as continuous fiber composites. The reasons for this decrease in strength are ; (1) the ineffectiveness in transmitting load from the matrix to the fibers is caused by the appreciable lengths at end of the fibers ; (2) the fiber ends act as stress concentrators and thus resulting in crack initiation ; (3) the strength of the composite is not contributed if the fibers do not appreciably overlap one another ; and (4) in general, it is impossible to achieve as perfect orientation with short fibers as with continuous fibers [8].

For discontinuous fiber composites, stress concentrations are built up in the vicinity of fiber ends or around fiber breaks during loading. Thus, the stress analysis of interest for the discussion of failure in composites is the one associated with the perturbed stress field in the vicinity of a fiber end. There are at least three important strengths in the case of uniaxially oriented fiber composites. These strengths include the longitudinal tensile strength, the transverse tensile strength, and the shear strength. The relative importance of these strengths depends on the angle between the fibers and the applied load.

When an external load is applied to the composite, the fibers are loaded as a result of stress transfer from the matrix to the fiber across the fiber - matrix interface. If a perfect fiber - matrix interfacial bond is assumed, the difference in longitudinal strains between the two constituents creates a shear stress distribution across the interface. Ignoring the stress transfer at the fiber end cross - sections and the interaction between neighboring fibers, the normal stress distribution in a short fiber can be calculated by a simple force equilibrium analysis. The variations of stresses along the length of a fiber were studied by Cox [6]. Cox used a shear lag analysis, which leaded to the following expressions for the tensile stress in the fiber, σ_f, and the shear stress at the interface, τ,

$$\sigma_f = E_f \varepsilon_m \left[\frac{1 - \cosh \beta (Ra - X_r)}{\cosh \beta Ra} \right] \qquad (2.13)$$

$$\tau = E_f \varepsilon_m \left[\frac{G_m}{2E_f \ln V_f^{-1/2}} \right]^{1/2} \frac{\sinh \beta (Ra - X_r)}{\cosh \beta Ra} \qquad (2.14)$$

Where $$\beta = \left[\frac{2\,G_m}{E_f r^2 \ln V_f^{-1/2}} \right]^{1/2} \qquad (2.15)$$

Where E_f and G_m are the tensile modulus of the fiber and shear modulus of the matrix, respectively, ε_m is the applied strain, Ra is the aspect ratio of the fiber, L / 2r, and X_r is the distance from the distance from the fiber end measured in units of the fiber diameter.

The degree of reinforcement that may be attained is a function of the fiber volume fraction (V_f), the fiber orientation distribution (FOD), the fiber length distribution (FLD) and the efficiency of stress transfer at the interface.

2.1.3.3 Impact strength

Impact failure of fiber - reinforced polymer composites is a very complex phenomenon. This failure behavior is not a unique function of the constituent fibers and matrix, the fracture properties (e.g., impact energy) can not be predicted by a simple rule - of - mixture law [9]. Izod impact tests are performed on commercially available machines in which pendulum hammer is released from a standard height to contact a beam specimen (either notched or unnotched) with a specified kinetic energy.

The energy absorbed in breaking the specimen, usually indicated by the position of a pointer on a calibrated dial attached to the testing machine, is equal to the difference between the energy of the pendulum hammer at instant of impact and the energy remaining in the pendulum hammer after breaking the specimen. Fibers also can cause the impact strength to reduce by at least two mechanisms, i.e., (1) the elongation to break is drastically reduced by the fibers and thus the area under the stress - strain curve may be reduced, and (2) stress concentrations occur at regions around fiber ends, areas of poor adhesion, and region where fibers contact one another. Thus, fibers can cause the apparent impact strength to either increase or decrease depending upon the nature of the composite and the type of impact test.

The fracture energy of short fiber composites is composed of the crack initiation energy and the crack propagation energy, which is entirely the fiber pull - out energy. The debonding energy required to failure of the fiber - matrix adhesion bond is negligible. For the notched test, the energy absorbed in order to fracture the energy needed to propagate the cracks.

The work of fracture (W) can be obtained by the following expression [10] :

$$W = \frac{A}{B\,(D-a)} \qquad (2.16)$$

Where A is the area under the load - deflection curve, B is thickness, D is width (depth) and a is initial crack length.

2.1.3.4 Fiber content, density, and void content

Theoretical calculations for strength, modulus, and other properties of a fiber - reinforced composite are based on the fiber volume fraction in the material. Experimentally, it is easier to determine the fiber weight fraction, W_f, from which the fiber volume fraction, V_f, and composite density, ρ_c, can be calculated [7] :

$$V_f = \frac{W_f / \rho_c}{(W_f / \rho_f) + (1-W_f) / \rho_m} \qquad (2.17)$$

$$\rho_c = \frac{1}{(W_f / \rho_f) + (1-W_f) / \rho_m} \qquad (2.18)$$

Where W_f = Fiber weight fraction,

$(1-W_f)$ = Matrix weight fraction,

ρ_f = Fiber density,

ρ_m = Matrix density

In terms of fiber volume fraction, V_f, the composite density, ρ_c, can be written as

$$\rho_c = \rho_f V_f + \rho_m V_m \qquad (2.19)$$

During incorporation of fibers into the matrix or during manufacturing of laminates, air or other volatiles may be trapped in the materials, which may significantly affect some of their mechanical properties.

The void content in a composite can be estimated by comparing the theoretical density with its actual density ;

$$Vv = \frac{\rho_c - \rho}{\rho_c} = 1-(V_f + V_R) \qquad (2.20)$$

Or $$Vv = 1-(W_f/\rho_f + W_R/\rho_R)$$

Where Vv = Volume fraction of voids,

ρ_c = Theoretical density,

ρ = Actual density, measured experimentally on composite specimens,

R = Polymer matrix,

f = Fiber,

W = Weight fraction

2.2 Theories of adhesion [5]

The interface is a dominate factor in the fracture toughness properties of composite materials and in their responses to aqueous and corrosive environments. Composite materials with weak interfaces have relatively low strength and stiffness but high resistance to fracture whereas materials with strong interfaces have strength and stiffness but are very brittle. In a simple system bonding at an interface is due to adhesion between fiber and matrix.

Adhesion can be attributed to five main mechanisms which can occur at the interface either in isolation or in combination to produce the bond.

2.2.1 Adsorption and wetting

When two electrically neutral surfaces are brought sufficiently close together there is a physical attraction which is best understood by considering the wetting of solid surfaces by liquids as illustrated in Figure 2.1a. The physical situation of a liquid drop on a solid surface, as Figure 2.1b , by using the Young's equation.

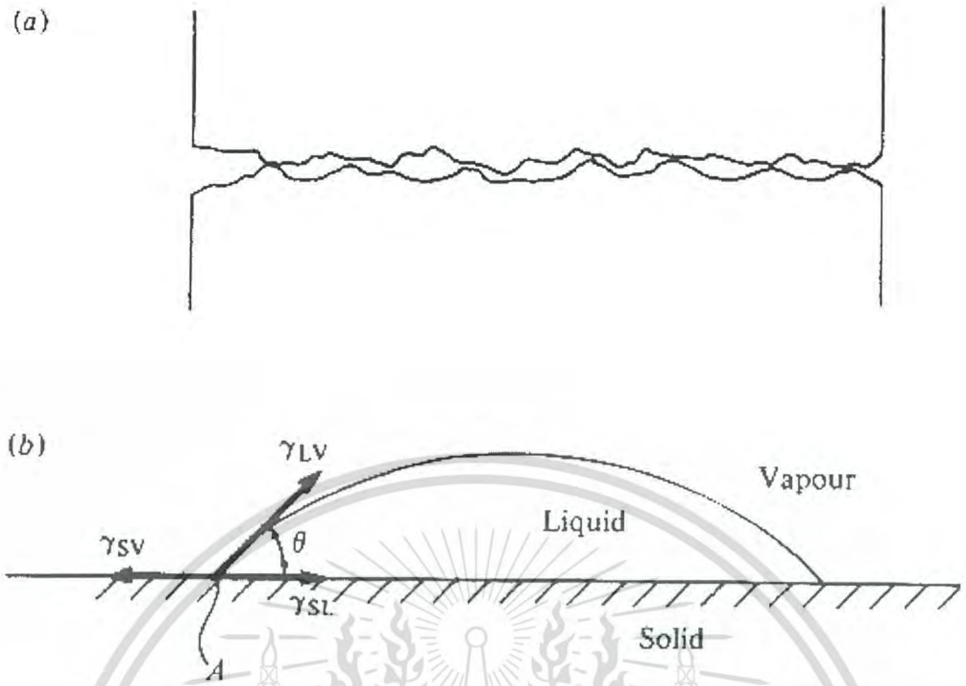


Figure 2.1 (a) Isolated contact points leading to weak adhesion between two rigid rough surfaces. (b) Surface tensions (γ) for a liquid drop on a solid surface

Work of adhesion, W_{SL}, as shown by the Young's equation

$$W_{SL} = \gamma_{LV}(1 + \cos\theta) = \gamma_{SV} + \gamma_{LV} - \gamma_{SL} \qquad (2.21)$$

Where θ is the contact angle and γ is the surface tensions of solid - vapor (SV), solid - liquid (SL), and liquid - vapor (LV) interfaces, respectively.

2.2.2 Interdiffusion

It is possible to form a bond between two polymer surfaces by the diffusion of polymer molecules on one surface into the molecular network of the other surface, as illustrated schematically in Figure 2.2 a. The bond strength will depend on the amount of molecular entanglement and the number of molecules involved.

2.2.3 Electrostatic attraction

Forces of attraction occur between two surfaces when one surface carries a net positive charge and the other surface a net negative charge as in the case of acid - base interactions and ionic bonding (Figure 2.2 b) and coupling agents laid down on the surface of glass fibers (Figure 2.2 c).

2.2.4 Chemical bonding

A chemical bond is formed between a chemical grouping on the fiber surface and a compatible chemical group in the matrix as seen in Figure 2.2 d. The strength of the bond depends on the number and type of bonds and interface failure must involve bond breakage.

2.2.5 Mechanical adhesion

Some bonding may occur purely by the mechanical interlocking of two surfaces as illustrated in Figure 2.2 e. The strength in shear may be very significant and depends on the degree of roughness.

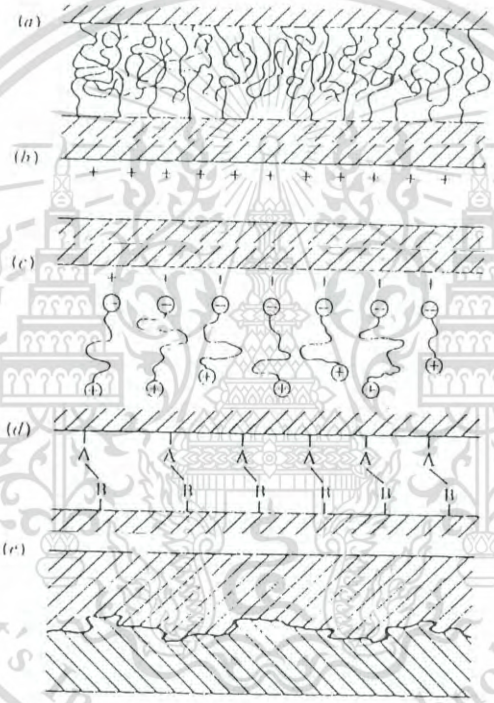


Figure 2.2 (a) Bond formed by molecular entanglement following interdiffusion. (b) Bond formed by electrostatic attraction. (c) Cationic groups at end of molecules attracted to an anionic surface. (d) Chemical bond. (e) Mechanical bond

The fiber - matrix interfacial adhesion plays a crucial role in determining the mechanical properties of a polymer composite. A better interfacial bond will import to a composite better properties, such as, interlaminar shear strength, delamination resistance, fatigue and corrosion resistance. In addition the surfaces are usually contaminated. Even if the contamination is removed, and strong adhesion occurs at the contact points, the adhesion averaged over the whole surface will be weak.

2.3 Polymer matrices

Polymers are popular as the matrices for composites because they can be easily fabricated, low density, and offered good mechanical and dielectric. Matrices are the materials that give body and grip or hold the reinforcements of composite together, and is usually of lower strength than the reinforcement. The roles of the matrix in a fiber - reinforced composite are (1) to transfer stresses between the fibers, (2) to provide a barrier against an adverse environment damage before, during, and after composite processing, and (3) to protect the surface of the fibers from mechanical abrasion. The matrix plays a minor role in the tensile load - carrying capacity of a composite structure.

Matrices can be divided into two groups ;

1. Thermosets, such as, epoxy, polyester, polyimide, etc.
2. Thermoplastics, such as, polycarbonate (PC), polyethylene (PE), etc.

2.3.1 Thermoplastic polymers

Thermoplastic matrices are normally used with short fiber reinforcement for applications in products made by injection molding. The feed - stock is usually in the form of pellets which contain the short fibers, typically 1 to 3 millimeters long. Thermoplastics readily flow under stress at elevated temperatures, so allowing them to be fabricated into the required component, and become solid and retain their shapes when cooled to room temperature. These polymers may be repeatedly heated, fabricated and cooled consequently scrap may be recycled, though there is evidence that this slightly degrades the properties probably because of a reduction in molecular weight.

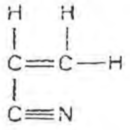
Advantages of thermoplastic polymers include :

1. Unlimited storage (shelf) life at room temperature
2. Shorter fabrication time
3. Postformability (e.g., by thermoforming)
4. Ease of repair by welding, solvent bonding, etc.
5. Ease of handling (no tackiness)
6. Can be recycled (recyclability)

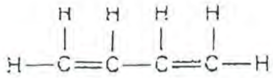
2.3.2 Acrylonitrile - butadiene - styrene (ABS)

ABS is a versatile family of thermoplastics produced by using acrylonitrile (A), butadiene (B), and styrene (S).

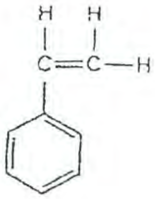
Molecular structures of ABS and its monomers usually have the following structure :



Acrylonitrile



Butadiene



Styrene

Acrylonitrile - butadiene - styrene (ABS)

The ratio of the comonomers as well as the microstructures of ABS can be controlled to produce a family of copolymers with a broad range of properties. ABS copolymers offer a unique combination of toughness, rigidity, chemical resistance, and quality surface appearance, along with the ability to process well into complex parts via almost any thermoplastic processing technology.

2.3.2.1 Preparation of ABS [11]

ABS can be produced by emulsion , suspension , or bulk copolymerization of styrene - acrylonitrile in the presence of a rubber. The rubber is either poly (1,3 - butadiene) or SBR (styrene butadiene rubber). NBR (also referred to as nitrile rubber), a copolymer of 1,3 - butadiene and acrylonitrile, is also used. The product of the reaction is a physical mixture of styrene - acrylonitrile copolymer and the graft copolymer of styrene - acrylonitrile onto the rubber. Additionally, SAN is often blended into the mixtures. The final product, ABS, consists of the glassy polymer (SAN) dispersed in the rubbery matrix (grafted rubber).

The two processes for the manufacture of ABS are the following [12] :

1. Graft polymerization of styrene and acrylonitrile on polybutadiene latex, blending with a separately manufactured SAN latex. The resulting blend is coagulated and dried.

2. Separate manufacture, isolation, and drying of the graft polymer and the SAN and blending of the two components at the compounding stage.

Most commercially important ABS products consist of blends of a grafted terpolymers, acrylonitrile - butadiene - styrene, dispersed in a glassy matrix of styrene - acrylonitrile (SAN) copolymer. The preparation of ABS refers to the polymerization of two individual components, the graft terpolymer and SAN. The graft terpolymer consists of a polybutadiene (PBD) rubber core and grafted SAN shell.

2.3.2.2 Properties of ABS

ABS materials are characterized as tough, opaque, high impact strength, excellent surface properties, good chemical resistance, and easily fabricated materials. The amorphous material may be compounded to meet specific properties by changing the component ratio. Each monomer is an important component of ABS. Styrene contributes to processability, rigidity, and strength, while acrylonitrile provides to surface hardness and chemical resistance. The butadiene rubber contributes toughness, but at the expense of rigidity. Increasing the rubber content increases impact strength but lowers tensile strength and surface gloss.

2.3.2.3 Examples for the use of ABS

ABS is found in an extensive range of applications because of its excellent balance of mechanical properties, surface appearance, desirable flow, processing latitude, recyclability, and economics. ABS is used in particular for the production of tough industrial components having good surface gloss, e.g., [11] , [12]

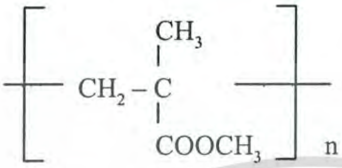
1. Precision engineering and electrical engineering, e.g., spools, housings for radio and television sets, tape recorders, photographic, and film equipment.
2. Household equipment, such as, housings for electrical household appliances, containers in refrigerators, refrigerator door linings, disposable dishes, toilet articles, and drawers.
3. Other fields of use, such as, toys, all types of packaging, and furniture components.

ABS can also be put to a number of other interesting industrial uses where usually the properties of impact - resistant polystyrene are inadequate.

2.3.3 Polymethyl methacrylate (PMMA)

PMMA is an important commercial thermoplastic material. PMMA is polymerized by solution, suspension, and emulsion processes via free radical polymerization of methyl methacrylate using the usual peroxide or azo initiators, or by thermal or photochemical initiation. PMMA is completely amorphous but has high strength and excellent dimensional stability due to the rigid polymer chains (Tg = 105 °C) [11]. PMMA is clear, colorless transparent plastic with a high soften point, impact resistance, and very good weatherability, good resistance to many chemicals, but attacked by organic solvents. It is available in molding and extrusion compositions, syrups, and cast sheets, rods, and tubes.

Molecular structures of PMMA can be shown as :



$$\left[-CH_2-\overset{\displaystyle CH_3}{\underset{\displaystyle COOCH_3}{C}}- \right]_n$$

PMMA can be modified by copolymerization of methyl methacrylate with other monomer, such as, acrylate, styrene, butadiene, and acrylonitrile. MMA is by far the most important methacrylate ester monomer, accounting for 90 % of the volume of methacrylic ester monomers [16]. In this work, acrylic esters (e.g., methyl methacrylate) was used for grafting on bamboo fibers. The structure and molecule formula, physical properties and rate and heat of polymerization of MMA can be shown in Table 2.3 [13].

Table 2.3 Structure and molecule formula, rate and heat of polymerization, and physical properties of MMA

Structure and molecular formula of MMA monomer	
Formula	$C_5H_8O_2$
Structure	$CH_2=C(CH_3)\ COOCH_3$
Physical properties of MMA monomer	
Boiling rang (°C)	100-101
n_D^{25}	1.4119
Flash point (°F)	55^a
Solubility at 25 °C	
- in water, parts / 100	0.015
- parts / 100 monomers	-
Density (g / cm^3)	0.939
Heat of vaporization (cal / g)	86
Specific heat (cal / g °C)	0.45

Table 2.3 (continued)

Heat of polymerization, Hp (kcal / mole) When, a = Tagliabue open cup	12.9
Rate and heat of polymerization	
Δ H (K.cal / mole)	13.8
Ka - 44.1 (°C)	27[a]
- 60 (°C)	123[a]
Kp/Kt$^{-1/2}$- 44.1 (°C)	0.105[a]
- 60 (°C)	1.1619[a]
When, a = Measured in the bulk	

2.3.3.1 Examples for the use of PMMA

Major uses of PMMA are safety glazing fixtures, windows, skylight and PMMA molding compound in the automotive industry for taillights. Applications include electrical components, lens, etc. Physical properties of thermoplastics at tests according to ASTM shown in Table 2.4 [14].

Table 2.4 Physical properties of thermoplastics at the tests according to ASTM

	ASTM Test	HDPE	PP	ABS	PMMA	PC	PBT
Young's modulus (GPa)	D790	0.8	1.5	2.1	3.2	2.3	2.2
Yield / fracture stress (MPa)	D638	28	33	41	72	65	50
Elongation at break (%)	D638	300	50	20	4	100	300
Notched Izod impact strength (J/m)	D256	> 1300	150	350	40	700	55
Heat distortion temperature (°C)	D648	< 23	< 23	110	95	140	55
Limiting oxygen index	D2863	18	18	19	17	25	20
Coefficient of linear expansion ($10^{-6}K^{-1}$)	D696	90	110	96	68	70	70
Specific gravity	D792	0.96	0.90	1.04	1.18	1.20	1.31

2.4 Natural fibers

Fibers are the principal constituent in fiber - reinforced composite materials. They occupy the largest volume fraction in a composite laminate and share the major portion of the load acting on a composite structure. Fiber is a fundamental form of solid (usually crystalline) characterized by relatively high tenacity and an extremely and high ratio of length to diameter. Proper selections of types, amount, and orientation of fibers are very important since they affect the following characteristics of the composites, i.e.,

1. Specific gravity
2. Tensile strength and modulus
3. Compressive strength and modulus
4. Fatigue strength and fatigue failure mechanisms
5. Electric and thermal conductivities
6. Cost

Fibers can be divided into three types, i.e., [15]

1. Synthetic fibers are made from high polymers (polyamides, polyesters, acrylics, and polyolefins) by extruding from spinneret, such as, nylon, polyethylene, etc.

2. Semisynthesis fibers include rayon and inorganic substances extruded in fibrous forms, such as, glass, boron carbide, boron nitride, carbon, graphite, aluminum silicate, fused silica, and some metals (steel).

3. Natural fibers can be divided into two types : (1) animal fibers consist of primary component of a protein, such as, wool and silk, (2) vegetable fibers consist of primary component of a cellulose, such as, ramie fibers, coconut fibers, cotton fibers, etc.

2.4.1 Advantages and disadvantages of natural fibers

Advantages and disadvantages of natural fibers can be concluded in Table 2.5.

Table 2.5 Advantages and disadvantages of natural fibers

Advantages	Disadvantages
1. Low density	1. High water absorption
2. Low production cost	2. Low fiber - polymer interfacial adhesion
3. High strength - to - weight ratio	
4. Abundant availability	

2.4.2 Examples of natural fibers into composites

Natural fibers used in composites, include akawara, bamboo, coconut, flax, jute, sisal, bagasse, wood, and others. Mechanical properties of some of these fibers are presented in Table 2.6. The following sections provide a brief description of these fibers.

Table 2.6 Properties of naturally occurring fiber [16]

Fiber type	Coconut	Sisal	Sugarcane bagasse	Bamboo	Jute	Flax	Elephant grass	Musamba	Wood fiber (kraft pulp)
Fiber length (mm)	50-350	NA*	NA	NA	180-300	500	NA	NA	2.5-5
Fiber diameter (mm)	0.1-0.4	NA	0.2-0.4	0.05-0.4	0.1-0.2	NA	NA	NA	0.015-0.08
Specific gravity	1.12-1.15	NA	1.2-1.3	1.5	1.02-1.04	NA	NA	NA	1.5
Modulus of elasticity (GPa)	19-26	13-26	15-19	33-40	26-32	100	4.9	0.9	NA
Ultimate tensile Strength (MPa)	120-200	280-568	170-290	350-500	250-350	1000	178	83	700
Elongation at break (%)	10-25	3-5	NA	NA	1.5-1.9	1.8-2.2	3.6	9.7	NA
Water absorption (%)	130-180	60-70	70-75	40-45	NA	NA	NA	NA	50-75

*Properties are not readily available or not applicable.

1 mm = 0.04 in

1 MPa = 0.145 ksi

2.4.2.1 Bamboo fibers [16]

Bamboo, which is a member of the grass family, grows in tropical and subtropical regions. Their hollow stalks have intermediate joints. The diameters of these stalks range from 0.4 to 4.0 inches (1 to 10 centimeters). Special techniques are needed to extract the fiber from bamboo. Bamboo fibers are strong in tension, but have a relatively low modulus of elasticity as seen in Table 2.6.

2.4.2.2 Coconut fibers

A mature coconut has an outer fibrous husk. Coconut fibers, called "coir", can be extracted simply by soaking the husk in water or, alternatively, by using mechanical processes. These short stiff fibers have been used for making rope for centuries. Coir has a low elastic modulus and is also sensitive to moisture changes.

2.4.2.3 Flax and vegetable fibers

Flax fibers are strong under tension and also possess a high modulus of elasticity (Table 2.6). Elephant grass fibers are extracted from elephant grass stems, which grow up to 10 feet (3 meters) tall and are packed with tough, sharp fibers bonded together by lignin.

2.4.2.4 Sisal fibers

A number of researchers have studied the properties of composites made with sisal fibers. These fibers, extracted from the leaves of Agava sisalana, are primarily made of hemicellulose, lignin, and pectin.

2.4.2.5 Wood fibers

The advantages of wood fibers are their availability, high tensile strength, high modulus of elasticity, and the well - developed technology to extract the fibers.

2.4.2.6 Jute fibers

Jute, grown solely for its fiber content, is cultivated mainly in Bangladesh, China, India, and Thailand. Jute plants can grow to a height of 8 feet (2.4 meters) with stalk diameters normally less than 1 inches (2.5 millimeters). They are relatively strong in tension as shown in Table 2.6. Traditionally the fibers have been used for making ropes and for weaving into gunny cloth used for making ropes and bags for transporting grains.

2.5 Bamboo

Bamboo is particularly attractive as a commercial crop because of its rapid growth. It can be used in three to six years after planting, at which time it reaches its maximum strength. Its advantages are low cost, abundant, ease of transport, its shape, high resistance to tension, compression, and flexsion.

The bamboos together with several groups of herbaceous grasses are classified by botanists as a subfamily *(Bambusoideae)* of the grass family *(Graminene)*. Bamboo generally grows well inplaces with temperature ranging from 8.8 to 36 ^{O}C. It grows best on well - drained sandy - loam to clay - loam soil.

2.5.1 Status of development in the utilization of bamboos [17] , [18]

Bamboo can be used for a variety of purposes. Some of which are mentioned belows :

1. Constructional, such as, scaffolding, bridges, support members, fencing, etc.

2. Cottage and rural industries, e.g., house hold goods including bed frames, brooms, blinds, umbrella handles, brushes, chopsticks, ladles, walking sticks, tooth picks, wickerwork, agricultural implements, furniture and other fancy artifices.

3. Others, including Polo mallets, afforestation and soil conservation as a source of indigenous medicine and bamboo shoot for food.

2.5.2 Culm structure of bamboo

Culm structure of bamboo can be divided into three groups, i.e., peripheral tissues, fibrovascular bundles, and ground tissue.

1. Peripheral tissues consist of sclerified parenchyma, chlorenchyme, and epidermis.

2. Fibrovascular bundles consist of both phloem and xylem with patches on sheaths of fibers on the outsides. A large number of vascular bundles scattered irregularly among the ground tissue.

3. Ground tissue composes mainly of continuous parenchymatous cells through out the entire thickness of the culm.

The total culm consists of about 50 % parenchyma, 40 % fibers, and 10 % conducting cell (vessels and sieve tubes). Figure 2.3 shows culm structure of bamboo and Figure 2.4 shows vascular bundle with large metaxylem vessels and phloem surrounded by fibers.

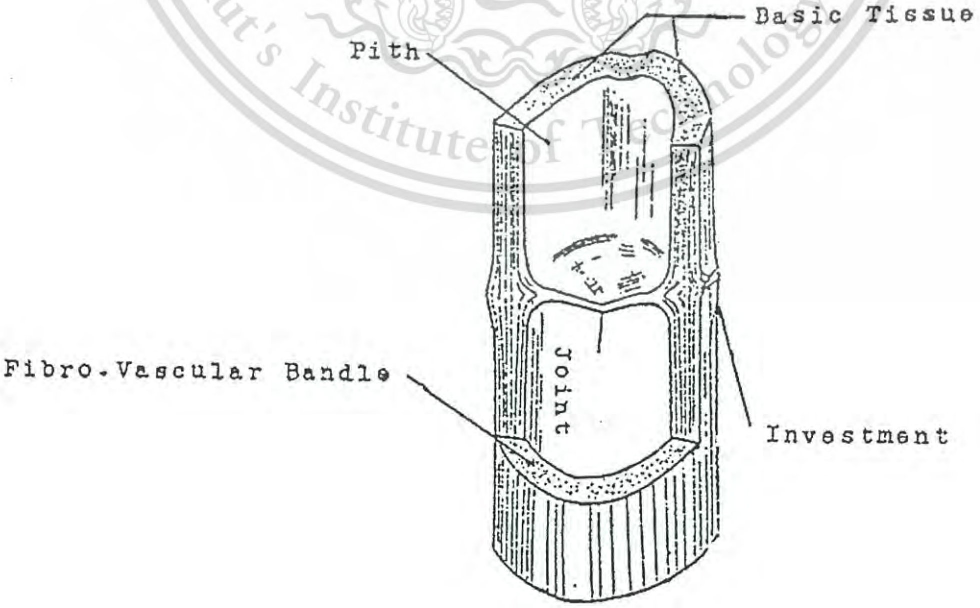


Figure 2.3 Culm structure of bamboo

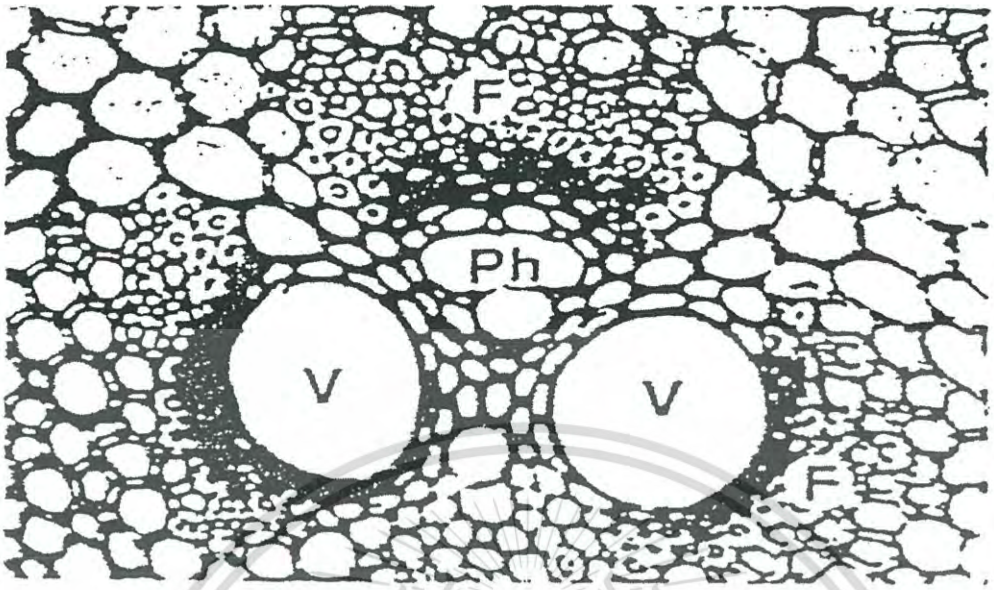


Figure 2.4 Vascular bundle with two large metaxylem vessels (V) and phloem (Ph) surrounded by fibers (F)

2.5.3 Anatomical properties of bamboo

2.5.3.1 Bamboo fibers

Bamboo is a natural ligno - cellulose composite which the cellulose fibers are embedded in a lignin matrix. Table 2.7 shows fiber morphology of *B.blumeana.*

Table 2.7 Fiber morphology of the *B.blumeana* [19]

Portion	Fiber			
	Length (mm)	Diameter (μm)	Cell wall Thickness (μm)	Lumen diameter (μm)
Basal	2.3	23.5	6.5	10.0
Middle	2.4	19.1	5.5	9.1
Top	2.1	24.1	8.5	7.2

The fibers constitute the sclerenchymatous tissue and occur in the internodes as caps of vascular bundles and in some species additionally as isolated strands. They contribute to 40 to 50 % of the total culm tissue and 60 to 70 % by weight [20]. The fibers are long and tapered at their ends. Natural fibers, except silk, have three distinct parts - an outer skin (or cuticle) an inner area and a central core that may be hollow. All of the celluloses, most of the hemicellulose, and about one half of the lignin, are found in the cell walls.

2.5.3.2 Physical properties of bamboo

Physical properties of bamboo can be shown in Tables 2.8 and 2.9, respectively.

Table 2.8 Physical properties of bamboo [21]

Bamboo	Density (10^3 kgm^{-3})	Tensile Strength (CoV)^a (MNm^{-2})	Elongation (mm)	Flexural Strength (CoV)^a (MNm^{-2})	Deflection (mm)	Impact strength (CoV)^a (kJm^{-2})
Across the fibers	0.802	8.6 (±1.02)	0.10	9.04 (±0.3)	Fiber split	3.02 (±1.08)
Along the fibers	0.802	200.5 (±7.08)	10.2	230.09 (±9.06)	6.3	63.54 (±4.63)

^{a}Coefficient of variance

Table 2.9 Specific gravity of the *B. blumeana* [19]

Vertical portion			
Basal	Middle	Top	Average
0.51	0.60	0.62	0.58

2.5.3.3 The chemical composition of bamboo

The basic chemical constituents of bamboo are cellulose, hemicellulose, and lignin. In the bamboo, cellulose and hemicellulose are present in the form of holocellulose which amounts to more than 50 % of the total chemical constituents. Most of the cellulose is present in the fiber. The second most abundant chemical constituent of the bamboo is lignin. It functions as a binder or a matrix for the cellulose fibers. Minor constituents, such as, extractives consist of resins, tannins, waxes, pectin, oil, protein, etc. [22]. The composition varies according to species, condition of growth, age of the bamboo and part of the culm. Table 2.10 shows proximate chemical analysis (%) of the *B. blumeana*.

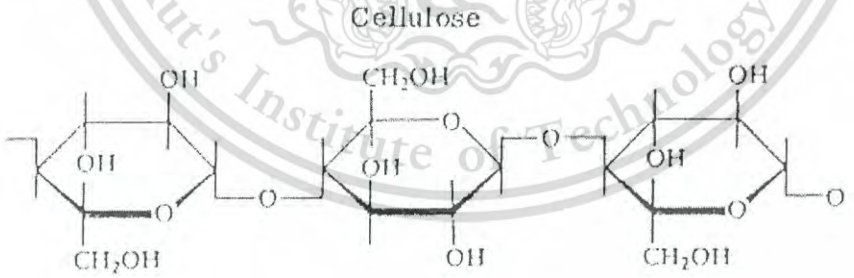
Table 2.10 Proximate chemical analysis (%) of the *B. blumeana* [19]

	Ash	Holocellulose	Alcohol-benzene Solubles	1%NaOH Solubles	Lignin	Hot water solubles	Cold water solubles
% Average	3.4	70.8	3.9	24.2	24.3	7.7	5.5

This works used *Bambusa blumeana* Schult as the sample (Figure 2.5). Local name is "Pai See Sook". It is native to Java, Sumatra and Borneo and is now found in Thailand scattered in field margins and homesteads. It is a medium to large bamboo, with the largest stem diameter 8 to 12 centimeters. The stem is yellow or brown, hard and smooth. It grows in dense clumps, especially at the base. Each stem branches heavily from the base up. It is used widely in construction, agricultural implements, ploughs, handles for implements, levelling of ploughed areas, tool handles, bridges, basketry, planting as a windbreak, fence, and animal shade. The shoot is also edible.

2.6 Cellulose

Cellulose is a polysaccharide made up of β - D (+) - glucose residues joined linear chains. It's the chemical structure can be show as :



With its three hydroxyl groups, cellulose has the opportunity of forming a number of hydrogen bonds. The resulting high intermolecular forces and the regular structure of the polymer yield an unusually high degree of crystallinity. The crystalline melting point of cellulose is far above its decomposition temperature. Figure 2.5 shows relationships of ultrastructural components of cellulose in wood. The linear nature conferred upon cellulose as a consequence of the β - (1→4) - glycosidic linkages results in a rigid, rod - like molecule. Each chain of cellulose may be as long as 8,000 to 12,000 glucose monomers, or up to 4 micrometers long. They are arranged linearly, with no side branching. Cellulose chains are aggregated into bundles of appoximately 40 chains each called the cellulose micelles which are held together by hydrogen bonds. The micelles themselves are embedded in the matrix of other polysaccharides known as the hemicellulose. Micelles, in bundles of variable numbers, are bound together into the cellulose microfibril. These, in turn, are bound together into macrofibrils.

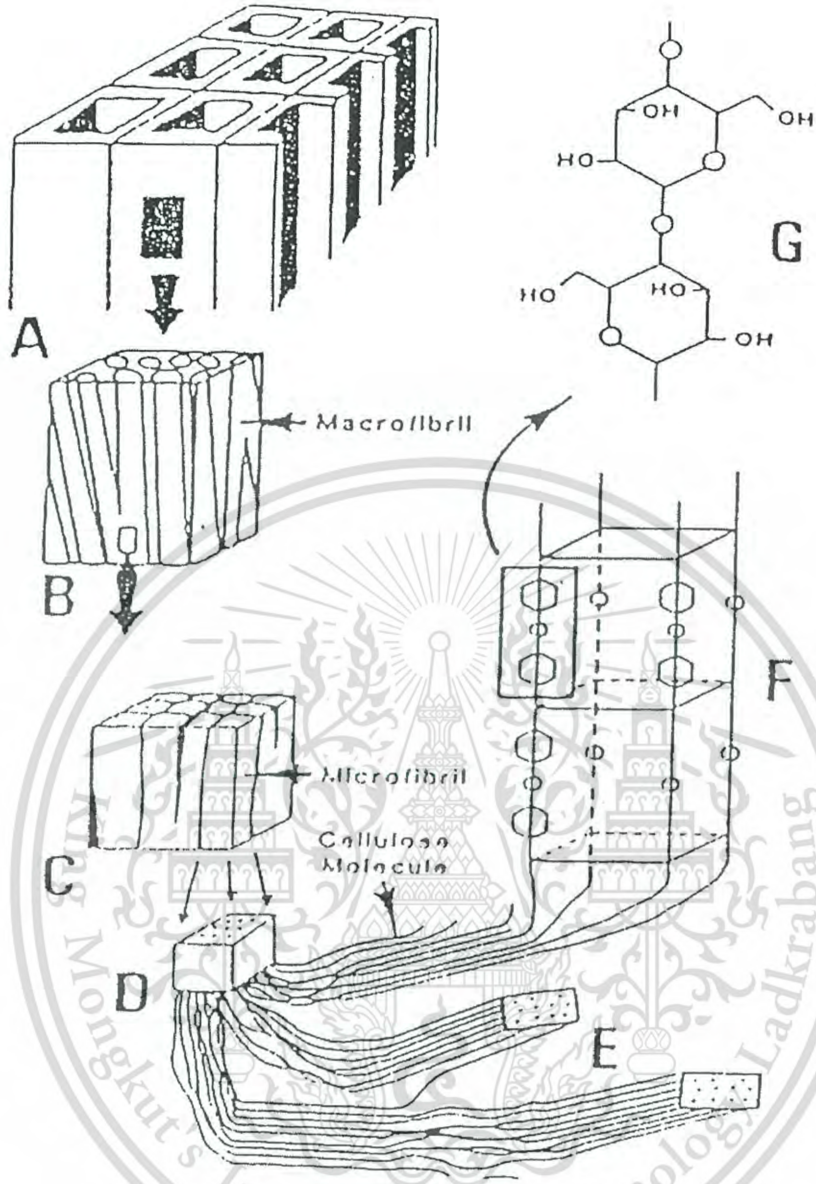


Figure 2.5 Schematic relationships of ultrastructural components of cellulose in wood a) Gross wood structure, b) Macrofibrils, c) Portion of macrofibril showing aggregates of microfibrils, d) A single microfibril, e) Cellulose crystallite, f) Unit cell of crystallite, and g) Cellobiose repeat (after Esau by Parham, 1983) [24]

2.6.1 Cellulose solvents

In nature, cellulose is generally admixed with other substances, including lignin, hemicellulose, pectins, fats, waxes, and protein. The solubility of the cellulose is very low as it is insoluble in water and in most organic solvents. Cellulose swells, howevere, in hydrogen bonding solvents. The swelling is, of course, restricted to the amorphous regions of the structure. Pure cellulose is obtained by removing all incrustations of lignin and other organic and inorganic matter by treatment with alkali, acid, sodium sulphite, etc. [24]. Several known systems dissolve cellulose. These systems range from solutions in protomic acids (e.g., 78 % phosphoric acid) to metallic complexes (e.g., cuprammonium).

2.6.2 Hemicellulose

Hemicelluloses are carbohydrates related to cellulose, but mixed with polysaccharides containing other sugars beside glucose, such as, hexoses (mannose, galactos, and glucose) and pentoses (xylose and arabinose) [25]. They are found in cell wall of plants which are extractable by dilute alkaline or hot dilute mineral acids by forming simple sugars. More than 90 % of the bamboo hemicelluloses consists of a xylan which seems to be a 1,4 - linked linear polymer forming a 4 - 0 - methyl - D - glucuronic acid, L - arabinose, and D - xylose in a molar ratio of 10 : 1.3 : 2.5, respectively. Formula of hemicellulose is $(C_6H_{10}0_5)_{2n}$.

2.6.3 Lignin

Lignin is a complex organic material found in the woody tissues of plants, often combined with hemicellulose materials to help bind the cells together and cellulose [26]. Lignin acts as a glue to hold the cellulose fibers in place with in the cell wall [27]. Lignin are usually insoluble in all solvents, unless they are degraded by physical or chemical treatment. Formula of lignin can be shown in Figure 2.6. It is noted that actual structure is three - dimensional.

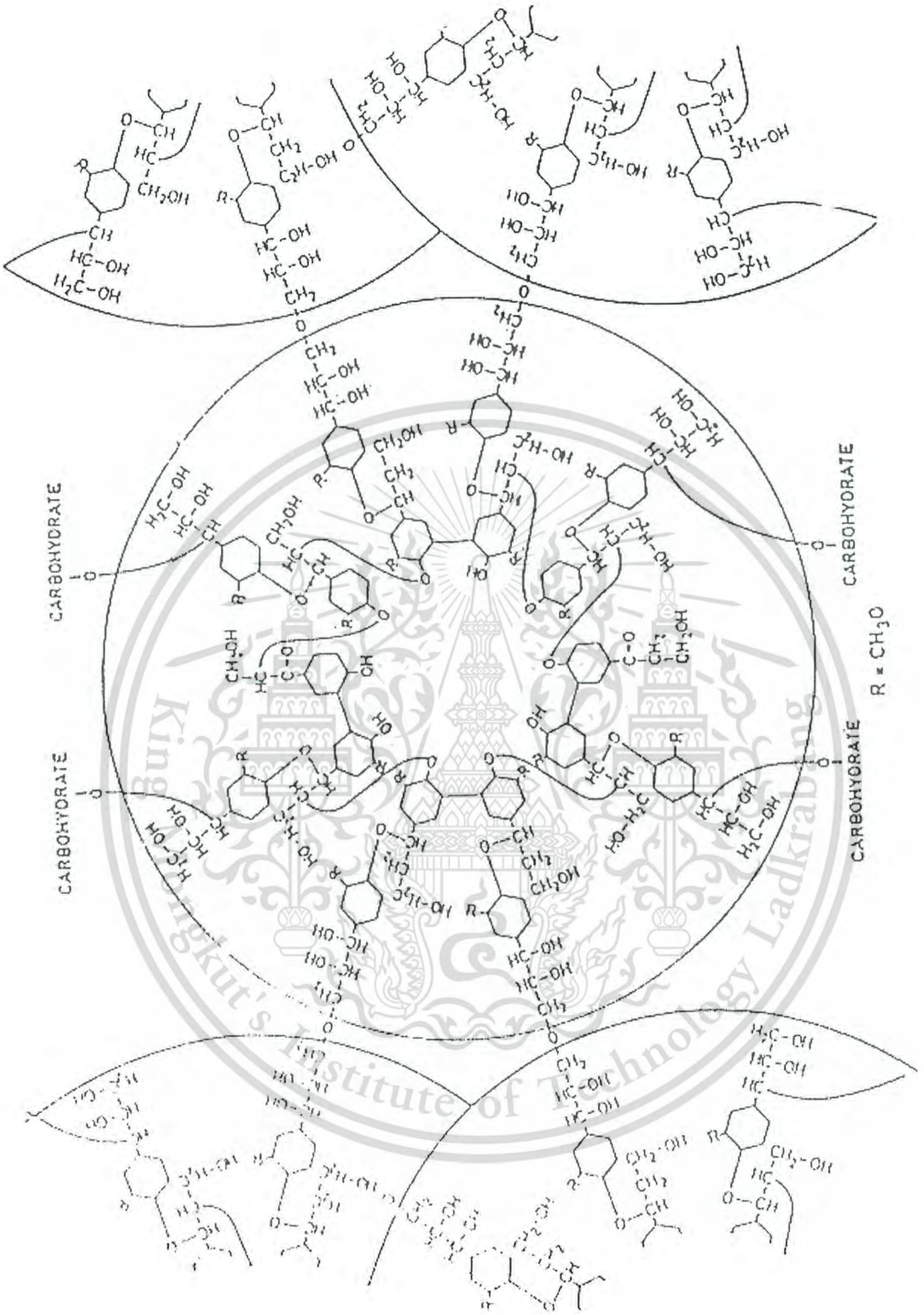


Figure 2.6 Formulation for the repeating unit of lignin [23]

2.6.4 Extractives

Extractives can be divided into two groups ; i.e. , soluble in neutral solvents and partly or wholly insoluble in neutral solvents. Figure 2.7 shows components of natural fibrous materials.

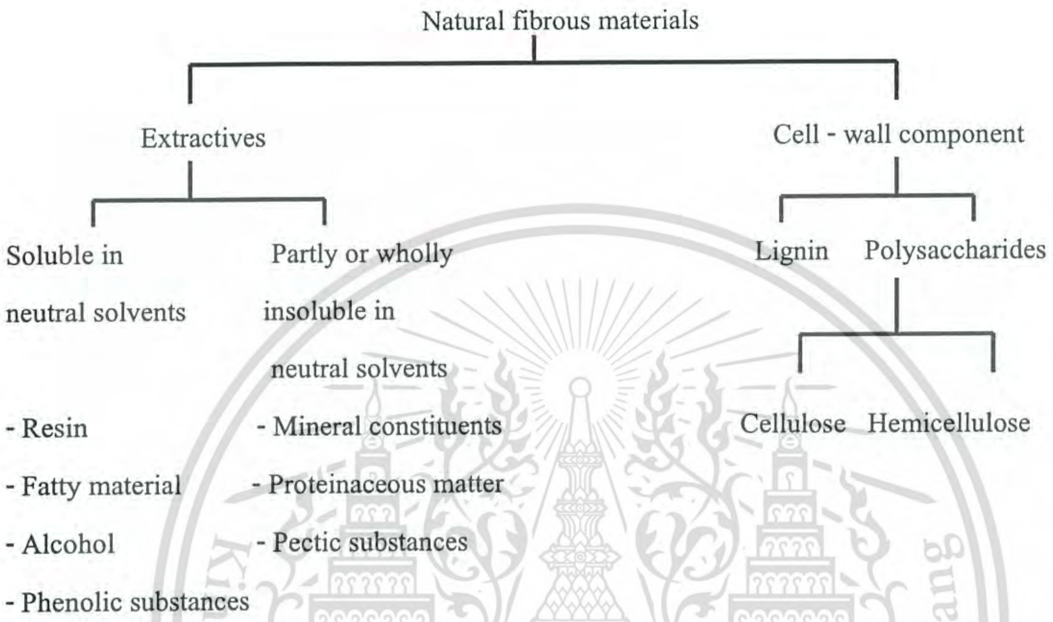


Figure 2.7 Components of natural fibrous materials

Cellulose content of natural fibers from natural sources shown in Table 2.11.

Table 2.11 Cellulose content of natural sources [28]

Plant source	Cellulose content (%)
Algae (green)	20-40
Bacteria	20-30
Bagasse	35-45
Bamboo	40-45
Bark	20-30
Cotton	90-99
Flax	70-75
Hemp	75-80
Jute	60-65
Kapok	70-75

Table 2.11 (Continued)

Plant source	Cellulose content (%)
Ramie	70-90
Straw	40-50
Wood	40-50
Coir [21]	43
Banana [21]	65
Sisal [21]	70
Mosses	25-30

2.7 Graft copolymerization

A graft copolymer contains a long sequence of one monomer (often referred as the backbone polymer) with one or more branches (grafts) of long sequences of second monomer. Graft copolymerization is a well - known method for modification of chemical and physical properties of polymeric materials. Graft copolymerization can be achieved by various methods, such as, exposure to ionizing radiation or ultraviolet light, and by using chemical initiators. Most graft copolymers are formed by radical polymerization. The major activation reaction is the chain transfer to polymers. In many instances the transfer reaction involves abstraction of hydrogen atoms. Vinyl graft copolymerization onto natural fibers is usually accomplished by the free radical initiation mechanism.

2.7.1 Radical graft polymerization

Most methods of synthesizing graft copolymers involve radical polymerization, although ionic graft polymerizations have received increasing attention [11].

2.7.1.1 Chain transfer and copolymerization

The radical polymerization of a monomer, in the presence of a dissolved polymer, by thermal decomposition of an initiation, results in a mixture of homopolymerization and graft polymerization.

2.7.1.2 Redox initiation

Redox initiation is often an efficient method for graft polymerization. Hydroxyl - containing polymers, such as, cellulose and poly (vinyl alcohol) undergo redox reaction with ceric ion or other oxidizing agents to form polymer radicals capable of initiating polymerization. Redox initiation usually results in grafting with a minimum of homopolymerization since only polymer radicals are formed. It is, however, limited to polymers containing the necessary function groups.

