ผลของแป้งมันสำปะหลังต่อสมบัติกายภาพของยางธรรมชาติผสม

นายวีรเดช ศิลป์สัมฤทธิ์

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EFFECT OF CASSAVA STARCH ON PHYSICAL PROPERTIES OF NATURAL RUBBER BLENDS

Mr. Weeradej Silpsamrith

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for the Degree of Master of Science in Petrochemistry and Polymer Science
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ยางธรรมชาติผสมเตรียมขึ้นจากน้ำยางธรรมชาติผสมกับแป้งเปียกมันสำปะหลังซึ่งเข้มข้นร้อยละ 18 น้ำหนักต่อปริมาตร ก่อนนำไปแยกเป็น 2 ส่วนเพื่อใช้ในกระบวนการผลิตเป็นแผ่นยางผสมแป้งอบแห้งและกระบวนการผลิตแบบผ่านการเกิดโฟม ทั้งนี้เพื่อศึกษาผลของปริมาณแป้งมันสำปะหลังต่อสมบัติกายภาพของยางธรรมชาติผสม สำหรับกระบวนการผลิตแผ่นยางผึ่งแห้งจะกวนของผสมด้วยความเร็ว 1.3 รอบต่อวินาที ก่อนจะเทลงในถาดเหล็กปลอดสนิมแล้วนำไปอบแห้งในเตาอบที่ 60 องศาเซลเซียส ในลักษณะเดียวกันกระบวนการผลิตแผ่นยางผสมแป้งแบบผ่านการเกิดโฟมนั้นจะกวนของผสมโดยเติมโซเดียมไบคาร์บอเนตแล้วเทลงในกล่องพลาสติก นำไปให้ความร้อนและอบแห้งในเตาไมโครเวฟที่ระดับความร้อนกลาง-สูงเป็นเวลา 3000 วินาที จะเกิดโฟมขึ้นในเวลาเดียวกัน เสร็จแล้วนำไปบดไล่โฟมและผสมให้เป็นเนื้อเดียวกันในเครื่องบดแบบสองลูกกลิ้ง

ผลการศึกษาแสดงว่าปริมาณแป้งมันสำปะหลังมีผลต่อสมบัติกายภาพของยางที่ได้จากทั้ง 2 กระบวนการโดยกระบวนการผลิตแผ่นยางผสมแป้งอบแห้ง ดัชนีความอ่อนตัว ความหนืดมูนี เวลาที่ยางคงรูป ความหนาแน่น ความแข็งและความยืดเมื่อขาดมีค่าสูงขึ้นตามปริมาณแป้งมันสำปะหลังที่เพิ่มขึ้น ขณะที่ความทนแรงดึงและความทนแรงฉีกลดลง ส่วนกระบวนการผลิตแผ่นยางผสมแป้งแบบผ่านการเกิดโฟมพบว่าเมื่อปริมาณแป้งมันสำปะหลังเพิ่มขึ้น เวลาที่ยางคงรูป ความหนาแน่นก่อนและหลังการคงรูป และความทนแรงกดเพิ่มขึ้น แต่ความหนาแน่นก่อนบดผสมลดลง ส่วนความยืดเมื่อขาดและความทนแรงดึงแสดงค่าสูงในช่วงปริมาณแป้งร้อยละ 20-30 แสดงการเป็นสารเสริมแรง

หลักสูตรปิโตรเคมีและวิทยาศาสตร์พอลิเมอร์ ลายมือชื่อนิสิต ....
สาขาวิชาปิโตรเคมีและวิทยาศาสตร์พอลิเมอร์ ลายมือชื่ออาจารย์ที่ปรึกษา ....
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WEERADEJ SILPSAMRITH: EFFECT OF CASSAVA STARCH ON PHYSICAL PROPERTIES OF NATURAL RUBBER BLENDS. THESIS ADVISOR : PIENPAK TASAKORN, Ph.D. 120 pp. ISBN 974-13-0573-7.

Natural rubber blends were prepared by mixing natural rubber latex with 18% W/V cassava starch paste, before dividing the mixture into two parts for the rubber/starch mix sheet production and rubber/starch mix de-foamed sheet production. This is to study the effect of cassava starch content on physical properties of natural rubber blends. In the rubber/starch mix sheet production, the mixture was stirred at 1.3 revolution per second before pouring into a stainless steel tray and dried at 60 degree Celsius in a vented air oven. Similarly, in the rubber/starch mix de-foamed sheet production, the mixture was stirred with sodium bicarbonate added then placed in a plastic box. It was heated and dried, using a microwave oven set at medium-high level for 3,000 seconds, foam was formed at the same time. The mass was de-foamed and homogenized using a two-roll mill.

It was found that cassava starch affects the physical properties for both processes. In the rubber/starch mix sheet production, plasticity retention index, Mooney viscosity, optimum cure time, density, hardness and %elongation at break increase with the increase of cassava starch content while both tensile and tear strengths decrease. In the rubber/starch mix de-foamed sheet production, optimum cure time, density before and after vulcanization and compression deflection increase with the increasing of cassava starch content whereas density before compounding decreases. However, %elongation at break and tensile strength exhibit high values at starch contents between 20-30% indicating it being a reinforcing filler.

Program Petrochemistry and Polymer Science Student's signature ....

Field of study Petrochemistry and Polymer Advisor's signature ....

Academic year 2000

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ABBREVIATIONS

ADS	Air dried sheet
AGU	Anhydroglucose unit
$^{\circ}C$	Degree Celsius
cal	Calorie
CBA	Chemical blowing agent
CBS	Cyclohexylbenzoyl sulphenamide
D.P.	Degree of polymerization
DRC	Dry rubber content
g	Gram
G'	Shear modulus
GHz	Gigahertz
ΔGm	Free energy of mixing
ΔHm	Enthalpy of mixing
k	Kilo
kg	Kilogram
L	Large rotor
LDPE	Low density polyethylene
m	Mass
m^2	Square meter
m^3	Cubic meter
M	Viscosity in Mooney unit or Mega
M_{HR}	Maximum torque
M_L	Minimum torque
max	Maximum
min	Minimum

MPa	Megapascal
N	Newton
NBR	Nitrile rubber
NR	Natural rubber
P	Plasticity value
PBA	Physical blowing agent
pphr	Part per hundred of rubber
pphp	Part per hundred of polymer
PRI	Plasticity retention index
r.p.s.	Revolutions per second
S	Sulphur
s	Second
$t_c(90)$	Optimum cure time
T_g	Glass transition temperature
t_{S1}	Time to increase one tenth of a unit of torque
TMTD	Tetramethyl thiuram disulphide
TSC	Total solid content
VFA	Volatile fatty acid
% V/V	Percent volume by volume
% W/V	Percent weight by volume
ZnO	Zinc oxide
α	Alpha
β	Beta
ρ	Density
γ	Gamma
%	Percent

CHAPTER I

INTRODUCTION

Natural rubber is one of the most important produce of Thailand. The quantity produced annually is the largest in the world as shown in Table A1 [1] in the Appendix A. Even though the consumption has been increased for the last five decades, the trend has declined by the substitution of synthetic rubber as illustrated in Figure 1.1.

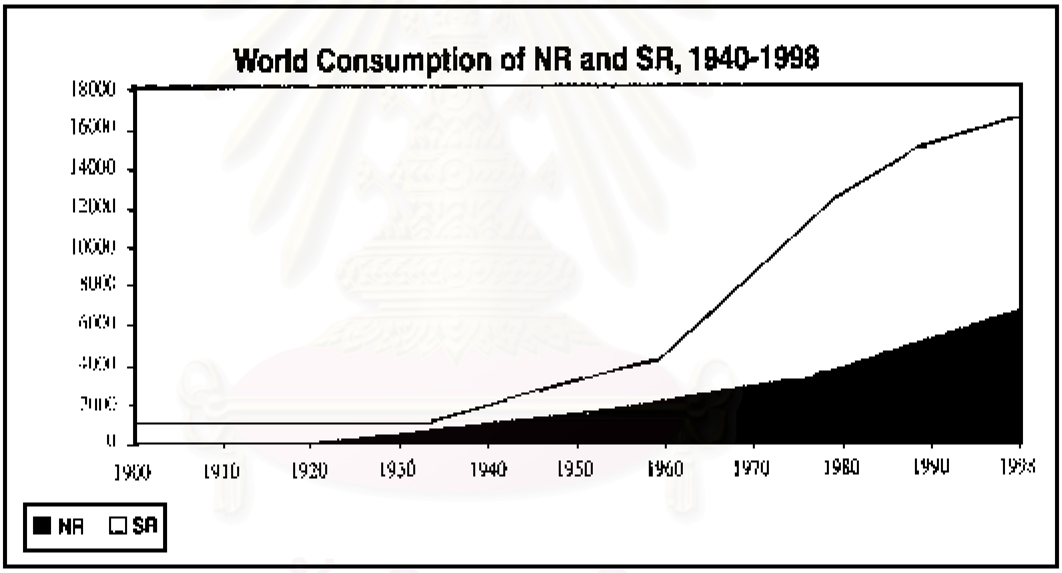


Figure 1.1 World consumption of natural rubber and synthetic rubber 1940-1998 [2]

The increase of world synthetic rubber consumption has an immense impact on the future of natural rubber. It is therefore a necessity for Thailand to explore new applications for natural rubber in a form of new material due to several advantages of natural rubber and cassava starch. For natural rubber, it is available and not expensive as same as cassava starch. It is intended for this thesis to emphasize on two objectives. The first one is to study the effect of adding cassava starch into field latex on the properties of dried rubber mix. The second one is to explore the possibility of the dried rubber production processes by using a vented air oven and a microwave oven. With the two objectives, two new natural rubber production processes are devised; however, both emphasize blending natural rubber latex with cassava starch to form a new material.

The purpose of the first process is to produce rubber/starch mix sheet from the blends by vented air oven. For the second process, it is to produce rubber/starch mix de-foamed sheet from the blends using microwave as a heating device and the starch as and sodium bicarbonate foam-forming agents. The properties of the materials from the two processes are determined to suggest their suitability for applications. It is envisaged that the processes may be applied to concentrated natural rubber latex and skim latex as well. Thus a new area of natural rubber application is opened for development to the betterment of its future.

CHAPTER II

THEORITICAL CONSIDERATIONS AND LITERATURE REVIEWS

2.1 Natural rubber latex

2.1.1 Rubber

Rubber is defined as a material that is capable of recovering from large deformations quickly and forcibly, and can be, or already is, modified to a state in which it is essentially insoluble (but can swell) in boiling solvent, such as benzene, methyl ethyl ketone, and ethanol toluene azeotrope. A rubber in this modified state, free of diluents, retracts within one minute to less than 1.5 times its original length after being stretched at room temperature (18 to 20 degree Celsius) to twice its length and held for one minute before release [3].

2.1.2 General properties

Fresh latex is tapped from the rubber tree known by scientific name as *Hevea brasiliensis*. It is milky white or slight yellowish opaque liquid with pH differing from 6.5 to 7.0. The density varies from 0.975 to 0.980 Mg/m^3, and viscosity varies from 12 to 15 centipoise. The chemical and physical properties of latex are influenced by clones of rubber, age of rubber, tapping intensity, soil characteristics and season of tapping [4].

In addition, latex can be separated into four fractions by ultra-centrifugation as shown in Figure 2.1.

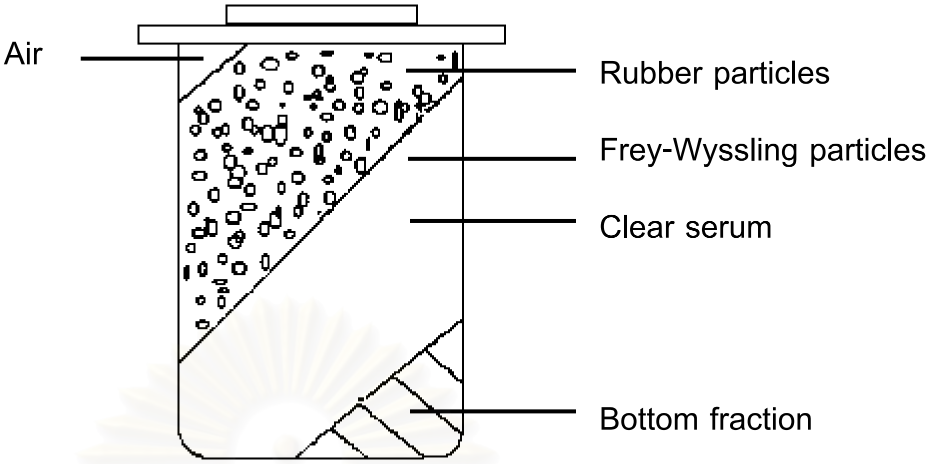


Figure 2.1 Fractions of latex after ultra-centrifugation [4]

(1) The top layer is composed of rubber particles.

(2) The next layer consists of Frey-Wyssling particles.

(3) The middle layer is serum.

(4) The bottom layer consists of lutoid and non-rubber particles.

2.1.3 Composition of latex

Latex can be separated into two main components [5].

(1) rubber matter	35%
(2) non-rubber matter	65%

(water 55%; lutoid and others 10%)

Detailed analysis of latex is summarized in Table 2.1.

Table 2.1 Composition of latex [5].

Composition	%
Total solid content (TSC)	27-48
Dry rubber content (DSC)	25-45
Protein matters	1-1.5
Resin matters	1-1.25
Ash	about 1
Sugar	1
Water	combine with other parts to be 100

From the composition of latex in Table 2.1, rubber matters may be considered to include three main components.

2.1.4 Rubber matters composition

(1) Rubber particle

Rubber particle is encapsulated with lipid and protein layer respectively as illustrated in Figure 2.2. Moreover, it disperses in water and almost is cis-1,4-polyisoprene; the structure is shown in Figure 2.3. The density is 0.92 Mg/m^3. It is spheriodal or elepsoidal, and the average size is about 1 micron; the particle size, however, can be broad distribution of sizes differing from 0.04 to 4 micron. Rubber particle also has the other physical properties listed in Table 2.2.

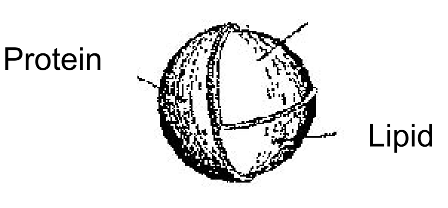


Figure 2.2 Rubber particle feature [5]

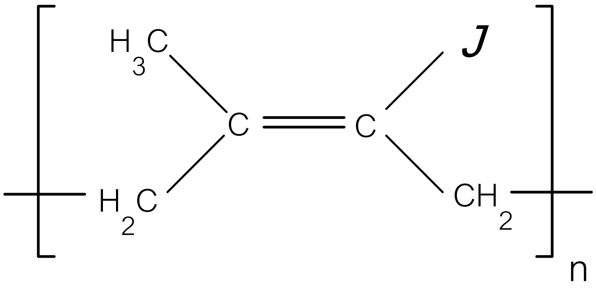


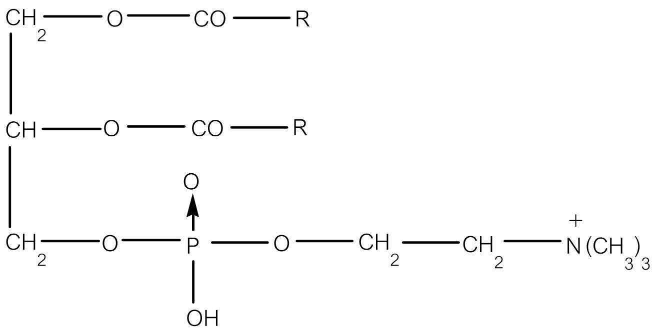
Figure 2.3 Structure of cis-1,4-polyisoprene

Table 2.2 Physical properties of rubber particle [6].

