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NAME: Miss PreeyanuchAnukul

THIS THESIS HAS BEEN ACCEPTED BY

.... **THESIS ADVISOR**
(Assistant Professor PhichitSomboon, D.Sc. (Tech))

.... **THESIS CO-ADVISOR**
(Associate Professor SomwangKhantayanuwong, Ph.D.)

.... **DEPARTMENT HEAD**
(Assistant Professor PhichitSomboon, D.Sc. (Tech))

APPROVED BY THE GRADUATE SCHOOL ON ....

.... **DEAN**
(Associate Professor GunjanaTheeragool, D.Agr.)

THESIS

DEVELOPMENT OF LABORATORY CREPING ON TISSUE PAPER FOR EVALUATING THE QUALITY OF INDUSTRIAL PULP RAW MATERIALS

PREEYANUCH ANUKUL

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The required properties of tissue paper including softness and liquid absorption are predominantly manipulated by the creping process, which cannot be simply produced in the laboratory. This causes problems in controlling the stock quality prepared using the various types of industrial pulps, and consequently affects the creping operation and tissue quality. Therefore, this research work had the objectives to develop a laboratory creping method and to apply it for the evaluation and control of the quality of the pulp raw materials used in industrial tissue production. The experiment consisted of the development of a laboratory wet creping method where the creping devices and the creping conditions including the basis weight of the base paper, the sheet dryness and the degrees of pulp refining were studied. The results showed that the developed wet creping method could produce crepes on laboratory sheets. The structures of the creped sheets were engineered to improve their softness and liquid absorption while typical laboratory sheets were not able to be so engineered. The tested pulps were found to produce significantly different responses to the laboratory wet creping depended on their morphology and the mechanical treatments. The examination of industrial pulps found that eucalypt, acacia, bagasse, bamboo, OCC and deinking pulps needed to be manipulated using different refining levels, and required optimization degree of their softness, liquid absorption and strength properties.

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Student's signature Thesis Advisor's signature

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LIST OF ABBREVIATIONS

MD = Machine direction
CD = Cross machine direction
ND = Non-direction
CSF = Canadian standard freeness
OCC = Old corrugated container
t = Caliper
L = Overhang length
W = Basis weight
1/g = Unit of softness
WRV = Water retention value
WHC = Water holding capacity
LF = Long fraction
MF = Medium fraction
SF = Short fraction

DEVELOPMENT OF LABORATORY CREPING ON TISSUE PAPER FOR EVALUATING THE QUALITY OF INDUSTRIAL PULP RAW MATERIALS

INTRODUCTION

Tissue paper in the world has been growing at the fast rate especially in Asia. Tissue paper refers to a hygienic paper with a lightweight paper. The tissue paper is designed to be soft and having high absorbency. It is intended for drying competes, wiping and automatic hot-air dryers. Tissue paper can be category into various types, e.g., bathroom tissue, facial tissue and table napkins, etc. It has a basis weight of 10-50 g/m^2. Each type of tissue paper is the product that made varies from typical 100% virgin pulp to 100% recycled pulp which depends on end use product (Kimari, 2000). Tissue paper is produced by using tissue paper machine; it consists of the wet end process, web forming and the dryer section. In the dryer section, it has a Yankee that is a single large diameter dryer cylinder; it consists of the special process which is called creping process (Furman *et al*., 1990).

Creping is one of the most important processes in tissue manufacture where mechanical force is applied on the tissue web by using a doctor blade to create small creasing lines on the tissue paper and to break down the bonding of the pulp networks (Norris, 1952; Zhaohui and Gupta, 2011). Creping produces internal structure changes in the tissue paper enhancing its softness and liquid absorption but reduces strength of the tissue paper (Furman, 1990; Ramasubramanian, n.d.; Ramasubramanian, 2011). Industrially, creping can be performed under wet and dry conditions. In the dry creping process, the blade is applied on the dried web adhered on the surface of the dryer, while wet creping is carried out on a wet web having a dryness of 55-80% which is then completely dried in the subsequent dryer (Norris, 1952; Klerelid, 2000; Raunio and Ritala, 2012).

In the creping process, the development of tissue properties including softness and liquid absorption are fundamentally influenced by the creping devices, the creping conditions, the adhesive degree of the base paper on the dryer surface, the base sheet properties and the raw material used (Uesaka *et al*., n.d; Kimari, 2000; Kuo and Cheng, 2000). Industrially, the tissue products are made using various types of raw materials, which causes difficulty in the control of stock quality, and consequently affects the creping operations and the required tissue qualities. The major obstruction to the control of pulp quality is that the creped tissue paper is not easily produced in the laboratory and there is no standard method available for laboratory creping. Thus, laboratory testing sheets and creped tissues have totally different structures, physical properties and mechanical properties.

Therefore, this study had the objectives to develop a laboratory creping method and to apply it for the evaluation of the quality of pulp raw materials including recycled pulp, non-wood pulp and wood pulp, and to apply the method for the control of stock quality in the production of the base sheets. The developed laboratory creping technique was focused on the wet creping process, for which the equipment and creping conditions were studied**.**

OBJECTIVES

1. To study and modify the laboratory testing methods for measuring the important tissue properties.

2. To develop wet creping method for producing crepe on the base sheet to change in the sheet structure.

3. To study effect of basis weight, dryness and degree of pulp refining on the creped structure and the creped sheets properties.

4. To evaluate the quality of various pulps used in tissue manufacture for improving their quality under the stock preparation process.

LITERATURE REVIEW

1. Definition of tissue paper

Tissue paper refers to a hygienic paper which made from paper pulp. Tissue paper is designed to be soft and having a high absorbency. It is intended for drying competes, wiping and automatic hot-air dryers. Tissue paper has a many types and each type has a different in their properties. Tissue paper can be categorized into 6 types, i.e., bathroom tissue, kitchen towels, table napkins, facial tissue and handkerchiefs, paper towels and industrials wipes, and other types. It has a basis weight of 10-50 g/m^2. Tissue paper can be produced from either hardwood or softwood pulps both virgin pulp and recycled pulp. The primary recovered paper grades used to create recycled pulp are printing writing paper and mixing wastepaper grades such as newsprints and magazines. Both are used in the tissue making process (Ampulski *et al.*, 1991; Kimari, 2000).

2. Type of Hygiene products

Tissue paper can be categorized into 6 types. It consists of bathroom tissue, kitchen towels, table napkins, facial tissue, paper towels and other types of tissue.

2.1 Bathroom tissue

The principle type of tissue is bathroom tissue. The consumer sector uses about 30%. Bathroom tissue has a basis weight of 14-22 g/m^2 and made with one to four piles. The composition varies from 100% virgin pulp to 100% recycled pulp. The essential properties of tissue paper are strength properties, softness and absorbency. Characteristic of bathroom tissue also depends on size, weight, roughness, smoothness and chemical additives. It has many kinds in color and embossing, with the choice depending on the market (Kimari, 2000).

2.2 Kitchen towels

Kitchen towels are the second most used type of tissue. Kitchen towels have basis weight of 20-24 g/m^2, 220-280 mm wide and 250-280 mm long. It has a composition which varies from 100% virgin pulp to 100% recycled pulp. The important properties is wet strength, this property can be improved by a chemical additive for wet tensile strength. Kitchen towels are usually embossed because Kitchen towels are a requirement for absorbency (Kimari, 2000).

2.3 Tables napkins

Table napkins are popular in home sectors and restaurants; and are used to replace textile in western restaurants. Table napkins are made with one ply, two plies, three piles or four plies. Majority of pulps in process are virgin pulp and some recycled pulp. Table napkins have many sizes, styles and have different qualities. The important properties are absorbency and wet tensile strength (Anonymous, 2005; Kimari, 2000).

2.4 Facial tissue and handkerchiefs

Facial tissue and handkerchiefs have a basis weight of about 14-18 g/m^2. These are made from the lowest basis weight tissue, and rubbed by calender on tissue machine to improve their properties such as softness. Facial tissue is made with two plies and handkerchiefs consist of two or three plies. The main of pulps in process are virgin pulp and some recycled pulp. The important properties are the highest qualities that are suitable for use on face (Fish, 2013; Kimari, 2000).

2.5 Paper towels and industrials wipes

Paper towel is used to clean up things such as dirt spills. One ply of paper towel has a basis weight of about 33-50 g/m^2, and has a basis weight of 22-24 g/m^2 with two plies. The composition varies from 100% virgin pulp to 100% recycled pulp. The main property is wet strength which can be improved by adding resin additive.

Moreover, softness is an important property in paper towel; it is improved by produced embossing or printed on surface. Industrials wipes are made from 25-50 g/m^2 and consist of one to four plies. Paper towels and industrials wipes are used in the different ways. Paper towels are used in home sector and industrials wipes are used in hospital surgical wards for wiping grease in engineering workshops to personal hygiene (Kimari, 2000).

2.6 Other types

Other types of tissue have a huge range of different using such as coffee filter papers, padding for meat packaging and cigarette filters. Nonwoven fabrics may be used in products for disposable clothing for use in health care (Kimari, 2000).

3. Raw Materials

Virgin pulp and recycled pulp are used in tissue paper making. Each types of tissue paper is made varies from 100% virgin pulp to 100% recycled pulp.

3.1 Virgin pulp

Virgin pulp is a cellulosic material which is produced from natural plants. Virgin pulp which is used in the tissue making process is made by using chemical sulfate and sulfite a process. The most common chemical pulping process used in manufacture is sulfate (kraft) pulp. Tissue paper is made from either hardwood or softwood pulp; either bleached or unbleached. Softwood pulp can be made from pine; and hardwood pulp can be made from wood such as birch, eucalypt, beech and acacia. Hardwood has shorter pulp. It gives the smoothness and softness on the paper surface whereas softwood pulp gives strength. In addition, bleaching also improves properties such as absorbency and brightness while reduce dirt; and gives it a longer life. (Chandra, 1998; Kimari, 2000).

3.2 Recycled pulp

Recycled paper is an important raw material in tissue paper industry which will be helpful in minimizing production costs. The primary recovered paper grades used to create recycled pulp are printing writing paper and mixing wastepaper grades such as newsprints and magazines. Both are used in the tissue making process. Printing writing paper or office waste is the best raw material to produce recycled paper (Kimari, 2000).

3.3 Pulp mix

The type of the raw materials which are used in the tissue process depends on the quality requirements such as paper towel which mainly consists of softwood pulp to increase strength and liquid absorption while facial tissues consists of hardwood pulp to increase softness. Some types of tissue paper that lower quality of the paper are made from household waste paper. Higher-quality tissue paper is made from printing writing paper or office waste paper; it is a brighter more than the tissue paper that is made from the household waste paper (Kimari, 2000).

4. Tissue making process

Tissue making process mainly consist of the deinking process which makes a new pulp from a recycled pulp, refining process which used to modify the pulp properties, web forming, drying and the special process is creping.

4.1 Deinking process

Deinking is an important in waste paper recycling process which used about 10.5-17% in tissue manufacturing (Tom, 2002). Deinking is a process which makes a new product by remove and detaches particles from recycled pulp (Weissman, 2004). The particles that still remain in recycled pulp are fillers, finer ink particles, coating, pigments, and dyes. All of the particles affect paper properties, drainage. It prevents flocculation of colloidal-sized particles and affect adhesion force between wet web and Yankee dryer surface. The small particles are the source of problem in the tissue production; create dirt on the tissue surface which effect to optical properties and mechanical properties such as optical, whiteness and printing. Removing of the small particles in the recycled paper is an important step in the deinking process and in the tissue production (Johansson, 1999; Miyoung *et al*., 2008; Solberg and Wagberg, 2002).

There are two techniques in the deinking process that is washing and flotation. The washing is the most important step to remove small particles. It can detach small particles from the pulp surface and decrease the small size of fines and fillers in recycled pulp while the larger particles that mainly are fines, fillers and ink particles from the recycled paper will be removed in the flotation step by using bubbles to catch particles and separated from pulp.

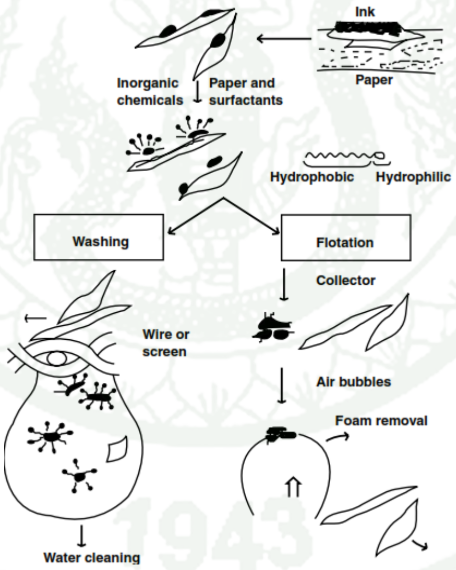


Figure 1 Flotation and washing process.

Source: Lassus (2000)

Result of deinking is single pulp, higher pulp yields and better qualities especially brightness. The deinking process will improve brightness from 42% to 84% while ash content reduces from 8-35% to 1.5-5%. The result of deinking will increase pulp yields from 52% to 75% while brightness of printing writing paper or office waste paper has about 80% and mixed wastepaper which consists of newspapers and magazines has a brightness of 60% (Kimari, 2000; Putz, 2000).

4.2 Refining

Refining is a process to modify the pulp properties which increases the specific surface area while the length of the pulp will reduce (Anonymous, 1996; Lumianien, 2000; Holik, 2000). The pulp structure, size, shape, surface properties and fines properties are various in the different refining levels. Increasing refining levels make the pulp collapse, pulp flexible, create pulp bonding and internal fibrillation of pulp wall that impact on increasing tensile strength of sheets (Heijnesson *et al.*, 1995; Heydari *et al*., 2013). Moreover, increase refining level affects inner swelling in the pulp. It is called water retention. (Jorma, 2000; Seo *et al.*, 2002). Water retention is defined by using a ratio of water that still remain in the fiber pad after centrifugation and dry fiber pad after oven dry under standard conditions (Caprita, 2012).

4.3 Web forming

Web forming is the section which produces a wet web from pulp and other compositions. The pulp and other compositions about 0.15 - 0.25% consistency in the short circulation are injected on a felt or wire of a forming machine with headbox. The wet web is formed consisting of two, three, four to ten plies of pulp which creates the range of the basis weight is about 10 to 50 g/m^2 (Joseph, 2008). In the cases of kitchen towel, it may consist of thirty plies of fiber because it requires higher wet tensile strength and better water holding capacity.

The tissue sheet can be formed by using 4 types of forming machines, i.e., fourdrinier machine, suction breast roll machine, twin wire machine and crescent former machine. The fourdrinier is the oldest machine which still uses a few in the tissue web forming. The suction breast roll is the forming machine which uses a suction to remove water from the wet web. The twin wire is the machine that the headbox spray the pulp between two wire and crescent former machine is the highest speed machine which consists of a felt wire. The water is drained through the wire; and the felt is wrapped around the forming cylinder. (Kimari, 2000; Urbanek and Wells, 2008).

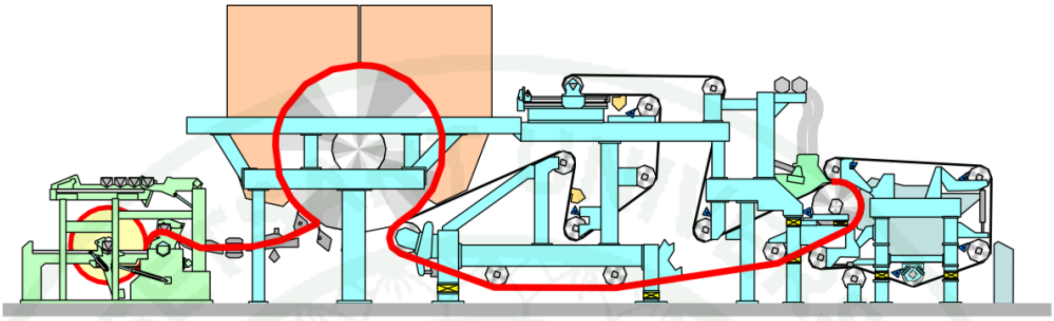


Figure 2 Tissue machine structures.

Source: Kimari (2000)

4.4 Drying

Drying is the section of the paper machine to dry the paper by using through-air drying system and Yankee dryer cylinder. The Through-air drying is contained under the hood. It is used to drain off the water by using air flow system. The air in the though-air drying is blown from the dryer hood through the web and blown into the cylinder. The through-air drying results in lower strength, higher bulk and higher softness while nip pressures that used to drain off water in the production of the other type of paper make the web at higher strength but reduce softness. Then the web which passes from the through-air drying, it will be transmitted to the Yankee dryer by touch roll. The touch roll in the tissue production is used to make the web adhere to the Yankee dryer surface (Kimari, 2000; Klerelid, 2000; Lindsay *et al.*, 2003).

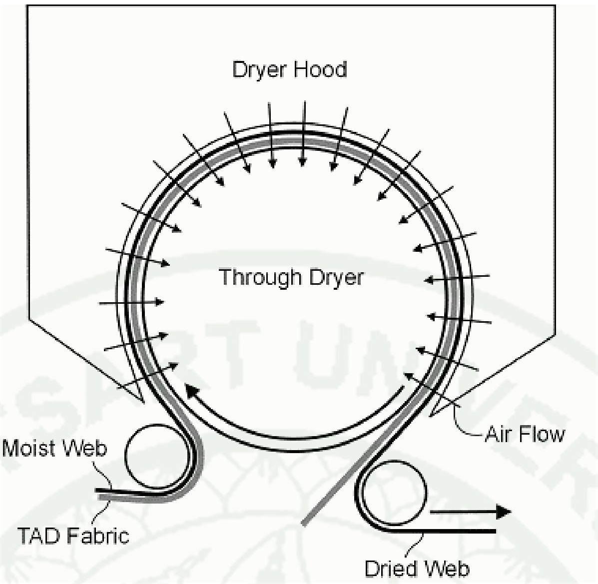


Figure 3 The structure of through-air drying system.

Source: Jeffrey *et al.* (2003)

Tissue machine has a single large diameter dryer cylinder which is called Yankee dryer that can range in diameter from 10 to 15 feet; it is a larger cylinder than the common dryer cylinder paper machines that conflict with the manufacture of heavier basis weight papers where a small dryer cylinder can be used with lightweight paper. The dryer is contained under the hood to maintain the heat of steam; and the heat is released by cooling system. Dryer cylinder has a glossy surface where make the surface smooth and prevent the sticking of pulp on the cylinder. which increases the adhesive force between surface of the dryer and the wet web (Furman *et al*., 1990; Norris, 1952).