2.7.1.3 Ionizing radiation

Polymer radicals can also be produced by the irradiation of a polymer - monomer mixture with ionizing radiation.

Radiation processing may include ionizing and nonionizing system. Ionizing radiation causes (ionization) atoms and molecules to become highly reactive. The interactions of radiation with matters are more complex than those of light. Radiation processes have found acceptance along with chemical and thermal processing. The chemical effects of the different types of radiation are qualitatively the same, although there are quantitative differences. Nonionizing radiation may include induction, dielectric, microwave, ultraviolet, and infrared sources.

In these applications, two types of radiation sources can be used : either a radioisotope (e.g., cobalt (Co^{60})) giving gamma radiation or a particle accelerator (e.g., direct electron beam). Gamma radiation has advantages since no need for constant supervision ; also, no shutdowns, greater penetration, and currently suitable for high - capacity production where relatively long dwell times are allowable. Disadvantages are the high cost of installation and slow transmission of energy. The effects of radiation on polymers include (1) damage, (2) property improvements, and (3) polymerization and grafting. Molecular excitation may occur with the subsequent formation of radicals in the same manner as in photolysis, but ionization of a compound C by ejection of an electron

$$\mathrm{C} + \text{radiation} \longrightarrow \mathrm{c}^{+\cdot} + \overline{\mathrm{e}}$$

is more probable because of the higher energies of these radiations compared to visible or ultraviolet light energy. Ionizing radiations have particle or photon energies in the range of 10 keV to 10 meV (1 fJ to 16,000 fJ) compared to 1 to 6 eV for visible - ultraviolet photons.

2.7.2 Surface grafting [29]

Polymer surfaces have frequently been modified by graft polymerization to change their physical and chemical properties for such application as biomaterials, membranes, and adhesives. Various commonly used grafting methods are illustrated in Figure 2.8.

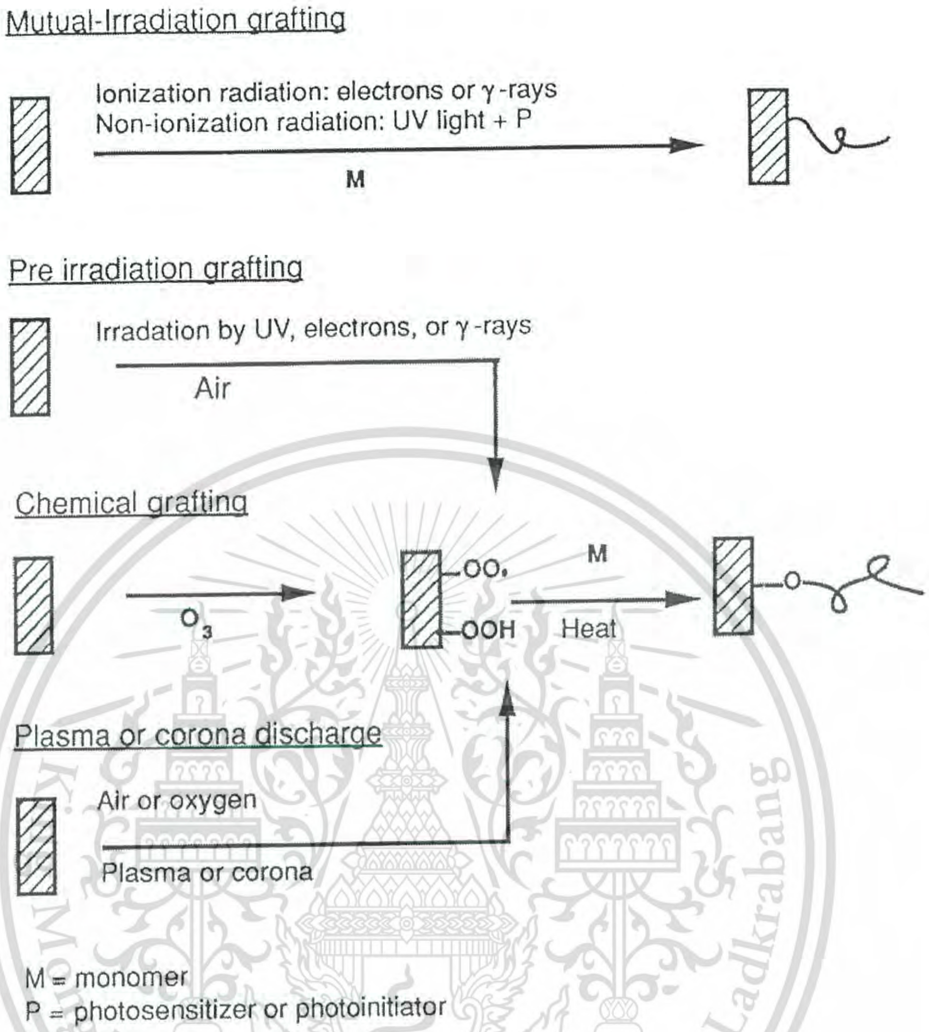


Figure 2.8 Various surface grafting methods

The key advantage of these techniques is that the surface of the same polymer can be modified to have very distinctive properties through the choice of different monomers. Grafting is most commonly performed by irradiating the polymer in the presence of a solvent containing a monomer. Mutual irradiation grafting (direct method), which involves only one step, is very efficient. Grafting can occur at the surface and in the bulk. The depth of grafting is mostly controlled by the interaction between the substrate polymer and the solvent. If penetration of the solvent is limited to a very small depth, surface grafting predominates (Figure 2.9). On the other hand, if the solution can diffuse uniformly into the polymer film, the homogeneous grafting occurs (Figure 2.9).

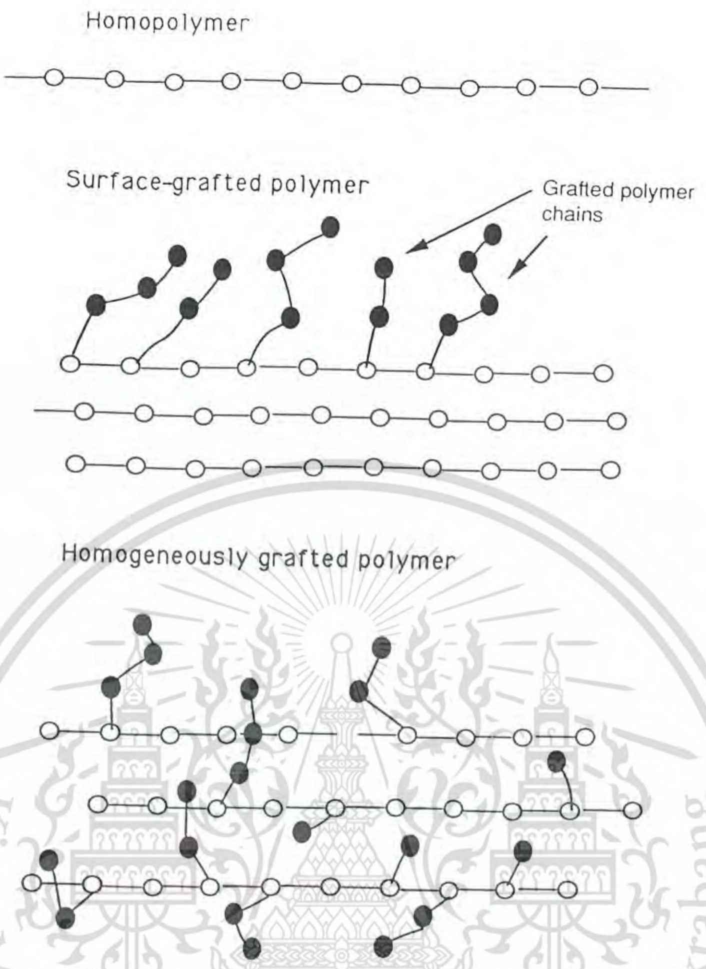


Figure 2.9 Schematic diagram showing surface and homogeneously grafted polymer

The mechanism of irradiation by ultraviolet and an initiator (BP) as the photoinitiator, is summarized as follows :

Initiation : $BP \xrightarrow{h\nu} {}^{1}BP^* \longrightarrow {}^{3}BP^*$ (BP is the benzophenone)

$PH + {}^{3}BP^* \longrightarrow {}^{3}BPH^* + P^{\circ}$ (PH is the polymer substrate)

$MH + {}^{3}BP^* \longrightarrow {}^{3}BPM^* + M^{\circ}$ (MH is the monomer)

$P^{\circ} + M \longrightarrow PM^{\circ}$

Propagation : $PM^{\circ} + nMH \longrightarrow P(MH)_nM^{\circ}$ (Grafting)

$M^{\circ} + nMH \longrightarrow (MH)_nM^{\circ}$ (Homopolymer formation)

Termination with a radical (R°) :

$P^{\circ}(MH)^{\circ}_n + R^{\circ} \longrightarrow P(MH)_nR$ (Graft copolymer)

$(MH)_n M^{\circ} + R^{\circ} \longrightarrow (MH)_n MR$ (Homopolymer)

A two - step method used to minimize formation of the homopolymer, such as, pre-irradiation grafting in air, corona discharge, ozone treatment, and plasma treatment have also been used to generate peroxide on polymer surfaces. Grafting is subsequently initiated thermally in contact with a monomer. Peroxides can be generated by UV, high - energy electron, and γ - ray irradiation of a polymer film.

Irradiation of polymers with ionization radiation in the presence of oxygen is known to produce hydroperoxides and diperoxides. The peroxidation mechanism is summarized as follows :

$$\text{PH (polymer)} \xrightarrow{\bar{e} \text{ or } \gamma\text{-ray}} P^{o} + H^{o}$$

$$\text{Propagation : } P^{o} + O_2 \longrightarrow P0^{o}_{2}$$

$$P0^{o}_{2} + PH \longrightarrow P0_2H + P^{o}$$

$$\text{Termination : } P0^{o}_{2} + P \longrightarrow P0^{o}_{2}P$$

$$P0^{o}_{2} + P0^{o}_{2} \longrightarrow P0_2P + 0_2$$

$$P0^{o}_{2} + H \longrightarrow P0_2H$$

$$P0^{o}_{2} + H0^{o}_{2} \longrightarrow P0_2H + 0_2$$

$$H0^{o}_{2} + P^{o} \longrightarrow P0_2H$$

These peroxides can initiate copolymerization. Diperoxides produce only graft copolymers, whereas hydroperoxides generate equal amounts of graft copolymers and homopolymers.

$$POOP \longrightarrow 2PO^{o} \xrightarrow{+\,nB} 2\,POB_n$$

Graft copolymer

$$POOP \longrightarrow PO^{o} + HO^{o} \xrightarrow{+\,nB} POB_n + HOB_n$$

Graft copolymer Homopolymer

The irradiation film is then put into a reactor containing a deaerated monomer solution which is kept at an elevated temperature. Decomposition of the peroxides at high temperatures initiates surface grafting. This technique has been applied successfully to produce surface grafting on various polymers, except poly (ethylene terephthalate), which produces only a very small amount of peroxides after UV irradiation.

The energy sources most commonly used in radiation grafting are high - energy electrons, γ - radiation, X - rays, ultraviolet (UV), and visible light. Electron - beam radiation, γ - radiation, and X - rays are usually classified as ionization radiation. The study of the chemical effects caused by ionization radiation is referred to as radiation chemistry. The study of the chemical effects produced by UV or visible light is known as photochemistry. The principal difference between radiation chemistry and photochemistry is that energy of the ionization radiation employed in radiation chemistry is usually much greater than that of the light source employed in photochemistry.

Photochemistry is a branch of chemistry concerned with the effect of absorption of radiant energy (light) in inducing or modifying chemical changes [26]. In photochemistry, the absorption of a photon causes excitation of the reacting molecules to a definite state usually known as excited electronic state.

2.7.3 Chemical effects in irradiating polymers

Irradiating polymers with ionization radiation can cause several chemical effects, such as, crosslinking, degradation, grafting and polymerization (in the presence of a monomer) as seen in Figure 2.10.

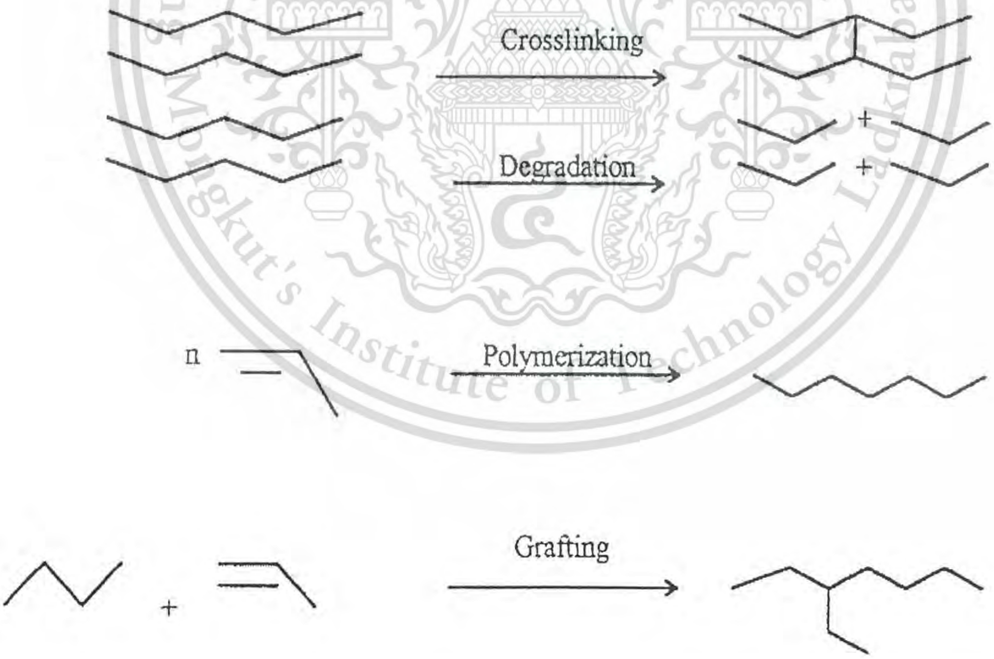
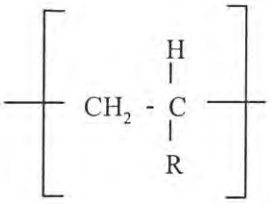


Figure 2.10 Chemical effect caused by radiation in polymers

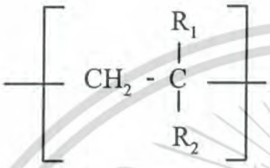
By irradiating, some polymers would be degraded and other would be crosslinked depending on their chemical structures. Crosslinking can be found to predominate in polymers that generally posses the following structure :



$$\left[CH_2 - \underset{R}{\overset{H}{C}} \right]$$

Polymers crosslinked when exposed to radiation, such as, polyethylene, polyester, polypropylene, natural rubber, and polyamides.

Polymers degraded by chain scission usually have the following structure :



$$\left[CH_2 - \underset{R_2}{\overset{R_1}{C}} \right]$$

Examples of such polymers are polyisobutylene, poly (methyl methacrylate), poly (vinylidene chloride), cellulose, and polytetrafluoroethylene.

Polymerization can be induced by ionization radiation. It is a versatile technique for producing polymer surfaces with specific properties through the choice of various monomers. Radiation - grafting is one of the most promising methods for polymer modification due to its penetration in the polymer matrix, resulting in rapid and uniform formation of active sites for initiating grafting throughout the matrix.

Grafting of a vinyl monomer onto a polymer can be achieved by simultaneous irradiation or by preirradiation of the polymer. When the ionization radiation is used for grafting, crosslinking or degradation can be occurred simultaneously. Crosslinking or degradation of the polymer substrates during irradiation can significantly affect the grafting yield and their properties.

2.8 Literature review

Polymer composites having both economic and environmental benefits have been considering for several applications, such as, automotive, furniture, building, and packaging industries. Most commercially important composites are based on synthetic fibers, including carbon fibers, boron fibers, abestos fibers, etc., and thermoplastics, such as, PP, PE, Nylon 6, etc.

Natural fibers based composites offer a number of benefits. Natural fibers have emerged as a renewable and cheaper substitute to synthetic fibers which have high cost, high energy requirement in their production, and increasing the density of the system. Ligno - cellulosic based natural fibers are relatively inexpensive and abundantly available. Natural fibers have been studied, such as, coir, banana, sisal, straw, jute, bagasse, *Typha angustifolia,* flax, and ramie. The disadvantages of the natural fibers include high water absorption and low fiber - polymer interfacial adhesion.

Graft copolymerization is a well - known technique for modification of the chemical and physical properties of polymeric materials. Most graft copolymers are formed by radical polymerization. Ultraviolet or ionizing radiation, or redox initiation, among other methods, can also be used to produce the polymer radicals leading to graft copolymers. Radiation - grafting is one of the most promising methods for modification of the chemical and physical properties of polymer materials. A number of papers have been published on radiation - grafting onto natural fibers and plastics.

Han Wilski [30] found that mineral acid and polyfunctional monomers in additive (1 % V/V) were shown to act synergistically in enhancing radiation grafting yields for a typical system involving the copolymerization of styrene in methanol to the polyolefins. B. Tome', et.al. [31] studied irradiated samples of different commercial plastics scintillating fibers in several atmospheres at dose rate of 1.4 and 5.8 Krad / hr up to 500 Krad total dose. The data analysis indicated that the loss in transmission immediately after irradiation was bigger in fiber irradiated in inert gas (argon and nitrogen) than in fibers irradiated in air and dry air. In a week after radiation all fibers had largely recovered and their light transmission depended on the type of fibers, but not on the atmosphere during irradiation nor on dose rate.

N. Sheikh and F.A. Taromi [32] studied radiation induced polymerization of vinyl monomers and their applications for preparation of wood - polymer composites (WPC). It was found that chemical bonding between polymers and the cell wall component leaded to better strength properties in composites. M.A. Khan and K.M. Idriss Ali [33] investigated WPC prepared with low density wood simultaneous under Co - 60 gamma radiation using acrylamide, butyl methacrylate, and styrene as bulk monomers of differents compositions with methanol as swelling agent. It was found that radiation yielded lower polymer loading with styrene than acrylamide and butyl methacrylate. The effects of radiation induced polymer impregnation on the moisture absorption of WPC were studied by Freddy Y.C. Boey and Lawench H.L. Chia [34]. It was believed that the impregnation of the polymer into the wood affected the moisture diffusion in the wood, so that its adverse effects on the mechanical properties were reduced.

The physicomechanical properties of ultraviolet - cured films reinforced with hessian cloths in the presence of urethane acrylate mixed with additives and coadditives were investigated by K.M. Idriss Ail, et.al. [35]. Though the plasticizers decreased the tensile properties of the UV - cured films, but they substantially enhanced both tensile strength by 80 % and elongation of the coated hassian cloths by more than 300 %. Uptake of water and moisture at different relative humidity conditions decreased significantly by the hessian cloths. Jute materials with urethane acrylate were applied to prepare different polymer films under UV radiation [36]. It was found that jute materials can be improved in normal used conditions (in soil and water), but not in mud in which it was completely degradable and decomposed like natural jute (untreated) samples.

The radiation induced grafting of some vinyl monomers, such as, styrene on cotton fabric for improved properties was studied by A.H. Zahran, et.al. [37]. It was found that the increase recovery showed a good improvement even at low grafting percentages. W.K. Walsh, et.al. [38] applied two approaches in grafting ethyl acrylate to cotton fabric to impart abrasion resistance. They found that surface grafting resulted in a four - fold improvement in abrasion resistance whereas the bulk grafting actually decreased the abrasion resistance by 50 %. S.R. Shikla, et.al. [39] carried out the photoinitiators - uranyl nitrate (UN), ceric ammonium nitrate (CAN), and benzoin ethyl ether (BEE) were used in the UV radiation - induced grafting of styrene onto cotton fibers. They found that UN gave somewhat higher graft add - on.

The effect of radiation pretreatment of agricultural cellulosic wastes was investigated through hydrolytic reactions of cellulose by A.M. Dela,et.al. [40]. They concluded that the radiation pretreatment accelerated the subsequent enzymatic hydrolysis of rice straw and rice hull by cellulase. The effect of additives on the enhancement of MMA grafting to cellulose in the presence of UV and ionizing radiation was studied by Visay Viengkhou, et.al. [41]. A range of additives were shown to accelerate rate of reaction in radical polymerization and grafting. Thermal initiators and photoinitiators, such as, azobisisobutyronitrile (AIBN), benzoin ethyl ether (BEE), and Irgacure 1700 (TFI) were reported to be useful additives for enhancing the grafting of MMA to cellulose in the presence of both UV and ionizing radiation. Results with these additives were compared with acid which previously found to accelerate grafting in the presence of ionizing radiation. The effect of nitrogen in grafting was significant as it leaded to high yields under certain conditions. The effect of γ - ray pre - irradiation of cellulose materials on glucose production on enzymatic hydrolysis by cellulase was investigated by S. Ardica, et.al.

[42]. It was found that the radiation - induced degradation of cellulose into low molecular weight polysaccharides was dependent on the nature and chemical composition of the cellulose materials and on the radiation environmental conditions. Rahayu Chosdu, et.al. [43] invertigated radiation and chemical pretreatment of cellulosic wastes and the effect of 2 % NaOH and irradiation. It was found that electron - beam radiation current gave acceleration on the enzymatic hydrolysis. Reduction of the required irradiation dose to hydrolyze cellulosic wastes was suggested to use in combination with chemical and temperatures.

Chemical modification of natural fibers by graft copolymerization has been extensively studied by a number of researchers. The graft copolymerization of acrylic acid onto caesarweed fibers by using ceric - toluene redox pair was reviewed by I.C. Eromosele [44]. The results of % grafting depended on ceric ion concentration, toluene concentration, acetic acid concentration, and temperature. I.C. Eromosele and T.J. Hamagadu studied [45] graft copolymerization of methyl methacrylate onto caesarweed fibers by the potassium permanganate - toluene redox system. The results of the percentage graft depended on the effects of varying concentrations of temperature, monomer, and permanganate.

Grafting of N - vinylpyrrolidone (NVP) onto cellulose was carried out in a dimethyl sulfoxide / paraformaldehyde (DMSO / PF) solvent system by Nishioka, et.al. [46]. They concluded that the solute permeability through the NVP - grafted cellulose membranes was superior to that through the cellulose membrane.

S.S. Tripathy, et.al. [47] reported a kinetic study of graft copolymerization of MMA onto jute fiber using $KMnO_4$ - malonic acid redox initiator system and $K_2S_2O_8$ - thiourea (TU) redox - initiating system [48]. They found that grafting improved the light fastness of jute fibers dyed with basic dyes. More than 200 % graft yield could be achieved in the investigation. Grafting of polyacrylonitrile on (dewaxed and bleached) jute fibers was carried out by Ghosh and K. Ganguly [49]. At 20 to 30 percent PAN - grafting was found to impart a most desirable balance of physical properties including fiber strength and modulus, moisture regain, whiteness index, and light - fastness rating. Morphology of the fibers using SEM indicated that PAN grafting occured on the surfaces and intercellular regions as well as within the lumens of the multicellular jute fibers.

R.A. Young [50] investigated a series of high lignin content pulps graft - copolymerized with acrylonitrile, styrene, and acrylamide by using xanthate method. He found that the degree of conversion of the monomers to polymers and percent grafted polymers were much lower for modification reactions with mechanical pulps (stone groundwood, thermomechanical) pulps. The amount of grafted polymers appeared to be correlated with the lignin content of the pulp. La'szlo' Zara, et.al. [51] found that the iron (II) / H_2O_2 redox system used to initiate the grafting of cellulose pulp with vinyl acetate monomer. The results on the parameters for most efficient grafting could be optimized, including temperature, reaction time, monomer concentration, and H_2O_2 concentration.

ESCA technique to monitor grafting polymerization onto wood fibers as a surface phenomenon was studied by D.P. Kamdem, et.al. [52]. ESCA analysis confirmed that the grafting polymer onto wood fibers modified the surface composition on the wood fibers. L. Kessira and A. Ricard [53] reported the study of thermal behavior of ungrafted and grafted bagasse loaded with $CaCO_3$ and wood pulps by DSC and TGA. It was found that the grafting of MMA onto the bagasse or the wood pulps improved their thermal stability. This was not the case for wood grafted with poly (AN). The $CaCO_3$ filler made the pulp of bagasse thermally more stable.

C. Eromosele [54] presented the results of graft copolymerization of acrylonitrile onto cotton cellulose by potassium permanganate - thioacetamide redox system. It was found that the percentage graft yield depended on concentrations of $KMnO_4$, acrylonitrile, thioacetamide, and temperature. A. Hebeish, et.al. [55] reviewed the treated fabric formed with pentavalent vanadium ion and an effective redox system capable of initiating grafting of MMA and other monomers onto the cotton fabric. They found that the used monomer and the graft yield followed the order : methyl methacrylate > methyl acrylate > methacrylic acid > ethyl methacrylate > acrylic acid. The characterization of cotton - polystyrene graft copolymers prepared by ceric ion initiating were reported N. Thejappa and S.N. Pandey [56]. Various techniques studied, including moisture sorption, solubility in cupriethylenediamine (CED), infrared spectra, DTA, electron micrographs and X - ray diffractograms. The results of the graft copolymers showed a slight fall in breaking load and improved resistance to wetting.

A few works have been reported on natural fiber - reinforced plastic composites. The physicomechanical properties wood and wood - plastic composite (WPC) were carried out by M.A. Khan and K.M. Idriss Ali [57]. They found that the strength properties increased with increasing polymer loading. They also investigated the swelling behavior of wood and WPC [58]. It was found that the uptake of water by WPC was less than that of wood and sought to describe some of the changes of mechanical properties [59] of wood and WPC which might be occurred with the variation of moisture content at different temperatures. WPC was made by impregnation MMA monomer into simul, a native timber of Bangladesh, under Co - 60 γ - radiation. Water - swelling behavior of both wood and its WPC was found to be lower compared to the untreated wood [60]. High tensile strength values were obtained with untreated WPC than with the corresponding timbers both before and after the water - swelling treatments. It was found that the tensile strength and Young 's modulus of treated WPC were increased about 1.6 and 1.5 times, as compared with the strength and modulus of untreated wood. WPCs [61] were prepared with kadom and mango wood of Bangladesh under Co - 60 gamma irradiation using MMA mixed with methanol at different proportion in presence of a number of additives, such as, *N* - vinyl pyrrolidone, tripropylene glycol diacrylate, trimethylol propane triacrylate, copper sulfate, sulfuric acid, and urea. Composites prepared with urea, NVP, and $CuSO_4$ possessed better tensile and protective properties. In another study of the effect of chemical corrosion on the tensile strengths of five types of Bangladeshi timbers (*Antrocephalus cadamba,Salmalia malabarica, Samanea Samane, Mangifera indica, and Polythia logifolia*) and their composites which were formed by the gamma - radiation, illuminated facts useful in selecting types of wood for preparing wood - plastic composites to be used for different purposes [62].

Compounding of polypropylene with Kraft pulp was carried out in a shear roller blender by R.G. Rat and B.V. Kokta [63]. The fibers were treated with stearic acid (by vapor phase or solution phase) to facilitate dispersion of the fibers in the polymer matrix. They found that Kraft pulp surface treated with stearic acid showed an improvement in the dispersion of fibers in the polypropylene matrix. The characterization of fiber surface showed that 3 % stearic acid was sufficient to achieve maximum reduction in the size and number of aggregates.

Mechanical properties of coir fibers were evaluated as functions of retting treatment by A.G. Kulkarni,et.al. [64]. The observed the strength and percentage elongation seemed to increase for both retted and unretted fibers but no significant differences in mechanical properties was observed between retted and unretted. Structural changes of cellulose, wood, and paper undershear deformation and high pressure (SDHP) at up to 6 GPa were observed by R. Teeaar, et.al. [65]. It was found that destruction of the wood lignin network required more severe treatment conditions than cellulose destruction did.

Jute fiber composites of epoxy and polyester with Polyesteramide polyol (PEAP) resins as interfacial agents were studied by R.N. Mukherjea, et.al. [66]. An increasing the hydroxyl value of PEAP resulted in a better bonding of composites up to a certain optimum limit and improved the water resistance capacities of composites. Water - uptake of jute fiber - reinforced polypropylene on their mechanical properties was investigated by A.C. Karmaker, et.at. [67]. The results on the thermal shrinkage of polypropylene melt caused gaps between fibers and polypropylene. The swelling was able to fill this gap and to increase the shear strength. P.J. Roe and M.P. Ansell [68] reported the mechanical properties of jute - reinforced polyester composites containing uniaxially oriented jute fibers containing up to 60 vol % fiber. The properties of jute and glass fibers were compared. It was concluded that the specific gravity and of jute fiber were superior to glass fiber and on a modulus per cost basic jute was superior. However, glass-reinforced plastics was more environmentally stable in most conditions than jute - reinforced plastic.

The properties of the fibers and composites of straw fibers incorporated in a polyester resin were carried out by N.M. White and M.P. Ansell [69]. The results showed that straw fibers improved the stiffness, strength and toughness of the resin alone, and reduced its density. Surfaces of cellulose fibers with polypropylene - maleic were studied by J.M. Felix and Paul Gatenholm [70]. SEM showed wetting of fibers, improved dispersion, and adhesion. The nature of adhesion was studied using FTIR. It was found that the surface modifying agent was covalently bonded to the fibers through esterification. The mechanical properties of cellulose fiber / PP composites, were improved.

P.S. Mukher Jee and K.G. Satyanarayana [71] investigated mechanical properties of sisal fibers, such as, initial modulus, ultimate tensile strength, average modulus and percent elongation as functions of fiber diameter, test length and speed of testing. D. Maldas and B.V. Kokta [72] reviewed the mechanical properties and dimensional stability of hardwood aspen in the form of sawdust and surface - treated glass - polyester composites under extreme conditions. It was found that the mechanical properties of the composites, in particular, treated sawdust / glass fiber - filled composites, increased under extreme conditions in comparison with those filled with nontreated sawdust / glass fiber. O.Y. Mansour [73] investigated fillers, such as, china clay, talc, and glass were compared regarding their effects on grafting reaction and composite properties. The effect of waxes and resins of the ligno - cellulose as well as the hemicellulose on the properties of the composite was investigated. The results showed that china clay is better than talc and removal of part of hemicellulose, waxes and resins of the ligno - cellulose had increased the effect on hardness.

Strength of bagasse fiber - reinforced composites was showed by E.C. McLaughlin [74]. It was found that the increasing board densities resulting from increased final platen pressure applied during production (or maximum molding pressure) provided the reason for observations of similar increase in the Young 's modulus. The effect of processing conditions and binding materials on the mechanical properties of bagasse fiber composites were worked by R.G. Raj and B.V. Kokta [75]. Polyethylene (high, medium, and linear low density) was used as the binding material to improve the mechanical properties and dimensional stability of the composites. Significant increases in tensile strength and modulus were observed for the composites of bagasse fiber pretreated with polyethylene as compared to untreated composite.

Bamboo fibers and bamboo orthogonal strip mats (bamboo mat) reinforced epoxy resin were studied by Jain, et.al. [21]. For the bamboo mat composites, the fiber volume fraction,V_f, achieved was as high as 65 % and the high strengths of bamboo was in the fiber direction. SEM studies of the fractured BFRP composite specimens revealed aperfect bonding between bamboo fibers and the epoxy. Furthermore, high strength, low density, low production cost, and ease of manufacturing made BFRP composite a commercially viable material for structural applications. X.J. Xian, et.al. [76] worked on comparative analysis of properties of plastic composites, which were reinforced with bamboo fibers, coconut husk (coir) fibers, and a marsh grass (*Phragmites sp.*). Choice of resins included epoxy, resorcinal formaldehyde (RF), and urea formaldehyde (UF). The results on terms of overall performance were ranked as follows : long bamboo fiber > short bamboo fiber > chipped bamboo fiber > coir fiber > *Phragmites* fiber. The performance of the three resin types were ranked as follows : epoxy > RF > UF.

CHAPTER III

EXPERIMENTAL DETAILS

3.1 Materials

The materials used in this study were :

3.1.1 Polymer matrix

Injection-grade acrylonitrile - butadiene - styrene (ABS) (Porene MH - 1) was obtained from TPI Co., Ltd. Some properties of ABS can be shown in Table 3.1.

Table 3.1 Some physical properties of ABS*

Properties	Test method	Test condition	Unit	Value
MFI	D 1238	220 °C , 10 kg	g / 10 min	18
Izod notched impact strength	D 256	¼″ at 23 °C	kg - cm / cm	26
Tensile strength	D 638	at 23 °C	kg / cm^2	530
Flexural strength	D 790	at 23 °C	kg / cm^2	700
Flexural modulus	D 790	at 23 °C	kg / cm^2 x 10^4	2.3
Rockwell hardness	D 785	¼″ at 23 °C	R - scale	116
Heat distortion temperature	D 648	¼″ at 18.6 kg - cm	°C	86
Heat distortion temperature	D 648	¼″ at 4.6 kg - cm^2	°C	94

*Data from the manufacturer

3.1.2 Reinforcing fibers

Bamboo fibers (*Bambusa blumeana* Schult) were chosen for evaluation. The average length of the fibers was 2 to 3 millimeters and moisture regain of 7 to 10 %.

3.1.2.1 Preparation of bamboo fibers [27]

1. Bamboos are cut into small chips by using chipper machine (Figure 3.1).
2. The chips form an oat - meal - like pulp as they were soaked with water.
3. The chips were cooked under steam pressure at about 180 ° C in the defibrator machine (Figure 3.2).
4. The steam was passed through chips for 3 minutes and spinning for 45 seconds.

5. The pulp was sent to the refiner machine (Figure 3.3) to beat and roughen up the fibers. A large quantity of water was added to the pulp to form a slurry and oven - dryed.

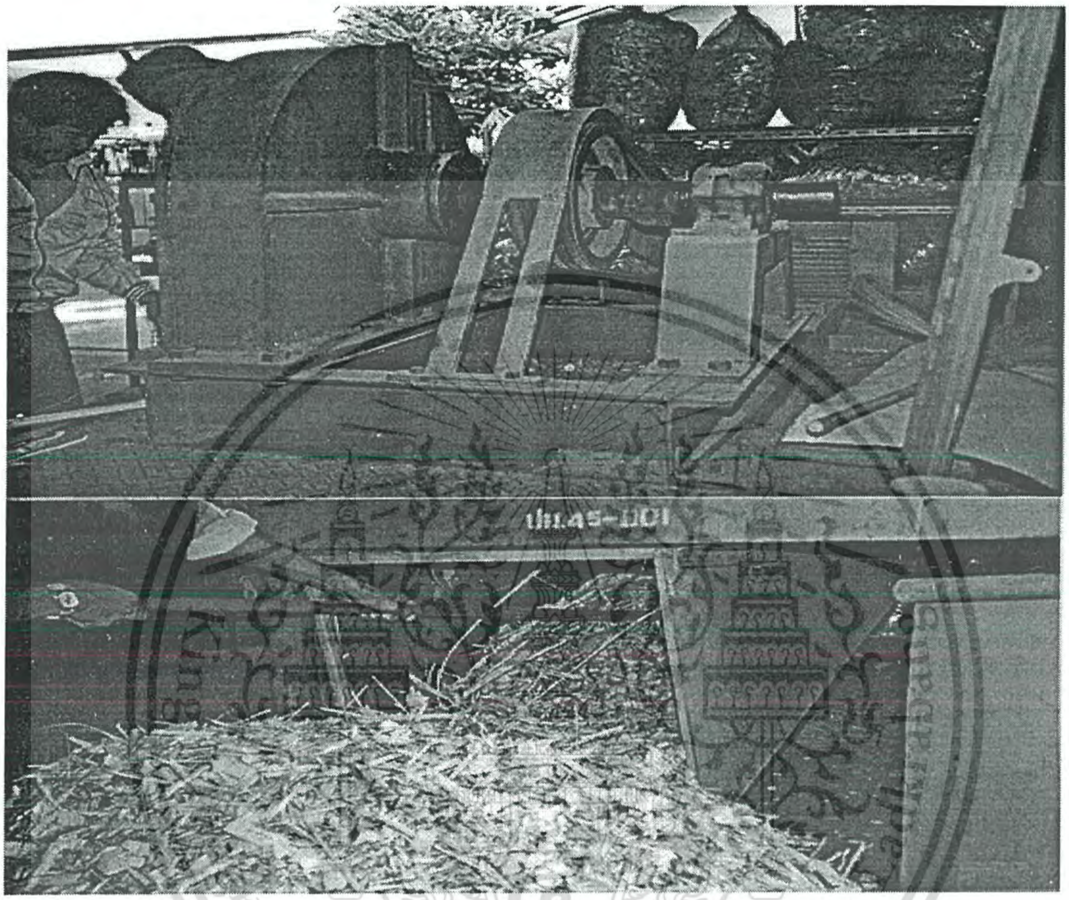


Figure 3.1 Chipper machine

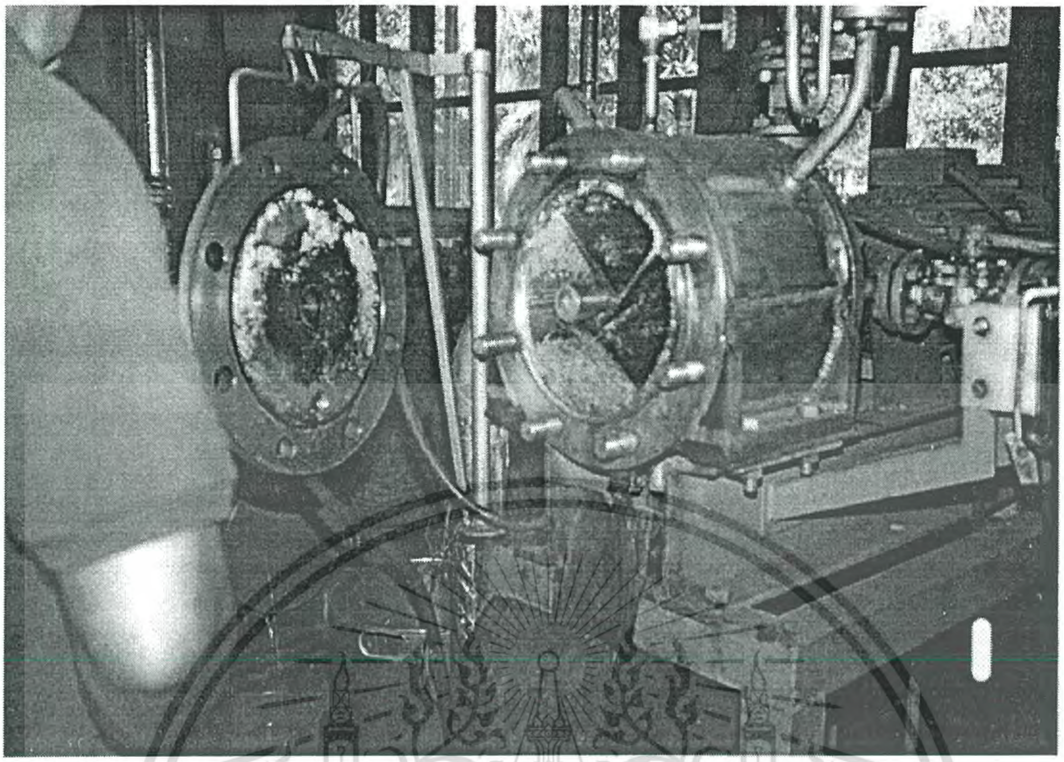


Figure 3.2 Defibrator machine

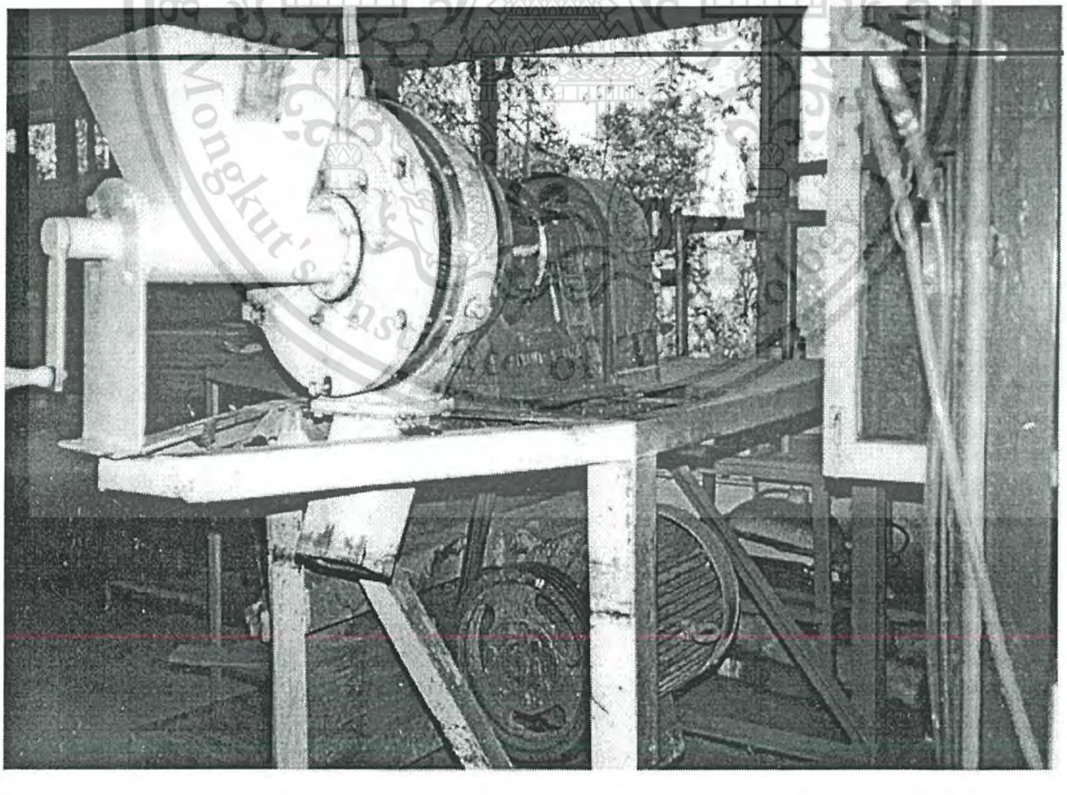


Figure 3.3 Refiner machine

3.1.2.2 Treatment of bamboo fibers [47]

Bamboo fibers were extracted with acetone in soxhlet apparatus for 24 hours, followed by washing with distilled water and air - drying. The soxhlet dimension was 30 x 100 millimeters and using 30 x 100 millimeters of cellulose extraction thimble. The fibers were extracted in a 1 : 2 mixture of methanol and benzene for about 14 hours to dewax the sample, then treated with 17 % NaOH for 30 to 45 minutes and thoroughly washed with distilled water and air - dried. The pretreatment of the bamboo fibers to remove impurity, such as, oil, wax, etc.

Acetone, benzene and sodium hydroxide were AR graded chemicals from Mallinckrodt Backer, Inc.. Methanol and anhydrous calcium chloride were AR graded chemicals from Mallinckrodt Chemical, Inc. and Fluka Chemical, respectively.

3.1.2.3 Graft polymerization of MMA onto bamboo fibers using γ - radiation

In this work, the simultaneous irradiation technique was employed for grafting MMA monomer onto the bamboo fibers by using γ - radiation from a cobalt - 60 source. The dose rate was 10 kGy / hr at the exposure time of 30, 60, 90, and 120 minutes, respectively. The aim was to find an optimum irradiation condition and to compare the grafting yield by varying total doses using the monomer - to - fiber ratio of 3 : 1 and at liquor - to - fiber ratio of 20 : 1 [77].

Weighted bamboo fibers (Oven dry) were placed in a bottom fitted with a quick - fit stopper. Distilled water was added to each sample, which was then stoppered for 24 hours. Nitrogen was passed through the sample, to which the purified monomer was added. The bottom was then quickly stoppered. Irradiation was carried out at different exposure times to achieve different doses by using ^{60}Co rads at dose rate 10 kGy / hr. Afterward, the sample was thoroughly washed with distilled water, then dried at 60 ^{O}C for 24 hours and weighed.

3.1.2.4 Extraction of homopolymer [47], [78]

The homopolymer along with the grafted bamboo fibers were filtered off, washed with distilled water, and dried to a constant weight. Finally, the fibers were extracted with acetone in a soxhlet apparatus for 14 hours to dissolve all homopolymers (PMMA). Percentage of grafting was estimated as follows :

$$\%\ \text{Grafting yield (GY)} = \frac{G - S}{S} \times 100 \qquad (3.1)$$

Where, G is the weight of the grafted sample and S is the weight of the bamboo fibers.

The measured weight increase divided by the weight of the substrate, multiplied by 100, was reported as the percentage graft level. The percentage efficiency of grafting was taken as the weight of polymer grafted divided by the weight of the polymer grafted plus the weight of homopolymer, multiplied by 100.

3.1.3 Monomer

MMA was used as the monomer for fiber surface grafting by irradiation in the presence of distilled water. MMA was a commercial graded monomer from J.T. Baker Analyzed Co. , Ltd..

3.1.3.1 Purification of methyl methacrylate (MMA) [79]

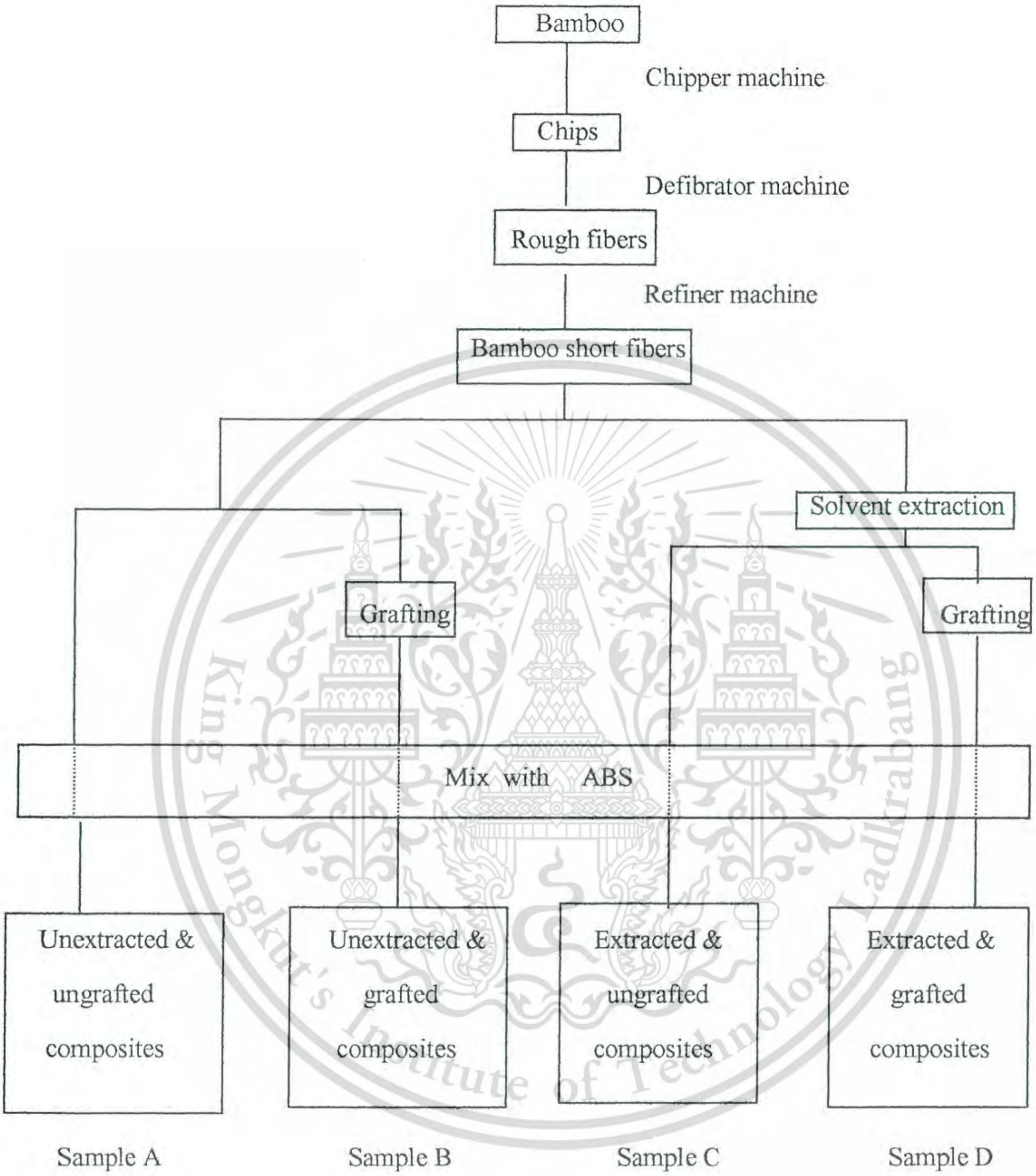
MMA was purified by washing the monomer with 5 % NaOH. The same amount of the basic solution and the monomer were placed in a seperatory funnel and mixed by tumbling. The heavier aqueous phase was drained off. The monomer was then washed with distilled water until litmus paper showed all the base was removed. A drying agent, such as, anhydrous calcium chloride was added to the monomer. With occasional tumbling, drying was completed in about 30 minutes and stored in a dark bottle in a refrigerator at 4 to 5 °C.