Physical properties	Unit	
Density	Mg/m^3	0.92
Refractive index (20 °C)		1.52
Coefficient of cubial expansion	/°C	0.00062
Cohesive energy density	$kcal./m^3$	6.4×10^{-8}
Heat of combustion	kcal./kg	0.1
Thermal conductivity	$kcal./s/m^2/°C$	0.0032
Dielectric constant		2.37
Power factor (1,000 cycles)		0.15-0.2
Volume resistivity	$ohms/m^3$	10^{21}
Dielectric strength	$Mvolts/m^3$	1

(2) Lipid

Lipid is between rubber particle and protein layer [5]. Most of lipid is called alpha-lecithin as shown in Figure 2.4, which is phospholipid compound. Alpha-lecithin is believed to attach protein layer with rubber particle.



R is either heptadecyl ($C_{17}H_{35}$) or heptadenyl ($C_{17}H_{33}$)

Figure 2.4 Structure of alpha-lecithin [5]

(3) Protein

Protein coating at the outer layer of rubber particle is about 25% of all proteins in latex. In addition, 50 and 25% of proteins are in water and lutoid parts respectively. Almost all protein at the outer layer of rubber particle is known as alpha-glubulin, and the residual protein is known as Hevein alpha-glubulin. It does not dissolve in distilled water, yet it dissolves in acid alkali and salt; furthermore, its iso-electric point is pH 4.8, so rubber particle always coagulate at this pH. On the other hand, Hevein dissolves in distilled water, and its iso-electric point is pH 4.5. Hevein protects coagulation when dehydration occurs like filling either alcohol or acetic acid into latex.

Besides, protein at the outer layer of rubber particle consists of cystine disulphide linkage, which is sulfur compound about 5 percent. Therefore, when coagulation occurs, protein at this part degrades into hydrogen sulfide and mercaptan compound giving bad smell.

According to the main composition of latex, the other compositions are non-rubber matters. They compose of two main fractions.

2.1.5 Non-rubber matters composition

(1) Water or serum

The density fraction approximates 1.02 Mg/m^3; this fraction consists of two types of substances, carbohydrate; protein and amino acid.

Carbohydrate is sugar and starch substances, and it presents in latex about 1 percent. Almost sugar in serum fraction is called quebrachitol as illustrated in Figure 2.5 and the residual sugars are glucose, fructose and sucrose respectively.

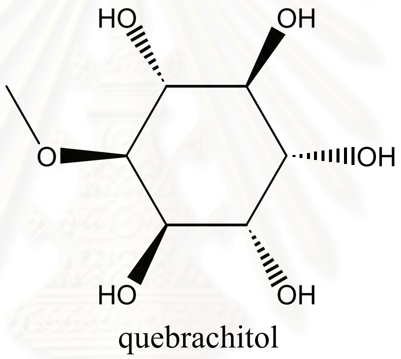


Figure 2.5 Chemical structure of quebrachitol sugar

Furthermore, these sugars can be fed by bacteria causing degradation of sugar into short chain fatty acids called volatile fatty acid (VFA) such as formic, acetic and propionic acid, which brings coagulation to latex.

Protein and amino acid

Almost protein in serum fraction is alpha-glubulin which is between water-air and oil-water interface.

(2) Lutoid and others

This fraction is composed of two main types, which are lutoid and Frey-Wyssling.

Lutoid

Lutoid is spherical, and its diameter is between 0.5 and 3 micron. Lutoid is encapsulated by thin layer having both solution and colloid. The pH of lutoid is 5.5; it, moreover, has 3 percent of dissolved water protein and 2 percent of undissolved water protein. In addition, lutoid has phospholipid about 0.5 percent and polyphenoloxydase, which causes rubber more yellow or brown when it is oxidized by oxygen in air.

Besides, osmosis can occur easily on lutoid because of both encapsulation by one layer and hot weather. When lutoid swells, latex viscosity increases, and when lutoid breaks down, latex viscosity decreases. Furthermore, breaking down of lutoid releases positive charge colloid and metal ions such as calcium and magnesium. These ions, coming out from lutoid to latex, causes coagulation. Moreover, adding ammonia into latex causes brown or purple precipitate at the bottom layer of latex because both magnesium ion and residual pieces of breaking lutoid combine with ammonia.

Frey-Wyssling

The size of Frey-Wyssling is bigger than rubber particle; however, its density is less than rubber particle. It is spherical with encapsulation by two carotenoid layers, which make rubber to be dark yellow. It can also combine with ammonia and precipitates into serum fraction.

The non-rubber matters are composed of many constituents as shown in Table 2.3.

Table 2.3 Non-rubber constituents in latex [6].

Constituents	Percentage by weight of latex
Fatty acid soaps (e.g., ammonium oleate)	0.5
Sterols and sterol esters	0.5
Proteins	0.8
Quebrachitol	0.3
Choline	0.1
Glycerophosphate	0.1
Water-soluble carboxylic acid salts (acetate, citrate, etc.)	0.3
Amino acids and polypeptides	0.2
Inorganic salts (ammonium and potassium carbonate and phosphate, etc.)	0.2

2.2 Coagulation of latex

Coagulation is defined as irreversible agglomeration of particles originally dispersed in rubber latex as shown in Figure 2.6. In addition, good coagulation brings good dynamic properties of rubber products.

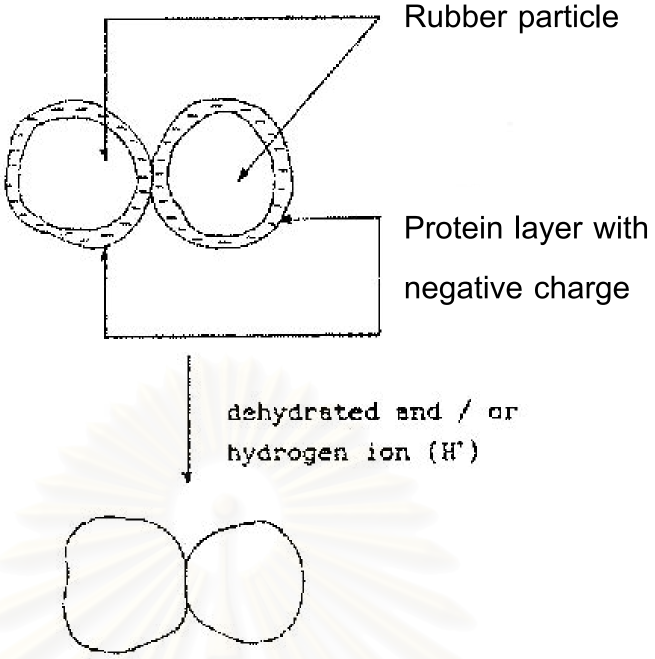


Figure 2.6 Coagulation model of latex [7]

There are other methods for coagulation which are listed below.

(1) Acid coagulation [4]

This method is the most useful for coagulation. It is accomplished by adding 2% V/ V formic acid at pH 5 into latex.

(2) Auto-coagulation

This method stores latex in open container for 24 hours.

(3) Biological coagulation

This method involves addition of anionic surfactant (Aerosol GPG) and molasses.

(4) Thermal coagulation

This method evaporates water or preservatives such as ammonia, formaldehyde and borax by various techniques such as steam coagulation [8].

2.3 Starch

2.3.1 Chemistry of starch

Starch is composed of carbon, hydrogen and oxygen in the ratio of 6:10:5 as an empirical formula of $C_6H_{10}O_5$. It is condensation polymer of glucose. The glucose units in starch are anhydroglucose units (AGU), the linkage called glycoside bond between glucose units are formed when water molecule is removed during a step polymerization [9]. Furthermore, starch is composed of two main compositions.

(1) Amylose

Amylose is linear polymer of glucose with 1,4'-glycosidic linkages (Figure 2.7). Amylose has an α-1,4' link, while cellulose has a β-1,4' link [9]. The degree of polymerization (D.P.) varies from about 250 to 4,000 AGU per amylose molecule with molecular weight about 40,000 to 650,000 [10]. Besides, amylose is the amorphous part of starch particle [11].

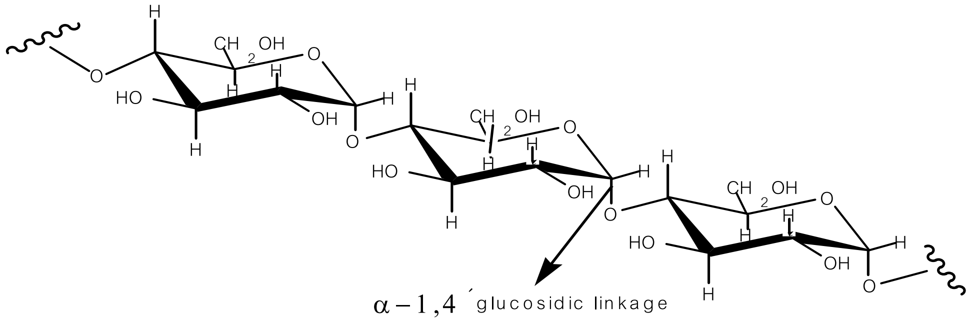


Figure 2.7 Chemical structure of amylose [9]

(2) Amylopectin

Amylopectin is a branch polymer molecule consisting of short linear amylose chains connected to each other by 1,6-linkage (Figure 2.8). The D.P. varies from 12 to 50 AGU, yet the average D.P. is about 20 AGU [10]. Besides, amylopectin is the crystalline part of starch particle, so if there is only amylopectin, starch can exist itself. Moreover, most of various starch also has amylopectin more than amylose [11].

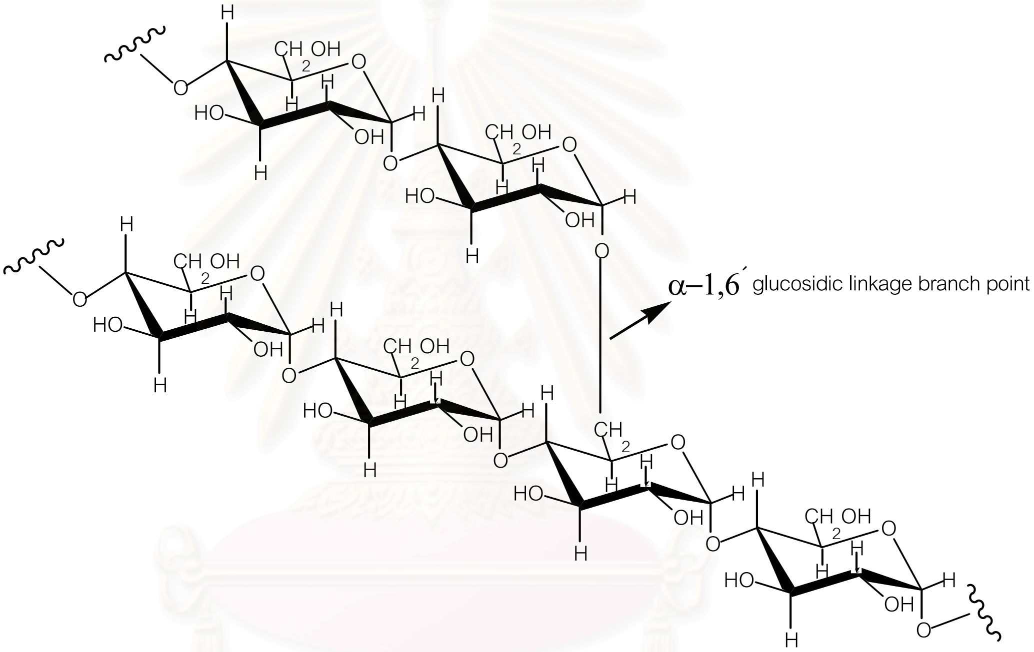


Figure 2.8 Chemical structure of amylopectin [9]

2.3.2 Phenomena of starch

There are two important phenomena of starch which are explained below.

(1) Gelatinization

Starch can adsorbs and swells in water, yet it does not dissolve in water until it is heated over gelatinized or pasting temperature which starch slurry begins to have viscosity because hydrogen bond of starch is disrupted by heating, then starch slurry becomes more clear in color and viscous to be starch paste [12]. This phenomena is illustrated in Figure 2.9.

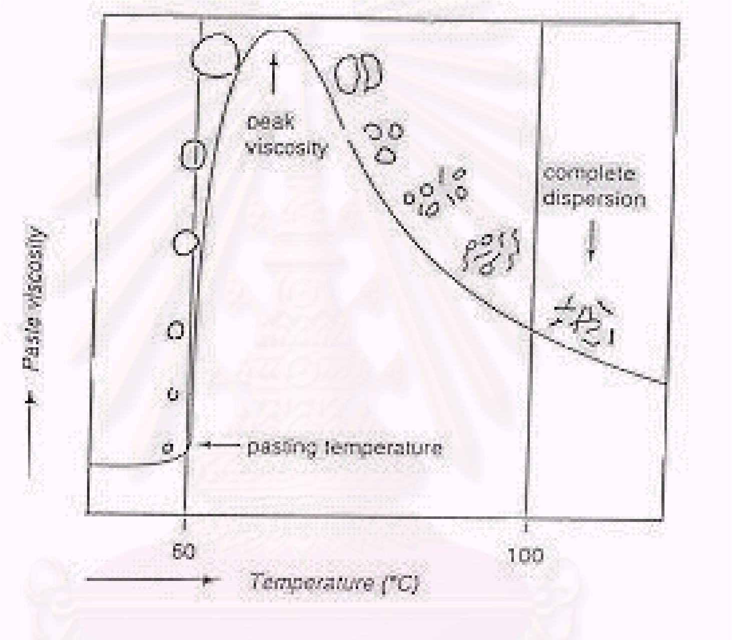


Figure 2.9 Swelling, disruption and dispersion of a starch granule during gelatinization [12]

(2) Retrogradation

When the starch paste continues increasing in temperature over gelatinized temperature, the starch particle extremely swell and break down [11]. Then amylose, which distributes in the starch paste, makes viscosity decrease. When the starch paste is cooled down, amylose forms three dimensional structure by attaching between hydrogen bond. This makes the starch paste more constant in viscosity and cloudy in color. This phenomena is known as retrogradation or set back. If the starch paste is still cooled down, the structure is more tight. This phenomena is called syneresis which the starch paste becomes more constant in viscosity and cloudy in color.

2.4 Polymer blends

2.4.1 Definition

The polymer blends is defined as combination of two or more polymers by various mixing methods such as in the molten method, in latex, etc. However, mixing methods do not influence forming of chemical bonding between the compound [13].

2.4.2 Reasons for blending

There are many reasons for blending [14].

(1) Extending engineering resin performance by diluting with lower cost polymer

(2) Developing materials with various desired properties

(3) Forming a high performance blend from synergistically interacting polymers

(4) Adjusting composition of the blend according to

customer requirements

(5) Recycling industrial waste by using as composition of polymer blends

2.4.3 Preparation method of polymer blends

There are various preparation methods of polymer blends; melt mixing, solution blends and latex mixing are the main methods for preparing polymer blends [13].

Melt mixing

This method reduces the contamination and diluents problems and assures that system do not change in molding operations because the necessary heat maintains a low viscosity and the shear rates through mixing. However, degradation of either one or all polymers can occur. The main melt mixing machines such as open-roll mill, internal mixer and extruder are described below:

Open-roll mill

A two-roll mill consists of two horizontal parallel rotating rollers closing to another with a small separating gap called nip. The nip is adjustable by moving the rollers. Material reaching the nip is deformed by friction forces between itself and the rollers and is made flow through the nip in the direction of roll motion. Besides, the front roll is usually slower than the back roll.

Internal mixer

An internal mixer consists of a feed chamber called hopper standing above a mixing chamber, a floating ram which forces material into a mixing chamber and a mixing chamber which contains different speeds. Disperse mixing requires high shear stress, so it is important to remove heat efficiently for maintaining a high viscosity by drilling passages which allow flow of cooling close to the inner surface of a mixing chamber.

Extruder

An extruder is one of the most distributive mixing, for it modifies mixing by exchange of materials between planes. Besides, there are many approaches to improve mixing in extruder. For example, the first approach is using pins in the barrel to divert and divide flow of materials. The second approach is using cavity transfer mixer to promote exchange of materials. Consequently, these two approaches improve mixing of extruder by diversion and reorientation of the flow stream. The third approach is using twin-screw to develop shear force.