The factors that affect both sides of the paper are the moisture content of the web at press roll nip and refining level. The result of too much refining is too much short pulp while too much moisture content is not adhering the web to the Yankee cylinder; that will create defects on the paper. Thus, the optimum of moisture content of the wet web is about 35-40%. The wet web at 35-40% moisture content is transferred to the Yankee dryer by the felt and cylinder pressure. The web will be dried by heat transfer from the Yankee dryer; it is about 100 °C. The web is transferred to the Yankee dryer as heat transferred slowly to the web. (Furman *et al.*, 1990).

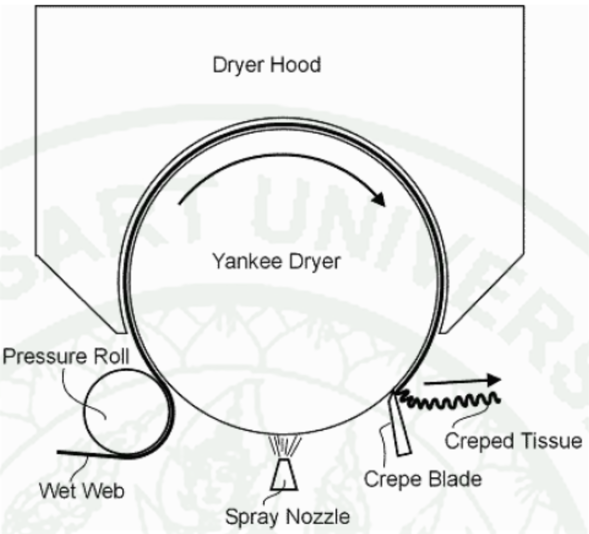


Figure 4 The structure of Yankee and Creping process.

Source: Patterson and Choi (2010)

The last section of the Yankee dryer has a creping process that produces small creases on tissue surface. It is a special process for the tissue paper especially napkins and toweling (Rappolt, 1962). The creping process are describes in section 5. The crease or crepe is made by Yankee’s doctor blade; it is produced when the sheet has low moisture content. The crepe is controlled by force between chemical adhesives and the dryer surface; and the quantity of crepe is controlled by the speed difference between the Yankee dryer and winding. The quality of tissue paper can be controlled by consumer usability. The creping is the biggest characteristic to make the tissue paper different from the other types of paper (Norris, 1952).

4.5 Finishing and converting

Finishing and converting is the process which restructures of the surface, and change mechanical properties of paper. There are several processes in tissue finishing and converting, i.e., embossing, printing, perforation, winding, tail seals, log sawing and packing. Embossing is the process for increasing the surface area which results in the tissue having a higher bulk, softness and absorption. Some type of tissue may be designed the tissue surface by using color which is called printing. Perforation is the process to drill the tissue paper in each section which makes the sheets easier to separate. When the paper is produced successfully, the tissue will be transferred to winding, cut into a small size roll and pack a small size roll by using plastic or paper (Kimari, 2000; Klerelid, 2000).

5. Creping process

Creping is the special process to produce crepe on tissue surface to increase liquid absorption and softness. The crepe is made by the Yankee’s doctor blade that install at the first or the last position of the Yankee dryer. Creping blade is the main structure of the dryer section. It is designed with the suitable instrument and the suitable angle. Creping blades is adjusted for the suitable position to apply force to the dryer surface, making a crease and breaking bonds in the sheet that change over the tissue paper properties such as bulk, softness, absorption (Kuo and Cheng, 2000).

Creping process consists of three doctor blades that are a cut-off doctor or skinning doctor, creping doctor and cleaning doctor blade. A cut-off doctor blade or skinning doctor blade is installed before the creping doctor blade, and cleaning is installed after the creping doctor; it is used to remove pulp and inordinate coating (Klerelid, 2000). The contact angle of the blade angle is called the shelf, cutting angle or mediates creping. The effect of the different contact angle is roughness and frequency of the crepe. Roughness and frequency of the crepe indicate smoothness on the tissue surface. The effect of a small bevel angle is increasing the cutting angle; it produces a smaller crease (Jonna and Luciano, n.d.; Kuo and Cheng, 2000). The frequency of the crepe fold can be control by adjusting the angle between the creping blade and the Yankee dryer (Raunio *et al*., 2012).

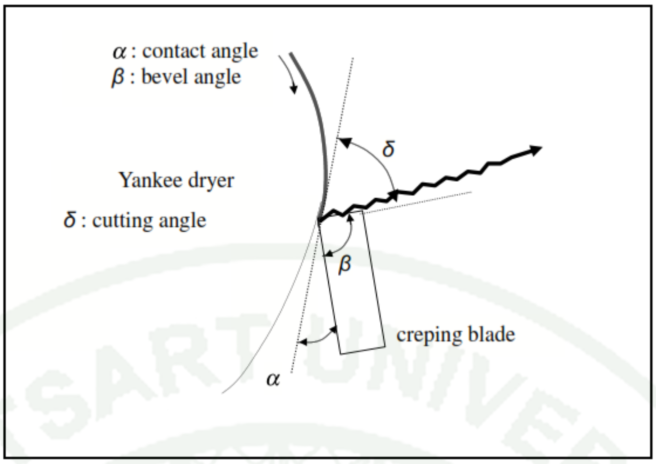


Figure 5 Structure and angle of the creping blade.

Source: Kuo and Cheng (2000)

5.1 Creping chemicals

Creping chemical is coating chemical which helps to control the creping production. The function of chemical agent is used to produce the crepe on surface, change their properties and release a sheet to the next process. The creping chemical will react with heat, dissolved the water and it occurs a coating layer on the dryer surface. Coating layer is a thin layer of the adhesive agents and the release agents on the Yankee (Kuo and Cheng, 2000). The adhesive necessary to produce the dry crepe; it is provided by a creping chemical on the Yankee surface (Furman *et al.*, 1990). It may be added to the wet end of machine or sprayed directly on the Yankee dryer (Rezaei-Arjomand *et al*., 2013). In general, the crepe adhesives consist of polyvinyl alcohol (PVOH), polyaminoamide-epi (PAE), polyacrylamide (PAM), carboxymethyl cellulose (CMC) and polyvinyl acetate in water soluble (Rose, 2004). The crepe is controlled by holding and adhesion force on the Yankee and the sheet surface. Holding and adhesion force must be balanced between the Yankee and the sheet surface because it affects crepe characteristic and tissue properties such as softness and bulky. (Furman *et al.* 1990; Klerelid, 2000).

5.2 Wet/Dry creping

Tissue paper machine can produce both wet and dry creping. The dry creping is the most common type of the tissue machine (Raunio and Risto. 2012). In the case of the wet crepe, creping blade will be installed before the drying section; and the moisture content of the paper is used about 20-45%. After finishing the creped wet web operation, it will be transferred to the drying section. For dry crepe, the paper is dried and reduced the moisture content by the Yankee cylinder. The wet web will be transferred to the creping blade when the paper has the moisture content about 3-15%. The sheet is transferred slowly into the creping doctor blade to produce the crepe. (Urbanek and Wells, 2008).

5.3 Creping mechanism

The beginning of the creping process is the wet web transferred into the dryer surface by touch roll. The wet web will be decreased a moisture content and increased an adhesion force between the sheet and the Yankee. When the web sheet contacted with the dryer surface, it will be dried rapidly with dryer and heated air transfer from a drying hood. As the paper dried, hydrogen bond forms in the paper structure, pulp collapse and paper dense. Dryer will be rotated and the web will be transmitted to the creping blade which is the main structure of the dryer section. It is used to produce a crease on the tissue surface, crack in paper structure, destroy the fiber bond and reduce the specific bond strength. Specific bond strength can be explained in term of fiber bonding strength and number of the bonding area, which depends on basis weight, size of fiber, external fibrillation, chemical composition, pulp charge and fines. The most bonding is hydrogen bond between pulp and fibrils which is an important to creping characteristic, paper properties and other theory of paper (Ramasubramanian, n.d.; Uesaka *et al*., n.d.).

In creping operation, the wet web is transferred to the creping blade. The creping blade will be made the fiber bonding crack and changed in their paper properties, e.g., softness and absorbency (Ramasubramanian, n.d.; Ramasubramanian, 2011). When the sheet is produced the crepe by creping blade and separated fiber from each other by using different speed of dryer cylinder and winding, stress will be made in the sheet. The result of the stress in the sheet, it breaks bond, loose the fiber network and creates a small pore in the sheet (Zhaohui and Gupta, 2011).

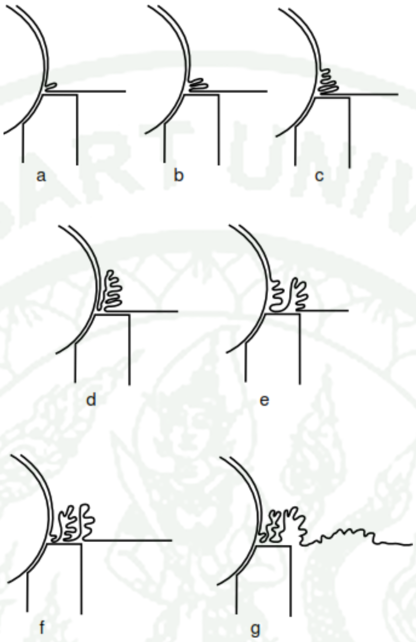


Figure 6 Mechanism of creping during the sheet release from the Yankee with blade.

Source: Klerelid (2000)

5.4 Creping characteristic

The creping process is an important in the production of tissue paper. The paper quality can be evaluated by the crepe characteristic. The crepe characteristic can be analyzed by macrostructure analysis that describes the frequency and amplitude of fold or ridges of crepe. This analysis is aware of the number of fold or ridges per unit length of the paper. The basic creping structure can be categorized into two characters, i.e., microcrepe and macrocrepe. When the crepe fold is small, higher frequency and small wavelength, the crepe is called microcrepe or finer crepe while the crepe fold is large, the crepe is called macrocrepe. The microcrepe can be made the paper softer whereas the macrocrepe has a higher strength (Furman *et al.,* 1990; Kuo and Cheng, 2000; Ramasubramanian, n.d.).

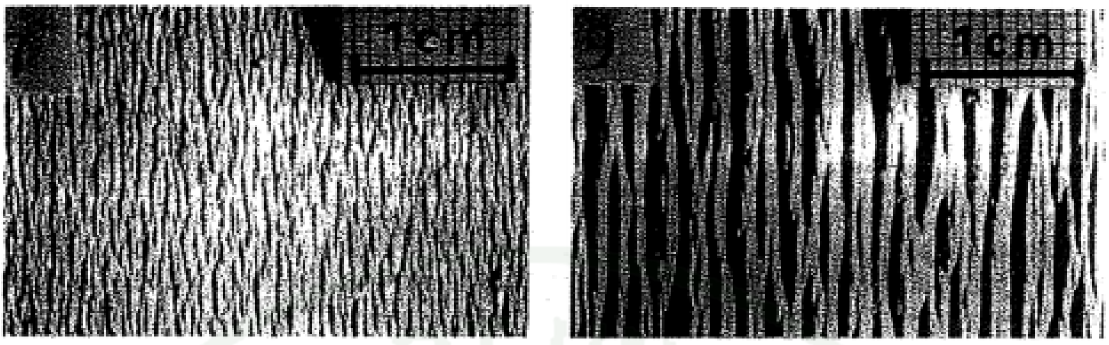


Figure 7 Creping characteristic.

Source: Ramasubramanian (n.d.)

Factors affecting the crepe structure are mechanical properties of the paper, blade and adhesion force between the web and the dryer surface. The frequency of occurrence of the crepe can be controlled with the blade angle which contact with the Yankee including adhesion force can produce the finer crepe as well. However, it is so hard to make the finer crepe on a high weight paper because that has a higher bending resistance and folding resistance. (Furman *et al*.,1990).

6. Tissue paper properties

Requirements properties of tissue paper have many benefits. It depends on the usage of each type, and can choose by properties. The main tissue properties required for product are softness, absorbency and strength.

6.1 Softness

Softness is the most important property which can be explained in a term of smoothness, compressibility and stiffness. The softness indicates that the pulp collapse and the amount of fine to improve density. It is an important for the softness values, it makes the paper stiff and characteristic of the paper structure affects directly the softness. (Liu and Hsieh n.d.). Normally, the softness of tissue paper can be improved by using softening chemicals (Bhatia, 2004).

Tissue is a special grade of paper which is designed to be soft. Softness has been measured using consumers and human participants. It can be tested by hand which is called Hand Feel (HF) method and Paired Comparison method. These methods are called subjective method. It is used to compare the tissue paper grade in mill (Ampulski *et al.*, 1991; Kimari, 2000). However, human panelists and consumer cannot perceive a small change in the sample. Thus, there is different measurement such as objective softness measurement and direct softness measurement. Objective softness can be known insight into what process parameters need adjustment and can be related to process parameters. Parameters and components of softness are measured and developed to relate physical properties to the subjective softness. Direct softness measurement, equipment is used in this measurement. There have been several attempts to create a single softness measuring apparatus Clark's softness tester. Clark softness has a dimension of softness divided by weight and thickness of its own (Ramasubramanian, n.d.). It can be used to calculate a softness value as

$$softness = 10x10^6 \frac{\log(t+1)}{L^3 W}$$

Where t is the caliper

L is the overhang length between two nip and

W is the basis weight.

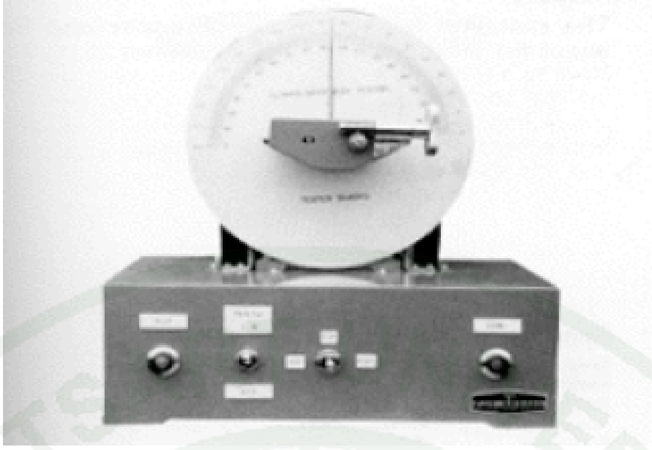


Figure 8 Clark softness-stiffness tester.

Source: Bhatia (2004)

6.2 Absorbency

Absorbency is absorption ability including absorption speed and water holding capacity which is important in tissue products. Absorption ability is complicate because creping, wood pulp and direction of machine are involved. The absorbency of tissue paper is measured using water by how fast it absorbs the water (s/cm) and how much water it can hold (g water/g paper). Liquid penetration into a pore is a system of capillarity force and capillarity pressure. When the liquid flow into the pore, it was randomly distributed in the tissue paper by using the system of capillarity force and capillarity pressure. The water holding capacity might be as high as 18 g water/ g paper while a one- ply tissue made from recycled pulp and embossed has an water holding capacity of about 4 g water/g paper (Kimari,2000; Rioux, 2003).

6.3 Tensile strength

Tensile strength is an important property which relates to elastic modulus, load-elongation, bending stiffness and bonding degree of the pulp network. Tensile strength is the maximum force (tensile force per unit width) that a sample of paper will withstand, before breaks, under the specified conditions (Abbott and Schnabel, 2000). Tensile strength will be measured both wet and dry. It can be measured in both machine and cross-machine directions. The strength of pulp and inter-pulp bonds depend on tensile strength and fracture toughness of paper. In the tissue industry, tissue paper intended mix with recovered paper. Recovery paper affects tensile strength and elastic modulus of the paper (Niskanen and Karenlampi, 2000).

6.4 Basis weight

Basis weight of the tissue paper has about 10-50g/m^2. Higher basis weights are used in single-ply products where strength is important such as industrial wipes; and multiply products such as bathroom tissue and facial tissue, which have to be soft, are made with a lower basis weight (Kimari, 2000).

6.5 Thickness, bulk and density

Thickness and bulk is distance between paper surfaces which is measured in micrometers (μm) (Kimari, 2000). A major different between other types of paper and tissue paper is its compressibility which relate to thickness; it affects density (Abbott and Schnabel, 2000; and Anonymous, 1963). Thickness and bulk depends on pulp structure and inter –pulp bonding and embossing (Shmagin, 2000).

MATERIALS AND METHODS

Materials

The commercial tissues used to study and modify the laboratory testing methods were bathroom tissue, kitchen towels, table napkins, facial tissue, paper towels and low quality of tissue paper that made from recycled paper.

The industrial pulps used in this study were bleached kraft hardwood pulps produced from eucalypt, acacia and bleached non-wood pulps produced from bamboo, bagasse and recycled pulps produced from deinked, OCC pulps, which were obtained from Tanatarn Paper Co., LTD, Samutprakarn, Thailand.

Methods

1. Study and modify the laboratory testing methods

The standard methods were studied and modified to evaluate the tissue properties of commercial tissues and light weight sheet which produced in laboratory. It described the absorption ability and physical properties, i.e., strength properties, softness and absorption ability including liquid absorption speed and water holding capacity. A tensile tester was used to test a tensile strength when it received a maximum force. A Clark softness tester was used to estimate and compare their flexing resistance paper softness value. A liquid absorption speed was used to test liquid absorption rate on a porous in a lightweight paper. A water holding capacity was used to test the liquid that could be hold in a porous of lightweight paper after immersion in water. The testing was carried out at conditioning room under temperature 23±1°C and humidity 50±2% according to ISO 187.

1.1 Basis weight, thickness and density

Basis weight was tested according to ISO 536 (Determination of grammage). Determination of thickness was measured by using thickness tester or micrometer. For the commercial tissues, the thickness was measured by using 10 plies (ten test specimens from a single ply product sampled) according to T3012 (Standard thickness tissue). The thickness and density of the light weight sheet which produced in laboratory was measured by using 1 ply and was tested according to ISO 534 (Determination of thickness and apparent bulk density or apparent sheet density).

1.2 Tensile strength

Tensile strength testing using tensile tester agrees with ISO 1924-2 (Paper and board – Determination of tensile properties). Tensile strength was measure both machine and cross-machine directions. The samples were cut at 15 mm wide and 150 mm long. The commercial tissue was tested with a gauge length of 50 ± 5 mm. and the testing speed of 75 ± 5 mm/min because embossing of the commercial tissues affected the tensile strength. It was sensitive to break the sheet when it received the maximum force. The test sheets were tested with a gauge length of 50 ± 5 mm and testing speed of 50 ± 5 mm /min.