3.2 Instruments

The instruments used in this study are listed below :

1) Chipper machine
2) Defibrator machine (No. 680)
3) Refiner machine (SPROUT - WALDRON D 2202)
4) Soxhlet apparatus
5) Gamma cell 220
6) Brabender / twin - screw extruder machine (PL 2100 Plasti - cordor)
7) Injection molding machine (Cosmo, ITI - 220 / 80 Hitech)
8) Tensile tester (LR 30, LLOYD instruments Co., Ltd.)
9) Impact tester (Model 258 - PC, Yasuda Seiki Seisakusho Co., Ltd.)
10) Hardness tester (Shore D)
11) Scanning Electron Microscope (JEOL JSM - 6400)
12) Fourier Transform Infrared Spectrophotometer (IFS 28 Bruker analytic)
13) Thermogravimetric Analyser (NETZSCH STA 409 C)

3.3 Flow chart of work operation



<u>Note</u> Sample A : unextracted & ungrafted bamboo fiber / ABS composites,

Sample B : to study the effect of grafting on the unextracted fibers,

Sample C : to study the effect of the extractives and impurity on the properties of composites,

Sample D : to study the effect of grafting on the extracted fibers

3.4 Preparation of bamboo fibers for mixing

Bamboo fibers used in this study were prepared into 4 forms :

1. Unextracted & ungrafted bamboo fibers (Sample A)
2. Unextracted & grafted bamboo fibers (Sample B)
3. Extracted & ungrafted bamboo fibers (Sample C)
4. Extracted & grafted bamboo fibers (Sample D)

3.5 Mixing procedure

Conditions of mixing were studied by varying two factors ; (1) mixing temperature and (2) rotor speed.

Mixing temperature was varied from 165 to 180 °C (165, 170, 175, and 180 °C) in the system of 500 g of ABS and 15 g of the unextracted & ungrafted bamboo fibers, mixed in the brabender / twin - screw extruder at constant rotor speed of 5 and 10 rpm, respectively.

Condition of injection molding of ABS was studied by varying temperatures from 165 to 180 °C (165, 170, 175, and 180 °C). The testing specimens were prepared by injection molding machine.

3.6 Bamboo fiber loading

a) The amounts of unextracted & ungrafted bamboo fibers were varied from 0 to 40 phr (0, 3, 5, 10, 20, 30, and 40 phr). Bamboo fibers and ABS were mixed the brabender / twin - screw extruder at a temperature of 180 °C and rotor speed of 5 rpm.

b) The amounts of extracted & ungrafted, unextracted & grafted, and extracted & grafted bamboo fibers were varied from 0 to 10 phr (0, 3, 5, and 10 phr). Bamboo fibers and ABS were mixed in the brabender / twin - screw extruder at a temperature of 180 °C and rotor speed of 5 rpm.

3.7 Physical and mechanical properties testing

Tensile tests were conducted according to ASTM D 638 and Izod impact strength tests according to ASTM D 256. The cross - head speed during the tension testing was 5 mm / min with 30 kN load cell. Tensile properties were measured with LLOYD instrument material testing machine model LR 30, equipped with laser strain detector with "Windap" software program. Water absorption was tested according to ASTM D 570.

Mechanical properties test method of composites showed in Table 3.2.

Table 3.2 Mechanical properties test method

Mechanical properties	Test method	Unit
Tensile strength	ASTM D 638	N/mm^2 (MPa)
Elongation at break	ASTM D 638	%
Modulus of elastic	ASTM D 638	N/mm^2 (MPa)
Impact strength	ASTM D 256	kJ/m^2
Hardness	Shore D	
Water absorption	ASTM D 570	%

3.7.1 Tensile testing

The composites obtained from the brabender / twin - screw extruder were pelletized. The test specimens were prepared by injection machining operations, in the form of rectangular bars. The tensile bar of size 10.4 mm wide x 2.5 mm thick x 151 mm long was tested on LLOYD instruments Co., Ltd.. Ten specimens were tested at maximum load cell of 30 kN, crosshead speed of 5 mm / min and gauge length of 50 mm. This method was carried out according to ASTM D 638.

3.7.1.1 Tensile strength

The tensile strength (σ) was determined by load at break (N) per initial cross - sectional area of gauge length section (mm^2). The tensile strength was calculated as :

$$\sigma = \frac{F}{A} \qquad (3.2)$$

Where σ = Tensile strength in the unit of N/ mm^2 or MPa,

F = Load at break (N),

A = Initial cross - sectional area of gauge length section (mm^2)

3.7.1.2 Elongation at break

The elongation at break (E) was calculated as follow :

$$E\,(\%) = \frac{l - l_0}{l_0} \times 100 \qquad (3.3)$$

Where E = Elongation at break (%),

l = The distance between gauge marks at break in millimeter,

l_0 = The initial distance between gauge marks or gauge length, which set at 50 millimeters

3.7.1.3 Modulus (at 3 % strain)

From the load vs. elongation curve, modulus at 3 % strain could be calculated by the equation,

$$E = (F / A) / (3 / 100) \qquad (3.4)$$

Where E = Modulus at 3 % strain, in MPa,

F = Load at 3 % strain,

A = Initial cross - sectional area of the test specimen

3.7.2 Impact testing

According to ASTM D 256, V - notch type Izod impact test specimens were injected with injection machine. Impact strengths were measured with Yazuda impact tester model 285 - PC, linked with a computer. The testing results were analyzed by a software programming. Notched Izod impact strengths of ten specimens were measured at a temperature of $23 \pm 2\ ^{\circ}C$ and reported as an average value of at least ten specimens of each system.

The impact strength (IS) of each specimen could be calculated from the equation :

$$IS = W / A \qquad (3.5)$$

Where IS = Impact strength in the unit of kJ / m^2,

W = Loss energy read from the meter scale,

A = Cross - sectional area of the notched test specimen

3.7.3 Hardness testing

The hardness value was measured from hardness tester in Shore D type. The samples were laid down on the stand and where then pressed under 5 kg of load for 3 seconds. The results can be read from the dial.

3.7.4 Determination of moisture content [80]

Samples of chips, fibers, and composites were weighed (fw) from each lot using an analytical balance. The dry weight of the samples was determined after drying in a hot - air oven maintained at 105 ± 2 °C for 24 hours. The dried samples were cooled in a descicator for 30 to 45 minutes and then reweighed (dw). The moisture content (MC) was calculated as follows :

$$\text{MC (\%)} = \frac{\text{fw} - \text{dw}}{\text{fw}} \times 100 \qquad (3.6)$$

Where MC = Moisture content (%),

fw = Initial weight of sample,

dw = Weight of sample after dried

3.7.5 Water absorption [81]

Specimens of materials water absorption were dried in an oven for 1 hour at 105 ± 2 °C, cooled in a descicator for 30 to 45 minutes, and weighed to the nearest 0.001 g. The samples with accurately weight were immersed in a container of distilled water maintained at temperature of 23 ± 2 °C (734 ± 1.8 °F) for 43 days. After 2 days under water, they were removed from the water, wiped off with a dry cloth, and weighed to the nearest 0.001 g immediately.

Water absorption can be calculated as follows :

$$\text{\% Water absorption} = \frac{\text{wet weight - conditioned weight}}{\text{conditioned weight}} \times 100 \qquad (3.7)$$

3.7.6 Scanning electron microscopy (SEM)

The surface of fibers and liquid - nitrogen fracture of composite specimens was studied by SEM. The samples were coated with a thin film of gold by using a sputter coater. The coated samples were then examined under on a scanning electron microscope (JEOL JSM - 6400).

3.7.7 Thermogravimetric analysis (TGA)

The thermogravimetric diagrams of composites were measured by NETZSCH STA 409 C equipped with recorder and purged with air. The heating rate was 10 °C / min from the room temperature to 700 °C.

CHAPTER IV

RESULTS AND DISCUSSION

In this work, bamboo fiber / ABS composites were studied. First, the effect of mixing and shaping conditions were studied in order to find the optimum conditions to fabricate the bamboo fiber / ABS composites. The effect of the percent fiber loading on the properties of the composites was also studied. Comparative study of unextracted & ungrafted and solvent - extracted & ungrafted bamboo fiber / ABS composites was carried out in order to find the effect of impurity and extractives in the fibers on the properties of the composites. Solvent extraction would determine ease of processability and cost of composite production. The fibers were grafted with MMA by using simultaneous γ - ray irradiation method at various total doses in order to enhance the properties of the composites. Therefore, the samples for this research work were prepared and designated as :

Sample A : unextracted & ungrafted bamboo fiber / ABS composites,

Sample B : the unextracted & grafted bamboo fiber / ABS composites,

Sample C : the extracted & ungrafted bamboo fiber / ABS composites,

Sample D : the extracted & grafted bamboo fiber / ABS composites were studied

Properties of four composite sample (A, B, C, and D) were investigated, including mechanical properties, thermal behavior, physical properties, and morphological study. The maximum mixing temperature used in this experiment was limited by the degradation of the bamboo fibers at high temperatures. Also the high rotor speeds can not be used in this work since the high melt viscosity of the mixture.

4.1 Effect of mixing parameters on mechanical properties of the unextracted & ungrafted bamboo fiber / ABS composites

Mixing parameters were first investigated in order to find the optimal condition for preparing the composites prior study of other effects. Mixing temperatures and rotor speeds were varied in the range of 165 to 180 °C and 5 to 10 rpm, respectively. The tensile properties of the sample A (unextracted & ungrafted bamboo fiber / ABS composites) were measured and chosen to use as the criteria to obtain the optimum mixing conditions. Three percent fiber volume fraction was chosen to prepare the tested composites.

Figures 4.1 to 4.3 show the effect of the mixing temperature and the rotor speed of the brabender / twin - screw extruder on tensile strength, modulus at 3 % strain, and % elongation at break of sample A, respectively. It was seen that tensile properties were changed at various mixing temperatures and rotor speeds. It can be concluded that the lower rotor speed (5 rpm) yielded the composites with higher tensile strength and modulus at all mixing temperatures. It can be seen that the higher the mixing temperature, the higher the tensile strength and modulus. Therefore, temperature of 180 °C and rotor speed of 5 rpm were chosen for all mixing conditions for preparing the bamboo fiber / ABS composites for other tests.

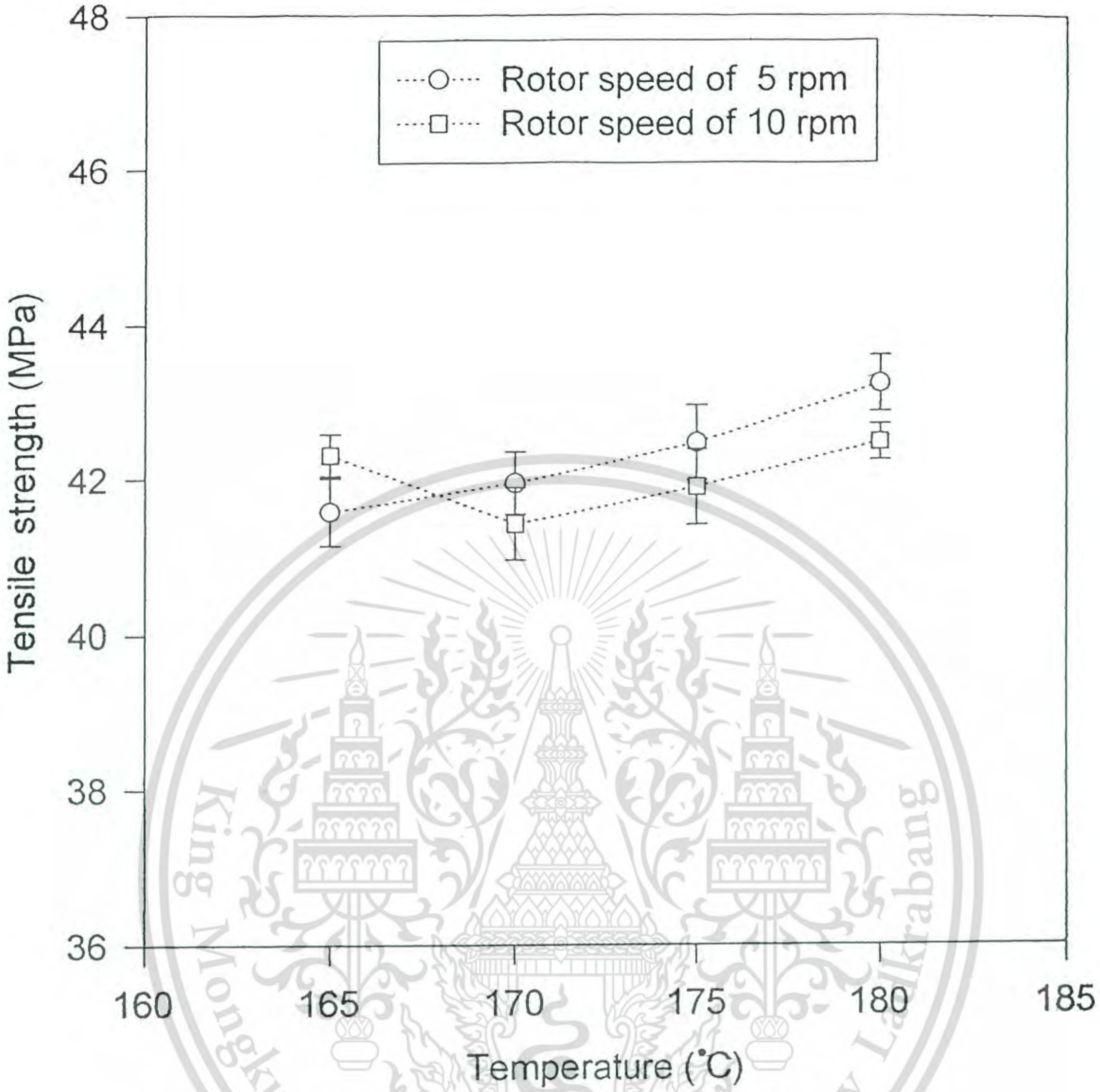


Figure 4.1 Effect of mixing temperature and rotor speed on tensile strength of sample A (unextracted & ungrafted bamboo fiber / ABS composites) (3 phr)

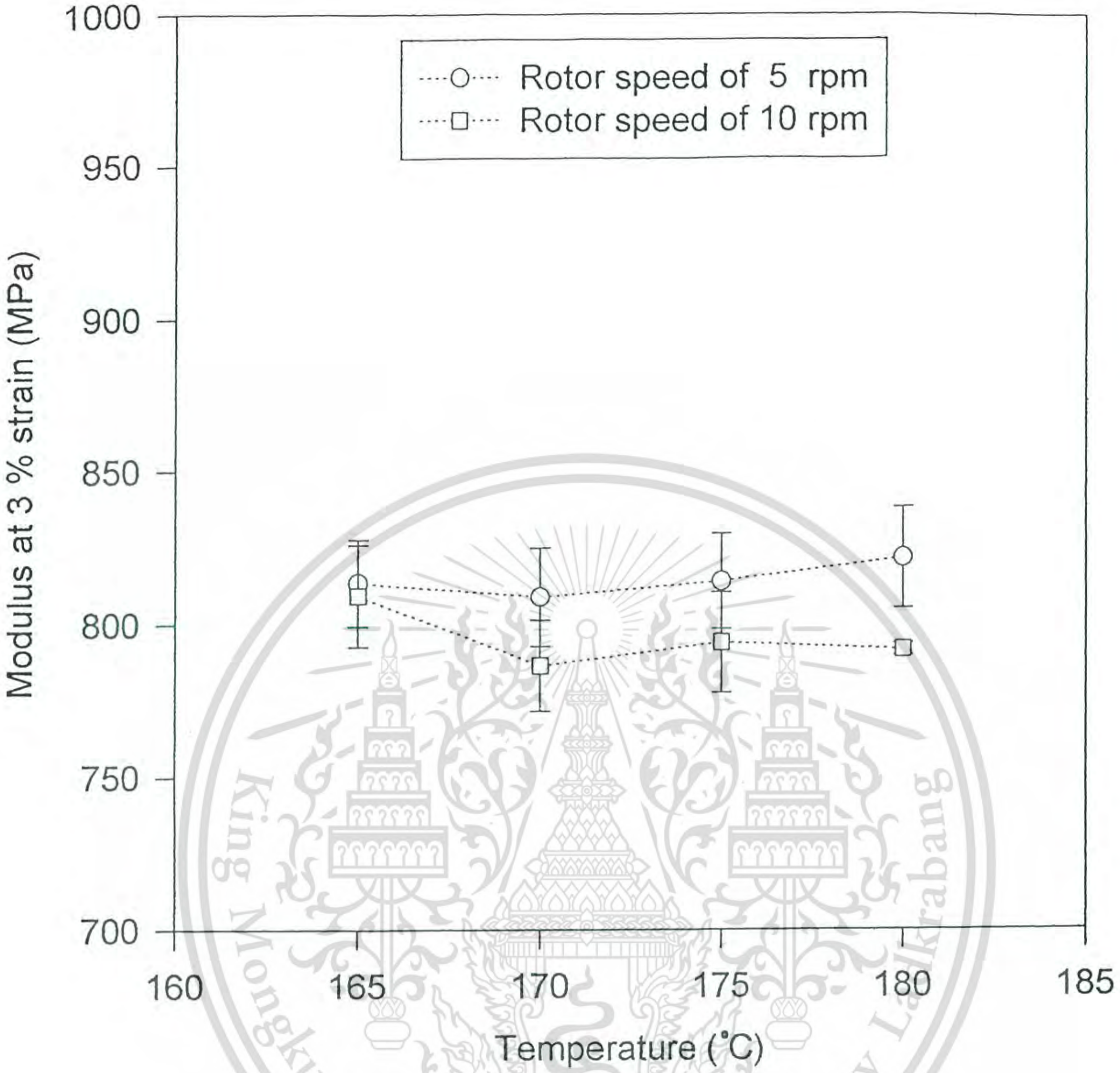


Figure 4.2 Effect of mixing temperature and rotor speed on modulus at 3 % strain of sample A (unextracted & ungrafted bamboo fiber / ABS composites) (3 phr)

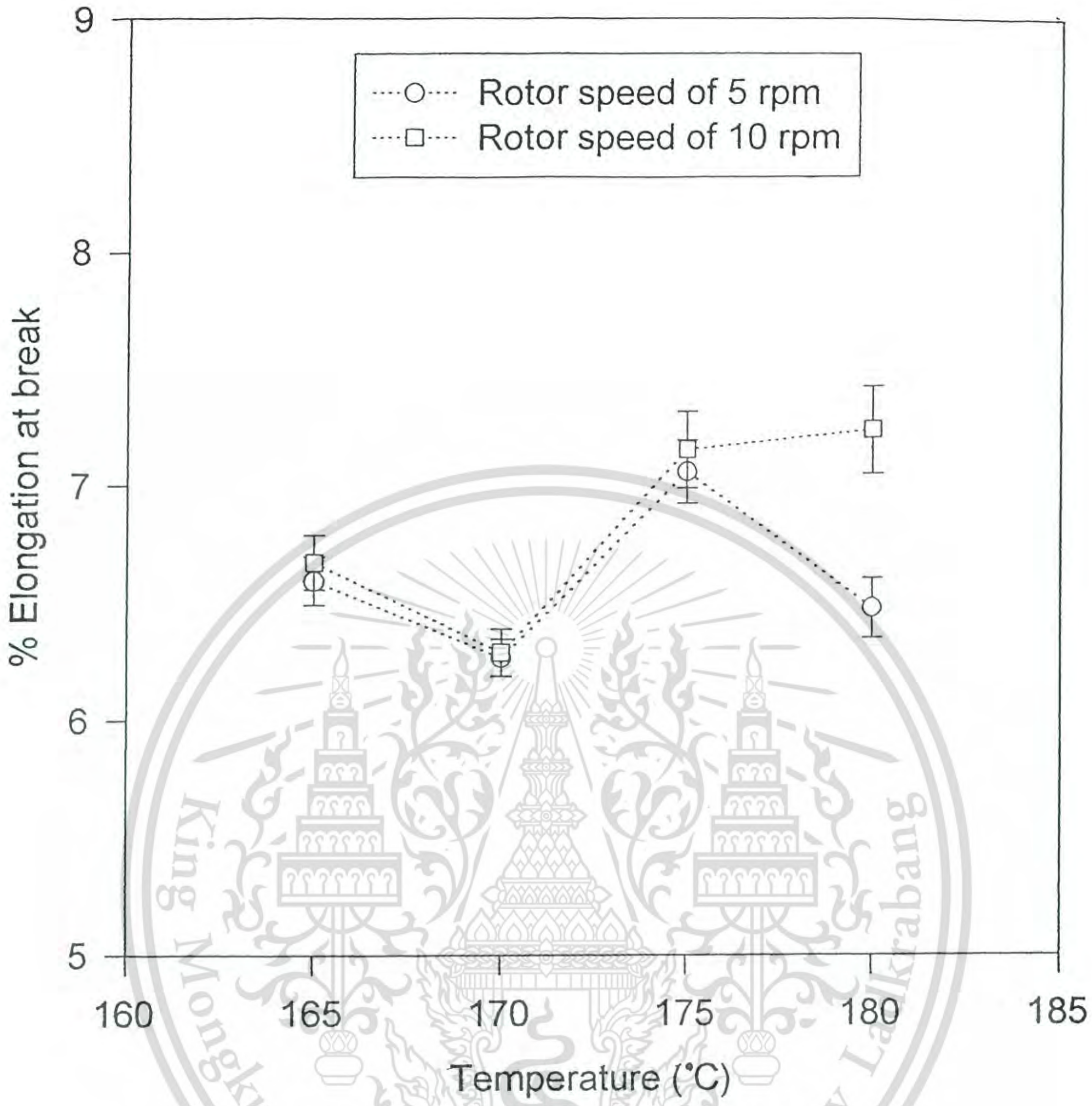


Figure 4.3 Effect of mixing temperature and rotor speed on % elongation at break of sample A (unextracted & ungrafted bamboo fiber / ABS composites) (3 phr)

4.2 Effect of injection temperature on mechanical properties of the ABS

Injection molding technique was used to prepare the composite samples for tensile and impact tests. Injection temperature of the injection molding machine was varied in the range of 165 to 180 °C. The tensile properties of ABS were measured and chosen to use as the criteria to obtain the optimum shaping conditions. Figures 4.4 to 4.6 show the effect of injection temperature on tensile strength, modulus at 3 % strain, and % elongation at break of ABS, respectively. Temperature of 180 °C seemed to yield ABS with the optimum tensile properties.

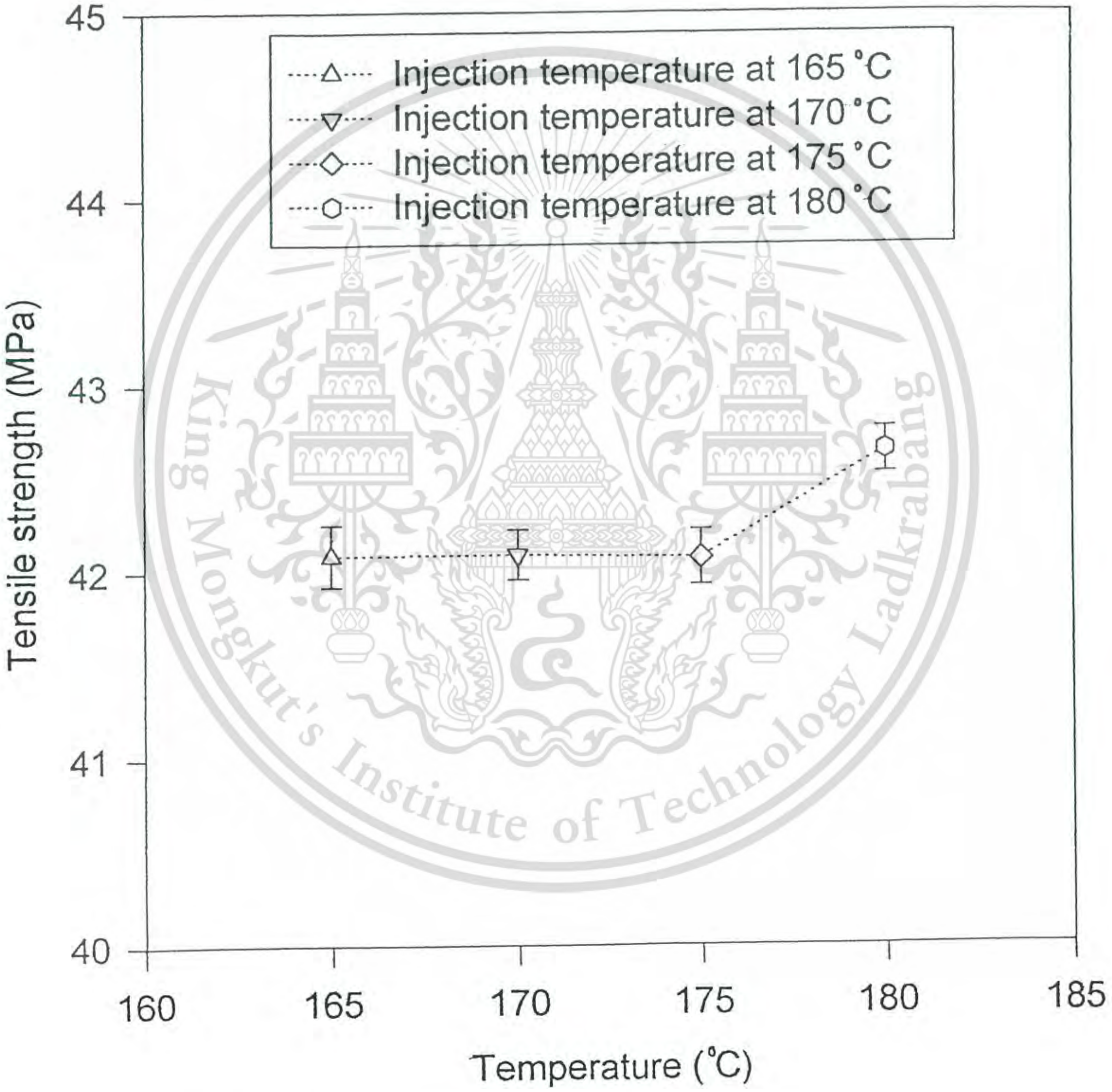


Figure 4.4 Effect of injection temperature on tensile strength of ABS

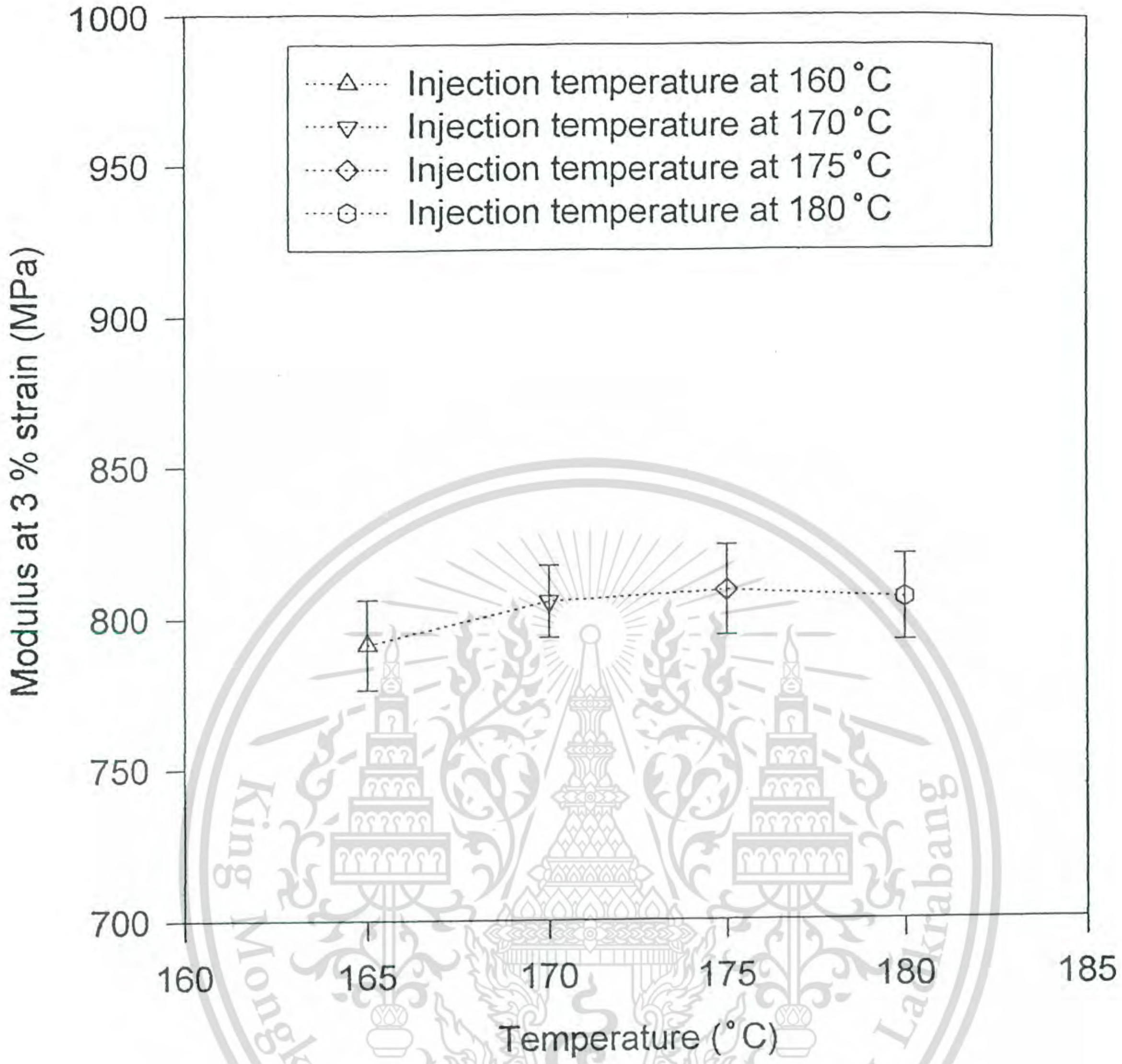


Figure 4.5 Effect of injection temperature on modulus at 3 % strain of ABS

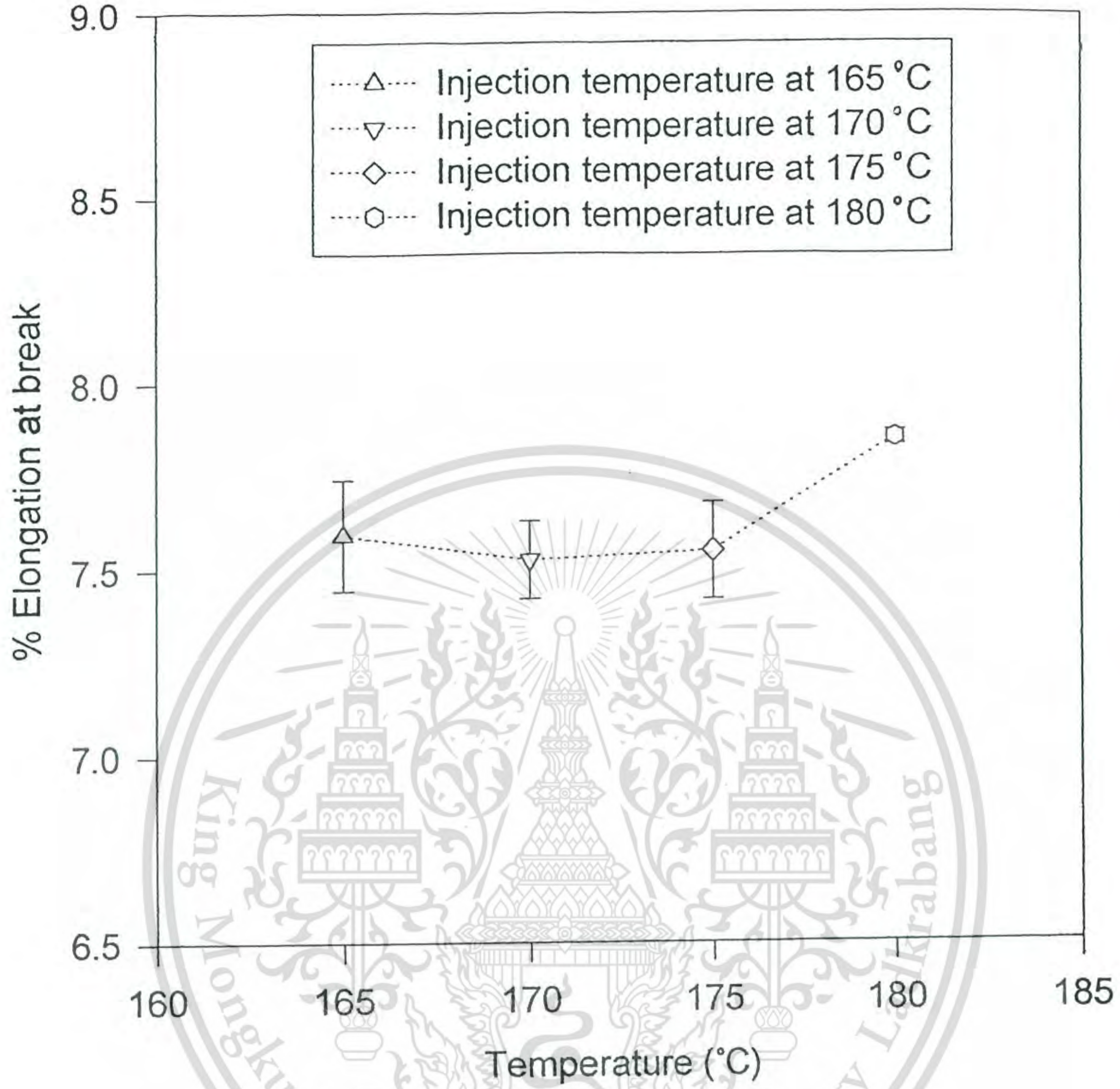


Figure 4.6 Effect of injection temperature on % elongation at break of ABS

4.3 Effect of the unextracted & ungrafted bamboo fibers on mechanical properties of the composites

Addition of the bamboo fibers onto ABS was expected to improve mechanical properties of ABS because of the high tensile strength and modulus of the fibers. By varying the % fiber loading in the range of 0 to 40 phr on the composites, tensile properties of the composites were obtained and shown in Figure 4.7. It was found that the strength of the composites was increased as % fiber loading increased. Figure 4.8 shows that modulus at 3 % strain was increased with more addition of the fibers in the same manner as tensile strength. The tensile strength was very crucial since it gave information about the maximum allowable load without considerable plastic deformation. From these results, it could be explained that the bamboo fibers had much more strength than ABS. It acted as reinforcing fibers for the composites due to large surface areas of the fibrous form.

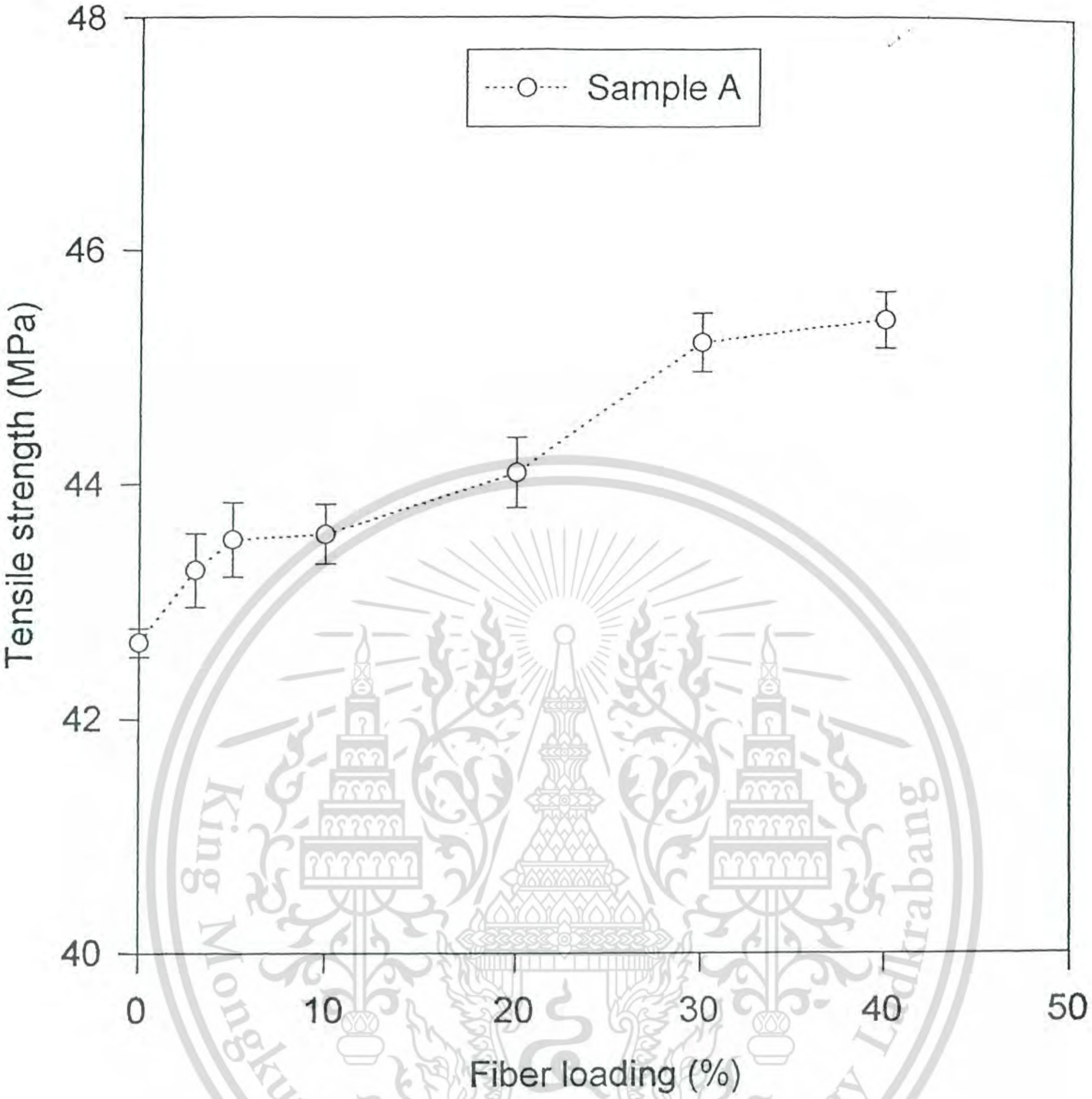


Figure 4.7 Effect of % fiber loading on tensile strength of sample A (unextracted & ungrafted bamboo fiber / ABS composites)

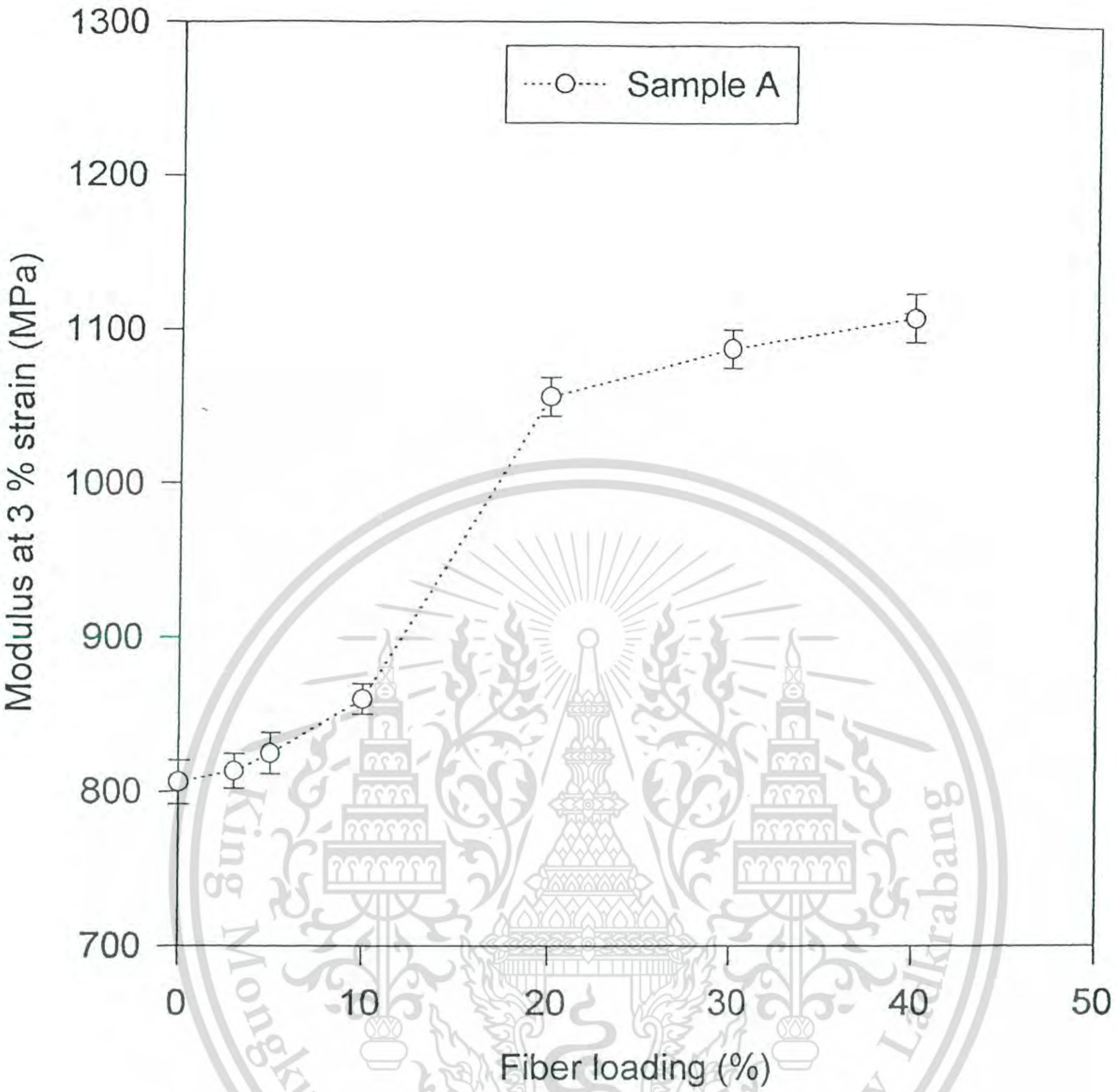


Figure 4.8 Effect of % fiber loading on modulus at 3 % strain of sample A (unextracted & ungrafted bamboo fiber / ABS composites)

The opposite result was found in elongation testing (Figure 4.9) as the % elongation at break of sample A (unextracted & grafted bamboo fiber / ABS composites) decreased with increasing the fiber content. From this result, it could be explained that the addition of the rigid bamboo fibers reduced the % elongation at break of composites. It was expected that the decrease in composite ductility corresponded with the increase in composite rigidity caused by the addition of the bamboo fibers (as cellulose content increased) [82]. The addition of the bamboo fibers into ABS partly destroyed the continuity of the matrix and caused premature failure. It has also known that the more the fiber loading, the more the possibility of poor contact areas between the fibers and the matrices which are the source of premature failure and lower % elongation at break.

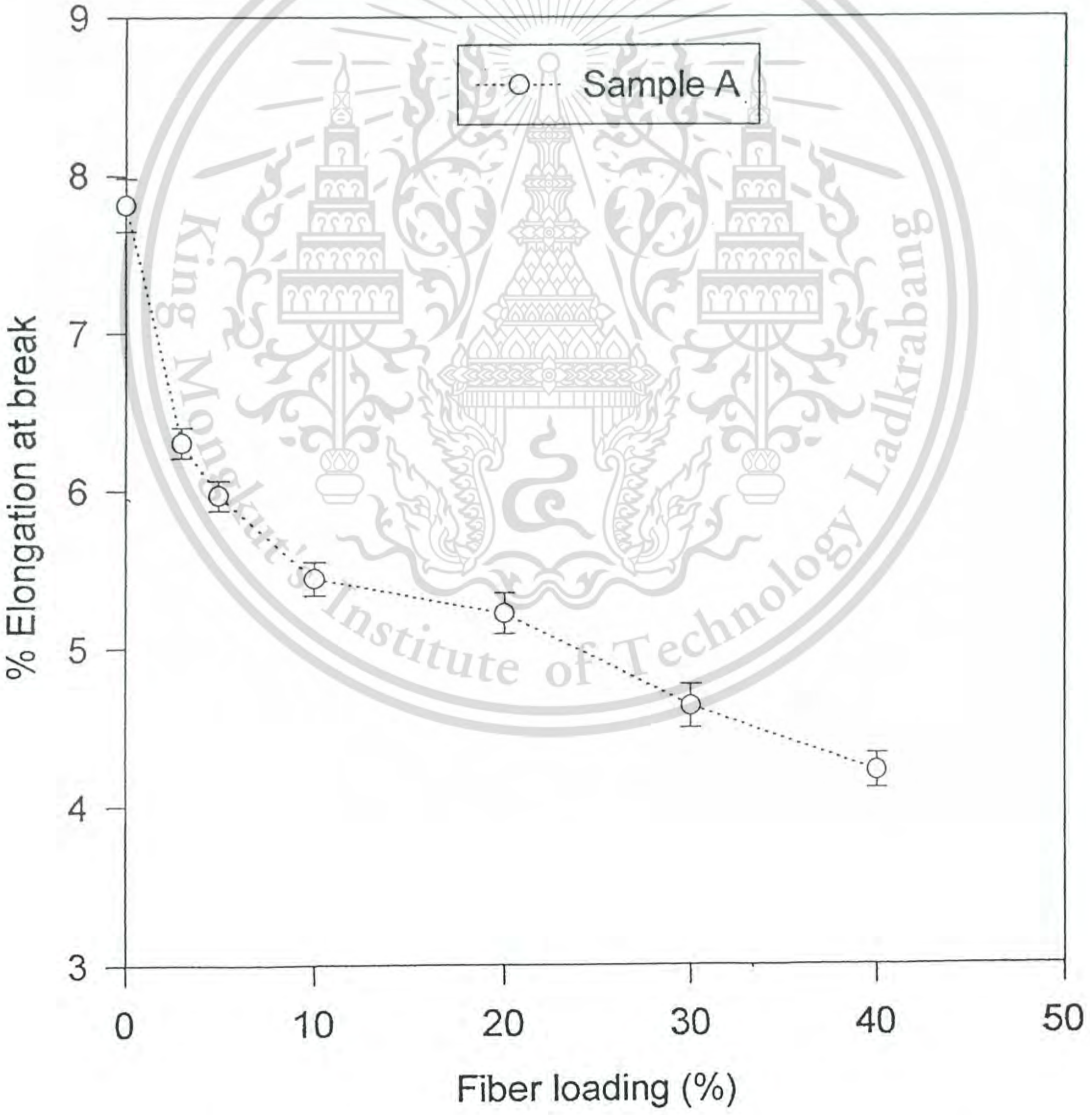


Figure 4.9 Effect of % fiber loading on % elongation at break of sample A (unextracted & ungrafted bamboo fiber / ABS composites)

The effect of % fiber loading on impact strength of the composites was shown in Figure 4.10. Addition of the bamboo fibers reduced the impact strength of the composites. It could be explained that the fibers introduced a decrease in toughness of the composites. Lumen as well as the presence of defects in the bamboo structure could reduce the impact strength [83]. There are two mechanisms by which the fibers can reduce the impact strength : 1) Fibers tend to reduce the elongation to break and may reduce the area under the stress - strain curve. 2) Stress concentrations may occur at regions around fiber ends, areas of poor adhesion, and regions where fiber contact one another [10].

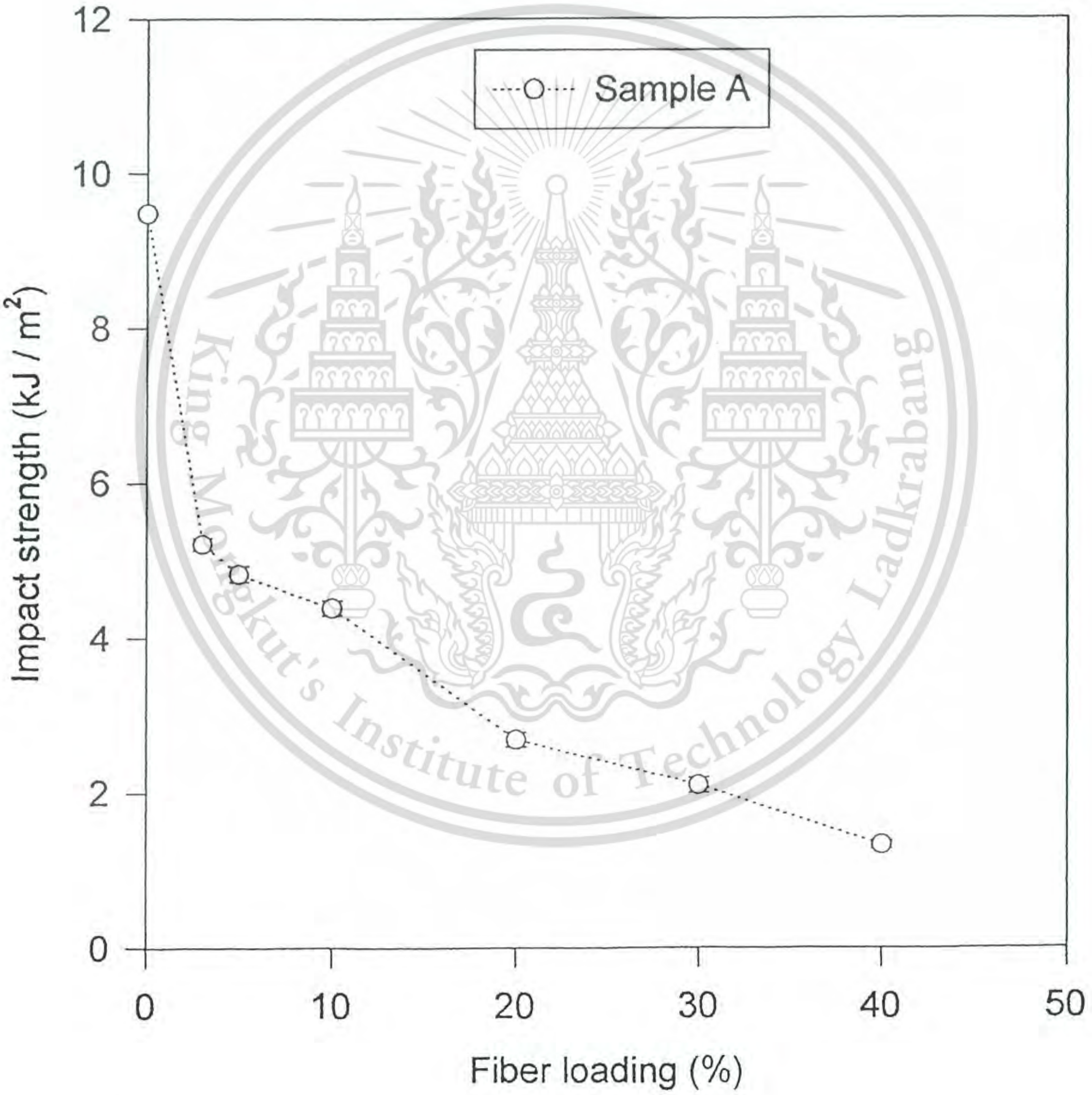


Figure 4.10 Effect of % fiber loading on impact strength of sample A (unextracted & ungrafted bamboo fiber / ABS composites)

4.4 Effect of the unextracted & ungrafted and extracted & ungrafted bamboo fibers on mechanical properties of the composites

The plot of % fiber loading vs. tensile strength of sample A (unextracted & ungrafted bamboo fiber / ABS composites) and sample C (extracted & ungrafted bamboo fiber / ABS composites) was compared in Figure 4.11. It was found that sample C showed higher strength than sample A. In Figure 4.12, modulus of sample C showed higher than sample A in the similar trend as the tensile strength. This could be explained that in the extracted samples the extractives, contaminates, weak layers, and waxes were removed from the fiber surfaces resulting cleaner surfaces and better contact with the polymer matrix and stronger interfacial bonding. It has been known that impurities on the fibers area the origins or source of the failure of the composites under loading [5].