Solution blending

This approach requires adding diluent to reduce both temperature and shear force for a satisfied mixing without degradation. However, removing of diluent can change the domain sizes of the blend, and some severe cases cause complete polymer separation due to moving of solvent to another phase.

Latex mixing

This approach is one of the most favorite techniques for preparation commercial polymer blends. In latex, polymers are presented as suspended microspheres with repulsion force protecting their contact by suspending medium (soap). After blending, a mixture of two latices with different polymers contains a random suspension of dissimilar particles which each one is unaffected by the other. However, coagulation can occur randomly because the rate of flocculation is dependent entirely on the soap concentration and is not on polymer characteristics. Coagulated material contains an intimate mixture of the polymers. Besides, both compounding and pelletizing of latex-blend material are often employed by melt mixing, and necessary precaution in this stage must be taken to avoid degradation.

2.4.4 Categories of polymer blends

Polymer blends can be separated into three categories [14].

(1) Miscible polymer blend

It is a class of materials found to be homogeneous down to the molecular level. It has negative value of free energy of mixing; $\Delta Gm = \Delta Hm < 0$

(2) Immiscible polymer blend

It has positive value of the free energy of mixing; $\Delta Gm = \Delta Hm > 0$

(3) Partially miscilble polymer blend

It is composed of two separated phases comprising A and B alone and mixture phase between A and B.

The different characteristics of polymer blends can be distinguished by observing the transition temperature demonstrated in Figure 2.10.

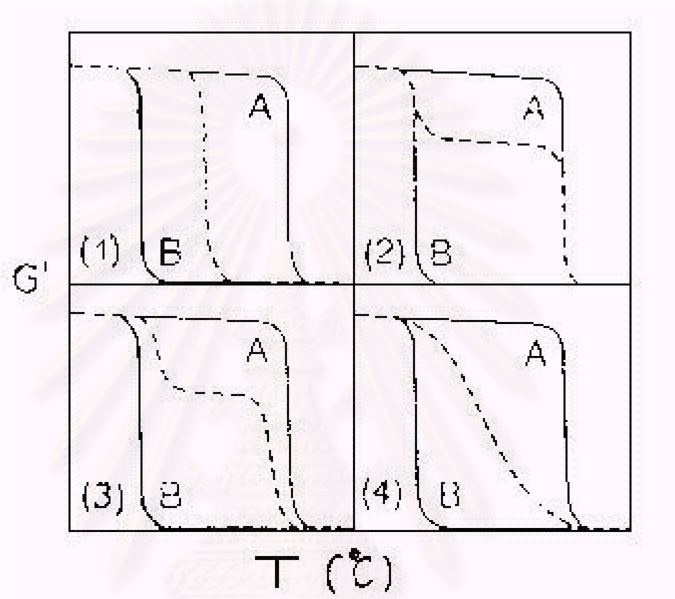


Figure 2.10 Diagrams of temperature dependence of storage shear modulus for polymer A and B (solid line) and their 50:50 mixture (dash line). (1) Miscible blend, (2) immiscible, (3) partially miscible and (4) jmmiscible blend with fine dispersion and broad glass transition region [14]

According to Figure 2.10, it shows the relationship between storage modulus and temperature. The solid lines represent the behaviors of neat polymers and the broken line of 50:50 blend. The sharp drop of a modulus is associated with the onset of molecular thermal motion in the region of glass transition temperature (T_g). The first diagram represents the miscible blend with one T_g. The second diagram represents the immiscible blend with two T_g showing T_g of each polymer. The third diagram shows the miscible blend having two T_g, yet both are shiftily. The last diagram shows an immiscible blend with fine dispersion. Thus, the broad glass transition is obtained. According to the difficulty in making miscible blend, the compatibilizer is used for modifying the interfacial properties of immiscible polymer blend providing the formation of polymer alloy as illustrated in Figure 2.11.

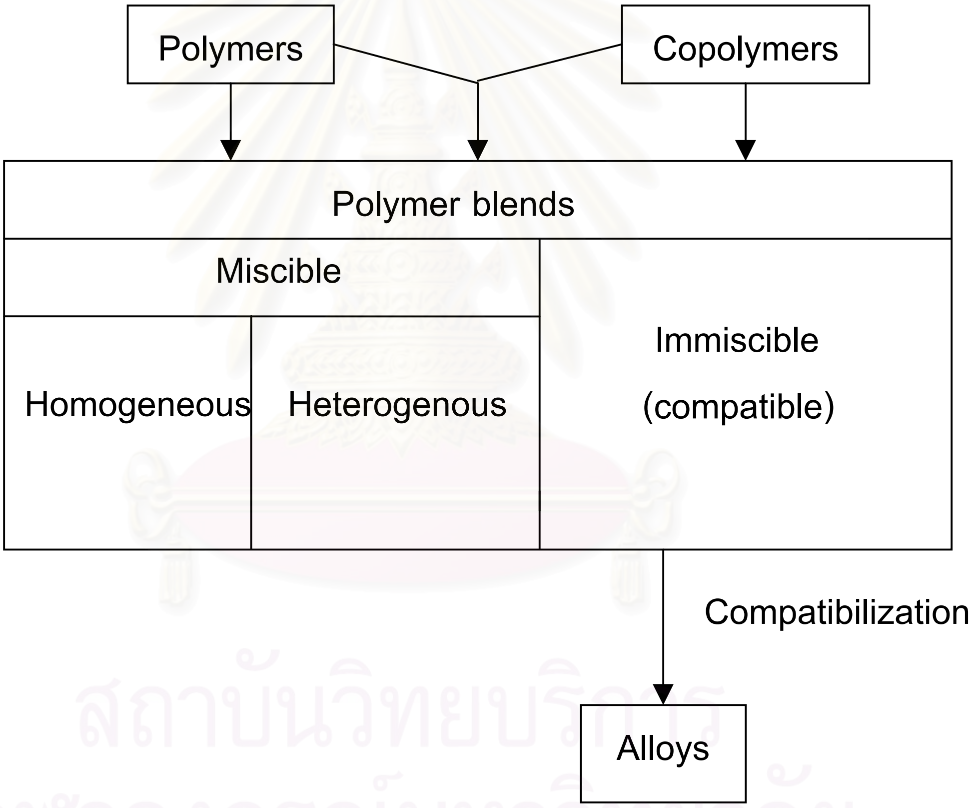


Figure 2.11 Relation in polymer blend nomenclature [14]

2.5 Foam

2.5.1 Foam formation

Foam occurs by three steps of production [15].

(1) Nucleation

This is the first step of foam formation occurring bubbles in liquid phase by agitation.

(2) Bubble growth

Bubbles in liquid phase grows by diffusion of gas from solution in liquid phase into bubbles.

(3) Expansion

When gas is liberated from bubbles because of heating, the bubbles touch each other and form solid foam.

Moreover, foam formation is illustrated in Figure 2.12.

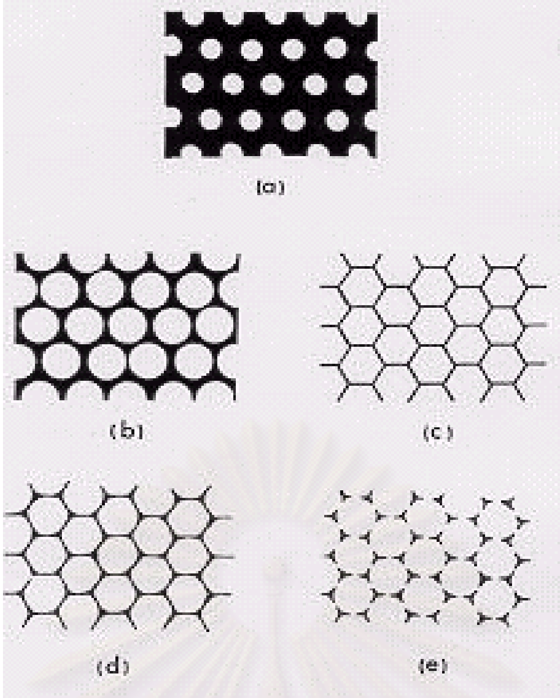


Figure 2.12 Schematic diagram of foam formation. (a) Nucleation, (b) Bubble growth, (c) Expansion, (d) Closed-cell foam and (e) Opened-cell foam [15]

2.5.2 Blowing agent

Blowing agent is the chemical liberating gas during foam formation [16]. Furthermore, it can be classified into two types.

(1) Chemical blowing agent (CBA)

It is either individual or mixture compound liberating gas as a result of chemical reaction, including thermal decomposition, and most of CBA are solids. Moreover, the great interesting CBA in industry are sodium carbonate and sodium bicarbonate, especially sodium bicarbonate which is rather stable than sodium carbonate during storage. Sodium bicarbonate decomposes on heating according to Equation 2.1.

$$2\ NaHCO_3 \rightleftarrows Na_2CO_3 + CO_2 + H_2O \qquad ......(2.1)$$

(2) Physical blowing agent (PBA)

It is compound liberating gas as a result of physical processes such as evaporation or desorption at elevated temperatures or reduced pressures. Moreover, PBA does not undergo chemical transformation itself, and most of PBA are liquids such as xylene, toluene, benzene and alcohol.

2.6 Literature reviews

Kongsin, and Lewan [17] reported blending of natural rubber (NR) with nitrile rubber (NBR) had a problem of incompatible polarities. Polychloroprene was a very good compatiblizer for NR/NBR blends because it could reduce phase sizes; however, it did not increase further movements in tensile strength.

Tangboriboonrat, and Tiyapiboonchaiya [18] reported the γ-radiation vulcanized natural rubber latex could be used to prepare new toughened polystyrene by phase transfer and bulk polymerization. The negative charge γ-radiation vulcanized natural rubber latex with styrene monomer was titrated with benzyldimethylhexadylammonium chloride until end point reached before polymerized of styrene monomer in mixture at 70°C. The final product increased in the unnotched Izod impact energy over the unmodified polystyrene. However, irradiation dose, initiator concentration and rubber content also affected the impact property of new toughened polystyrene.

Thiebaud, et al. [19] reported the modified starch ester was mixed with low density polyethylene (LDPE) in Rheomixer at 1.3 r.p.s. for 900 seconds. The content of starch ester was determined for mechanical properties. The tensile strength decreased with increase of starch ester content in the blends.

Kiatkamjornwong, Pabunruang, Wangvisetsirikul, and Prasassarakich [20] presented blending of low density polyethylene (LDPE) with cassava starch, soya oil, iron stearate and Epolene wax to form biodegradable polyethylene films. The tensile strength and elongation at break decreased with increase in starch content.

Stenhouse, Ratto, and Schneider [21] presented blending of starch with poly(ethylene-co-vinyl alcohol) for blown films. The films were conditioned at various equilibrium moisture content. The tensile strength and the Young's modulus decreased rapidly when moisture content increased. On the other hand, the elongation at break increased when moisture content increased.

Alfani, Iannace, and Nicolais [22] presented starch-based polyurethane foams which were synthesized by reacting a mixture of starch and polycaprolactone triol with an aliphatic diisocyanate, in the presence of water as blowing agent. The modulus of products increased when the starch content increased; furthermore, increase of starch content reduced density of opened-cell foam.

2.7 Hypothesis

Cassava starch when added to natural rubber it may reinforce the rubber/starch mix. Furthermore, a latex/starch paste mix may be made more homogenized by inducing foaming during drying and the material is masticated afterward. The starch/DRC ratio must be in a range that the starch acts only as filler and not as a major component, otherwise a plastic-like material will be produced.

This is a novel process and is a preliminary laboratory trial that by testing the physical properties such as tensile strength and % elongation at break of the rubber/starch mix it should indicate useful applications.

CHAPTER III

EXPERIMENTAL METHOD

3.1 Materials and equipment

3.1.1 Chemicals

(1) The super high grade cassava starch was obtained from Thai Wah (Public) Ltd. It was produced from *tapioca* grown in summer. Physical properties of super high grade cassava starch are listed in Table 3.1.

Table 3.1 Physical properties of super high grade cassava starch.

Properties	Value
Moisture (%)	13.5 max.
Starch (%)	84 min.
pH	4.00-7.00
Pulp (ml.)	0.20 max.
Ash (%)	0.20 max.
Colour	White
Viscosity (B.U.)	550 min.

(2) Acetic acid (commercial grade) was purchased from SR Lab. Co.,Ltd.

(3) Sodium bicarbonate (commercial grade) was purchased from SR Lab. Co.,Ltd.

3.1.2 Equipment

(1) Mixing equipment as shown in Figure 3.1

Figure 3.1 Mixing equipment

(2) Two-roll mill compounding machine model R11-3FF (Kodaira Seisakusho Co.,Ltd.) for homogenization and compounding the rubber

(3) Compression molding machine model 2625 (Carver laboratory Co.,Ltd.) for vulcanization

(4) Wallace rapid plastimeter model MK II for determining plasticity retention index (PRI)

(5) Mooney viscometer (Techpro Co.,Ltd.) for determining Mooney viscosity

(6) Rheometer model MDR 2000 (Monsanto Co.,Ltd.) for determining optimum cure time (t_c90)

(7) Instron testing machine model 1011 for determining tensile strength and % elongation at break

(8) Lloyd testing machine model LR 5K for determining tear strength

(9) Lloyd testing machine model LR 50K for determining compression deflection

(10) Durometer Shore A model 917 (Instrument and MFG Co.,Ltd.) for determining hardness

(11) Cutting machine (Intro enterprise Co.,Ltd.) for cutting rubber specimen

(12) Densitometer model Densitech II (Techpro Co.,Ltd.) for determining density

(13) Microwave oven model TRX-2500 BS (Turbora Co.,Ltd.) as shown in Figure 3.2 for forming natural rubber-cassava starch foam

3.2 Experimental methods

3.2.1 Rubber/starch mix sheet production

Natural rubber latex was mixed with 18% W/V cassava starch paste in which the starch slurry was prepared beforehand. The starch paste was heated and stirred until it reached 60 °C when it became more viscous yet it was cloudy. The ratio of mixture chosen is shown in Table 3.2. The rubber/starch mixture was stirred well using a mixing equipment at 1.3 r.p.s., coagulated in a deep tray and then dried in a vented air oven at 60 °C.

Table 3.2 Percentages of mixture between natural rubber latex and 18% W/V cassava starch paste.

Natural rubber latex	18% W/V cassava starch paste	Ratio of DRC:starch
100	0	100:0
90	10	90:10
80	20	80:20
70	30	70:30
60	40	60:40
50	50	50:50
40	60	40:60

3.2.2 Rubber/starch mix de-foamed sheet production

Natural rubber latex was mixed with 18% W/V cassava starch paste and sodium bicarbonate ($NaHCO_3$) dispersion added at a ratio given in Table 3.3. The mixture was then poured into a plastic box and heated at medium-high level in a microwave oven about 3,000 seconds, then the product was de-foamed by two-roll mill. For each cassava starch content the sodium carbonate was varied to 5,10 and 15 pphp.

Table 3.3 Ratios of natural rubber latex, 18% W/V cassava starch paste and $NaHCO_3$ dispersion.

Natural rubber latex:18% W/V cassava starch paste	$NaHCO_3$ dispersion (part per hundred of polymer, pphp)
100:0	5
	10
	15
90:10	5
	10
	15
80:20	5
	10
	15
70:30	5
	10
	15
60:40	5
	10
	15
50:50	5
	10
	15
40:60	5
	10
	15

3.3 Preparation of rubber specimen

3.3.1 Preparation of homogenized rubber specimen [23]

Raw rubber specimens were homogenized prior to testing by passing six times through two-roll mill with gap setting at 1.7×10^{-3} m at room temperature. At the sixth passing each specimen was rolled into sheets and cut into several dumbbell-shape samples for testing.

3.3.2 Preparation of compound rubber specimen [23]

Compound rubber specimens were prepared for testing of cure characteristics and vulcanizate properties with the compound rubber formulation as shown in Table 3.4.

Table 3.4 Compound rubber formulation.