1.3 Softness

Softness was tested by using Clark Softness-Stiffness tester according to TAPPI T 451 cm-84 (Flexural properties of paper (Clark stiffness)). The samples were cut at 30 mm wide and 150 mm long. The test sheets were gripped between two nip steel at one end and was free at the other. The two rollers forming the nip can be rotated about the horizontal axis and parallel to the length of nip. In a given position where the nip was rotated through 90° to the right, the sample falled over in right or rotated through 90° to the left, the sample falled over in left direction due to its flexibility and weight. If the sample continues to fall down in the same direction as before, the length of the overhang was reduced. The sample would fall over equally on either side of the nip, when the nip was rotated through 90°. The softness model predicted by three variables, i.e., thickness, basis weight and overhang length from the Clark softness tester. Each sample was calculated the softness value by using the Clark softness equation. It can be used to calculate a softness value as

$$softness = 10x10^6 \frac{\log(t+1)}{L^3W}$$

Where t is the caliper (um)

L is the overhang length between two nip and (mm)

W is the basis weight. (g/m^2)

1/g is unit of softness (when L used in millimeter)

1.4 Absorbency

Absorbency measuring was set and adapted with ISO 8787 (Determination of capillary rise Klemm method). The water was filled in the pan at 23±1°C and the samples were cut for measuring at 15 mm wide and 120 mm long. The samples were marked by the pencil lines. Lower the sample until the marks concur with the water level in the pan and start the timer. Record the time when the water transfers nearest the pencil mark (every 1 cm) completely 10 cm or completely capillary action stop. Calculate the mean value in the unit of mm/s.

1.5 Water holding capacity

The water holding capacity was tested according to ISO 5637 (Determination of water absorption after immersion in water). The whole sheet was used in the water holding capacity test. This method was determination of the water absorption of paper after total immersion in water for a specified time. In lightweight paper, the time was select immersion 5 minutes for low water resistance. After completely immersion time, the specimen was removed from the water and suspending them for allows the water to drain off for 2 minutes. The mass of the each specimen was measure and calculate water holding capacity with ISO 5637.

2. Fiber morphology analysis

2.1 Fiber morphology

Fiber length and fiber coarseness were analyzed using a Metso FS5 automated fiber analyzer. The fiber surface energy was analyzed using a Fiber Potential Analyzer.

2.2 Water retention value

Water retention value method is a method to measure the inner swelling of the pulp. It was carried out on SCAN-C 62:00 (Water retention value). The pulp samples were used; consist of OCC, deinking, bagasse, bamboo, acacia and eucalypt pulps which were used both unrefined and refined at 500, 400, 300 and 200 ml CSF.

2.3 Pulp fractionation

Pulp fractionation was carried out on laboratory Bauer McNett pulp classifier Tappi T 233 cm-95 (Pulp length of pulp by classification). The unrefined pulp samples were used; consist of OCC, deinked, bagasse, bamboo, acacia and eucalypt pulps. It was used to separate pulp into long, medium, short and fine components. The screen opening that used in the Bauer McNett classification method consists of R50 fraction (mesh opening 0.297 mm), R100 fraction (mesh opening 0.149 mm) and R200 fraction (mesh opening 0.074 mm) whereas P200 is the fraction that passes through the 200 mesh wire.

3. Develop laboratory wet creping device

Creping process is the process that produces a crease and changes the pulp bond structure in the sheets. Tissue paper can be produced both wet and dry crepe. However, the laboratory creping method was developed based on wet creping conditions because wet web had still remained the moisture that made the surface tension between glass creping blade and the surface of wet sheets. The wet creping could be produce without creping chemical while dry crepe could not be produce without creping chemical due to the tension force that was not enough. The creping chemical that used in dry creping would affect the paper structure. Wet creping method can be developed in laboratory by using glass creping blade, light weight roller and creping blade. A mechanistic description of the wet creping process can be developed as follows (Figure 9 and 10)

The creping equipment consisted of the glass creping base, the light weight roller and the creping blade with an adjustable angle. The creping devices were arranged at the suitable position (Figure 9a). The base sheets were made according to ISO 5269-1. The wet sheets were attached on the glass creping base and the sample was absorbed the water to make the surface tension between the glass creping base and the handsheet surface by using the blotter and the light weight roller (Figure 9b). The wet sheets were creped by the blade at an angle of 30° to produce folded samples, and subsequently stretched backwards close to the beginning position as shown in Figure 9c – 9h. As soon as the creping blade hit the handsheet, stresses created in the handsheet, crack propagation continues to destroy the pulp bonding when the cracking was complete; the handsheet completely collapses and had the creped fold on the handsheet surface. The creped sheets were carried out at room temperature for 2 hours and applied mechanical force by using the creping blade on the top and the wire sides to produce the flat sheets without the changes of the creped structure before testing, then the creped sheets were continuously dried under the conditioning room of the temperature of 23±1 °C and the room humidity 50±2% according to ISO 187 (Figure 9i and 9j).

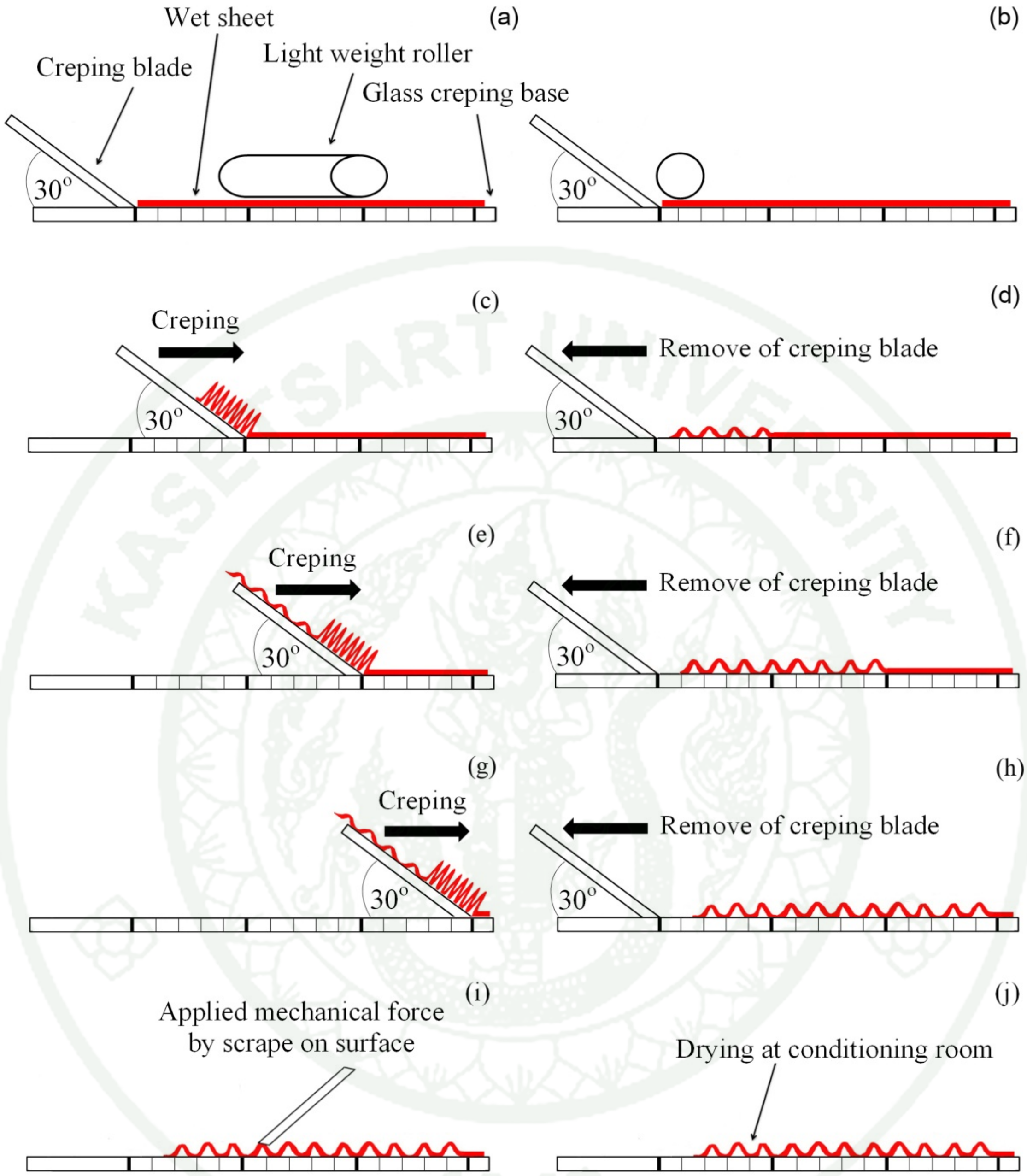


Figure 9 Schematic description of the laboratory wet creping method, position of the creping devices (a), creating a surface tension (b) and destroying the sheet structure(c, d, e, f, g and h).

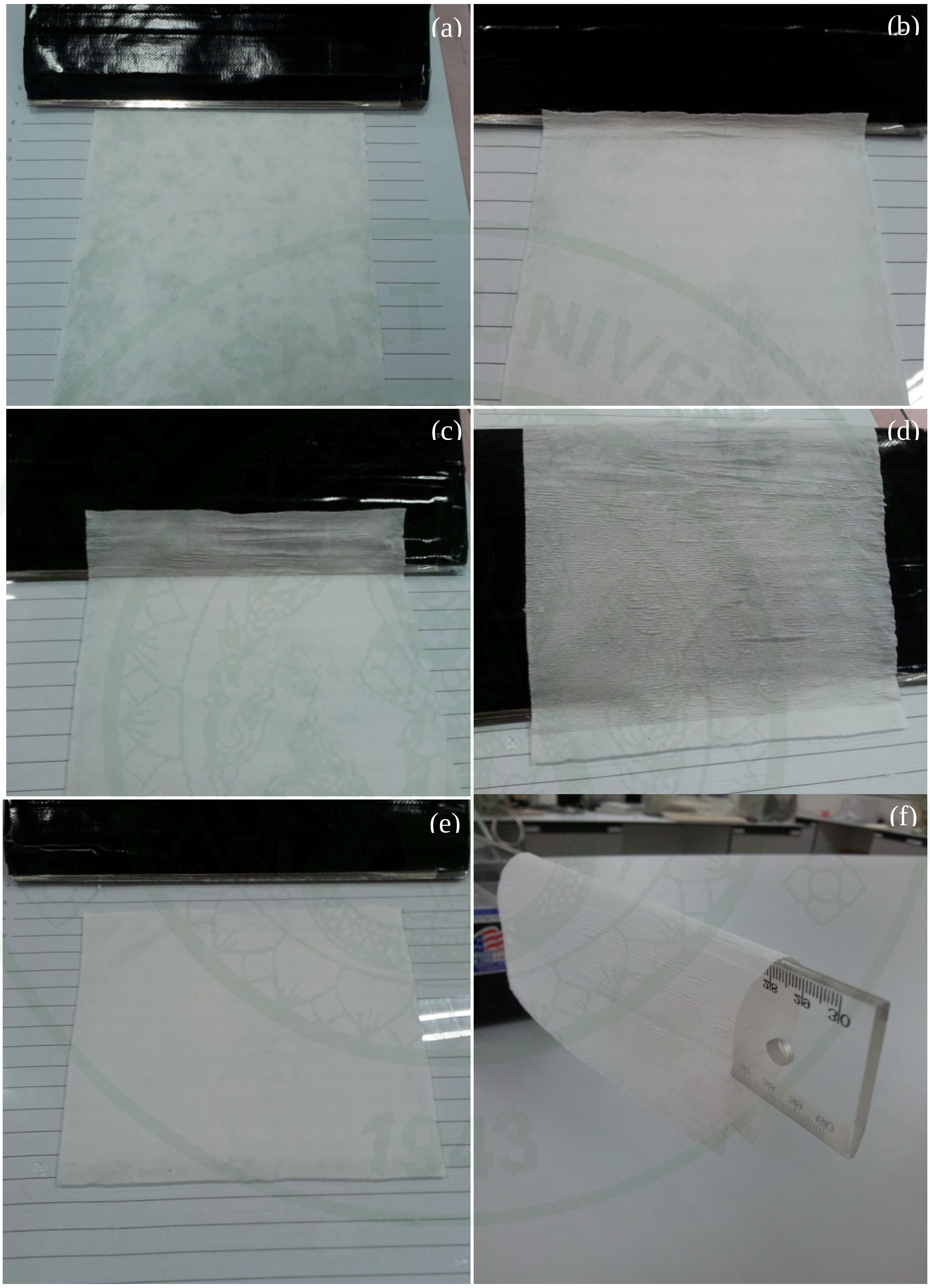


Figure 10 Laboratory wet creping method, base sheets (a), destroying the sheet structure (b, c and d), wet creped sheet (e) and dried creped sheet (f).

4. Study the effect of creping conditions on the crepe structure and crepe sheets properties

The effect of variation of crepe structure and creped sheet properties was examined. Three main categories of creping condition, i.e., dryness, basis weight and drainability were chose in this study. The tested pulps were disintegrated according to ISO 5263 and manipulated to various degrees of drainability using a Valley beater according to ISO 5264/1. The pulps were tested drainability by using ISO 5267-2 and the base sheets were made according to ISO 5269-1.

4.1 The effect of dryness and basis weight

The factors that were change in this experiment were the dryness and basis weight. Dryness was varies between 20 and 30%. Basis weight was varies from 30, 40 and 50 g/m^2. The drainability of pulp was kept constant at 300 ml CSF and the creped sheets were made from eucalypt pulp and made by using the laboratory wet creped method which described previously. The creped sheets were kept under the conditioning room of the temperature of 23±1 $^{\circ}$C and the room humidity 50±2% according to ISO 187 before testing. The whole samples were tested by using the laboratory testing methods, recorded and analyzed the values.

4.2 The effect of degree of refining

The factors that were change in this experiment were the degree of refining and degree of creping. Degree of refining was varies from 500, 400, 300 and 200 ml CSF. Degree of creping was varies in two level, uncreped and creped sheets. The basis weight was kept constant at 30 g/m^2 and the dryness was kept constant at 20%. Ten uncreped sheets and ten creped sheets were made from eucalypt pulp and the creped sheets were made by using laboratory wet creping method. The uncreped and creped sheets were kept under the conditioning room of the temperature of 23±1 $^{\circ}$C and the room humidity 50±2% according to ISO 187 before testing. The whole samples were tested by using the laboratory testing methods, recorded and analyzed the values. Comparison the results of each property between the samples were creped and uncreped in each degree of refining and degree of creping.

5. Study various pulps used in tissue manufacture

The main objective of the part was to evaluate the quality of industrial pulp raw materials. Hence, the factors that were changed in this experiment were the various types of pulp raw materials. The handsheets were made using six types of pulp raw materials, i.e., OCC, deinked, bagasse, bamboo, acacia and eucalypt pulps; and varies degree of refining from 500, 400, 300 and 200 ml CSF. The basis weight was kept constant at 30 g/m^2 and the dryness was kept constant at 20%. Ten creped sheets were made from each type of the pulp raw materials and degree of refining by using laboratory wet creping method. The creped sheets were continuously dried under the conditioning room of the temperature of 23±1 $^{\circ}$C and the room humidity 50±2% according to ISO 187 before testing. The whole samples were tested by using the laboratory testing methods, recorded, analyzed the values and comparison the results of each property.

RESULTS AND DISCUSSION

1. The laboratory testing methods

The study of characteristic of commercial tissues found that the various types of commercial tissues had different in their properties. The properties were analyzed by using the laboratory testing methods. The methods involve measuring the tensile strength, softness, liquid absorption speed and water holding capacity of the light weight sheets. It was found that the tensile strength can be measured by using tensile tester with adapt at 50 mm of gauge length and speed rate 50-75 mm/min. The softness can be measured by using the Clark softness equation by three variables, i.e., thickness, basis weight and overhang length from the Clark softness and stiffness tester. The liquid absorption speed was recommended for the light weight sheets having a capillary rise less than 200 sec or 30 mm and the water holding capacity with an immersion of 5 min and drainage of water for 2 min was recommend for the sheets which had a low water resistance.

The results showed that the commercial tissues can be divided into six types, i.e., bathroom tissue, kitchen towels, table napkins, facial tissue and handkerchiefs, paper towels and industrials wipes including low quality of tissue which made from recycled pulp, as shown in Figure 11. Each type of commercial tissues consists of 1 – 5 plies and characteristic of each ply was closely similar. Each ply was produced creped on surface and some type had an embossed. Almost of the commercial tissues had a crease and embossed while bathroom tissue, facial tissue and handkerchiefs had only crease on the tissue surface. Each type of commercial tissue was designed properly for end used product. For the basis weight of 1 ply of the commercial tissues, facial tissue and handkerchiefs had a minimum basis weight, it was about 13.95 g/m^2 while kitchen towel had a maximum basis weight, and it was about 21.12 g/m2 whereas the other type of commercial tissues had a basis weight between facial tissue and kitchen towels. The commercial tissues had a density about 0.245 – 0.322 g/cm^3. The minimum density was facial tissue and handkerchiefs, it was about 0.245 g/cm^3 while the maximum density was kitchen towels, it was about 0.322 g/cm^3. The thickness of commercial tissues was varies from 54.40 µm to 65.50 µm, as shown in table 1.