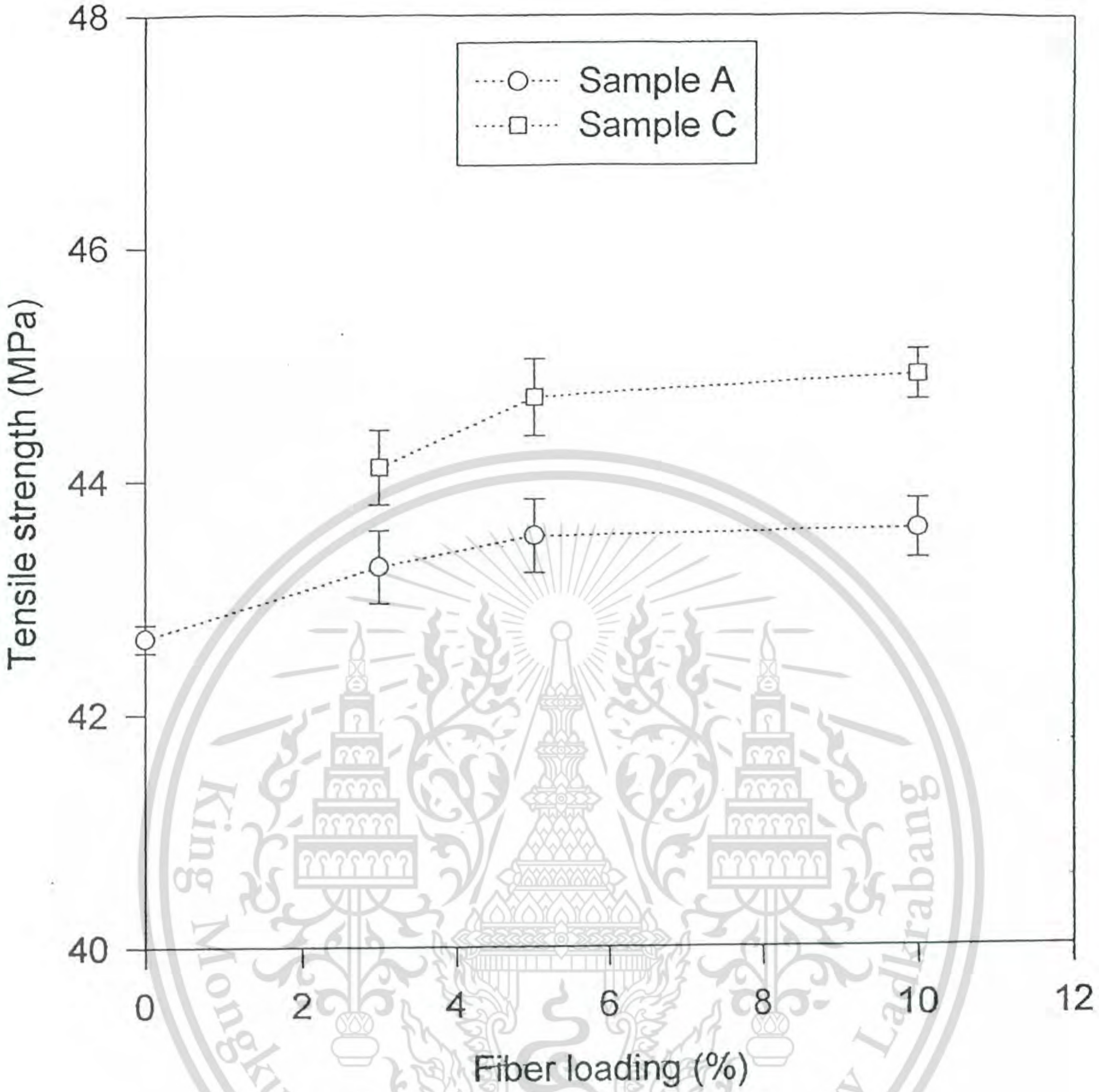


Figure 4.11 Effect of % fiber loading on tensile strength of sample A (unextracted & ungrafted bamboo fiber / ABS composites) and sample C (extracted & ungrafted bamboo fiber / ABS composites)

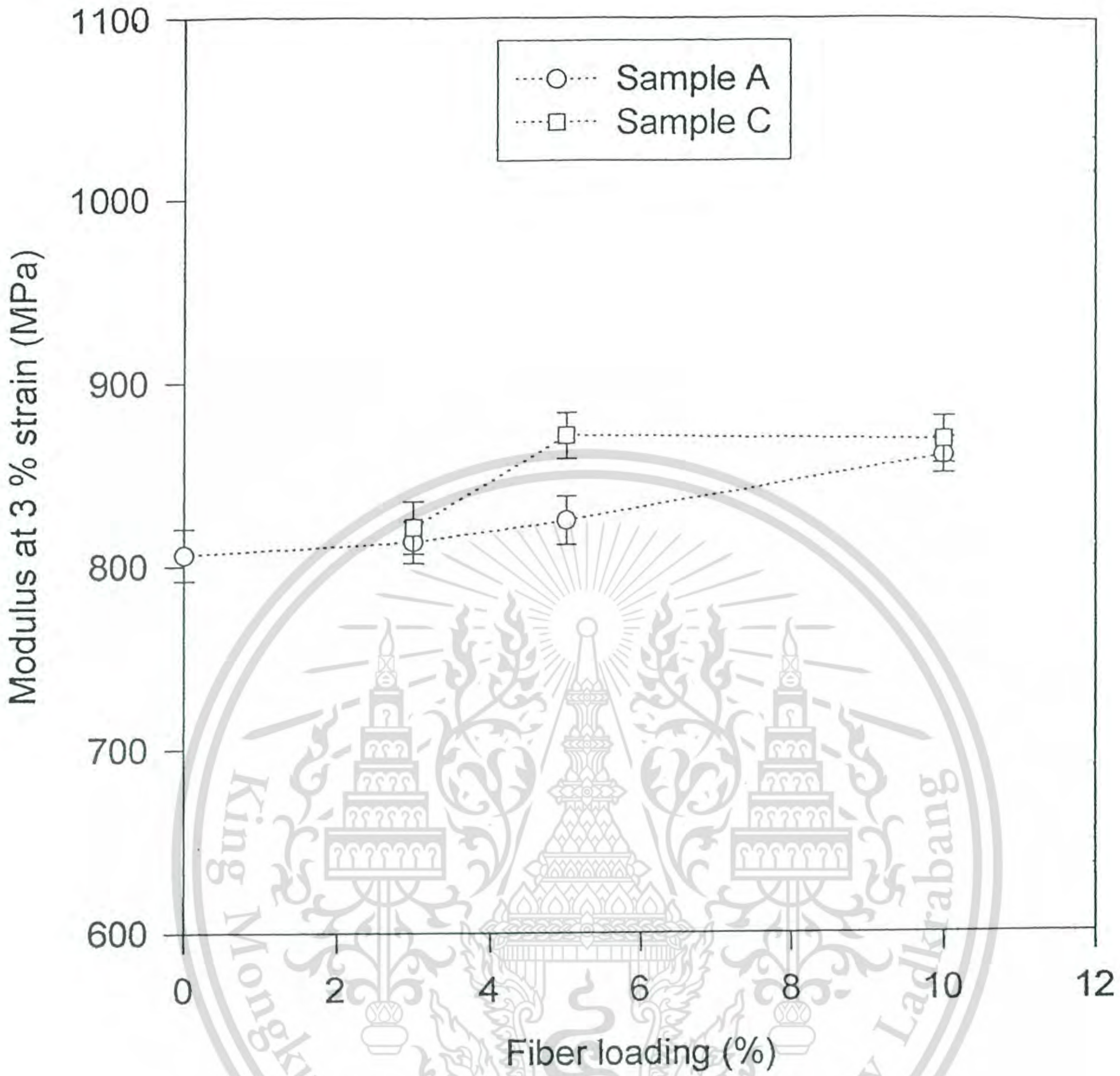


Figure 4.12 Effect of % fiber loading on modulus at 3 % strain of sample A (unextracted & ungrafted bamboo fiber / ABS composites) and sample C (extracted & ungrafted bamboo fiber / ABS composites)

Figure 4.13 shows the effect of % fiber loading on % elongation at break of sample A (unextracted & ungrafted bamboo fiber / ABS composites) and sample C (extracted & ungrafted bamboo fiber / ABS composites). It was obviously seen that sample C had higher % elongation at break than sample A. % Elongation at break of the composites was decreased with more addition of fiber content. As explained previously, the decrease in composite ductility corresponds with the increase in composite rigidity caused by the addition of the fibers.

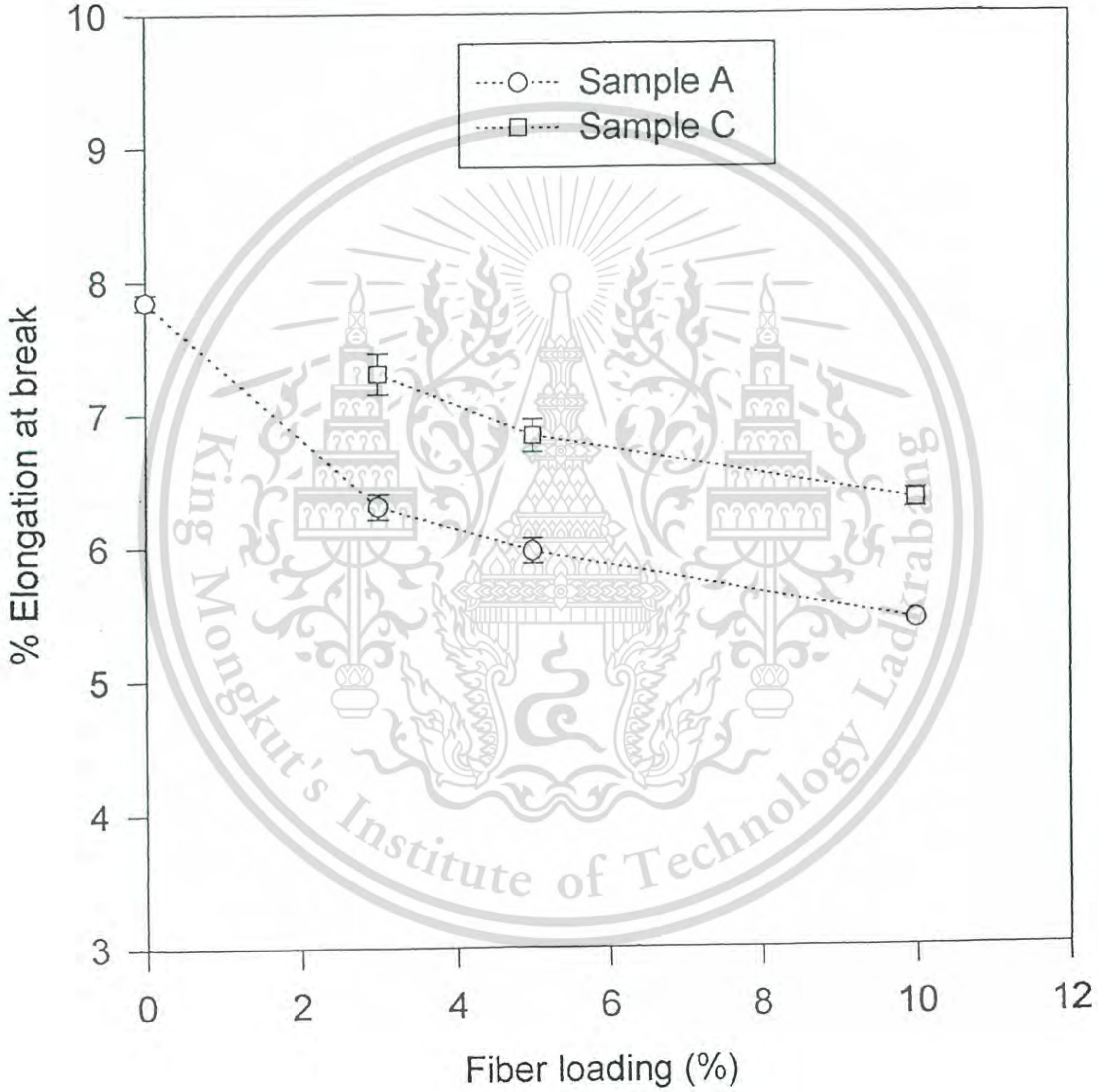


Figure 4.13 Effect of % fiber loading on % elongation at break of sample A (unextracted & ungrafted bamboo fiber / ABS composites) and sample C (extracted & ungrafted bamboo fiber / ABS composites)

In Figure 4.14, impact strength of sample C showed higher than sample A at all three fiber volume fractions (3, 5, and 10 phr). This could be explained by the better interfacial bonding at the extracted composites. After the solvent extraction, the extractives, weak layers and contaminates were removed from the bamboo fiber surfaces resulting the cleaner surfaces. Addition of the bamboo fibers reduced the impact strength of the composites. From this result, it could be described that defects in the bamboo structure and composites could reduce the impact strength of the composites.

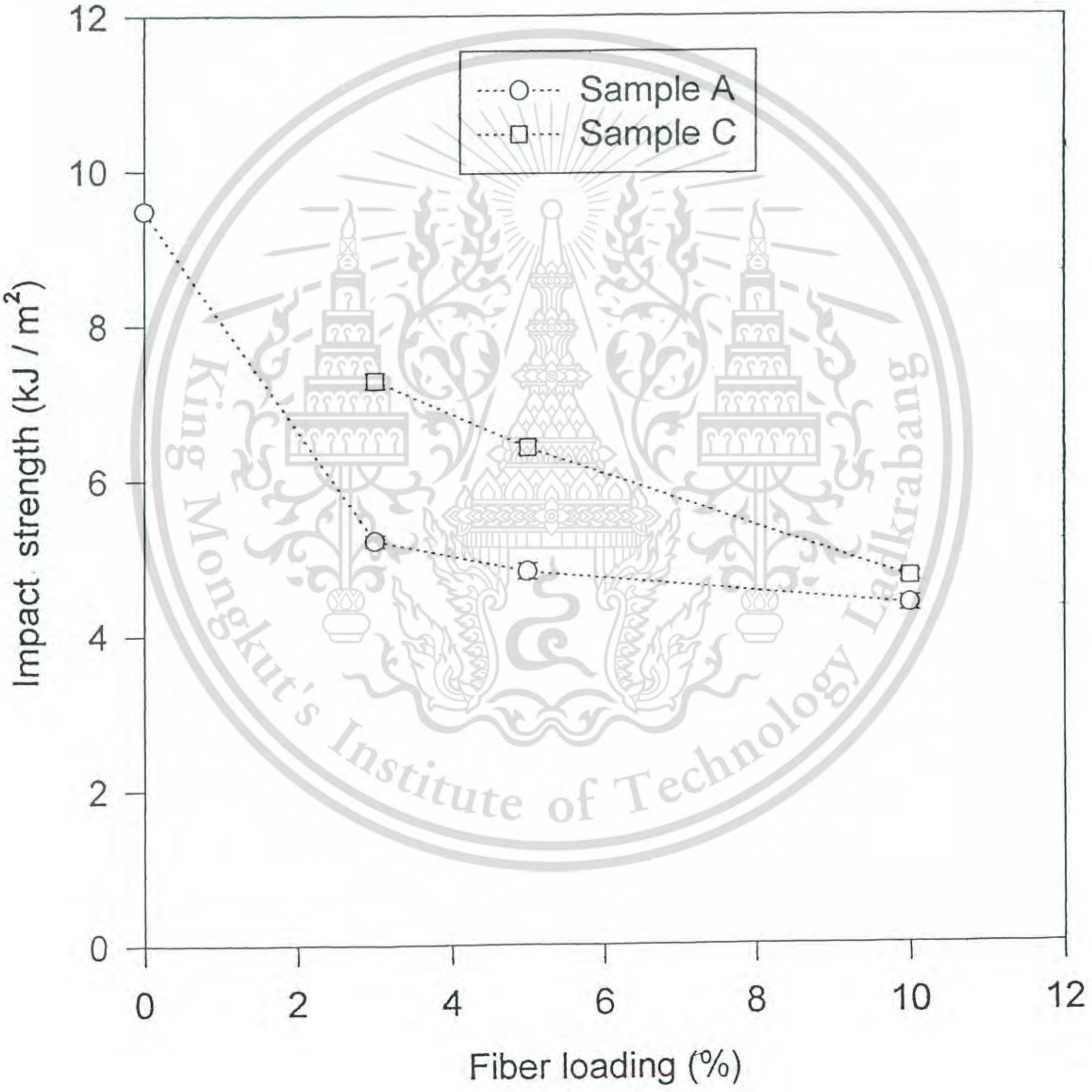


Figure 4.14 Effect of % fiber loading on impact strength of sample A (unextracted & ungrafted bamboo fiber / ABS composites) and sample C (extracted & ungrafted bamboo fiber / ABS composites)

4.5 % Grafting of MMA onto the unextracted and extracted fibers by γ - ray irradiation

Figure 4.15 shows % grafting yield of the fibers on grafting by γ - ray irradiation vs. total dose. It was found that total dose of 15 kGy gave the highest % grafting yield for both the extracted and unextracted fibers. It could be explained that the rate of grafting was increased by increasing the radiation dose since the γ - ray bombarded on the cellulose surfaces and generated more radical sites resulting in the increase of grafting of MMA on the fiber surfaces [77]. At the total dose of 20 kGy, the % grafting yield of the fibers was decreased. This phenomenon could be explained that irradiation could result in degradation of the cellulose. During irradiation, the β - 1, 4 - glucosidic bonds can be claved and the degree of polymerization of the cellulose would decrease [40].

The extracted bamboo fibers had higher % grafting yield than the unextracted bamboo fibers. When the bamboo fibers were extracted by NaOH aqueous solution, the crystalline regions in the fiber structure can be dissolved and converted into amorphous regions [85]. It has been known that graft copolymerization can take place better in these amorphous regions compared to in the crystalline regions since they have less density. Another reason came from retardation of the irradiation by some substances in the fibers. The phenolic and quinone groups of the lignin can retard or inhibit the polymerization reactions of some vinyl monomers, such as, MMA [77]. By extracting the bamboo fibers, a part of the lignin was removed from the fiber structure resulting in a better grafting reaction.

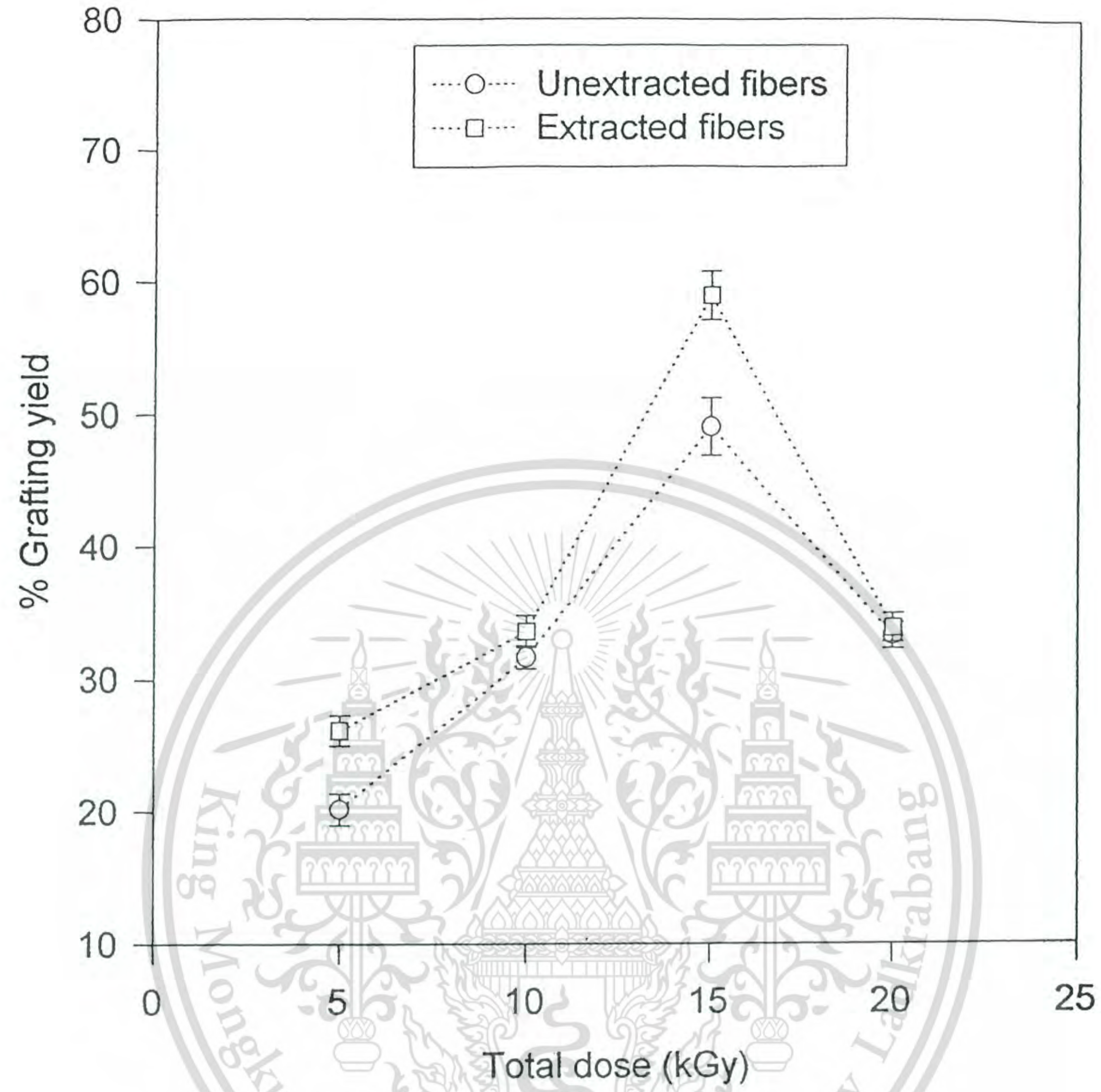


Figure 4.15 % Grafting yield of the grafted fibers with MMA by varying the total dose of γ - ray irradiation

4.6 Effect of the total irradiation dose on mechanical properties of the unextracted & grafted bamboo fiber / ABS composites

By varying the total irradiation dose in the range of 0 to 20 kGy of γ - ray irradiation on the bamboo fibers, the effect of the total irradiation dose on mechanical properties of sample B (unextracted & grafted bamboo fiber / ABS composites) was studied at different % fiber loading. From Figures 4.16 and 4.17, it was clearly shown that the tensile strength of the grafted bamboo fiber / ABS composites was increased as % fiber loading increased. As the total irradiation dose increased, the tensile strength of the composites yielded the maximum strength at total dose of 15 kGy and then decreased. Modulus of the composites was slightly increased shown in Figure 4.18.

The optimum irradiation dose for grafting could be explained as follows. As the total irradiation dose increased, free radicals generated by γ - ray bombardment increased resulting in the increase of grafting of MMA on the bamboo fiber surfaces. However, the overdose irradiation can cause the degradation of the fibers yielding the lower strength fibers. Also, the overdose irradiation can yield high rate of radical formation and thus radical - radical recombination is favorable, creating more homopolymer (PMMA).

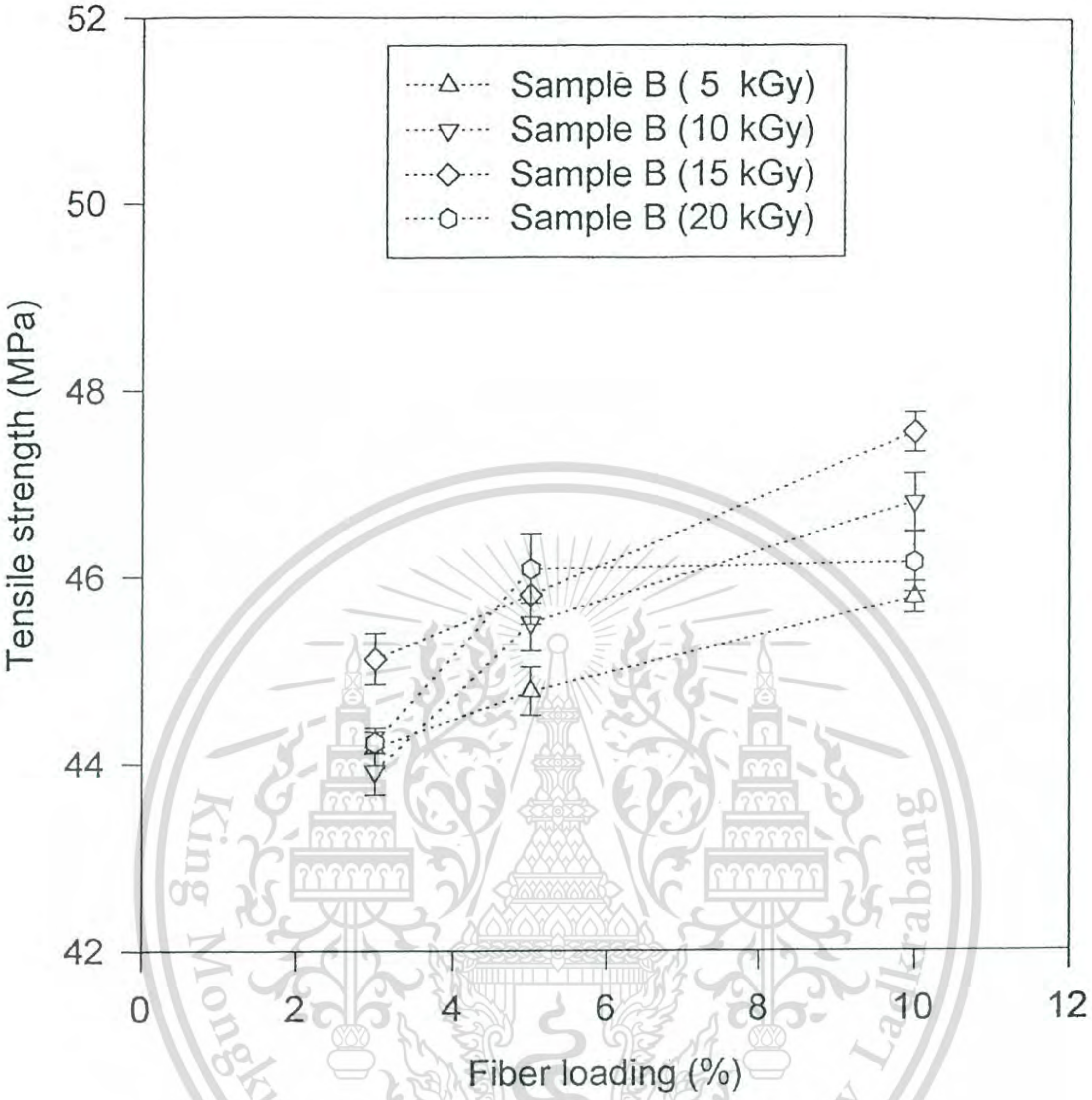


Figure 4.16 Effect of % fiber loading on tensile strength of sample B (unextracted & grafted (5 - 20 kGy) bamboo fiber / ABS composites)

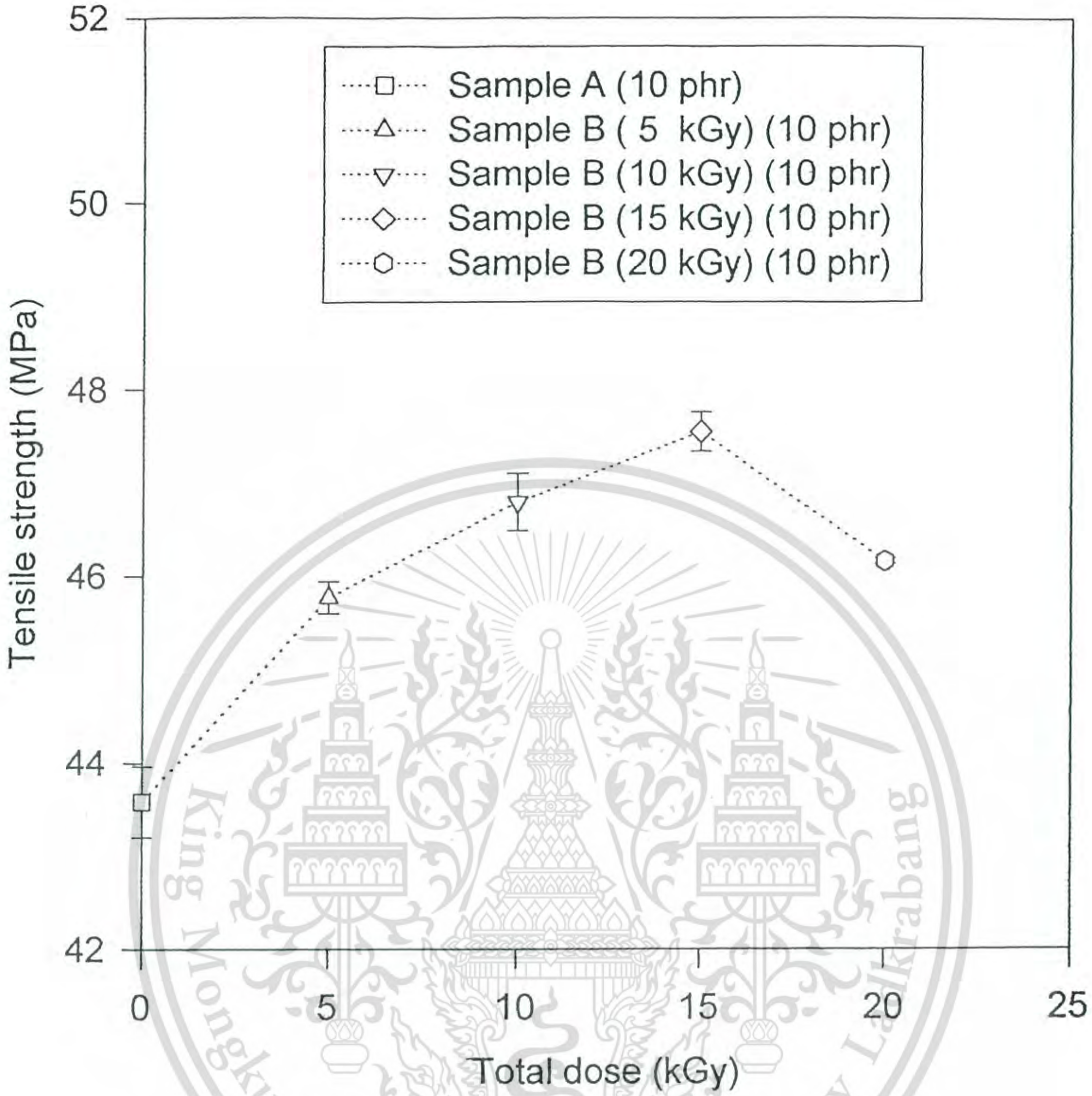


Figure 4.17 Effect of total irradiation dose on tensile strength of sample B (unextracted & grafted (0 - 20 kGy) bamboo fiber / ABS composites) (10 phr)

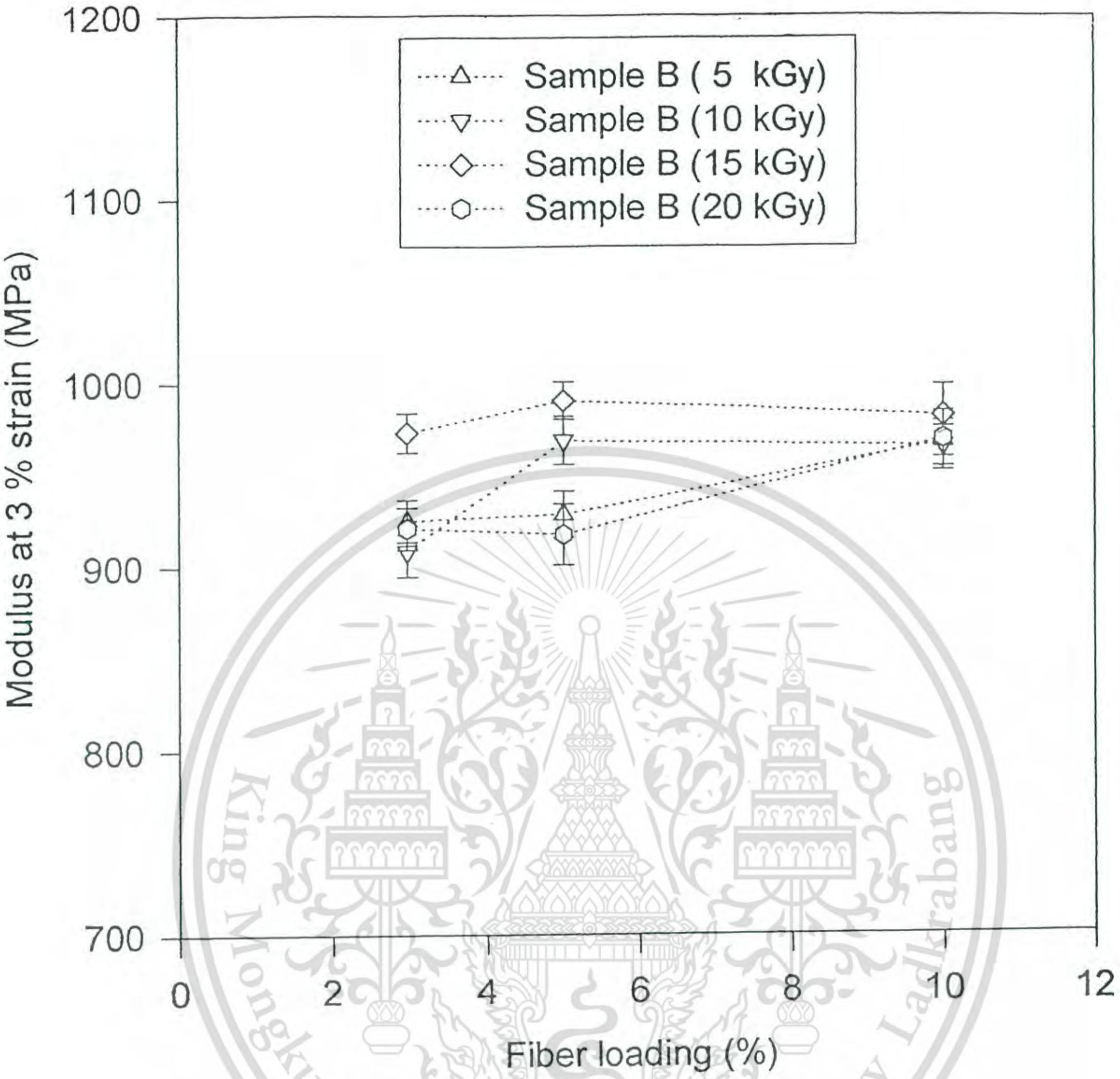


Figure 4.18 Effect of % fiber loading on modulus at 3 % strain of sample B (unextracted & grafted (5 - 20 kGy) bamboo fiber / ABS composites)

By varying the total dose of γ - ray irradiation, sample B (unextracted & grafted (5 - 20 kGy) bamboo fiber / ABS composites) showed a small effect on % elongation at break result (Figure 4.19). Similar to the previous samples, the % elongation at break of the composites at different dose was decreased as the % fiber loading increasing.

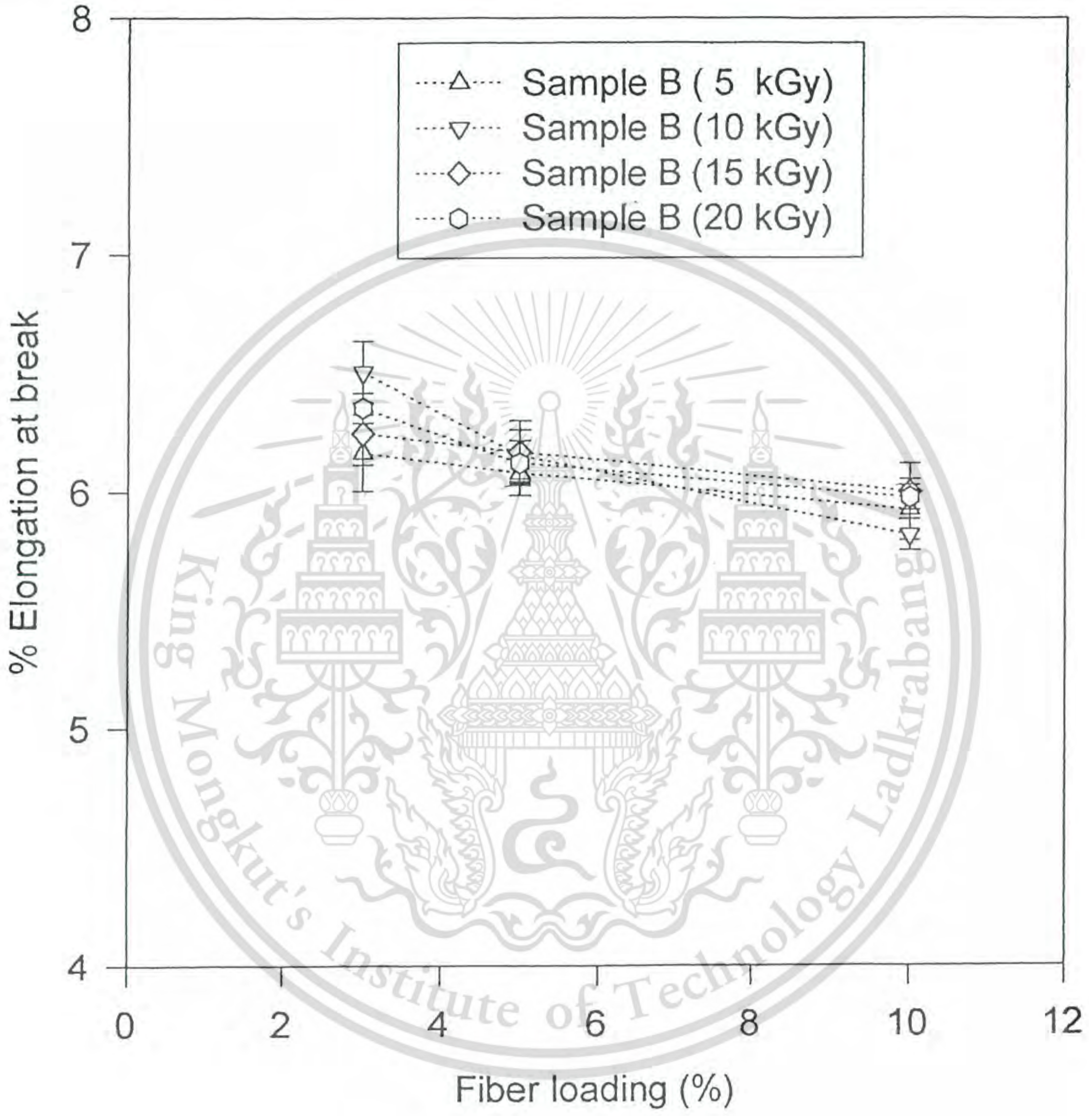


Figure 4.19 Effect of % fiber loading on % elongation at break of sample B (unextracted & grafted (5 - 20 kGy) bamboo fiber / ABS composites)

In Figure 4.20, it was observed that the impact strength of the irradiated composites was decreased with more addition of the fibers. As described above, the stress was increased steadily with the addition of the fibers. As the total dose increased, the impact strength of the irradiated composites was increased and yielded the maximum values at total dose of 20 kGy. However, at total dose of 15 kGy the impact results deviated from the rest. Since the PMMA is a glassy polymer with low impact strength, with the increase in the PMMA graft add - on via irradiation, the amount of glassy domain in the composites was increased. That makes the fibers brittle and decrease their load - bearing ability.

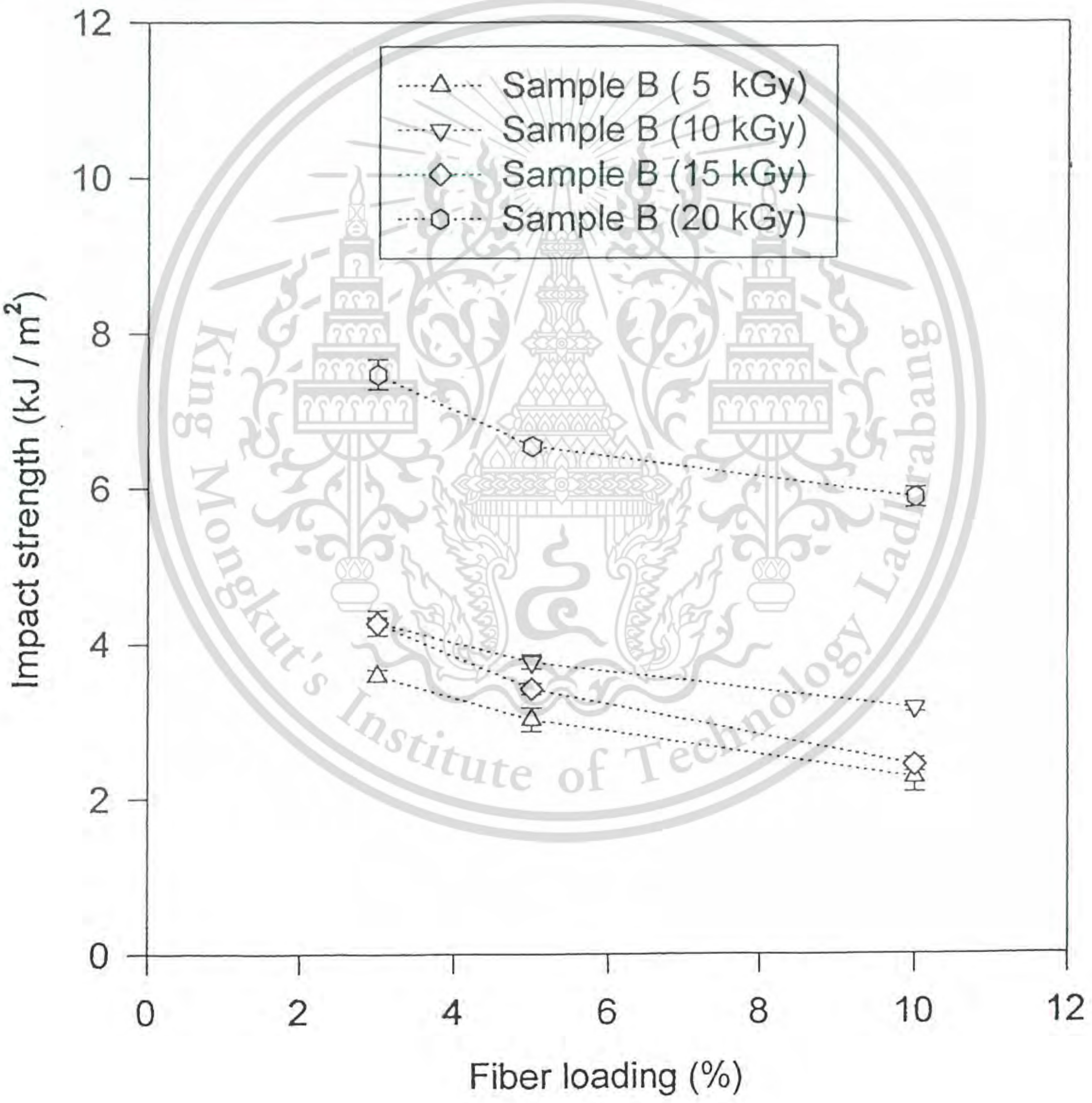


Figure 4.20 Effect of % fiber loading on impact strength of sample B (unextracted & grafted (5- 20 kGy) bamboo fiber / ABS composites)

4.7 Effect of the the unextracted & grafted (15 kGy) and extracted &grafted (15 kGy) bamboo fiber / ABS composites

Bamboo fibers before and after solvent extraction were grafted with PMMA γ - ray irradiation at the same amount of total dose (15 kGy) in order to study the effect of the extractives on grafting on the fibers. From Figures 4.21 and 4.22, it was found that sample D (extracted & grafted bamboo fiber / ABS composites) had higher tensile strength and modulus than sample B (unextracted & grafted bamboo fiber / ABS composites) at all three fiber volume fractions (3, 5, and 10 phr). This could be explained by the better interfacial bonding at the extracted and grafted composites. After the solvent extraction, the extractives, contaminates and weak layers were removed from the fiber surfaces resulting the cleaner surfaces.

When the extracted fibers were irradiated in the presence of the monomer (MMA) the clean surfaces yielded better contact areas for surface grafting. It has been known that the chemical composition of fibers in the form of aromatic compounds, such as, lignin can retard and inhibit the free - radicals generated on the fiber surfaces by γ - ray irradiation [77]. SEM and tensile testing results also confirmed that the extracted & grafted composites had a better interfacial bonding between the fibers and the polymer matrix.