Ingredients	Part per hundred of rubber (phr)
Natural rubber	100.0
Zinc oxide (ZnO)	5.0
Stearic acid	2.0
Tetramethyl thiuram disulphide (TMTD)	0.5
Cyclohexyl benzothiazyl sulphenamide (CBS)	1.5
Sulphur (S)	2.5
Wingstay-L	1.0

The 0.3 kg of homogenized rubber was passed through two-roll mill for two times with gap setting of 0.5×10^{-3} m at $70\pm5^{\circ}C$, then it was passed with gap setting of 1.4×10^{-3} m until it was soft and smooth before adding zinc oxide, stearic acid, TMTD, CBS, sulphur and Wingstay-L, respectively with gap setting of 1.9×10^{-3} m. Then, the compound rubber was passed six times with gap setting of 0.8×10^{-3} m. At the sixth time the compound rubber was rolled into sheet with thickness at least 6×10^{-3} m.

3.3.3 Preparation of vulcanized rubber specimen

The vulcanized rubber was prepared using a compression molding machine by compressing the compound rubber and kept at $150^{\circ}C$ for its $t_c(90)$ testing. The properties tested were tensile strength, % elongation at break and tear strength.

3.4 Determination of rubber/starch mix properties

3.4.1 Testing properties of rubber before vulcanization

(1) Plasticity retention index (PRI) [24]

A test portion of 0.03 kg from the homogenized piece was passed three times between two-roll mill with adjustment of the nip until the final thickness was 1.7×10^{-3} m, then the sheet was doubled and pressed the two halves lightly together by hand. After a uniform sheet was obtained, it was doubled and punched to make six specimens, then the specimens were separated into two sets of three, one set for test before aging and the other for test after aging (after heated in an oven at 140°C for 1,800 seconds). Each specimen was sandwiched by two pieces of cigarette paper and pressed between the two parallel plates with compressive force of 98 N for 15 seconds. The final thickness was calculated, and the plasticity retention index (PRI) was determined by Equation 3.1.

$$PRI = \frac{P_1}{P_0} \times 100 \qquad \ldots(3.1)$$

P_1 is defined as a median plasticity value of three aged specimens

P_0 is defined as a median plasticity value of three Un-aged specimens

(2) Mooney viscosity [25]

Before testing, each homogenized specimen was prepared by cutting into two pieces with a diameter of 0.05 m and a thickness of 6×10^{-3} m. The rotor was, at the same time, heated to 100±5°C. After preparation of both the rotor and the specimen, the first piece was placed in the lower die before inserting the rotor stem through its center, then the second piece was placed on the center of the rotor, and the die was closed immediately. Then the motor was started for 60 seconds, and the viscosity was reported in the following format:

50 ML (60+240)100°C

where 50M being designated as viscosity in Mooney units;

L being designated as using a large rotor;

60 being designated as preheating time of specimen before starting rotor (seconds);

240 being designated as testing time after starting rotor (seconds);

100°C being designated as testing temperature.

(3) Cure characteristics [26]

The cure characteristics of compound rubber was determined for finding the condition of rubber vulcanization. The specimen was cut into 0.03 m in diameter and 13×10^{-2} m in thickness, it was then placed on the top of the oscillating disc before closing of die. The specimen was heated at 150°C until it reached the optimum cure or 90% cross-linked time. The typical cure curve as shown in Figure 3.2 was determined.

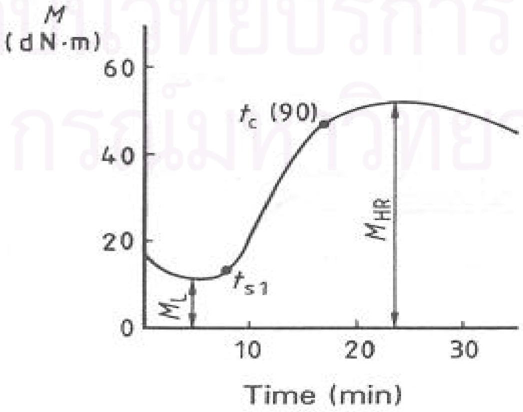


Figure 3.2 Cure characteristics curve from Rheometer [26]

where M_L defined as minimum torque (N.m)

M_{HR} defined as maximum torque (N.m)

t_{S1} defined as time to increase one tenth of a unit of torque (seconds)

$t_c(90)$ defined as optimum cure time (seconds)

3.4.2 Testing properties of rubber after vulcanization

(1) Tensile strength and % elongation at break [27]

The specimen was punched from vulcanized rubber, and the specimen was marked for the benchmark and the thickness measured. At testing, the specimen was stretched at separating rate of 8±0.001 m/s. The tensile strength and % elongation at break were determined from Equations 3.2 and 3.3.

$$\text{Tensile strength (MPa)} = \frac{\text{force at rupture (N)}}{\text{cross-sectional area (m}^2\text{)}} \quad \ldots(3.2)$$

$$\%\ \text{elongation at break (\%)} = \frac{\text{(length at rupture-original length)}}{\text{original length}} \times 100 \quad ..(3.3)$$

(2) Tear strength [28]

The specimen was punched from the vulcanized rubber by cutting die. The thickness of specimen was measured, then the specimen was stretched with a separation rate of 8±0.001 m/s. The tear strength was determined from Equation 3.4.

$$\text{Tear strength (MPa)} = \frac{\text{maximum force (N)}}{\text{thickness of specimen (mm)}} \qquad \ldots(3.4)$$

(3) Compression deflection [29]

The specimen was punched into 28.6 $\pm 0.01\times10^{-3}$ m in diameter and $12.5\pm0.5\times10^{-3}$ m in thickness. The specimen was then placed between upper plate and sandpaper, which was between the specimen and lower plate, and the specimen was applied a force at the rate of $2\pm0.5\times10^{-4}$ m/s until the deflection was reached at 25%. The applied force was released immediately at the same rate.

3.4.3 Miscellaneous testing

(1) Dry rubber content (DRC) [30]

Natural latex was weighed approximately 0.01 kg into a porcelain evaporating dish, then 2% V/V acetic acid was added to coagulate latex into coagulum. After complete coagulation, a dish was left without shaking or stirring for 1,800 seconds, then coagulum was washed in running water, passed through roll-mill to reduce thickness of rubber sheet to 2×10^{-3} m and dried at 55±2°C in a vented air oven. After drying, the dry coagulum was cooled in a dessicator to reduce temperature to room temperature and weighed for determining dry rubber content (% DRC) as calculated using Equation 3.5.

$$\%\ \text{DRC} = \frac{\text{mass of dry coagulum (kg)}}{\text{mass of natural latex (kg)}} \times 100 \qquad \ldots(3.5)$$

(2) Hardness [31]

The flat surface, 6×10^{-3} m in thickness and 12×10^{-3} m in width, specimen was placed on hard horizontal surface of Durometer in a vertical position with the point of type A indentor at least 12×10^{-3} m. The presser foot was then released rapidly, and hardness was determined from the depth of penetrating indentor.

(3) Density [32]

The specimen was hooked on the balance, and it was weighed in air and in distilled water, respectively at the standard temperature (23±2°C or 27±2°C). For density more than 1.00 it was determined from Equation 3.6, and for density less than 1.00 it was determined from Equation 3.7.

$$\rho = \frac{m_1}{m_1 - m_2} \qquad \ldots(3.6)$$

where ρ was density of rubber (Mg/m^3)

m_1 was net mass of rubber (Mg)

m_2 was mass of rubber less mass of an equal volume of water, determined by weighing in water (Mg)

$$\rho = \frac{m_1}{m_1 + m_2 - m_3} \qquad \ldots(3.7)$$

where ρ was density of rubber (Mg/m^3)

m_1 was net mass of rubber (Mg)

m_2 was mass of sinker less mass of an equal volume of water, determined by weighing in water (Mg)

m_3 was mass of sinker and rubber less mass of a volume of water equal to their combined volumes, determined by weighing in water (Mg)

CHAPTER IV

RESULTS AND DISCUSSION

4.1 Physical properties of rubber/starch mix sheet

The effect of cassava starch content of rubber starch mix, prepared by vented air oven, was investigated by determining the physical properties shown in Table 4.1. This includes plasticity retention index (PRI) to find the best oxidation resistance condition; Mooney viscosity to explore the appropriate viscosity during vulcanization; optimum cure time called $t_c(90)$ to select the appropriate vulcanization time; density to be used for estimation of material cost; hardness to explore the applicability of the material; tensile strength, % elongation at break and tear strength to explore its usefulness as a construction material.

4.1.1 Effect of cassava starch content on plasticity retention index (PRI)

PRI was examined before compounding of rubber/starch mix, and the value shown in Figure 4.1.

Table 4.1 Effect of cassava starch content on physical properties of rubber/starch mix sheet

Cassava starch content (%)	PRI	Mooney viscosity	$t_c(90)$ (seconds)	Density (Mg/m^3)			Hardness		Tensile strength (MPa)		% elongation at break (%)		Tear strength (kN/m)	
				Before compounding	Before vulcanization	After vulcanization	Before vulcanization	After vulcanization	Before vulcanization	After vulcanization	Before vulcanization	After vulcanization	Before vulcanization	After vulcanization
0	82	41	152	0.79	0.98	0.99	11.3	48.2	0.30	3.21	624	255	2.96	34.51
10	84	42	168	0.95	1.00	1.00	11.8	52.7	0.28	2.60	590	256	2.81	23.23
20	86	43	170	1.00	1.02	1.01	12.4	54.0	0.23	2.49	575	259	2.71	22.56
30	87	47	172	1.03	1.05	1.10	15.2	56.0	0.19	2.58	564	265	2.20	23.02
40	88	43	176	1.08	1.02	1.09	17.2	59.2	0.42	2.57	550	285	3.44	22.39
50	88	45	170	1.08	1.04	1.14	18.4	59.0	0.47	2.64	388	349	4.37	19.31
60	93	48	214	1.11	1.14	1.04	23.0	64.0	0.28	2.42	51	547	3.01	18.32

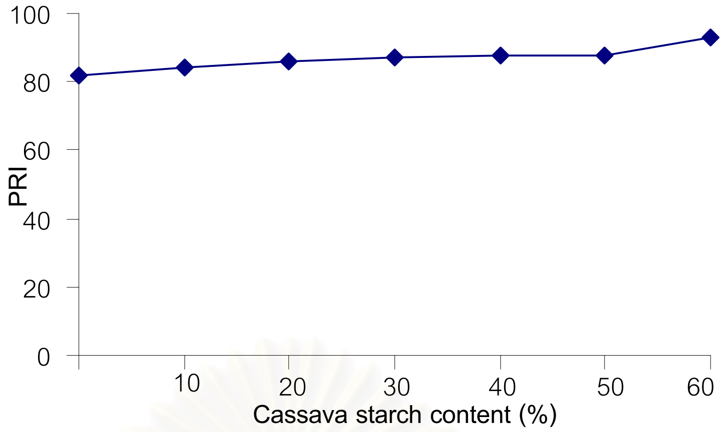


Figure 4.1 Effect of cassava starch on PRI of rubber/starch mix sheet

PRI increases slightly with the cassava starch content being 82 for rubber only and gradually increases up to a value of 93 at the starch content of 60 %. This is due to the high melting point of the starch, however, the starch does not melt at these testing temperatures.

4.1.2 Effect of cassava starch content on Mooney viscosity

Mooney viscosity was examined after compounding rubber starch mix with vulcanizing chemicals. Results are shown in Figure 4.2.

It is observed that Mooney viscosity is insensitive to the starch content, being about 45.

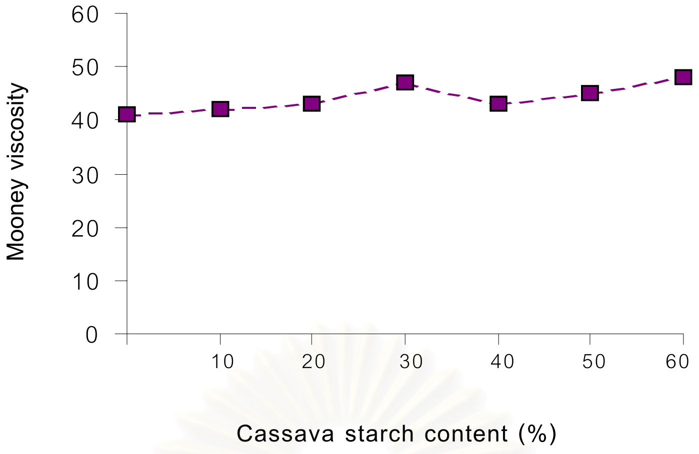


Figure 4.2 Effect of cassava starch on Mooney viscosity of rubber/starch mix sheet

4.1.3 Effect of cassava starch content on $t_c(90)$

The optimum cure time known as $t_c(90)$ was determined and the results shown in Figure 4.3.

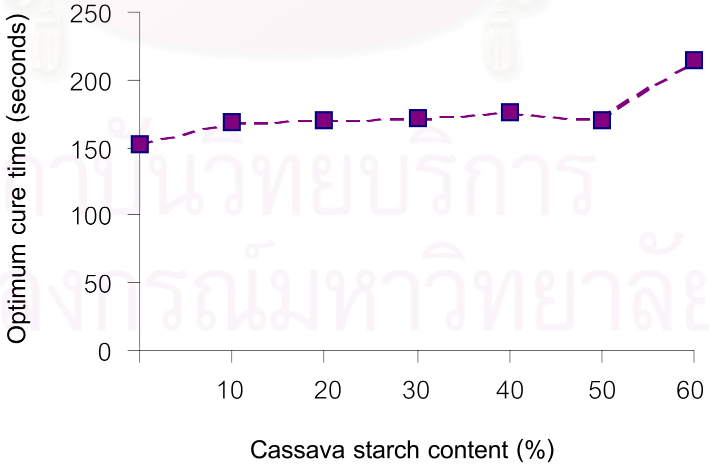


Figure 4.3 Effect of cassava starch on $t_c(90)$ of rubber/starch mix sheet

It can be seen from Figure 4.3 that $t_c(90)$ tends to increase slightly with the starch content. Starch, acting as filler, interferes somewhat with the curing rate. The effect is more pronounced at starch content greater than 50%. Nonetheless, a cure time between 150 and 210 seconds is acceptable.

4.1.4 Effect of cassava starch content on density

Three sets of density, i.e. density before compounding, before vulcanization and after vulcanization, were determined as shown in Figure 4.4.

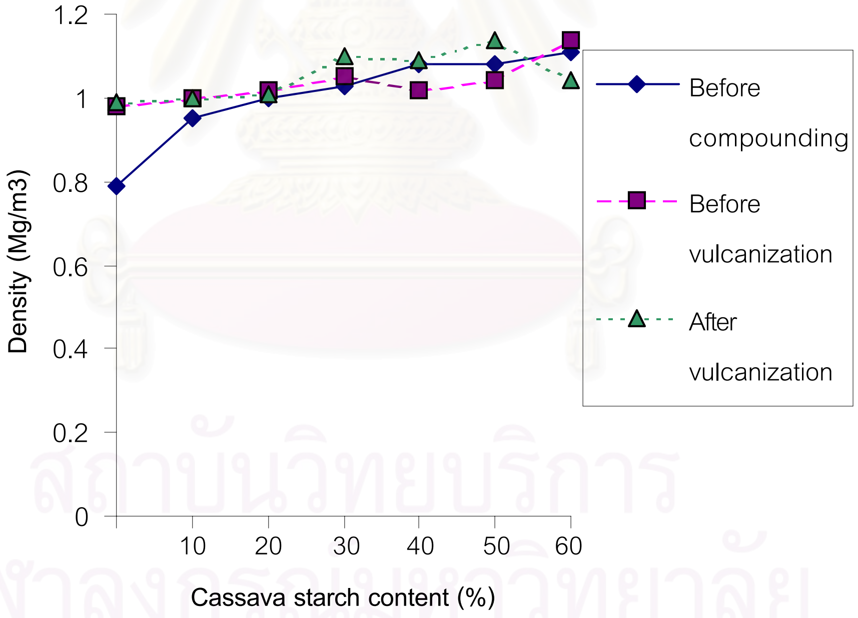


Figure 4.4 Effect of cassava starch on density of rubber/starch mix sheet

It can be seen from Figure 4.4 that the density increases slightly from about 0.9 to 1.1 Mg/m^3 with the increase of cassava starch content. Rubber without cassava starch has its density changes, before compounding, before vulcanization and after vulcanization being 0.79, 0.98 and 0.99 Mg/m^3, respectively. Not only does cassava starch have higher density than rubber particle, but also the rubber/starch sheet is homogenized resulting in the increase of its density.