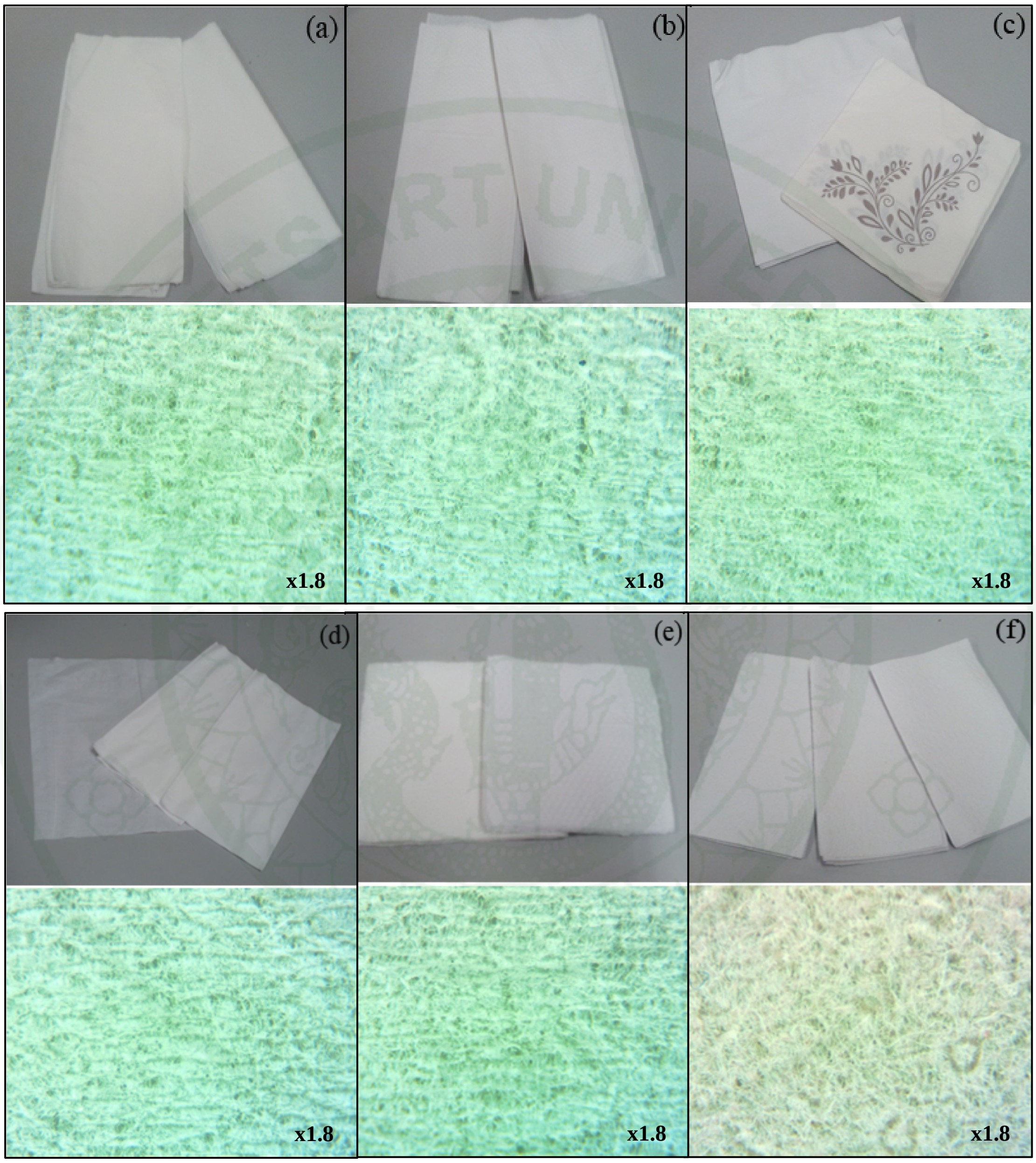


Figure 11 Various types of commercial tissues, bathroom (a), kitchen towels (b), table napkins (c), facial tissue (d), paper towels (e) and low quality of commercial tissue (f).

Table 1 Characteristic of each types of commercial tissues

Types	Thickness (μm)	Basis weight (g/m^2)	Density (g/cm^3)
Bathroom tissue	60.10	17.28	0.288
Kitchen towels	65.50	21.12	0.322
Table napkins	50.37	15.72	0.316
Facial tissue and handkerchiefs	56.95	13.95	0.245
Paper towels	54.40	16.30	0.300
Low quality of tissue paper	55.70	17.80	0.320

1.1 Tensile testing of commercial tissues

Figure 12 shows tensile strength of commercial tissues with the average of MD and CD. The tensile strength of commercial tissues was about 3.45 – 12.89 Nm/g. The tensile strength of kitchen towel was the highest while the tensile strength of the paper towels was the lowest. Kitchen towels had a special strength property whereas other types of commercial tissue were not necessary in a higher strength. Higher strength property made the tissue paper stiff and improper to use with body and face.

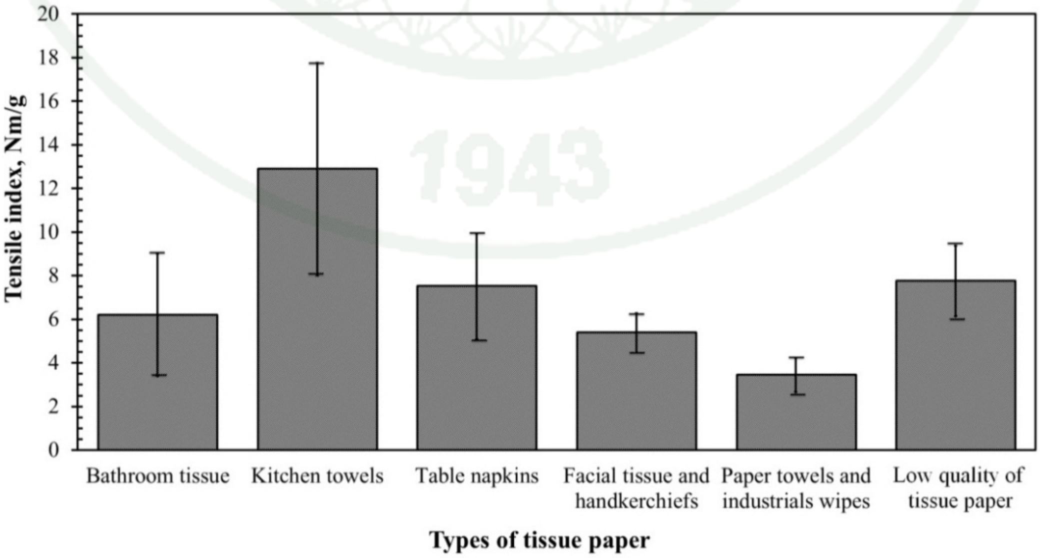


Figure 12 Tensile strength of various types of commercial tissues.

1.2 Softness testing of commercial tissues

Figure 13 shows the result of softness of commercial tissue with the average of MD and CD. The softness of commercial tissues was about 4.21 – 57.94 1/g. The softness of facial tissue and handkerchiefs was the highest while the softness of the kitchen towels was the lowest. According to above result, it showed that the quality requirement of facial tissue and handkerchiefs was the softness. The softness was very important to touch a body and face. In addition, the different softness depended on the embossed that produced after creping process. Embossing process in the tissue production resulted in increasing the softness value while the some type of commercial tissues that made without embosses had a lower softness.

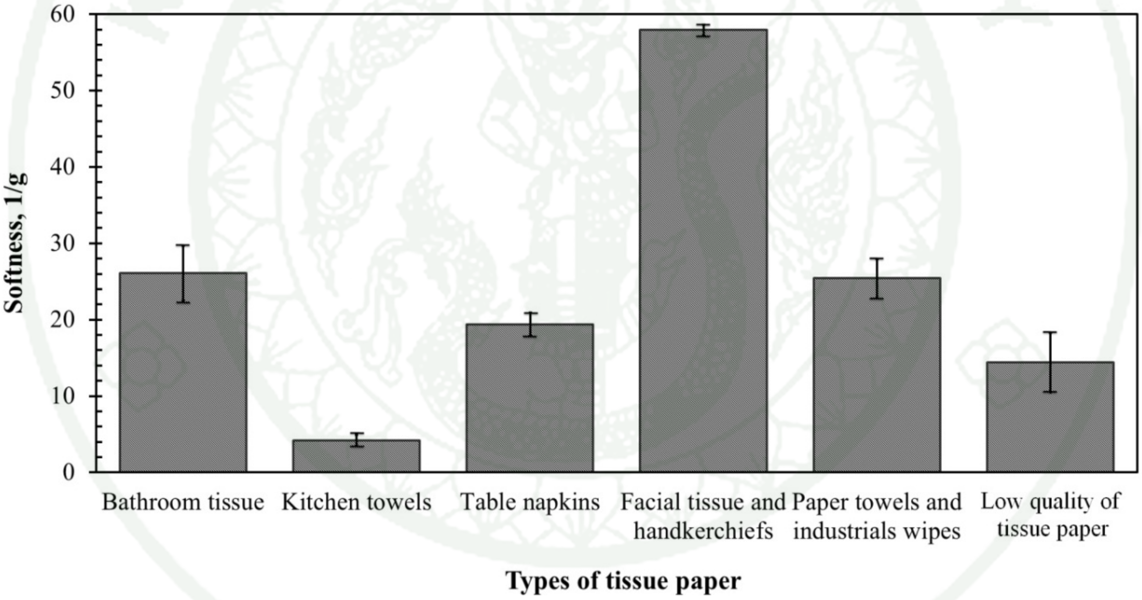


Figure 13 Softness of various types of commercial tissue.

Figure 14 shows the correlation of the tissue softness with the density. The softness was a steady downward trend in both directions. Tissue paper structure was changed during tissue production which effected to the density. Increasing density directly affected their properties especially softness. It made the paper stiff and had a greater strength whereas softness decreased (Figure 15).

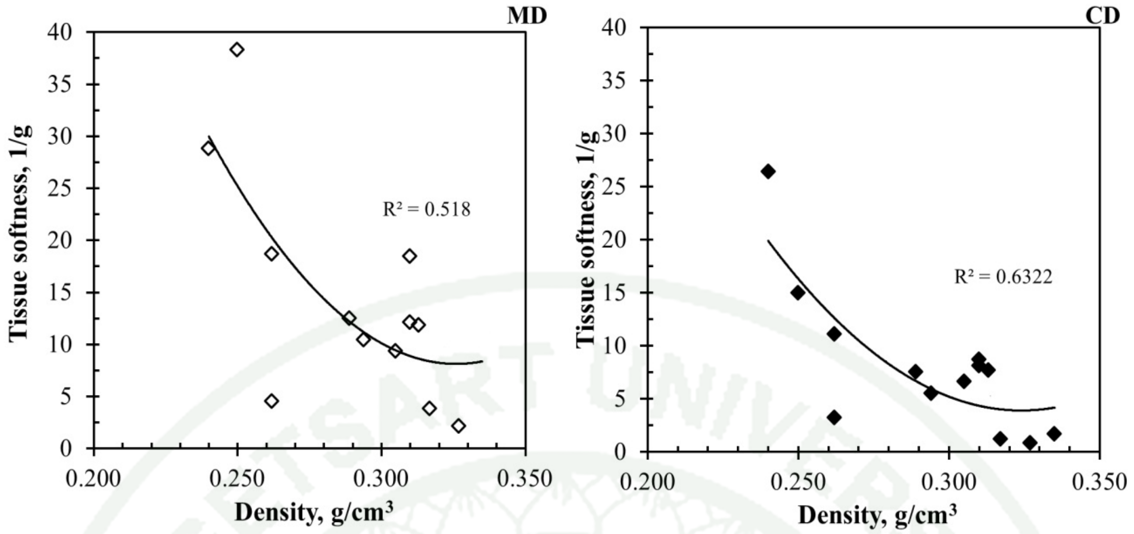


Figure 14 Tissue softness as a function of density.

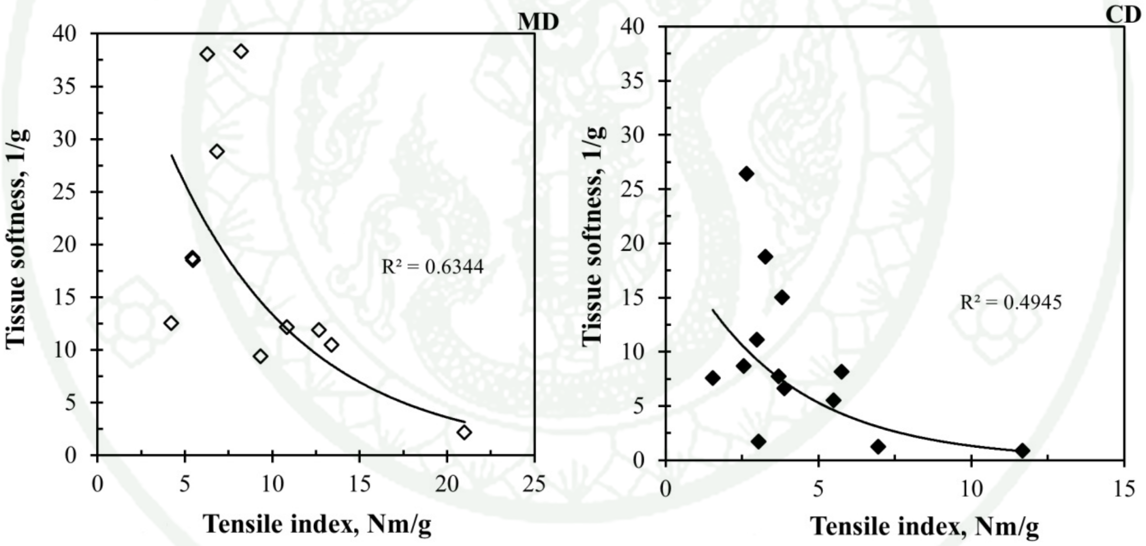


Figure 15 The correlation of tissue softness with tensile index in both direction.

Figure 15 shows the inverse correlation between the softness and the tensile strength of various types of tissue papers. The softness was correlated with the tensile index while a higher softness was obtained at a lower tensile index. The tissue softness (MD) correlation with tensile index (MD) was high (R^2 = 63.44%) while the tissue softness (CD) correlation with tensile index (CD) was poor (R^2 = 49.45%).

1.3 Water holding capacity of commercial tissues

Figure 16 shows the correlation of water absorption with various types of commercial tissues. The water holding capacity of kitchen towel was the highest while for the table napkins it was the lowest. For bathroom tissue, facial tissue, handkerchiefs, paper towels and low quality of tissue paper that made from recycled pulp had similar value. Water holding capacity depended on characteristic of various types of commercial tissues, interaction between liquid and tissue paper that due to chemical used in the tissue paper process including a number of piles. The sample was embossed on the surface and the tissue sheet used as two to three plies that was generated having impact on water holding capacity.

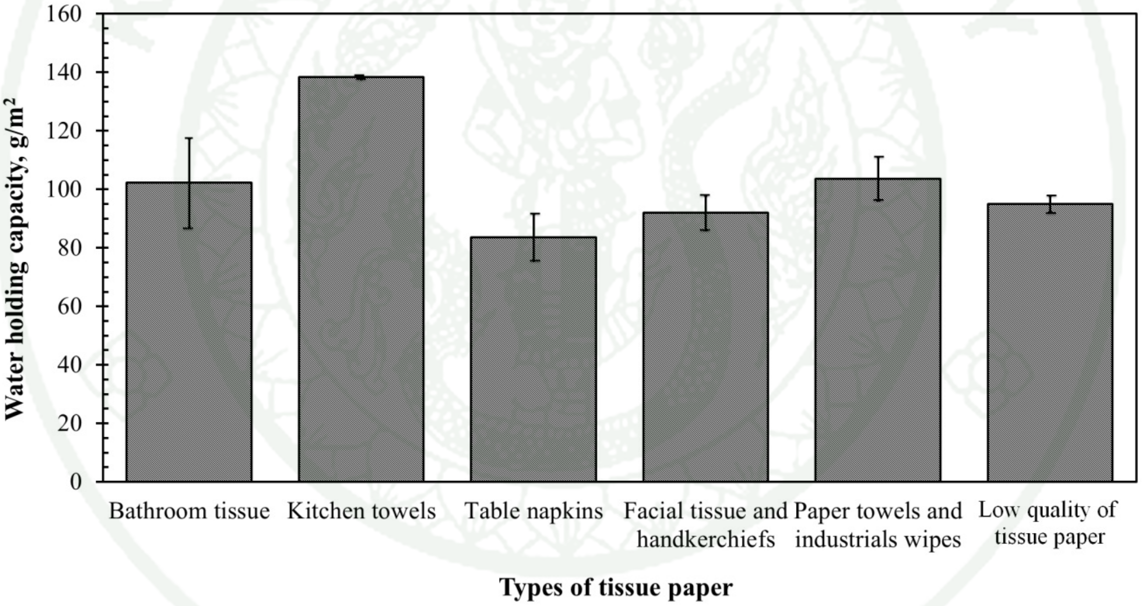


Figure 16 Water holding capacity of various types of commercial tissue.

1.4 Liquid absorption speed of commercial tissues

The influence of creping on the liquid absorption speed was examined in adaptation of capillary rise Klemm method. Figure 17 shows the average liquid absorption speed of the commercial tissues which was rapidly absorbed and slightly decreased. Facials tissue had the highest absorption speed while low quality of tissue paper that made from recycled pulp had the lowest.

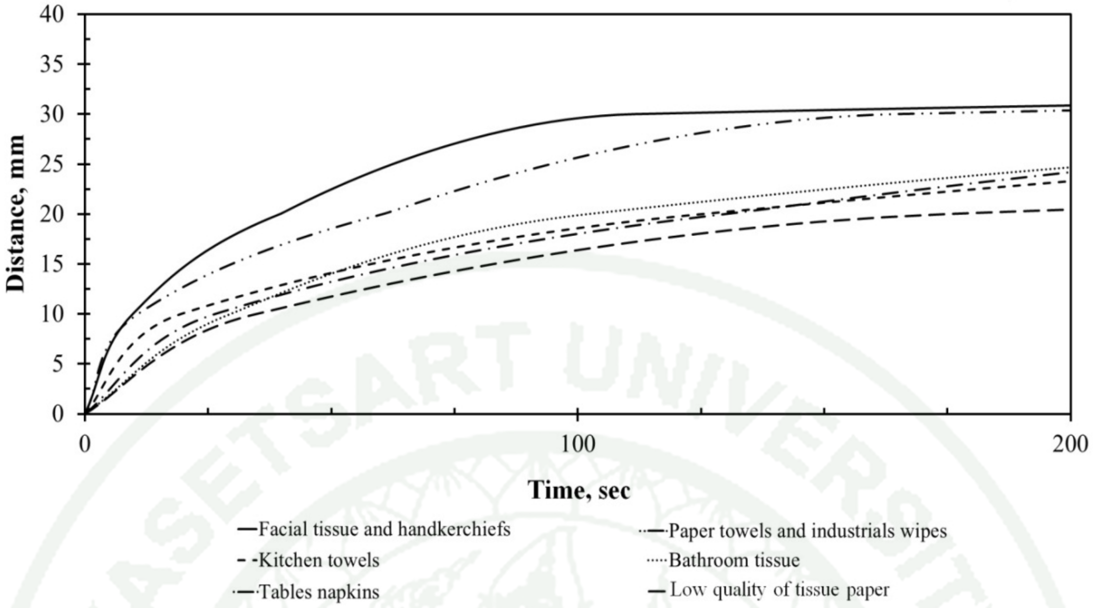


Figure 17 The correlation of distance with time of commercial tissues.

The different absorption speed of commercial tissues both MD and CD is shown in Figure 18. It showed the liquid absorption speed with the average of MD and CD in initial phase. At a given time, the liquid absorption speed of commercial tissues at MD was lower than CD and the absorption speed could be categorized into 2 groups. The first group consisted of facial tissue, handkerchiefs, paper towels and industrials wipes, it was special designed to absorb the water quickly and the second group that consisted of kitchen towels, bathroom tissue, table napkins and low quality of tissue paper that made from recycled pulp. This result can be explained about the difference of absorption speed between MD and CD. It was due to the direction of creping. It affected absorption ability especially the liquid absorption speed. The creping process that broke the pulp bond on CD with separate the pulp from each other, it created a small pore in this direction. It affected the velocity to lift up the water that through by using capillary force.