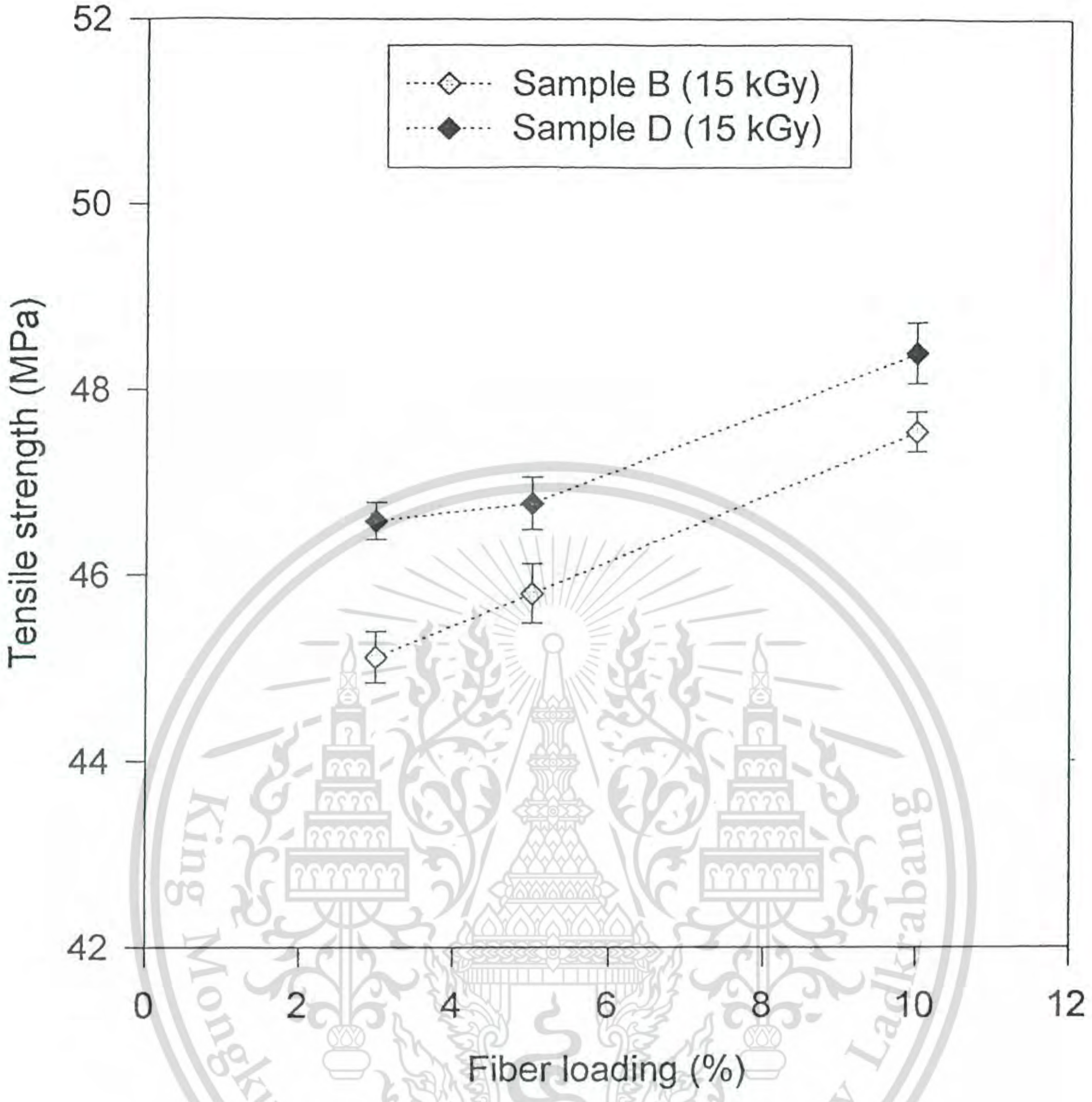


Figure 4.21 Effect of % fiber loading on tensile strength of sample B (unextracted & grafted (15 kGy) bamboo fiber / ABS composites) and sample D (extracted & grafted (15 kGy) bamboo fiber / ABS composites)

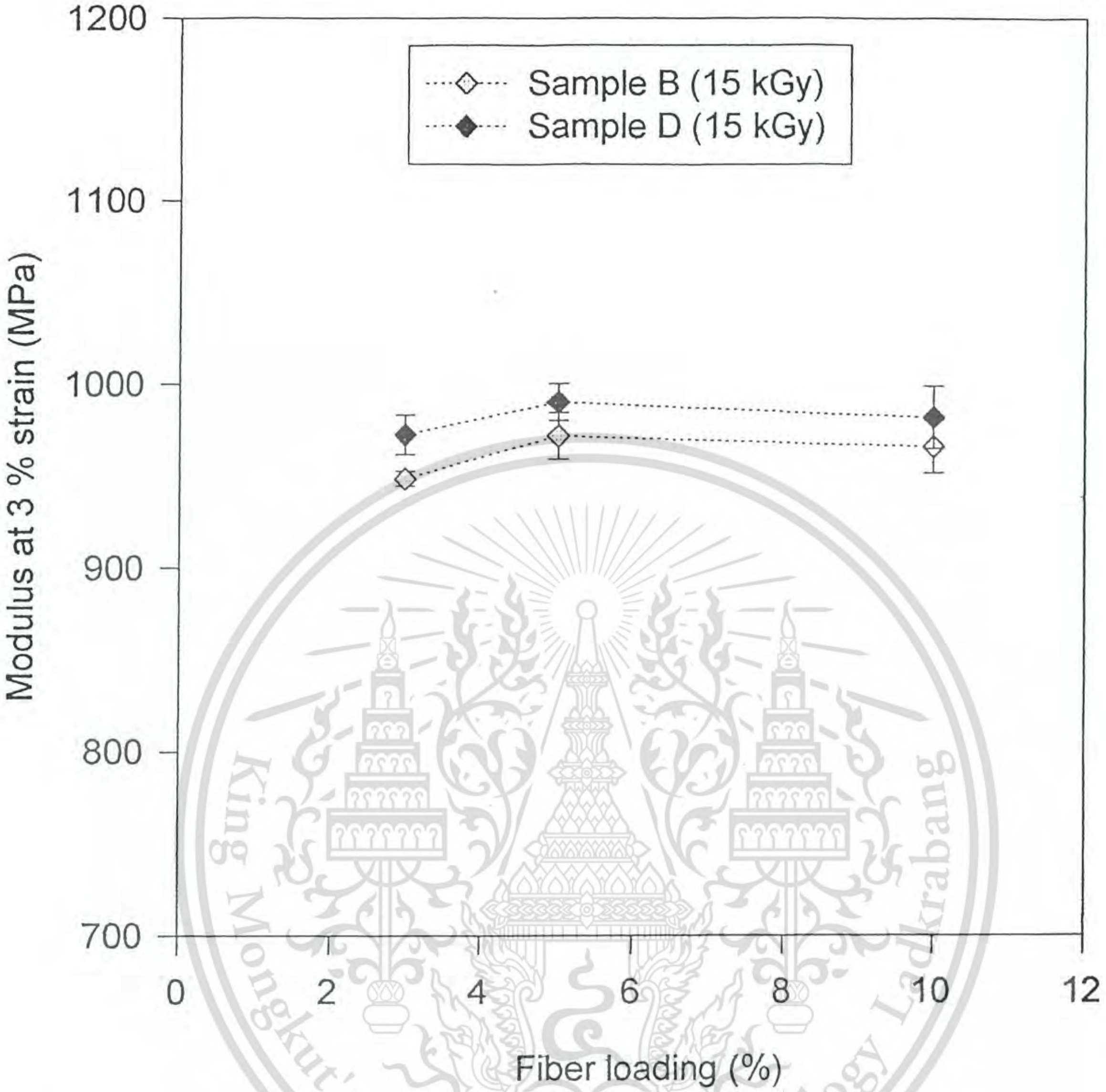


Figure 4.22 Effect of % fiber loading on modulus at 3 % strain of sample B (unextracted & grafted (15 kGy) bamboo fiber / ABS composites) and sample D (extracted & grafted (15 kGy) bamboo fiber / ABS composites)

Figure 4.23 shows effect of the extractive on grafting of the fibers on % elongation at break of sample B and sample D. Both composites (sample B and D) showed lower % elongation at break as the % fiber loading increased. By comparing sample B and D, the effect was seen clearer at higher % fiber loading (5 and 10 phr). It was found that % elongation at break of sample D was lower than those of the unextracted ones. This could be explained that the extracted fibers had the cleaner surface resulting in the better grafting on the fibers. The higher extent of grafting and chain entanglement of the extracted & grafted bamboo fiber / ABS composites yielded the lower % elongation at break.

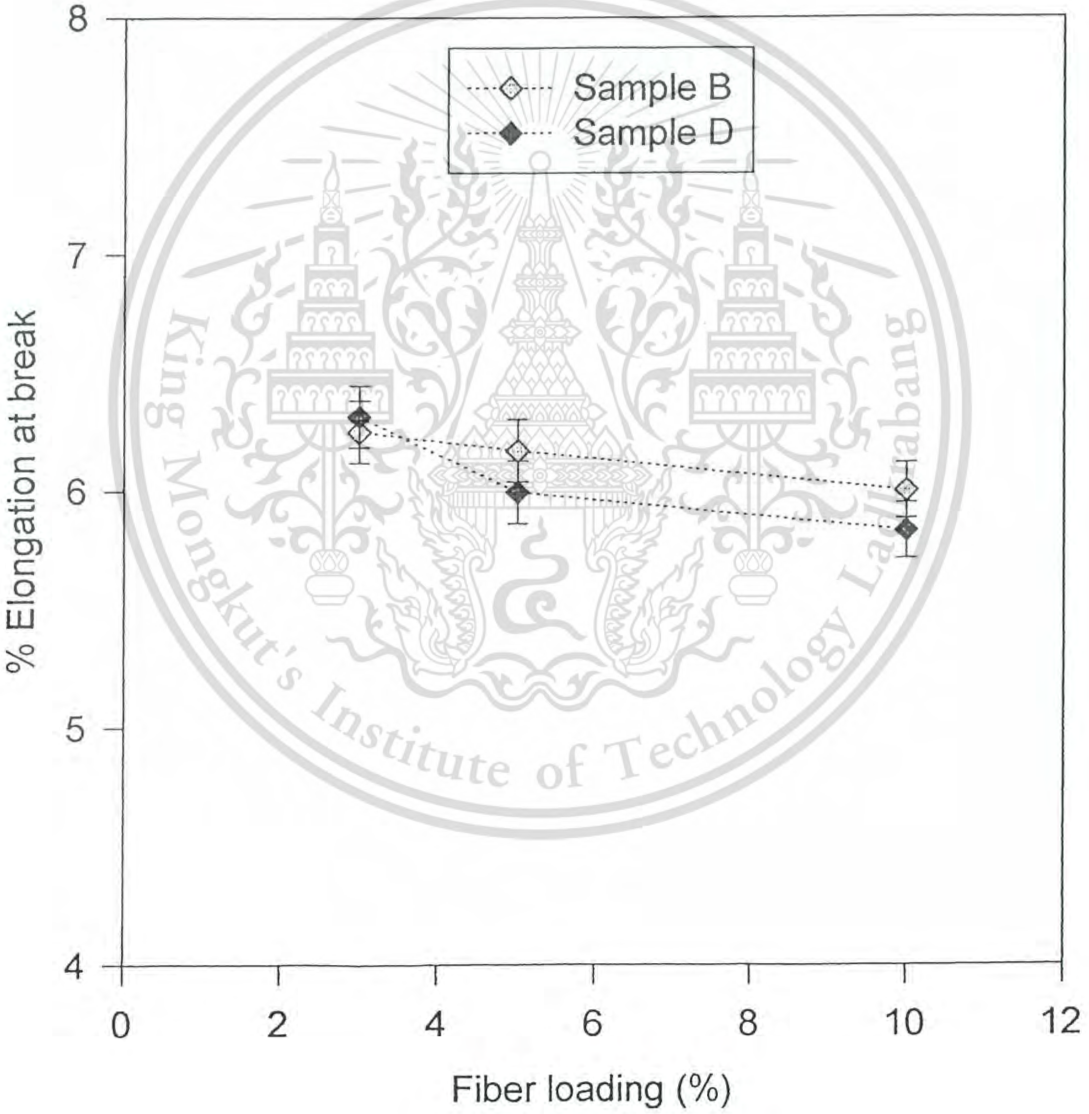


Figure 4.23 Effect of % fiber loading on % elongation at break of sample B (unextracted & grafted (15 kGy) bamboo fiber / ABS composites) and sample D (extracted & grafted (15 kGy) bamboo fiber / ABS composites)

Similarly, Figure 4.24 shows the effect of the extractives on grafting of the fibers on impact strength of sample B (unextracted & grafted (15 kGy) bamboo fiber / ABS composites) and sample D (extracted & grafted (15 kGy) bamboo fiber / ABS composites). It was obviously seen that sample D had higher impact strength than sample B at all % fiber loading.

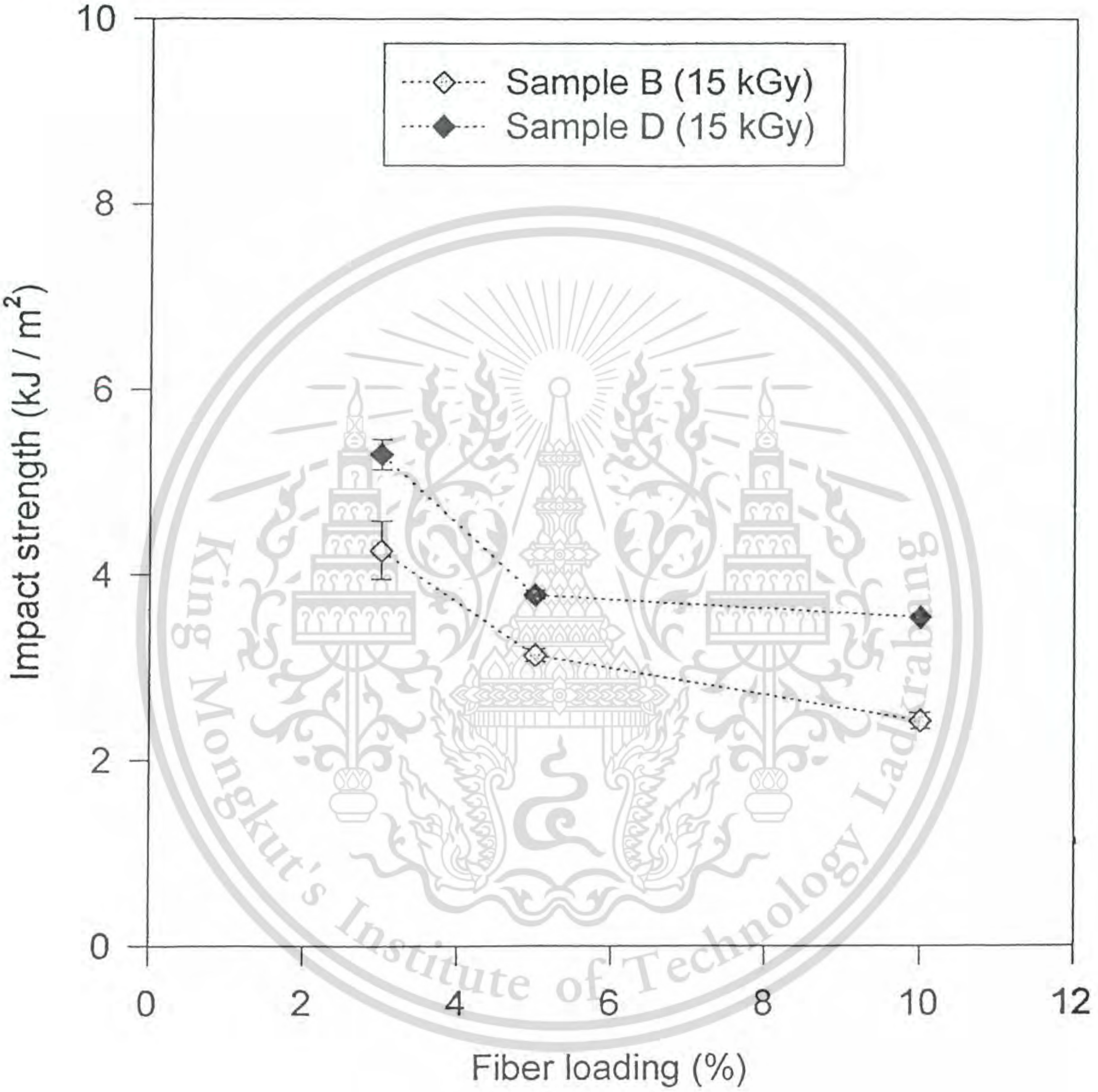


Figure 4.24 Effect of % fiber loading on impact strength of sample B (unextracted & grafted (15 kGy) bamboo fiber / ABS composites) and sample D (extracted & grafted (15 kGy) bamboo fiber / ABS composites)

4.8 Effect of % water absorption with soaking time of the unextracted & ungrafted and extracted & ungrafted bamboo fiber / ABS composites

% Water absorption increased with soaking time and reached a constant moisture content (an equilibrium) within about 1,000 hours soaking time for all samples of different the % fiber loading. The results were shown in Figure 4.25 as the plot of % water absorption vs. soaking time. It was found that % water absorption of sample A (unextracted & ungrafted bamboo fiber / ABS composites) increased with increasing the fiber content. It can be explained that the cellulose in the fibers had some polar groups, e.g., free hydroxyl groups where are attractive to water by hydrogen bonding. The fibers also had porous structure which water can penetrate easily. So the fibers can absorb higher amount of water as the fiber loading increased.

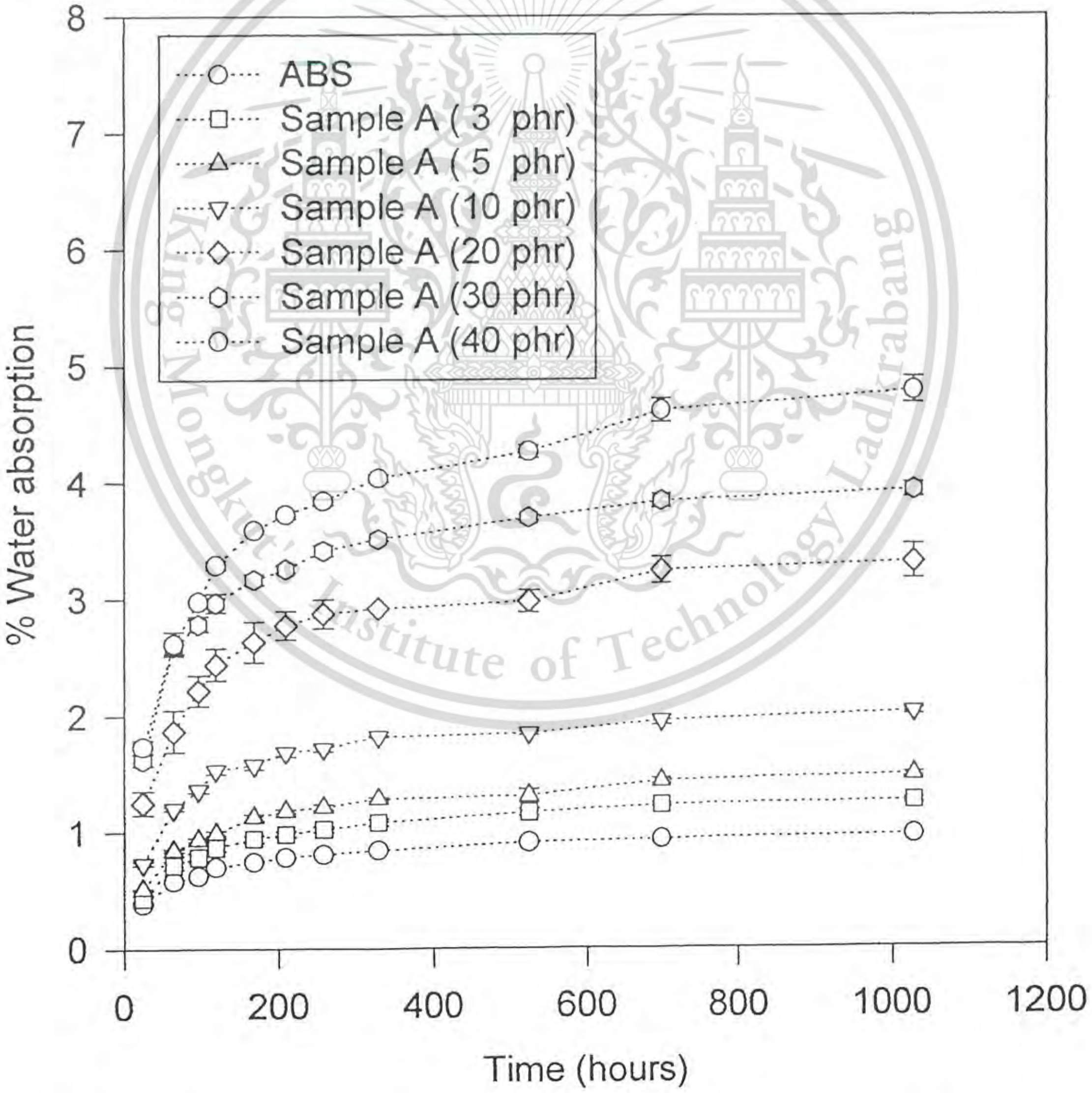


Figure 4.25 Effect of time on % water absorption of ABS and sample A (unextracted & ungrafted bamboo fiber / ABS composites) (0 - 40 phr)

The comparison of % water absorption of sample A (unextracted & ungrafted bamboo fiber / ABS composites) and sample C (extracted & ungrafted bamboo fiber / ABS composites) was shown in Figure 4.26. It was found that sample C had slightly higher % water absorption than sample A. As explained in the previous section, when the fibers were extracted by NaOH, the free hydroxyl groups generated in amorphous region were increased resulting in the increase of absorb water [85].

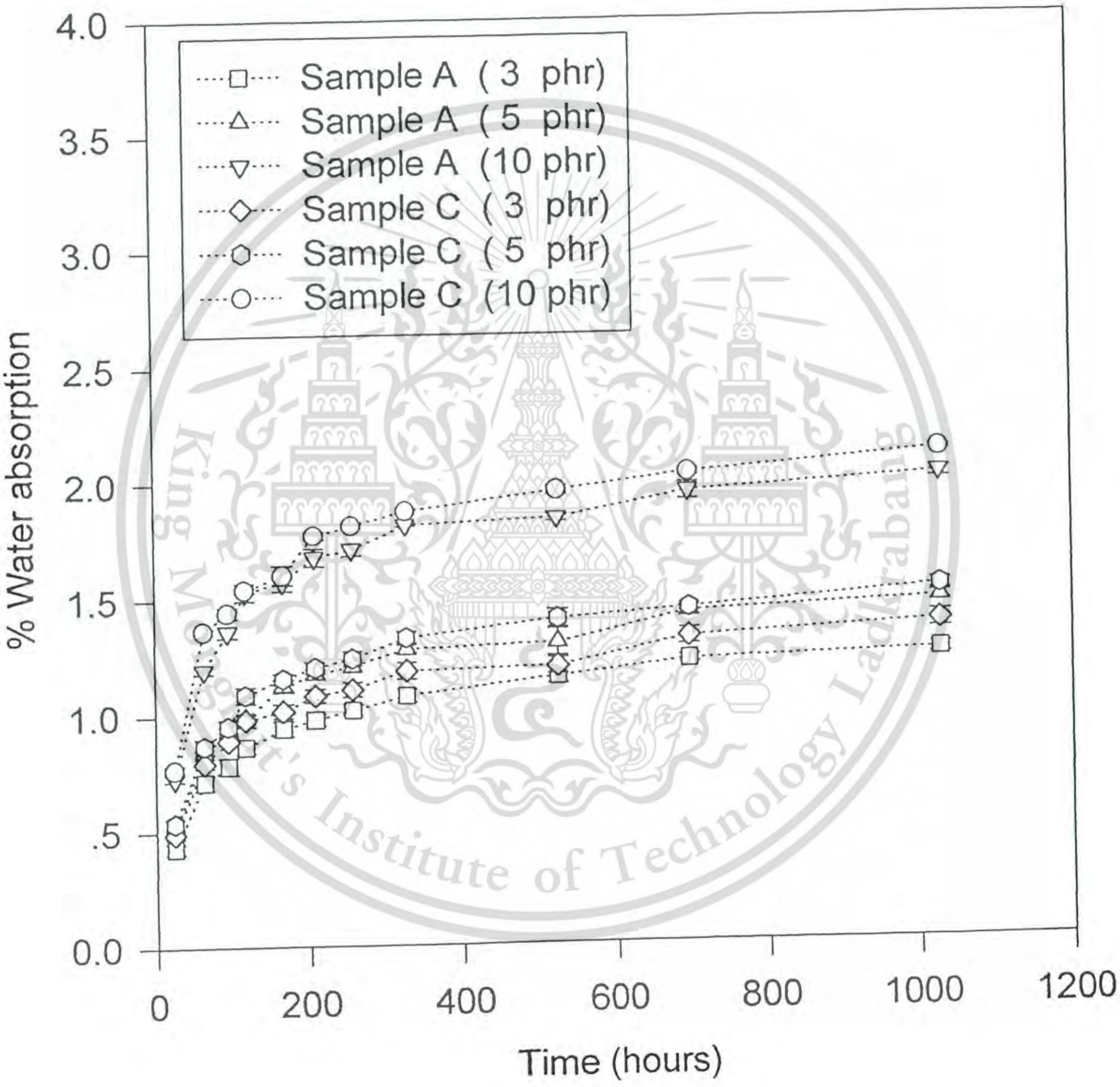


Figure 4.26 Effect of time on % water absorption of sample A (unextracted & ungrafted bamboo fiber / ABS composites) and sample C (extracted & ungrafted bamboo fiber / ABS composites) (3 - 10 phr)

4.9 Effect of the total irradiation dose on % water absorption of the unextracted & grafted and extracted & grafted bamboo fiber / ABS composites

% Water absorption was measured by soaking sample B (unextracted & grafted bamboo fiber / ABS composites) for about 1,000 hours in water. Figure 4.27 shows the results of % water absorption of the unextracted & grafted bamboo fiber / ABS composites vs. soaking time. By varying the total dose in the range of 0 to 20 kGy of γ - ray irradiation on the fibers, the effect of total dose on % water absorption was studied by using the composites with the same fiber loading (10 phr). It was also noticed that the % water absorption decreased with the increase of % grafting. In grafting reaction by irradiation, the hydroxyl groups of the cellulose in the fibers were replaced by PMMA polymer chains which are less active for water. This is the reason why % water absorption was decreased as % grafting increased.

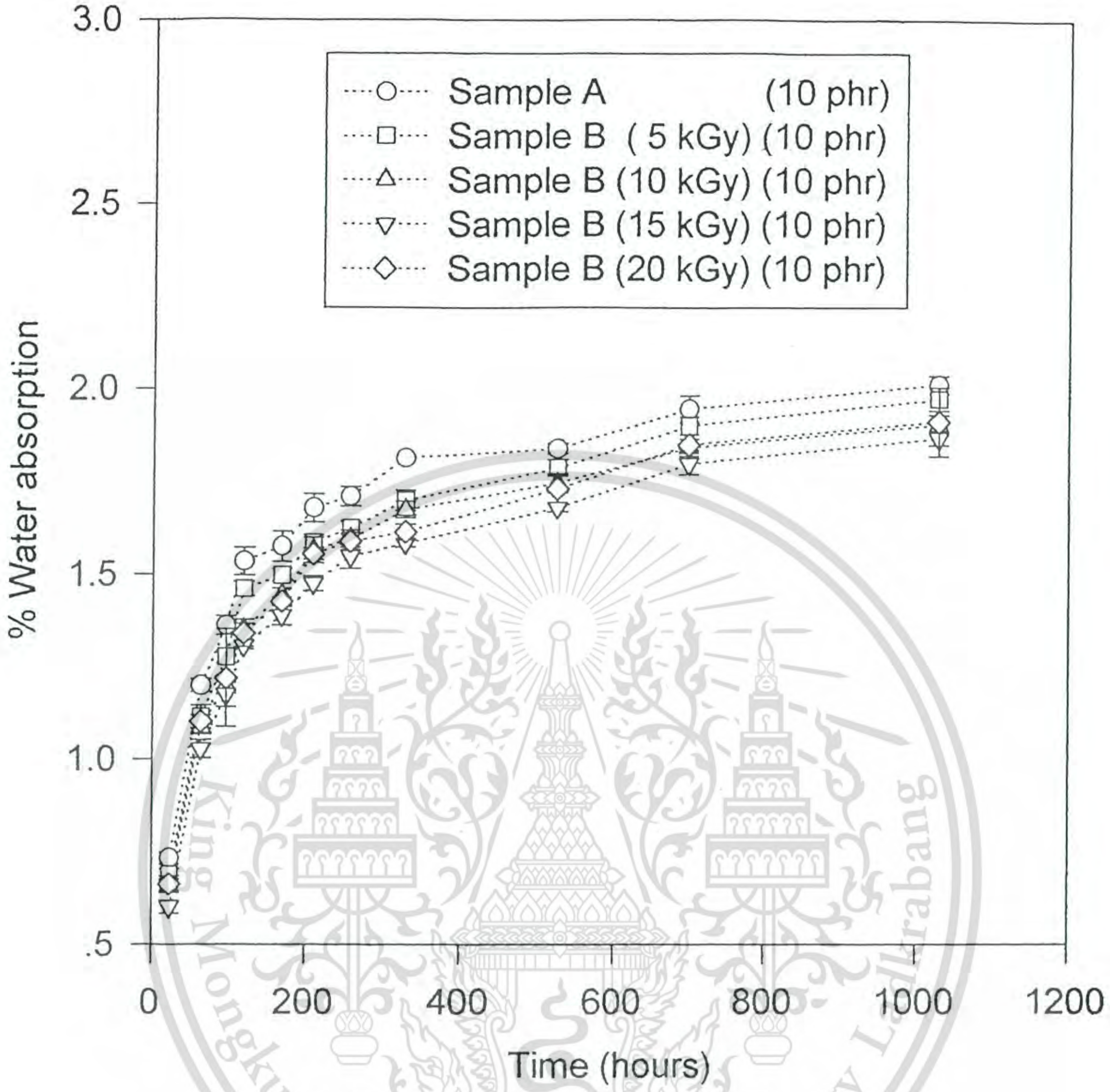


Figure 4.27 Effect of time on % water absorption by varying the total irradiation dose (0 - 20 kGy) of sample B (unextracted & grafted bamboo fiber / ABS composites) (10 phr)

Figure 4.28 shows the results of % water absorption of the composites at fixed total dose (15 kGy), but varied % fiber loading with soaking time. It was seen that sample D (extracted & grafted bamboo fiber / ABS composites) absorbed higher amount of water than sample B (unextracted & grafted bamboo fiber / ABS composites). The effect was seen clearer at higher % fiber loading (10 phr). The result was similar to the ungrafted one. As pointed out earlier, the amount of % water absorption increased with increasing the fibers in the composites. As explained previously in the topic of 4.8, % water absorption was increased because the free hydroxyl groups in the fibers increased by NaOH treatment.

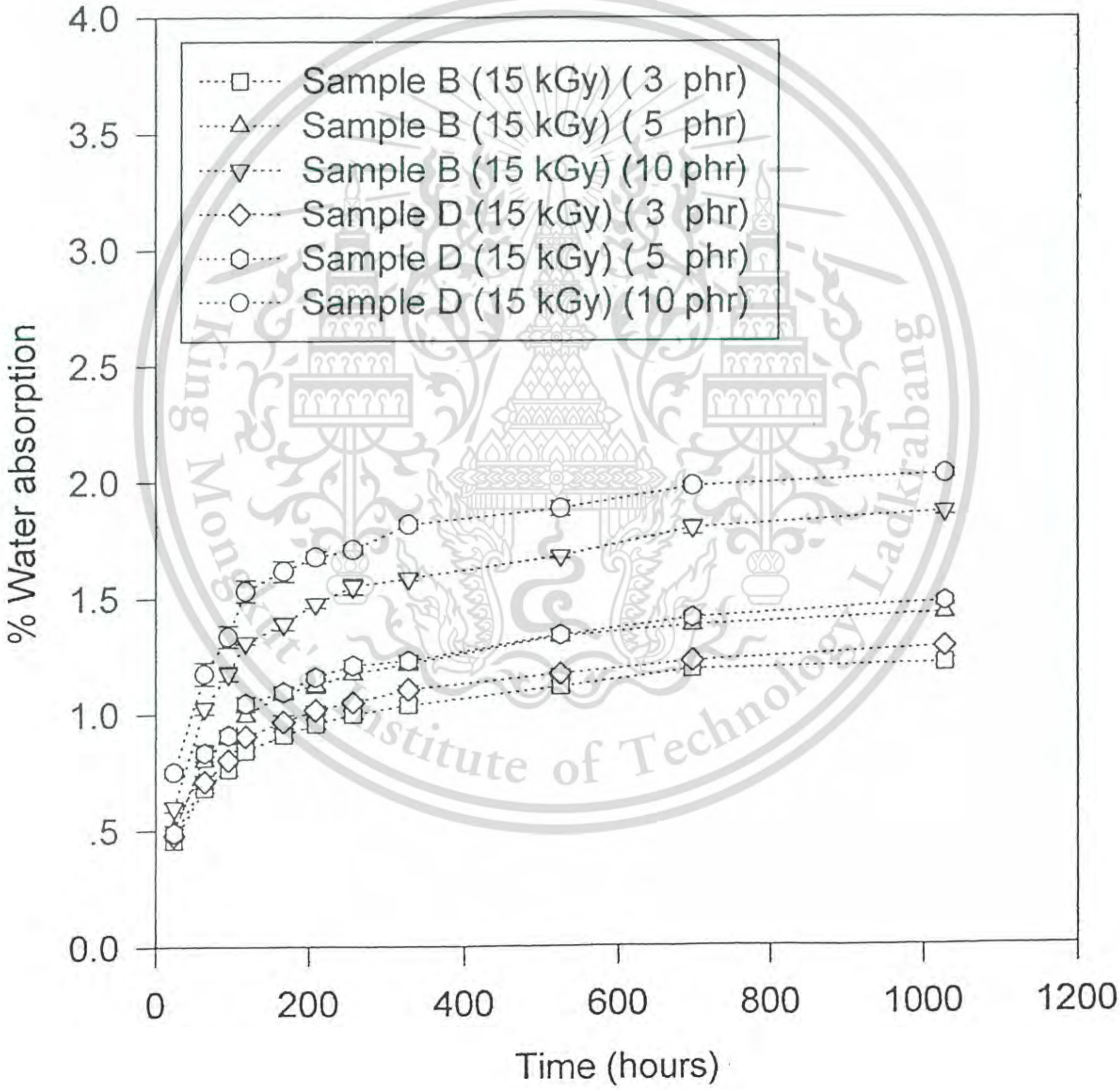


Figure 4.28 Effect of time on % water absorption of sample B (unextracted & grafted (15 kGy) bamboo fiber / ABS composites) and sample D (extracted & grafted (15 kGy) bamboo fiber / ABS composites) (3 - 10 phr)

4.10 Effect of % fiber loading on moisture content of the bamboo fiber / ABS composites

The moisture content results also agreed with the water absorption results. In Figure 4.29, it was observed that higher moisture absorption of the composites with more addition of the fibers since the fibers can absorb water from humid atmosphere. Moisture content of sample C (extracted & ungrafted bamboo fiber / ABS composites) was slightly higher than sample A (unextracted & ungrafted bamboo fiber / ABS composites) as seen in Figure 4.30. Figure 4.31 shows % fiber loading on moisture content of sample D extracted & grafted (15 kGy) bamboo fiber / ABS composites) and sample B (unextracted & grafted (15 kGy) bamboo fiber / ABS composites). It was found that sample D had higher moisture content than sample B.

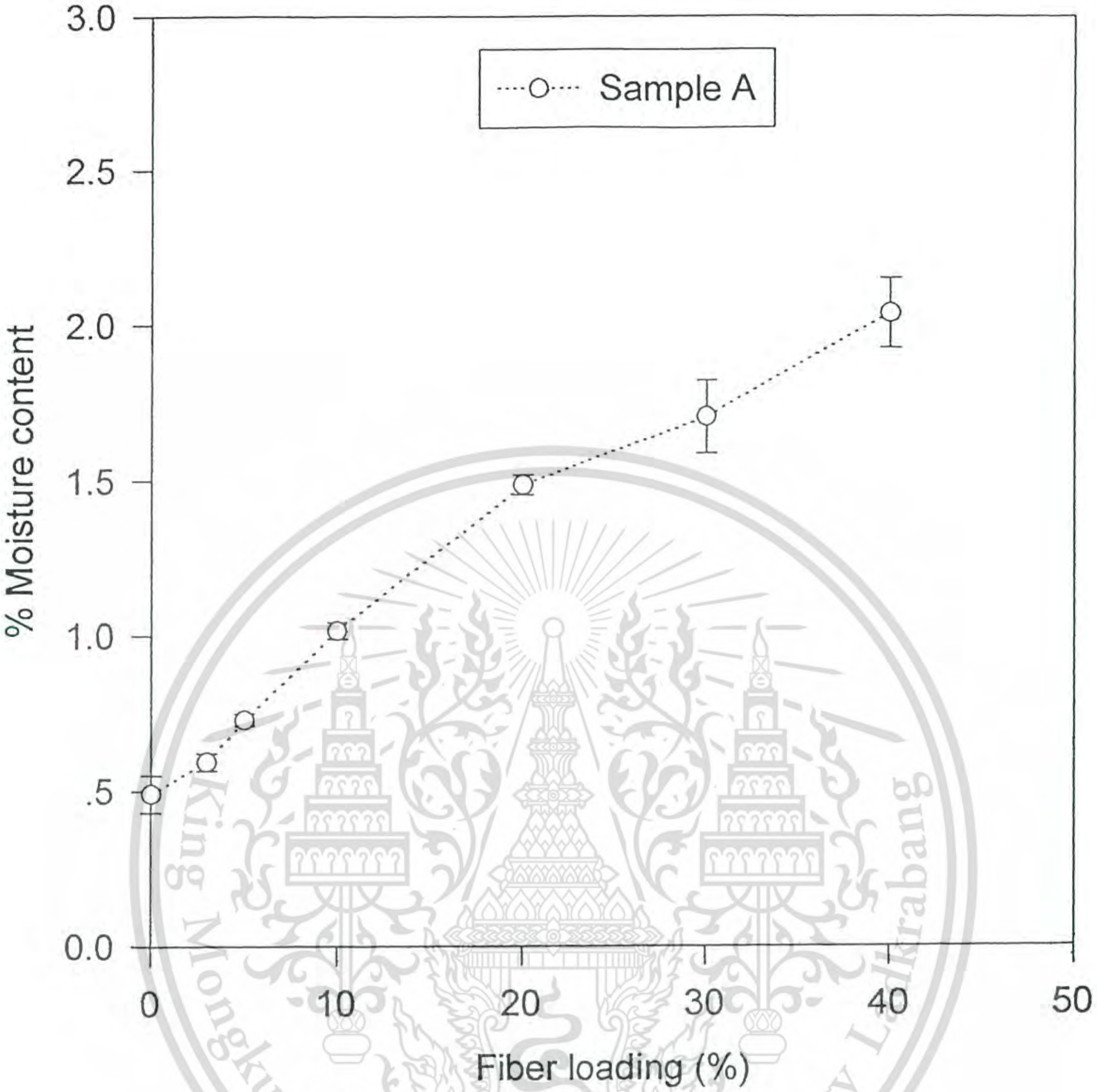


Figure 4.29 Effect of % fiber loading on % moisture content of sample A (unextracted & ungrafted bamboo fiber / ABS composites)

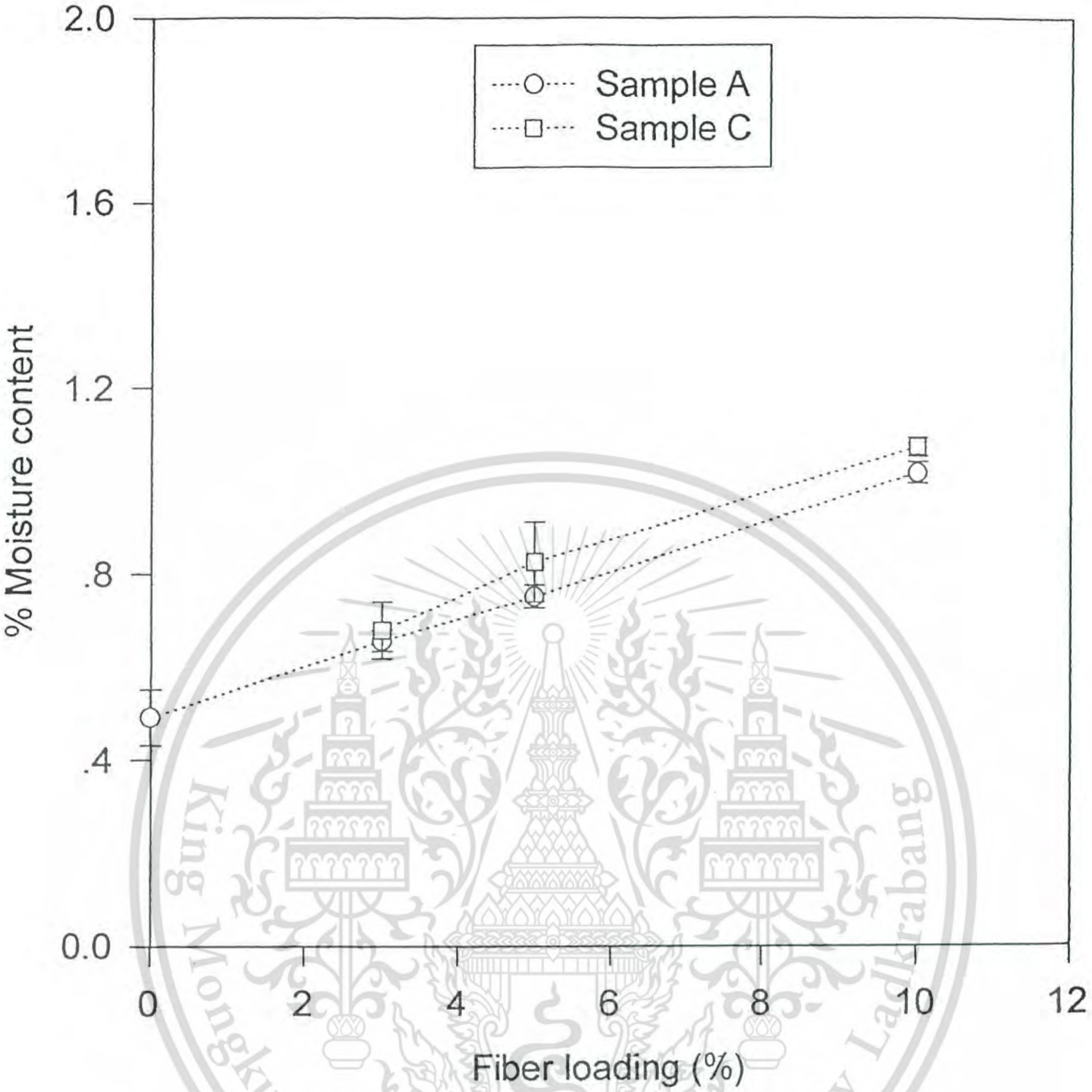


Figure 4.30 Effect of % fiber loading on % moisture content of sample A (unextracted & ungrafted bamboo fiber / ABS composites) and sample C (extracted & ungrafted bamboo fiber / ABS composites)

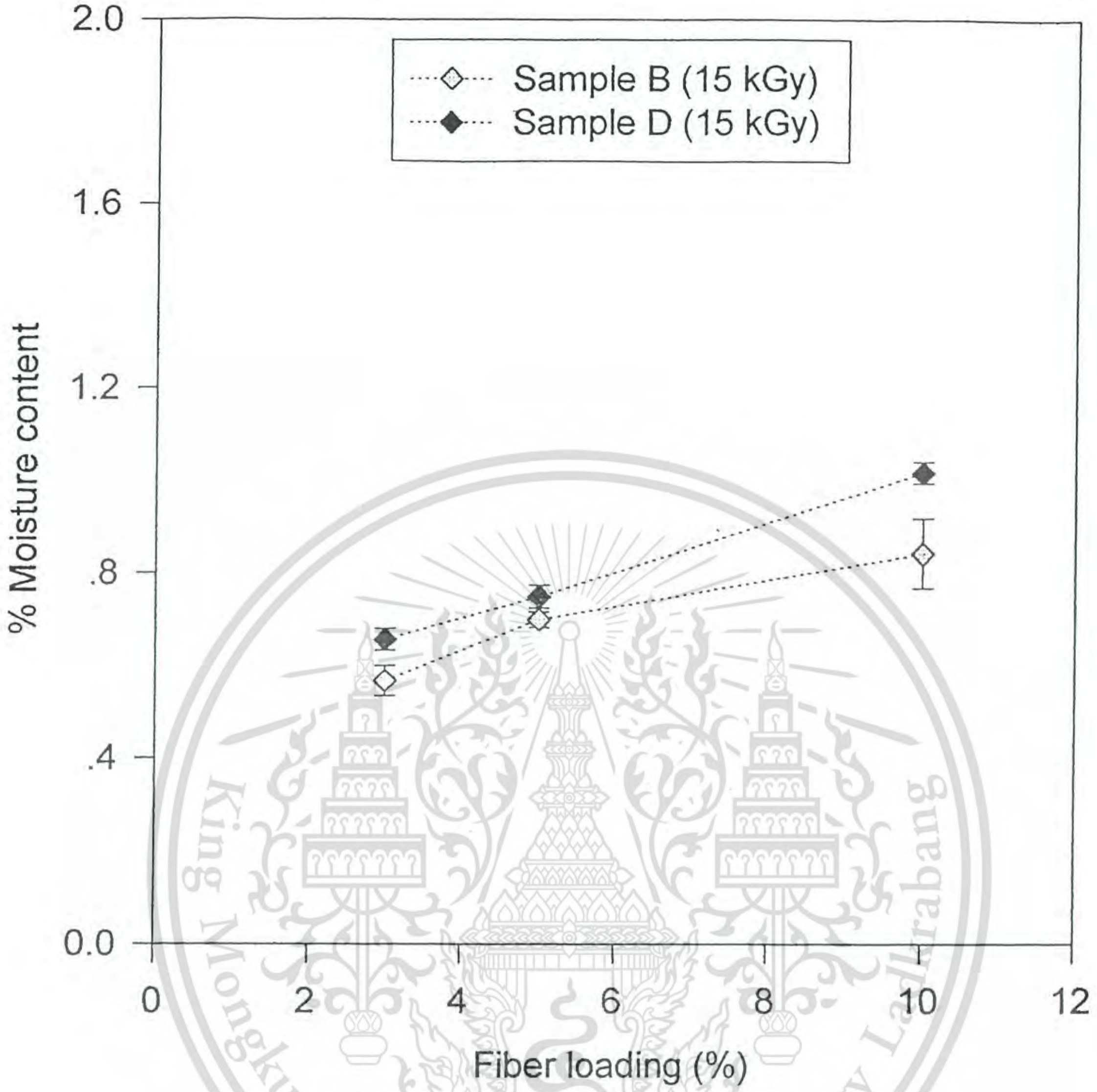


Figure 4.31 Effect of % fiber loading on % moisture content of sample B (unextracted & grafted bamboo fiber / ABS composites) and sample D (extracted & grafted bamboo fiber / ABS composites)

4.11 Effect of the unextracted & ungrafted and extracted & ungrafted bamboo fibers on hardness of the composites

By varying the % fiber loading in the range of 0 to 40 phr on the composites, the hardness of the composites was studied and shown in Figure 4.32. The results show that the hardness of sample A (unextracted & ungrafted bamboo fiber / ABS composites) was increased as % fiber loading increased. It could be described that addition of the fibers reduce ductility of the composites because of the introduction of the fibers with higher stiffness and modulus compared to the matrix.

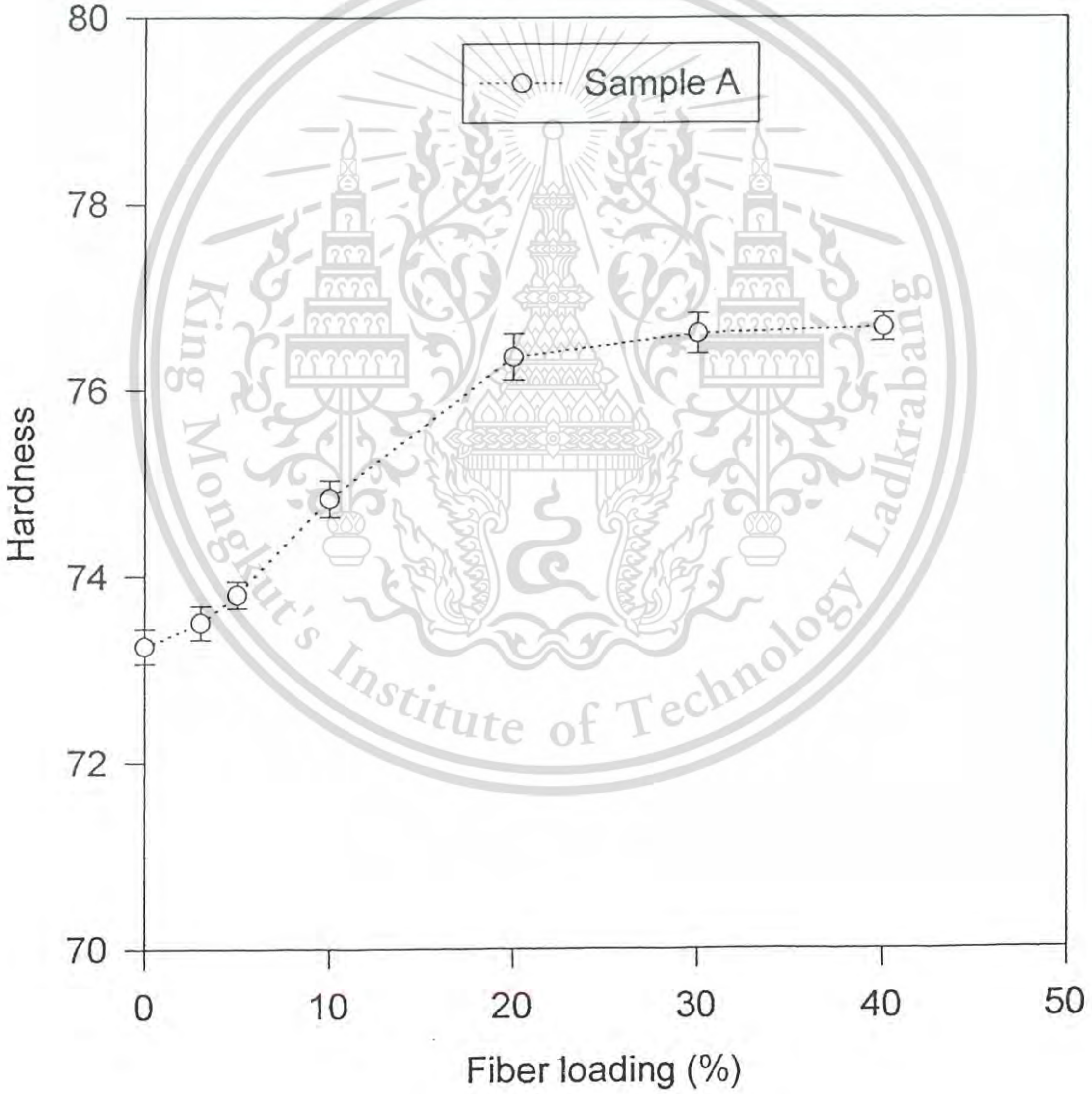


Figure 4.32 Effect of % fiber loading on hardness of sample A (unextracted & ungrafted bamboo fiber / ABS composites)

As seen in Figure 4.33, sample C (extracted & ungrafted bamboo fiber / ABS composites) had higher hardness than sample A (unextracted & unextracted bamboo fiber / ABS composites). This phenomenon could be explained that the presence of waxes and resins in the fibers weakens the bonding between the polymer and the fibers in sample A. By extracting the fibers, the waxes, resins, and a part of the hemicellulose were removed by methanol - benzene and NaOH aqueous solution [73].