4.1.5 Effect of cassava starch content on hardness

Two sets of hardness which were hardness before vulcanization and after vulcanization were examined as illustrated in Figure 4.5.

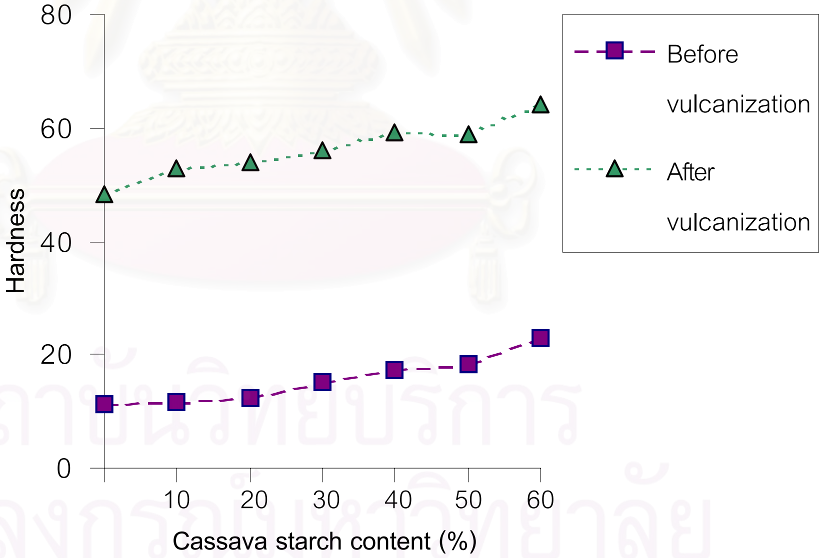


Figure 4.5 Effect of cassava starch on hardness of rubber/starch mix sheet

It is generally observed that the hardness from both before and after vulcanization increases with the increase in cassava starch content as shown in Figure 4.5. Because starch is more rigid than rubber, so adding starch into a rubber/starch mix sheet will contribute to its hardness.

4.1.6 Effect of cassava starch content on tensile strength

Both tensile strength of before and after vulcanization conditions were determined as shown in Figure 4.6.

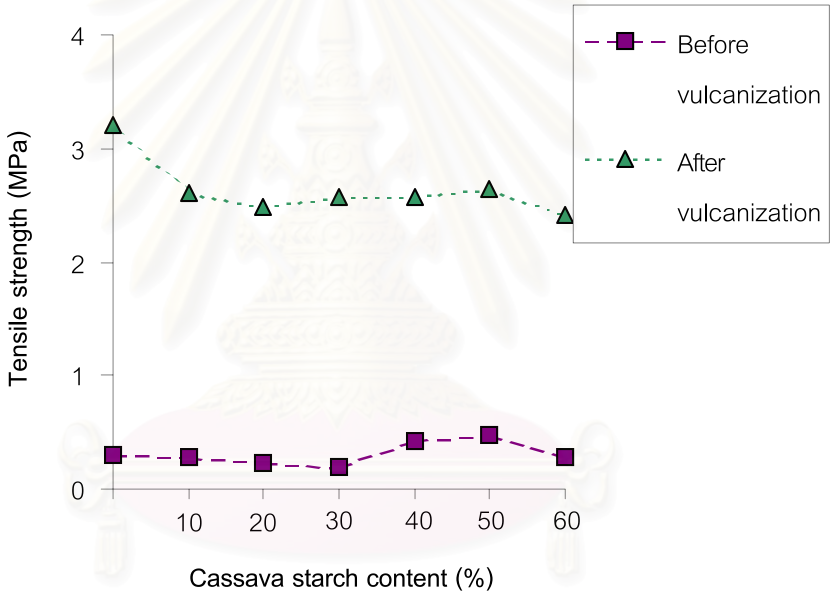


Figure 4.6 Effect of cassava starch on tensile strength of rubber/starch mix sheet

It is illustrated in Figure 4.6 that tensile strength does not change appreciably with the cassava starch content since the homogenization of rubber/starch sheet is insufficient.

4.1.7 Effect of cassava starch content on % elongation at break

The % elongation at break of samples both before and after vulcanization conditions were studied. The results are illustrated in Figure 4.7.

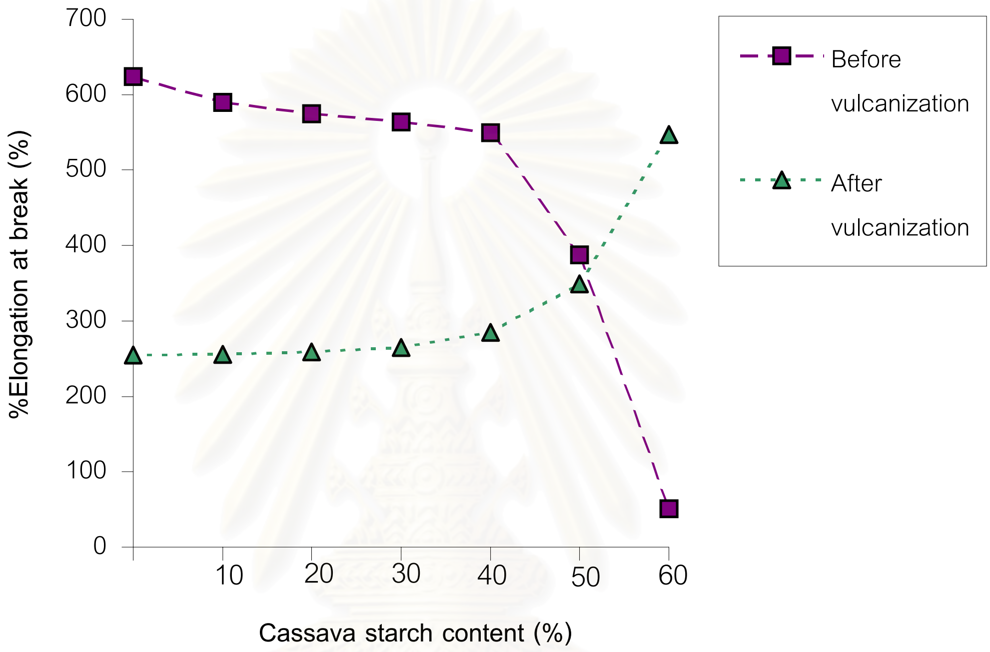


Figure 4.7 Effect of cassava starch on % elongation at break of rubber/starch mix sheet

The % elongation at break for unvulcanized samples show decreasing trend due to insufficient homogenization of rubber/starch mix sheet. However, the vulcanizate shows a tendency of increasing value with the cassava starch content because there is molecular cross-linking of rubber. In addition, the starch acts as solid lubricant so the polymer chain of rubber can easily slippage.

At low starch content, the unvulcanized rubber/starch mix sheet exhibits high % elongation at break with value greater than 500%. When its starch content is higher than 40% the value drops sharply due mainly to the in-elasticity of starch.

4.1.8 Effect of cassava starch content on tear strength

Tear strength of the unvulcanized samples and vulcanizates are shown in Figure 4.8.

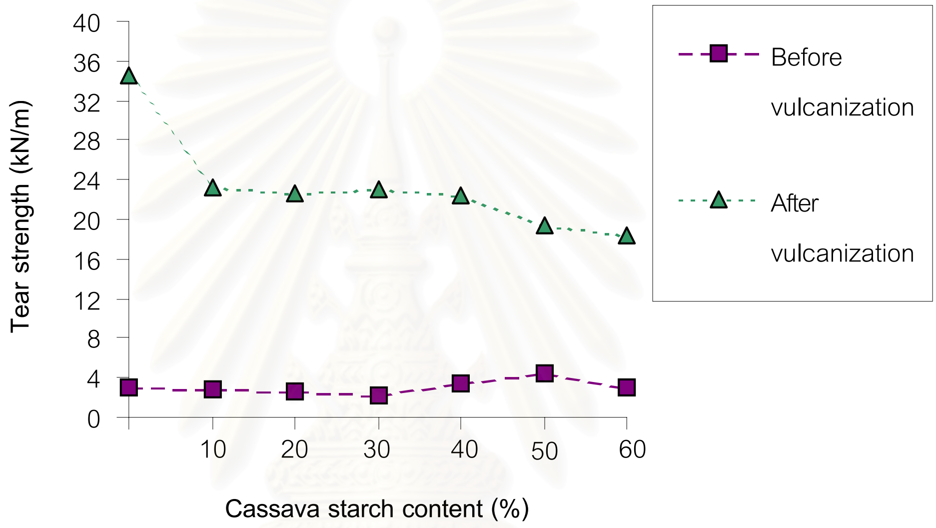


Figure 4.8 Effect of cassava starch on tear strength of rubber/starch mix sheet

It is illustrated in Figure 4.8 that tear strength does not change appreciably with the cassava starch content since the homogenization of rubber/starch sheet is insufficient.

Table 4.2 Effect of cassava starch content on physical properties of rubber/starch mix de-foamed sheet using $NaHCO_3$ dispersion as blowing agent.

Cassava starch content (%)	$NaHCO_3$ content (pphp)	$t_c(90)$ (seconds)	Density (Mg/m^3)			Compression deflection (MPa)	Tensile strength (MPa)	% elongation at break (%)
			Before compounding	Before vulcanization	After vulcanization			
0	5	122	0.97	1.00	1.00	0.98	3.14	243
	10	124	0.93	1.01	1.01	0.95	3.26	238
	15	173	0.85	1.00	1.02	0.88	3.33	221
10	5	135	0.95	1.02	1.03	1.04	3.70	285
	10	140	0.85	1.02	1.04	1.35	3.48	245
	15	173	0.84	1.02	1.04	1.28	3.19	230
20	5	137	0.92	1.04	1.06	1.07	11.00	544
	10	142	0.83	1.06	1.06	1.31	3.92	262
	15	178	0.89	1.06	1.07	1.36	3.34	250
30	5	148	0.89	1.07	1.08	1.37	6.77	387
	10	178	0.78	1.06	1.07	1.43	10.42	516
	15	185	0.83	1.09	1.10	1.73	6.62	376
40	5	173	0.89	1.12	1.12	2.50	3.56	249
	10	248	0.70	1.19	1.14	1.83	7.40	361
	15	192	0.63	1.24	1.13	2.08	5.72	371

Table 4.2 (continued) Effect of cassava starch content on physical properties of rubber/starch mix de-foamed sheet using $NaHCO_3$ dispersion as blowing agent.

Cassava starch content (%)	$NaHCO_3$ content (pphp)	$t_c(90)$ (seconds	Density (Mg/m^3)			Compression deflection (MPa)	Tensile strength (MPa)	% elongation at break (%)
			Before compounding	Before vulcanization	After vulcanization			
50	5	217	0.86	1.13	1.19	3.55	3.06	223
	10	249	0.69	1.28	1.18	2.31	4.26	277
	15	198	0.54	1.35	1.14	1.95	4.87	335
60	5	220	0.74	1.17	1.23	6.18	2.91	84
	10	248	0.47	1.30	1.25	10.84	3.11	39
	15	225	0.48	1.38	1.25	11.17	3.22	16

4.2 Physical properties of rubber/starch mix de-foamed sheet

Attempt has been made to produce foam from rubber/cassava starch mix by the addition of sodium bicarbonate. Foams were formed during heating by microwave; however, they were mostly removed during blending operation. The specimen was tested for its physical properties as shown in Table 4.2.

These include optimum cure time called $t_c(90)$ to find the appropriate vulcanization time; density to optimize the appropriate density; compression deflection to explore the compressive resistance; tensile strength to characterize its stretching resistance; and % elongation at break.

4.2.1 Effect of cassava starch content on $t_c(90)$

The effect of cassava starch content on $t_c(90)$ for specimens containing 5,10 and 15 pphp of $NaHCO_3$ were examined and the results shown in Figure 4.9.

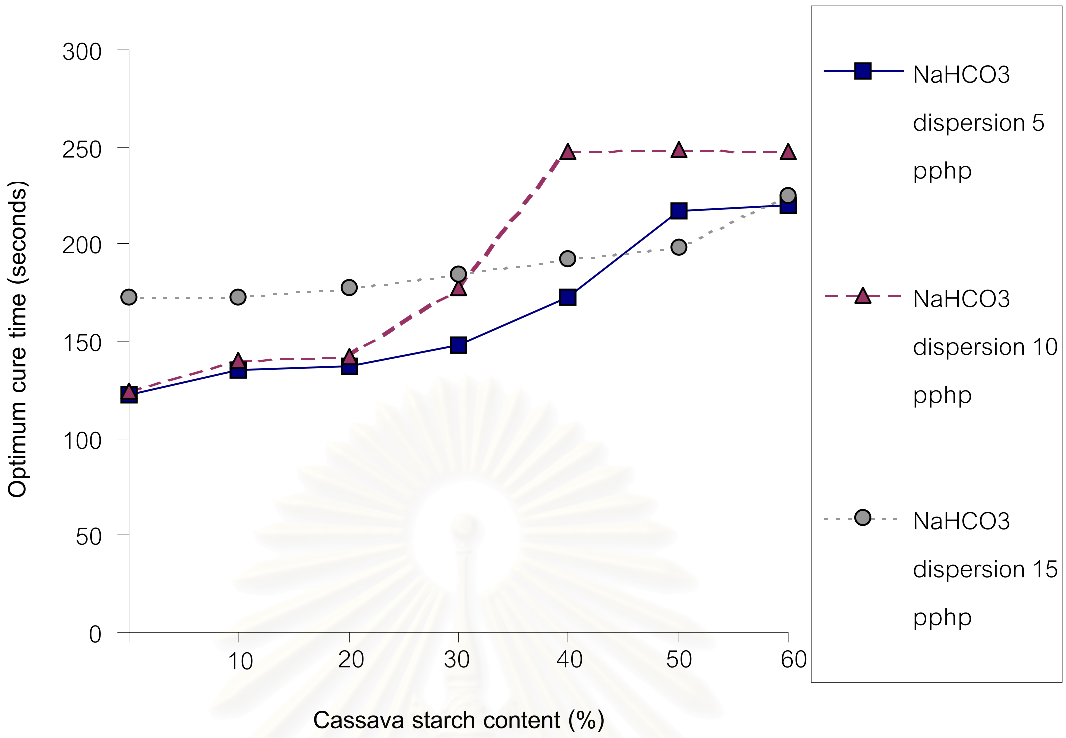


Figure 4.9 Effect of cassava starch on $t_c(90)$ of rubber/starch mix de-foamed sheet

The optimum cure time shows a gradual increase with the cassava starch content, being about 120 to 240 seconds. The larger content of starch is in the rubber/starch mix, the more cure time is needed.

4.2.2 Effect of cassava starch content on density

The density of rubber/starch mix foamed by $NaHCO_3$ was determined and the results are shown in Figure 4.10.