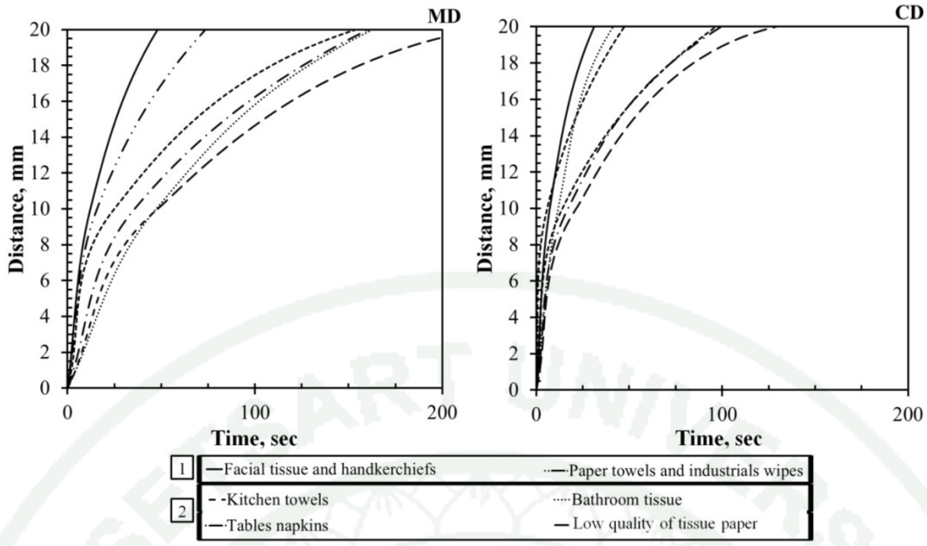


Figure 18 The correlation of distance with time in machine direction and cross machine direction.

Figure 19 shows the liquid absorption speed of machine and cross machine direction of bathroom tissue and paper towel were various. The absorption speed of paper towel and industrials wipes was rapidly absorbed and reached a peak of about 30 mm in about 200 sec and then it had a constant speed or slowly increasing. After 200 sec, it was found that the absorption speed was stable, as a result the distance and time that could be predicted the absorption speed was the distance about 30 mm or about 200 sec.

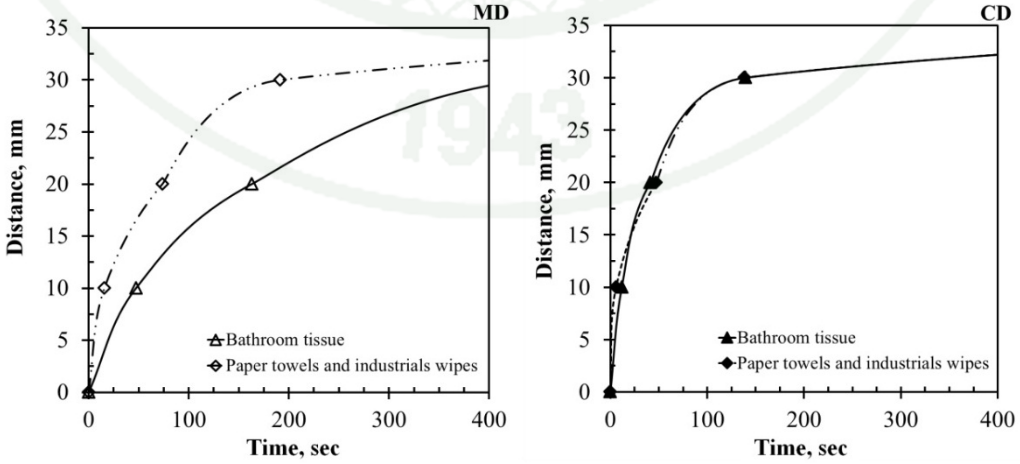


Figure 19 The correlation of distance with time in machine direction and cross machine direction of bathroom tissue, paper towel and industrials wipes.

2. Development of laboratory wet creping

Since standard laboratory sheets cannot be used to test the softness and water holding capacity as the pulp is developed in the refining process, the creping method was developed. The test sheet was attached onto the creping base with the optimum adhesive for surface tension. The adhesion force and creping size were controlled by the sheet dryness, the basis weight and the blade angle. The developed laboratory wet creping method could produce crepes on the base sheets causing changes in their structure. The results showed clearly that important properties, i.e., softness and liquid absorption, could be determined while the standard uncreped sheets showed indistinct results for these properties. Hence, this developed method could be applied to evaluate the quality of the various pulps used in tissue manufacture.

Due to tissue paper that made from a new raw material has been unable to evaluate before creping process result in this thesis is based on the developing of laboratory wet creping. The objective of this part was to identify the main factors in the wet creping process that affects liquid absorption ability and physical properties. The properties of the creped sheets, which were characterized in term of pulp bonding, density and porous with an image analysis, were observed to be affected by laboratory wet creping. The result of testing properties was analyzed and compared the quality of samples between uncreped and creped sheets. It describes characteristic, liquid absorption speed, water holding capacity, softness and tensile strength. This study focused mainly on the impact of creping, pulp orientation was removed. Machine direction (MD) called across crepe direction and cross machine direction (CD) or horizontal of creping called crepe direction as shown in Figure 20.

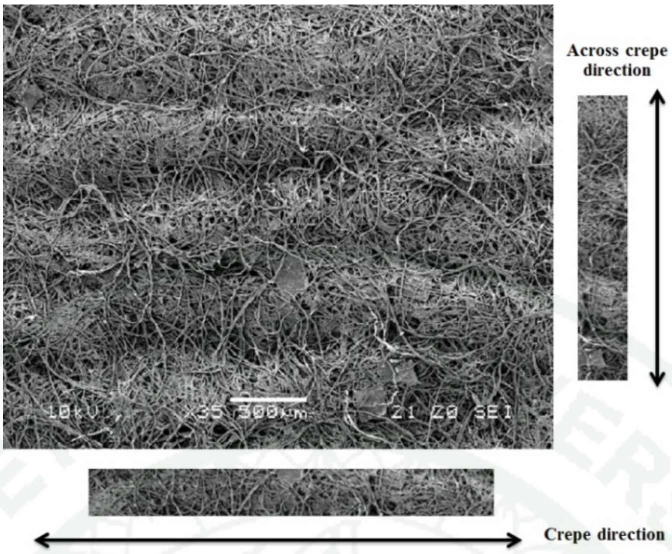
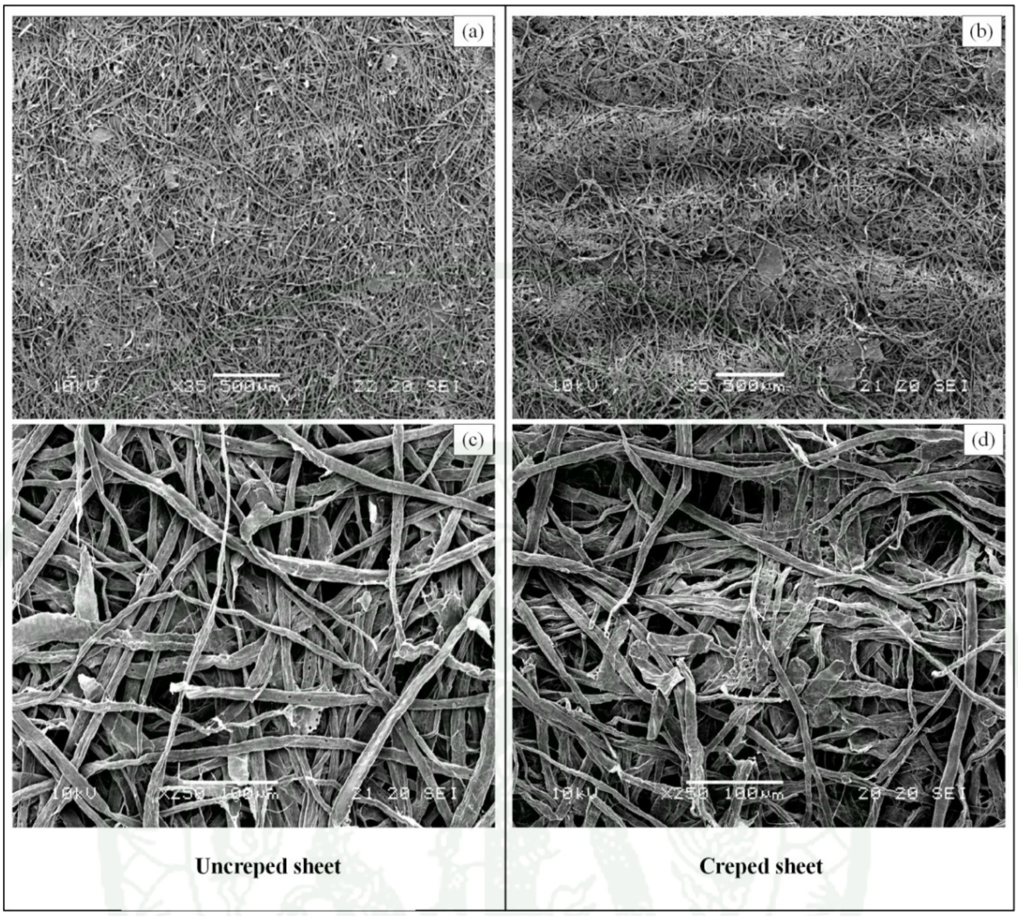


Figure 20 Creped sheet with across crepe direction and crepe direction**.**

The creped sheets produced from the eucalypt and then treated by the laboratory wet creping method are shown in Figure 21. It shows a specific characteristic surface that was considered with scanning electron microscopy (SEM). As can be seen in Figure 21 and 22, the laboratory creping produced buckling on the base sheets within a crepe size of 300-600 µm. Along the creasing lines, the fiber network was loosened and delaminated which increased the pore in the creped sheets. Figure 22 shows the uncreped and creped sheet in vertical. Bonding structure of the creped sheet was destroyed and was out of shape.



Uncreped sheet **Creped sheet**

Figure 21 Scanning electron microscope images of uncreped sheet and creped sheets made from eucalypt pulp.

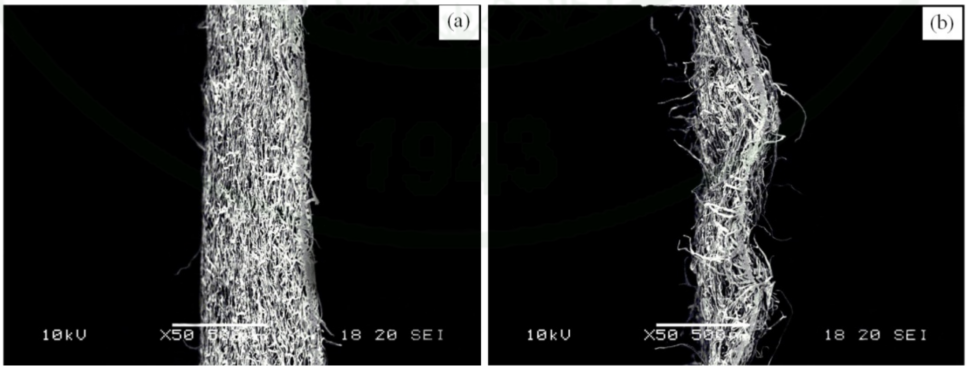


Figure 22 Uncreped (a) and creped sheet (b) in which the creping direction is vertical.

2.1 Effect of dryness and basis weight on laboratory creped sheet

The study of creping condition found that the creped sheets produced at dryness 20% and basic weight 30 g/m^2 had higher in softness and liquid absorption speed. Increasing of pressing pressure and basis weight in the creping production directly affects the creped structure and the creped sheets properties. Pressing pressure made the pulp into close contact and created hydrogen bonding. It made the dense structure which had the greatest effect to the creped sheets properties, while increasing of basic weight was found that improving of the number of fiber raised thickness and fiber bonding area but it reduced the sheet softness and liquid absorption speed.

One of the most important factors which effected to the creped sheet properties was its density which was found out in this research. It was the indicator of the sheet characteristic such as some physical properties and absorption ability, and closely related to pulp bonding. The density was presented for two reasons, i.e., increasing pressing pressure to remove the water from the wet sheet and increasing degree of refining. For the effect of degree of refining, it was presented in section 2.2. During creping production, the creped sheets were made at the different dryness by control a number of blotter and pressure that removed the water from the wet web. Figure 23 shows the results of density at the different basis weight and dryness of uncreped and creped sheets. The tendency of the density of the creped sheets when compare with the uncreped sheets, it had lower both 20% and 30% dryness. Increasing of basis weight from 30 g/m^2 to 50 g/m^2 and increasing of dryness from 20% to 30% greatly increased the density both uncreped and creped sheets. The density of creped sheets was about 0.244-0.280 g/cm^3, while for the uncreped sheet it was about 0.306-0.381 g/cm^3. The pressing pressure directly effect to the density of the wet sheet. A higher pressing pressure improved the dryness of the web, increased adhesive force between the wet sheet and the glass creping blade and increased the density simultaneously whereas a lower pressing pressure resulted in the wet web have a lower density and lower adhesive force.

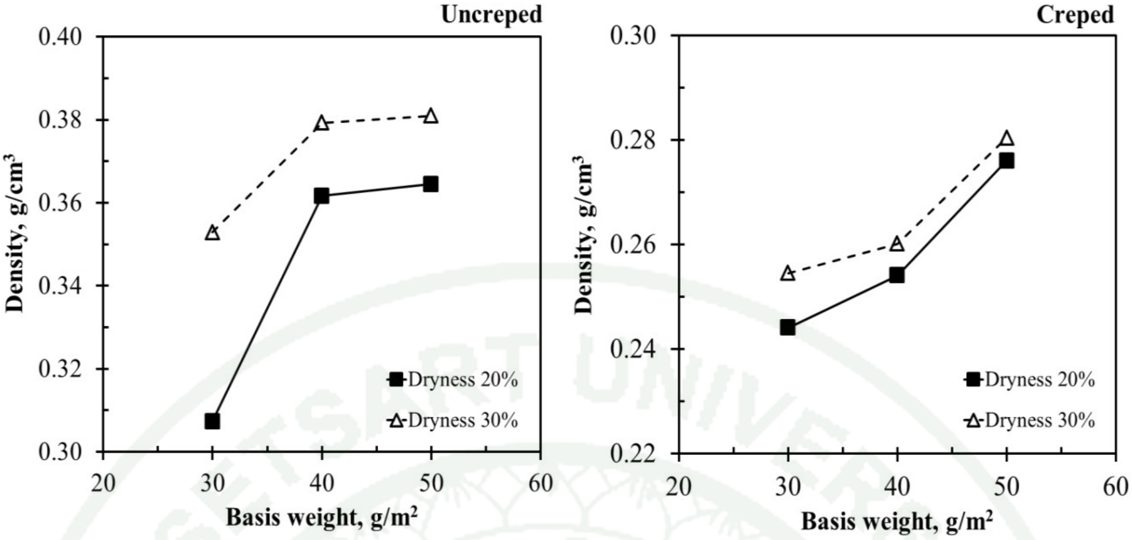


Figure 23 Effect of basis weight and dryness on a density of uncreped and creped sheets.

2.1.1 Effect of dryness and basis weight on tensile strength

Figure 24 shows, tensile strength of creped sheets at the different basis weight and dryness both crepe and across crepe direction. The tensile index of creped sheets increased rapidly with the increasing of basis weight. At a given basis weight, the tensile strength of creped sheets at 20% dryness was lower, while for the creped sheets at 30% dryness was higher. Increasing pressing pressure affected the tensile strength especially across crepe direction. At across crepe direction, creped sheets was weaker bond; due to this direction was the direction of creping production. The experimental indicated that the creped sheets at across crepe were easier to break a fiber-fiber bond than the creped sheets at crepe direction. The study was found that the tensile strength of creped sheet at 30% dryness was increased by wet pressing pressure which changed fiber bonding about created a larger fiber bonded area, increased the number of bonds and decreased the free pulp segments.

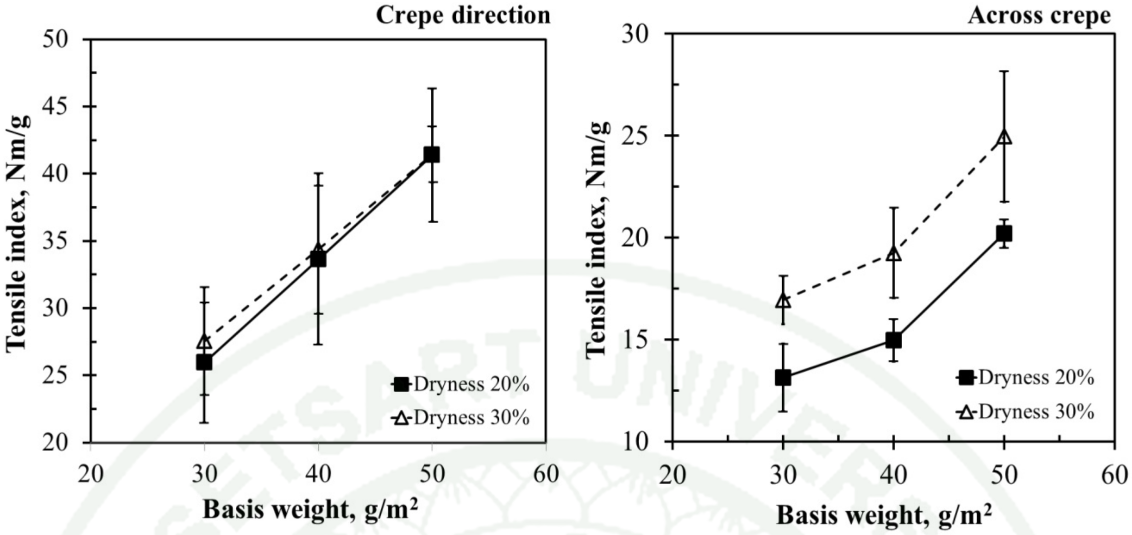


Figure 24 Tensile strength of creped sheets at 20% and 30% dryness both crepe and across crepe direction as a function of basis weight.

2.1.2 Effect of dryness and basis weight on softness

The creped sheets produced from the laboratory wet creping at the different of dryness showed different levels of sheet softness. At a given basis weight, the softness of the creped sheet at 20% dryness was higher while the average of softness was reduced with increasing basis weight, as shown in Figure 25. Dryness and basis weight also influenced the softness of creped sheets. Increasing basis weight and wet pressing pressure generally had stronger creped sheets whereas it reduced the softness. Although, the creping production at higher basis weight destroyed the interaction bonding in the paper structure but the creped sheets also had a greater stiff, it made the creped sheets difficult to rotate in Clark softness tester which resulted in the creped sheets at higher basis weight had a lower softness.