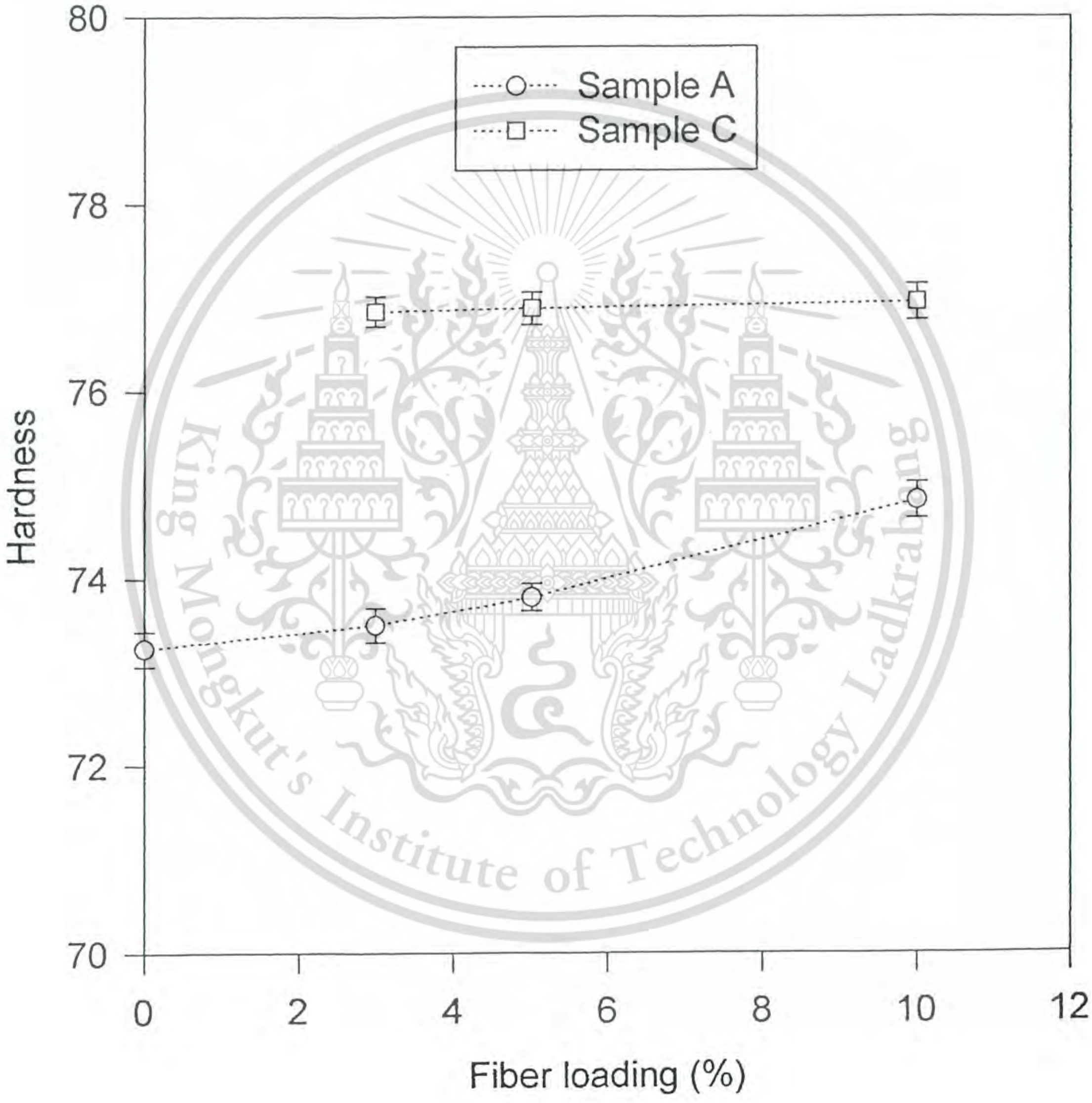


Figure 4.33 Effect of % fiber loading on hardness of sample A (unextracted & ungrafted bamboo fiber / ABS composites) and sample C (extracted & ungrafted bamboo fiber / ABS composites)

4.12 Effect of the total irradiation dose on hardness of the unextracted & grafted and extracted & grafted bamboo fiber / ABS composites

Figure 4.34 shows the results of the total dose on hardness of sample B (unextracted & grafted bamboo fiber / ABS composites) by varying % fiber loading. It was found that the hardness was slightly decreased with more addition of the grafted fibers in the composites. This phenomenon could be explained that the irradiated fibers could be introduced a decrease in the hardness of the composites since the fibers may be brittle or degrade during irradiation. At the total dose of 15 kGy, the composites had the highest hardness because of the PMMA is a glassy polymer with low impact strength, with the increase in the PMMA graft add - on via irradiation, the amount of glassy domain in the composites was increased. That makes the fibers rigid but brittle. The total dose of 20 kGy had the lowest hardness because of the overdose irradiation can cause the degradation of the fibers yielding the lower strength fibers. During irradiation, the β-1, 4 - glucosidic bonds can be claved and the degree of polymerization of the cellulose would decrease.

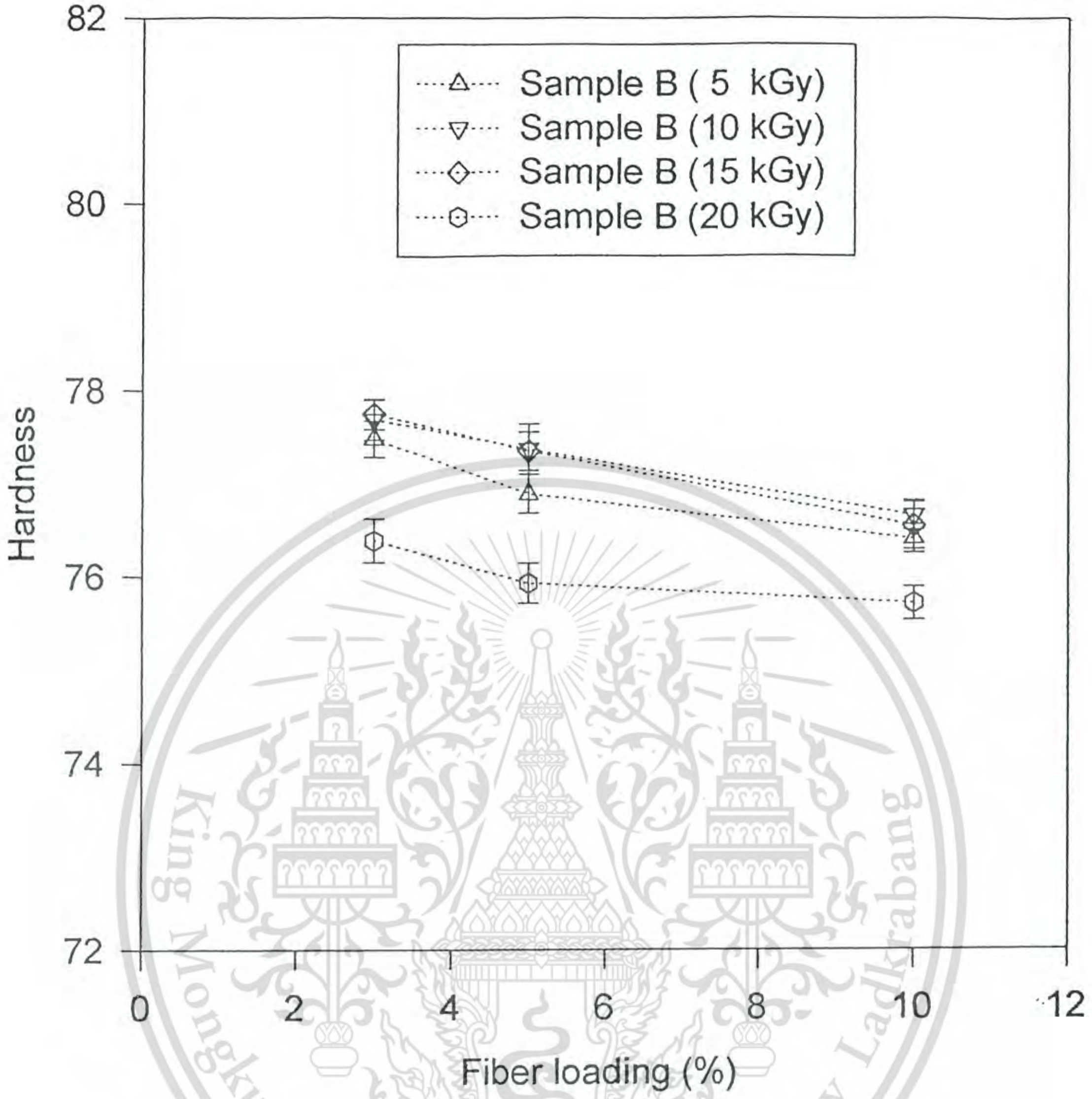


Figure 4.34 Effect of % fiber loading on hardness of sample B (unextracted & grafted (5-20 kGy) bamboo fiber / ABS composites)

Figure 4.35 shows the results of % fiber loading on hardness of sample B (unextracted & grafted bamboo fiber / ABS composites) and sample D (extracted & grafted bamboo fiber / ABS composites) at fixed total dose (15 kGy). It was seen that sample D had higher hardness than sample B but both the sample B and sample D, the hardness had in the similar effect at % fiber loading. As described above, by the extracting the fibers, the waxes, resins, and a part of the hemicellulose were removed resulting a better contact with the polymer and stronger interfacial bonding.

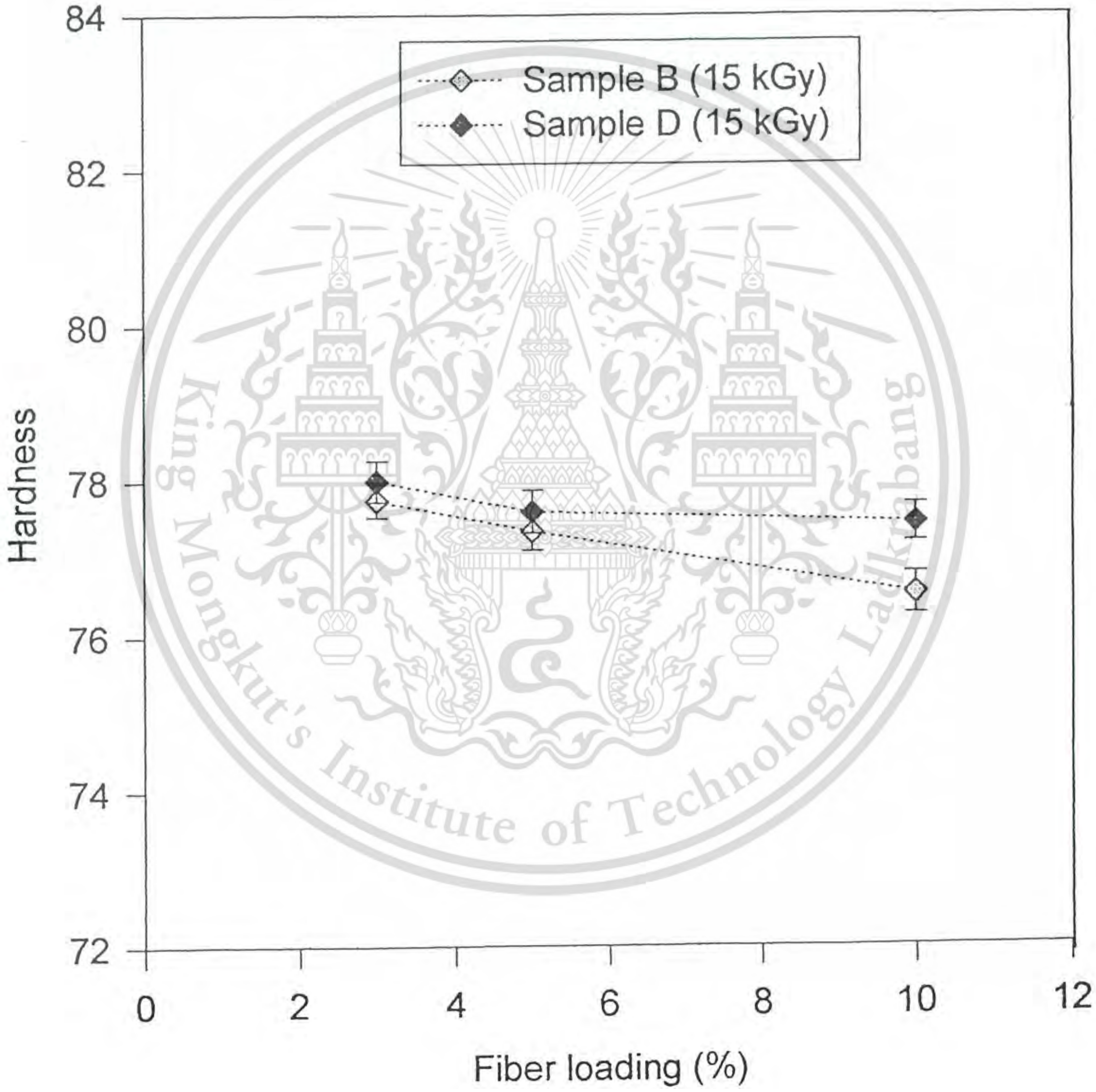


Figure 4.35 Effect of % fiber loading on hardness of sample B (unextracted & grafted (15 kGy) bamboo fiber / ABS composites) and sample D (extracted & grafted (15 kGy) bamboo fiber / ABS composites)

4.13 Density of the composites

In Figure 4.36, it was seen that density was increased as % fiber loading increased. The density of all composites was in the similar trend but the grafted bamboo fiber / ABS composites had slightly higher density than another composites. The density of the grafted samples was increased because of the increasing weight of the graft add - on PMMA in the fibers.

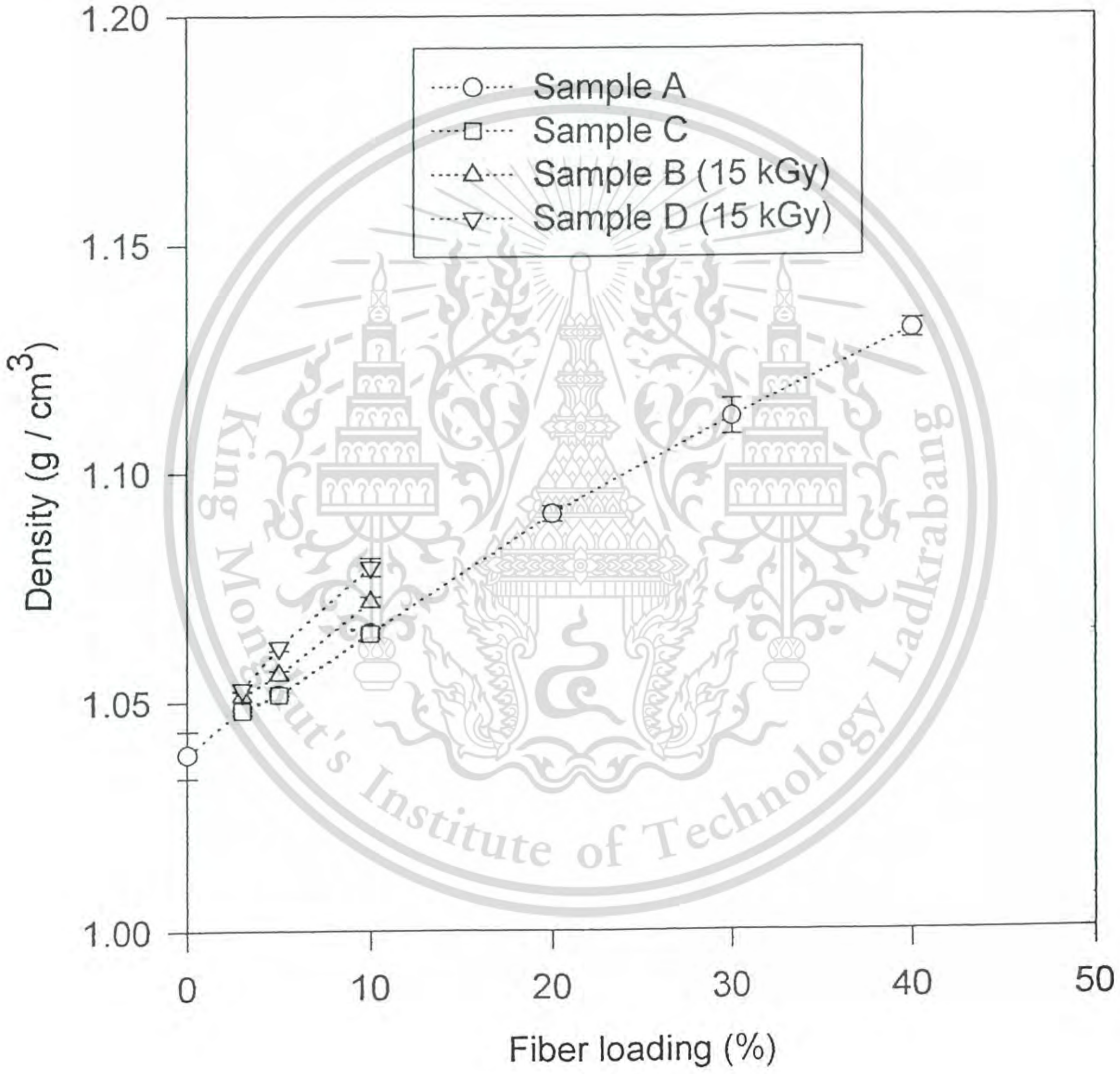


Figure 4.36 Effect of % fiber loading on density of the composites

4.14 Determination of ester group on the grafted bamboo fibers with MMA by γ - ray irradiation

Figure 4.37 shows FTIR spectrums of the unextracted & ungrafted fibers, unextracted & grafted fibers, and extracted & grafted fibers. An additional peak of the ester group at about 1,735 cm^{-1} was observed in the grafted sample thereby indicating the occurrence of grafting. FTIR spectrums of ABS and its composites were shown in the appendix D (Figures D1 to D5). Peak height at about 1,731, 2,235, 996, and 1,602 cm^{-1} are characteristic of C=O stretching of the ester group, C $\equiv$ N group in the PAN, trans - butadiene, and styrene, respectively.

The details explaination of the FTIR spectrums of the fibers can be described as follows. The broad band between 3,600 and 3,200 cm^{-1} is caused by the H-bonded O-H stretching. The OH is present in the cellulose and hemicellulose of the fibers. The usual glucose linkage in the cellulose is characterized through the C-H stretching around the 2,940 to 2,890 cm^{-1} band and 1,377 cm^{-1} . The linkage vibration is also observed at 895 cm^{-1}. The unconjugated keto groups of the lignin and C=O stretching of the uronic acid of the hemicellulose can also be observed around 1,700 cm^{-1}, but the conjugated aryl carbonyl stretching can be noticed at 1,644 cm^{-1} and the aromatic skeletal vibration at 1,497 cm^{-1}. The asymmetric C-H deformation present in methyl and methylene groups is observed by the 1,454 cm^{-1} band. The aromatic skeletal of the lignin is observed at 1,418 cm^{-1} and 1,497 cm^{-1}. The peak at 1,318 cm^{-1} is attributed to the aromatic ring breathing with C-O stretching in syringyl units of the lignin ; but the peak at 1,111 cm^{-1} is due to the aromatic C-H in plane deformation of guaiacyl and syringyl units. The antisymmetric bridge oxygen stretching is observed at the 1,156 cm^{-1} peak [86].

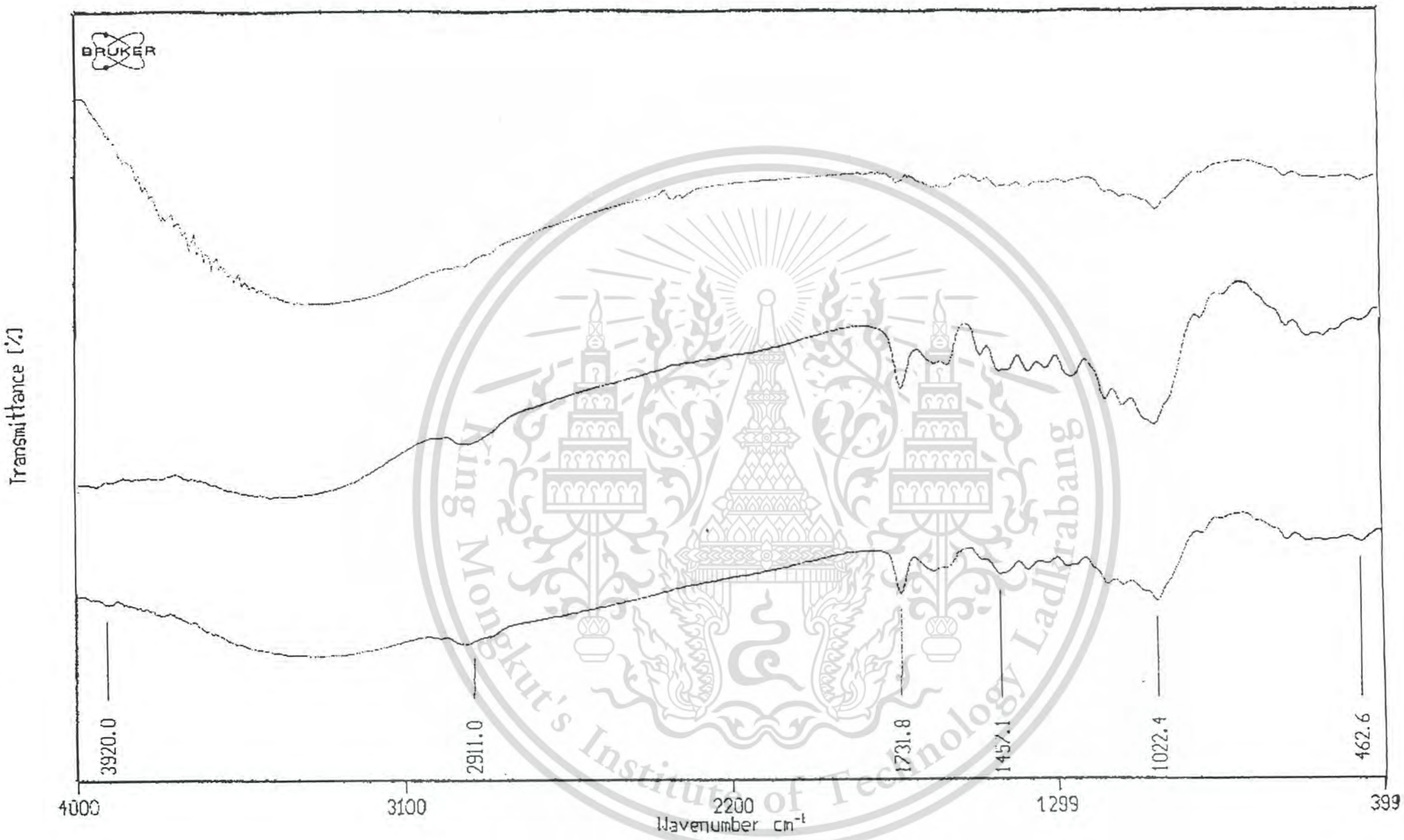


Figure 4.37 FTIR spectra of unextracted & ungrafted, unextracted & grafted, and extracted & grafted bamboo fibers

4.15 Thermal behavior of the bamboo fiber / ABS composites

Thermogravimetric analysis (TGA) of ABS and the composites was shown in Figures 4.38 to 4.45. The TGA thermogram the decomposition temperature (T_D) of which indicates thermal stability of polymer (reported onset temperature). The weight loss (T_D) of ABS occurred in the range of 270 to 440 $^\circ$C shown in Figure 4.38. Figures 4.39 and 4.45 represent thermograms of sample A (unextracted & ungrafted bamboo fiber / ABS composites), sample B (unextracted & grafted (5 - 20 kGy) bamboo fiber / ABS composites), sample C (extracted & ungrafted bamboo fiber / ABS composites), and sample D (extracted & grafted bamboo fiber / ABS composites). It was found that the temperature of the grafted bamboo fiber / ABS composites was similar to that of the ungrafted bamboo fiber / ABS composites.

L. Kessira and A. Ricard [53] reported the study of thermal behavior of ungrafted and grafted bagasse loaded with $CaCO_3$ and wood pulps by DSC and TGA. He was found that in the temperature range 30 to 153 $^\circ$C, dehydration of the samples occurs, and in the temperature range 174 to 242 $^\circ$C, the most of the cellulose was decomposed. The grafting of MMA onto the bagasse or the wood pulps improved their thermal stability. The pyrolysis of the grafted fibers with PMMA samples takes place in two steps : The first one was in the temperature range 30 to 153 $^\circ$C corresponding to the phenomenon of dehydration ; the second one from 180 to 300 $^\circ$C (depending on the grafting yield) was attributed to the degradation of the glycosyl units. At the lower temperature (~270 $^\circ$C), the radical chain unzipping reaction was characterized by unsaturated chain - end initiation. A higher temperature (~350 $^\circ$C) initiation occured randomly along the polymer chain [87].

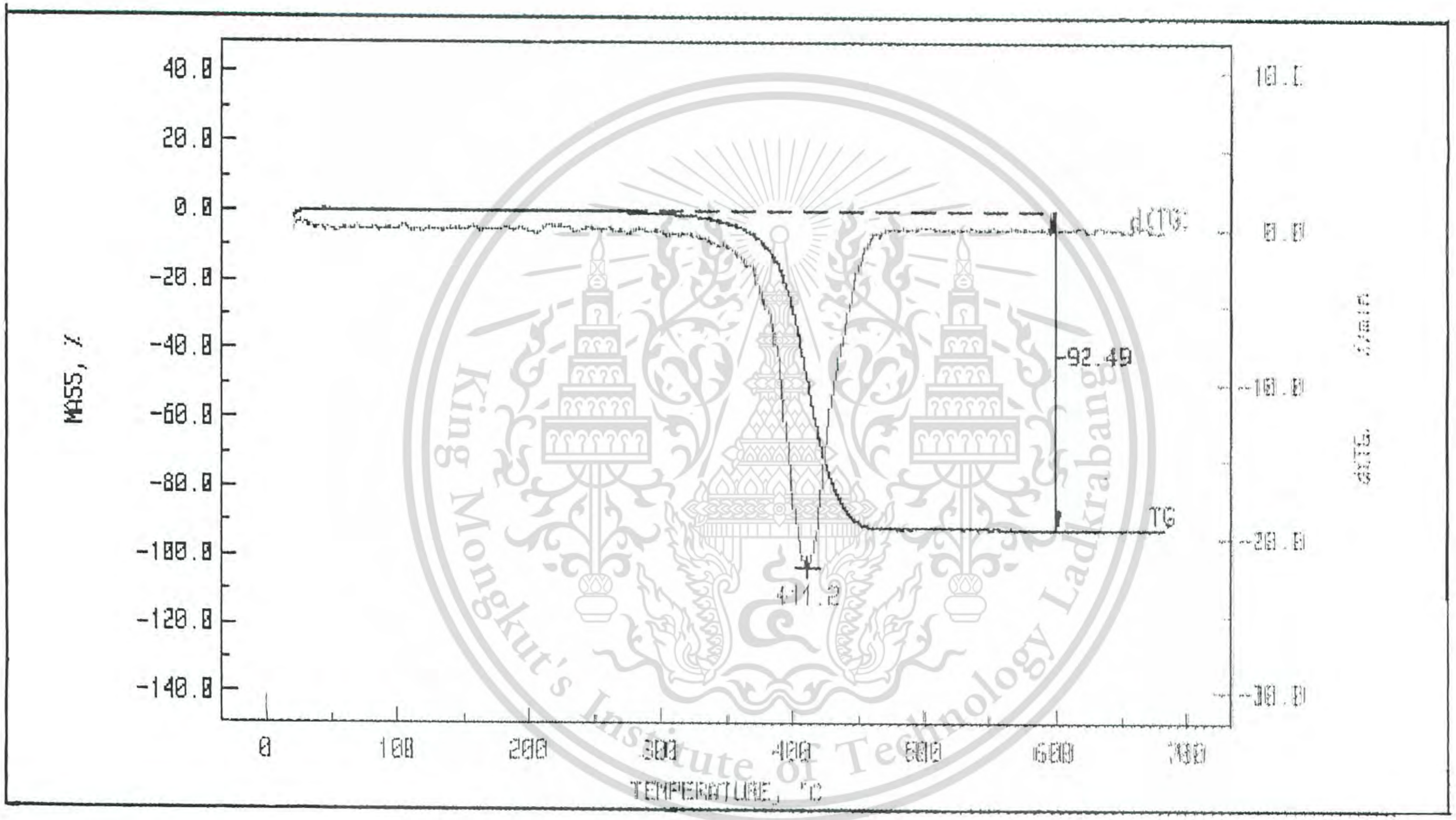


Figure 4.38 TGA thermogram of ABS

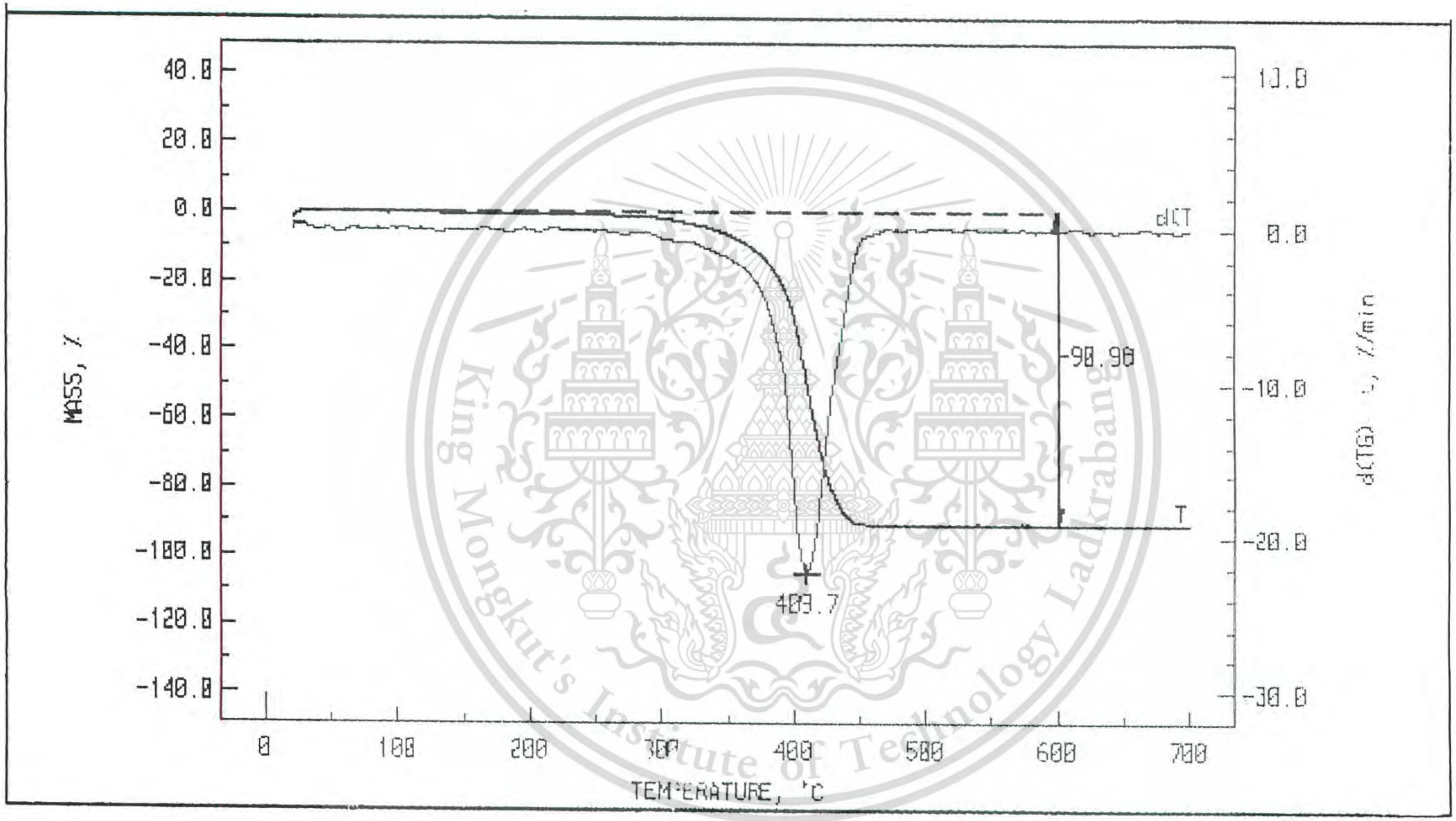


Figure 4.39 TGA thermogram of sample A (unextracted & ungrafted bamboo fiber / ABS composites) (5 phr)

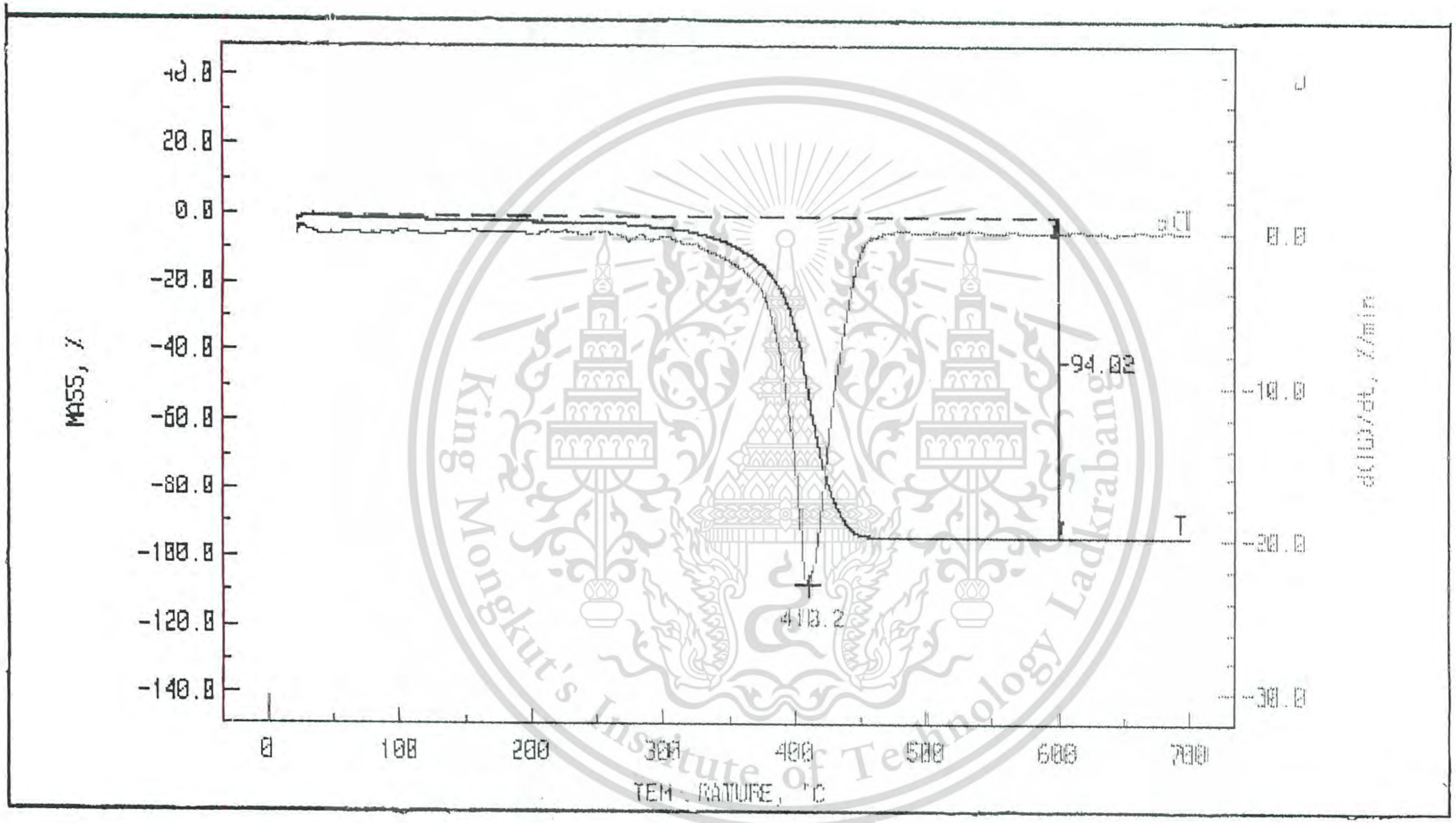


Figure 4.40 TGA thermogram of sample C (extracted & ungrafted bamboo fiber / ABS composites) (5 phr)

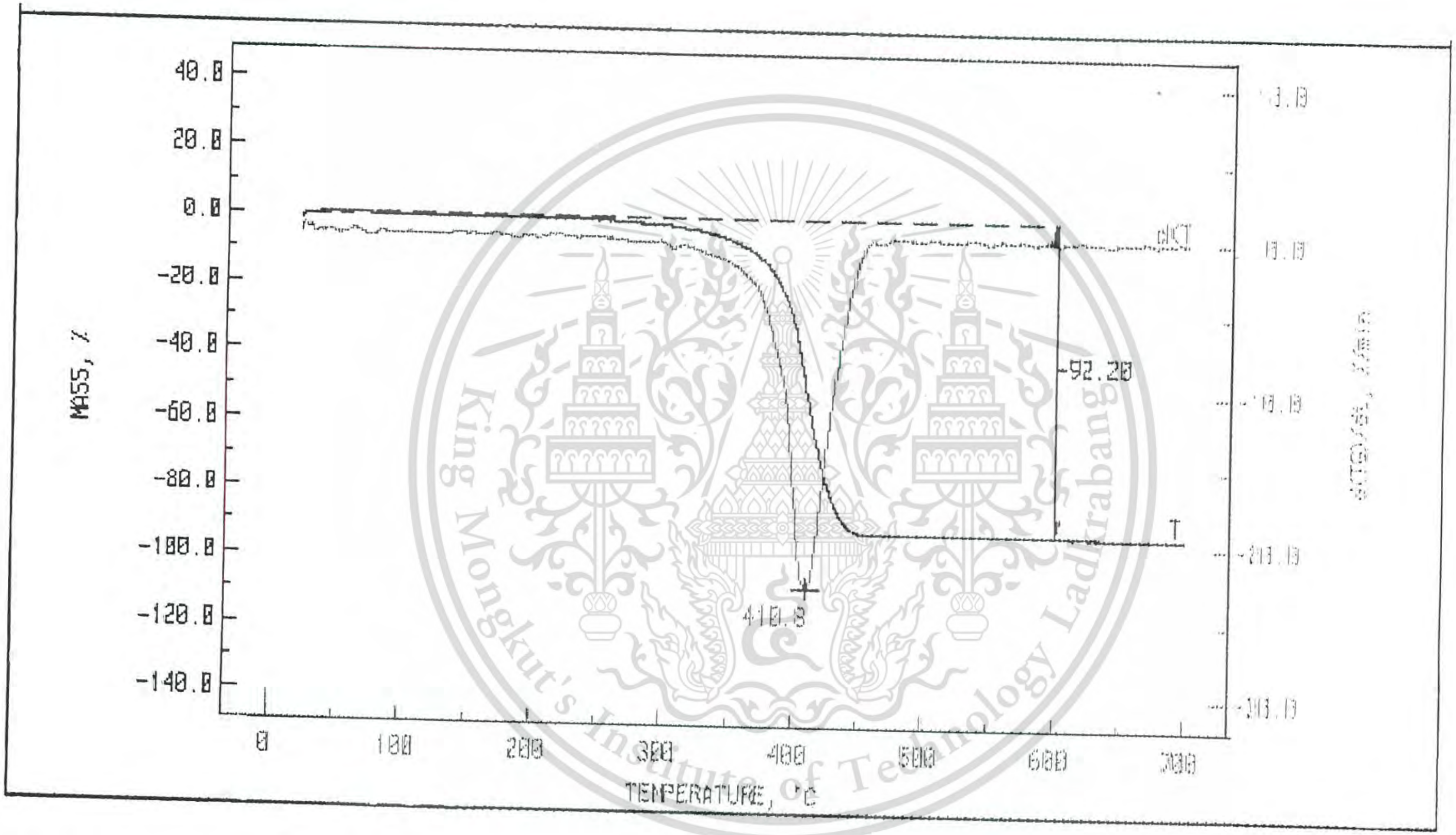


Figure 4.41 TGA thermogram of sample B (unextracted & grafted (5 kGy) bamboo fiber / ABS composites) (5 phr)

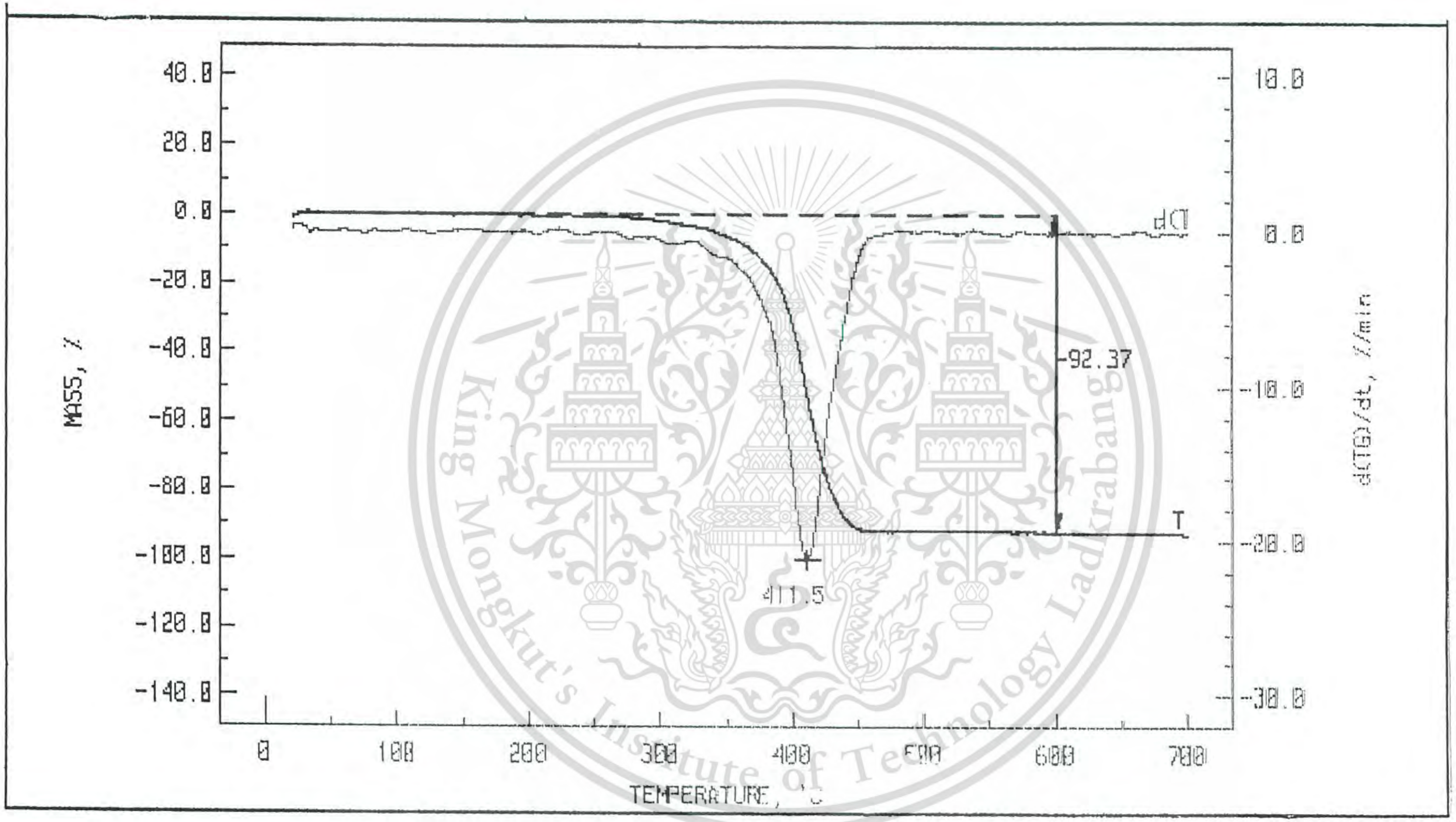


Figure 4.42 TGA thermogram of sample B (unextracted & grafted (10 kGy) bamboo fiber / ABS composites) (5 phr)

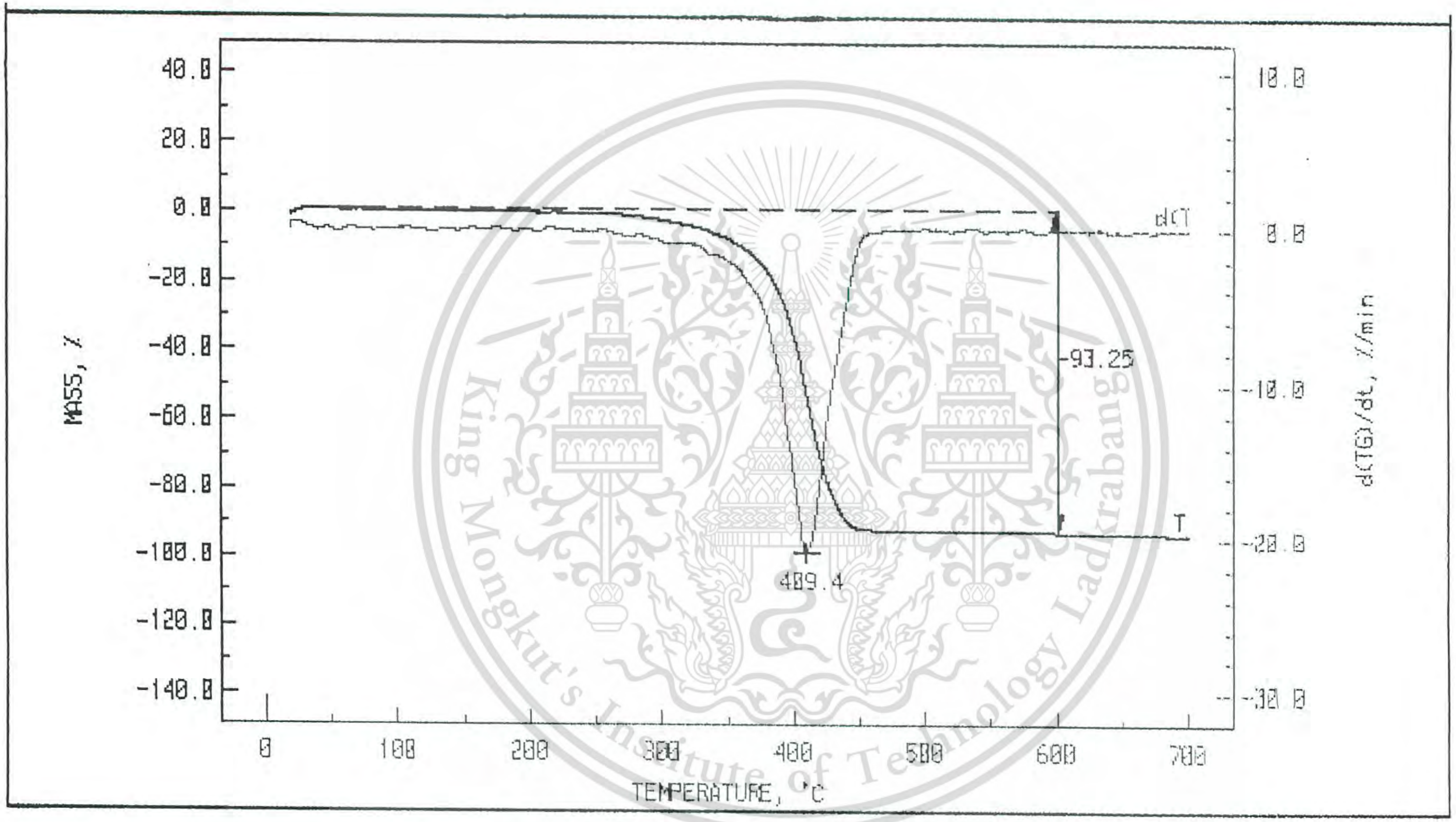


Figure 4.43 TGA thermogram of sample B (unextracted & grafted (15 kGy) bamboo fiber / ABS composites) (5 phr)

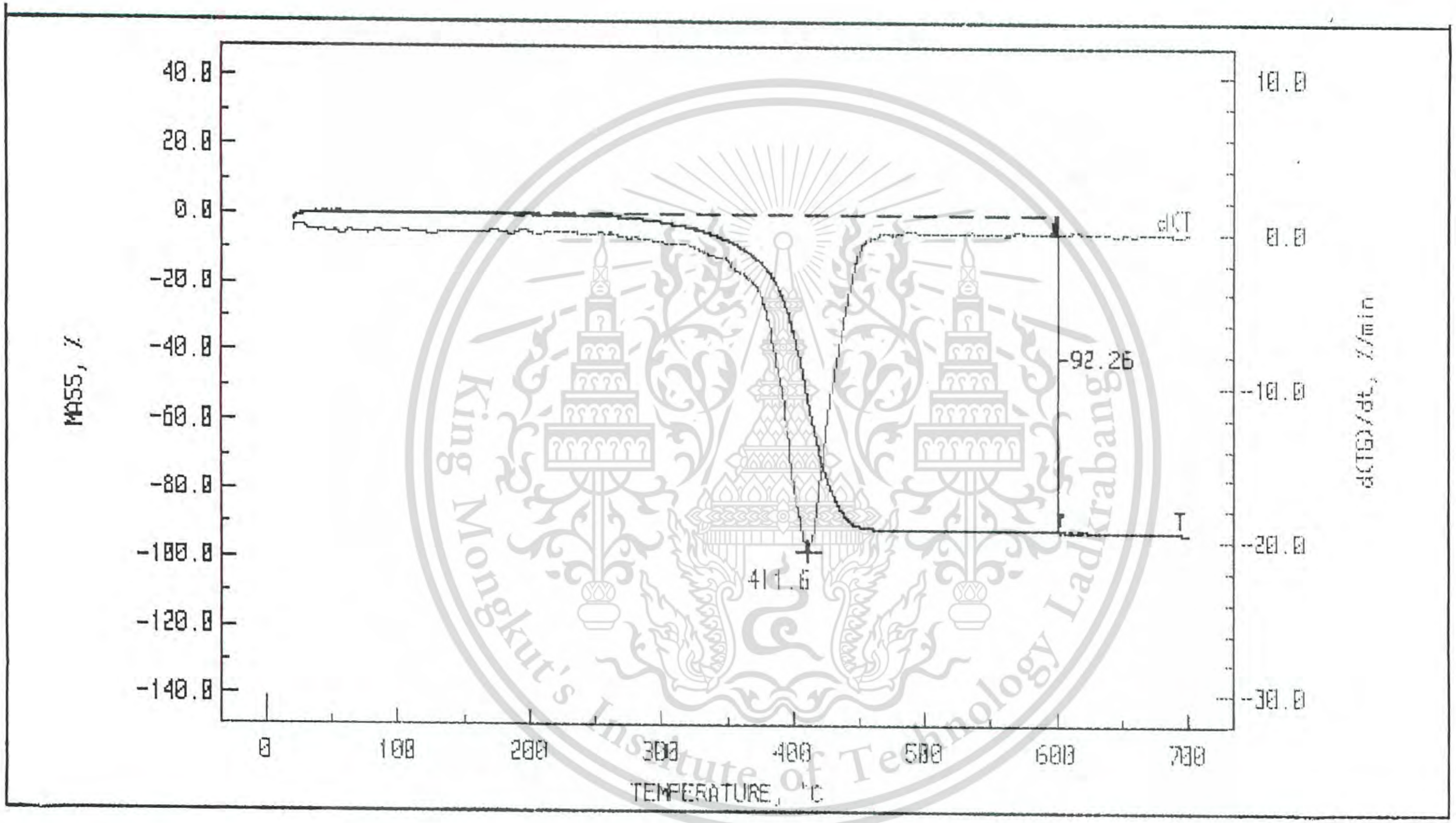


Figure 4.44 TGA thermogram of sample D (extracted & grafted (15 kGy) bamboo fiber / ABS composites) (5 phr)

4.16 Morphological study of the bamboo fibers and the composites

SEM showed dispersion of fibers in matrix, wettability of matrix on fibers, and interfacial adhesion between fibers and matrix. The specimens were cryogenically fractured and examined by SEM. The SEM results showed that fibers pull - out, fiber breakage, and fibrillation of the fibers were revealed in SEM micrographs. These results can be related to the adhesion between the fibers and ABS. If the fiber pull - out is found it means it has poor adhesion between two components. On the other hand, if fiber breakage and fibrillation are observed in the fractured surface that means there are some degrees of adhesion between those two components.