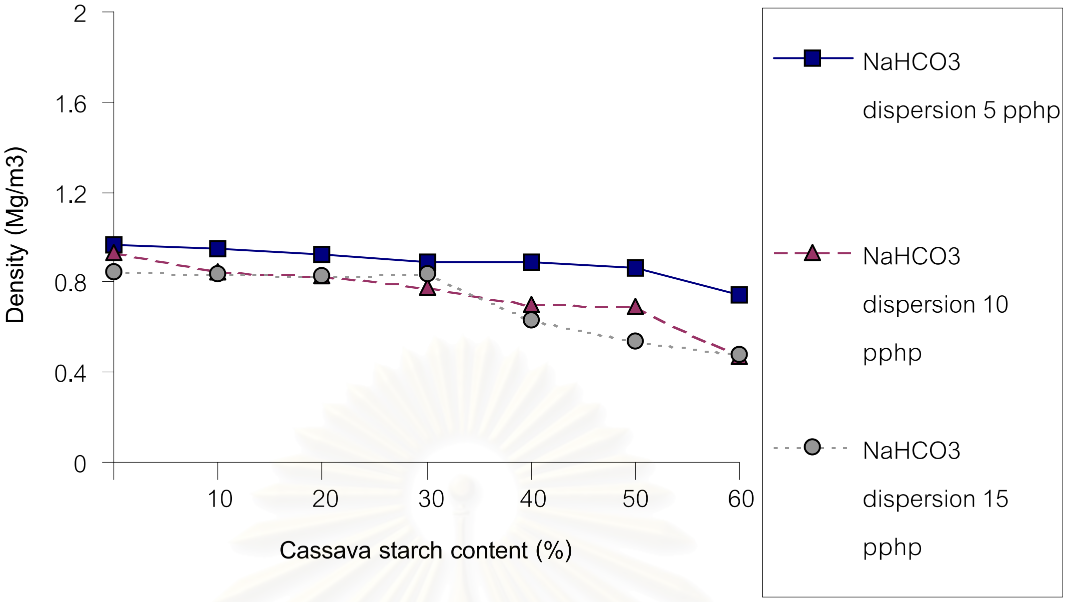


Figure 4.10 Effect of cassava starch on density of rubber/starch mix foam

It can be seen that the density decreases with starch content, being less than that of water. It indicates the presence of foam. It is assumed that the increase of starch content may expand the volume of specimen while the mass may not significantly change, so the density decreases.

4.2.3 Effect of cassava starch content on density before vulcanization

As the specimens was prepared for compounding, most or all foam was removed during mixing in two-roll mill. The resulting material shows an increase of density with starch content as shown in Figure 4.11.

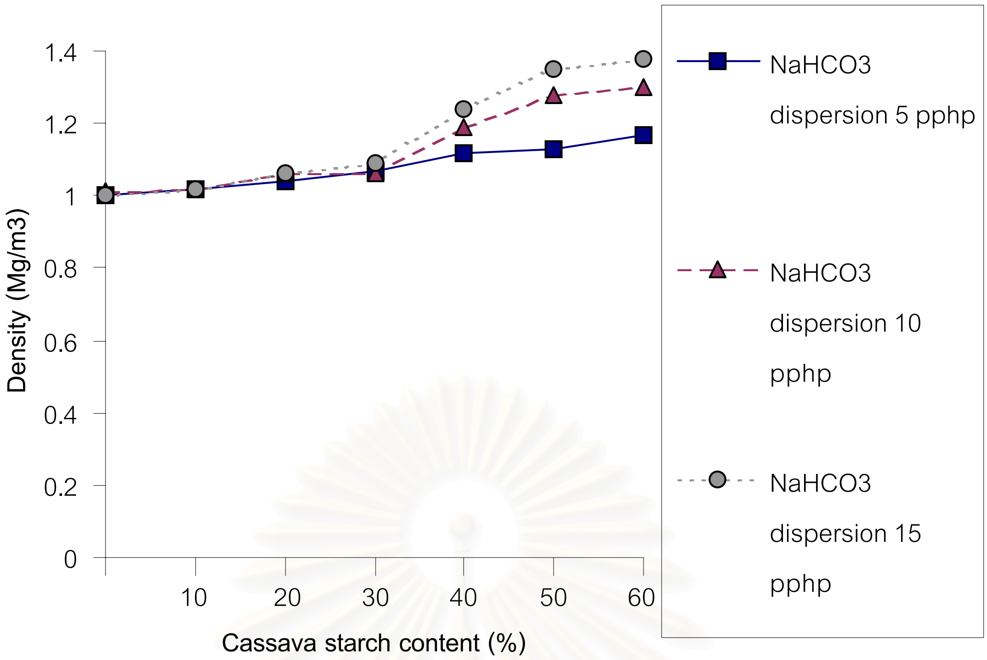


Figure 4.11 Effect of cassava starch on density of rubber/starch mix de-foamed sheet before vulcanization

It can be seen that the density gradually increases with starch content and is higher than water. This observation suggests the inclusion of starch into the inter-particle void of rubber rendering it denser.

4.2.4 Effect of cassava starch content on density after vulcanization

The density of vulcanizates prepared from rubber/starch mix de-foamed containing $NaHCO_3$ is shown in Figure 4.12.

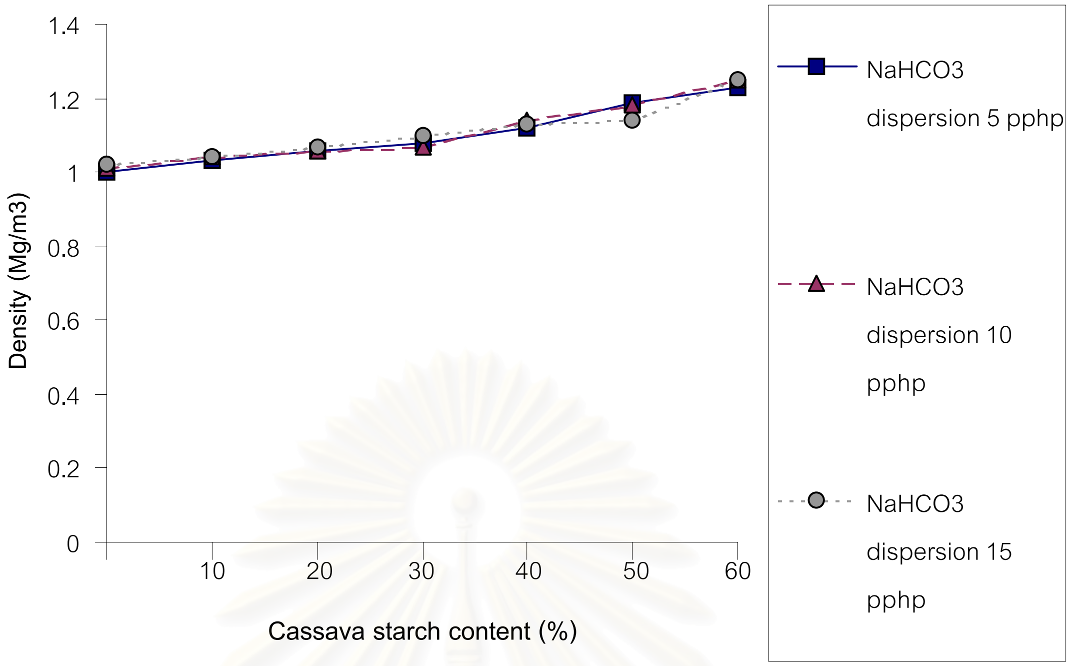


Figure 4.12 Effect of cassava starch on density of rubber/starch mix de-foam sheet after vulcanization

The density of vulcanizates is similar to the compounds and is gradually increased with the starch content.

4.2.5 Effect of cassava starch content on compression deflection

The compression deflection of rubber/starch mix de-foamed containing $NaHCO_3$ was determined and the result is shown in Figure 4.13.

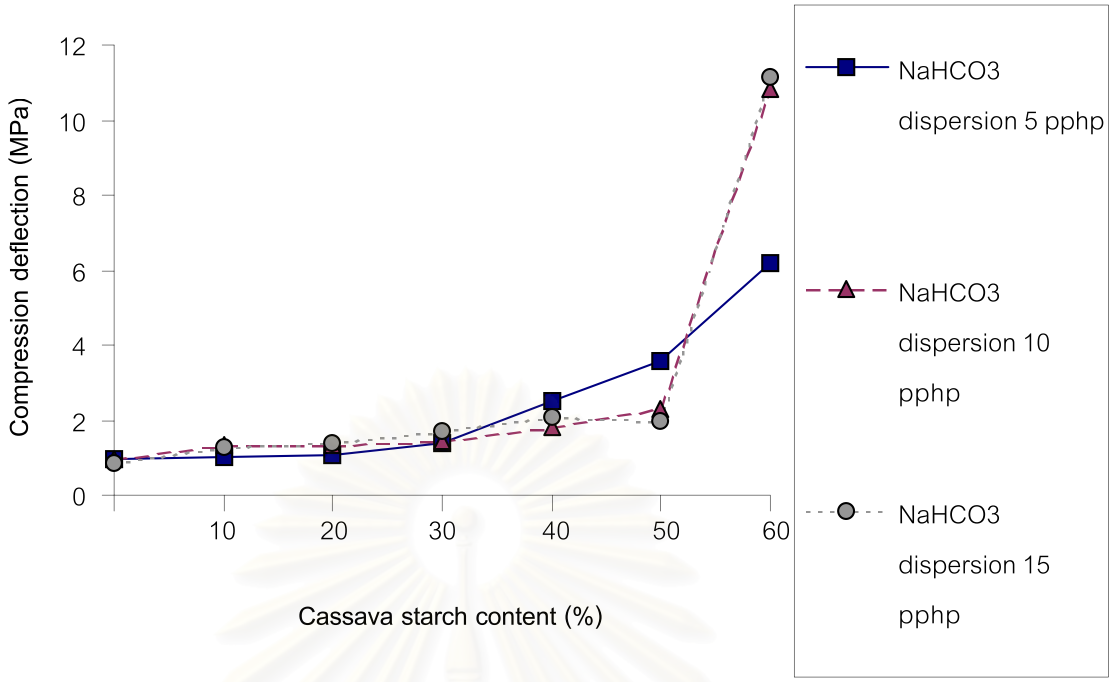


Figure 4.13 Effect of cassava starch on compression deflection of rubber/starch mix de-foamed sheet

The tensile strength increases gradually with starch content up to 30% then reduces rapidly. At the same time, the compression deflection increases rapidly after 30% of cassava starch content. It is postulated that rubber/starch mix de-foamed become harder when starch content is high due to the more rigidity of starch particle than rubber particle.

4.2.6 Effect of cassava starch content on tensile strength

The influence of starch on tensile strength of rubber/starch mix de-foamed containing $NaHCO_3$ is shown in Figure 4.14.

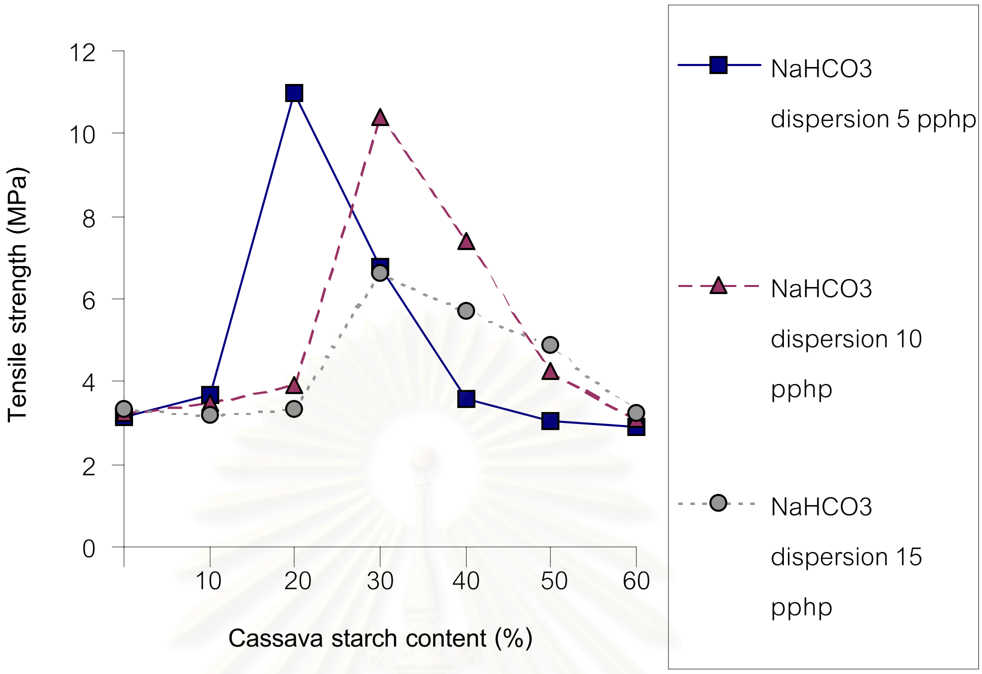


Figure 4.14 Effect of cassava starch on tensile strength of rubber/starch mix de-foamed sheet

It can be seen from Figure 4.14 that starch acts as re-inforcing filler at low content showing a peak between 20-30% while at higher content the strength decreases because it may exhibit as degrading filler. At such ratio, rubber behaves more as a modifier with the aspect of making it more energy absorbing material.

4.2.7 Effect of cassava starch content on % elongation at break

The result of a test on % elongation at break of rubber/starch mix de-foamed containing 5,10 and 15 pphp of $NaHCO_3$ is shown in Figure 4.15.

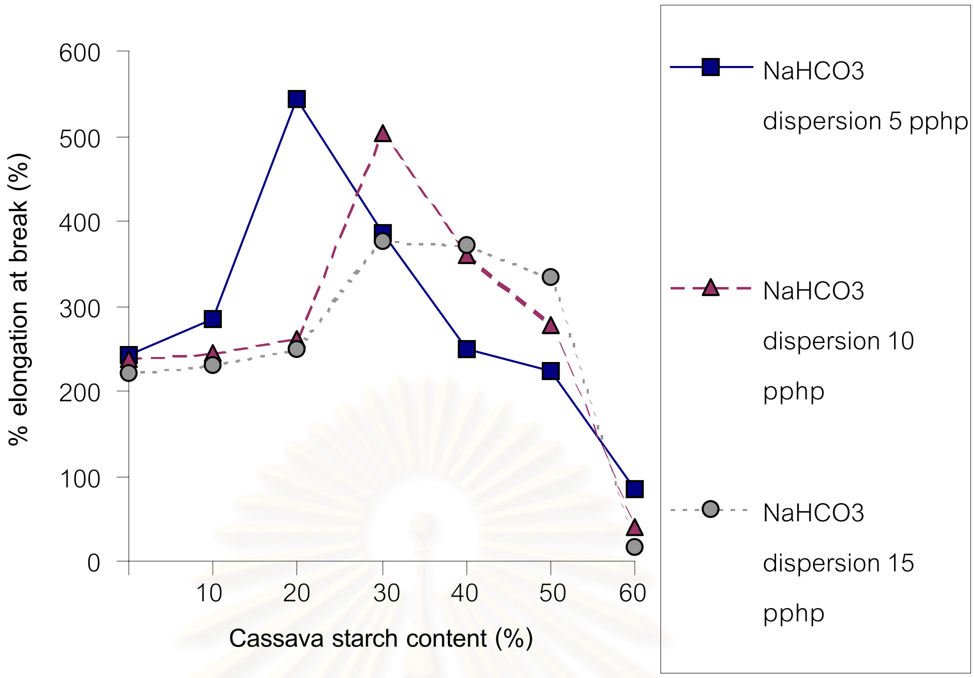


Figure 4.15 Effect of cassava starch on % elongation at break of rubber/starch mix de-foamed sheet

It is clearly seen from Figure 4.15 that starch behaves as reinforcing filler when its content is between 20-30%, at higher content it exhibits a degrading effect. As mentioned in Chapter 2, rubber particles have on their surface phospholipids and proteins which form a hydrophilic layer rendering a stable latex. The addition of alkali such as sodium bicarbonate enhances the stability even more. When starch is added the starch particle will collect rubber particles on its surface, thereby making rubber particles loosely packed. It is envisaged that upon drying the starch acts as a solid lubricant making rubber to extend more easily due to less entanglement within the rubber mass. Therefore, the % elongation at break is higher, attaining more than 500% for certain mix.

CHAPTER V

CONCLUSIONS AND SUGGESTIONS

1. Natural rubber-cassava starch sheet can be prepared from latex by a process described below:

Natural rubber latex with 34 % DRC is added with a cassava starch paste (18% W/V), the mixture is stirred at 1.3 r.p.s., coagulated then dried at 60°C.

With the increasing content of cassava starch, PRI, Mooney viscosity, $t_c(90)$, density, hardness and % elongation at break after vulcanization increase whereas % elongation at break before vulcanization, tensile strength and tear strength decrease.

2. Natural rubber-cassava starch foam can be prepared from latex by a process described below:

Natural rubber latex with 34% DRC is added with a cassava starch paste (18% W/V) and $NaHCO_3$ as a blowing agent. The mixture is then stirred at 1.3 r.p.s. and heated using a microwave oven at medium-high level until dry and foaming is completed.