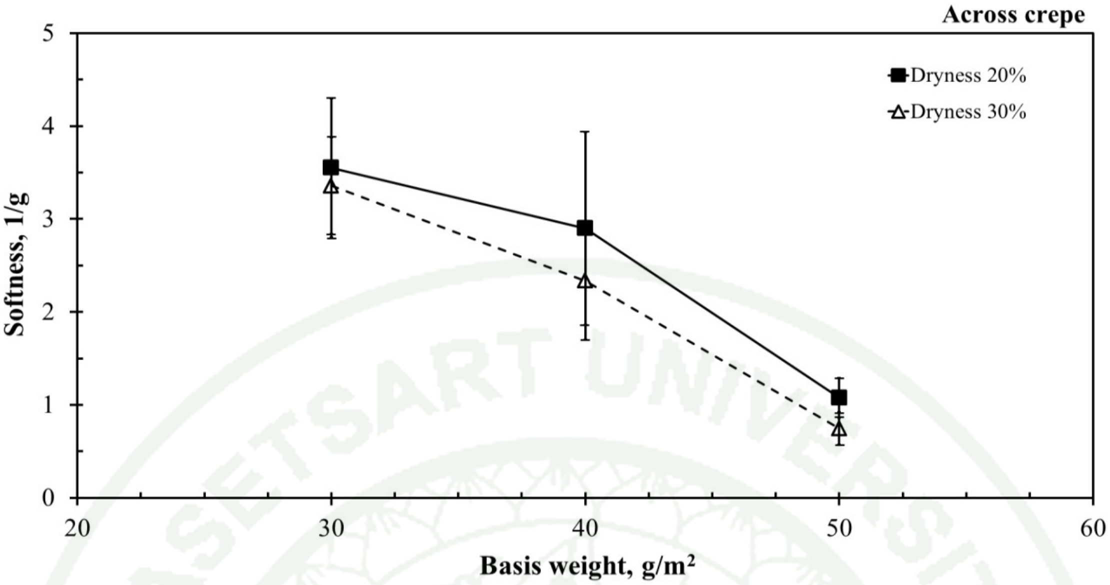


Figure 25 Softness of creped sheets at 20% and 30% dryness at across crepe direction as a function of basis weight.

2.1.3 Effect of dryness and basis weight on liquid absorption speed

The tendency of creped sheets at 30 to 50 g/m^2, there was a downward trend in liquid absorption speed both 20% and 30% dryness. At a given basis weight, the liquid absorption speed of creped sheet at a higher dryness was lower, while for the creped sheets at 20% dryness it was higher, as shown in Figure 26. The study found that the pressing pressure created dense structure. The structure of the creped sheets at 30% dryness was dense, difficult to break a bond while the creped sheets at 20% dryness made the creped fold and broke the bond easier. The structure of creped sheets at 20% dryness was loose that created a small pore which result in rapidly absorbed the liquid through by capillary pressure within the creped sheets. Thus, decreasing the absorption speed depended on density and distance to diffuse the water throughly in the creped sheets.

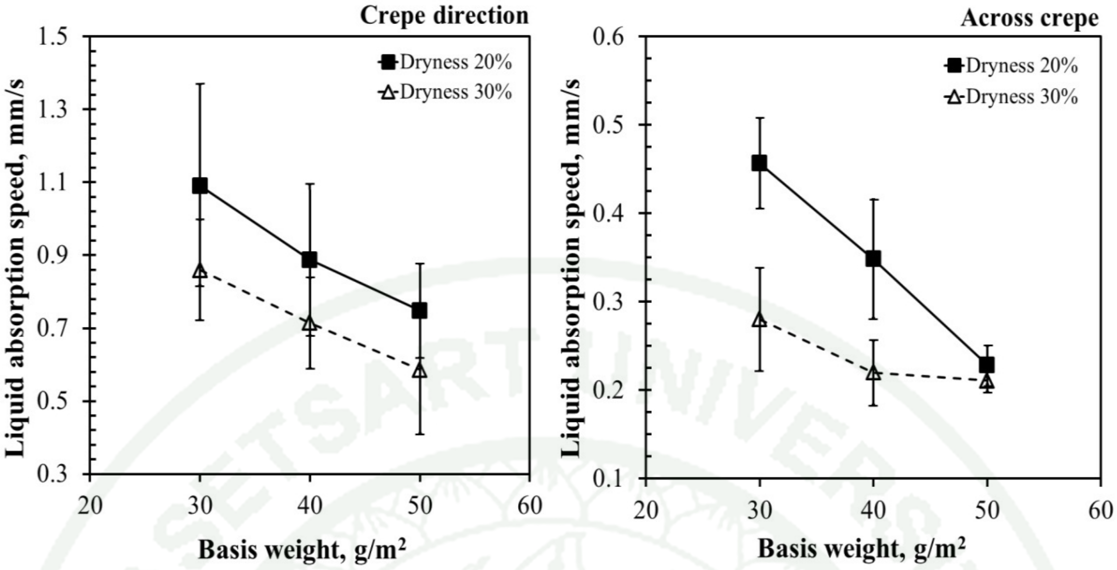


Figure 26 Liquid absorption speed of creped sheet at the different dryness as a function of basic weight.

2.1.4 Effect of dryness and basis weight on water holding capacity

Figure 27 shows the effect of dryness and basis weight on water holding capacity. The water holding capacity was proportional to basis weight and it was upward trend with increasing the basis weight both 20% and 30% dryness. At a given basis weight , the water holding capacity of the creped sheets at 20% dryness was higher, while for the creped sheets at 30% dryness was lower. The water holding capacity indicated that increasing the basis weight affected thickness of creped sheets, fiber bonding area, pore structure and the water holding capacity.

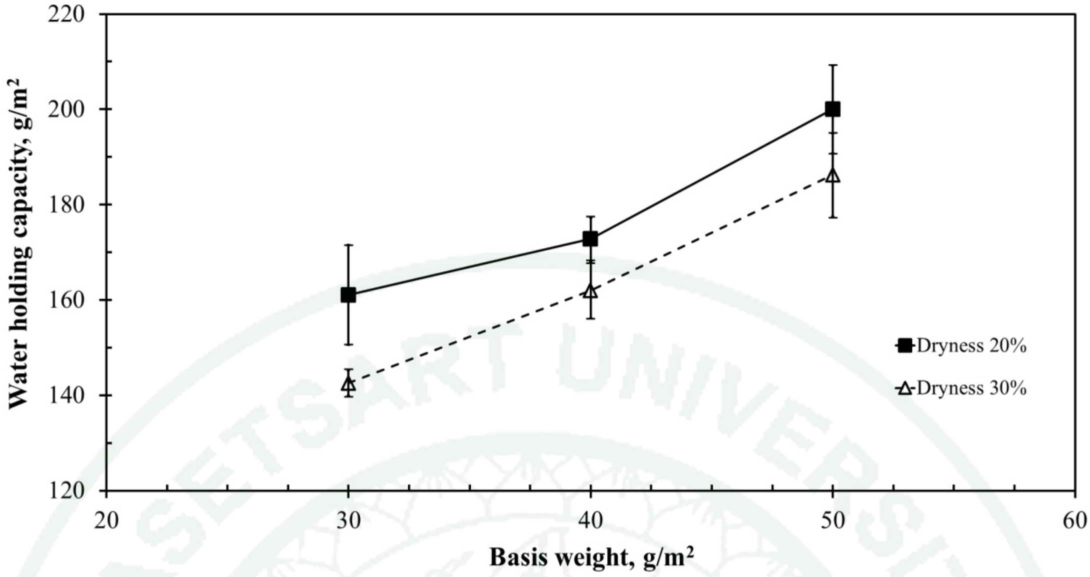


Figure 27 Water holding capacity of creped sheet at the different dryness as a function of basic weight.

2.2 Analysis of effect of refining degree on laboratory wet creping

The study of creping condition found that the creped sheet and uncreped sheets at a given pulp freeness were clearly different in their properties. The creped sheet had a higher degree of softness, liquid absorption speed and water holding capacity whereas tensile strength was lower. The obtained softness, liquid absorption speed and water holding capacity were correlated to the development of pulp fibers under refining in a pulp freeness range of 200-500 ml while the strength property was inversely.

Figure 28 shows the creped sheets had lower density or higher bulk than the uncreped sheets at a given pulp freeness and the laboratory produced test sheet having the various densities depending on the refining level. The density was in a range of 0.170-0.287 g/cm^3 with the pulp freeness reduced from 500-200 ml. It was showed that a pulp bonding was destroyed; the pulp space was increased.

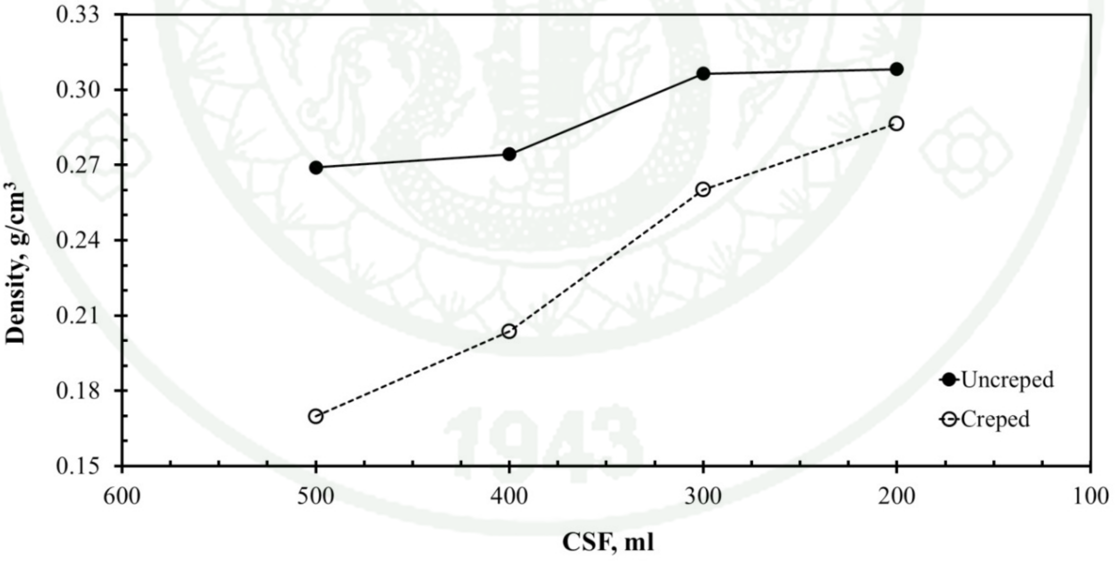


Figure 28 Density of uncreped and creped sheets as a function of pulp freeness.

2.2.1 Effect of degree of refining on tensile strength

The tensile strength of the creped samples was analyzed in two directions, that is, across the crepe and in the crepe direction. It was found that across the creped sheets had a lower tensile strength which indicated that the laboratory creped sheets had an anisotropic structure whereas the across crepe direction resulted in greater loosening of the structure of the fiber network. It indicated by the laboratory wet creping method that broke the bond in the web structure. In addition, the changes in tensile index induced by increasing degree of refining. The sheets at higher degree of refining were created higher bonding strength result in higher sheet strength as shown in Figure 29.

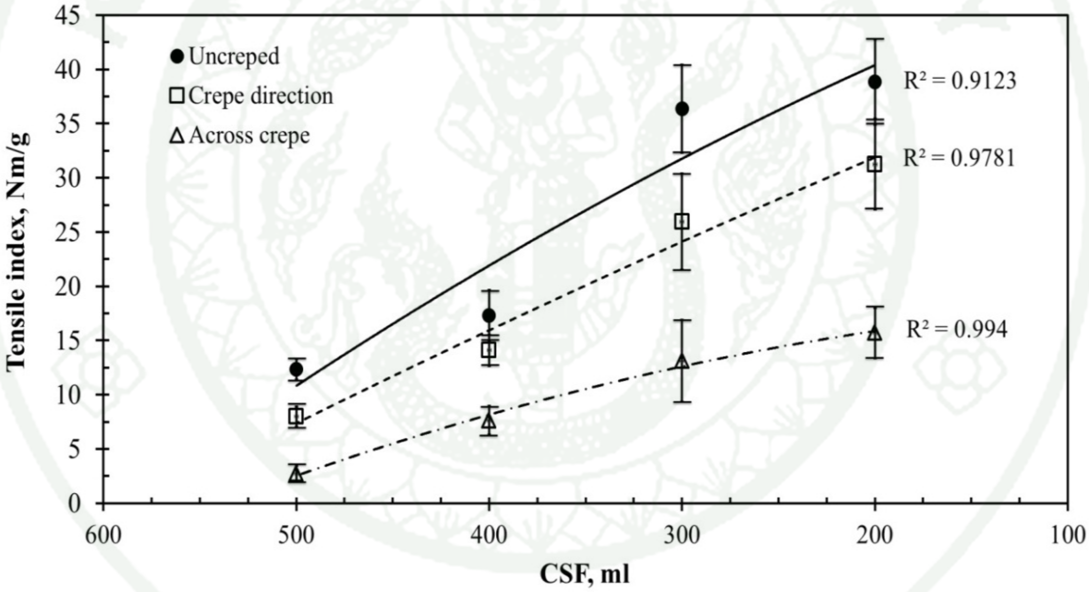


Figure 29 Tensile strength of uncreped and creped in across crepe direction and in crepe direction as a function of pulp freeness.

2.2.2 Effect of degree of refining on softness

The softness of the creped sheet measured using the Clark Softness-Stiffness tester was about 3.551-17.188 1/g, while the standard sheets was 0.378-0.813 1/g with no distinct differences in the pulp freeness which ranged from 200 to 500 ml as shown Figure 30. It shows Clark softness was proportional to Canadian standard freeness. There was a downward trend on across crepe direction and the softness on crepe direction and uncreped sheet was poor.

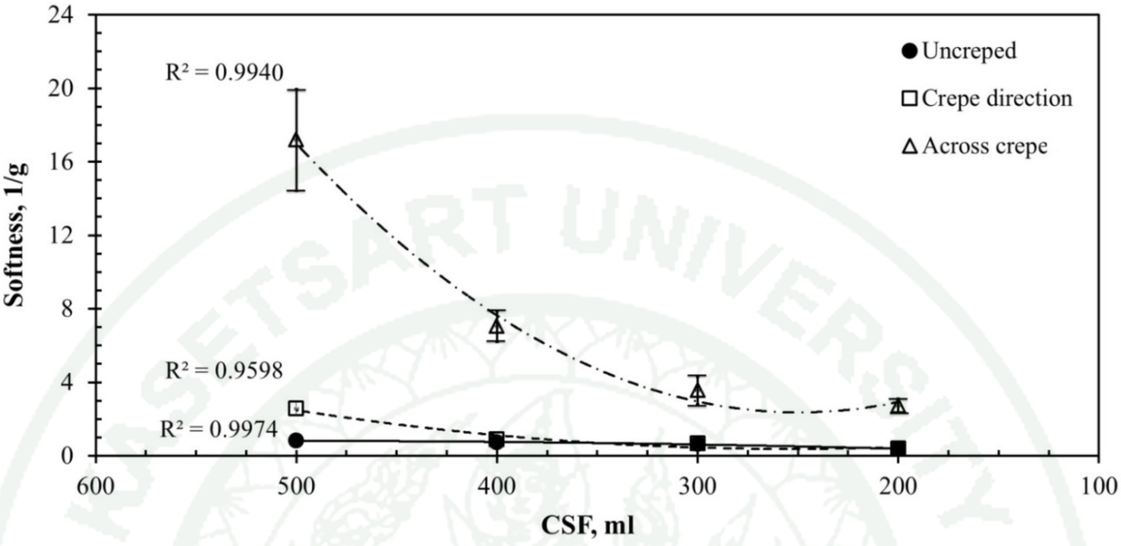


Figure 30 Softness of uncreped and creped sheet in crepe direction and across crepe direction as a function of pulp freeness.

Figure 31 shows the correlation of softness with tensile index. This result was found that softness was inversely related to tensile strength. At a given pulp freeness, the tensile index of uncreped sheets had a higher than crepe sheets both crepe direction and across crepe direction For across crepe, the softness values was the highest and it decreased rapidly when tensile index increased slightly. Although, tensile index decreased, the softness in crepe direction and uncreped sheet was also still poor. It was found that the increase in tensile strength had a greater effect on the sheet softness especially at across crepe direction. Because of the creped structure at across crepe direction loose in bonding strength, raised a space in the web structure.

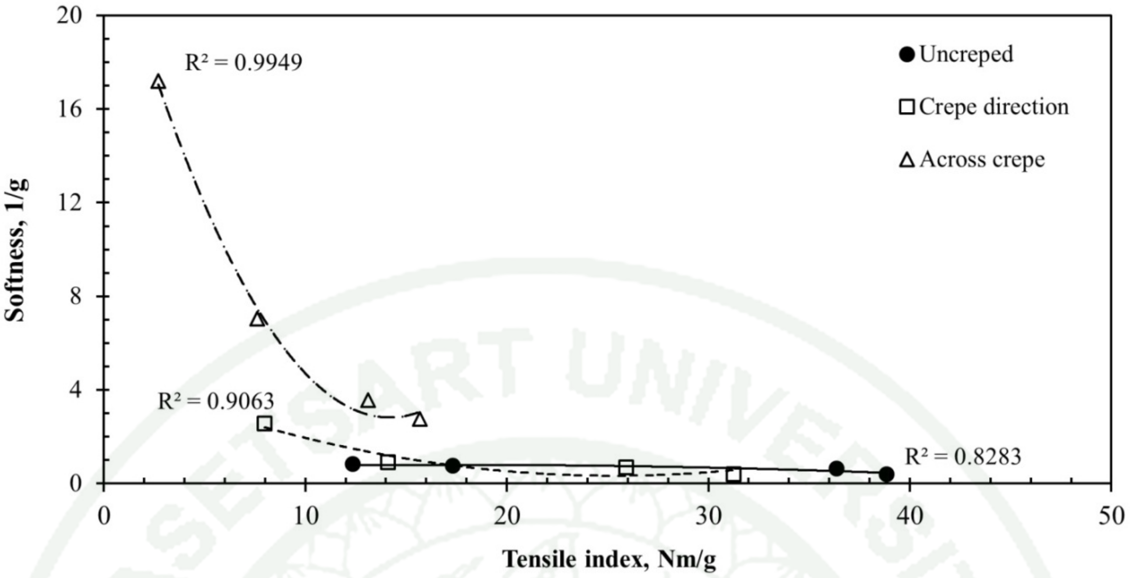


Figure 31 Softness of creped sheet as a function of tensile strength

2.2.3 Effect of degree of refining on liquid absorption speed

Figure 32 shows the liquid absorption speed of laboratory handsheets with uncreped and creped at a given pulp freeness. The liquid absorption speed was proportional to Canadian standard freeness. There was a downward trend in both uncreped and creped sheets. At a given pulp freeness, the liquid absorption speed of creped sheets at crepe direction was higher than creped sheets at across crepe direction and higher than uncreped sheets. The liquid absorption speed of creped sheets at crepe direction was about 0.704-1.562 mm/s while the liquid absorption speed of crepe sheets at across crepe direction and uncreped sheets was about 0.189-1.067 mm/s and 0269-1.271 mm/s respectively. It was found that the absorption speed was also depending on degree of creping and crepe direction. Normally, absorbency in the creped sheets depended on the pores structure in the interior of the handsheets, stretch of crepe direction, and the density of its own. In the creping method, the density was decreased by breaking bond structure which resulted in the pulp space increased; it affected the capillarity which increased the liquid absorption speed.