Figures 4.46 and 4.47 show the surfaces of the fibers before and after solvent extraction by organic solvent and NaOH aqueous solution. It was observed that after extraction, the extracted fibers had cleaner surfaces.

SEM micrographs of the fiber surfaces of the unextracted & grafted and the extracted & grafted fibers with different grafting levels were shown in Figures 4.48 to 4.55. It was found that the grafting with MMA on the fiber surfaces were masked with graft - on the fibers (PMMA). By increasing the total irradiation dose, the masking effect was more prominent with high grafting yield.

Figures 4.56 and 4.57 show the ungrafted and grafted fibers after processing. It was found that the deformation of the fibers were taken place after fabrication into composites. The fibers were shortened after processing. ABS was removed from fibers by soxhlet extraction using methyl ethyl ketone as the solvent.

Figures 4.58 to 4.63 show poor wetting of the fibers in the composites when the unextracted & ungrafted fibers were incorporated. The reason was the large difference in surface energy between the unextracted & ungrafted fibers and matrix. Thus, insufficient adhesion between the unextracted & ungrafted fibers and matrix, causing the fiber pull - out. In the unmodified samples (Figures 4.58 to 4.63), holes and spacings commonly occur along the fiber, resulting from poor contact and inferior stress transfer between the phases.

SEM micrographs of the composites were shown in Figures 4.64 to 4.69. In order to obtain the composite materials with satisfactory mechanical properties, good dispersion of the fibers in the matrix, effective wetting of the fibers by the matrix, and strong interfacial adhesion are reqiured. This is not the case, however, when the unmodified fibers are used in the matrix. By extracting the fibers, their surface energy was lowered to a level much closed to the surface energy of the matrix. Thus, better wetting was obtained as seen in Figure 4.64. The composites containing the extracted fibers showed better dispersion of the fibers in the matrix, more effective wetting of the fibers by the matrix and better adhesion between the two phases.

Figures 4.65 to 4.69 show the composites of the fibers modified with MMA by γ - ray irradiation. As the plastic phase more or less covers the fiber surfaces it can be concluded that the contact between the plastic and fibers phases were improved by the functionalized MMA. The better misibility of phases also enhances mechanical mixing, which explain the improved dispersion of the fibers in the matrix material.

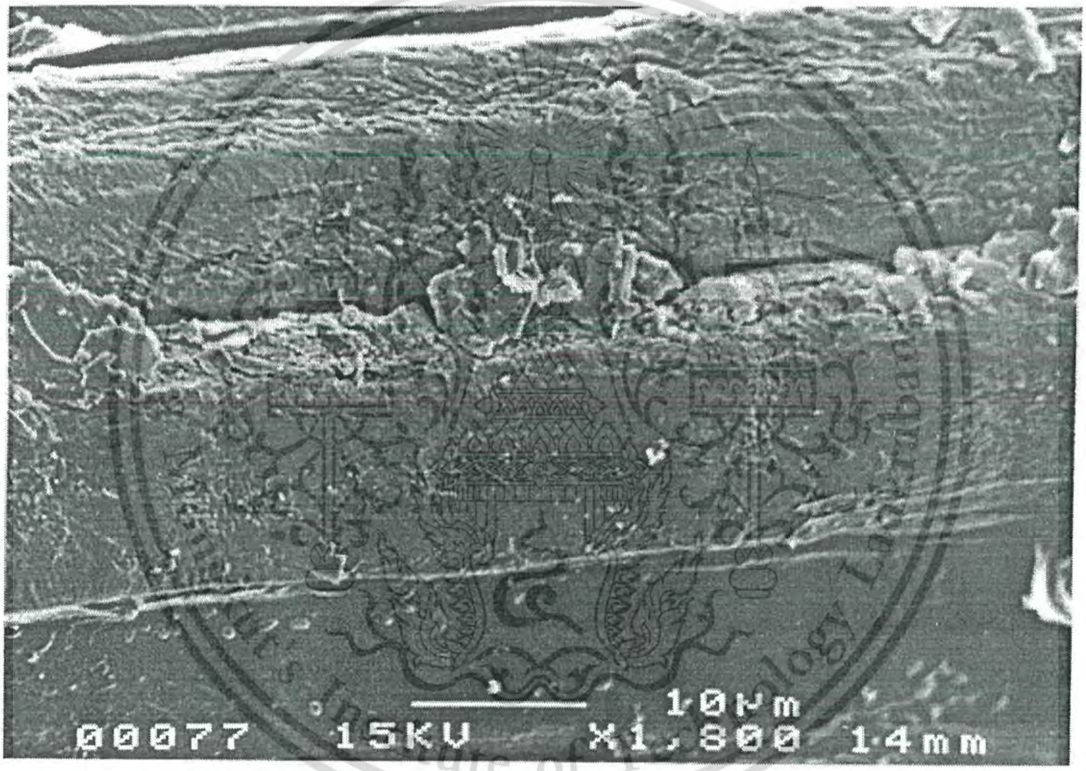


Figure 4.46 SEM micrograph of the unextracted & ungrafted bamboo fiber (× 1,800)

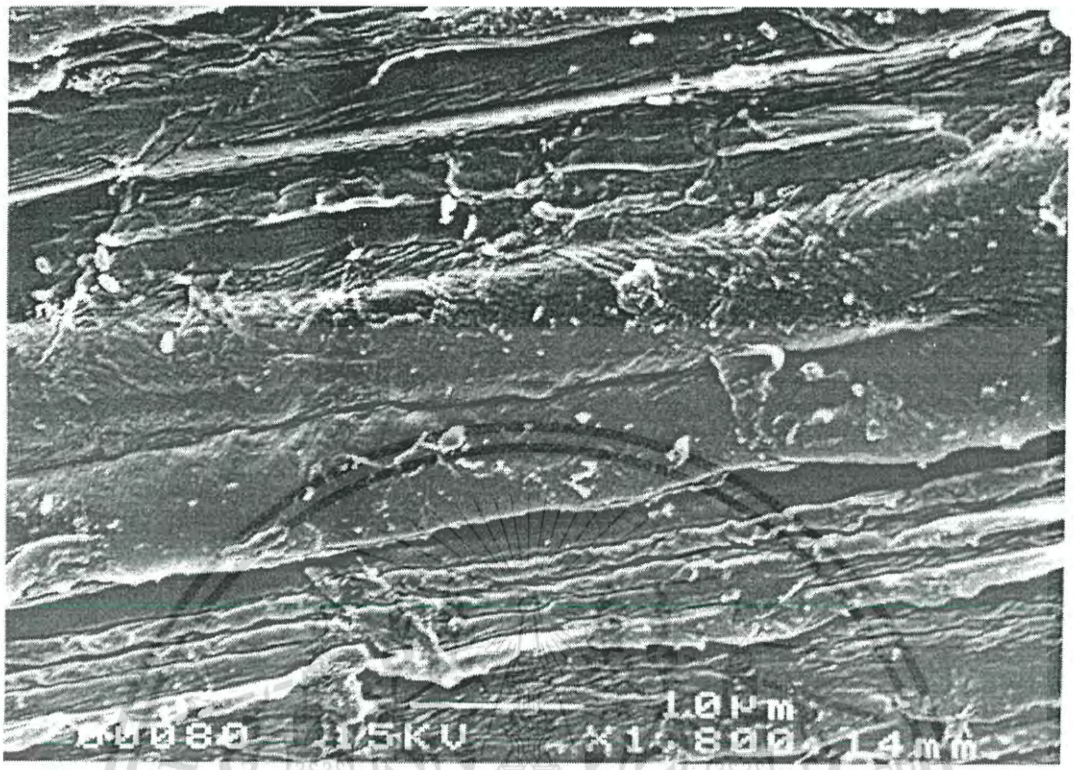


Figure 4.47 SEM micrograph of the extracted & ungrafted bamboo fiber (× 1,800)

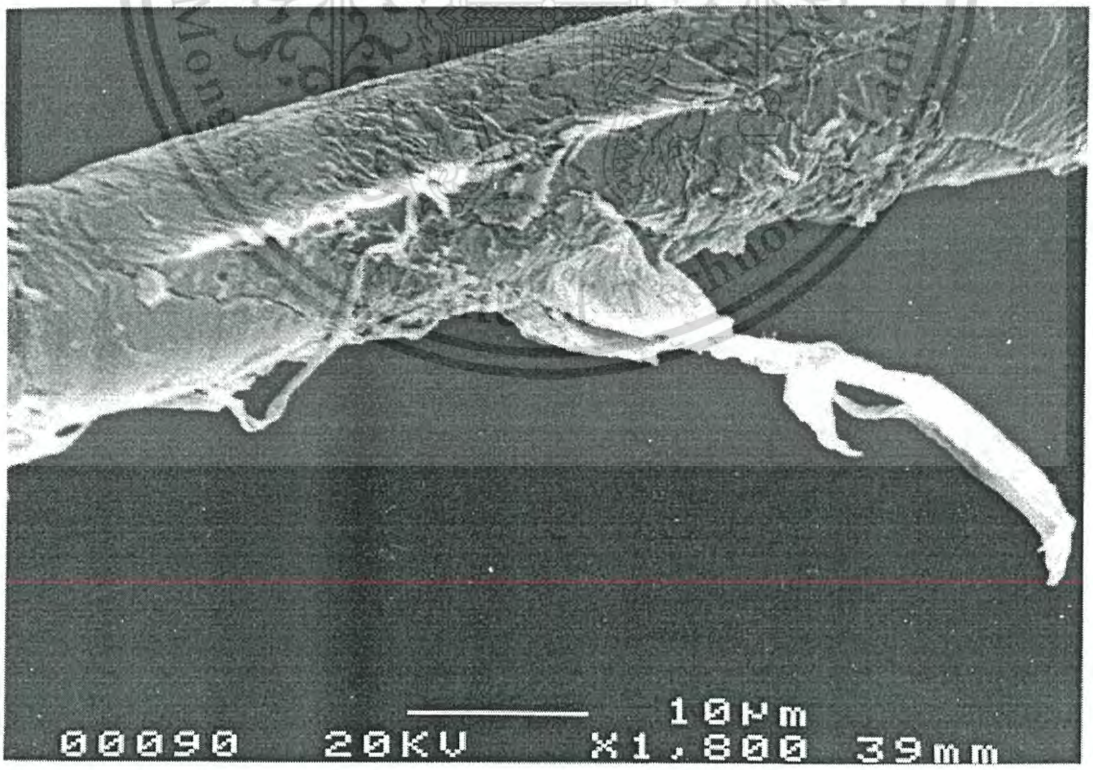


Figure 4.48 SEM micrograph of the extracted & grafted (5 kGy) fiber (× 1,800)

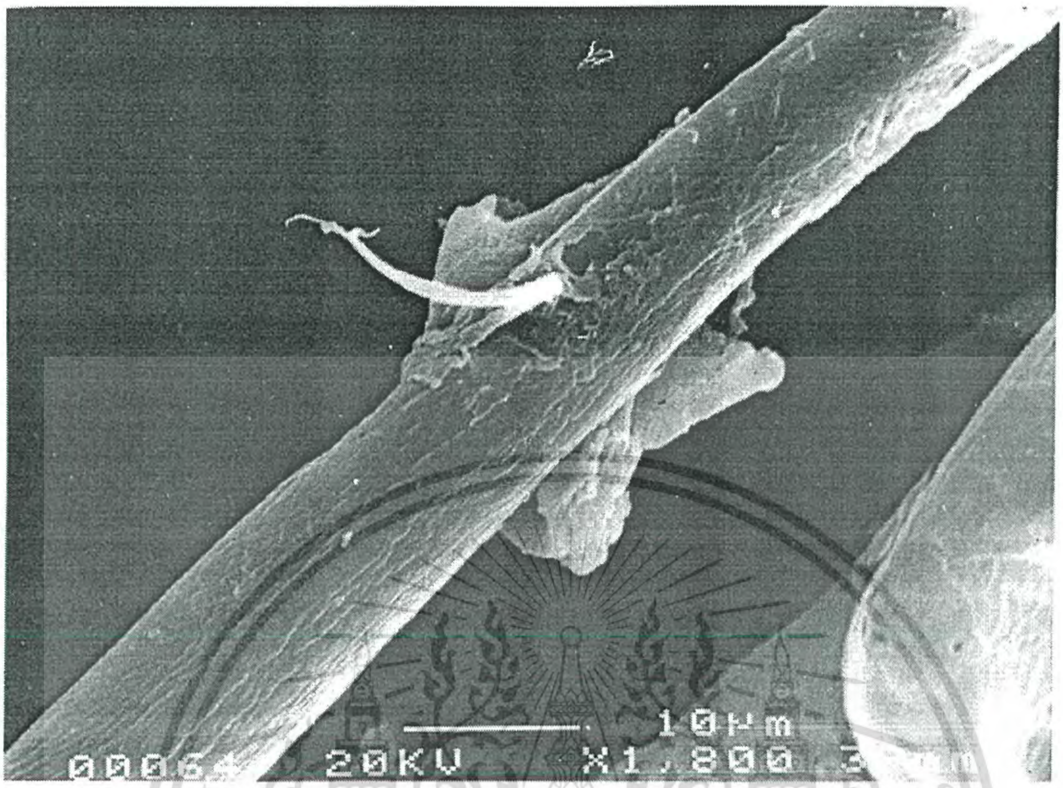


Figure 4.49 SEM micrograph of the extracted & grafted (10 kGy) bamboo fiber (× 1,800)

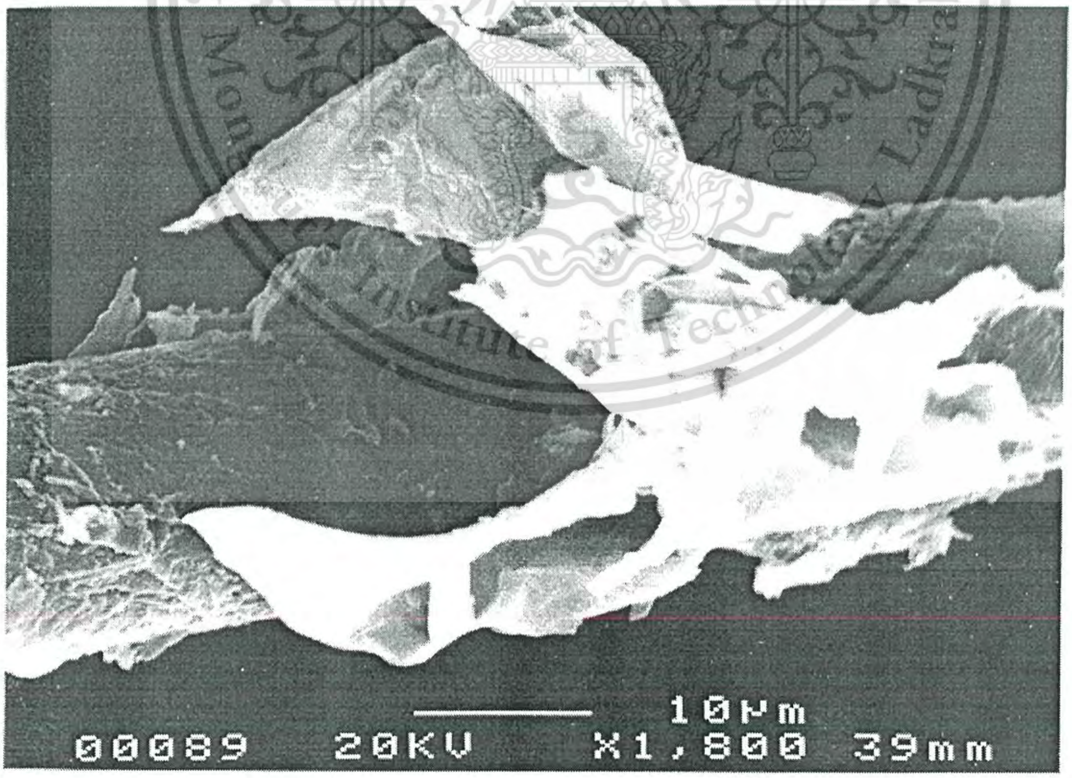


Figure 4.50 SEM micrograph of the extracted & grafted (15 kGy) bamboo fiber (× 1,800)

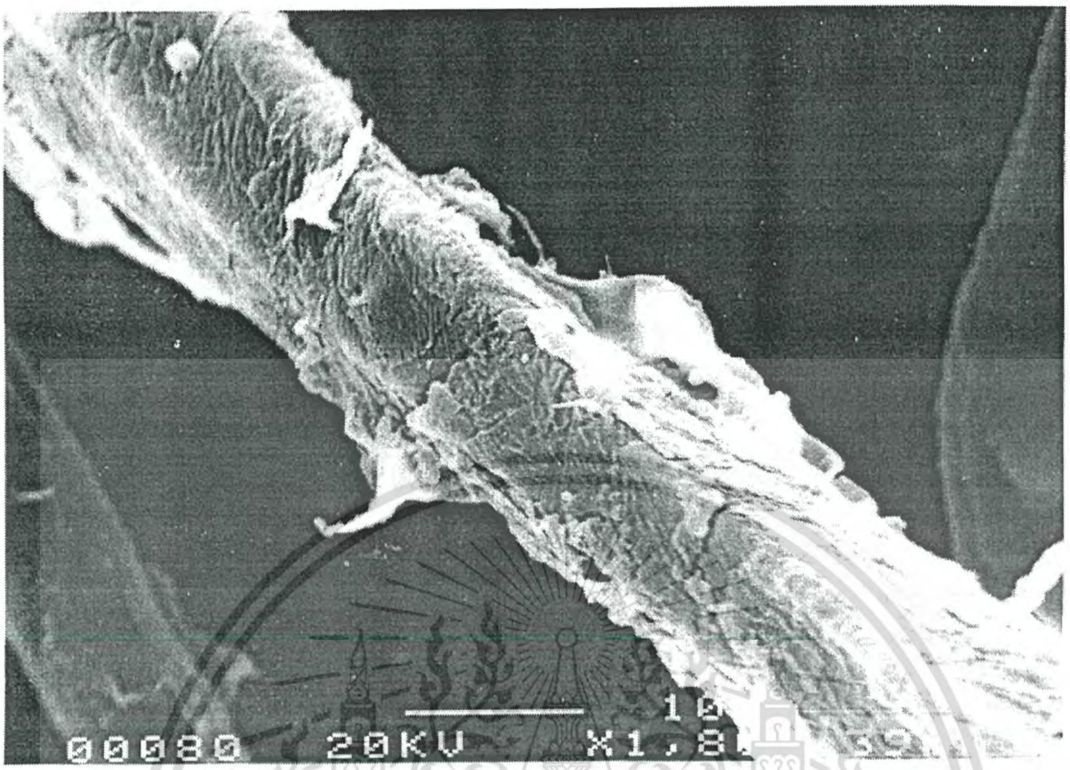


Figure 4.51 SEM micrograph of the extracted & grafted (20 kGy) bamboo fiber (× 1,800)

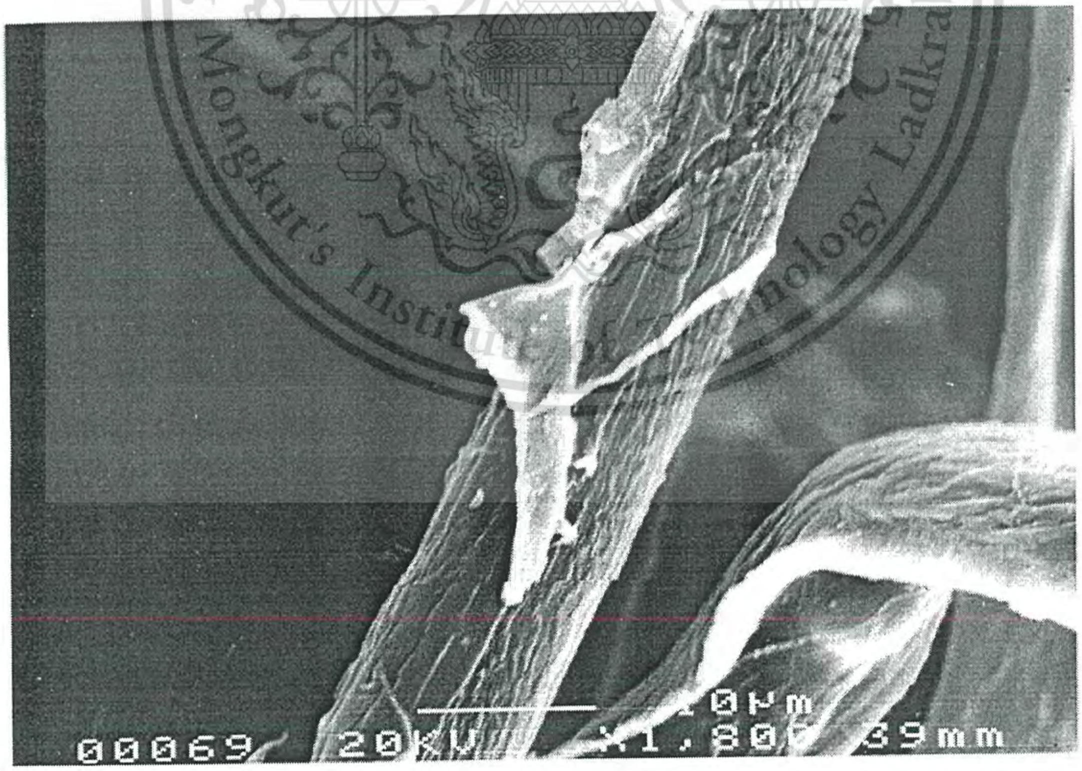


Figure 4.52 SEM micrograph of the unextracted & grafted (5 kGy) bamboo fiber (× 1,800)

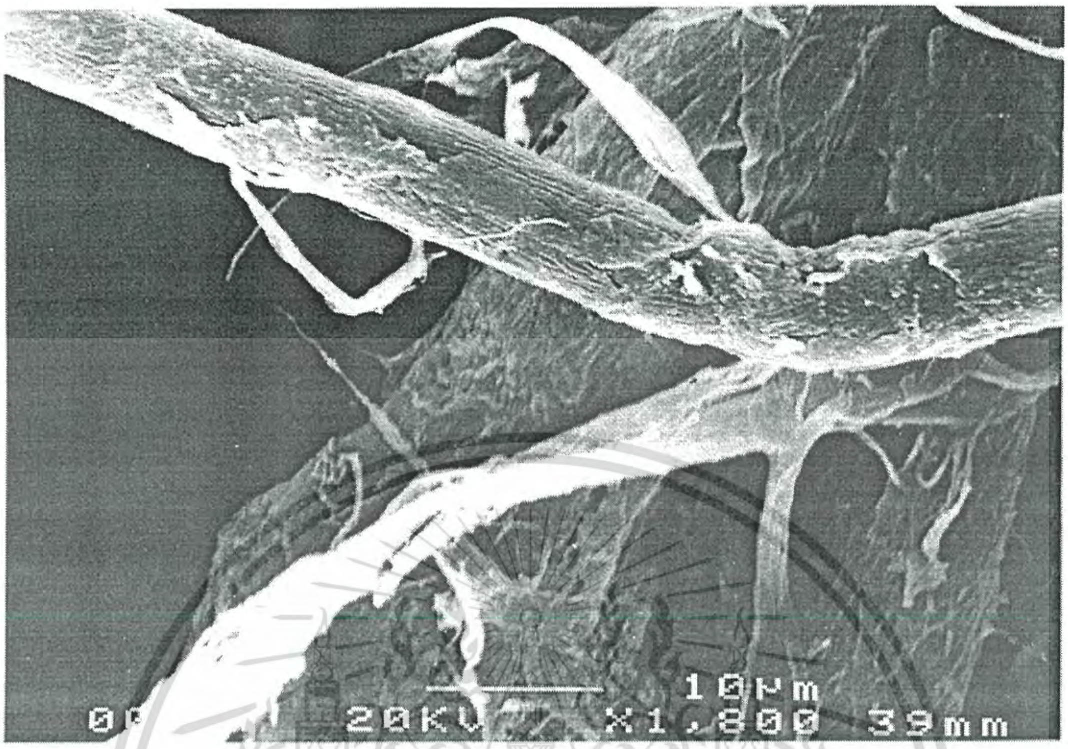


Figure 4.53 SEM micrograph of the unextracted & grafted (10 kGy) bamboo fiber (× 1,800)

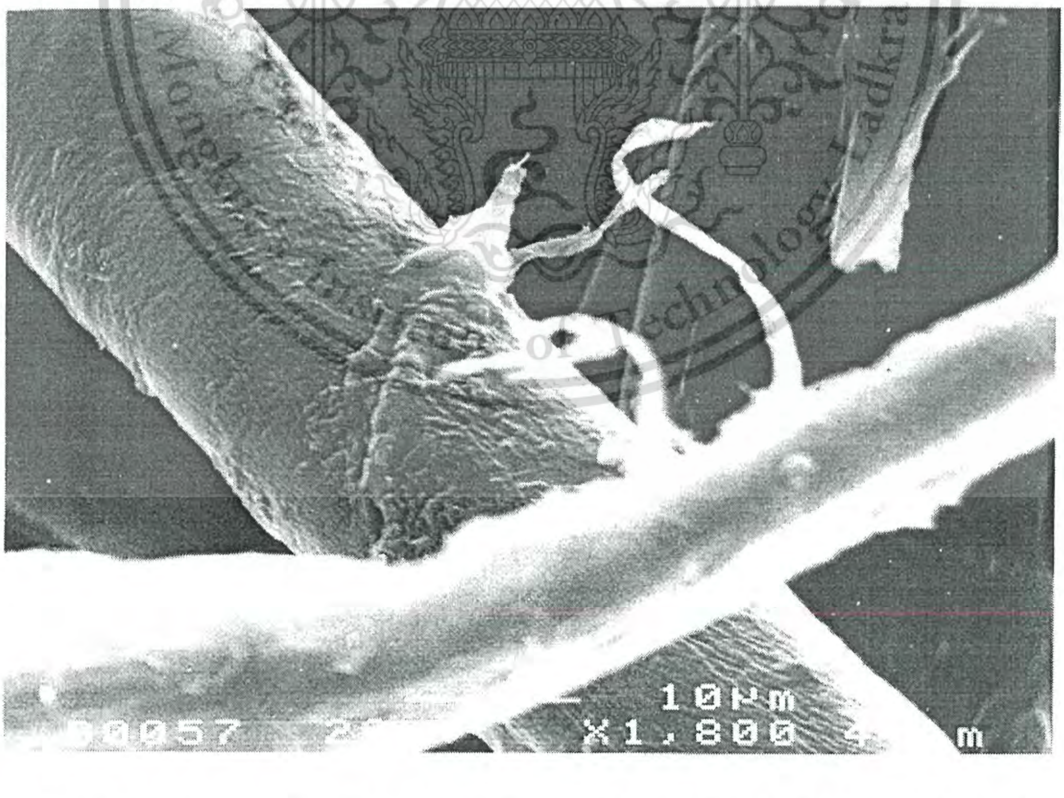


Figure 4.54 SEM micrograph of the unextracted & grafted (15 kGy) bamboo fiber (× 1,800)

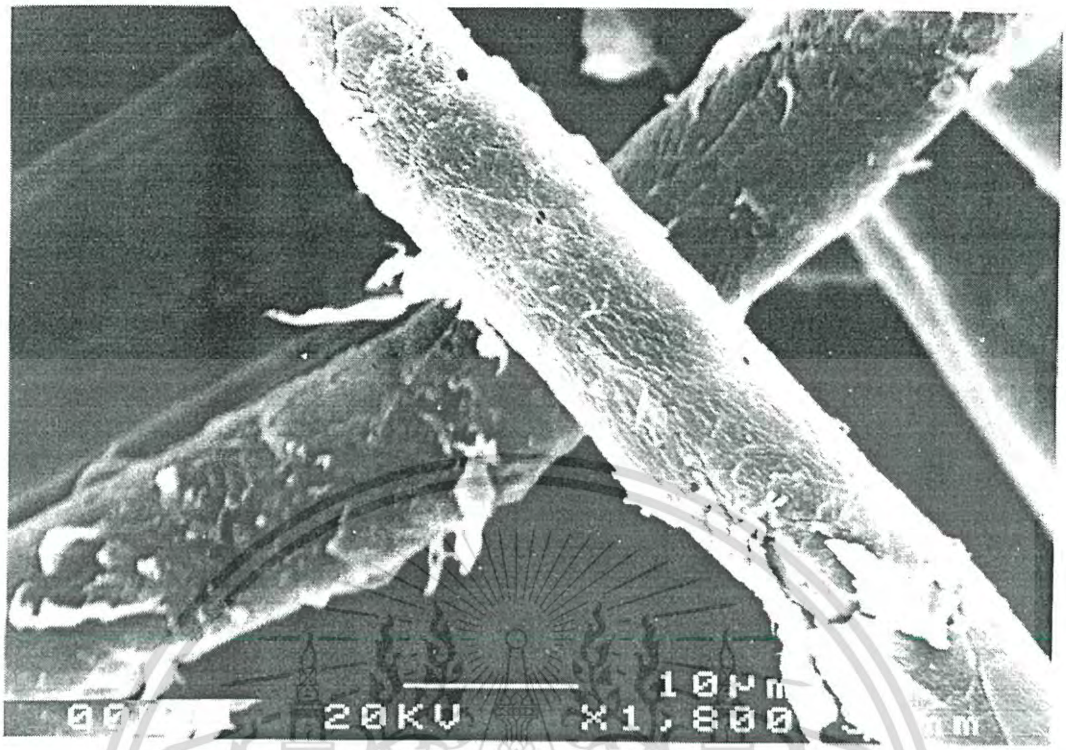


Figure 4.55 SEM micrograph of the unextracted & grafted (20 kGy) bamboo fiber (× 1,800)

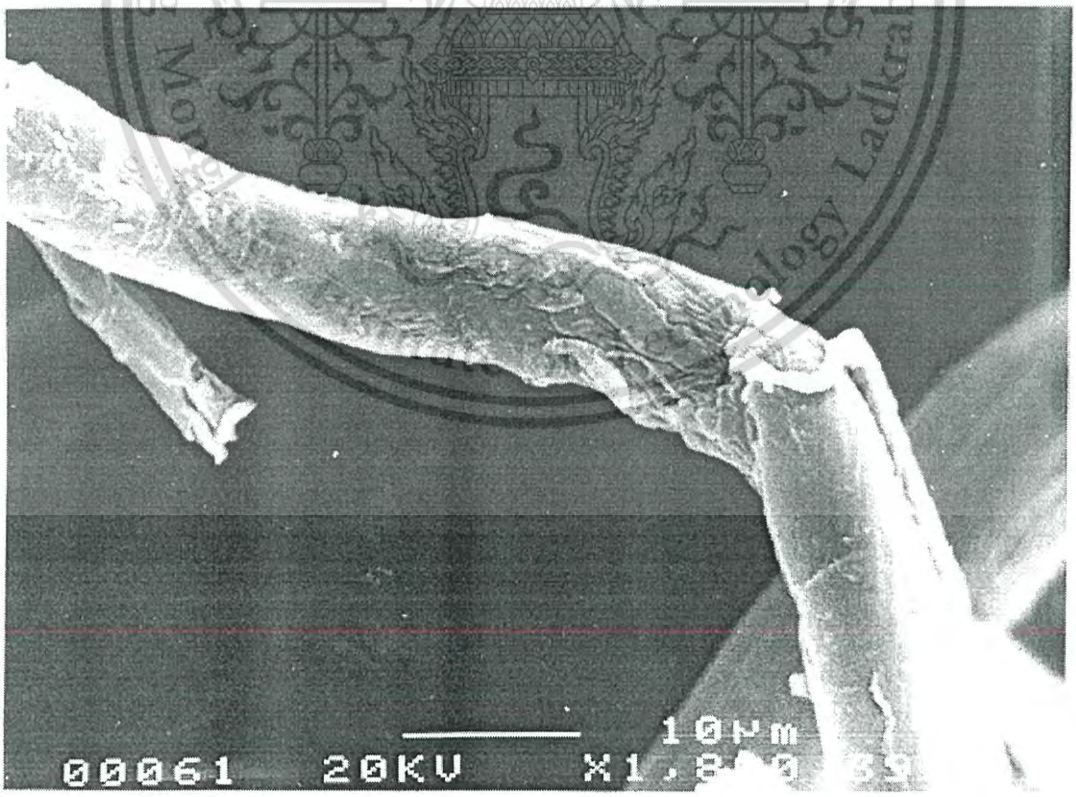


Figure 4.56 SEM micrograph of the ungrafted fiber after processing (× 1,800)

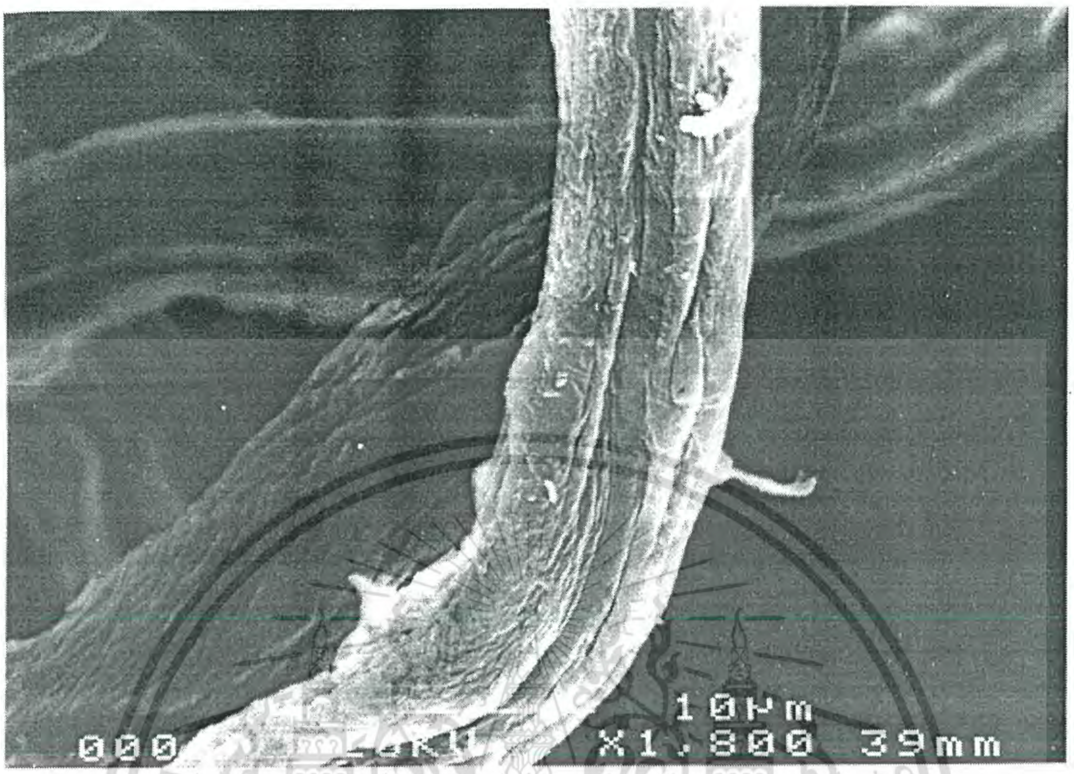


Figure 4.57 SEM micrograph of the grafted bamboo fiber after processing (× 1,800)

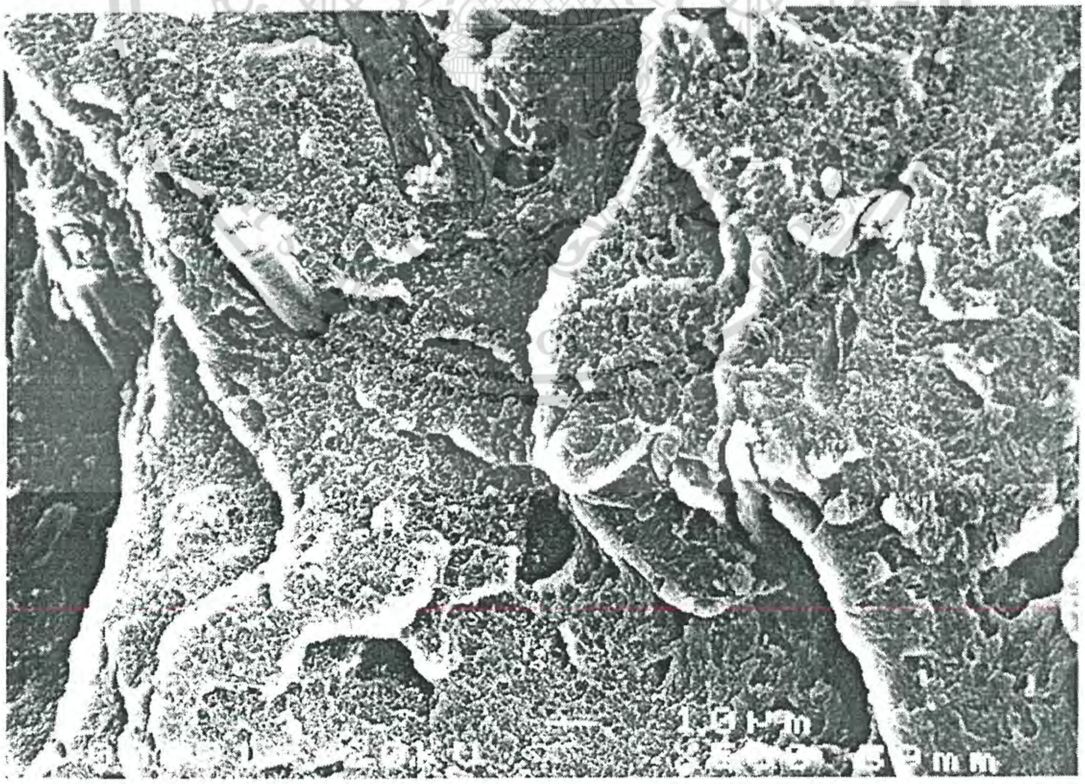


Figure 4.58 SEM micrograph of sample A (unextracted & ungrafted bamboo fiber / ABS composite) (3 phr) (× 500)

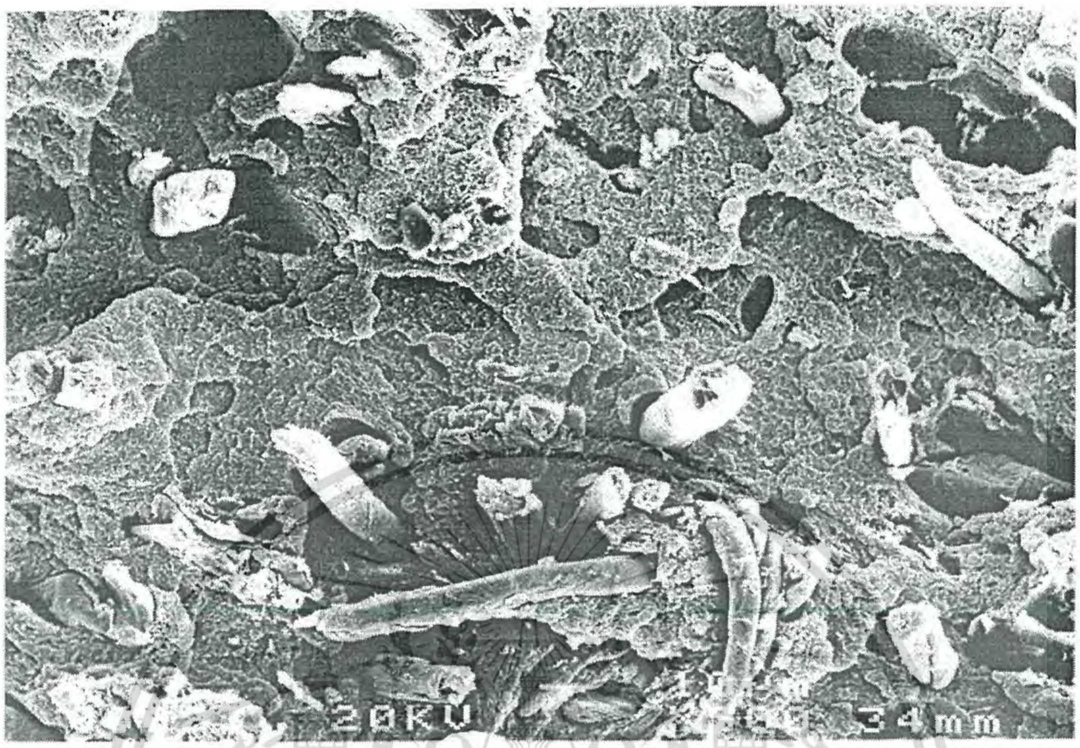


Figure 4.59 SEM micrograph of sample A (unextracted & ungrafted bamboo fiber / ABS composite) (5 phr) (X 500)

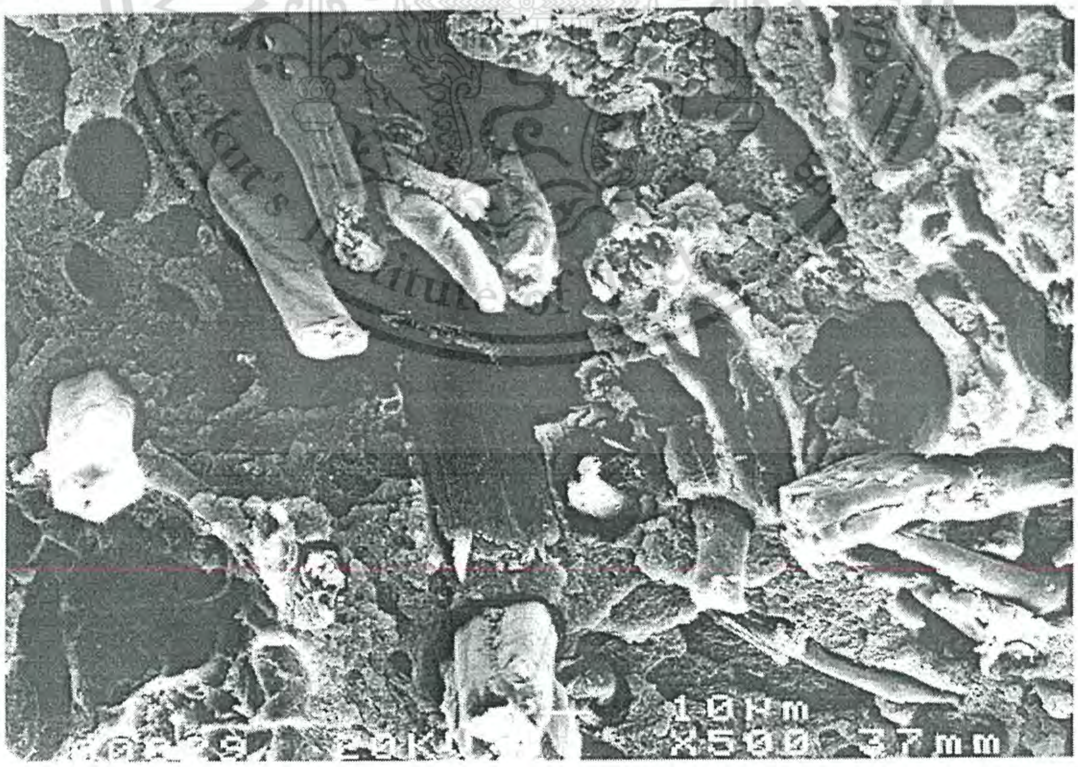


Figure 4.60 SEM micrograph of sample A (unextracted & ungrafted bamboo fiber / ABS composite) (10 phr) (X 500)

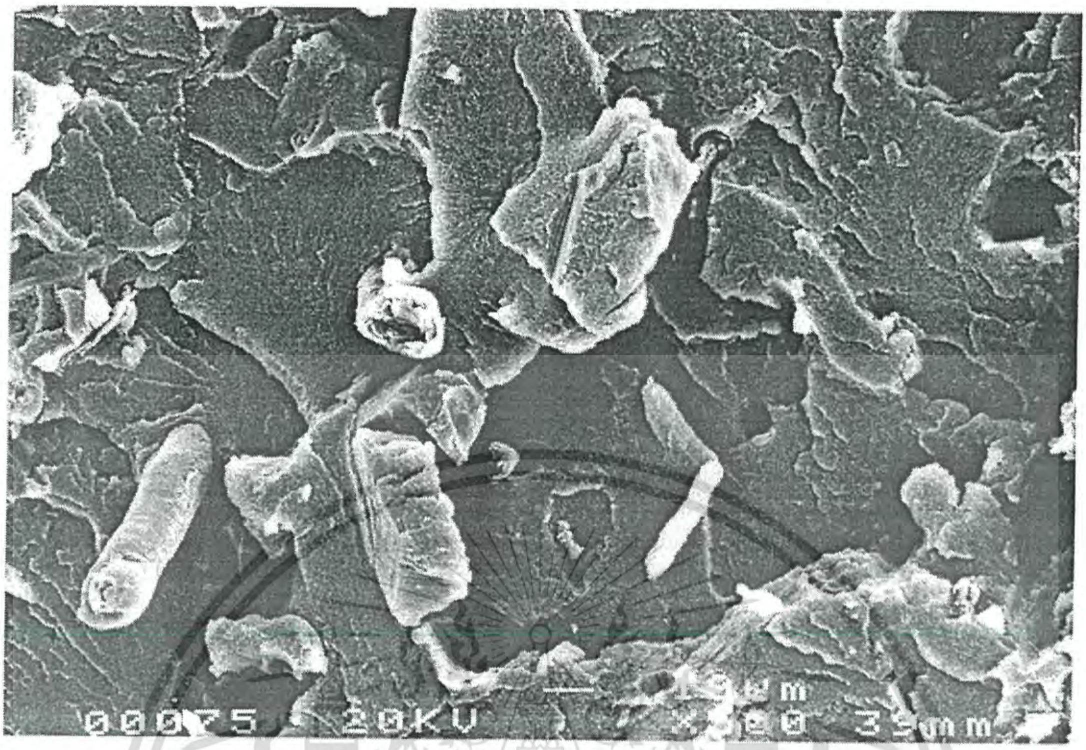


Figure 4.61 SEM micrograph of sample A (unextracted & ungrafted bamboo fiber / ABS composite) (20 phr) (X 500)