With the increase of starch content $t_c(90)$, density before and after vulcanization and compression deflection increase. The density of foam (rubber/starch mix before compounding) is less than water and decreases with starch content. The % elongation at break and tensile strength exhibit a maximum at starch content of about 20-30%.

3. It is concluded that cassava starch can reinforce the rubber/starch mix. Moreover, the new material can be produced from NR/cassava starch mix with varying properties depending on the content of the starch and homogeneity of the blend.

Suggestions

For the rubber/starch mix sheet production, the material obtained should be applicable for an easy tear-off packaging.

For the rubber/starch mix de-foamed sheet production, the cassava starch should be substituted with the agricultural materials which is locally available and more cheaper such as husk and straw.

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APPENDICES

APPENDIX A

World natural rubber production during 1994-1998

TableA1 World natural rubber production 1994 -1998 (×1,000 tonnes) [1].

Country	1994	1995	1996	1997	1998
Thailand	1,717.9	1,804.8	1,970.0	2,029.6	2,065.0
Indonesia	1,360.8	1,466.8	1,543.0	1,551.8	1,680.0
Malaysia	1,106.6	1,089.3	1,082.5	971.1	886.0
India	464.0	499.6	540.1	563.6	591.0
China	374.0	424.0	430.0	444.0	450.0
Vietnam	121.0	123.0	123.0	124.0	219.0
Sri Lanka	105.3	105.7	112.5	105.8	96.0
Other 15 Countries	460.4	526.8	538.9	630.1	618.0
Total	5,710.0	6,040.0	6,340.0	6,420.0	6,610.0
Average Growth (%)		5.78	4.97	1.26	2.96

APPENDIX B

1. Raw testing data of rubber/starch mix sheet before vulcanization

1.1 0 % cassava starch content

Table B1 Effect of 0 % cassava starch content on physical properties of rubber/starch mix sheet before vulcanization.

Sample	Tensile strength (MPa)	% elongation at break (%)	Tear strength (kN/m)
1	0.32	647	2.96
2	0.29	652	2.93
3	0.30	591	2.92
4	0.32	590	2.97
5	0.28	641	3.01
Mean	**0.30**	**624**	**2.96**
Standard deviation	**0.02**	**31**	**0.04**

PRI = **82**

$t_c(90)$ = **152** seconds

Mooney viscosity = **41**

$\text{Hardness}_{\text{Before vulcanization}}$ = **11.3**

$\text{Density}_{\text{Before compounding}}$ = **0.79** Mg/m^3

$\text{Density}_{\text{Before vulcanization}}$ = **0.98** Mg/m^3

1.2 10 % cassava starch content

Table B2 Effect of 10 % cassava starch content on physical properties of rubber/starch mix sheet before vulcanization.

Sample	Tensile strength (MPa)	% elongation at break (%)	Tear strength (kN/m)
1	0.31	611	2.91
2	0.24	588	2.75
3	0.26	598	2.72
4	0.28	575	2.86
5	0.30	580	2.81
Mean	**0.28**	**590**	**2.81**
Standard deviation	**0.03**	**14**	**0.08**

PRI = 84

$t_c(90)$ = 168 seconds

Mooney viscosity = 42

$\text{Hardness}_{\text{Before vulcanization}}$ = 11.8

$\text{Density}_{\text{Before compounding}}$ = 0.95 Mg/m^3

$\text{Density}_{\text{Before vulcanization}}$ = 1.00 Mg/m^3

1.3 20% cassava starch content

Table B3 Effect of 20 % cassava starch content on physical properties of rubber/starch mix sheet before vulcanization.

Sample	Tensile strength (MPa)	% elongation at break (%)	Tear strength (kN/m)
1	0.22	610	2.74
2	0.24	585	2.70
3	0.24	560	2.73
4	0.24	570	2.69
5	0.22	550	2.70
Mean	**0.23**	**575**	**2.71**
Standard deviation	**0.01**	**24**	**0.02**

PRI = 86

$t_c(90)$ = 206 seconds

Mooney viscosity = 43

$\text{Hardness}_{\text{Before vulcanization}}$ = 12.4

$\text{Density}_{\text{Before compounding}}$ = 1.00 Mg/m^3

$\text{Density}_{\text{Before vulcanization}}$ = 1.02 Mg/m^3

1.4 30% cassava starch content

Table B4 Effect of 30 % cassava starch content on physical properties of rubber/starch mix sheet before vulcanization.

Sample	Tensile strength (MPa)	% elongation at break (%)	Tear strength (kN/m)
1	0.19	581	2.33
2	0.21	570	2.14
3	0.19	568	2.05
4	0.19	561	2.19
5	0.19	541	2.30
Mean	**0.19**	**564**	**2.20**
Standard deviation	**0.01**	**15**	**0.12**

PRI = 87

$t_c(90)$ = 172 seconds

Mooney viscosity = 47

$\text{Hardness}_{\text{Before vulcanization}}$ = 15.2

$\text{Density}_{\text{Before compounding}}$ = 1.03 Mg/m^3

$\text{Density}_{\text{Before vulcanization}}$ = 1.05 Mg/m^3

1.5 40% cassava starch content

Table B5 Effect of 40 % cassava starch content on physical properties of rubber/starch mix sheet before vulcanization.

Sample	Tensile strength (MPa)	% elongation at break (%)	Tear strength (kN/m)
1	0.40	475	3.53
2	0.43	563	3.57
3	0.41	637	3.37
4	0.44	524	3.44
5	0.42	549	3.29
Mean	**0.42**	**550**	**3.44**
Standard deviation	**0.02**	**59**	**0.12**

PRI = 88

$t_c(90)$ = 176 seconds

Mooney viscosity = 43

$\text{Hardness}_{\text{Before vulcanization}}$ = 17.2

$\text{Density}_{\text{Before compounding}}$ = 1.08 Mg/m^3

$\text{Density}_{\text{Before vulcanization}}$ = 1.02 Mg/m^3

1.6 50% cassava starch content

Table B5 Effect of 50 % cassava starch content on physical properties of rubber/starch mix sheet before vulcanization.

Sample	Tensile strength (MPa)	% elongation at break (%)	Tear strength (kN/m)
1	0.47	438	4.40
2	0.46	319	4.45
3	0.48	411	4.32
4	0.47	365	4.41
5	0.48	406	4.27
Mean	0.47	388	4.37
Standard deviation	0.01	47	0.07

PRI = 88

$t_c(90)$ = 170 seconds

Mooney viscosity = 45

$\text{Hardness}_{\text{Before vulcanization}}$ = 18.4

$\text{Density}_{\text{Before compounding}}$ = 1.08 Mg/m^3

$\text{Density}_{\text{Before vulcanization}}$ = 1.04 Mg/m^3

1.7 60% cassava starch content

Table B7 Effect of 60 % cassava starch content on physical properties of rubber/starch mix sheet before vulcanization.

Sample	Tensile strength (MPa)	% elongation at break (%)	Tear strength (kN/m)
1	0.25	53	2.95
2	0.27	61	3.02
3	0.28	53	3.08
4	0.34	35	3.04
5	0.26	54	2.95
Mean	**0.28**	**51**	**3.01**
Standard deviation	**0.04**	**10**	**0.06**

PRI = 93

$t_c(90)$ = 214 seconds

Mooney viscosity = 48

$\text{Hardness}_{\text{Before vulcanization}}$ = 23.0

$\text{Density}_{\text{Before compounding}}$ = 1.11 Mg/m^3

$\text{Density}_{\text{Before vulcanization}}$ = 1.14 Mg/m^3

2. Raw testing data of rubber/starch mix sheet after vulcanization

2.1 0% cassava starch content

Table B8 Effect of 0 % cassava starch content on physical properties of rubber/starch mix sheet after vulcanization.

Sample	Tensile strength (MPa)	% elongation at break (%)	Tear strength (kN/m)
1	3.21	273	31.37
2	3.19	262	36.40
3	3.34	260	35.70
4	3.21	262	33.02
5	3.11	215	36.04
Mean	**3.21**	**255**	**34.51**
Standard deviation	**0.01**	**23**	**2.20**

Hardness$_{\text{After vulcanization}}$ = 48.2

Density$_{\text{After vulcanization}}$ = 0.99 Mg/m^3

2.2 10% cassava starch content

Table B9 Effect of 10 % cassava starch content on physical properties of rubber/starch mix sheet after vulcanization.

Sample	Tensile strength (MPa)	% elongation at break (%)	Tear strength (kN/m)
1	2.50	253	26.30
2	2.25	261	22.49
3	3.28	244	19.62
4	2.57	256	22.00
5	2.39	265	25.72
Mean	2.60	256	23.23
Standard deviation	0.40	8	2.77

$\text{Hardness}_{\text{After vulcanization}}$ = 52.7

$\text{Density}_{\text{After vulcanization}}$ = 1.00 Mg/m^3

2.3 20% cassava starch content

Table B10 Effect of 20 % cassava starch content on physical properties of rubber/starch mix sheet after vulcanization.

Sample	Tensile strength (MPa)	% elongation at break (%)	Tear strength (kN/m)
1	2.49	275	22.76
2	2.49	270	22.02
3	2.43	244	22.08
4	2.45	258	23.02
5	2.58	248	22.91
Mean	2.49	259	22.56
Standard deviation	0.06	14	0.47

$\text{Hardness}_{\text{After vulcanization}}$ = 54.0

$\text{Density}_{\text{After vulcanization}}$ = 1.01 Mg/m^3

2.4 30% cassava starch content

Table B11 Effect of 30 % cassava starch content on physical properties of rubber/starch mix sheet after vulcanization.

Sample	Tensile strength (MPa)	% elongation at break (%)	Tear strength (kN/m)
1	2.89	285	23.13
2	2.80	272	22.85
3	2.32	275	22.15
4	2.41	247	21.74
5	2.48	246	25.23
Mean	2.58	265	23.02
Standard deviation	0.29	18	1.35

$\text{Hardness}_{\text{After vulcanization}}$ = 56.0

$\text{Density}_{\text{After vulcanization}}$ = 1.10 Mg/m^3

2.5 40% cassava starch content

Table B12 Effect of 40 % cassava starch content on physical properties of rubber/starch mix sheet after vulcanization.

Sample	Tensile strength (MPa)	% elongation at break (%)	Tear strength (kN/m)
1	2.58	282	23.53
2	2.60	310	22.23
3	2.42	269	21.83
4	2.58	262	21.89
5	2.67	301	22.46
Mean	**2.57**	**285**	**22.39**
Standard deviation	**0.09**	**20**	**0.69**

$\text{Hardness}_{\text{After vulcanization}}$ = **59.2**

$\text{Density}_{\text{After vulcanization}}$ = **1.09** Mg/m^3

2.6 50% cassava starch content

Table B13 Effect of 50 % cassava starch content on physical properties of rubber/starch mix sheet after vulcanization.

Sample	Tensile strength (MPa)	% elongation at break (%)	Tear strength (kN/m)
1	2.49	349	19.64
2	2.35	293	19.94
3	2.42	309	19.04
4	2.95	373	18.96
5	2.97	419	18.98
Mean	2.64	349	19.31
Standard deviation	0.30	51	0.45

$\text{Hardness}_{\text{After vulcanization}}$ = 59.0

$\text{Density}_{\text{After vulcanization}}$ = 1.14 Mg/m^3

2.7 60% cassava starch content

Table B14 Effect of 60 % cassava starch content on physical properties of rubber/starch mix sheet after vulcanization.

Sample	Tensile strength (MPa)	% elongation at break (%)	Tear strength (kN/m)
1	2.53	570	19.05
2	2.31	561	17.07
3	2.64	522	17.64
4	2.21	534	19.39
5	2.40	551	18.43
Mean	2.42	547	18.32
Standard deviation	0.17	20	0.96

$\text{Hardness}_{\text{After vulcanization}}$ = 64.0

$\text{Density}_{\text{After vulcanization}}$ = 1.04 Mg/m^3

APPENDIX C

1. Raw testing data of rubber/starch mix de-foamed sheet used 5 pphp of $NaHCO_3$ dispersion as blowing agent

1.1 0 % cassava starch content

Table C1 Effect of 0 % cassava starch content on physical properties of vulcanized de-foamed sheet at 5 pphp of $NaHCO_3$ dispersion.

Sample	Tensile strength (MPa)	% elongation at break (%)	Compression deflection (MPa)
1	2.57	251	0.98
2	3.23	243	0.98
3	3.31	233	0.98
4	3.41	223	-
5	3.17	264	-
Mean	3.14	243	0.98
Standard deviation	0.33	16	0.00

$t_c(90)$ = 122 seconds

$\text{Density}_{\text{of foam}}$ = 0.97 Mg/m^3

$\text{Density}_{\text{Before vulcanization}}$ = 1.00 Mg/m^3

$\text{Density}_{\text{After vulcanization}}$ = 1.00 Mg/m^3

1.2 10 % cassava starch content

Table C2 Effect of 10 % cassava starch content on physical properties of vulcanized de-foamed sheet at 5 pphp of $NaHCO_3$ dispersion.

Sample	Tensile strength (MPa)	% elongation at break (%)	Compression deflection (MPa)
1	3.36	227	1.03
2	3.80	270	1.04
3	4.30	353	1.04
4	3.61	275	-
5	3.45	301	-
Mean	3.70	285	1.04
Standard deviation	0.37	46	0.00

$t_c(90)$ = 135 seconds

$\text{Density}_{\text{of foam}}$ = 0.95 Mg/m^3

$\text{Density}_{\text{Before vulcanization}}$ = 1.02 Mg/m^3

$\text{Density}_{\text{After vulcanization}}$ = 1.03 Mg/m^3

1.3 20 % cassava starch content

Table C3 Effect of 20 % cassava starch content on physical properties of vulcanized de-foamed sheet at 5 pphp of $NaHCO_3$ dispersion.

Sample	Tensile strength (MPa)	% elongation at break (%)	Compression deflection (MPa)
1	11.72	597	1.08
2	10.24	554	1.07
3	11.89	545	1.07
4	11.21	516	-
5	9.95	507	-
Mean	11.00	544	1.07
Standard deviation	0.87	36	0.00

$t_c(90)$ = 137 seconds

$\text{Density}_{\text{of foam}}$ = 0.92 Mg/m^3

$\text{Density}_{\text{Before vulcanization}}$ = 1.04 Mg/m^3

$\text{Density}_{\text{After vulcanization}}$ = 1.06 Mg/m^3

1.4 30 % cassava starch content

Table C4 Effect of 30 % cassava starch content on physical properties of vulcanized de-foamed sheet at 5 pphp of $NaHCO_3$ dispersion.

Sample	Tensile strength (MPa)	% elongation at break (%)	Compression deflection (MPa)
1	6.12	397	1.44
2	6.95	388	1.34
3	7.03	387	1.33
4	6.70	397	-
5	7.03	365	-
Mean	6.77	387	1.37
Standard deviation	0.38	13	0.06

$t_c(90)$	=	148	seconds
$Density_{of\ foam}$	=	0.89	Mg/m^3
$Density_{Before\ vulcanization}$	=	1.07	Mg/m^3
$Density_{After\ vulcanization}$	=	1.08	Mg/m^3

1.5 40 % cassava starch content

Table C5 Effect of 40 % cassava starch content on physical properties of vulcanized de-foamed sheet at 5 pphp of $NaHCO_3$ dispersion.

Sample	Tensile strength (MPa)	% elongation at break (%)	Compression deflection (MPa)
1	3.96	274	2.51
2	3.77	277	2.50
3	3.29	227	2.48
4	3.70	261	-
5	3.09	204	-
Mean	3.56	249	2.50
Standard deviation	0.36	32	0.01

$t_c(90)$ = 173 seconds

$\text{Density}_{\text{of foam}}$ = 0.89 Mg/m^3

$\text{Density}_{\text{Before vulcanization}}$ = 1.12 Mg/m^3

$\text{Density}_{\text{After vulcanization}}$ = 1.12 Mg/m^3

1.6 50 % cassava starch content

Table C6 Effect of 50 % cassava starch content on physical properties of vulcanized de-foamed sheet at 5 pphp of $NaHCO_3$ dispersion.