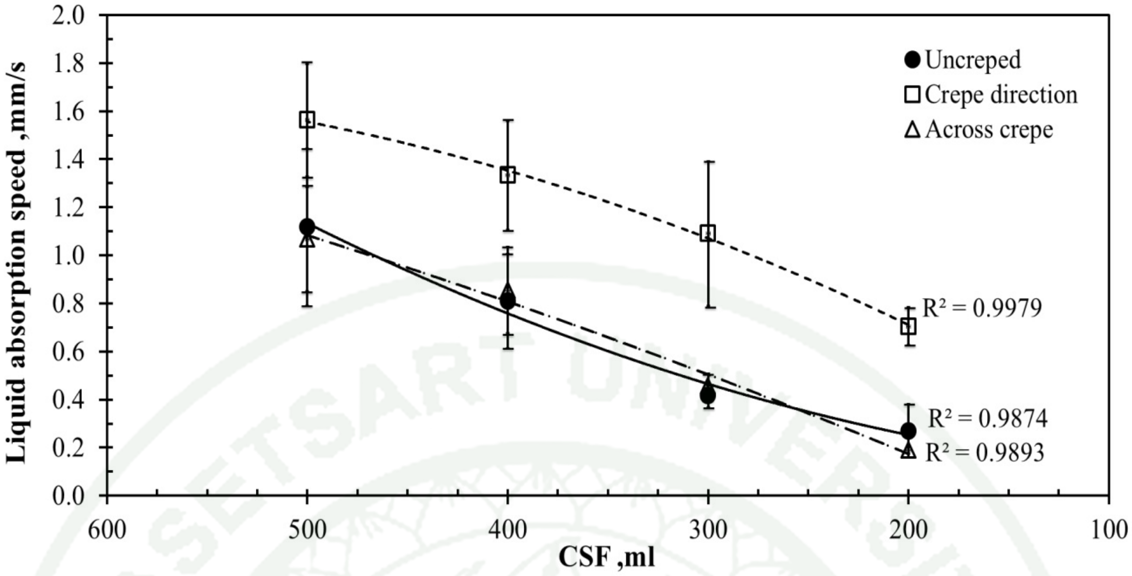


Figure 32 Liquid absorption speed of uncreped and creped sheets both across crepe and crepe direction as a function of pulp freeness.

2.2.4 Effect of degree of refining on water holding capacity

Figure 33 shows water holding capacity of laboratory handsheets with uncreped and creped at a given pulp freeness. The water holding capacity was proportional to Canadian standard freeness. There was a downward trend in both uncreped and creped sheets and the water holding capacity was about 137-210 g/m^2. The water holding capacity was indicated by free water that could be held in a gap between fibers. The water still remained in a gap but it was not bond in anyway. The important thing to hold the water in the pores was capillary force that depends on the pore size, degree of refining and the kind of pulp.

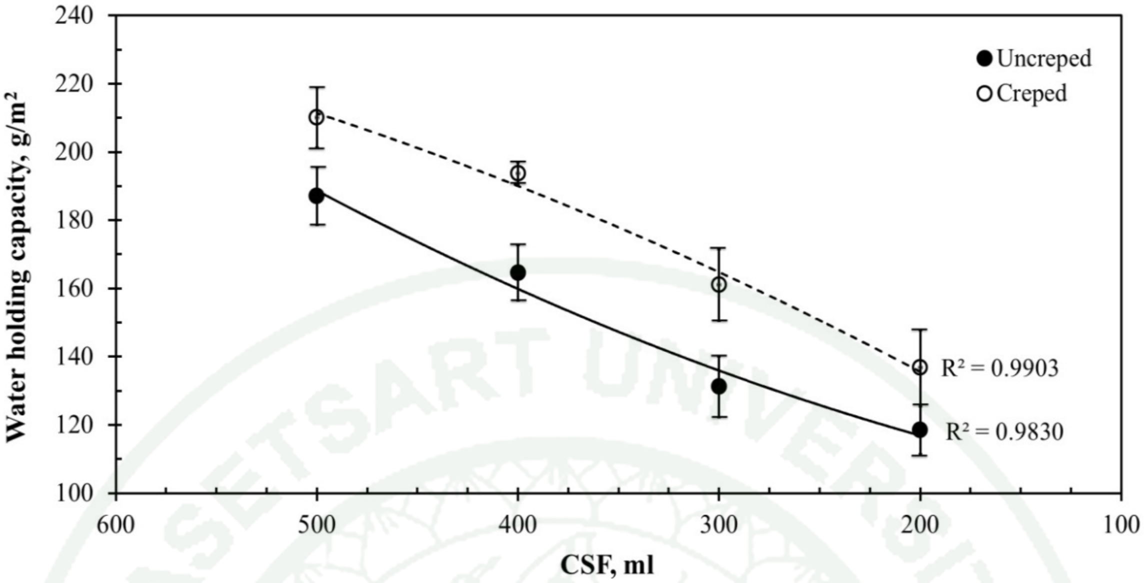


Figure 33 Water holding capacity of uncreped sheet and creped sheet with the across crepe and crepe direction as a function of pulp freeness.

3. Evaluation of industrial pulp quality

The study of the OCC pulp, deinked pulp, bagasse pulp, bamboo pulp, acacia pulp and eucalypt pulp obtained from the industry found that the creped sheets produced from these pulps had differences in softness, water holding capacity and strength properties at a given pulp drainability. The bagasse, acacia and eucalypt pulps were found to be of a superior quality and produced creped sheets with high softness, liquid absorption speed and water holding capacity at a given tensile strength. The bamboo pulp could be used to blend with other pulps improving the strength of tissue paper, but it might reduce the sheet softness and water holding capacity. In addition, the creped sheets produced from the bamboo pulp, deinked pulp and OCC pulp under various degrees of refining did produce an improvement in their water holding capacity. This would be due to their surface energy and fiber characteristic.

3.1 Fiber morphology analysis

Their fiber morphologies were analyzed using a Metso FS5 automated fiber analyzer. The fiber surface energy was analyzed using a Fiber Potential Analyzer. The tested pulps had freeness in the range 300-500 ml, with a length-weighted average fiber length of 0.651-1.147 mm, coarseness of 0.054-0.093 mg/m, and zeta potential of -35 to -95.5 mV, as shown in Table 2. The bamboo pulp was found to be different from the other materials having a longer fiber length and a lower zeta potential, while the others showed no large differences among their fiber lengths and coarseness.

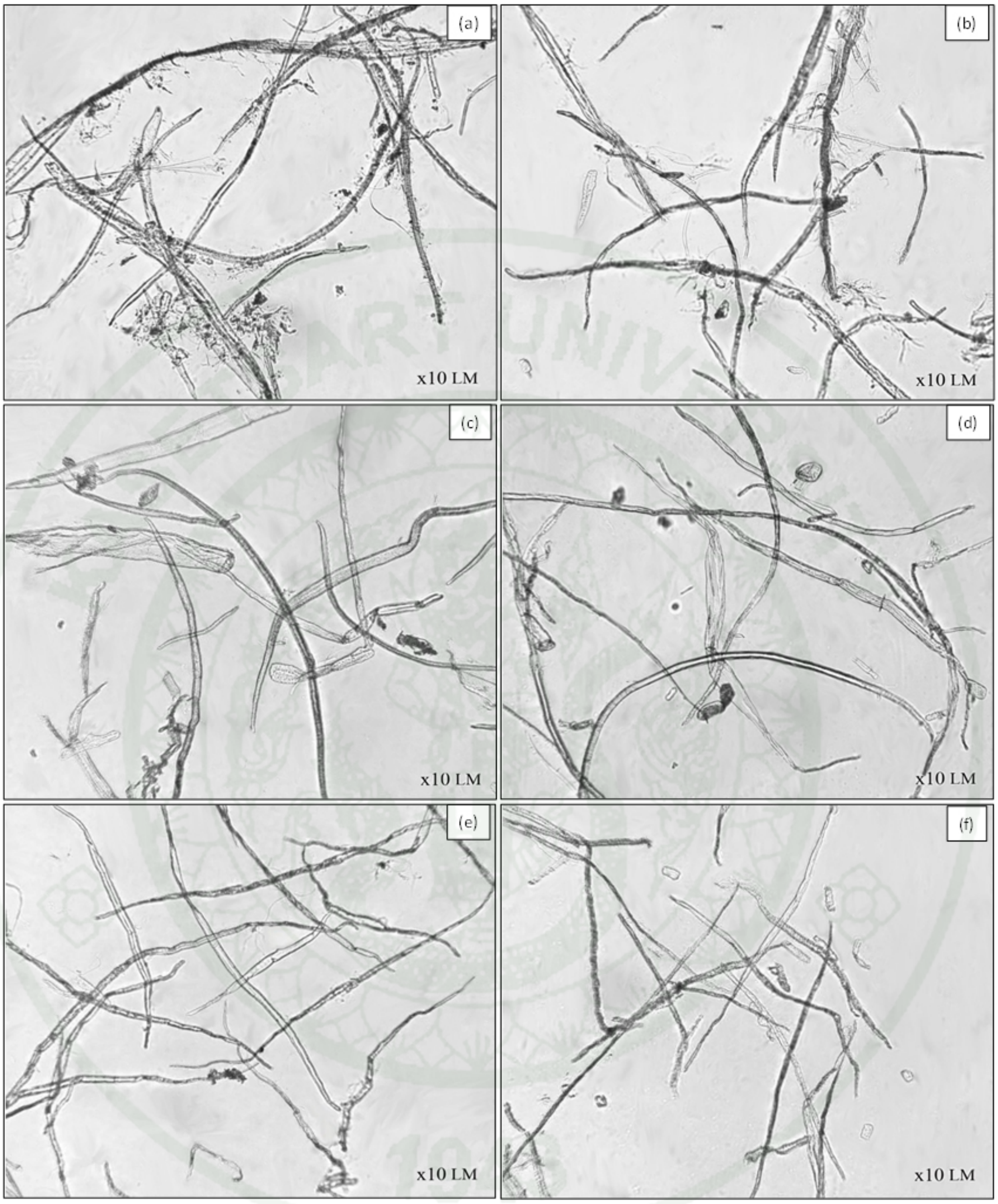


Figure 34 LM showing the pulp characteristic of OCC (a), deinked (b), bagasse (c), bamboo (d), acacia (e) and Eucalyptus pulp (f)**.**

Table 2 Pulps obtained from tissue manufacture and their fiber morphology.

Pulp types	**Freeness** (ml)	**Fiber length** (mm)	**Coarseness** (mg/m)	**Zeta potential** (mV)
OCC pulp	276	0.796	0.093	-36.0
Deinked pulp	272	0.858	0.075	- 43.9
Bagasse pulp	492	0.734	0.086	- 38.6
Bamboo pulp	651	1.147	0.071	- 35.4
Acacia pulp	495	0.742	0.054	-91.8
Eucalypt pulp	485	0.651	0.057	- 95.5

Pulp fraction was the method to separate short, medium, long pulp and fines. Long pulp needed to be refined to improve the pulp properties such as pulp fibrillation which resulted in some of the creped sheets properties, e.g., tensile strength; or it was possible decrease in degree of refining in short pulp to maintain the liquid absorption and the softness. With each pulp it could be seen that there were different in pulp fractions, as shown in Figure 36. Recycled pulp was the poor quality of furnish compared with wood pulp that could be seen fines components of recycled pulp both OCC and deinked. It was higher than wood pulp, and the resulting lower quality product especially effected to strength property. Fines fraction was also contained in bamboo pulp; it was the highest while long pulp was higher than other type of pulp except acacia pulp. This result indicated that the bamboo pulp was a special type of non-wood that was clearly full of long pulp and fines components while the ratio of fines, short, medium and long pulp of bagasse pulp was not different. Compared to wood pulp, long fraction was higher than recycled and non-wood pulp whereas a fines component was the lowest; it can improve the quality of pulp because the long fraction, in general, contained the better quality of pulp.

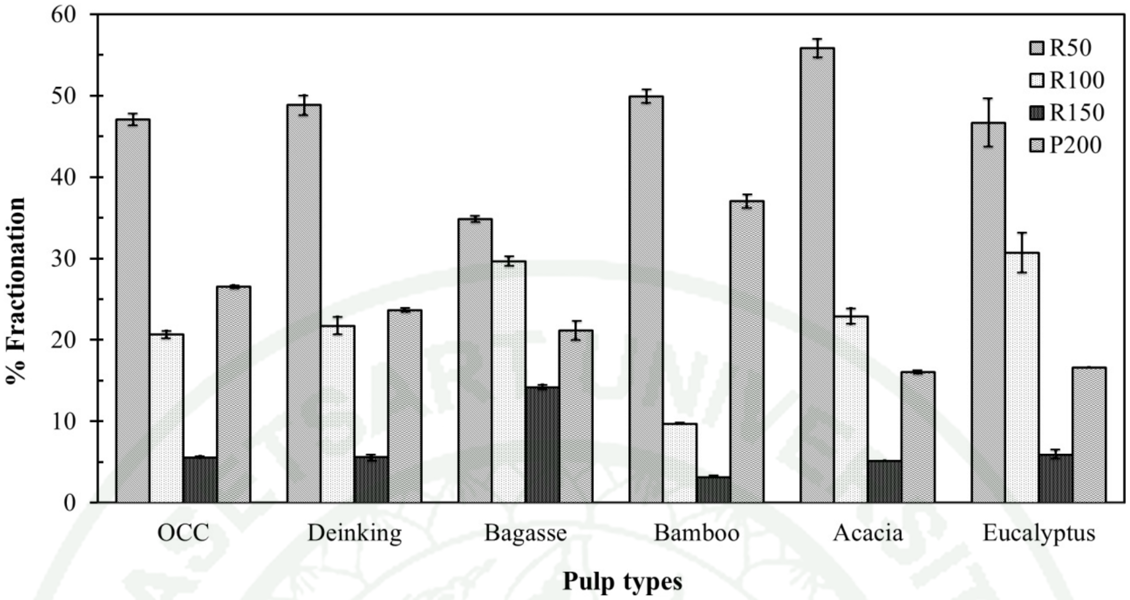


Figure 35 Pulp fractionation of various types of pulp

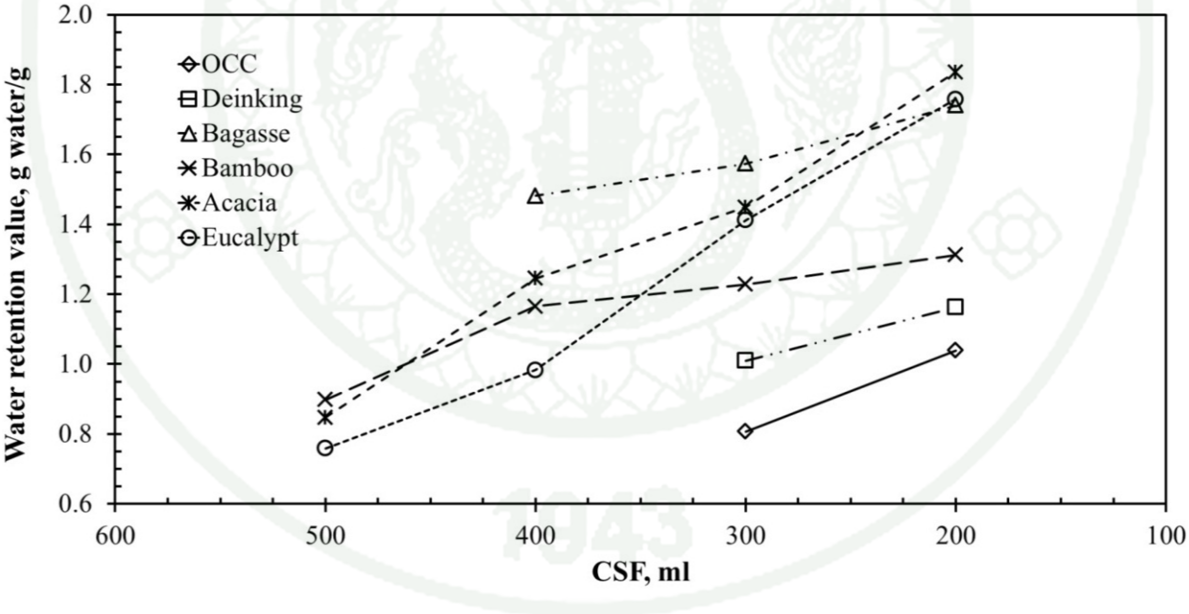


Figure 36 Water retention value of various of pulp as a function of degree of refining

Water retention values of various types of pulp were studies as shown in Figure 36. The recycled pulps had water retention value in the range of 0.087-1.163, whereas the non-wood and wood pulps had water retention value in the range of 0.847-1.836. At a given pulp freeness, the water retention value of recycled pulp was the lowest both OCC and deinked pulp. The water retention value of recycled pulps showed clearly different, while non-wood and wood pulps, there were no clear differences.

3.2 Effect of industrial pulp quality on tensile strength

Figure 37 shows the creped sheets produced from the eucalyptus and bamboo pulps were treated by laboratory wet creping method. It was found that the eucalypt creped sheet having the uniformity of the pore size and the pore size had a smaller than the bamboo creped sheets. The bamboo creped sheets were created the larger pores while some part of its structure was dense. It affected directly to tensile strength, softness, absorption ability both liquid absorption speed and water holding capacity.