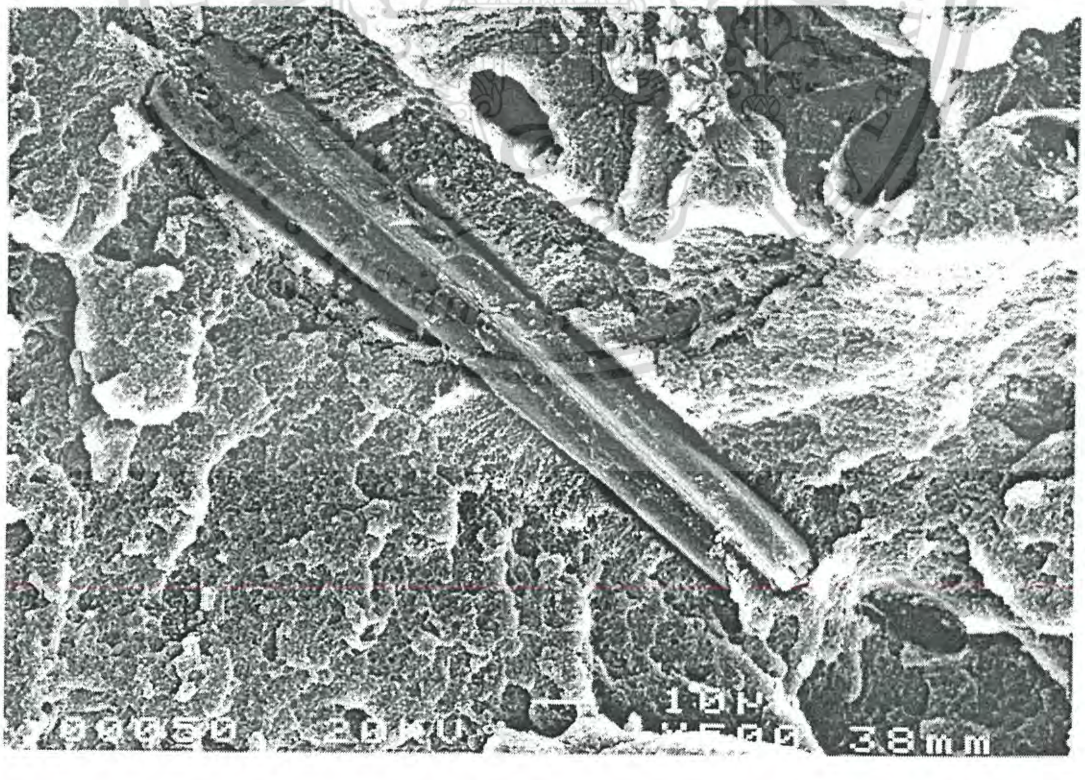


Figure 4.62 SEM micrograph of sample A (unextracted & ungrafted bamboo fiber / ABS composite) (30 phr) (X 500)

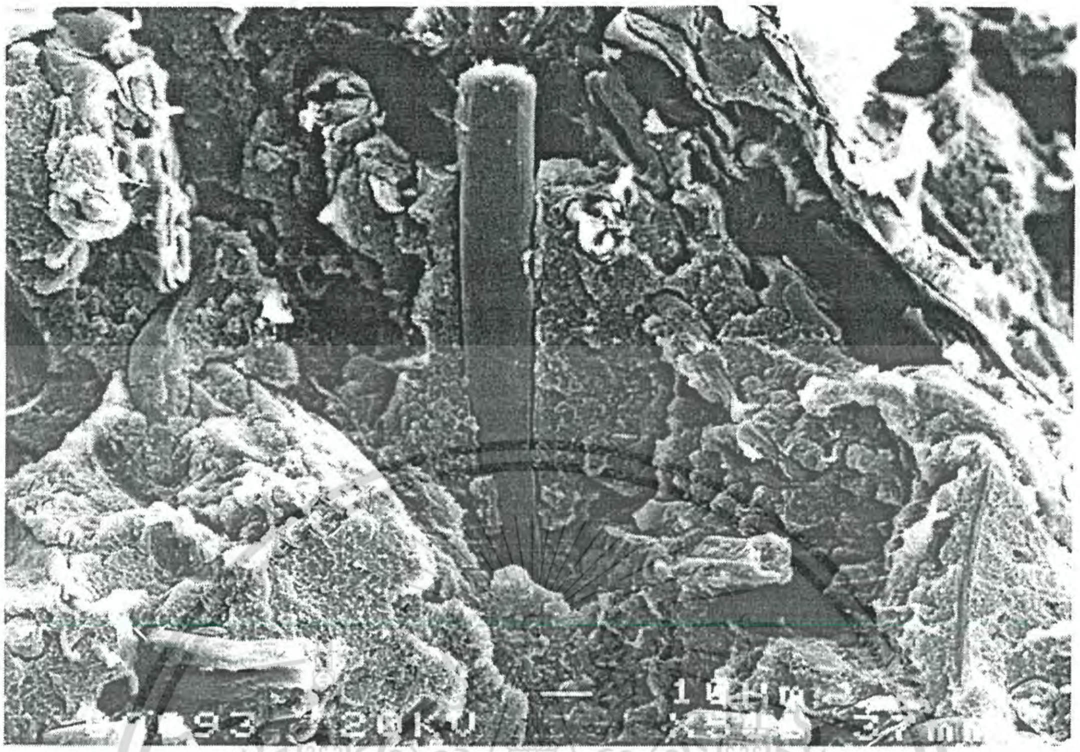


Figure 4.63 SEM micrograph of sample A (unextracted & ungrafted bamboo fiber / ABS composite) (40 phr) (× 500)

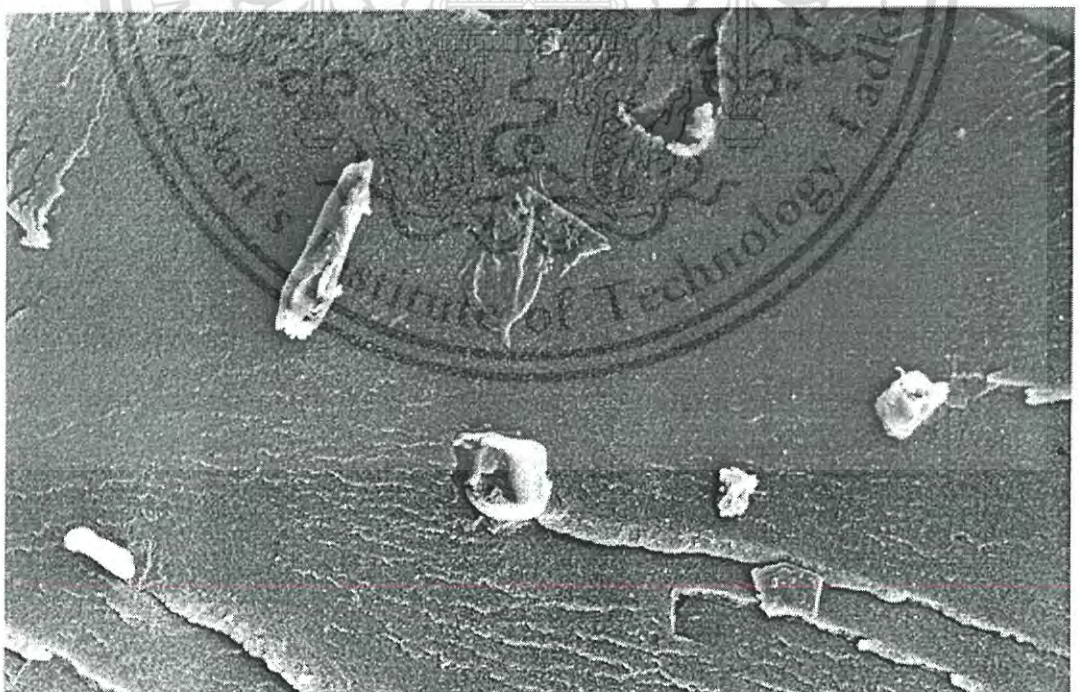


Figure 4.64 SEM micrograph of sample C (extracted & ungrafted bamboo fiber / ABS composite) (40 phr) (× 500)

Figure 4.65 SEM micrograph of sample B (unextracted & grafted (5 kGy) bamboo fiber / ABS composite) (5 phr) (× 500)

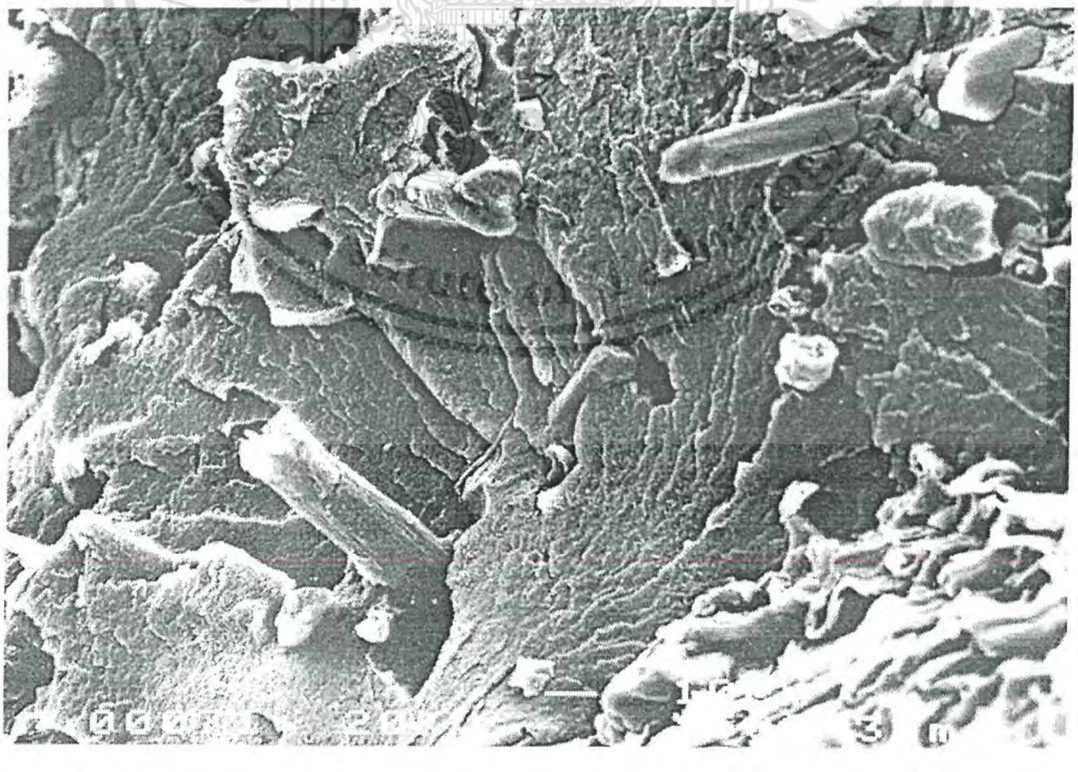


Figure 4.66 SEM micrograph of sample B (unextracted & grafted (10 kGy) bamboo fiber / ABS composite) (5 phr) (× 500)

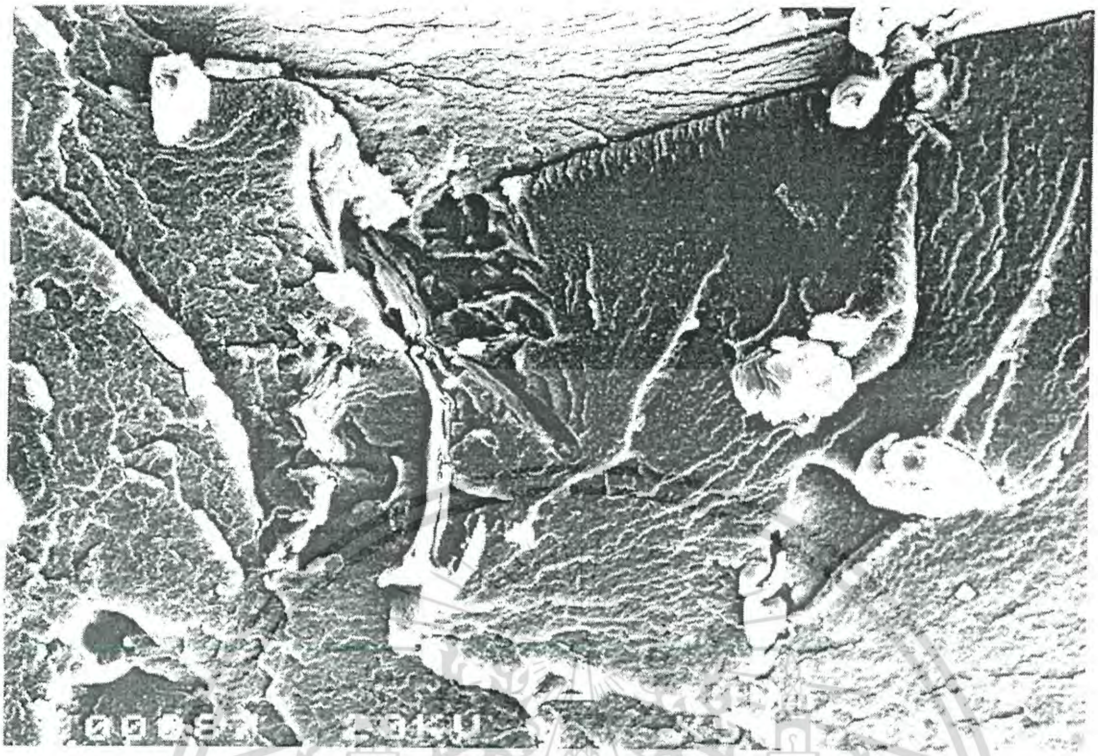


Figure 4.67 SEM micrograph of sample B (unextracted & grafted (15 kGy) bamboo fiber / ABS composite (5 phr) (X 500)

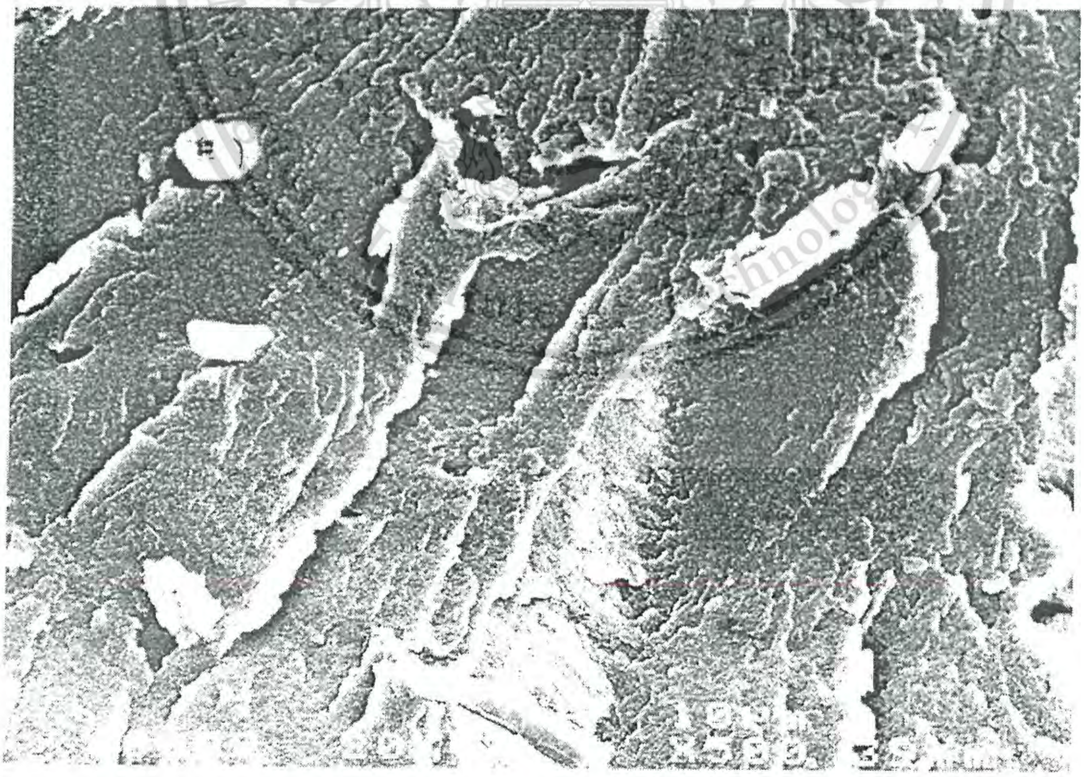


Figure 4.68 SEM micrograph of sample B (unextracted & grafted (20 kGy) bamboo fiber / ABS composite) (5 phr) (X 500)

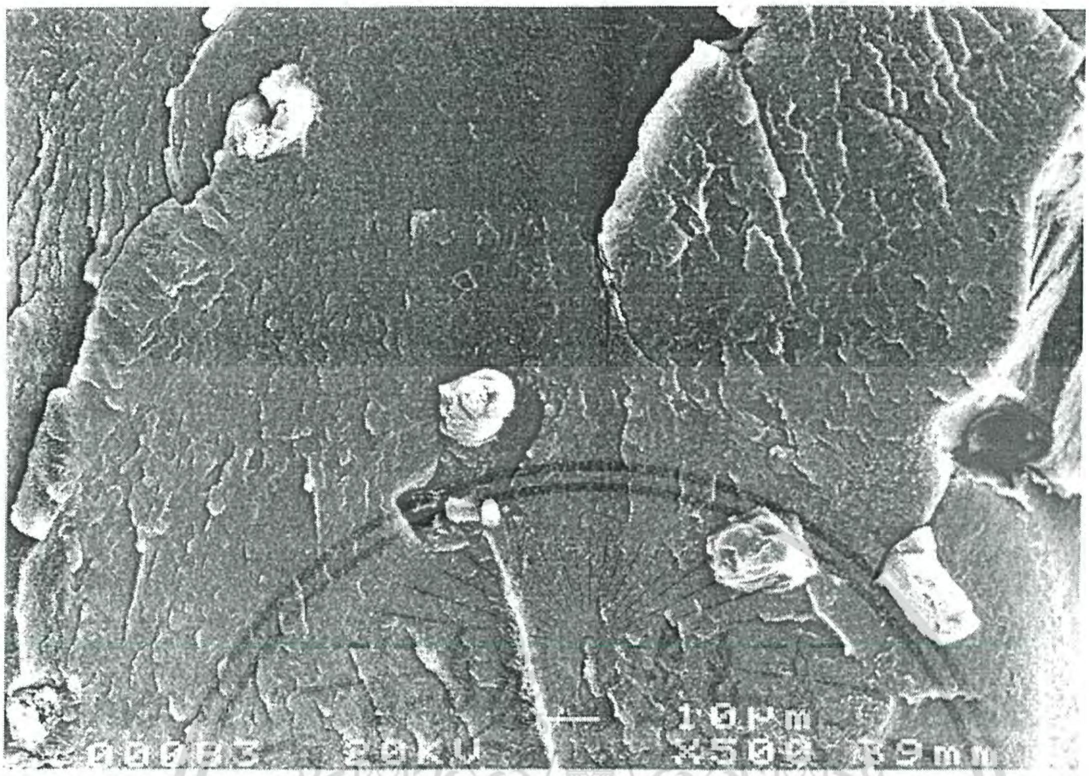


Figure 4.69 SEM micrograph of sample D (extracted & grafted (15 kGy) bamboo fiber / ABS composite) (5 phr) (× 500)

CHAPTER V

CONCLUSIONS AND SUGGESTION

The following conclusions could be made from the present study :

1. Natural fiber composites from bamboo can be fabricated in this work. By using the brabender / twin - screw extruder, temperature of 180 °C and rotor speed of 5 rpm were chosen for all mixing conditions to prepare the composites because of their optimum tensile properties of the composites. Injection molding technique was used to prepare testing samples. Injection temperature of 180 °C seemed to yield the composites with the optimum tensile properties.

2. Addition of the unextracted & ungrafted bamboo fibers into ABS up to 40 phr was improved mechanical properties of ABS. The tensile strength, modulus at 3 % strain, and hardness of the composites were increased as % fiber loading increased. The opposite results were found on % elongation at break and impact strength of the composites which were decreased with increasing the fiber content. % Water absorption and % moisture content of the composites were increased with increasing the fiber content.

3. Effect of extractives in the bamboo fibers was studied by extracting the fibers with acetone, methanol : benzene, and NaOH aqueous solution, respectively. The results indicated that mechanical properties of the composites were improved by using the extracted & ungrafted bamboo fibers compared to the unextracted & ungrafted ones. The extracted & ungrafted bamboo fiber / ABS composites had slightly higher % water absorption and % moisture content than the unextracted & ungrafted ones. When the fibers were extracted by NaOH aqueous solution, the crystalline regions in the fiber structure can be dissolved and converted into amorphous regions. Free hydroxyl groups generated in amorphous region were increased resulting in the increase of absorb water.

4. The effect of irradiation dose of gamma ray irradiation grafting PMMA on the fibers was investigated. The total dose of 15 kGy gave the highest % grafting yield for both the extracted and unextracted fibers. The extracted fibers had higher % grafting yield than the unextracted fibers. The composites made from grafted fibers with PMMA at total dose of 5 kGy had higher tensile strength and modulus than others. This could be explained that the rate of grafting was increased by increasing the radiation dose since the γ - ray bombarded on the cellulose surfaces and generated more radical sites resulting in the increase of grafting of MMA

on the fiber surfaces. It was shown that grafting was improved mechanical properties of the composites.

5. Addition of the grafted fibers into ABS improved mechanical properties of ABS high than the unextracted and extracted bamboo fibers without grafting. The tensile strength and modulus of the grafted bamboo fiber / ABS composites were increased but hardness, % elongation at break and impact strength were decreased as % fiber loading increased. % Water absorption and % moisture content of the grafted bamboo fiber / ABS composites were decreased with increasing the fiber content. It could be explained that in grafting reaction by gamma irradiation, the hydroxyl groups of the cellulose in the fibers were replaced by PMMA polymer chains which are less active for water. This the reason why % water absorption was decreased as % grafting increased.

6. FTIR spectrums of the MMA - grafted fibers were found that an additional peak of the ester group at about 1,735 cm^{-1} was observed in the grafted sample thereby indicating the occurrence of grafting on the fibers.

7. Thermal behavior of the composites was studied by TGA. It was found that the decomposition temperature of the grafted bamboo fiber / ABS composites was similar that of the ungrafted bamboo fiber / ABS composites.

8. In order to study the morphology of the cross - section of the composites, the composites were fractured in liquid nitrogen and observed by SEM. Fiber pull - out, fiber breakage, and fibrillation were observed on SEM micrographs of the composites. After the grafted bamboo fibers with PMMA for both the extracted and unextracted fibers, more fiber breakage and fibrillation were found than fiber pull - out. It can be concluded that the contact between the plastic and fibers phases were improved by the functionalized MMA.

Suggestions for future work

1. Long fibers composites should be studied and compared to short fibers system. This is expected that long fibers composites have more reinforcing ability than short fibers.

2. Other polymer matrices should be investigated and compared the results with ABS.

3. From this work, the highest grafting yield was not achieved. It is difficult to graft MMA alone in order to get high % grafting yield in the presence of ionizing radiation. Therefore, effect of additives and grafting with comonomers, i.e., MMA - styrene could be studied.

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APPENDICES

Appendix A Mechanical properties of the bamboo fiber / ABS composites

Table A1 Effect of mixing temperatures and rotor speeds on tensile properties of sample A (unextracted & ungrafted bamboo fiber / ABS composites) (3 phr)

Temperature / Properties	165 °C		170 °C		175 °C		180 °C	
	mean	stdev	mean	stdev	mean	stdev	mean	stdev
At 5 rpm								
Tensile strength (MPa)	41.60	1.23	41.95	1.37	42.47	1.13	43.37	0.99
Modulus at 3 % strain (MPa)	813.79	34.60	809.02	39.47	813.99	38.11	821.50	37.55
% Elongation at break	6.60	0.31	6.27	0.23	7.06	0.40	6.48	0.40
At 10 rpm								
Tensile strength (MPa)	42.33	0.77	41.43	1.32	41.90	1.36	42.48	0.65
Modulus at 3 % strain (MPa)	809.50	40.76	786.55	36.60	793.99	40.23	791.63	16.78
% Elongation at break	6.68	0.35	6.29	0.29	7.16	0.49	7.24	0.56

Table A2 Effect of injection temperature on tensile properties of ABS

Temperature / Properties	165 °C		170 °C		175 °C		180 °C	
	mean	stdev	mean	stdev	mean	stdev	mean	stdev
Tensile strength (MPa)	42.09	0.47	42.09	0.37	42.08	0.41	42.65	0.38
Modulus at 3 % strain (MPa)	791.36	33.31	805.45	26.71	809.08	33.34	806.31	24.63
% Elongation at break	7.30	0.33	7.23	0.23	7.25	0.28	7.85	0.06

Table A3 Effect of % fiber loading on mechanical properties of sample C

(extracted & ungrafted bamboo fiber / ABS composites)

Fiber volume fraction / Properties	3 phr		5 phr		10 phr	
	mean	stdev	mean	stdev	mean	stdev
Tensile strength (MPa)	44.12	1.00	44.72	1.04	44.90	0.67
Modulus at 3 % strain (MPa)	813.55	34.17	825.09	35.38	860.18	26.07
% Elongation at break	7.30	0.48	6.83	0.38	6.34	0.22
Impact strength (kJ / m^2)	7.28	0.25	6.42	0.24	4.73	0.18

Table A4 Effect of % fiber loading on mechanical properties of sample A

(unextracted & ungrafted bamboo fiber / ABS composites)

Fiber volume fraction / Properties	0 phr		3 phr		5 phr		10 phr		20 phr		30 phr		40 phr	
	mean	stdev	mean	stdev	mean	stdev	mean	stdev	mean	stdev	mean	stdev	mean	stdev
Tensile strength (MPa)	42.65	0.38	43.37	0.99	43.53	1.01	43.58	0.81	44.10	0.73	45.21	0.62	45.41	0.18
Modulus at 3 % strain (MPa)	806.3	24.63	821.5	37.55	871.40	38.64	868.84	39.56	9056.2	25.46	1087.5	25.29	1107.5	35.30
% Elongation at break	7.85	0.06	6.48	0.40	6.31	0.61	5.95	0.29	5.09	0.54	5.06	0.35	4.35	0.28
Impact strength (kJ / m^2)	9.48	0.28	5.21	0.22	4.82	0.33	4.38	0.31	2.68	0.23	2.10	0.26	1.32	0.14

Table A5 Effect of % fiber loading on mechanical properties of sample D (extracted & grafted (15 kGy) bamboo fiber / ABS composites)

Fiber volume fraction / Properties	3 phr		5 phr		10 phr	
	mean	stdev	mean	stdev	mean	stdev
Tensile strength (MPa)	46.59	0.48	46.78	0.68	48.39	0.79
Modulus at 3 % strain (MPa)	949.19	8.93	972.24	25.10	965.91	32.02
% Elongation at break	6.31	0.16	5.99	0.34	5.83	0.28
Impact strength (kJ / m^2)	5.30	0.08	3.78	0.13	3.54	0.32

Table A6 Data of % grafting yield of the grafted fibers with PMMA γ - ray irradiation both the extracted and unextracted bamboo fibers

% Grafting yield / Total dose (kGy)	Unextracted bamboo fibers		Extracted bamboo fibers	
	mean	stdev	mean	stdev
5	20.19	2.09	26.18	2.00
10	31.69	1.45	33.63	2.08
15	49.06	2.61	58.98	3.76
20	33.24	1.69	33.84	1.85

Table A7 Effect of % fiber loading on mechanical properties of sample B (unextracted & grafted bamboo fiber / ABS composites)

Fiber volume fraction Properties	3 phr		5 phr		10 phr	
	mean	stdev	mean	stdev	mean	stdev
At total dose of 5 kGy						
Tensile strength (MPa)	44.17	0.52	44.78	0.63	45.78	0.41
Modulus at 3 % strain (MPa)	925.2	28.09	928.79	35.86	967.08	16.38
% Elongation at break	6.17	0.42	6.08	0.18	5.92	0.31
Impact strength (kJ / m^2)	3.58	1.77	3.01	0.38	2.27	0.32
At total dose of 10 kGy						
Tensile strength (MPa)	44.19	0.50	45.51	0.85	46.80	0.87
Modulus at 3 % strain (MPa)	908.9	38.82	919.60	32.14	964.95	38.45
% Elongation at break	6.50	0.26	6.15	0.28	5.81	0.18
Impact strength (kJ / m^2)	4.27	0.13	3.76	0.20	3.16	0.12
At total dose of 15 kGy						
Tensile strength (MPa)	45.13	0.86	45.81	1.00	47.55	0.67
Modulus at 3 % strain (MPa)	973.0	27.95	990.66	26.65	981.73	38.00
% Elongation at break	6.24	0.39	6.17	0.39	6.00	0.35
Impact strength (kJ / m^2)	4.26	0.40	3.41	0.18	2.43	0.23
At total dose of 20 kGy						
Tensile strength (MPa)	44.23	0.22	26.09	0.73	46.16	0.71
Modulus at 3 % strain (MPa)	921.1	22.5	917.77	40.89	968.79	33.73
% Elongation at break	6.36	0.14	6.12	0.21	5.97	0.10
Impact strength (kJ / m^2)	7.47	0.32	6.54	0.12	5.88	0.25

Appendix B Physical properties of the bamboo fiber / ABS composites

Table B1 Effect of % fiber loading on physical properties of sample A

(unextracted & ungrafted bamboo fiber / ABS composites)

Fiber volume fraction / Properties	0 phr		3 phr		5 phr		10 phr		20 phr		30 phy		40 phr	
	mean	stdev	mean	stdev	mean	stdev	mean	stdev	mean	stdev	mean	stdev	mean	stdev
Density (g / cm^3)	1.038	0.001	1.048	0.001	1.052	0.002	1.065	0.002	1.091	0.003	1.112	0.008	1.131	0.004
Moisture content (%)	0.49	0.13	0.59	0.06	0.73	0.04	1.01	0.06	1.48	0.07	1.70	0.26	2.04	0.25
Hardness	73.25	0.52	73.50	0.55	73.80	0.43	74.83	0.47	76.30	0.74	76.60	0.48	76.67	0.37

Table B2 Effect of % fiber loading on physical properties of sample C

(extracted & ungrafted bamboo fiber / ABS composites)

Fiber volume fraction / Properties	3 phr		5 phr		10 phr	
	mean	stdev	mean	stdev	mean	stdev
Density (g / cm^3)	1.048	0.001	1.051	0.001	1.065	0.002
Moisture content (%)	0.67	0.13	0.82	0.19	1.07	0.04
Hardness	76.85	0.50	76.88	0.51	76.95	0.61

Table B3 Effect of % fiber loading on physical properties of sample D

(extracted & grafted (15 kGy) bamboo fiber / ABS composites)

Fiber volume fraction / Properties	3 phr		5 phr		10 phr	
	mean	stdev	mean	stdev	mean	stdev
Density (g / cm^3)	1.053	0.001	1.062	0.002	1.079	0.004
Moisture content (%)	0.65	0.05	0.75	0.05	1.01	0.05
Hardness	78.00	0.36	77.60	0.41	77.45	0.62

Table B4 Effect of % fiber loading on physical properties of sample B (unextracted & grafted (15 kGy) bamboo fiber / ABS composites)

Fiber volume fraction / Properties	3 phr		5 phr		10 phr	
	mean	stdev	mean	stdev	mean	stdev
At total dose of 5 kGy						
Hardness	77.48	0.55	76.89	0.41	76.40	0.37
At total dose of 10 kGy						
Hardness	77.69	0.70	77.37	0.48	76.65	0.69
At total dose of 15 kGy						
Density (g / cm^3)	1.051	0.002	1.056	0.001	1.070	0.002
Moisture content (%)	0.56	0.07	0.70	0.03	0.84	0.16
Hardness	77.75	0.69	77.35	0.83	76.54	0.53
At total dose of 20 kGy						
Hardness	76.39	0.43	75.93	0.54	75.71	0.41

Appendix C % Water absorption of the bamboo fiber / ABS composites

Table C1 Effect of % water absorption of the bamboo fibers

Type	% Water absorption	
	mean	stdev
Extracted & ungrafted bamboo fibers	425.42	0.76
Unextracted & ungrafted bamboo fibers	314.04	0.73

Table C2 Effect of % fiber loading on % water absorption of sample A (unextracted & ungrafted bamboo fiber / ABS composites) vs. soaking time

Time	ABS		3 phr		5 phr		10 phr		20 phr		30 phr		40 phr	
(hours)	mean	stdev	mean	stdev	mean	stdev	mean	stdev	mean	stdev	mean	stdev	mean	stdev
24	0.381	0.018	0.430	0.048	0.050	0.016	0.732	0.031	1.249	0.179	1.620	0.090	1.731	0.107
64	0.574	0.030	0.712	0.065	0.841	0.027	1.199	0.035	1.867	0.311	2.595	0.110	2.617	0.178
96	0.619	0.006	0.782	0.070	0.933	0.033	1.362	0.051	2.215	0.229	2.785	0.112	2.975	0.022
119	0.694	0.007	0.863	0.052	0.988	0.035	1.532	0.073	2.439	0.236	2.965	0.139	3.288	0.064
168	0.742	0.017	0.941	0.065	1.127	0.053	1.576	0.082	2.631	0.301	3.163	0.077	3.585	0.019
209	0.781	0.006	0.979	0.053	1.178	0.035	1.682	0.076	2.771	0.240	3.254	0.057	3.718	0.064
257	0.804	0.011	1.018	0.048	1.209	0.051	1.712	0.053	2.870	0.246	3.410	0.083	3.837	0.068
328	0.838	0.005	1.078	0.055	1.280	0.030	1.81	0.012	2.914	0.239	3.509	0.025	4.030	0.061
524	0.901	0.006	1.156	0.062	1.301	0.114	1.840	0.029	2.975	0.186	3.691	0.045	4.257	0.094
698	0.931	0.001	1.221	0.032	1.428	0.042	1.947	0.072	3.237	0.229	3.830	0.122	4.607	0.203
1028	0.961	0.009	1.249	0.045	1.472	0.041	2.012	0.048	3.3046	0.293	3.920	0.125	4.774	0.227

Table C3 Effect of % fiber loading on % water absorption of sample C (extracted & ungratfed bamboo fiber / ABS composites) vs. soaking time

Time (hours)	3 phr		5 phr		10 phr	
	mean	stdev	mean	stdev	mean	stdev
24	0.491	0.033	0.538	0.034	0.767	0.033
64	0.795	0.039	0.870	0.053	1.365	0.022
96	0.891	0.028	0.954	0.046	1.444	0.042
119	0.982	0.059	1.090	0.060	1.541	0.018
168	1.019	0.062	1.158	0.038	1.604	0.073
209	1.484	0.060	1.205	0.046	1.774	0.029
257	1.109	0.062	1.242	0.054	1.815	0.026
328	1.186	0.070	1.328	0.044	1.874	0.018
524	1.200	0.069	1.404	0.065	1.958	0.032
698	1.320	0.068	1.444	0.030	2.029	0.026
1028	1.375	0.072	1.525	0.039	2.116	0.011

Table C4 Effect of % fiber loading on % water absorption of sample B (unextracted & grafted (15 kGy) bamboo fiber / ABS composites) vs. soaking time

Time (hours)	3 phr		5 phr		10 phr	
	mean	stdev	mean	stdev	mean	stdev
24	0.426	0.062	0.505	0.038	0.600	0.035
64	0.680	0.035	0.801	0.038	1.027	0.050
96	0.762	0.050	0.899	0.048	1.175	0.063
119	0.840	0.040	0.993	0.033	1.309	0.017
168	0.908	0.033	1.092	0.054	1.388	0.053
209	0.957	0.040	1.123	0.063	1.476	0.041
257	0.998	0.033	1.173	0.047	1.549	0.067
328	1.038	0.041	1.216	0.054	1.584	0.020
524	1.116	0.045	1.334	0.053	1.680	0.022
698	1.189	0.003	1.379	0.045	1.800	0.057
1028	1.212	0.035	1.429	0.052	1.867	0.036

Table C5 Effect of % fiber loading on % water absorption of sample D (extracted & grafted (15 kGy) bamboo fiber / ABS composites) vs. soaking time

Time (hours)	3 phr		5 phr		10 phr	
	mean	stdev	mean	stdev	mean	stdev
24	0.480	0.029	0.493	0.029	0.750	0.039
64	0.710	0.056	0.834	0.069	1.174	0.099
96	0.803	0.030	0.910	0.051	1.334	0.092
119	0.904	0.035	1.047	0.054	1.5318	0.094
168	0.967	0.055	1.095	0.028	1.616	0.090
209	1.017	0.038	1.159	0.031	1.677	0.050
257	1.050	0.030	1.208	0.047	1.708	0.042
328	1.106	0.033	1.228	0.053	1.817	0.043
524	1.172	0.037	1.339	0.026	1.884	0.064
698	1.224	0.022	1.411	0.018	1.979	0.029
1028	1.282	0.019	1.479	0.021	2.028	0.033

Table C6 Effect of total irradiation dose on % water absorption of sample B (unextracted & grafted bamboo fiber / ABS composites) (10 phr) vs. soaking time

Time (hours)	0 kGy		5 kGy		10 kGy		15 kGy		20 kGy	
	mean	stdev	mean	stdev	mean	stdev	mean	stdev	mean	stdev
24	0.732	0.031	0.698	0.030	0.658	0.038	0.600	0.035	0.663	0.034
64	1.199	0.035	1.115	0.065	1.087	0.038	1.027	0.050	1.103	0.035
96	1.362	0.015	1.278	0.033	1.201	0.045	1.175	0.063	1.221	0.022
119	1.532	0.073	1.462	0.019	1.351	0.032	1.309	0.017	1.342	0.064
168	1.576	0.028	1.498	0.033	1.445	0.032	1.388	0.053	1.428	0.019
209	1.681	0.076	1.578	0.045	1.567	0.069	1.476	0.041	1.556	0.031
257	1.712	0.053	1.628	0.035	1.598	0.047	1.549	0.067	1.591	0.047
328	1.816	0.012	1.701	0.055	1.676	0.045	1.584	0.020	1.616	0.043
524	1.840	0.029	1.788	0.045	1.747	0.053	1.680	0.022	1.732	0.065
698	1.974	0.072	1.902	0.047	1.844	0.047	1.800	0.057	1.852	0.025
1028	2.012	0.048	1.973	0.063	1.903	0.054	1.867	0.036	1.912	0.018

APPENDIX D FTIR spectrums of ABS and the bamboo fiber / ABS composites

Figure D1 FTIR spectrum of ABS

Figure D2 FTIR spectrum of sample B (unextracted & grafted (5 kGy) bamboo fiber / ABS composites)

Figure D3 FTIR spectrum of sample B (unextracted & grafted (10 kGy) bamboo fiber / ABS composites)

Figure D4 FTIR spectrum of sample B (unextracted & grafted (15 kGy) bamboo fiber / ABS composites)

Figure D5 FTIR spectrum of sample B (unextracted & grafted (20 kGy) bamboo fiber / ABS composites)

Appendix E Bamboos and their are the common species found in Thailand [88]

Number	Local Name	Botanical Name	Diameter (cm)	Locality
1	Jote	*Arundinaria ciliate* A. Camus	0.75 - 1.00	Southern and Eastern Region
2	Yah Pet	*Arundinaria pusilla* A. Chev.et A. Camus	0.50 - 0.70	North Eastern Region
3	Pai Paa, Pai Namm	*Bambusa arundinaceae* Wild	10.00 - 15.00	Throughout Thailand
4	Pai See Sook	*Bambusa blumeana* Schult	7.00 - 10.00	Generally cultivated
5	Pai Waan, Pai Bong Naam (North Region)	*Bambusa burmanica* Gamble	10.00 - 12.00	Northern Region
6	Pai Lam Ma - lork, Pai Yai Gor (Rashaburi)	*Bambusa longispiculata* Gamble	7.00 - 9.00	Throughout Thailand
7	Pai Liang	*Bambusa nana* Roxb.	2.00 - 3.00	Generally cultivated
8	Pai bong [89]	*Bambusa nutans* Wall. ex Munro	5.00 - 8.00	North and Central Region
9	Pai Sangkum	*Bambusa pallida* Munro	5.50 - 7.50	North and North Eastern Region
10	Pai Hom	*Bambusa polymorpha* Munro	7.50 - 15.00	Chiengrai and Northern Region
11	Pai Long	*Bambusa valgaris* Schrader	5.00 - 10.00	Throughout Thailand
12	Pai Nam Tao [89]	*Bambusa valgaris* Schrader cv. "Wamin" (Brandis) McClure or *Bambusa wamin* Brandis		
13	Pai Num Tao	*Bambusa wamin* G. Camus	10.00 - 12.00	Chiengmai and Northern Region
14	Pai Kao laam	*Cephalostachyum pergracile* Munro	5.00 - 7.50	Northern Region
15	Pai Hia	*Cephalostachyum virgatum* Kurz. Syn. Melocanna virgata Munro	4.00 - 4.50	Northern Region

Number	Local Name	Botanical Name	Diameter (cm)	Locality
16	Pai Dtong [89]	*Dendrocalamus asper* Backer. Syn. *Gigantochloa aspera* Kurz. *Bambusa aspera* Schult	10.00 - 18.00	Prachinburi
17	Pai Bang Yai, Pai Bong Kay (Chiengray)	*Dendrocalamus brandisii* Kurz. Syn. *Bambusa brandisii* Munro	12.00 - 20.00	Throughout Thailand
18	Pai Hok	*Dendrocalamus giganteus* Munro	15.00 - 20.00	Throughout Thailand
19	Pai Nuan Yai, Pai Por	*Dendrocalamus Hamiltonii* Nees and Arn	10.00 - 17.00	Northern Region
20	Pai Sangkum	*Dendrocalamus latiflorus* Munro	10.00 - 12.00	Northern Region
21	Pai Lamalog	*Dendrocalamus longispathus*	7.50 - 10.00	Throughout Thailand except southern part
22	Pai Sang Nuan, Pai Sang Doi, Pai Nuan (North region)	*Dendrocalamus membranaceus* Munro	3.00 - 12.00	Throughout Thailand
23	Pai Sang	*Dendrocalamus Strictus* Nees	3.00 - 8.00	Northern Region
24	Pai Khlan	*Dinochloa maclellandi* Kurz	2.50 - 5.00	North and Southern Region
25	Pai Luai	*Dinochloa scanned* O.Kuntze	2.50	Throughout Thailand
26	Pai Rai [89]	*Gigantochloa alociliata* Kurz	1.50 - 3.00	Throughout Thailand
27	Pai Paak Man, Pai Paak, Pai Rai Lor (North region [89])	*Gigantochloa hasskarliana* Backer. *Syn. G. negrociliata* Munro	5.00 - 10.00	Throughout Thailand
28	Pai Takwang	*Gigantochloa kurzii*	7.50	Southern Region
29	Pai Hangchang	*Meloalamus Compactiflorus* Benth and Hook	2.50 - 4.50	Throughout Thailand
30	Pai or - lor [89]	*Melocanna humilis* Kurz	1.50 - 3.50	Surat Thani, Phitsanuloke

Number	Local Name	Botanical Name	Diameter (cm)	Locality
31	Pai Rai	*Oxytenanthera albociliata* Munro	1.50 - 2.50	Throughout Thailand
32	Pai Kai	*Oxytenanthera hosseusii* Pilger	1.50 - 2.50	Throughout Thailand
33	Pai Phak	*Oxytenanthera nigrociliata* Munro or *Oxytenanthera densa* A. Camus	5.00 - 10.00	Southern Region
34	Pai Lowt	*Schizostachyum aciculare* Gamble	1.00 - 1.50	Southern Region
35	Pai Torng, Pai Por (Turng)	*Schizostachyum brachycladum* Kurz	-	-
36	Pai Po	*Schizastachyum zollingeri* Steud	4.00 - 6.00	Southern Region
37	Pai Ruak	*Thyrosotachys siamemsis* Gamble	4.00 - 6.00	Throughout Thailand
38	Pai Ruak Dam, Pai Ruak Yai	*Thyrsotachys oliveri* Gamble	5.00 - 7.50	Northern Region

Bamboos in Thailand [90]

Bambusa arundinaceae Wild

In fertile forest it reaches a large size. Flowering occurs almost every year in scattered areas. The main use is in construction, especially for scaffolding, and in rural areas the load - bearing parts of houses. In Amphur Norng Mon, Chonburi the stem is used for making Kaou Laam.

Bambusa burmanica Gamble

It is a small shrubby bamboo, growing in dense dumps. The stem is not straight. The shoot used to be an important economic product in Laei. It is planted for the shoot, but is liable to be damaged by rodents. The stem is also used, but only for firewood.

Bambusa longispiculata Gamble

It grows in a light clump with the stem 1 to 1.5 feet apart. The bamboo is medium sized. The stem is deep green and shiny, and branches near the tip. It is widely used in construction, for furniture, as durable props and for basketry.

Bambusa nana Roxb

It is a medium - size bamboo. The stem is green with fine creamy white hairs and a white internode. It is planted as an ornamental or fire line. The stem is used to make furniture, pros and ladders. The shoot is edible, but not popular as the stem is more useful.

Bambusa nutans Wall. ex. Munro

It is medium - size bamboo, stems and grows in dense clumps. The stem is bent, rough, and has cream or gray powder - like hairs, especially near the base. Flowering is in scattered clumps and the seeds are similar to rice seeds. It is widely used in the North for construction and basketry.

Bambusa vulgaris Schrader

There are two kinds, one with a green stem and one with green and yellow, lengthwise strips of deferring width. It is medium - size bamboo. The main use is as an ornamental, but it can be used in construction or to make decorative goods.

Bambusa vulgaris Schrader cv. "Wamin" (Barndis) McClure

This was introduced from Southern China as an ornamental. The plant is small and shrubby, with a deep green stem and swollen internodes.

Cephalostachyum pergracile Munro

The bamboo is medium - sized and growing clumps. The stem surface is rough and creamy green. This bamboo is widely used because it is soft and elastic, and can be split into thin strips, which make it suitable for fine basketry. The stem is also used to make roof frames and animal pens.

Cephalostachyum virgatum Kurz

It is a medium - size bamboo with thin walls and long internodes. The young stem has white hairs, while the mature stem is deep green and rough. The stem is straight, with small even - sized branches, especially near the tip. It has limited used for ceilings and walls, but not floors as it forms sharp edges when split.

***Dendrocalamus asper* Backer**

The stem is large, up to 20 meters long. There are fire kinds : Pai Dtong Mor or Pai Dtong Yai has the largest stem, but is planted little ; Pai Dtong Dam is widely planted and has deep green stems and large, thick, deep green leaves ; Pai Dtong Khieo has a smooth, deep green stem, but is smaller and has smaller, thinner leaves than Pai Dtong Dam ; Pai Dtong Moo is the smallest type and is rare : Pai Dtong Lai is probably the second or third type. This bamboo is planted commercially for the shoot and the stem is used for pulp, to make chopsticks, tooth picks and in construction.

***Dendrocalamus brandisii* Kurz**

It also occurs widely in field margins. The stem is similar to but smaller than D. asper. The stem is large and the clump not dense. The stem is long and the wall thick so it is widely used in the construction and pulp industry.

***Dendrocalamus hamiltonii* Nees & Arn**

This bamboo is the largest in Thailand. The stem is dear and straight at the base, with no branching. Locally, it is widely used for the shoot, and the large stem which is used for house posts or split for basketry. The large sheaths are used to make shade.

***Dendrocalamus membranaceus* Munro**

The stem is not straight. In natural forest it occurs in light clumps. Flowering occurs from November to Mey in scattered clumps. The stem wall is of medium thickness so it is used widely in construction and basketry.

***Dendrocalamus strictus* Nees**

The bamboo is medium sized. It grows in clumps, but not densely. Mature stems are yellow - green and the flowers globular bunches. When fully - grow the flowers are thorn - like and sharp. The stem is used to make tools, houses, basketry a water container, flooring, ceilings, fencing, etc.

***Gigantochloa albociliata* Kurz**

The plant is small and shrubby. The fully grow stem bends down to the ground. The bamboo is widely used. The stem is small but thick, especially near the base, so is used to make tools. The stem can also be cut and bent for use in furniture etc. In North Thailand it is used as a rattan substitute.

Gigantochloa hasskarliana Backer Syn. G. negrocilliata Munro

In Kanchanaburi it forms pure forest. It is medium - size bamboo. The stem is rough with raised nodes. The bamboo is widely used. The stem is split lengthways and used for fencing, constructing propagating sheds or part of houses, basketry for rough and temporary use.

Metocanna humilis Kurz

It is a small bamboo. The internode length is 23 to 25 centimeters all along the stem. The bamboo is not common, not well - known. It is suitable for an ornamental plant.

Schizostachyum branchycladum Kurz

There are two varieties, Pai Torng has a yellow stem, and Pai Por which is native to Thailand, has a green stem. It is a small to medium-size bamboo, with thin stem walls and growing in dumps. Pai Torng is only planted as an ornamental, which Pai Por is used for basketry or partially split to make walls, floors and ceilings, and in construction which does not need durability.

Thyrosostachys oliveri Gamble

It has larger stem, longer internodes and thinner walls. Also the stem is straight and the sheaths wrap the stem from the base to the tip. It is an economically - valuable plant, widely used in constructions, as props for making tools, industrial baskets and for the shoots. It is also planted as an ornamental.

BIOGRAPHY

Name	Miss Piyawan Tangkawanwanit
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