Sample	Tensile strength (MPa)	% elongation at break (%)	Compression deflection (MPa)
1	3.30	171	3.97
2	2.75	203	3.36
3	2.98	257	3.33
4	3.21	244	-
5	3.08	237	-
Mean	**3.06**	**223**	**3.55**
Standard deviation	**0.21**	**35**	**0.36**

$t_c(90)$ = **217** seconds

$\text{Density}_{\text{of foam}}$ = **0.86** Mg/m^3

$\text{Density}_{\text{Before vulcanization}}$ = **1.13** Mg/m^3

$\text{Density}_{\text{After vulcanization}}$ = **1.19** Mg/m^3

1.7 60 % cassava starch content

Table C7 Effect of 60 % cassava starch content on physical properties of vulcanized de-foamed sheet at 5 pphp of $NaHCO_3$ dispersion.

Sample	Tensile strength (MPa)	% elongation at break (%)	Compression deflection (MPa)
1	3.25	62	6.09
2	3.06	85	6.30
3	2.66	91	6.16
4	2.89	101	-
5	2.71	82	-
Mean	2.91	84	6.18
Standard deviation	0.25	14	0.10

$t_c(90)$ = 220 seconds

$\text{Density}_{\text{of foam}}$ = 0.74 Mg/m^3

$\text{Density}_{\text{Before vulcanization}}$ = 1.17 Mg/m^3

$\text{Density}_{\text{After vulcanization}}$ = 1.23 Mg/m^3

2. Raw testing data of rubber/starch mix de-foamed sheet used 10 pphp of $NaHCO_3$ dispersion as blowing agent

2.1 0 % cassava starch content

Table C8 Effect of 0 % cassava starch content on physical properties of vulcanized de-foamed sheet at 10 pphp of $NaHCO_3$ dispersion.

Sample	Tensile strength (MPa)	% elongation at break (%)	Compression deflection (MPa)
1	3.40	235	0.92
2	3.31	229	0.90
3	3.24	264	1.04
4	3.68	215	-
5	2.69	249	-
Mean	**3.26**	**238**	**0.95**
Standard deviation	**0.36**	**19**	**0.07**

$t_c(90)$ = **124** seconds

$\text{Density}_{\text{of foam}}$ = **0.93** Mg/m^3

$\text{Density}_{\text{Before vulcanization}}$ = **1.01** Mg/m^3

$\text{Density}_{\text{After vulcanization}}$ = **1.01** Mg/m^3

2.2 10 % cassava starch content

Table C9 Effect of 10 % cassava starch content on physical properties of vulcanized de-foamed sheet at 10 pphp of $NaHCO_3$ dispersion.

Sample	Tensile strength (MPa)	% elongation at break (%)	Compression deflection (MPa)
1	3.66	292	1.35
2	3.64	259	1.35
3	3.51	230	1.36
4	3.51	242	-
5	3.08	203	-
Mean	3.48	245	1.35
Standard deviation	0.23	33	0.00

$t_c(90)$ = 140 seconds

$Density_{of\ foam}$ = 0.85 Mg/m^3

$Density_{Before\ vulcanization}$ = 1.02 Mg/m^3

$Density_{After\ vulcanization}$ = 1.04 Mg/m^3

2.3 20 % cassava starch content

Table C10 Effect of 20 % cassava starch content on physical properties of vulcanized de-foamed sheet at 10 pphp of $NaHCO_3$ dispersion.

Sample	Tensile strength (MPa)	% elongation at break (%)	Compression deflection (MPa)
1	3.13	182	1.32
2	4.19	277	1.31
3	5.02	373	1.31
4	4.28	303	-
5	3.00	174	-
Mean	3.92	262	1.31
Standard deviation	0.85	84	0.01

$t_c(90)$ = 142 seconds

$\text{Density}_{\text{of foam}}$ = 0.83 Mg/m^3

$\text{Density}_{\text{Before vulcanization}}$ = 1.06 Mg/m^3

$\text{Density}_{\text{After vulcanization}}$ = 1.06 Mg/m^3

2.4 30 % cassava starch content

Table C11 Effect of 30 % cassava starch content on physical properties of vulcanized de-foamed sheet at 10 pphp of $NaHCO_3$ dispersion.

Sample	Tensile strength (MPa)	% elongation at break (%)	Compression deflection (MPa)
1	9.05	531	1.51
2	10.70	495	1.44
3	10.75	523	1.35
4	9.94	515	-
5	11.59	-	-
Mean	10.42	516	1.43
Standard deviation	0.96	16	0.08

$t_c(90)$ = 178 seconds

$\text{Density}_{\text{of foam}}$ = 0.78 Mg/m^3

$\text{Density}_{\text{Before vulcanization}}$ = 1.06 Mg/m^3

$\text{Density}_{\text{After vulcanization}}$ = 1.07 Mg/m^3

2.5 40 % cassava starch content

Table C12 Effect of 40 % cassava starch content on physical properties of vulcanized de-foamed sheet at 10 pphp of $NaHCO_3$ dispersion.

Sample	Tensile strength (MPa)	% elongation at break (%)	Compression deflection (MPa)
1	7.75	362	1.97
2	7.62	380	1.78
3	6.97	350	1.73
4	6.68	344	-
5	7.99	370	-
Mean	7.40	361	1.83
Standard deviation	0.55	15	0.13

$t_c(90)$ = 248 seconds

$\text{Density}_{\text{of foam}}$ = 0.70 Mg/m^3

$\text{Density}_{\text{Before vulcanization}}$ = 1.19 Mg/m^3

$\text{Density}_{\text{After vulcanization}}$ = 1.14 Mg/m^3

2.6 50 % cassava starch content

Table C13 Effect of 50 % cassava starch content on physical properties of vulcanized de-foamed sheet at 10 pphp of $NaHCO_3$ dispersion.

Sample	Tensile strength (MPa)	% elongation at break (%)	Compression deflection (MPa)
1	4.39	278	2.25
2	3.92	252	2.35
3	4.44	295	2.34
4	4.67	297	-
5	3.88	262	-
Mean	4.26	277	2.31
Standard deviation	0.34	20	0.06

$t_c(90)$ = 249 seconds

$\text{Density}_{\text{of foam}}$ = 0.69 Mg/m^3

$\text{Density}_{\text{Before vulcanization}}$ = 1.28 Mg/m^3

$\text{Density}_{\text{After vulcanization}}$ = 1.18 Mg/m^3

2.7 60 % cassava starch content

Table C14 Effect of 60 % cassava starch content on physical properties of vulcanized de-foamed sheet at 10 pphp of $NaHCO_3$ dispersion.

Sample	Tensile strength (MPa)	% elongation at break (%)	Compression deflection (MPa)
1	3.24	38	10.54
2	2.87	38	10.96
3	3.18	30	11.01
4	2.95	45	-
5	3.32	44	-
Mean	3.11	39	10.84
Standard deviation	0.19	6	0.26

$t_c(90)$ = 248 seconds

$\text{Density}_{\text{of foam}}$ = 0.47 Mg/m^3

$\text{Density}_{\text{Before vulcanization}}$ = 1.30 Mg/m^3

$\text{Density}_{\text{After vulcanization}}$ = 1.38 Mg/m^3

3. Raw testing data of rubber/starch mix de-foamed used 15 pphp of $NaHCO_3$ dispersion as blowing agent

3.1 0 % cassava starch content

Table C15 Effect of 0 % cassava starch content on physical properties of vulcanized de-foamed sheet at 15 pphp of $NaHCO_3$ dispersion.

Sample	Tensile strength (MPa)	% elongation at break (%)	Compression deflection (MPa)
1	3.64	225	0.89
2	3.01	206	0.88
3	3.45	238	0.87
4	2.98	211	-
5	3.55	226	-
Mean	3.33	221	0.88
Standard deviation	0.31	13	0.01

$t_c(90)$ = 173 seconds

$\text{Density}_{\text{of foam}}$ = 0.85 Mg/m^3

$\text{Density}_{\text{Before vulcanization}}$ = 1.00 Mg/m^3

$\text{Density}_{\text{After vulcanization}}$ = 1.02 Mg/m^3

3.2 10 % cassava starch content

Table C16 Effect of 10 % cassava starch content on physical properties of vulcanized de-foamed sheet at 15 pphp of $NaHCO_3$ dispersion.

Sample	Tensile strength (MPa)	% elongation at break (%)	Compression deflection (MPa)
1	3.30	230	1.29
2	3.57	262	1.28
3	2.98	235	1.28
4	2.91	204	-
5	3.19	220	-
Mean	3.19	230	1.28
Standard deviation	0.26	21	0.01

$t_c(90)$ = 173 seconds

$\text{Density}_{\text{of foam}}$ = 0.84 Mg/m^3

$\text{Density}_{\text{Before vulcanization}}$ = 1.02 Mg/m^3

$\text{Density}_{\text{After vulcanization}}$ = 1.04 Mg/m^3

3.3 20 % cassava starch content

Table C17 Effect of 20 % cassava starch content on physical properties of vulcanized de-foamed sheet at 15 pphp of $NaHCO_3$ dispersion.

Sample	Tensile strength (MPa)	% elongation at break (%)	Compression deflection (MPa)
1	3.03	272	1.47
2	3.53	237	1.31
3	3.65	245	1.31
4	3.23	206	-
5	3.28	288	-
Mean	3.34	250	1.36
Standard deviation	0.25	32	0.09

$t_c(90)$ = 178 seconds

$\text{Density}_{\text{of foam}}$ = 0.89 Mg/m^3

$\text{Density}_{\text{Before vulcanization}}$ = 1.06 Mg/m^3

$\text{Density}_{\text{After vulcanization}}$ = 1.07 Mg/m^3

3.4 30 % cassava starch content

Table C18 Effect of 30 % cassava starch content on physical properties of vulcanized de-foamed sheet at 15 pphp of $NaHCO_3$ dispersion.

Sample	Tensile strength (MPa)	% elongation at break (%)	Compression deflection (MPa)
1	5.38	286	1.75
2	8.09	407	1.73
3	5.29	493	1.71
4	7.71	318	-
5	-	-	-
Mean	**6.62**	**376**	**1.73**
Standard deviation	**1.49**	**93**	**0.02**

$t_c(90)$ = **185** seconds

$\text{Density}_{\text{of foam}}$ = **0.83** Mg/m^3

$\text{Density}_{\text{Before vulcanization}}$ = **1.09** Mg/m^3

$\text{Density}_{\text{After vulcanization}}$ = **1.10** Mg/m^3

3.5 40 % cassava starch content

Table C19 Effect of 40 % cassava starch content on physical properties of vulcanized de-foamed sheet at 15 pphp of $NaHCO_3$ dispersion.

Sample	Tensile strength (MPa)	% elongation at break (%)	Compression deflection (MPa)
1	6.38	403	2.06
2	5.82	318	2.11
3	5.66	371	2.07
4	5.85	407	-
5	4.90	358	-
Mean	**5.72**	**371**	**2.08**
Standard deviation	**0.53**	**37**	**0.02**

$t_c(90)$ = **192** seconds

$Density_{of\ foam}$ = **0.63** Mg/m^3

$Density_{Before\ vulcanization}$ = **1.24** Mg/m^3

$Density_{After\ vulcanization}$ = **1.13** Mg/m^3

3.6 50 % cassava starch content

Table C20 Effect of 50 % cassava starch content on physical properties of vulcanized de-foamed sheet at 15 pphp of $NaHCO_3$ dispersion.

Sample	Tensile strength (MPa)	% elongation at break (%)	Compression deflection (MPa)
1	4.94	327	1.92
2	5.12	322	1.98
3	4.69	353	1.96
4	4.81	333	-
5	4.77	338	-
Mean	4.87	335	1.95
Standard deviation	0.17	12	0.03

$t_c(90)$ = 198 seconds

$\text{Density}_{\text{of foam}}$ = 0.54 Mg/m^3

$\text{Density}_{\text{Before vulcanization}}$ = 1.35 Mg/m^3

$\text{Density}_{\text{After vulcanization}}$ = 1.14 Mg/m^3

3.7 60 % cassava starch content

Table C21 Effect of 60 % cassava starch content on physical properties of vulcanized de-foamed sheet at 15 pphp of $NaHCO_3$ dispersion.

Sample	Tensile strength (MPa)	% elongation at break (%)	Compression deflection (MPa)
1	3.41	19	10.77
2	2.99	15	11.42
3	3.26	11	11.33
4	3.34	15	-
5	3.12	18	-
Mean	3.22	16	11.17
Standard deviation	0.17	3	0.35

$t_c(90)$ = 225 seconds

$\text{Density}_{\text{of foam}}$ = 0.48 Mg/m^3

$\text{Density}_{\text{Before vulcanization}}$ = 1.38 Mg/m^3

$\text{Density}_{\text{After vulcanization}}$ = 1.25 Mg/m^3

APPENDIX D

Determination of %DRC of natural rubber latex

Natural rubber latex was brought from Chonburi province which could calculate %DRC as below:

$$\mathrm{DRC}\ \#1 = (3.5129 \div 10.1406) \times 100 = 34.64\ \%$$

$$\mathrm{DRC}\ \#2 = (3.4470 \div 10.0641) \times 100 = 34.55\ \%$$

$$\mathrm{DRC}\ \#3 = (3.4620 \div 10.1329) \times 100 = 34.17\ \%$$

$$\mathrm{DRC}_{\mathrm{Average}} = (34.64 + 34.55 + 34.17) \div 3 = 34.45\ \%$$

Microwave

1. Characteristics of microwave

Microwave is the electromagnetic wave having frequency higher than 1 GHz or wavelength less than 0.3 m. [33]. It has three main properties [34].

(1) Microwave reflects if it impacts with metal or metal mixed container because microwave cannot pass through metal.

(2) Microwave transmits or passes through glass, paper, wood or plastic container.

(3) Microwave is adsorbed by water-composed material molecule.

2. Microwave oven

Microwave oven is useful in cooking by using three main characteristics. The first and second characteristics are adapted by using non-reflecting microwave container for good passing of microwave stream to water molecule in material. The third characteristic is adapted by placing material having water molecule in passing direction of microwave stream. When microwave passes to water molecule in material, it is adsorbed by water molecule, and water molecule vibrates and rotates with high frequency bringing friction between nearby water molecule which gives rapidly thermal energy to material until that material rips. The vibration and rotation of water molecule is shown in Figure D1.

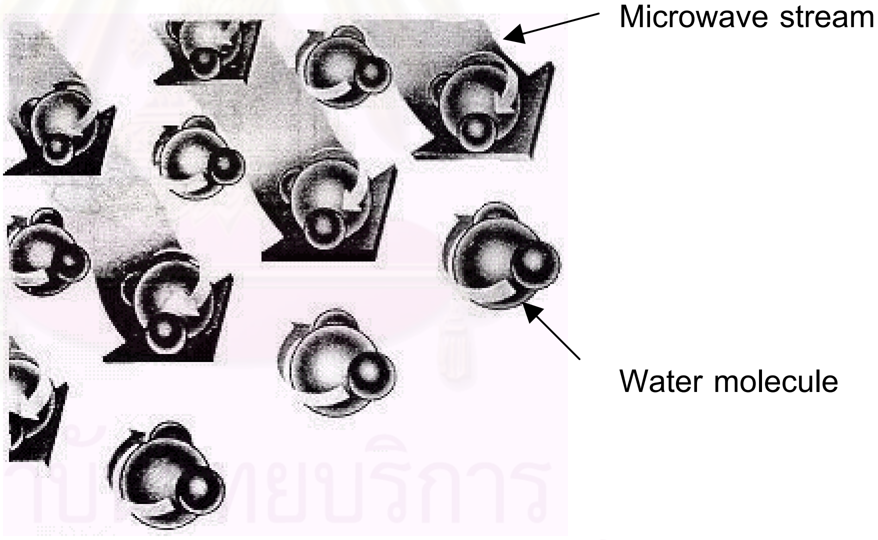

Figure D1 Vibration and rotation of water molecule during passing of microwave stream [35]

VITA

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