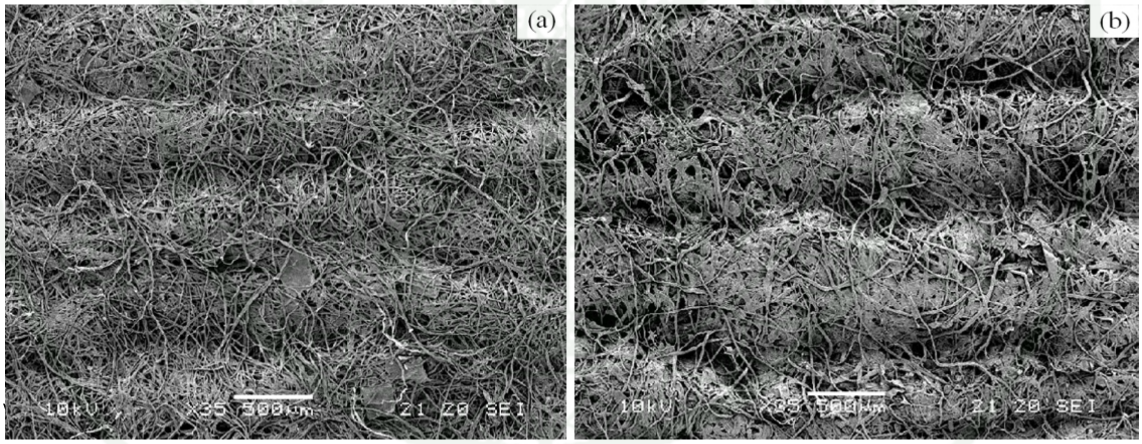


Figure 37 Eucalypt creped sheet (a), bamboo creped sheet (b), in which the creping direction is horizontal.

The comparison tensile strength of creped sheets of OCC, deinked, bagasse, bamboo, acacia and eucalypt pulps at across crepe direction was showed in Figure 38. There was upward trend when it was increased degree of refining. At a given pulp freeness, the tensile strength of the bamboo creped sheets was higher, while the other types was lower. The results indicated that the type of pulp, fiber bonding that created during the sheet forming and the fiber bonding that destroyed during the laboratory wet creping. At higher degree of refining, the bamboo creped paper difficult to separate fiber from each other, it was harder to break a bond and create a small pore in the interior of handsheets, it might result in the bamboo creped paper had the highest of tensile index.

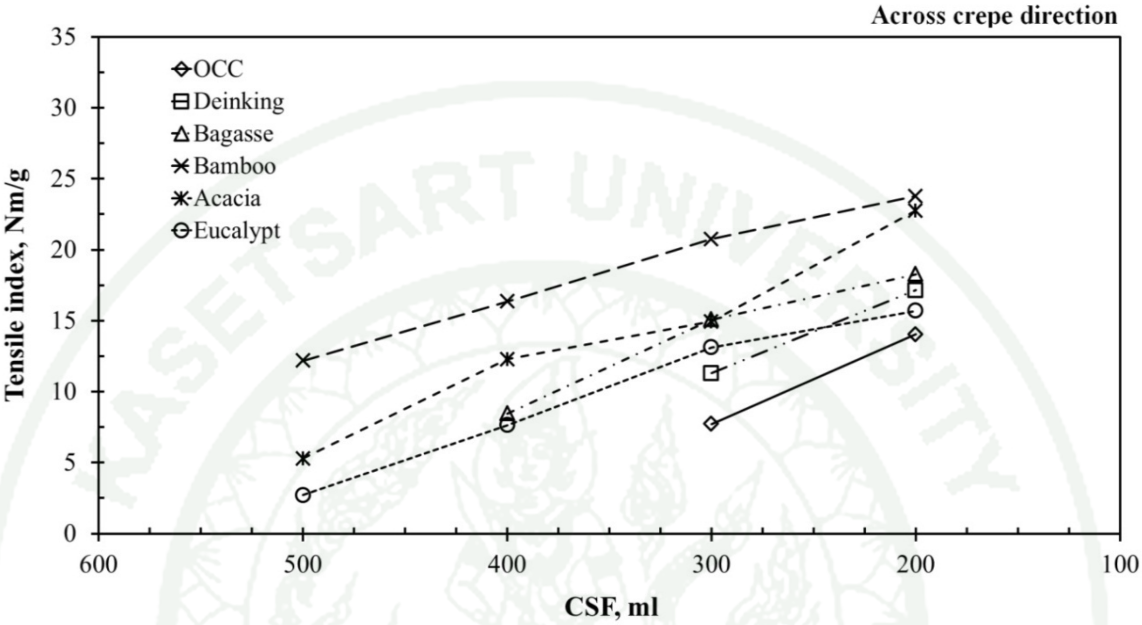


Figure 38 Tensile strength of creped sheets produced from various types of pulp material as a function pulp drainability.

3.3 Effect of industrial pulp quality on softness

The creped sheets produced from the various pulps at a high level of pulp freeness showed clearly different levels of sheet softness, while for a freeness below 300 ml, there were no clear differences in softness. At a given pulp freeness, the eucalypt pulp had a higher degree of softness, while the bamboo had poor softness. In addition, the bamboo pulp produced creped sheets with a lower change in their softness under various degrees of refining, as shown in Figure 39.

Figure 40 shows the inverse correlation between the softness and the tensile strength of the creped sheets produced by various pulps. The softness was strongly correlated with the tensile strength where a higher softness was obtained at a lower tensile strength. This study found that to obtain a given softness, the pulps needed to be refined to different levels to produce the desired fiber bonding correlated to sheet softness. This indicated that for the production of tissue at a given pulp freeness, the use of bamboo pulp might result in a lower sheet softness.

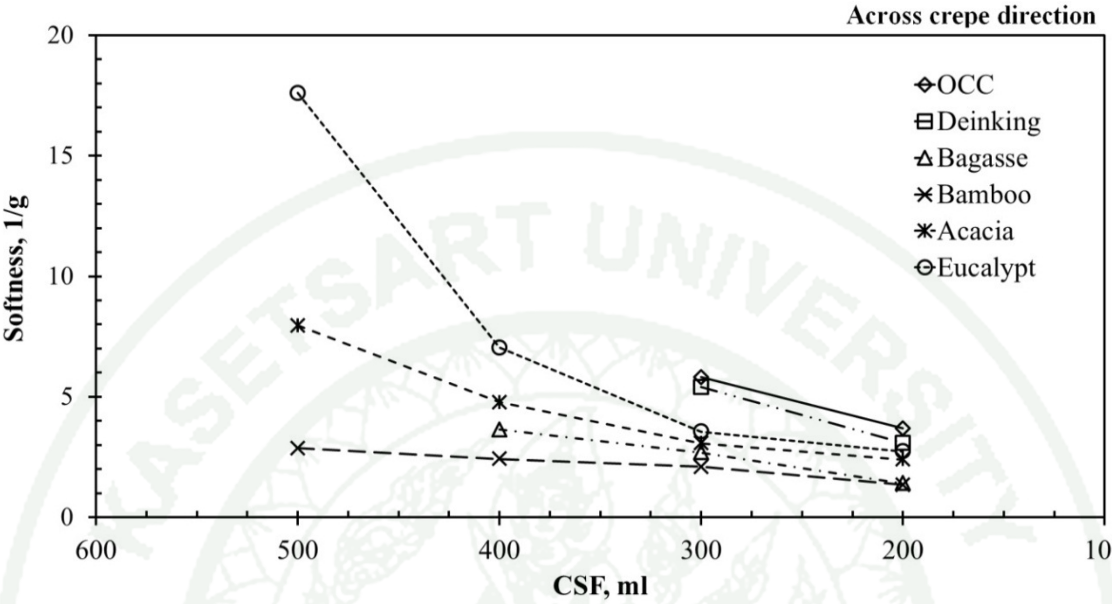


Figure 39 Softness of creped sheets produced from industrial pulps as a function of pulp freeness.

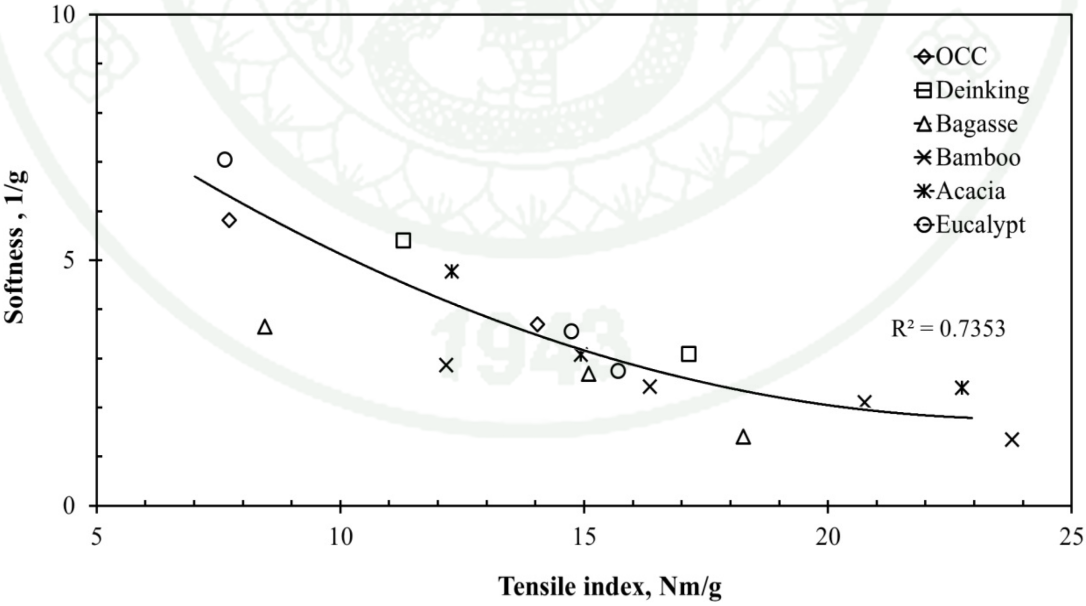


Figure 40 Softness of creped sheets produced from various types of pulp material as a function of tensile strength.

3.4 Effect of industrial pulp quality on liquid absorption speed

Average liquid absorption speed of creped sheets that produced from various pulps at a given pulp freeness showed clearly different levels. There was downward trend with increasing degree of refining both across crepe and crepe direction. At a given pulp freeness, crepe direction had a higher liquid absorption speed than across crepe direction; and the liquid absorption speed of recycled creped sheets and non-wood creped sheets was lower than creped sheets that produced from wood pulps. At a given pulp freeness, the eucalypt creped sheets had the highest liquid absorption speed both direction, while the recycled creped sheets especially OCC had the lowest liquid absorption speed.

The rate of absorbency was also depended on crepe direction and various pulps. The ability of creped sheets to absorb water quickly depended on having a high capillary pressure and the pore size distribution greatly affected the absorption speed; it also depended on permeability of creped sheet. The small pores produced a higher capillary force than from large pores. From the results of absorption speed, it could be explained that a dense structure pulled up the water slower and could not diffused the water throughly and continuously while a large pore structure can pulled up the water faster than a dense structure but it also could not diffused the water in the creped sheets structure. A small pores structure could pull up the water quickly and diffuse the water throughly and continuously; it was due to the continuous of capillary force due to the pulp characteristic and the creped sheets structure. The paper structure that had a un-uniformity of pore size would affect the capillary force which made some part of the creped sheets lifted the water quickly whereas some part slowly. Thus, the result of liquid absorption speed of the creped sheets that had a dense structure and had a many large pore size was lower.

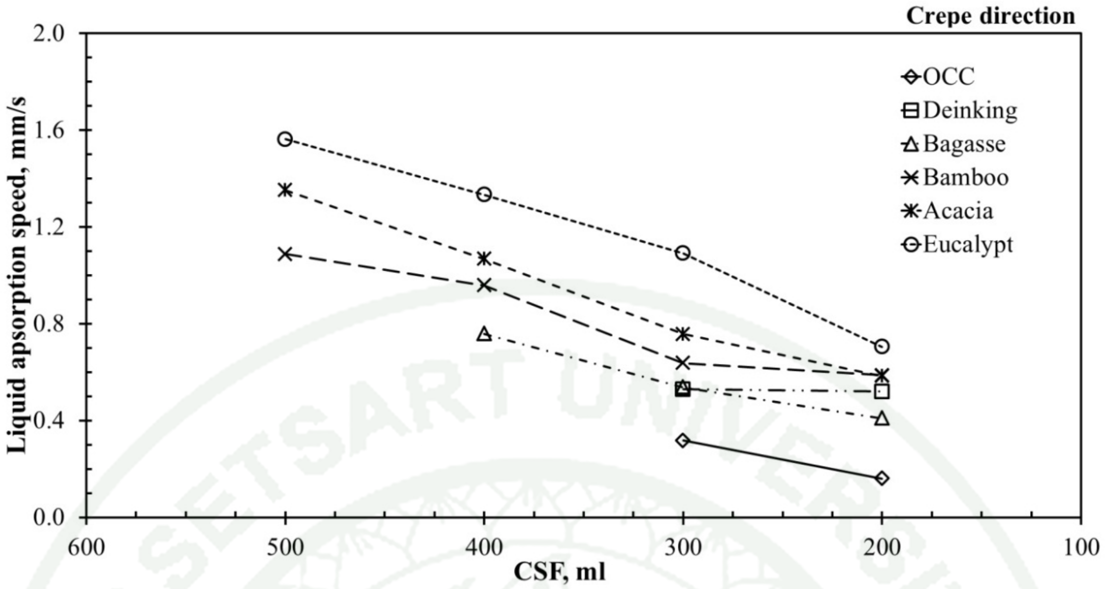


Figure 41 Liquid absorption speed of creped sheet on crepe direction produced from industrial pulps as a function of pulp freeness.

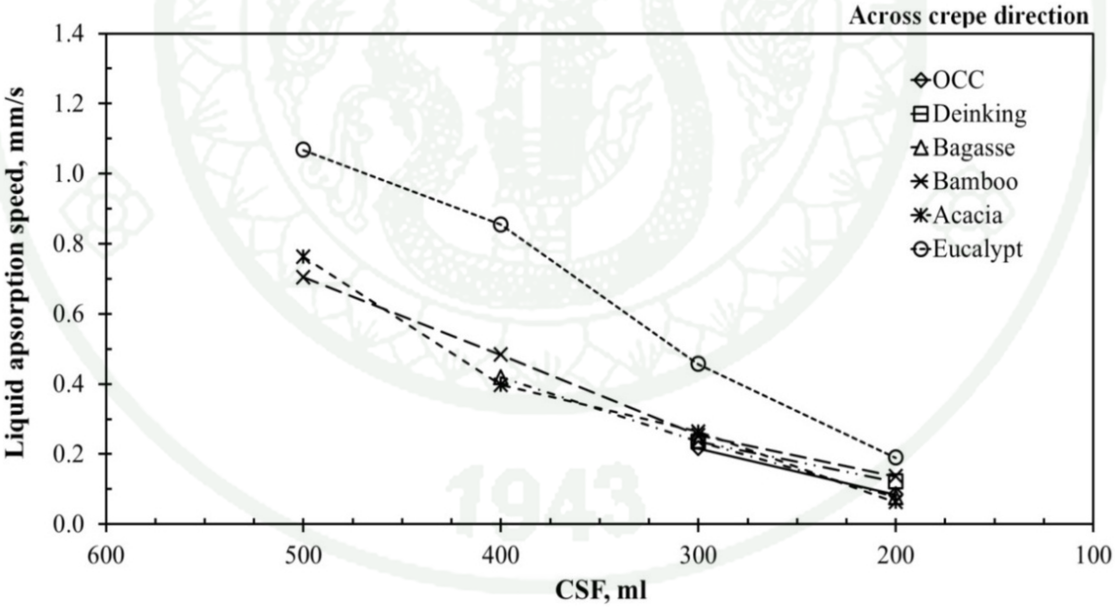


Figure 42 Liquid absorption speed of creped sheet on across crepe direction produced from industrial pulps as a function of pulp freeness.

3.5 Effect of industrial pulp quality on water holding capacity

Average water holding capacity of creped sheet which produced from recycled pulp, non-wood pulp and wood pulp at a given pulp freeness is shown in Figure 43. At a given pulp freeness, the water holding capacity of the eucalypt, acacia and bagasse creped sheets was higher, while the bamboo creped sheets had a lower.

At a given sheet strength, the water holding capacity of the eucalypt, acacia and bagasse creped sheet was higher, while for the bamboo and deinked and OCC creped sheets it was lower, as shown in Figure 44. In addition, the study found that the creped sheets produced from the bamboo, deinked and OCC pulps were less sensitive to an improvement in the water holding capacity.

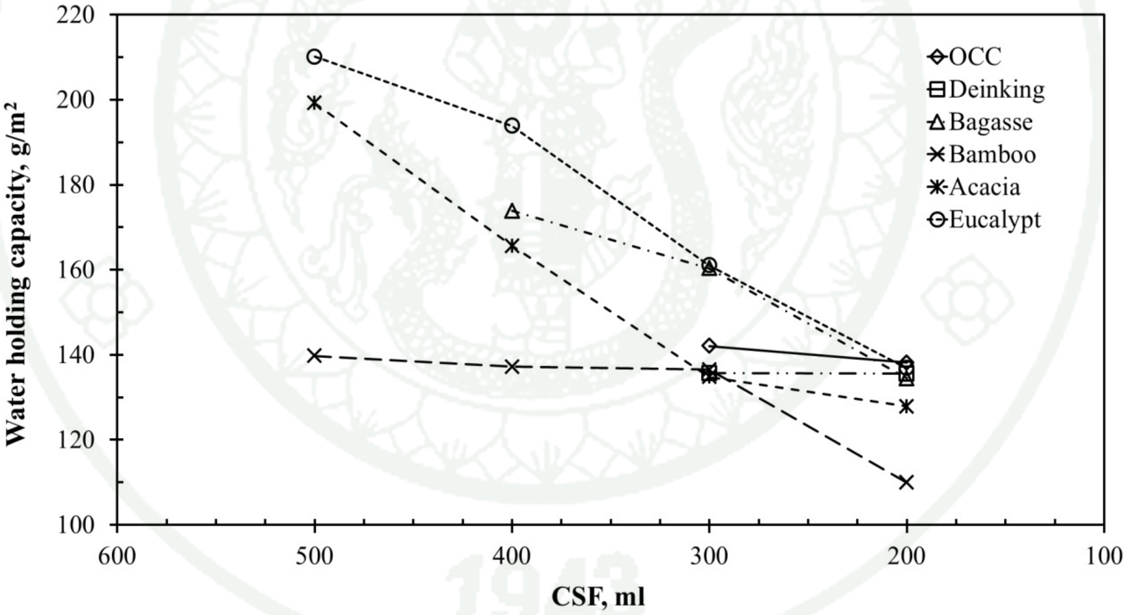


Figure 43 Water holding capacity of creped sheets produced from industrial pulps as a function of pulp freeness.

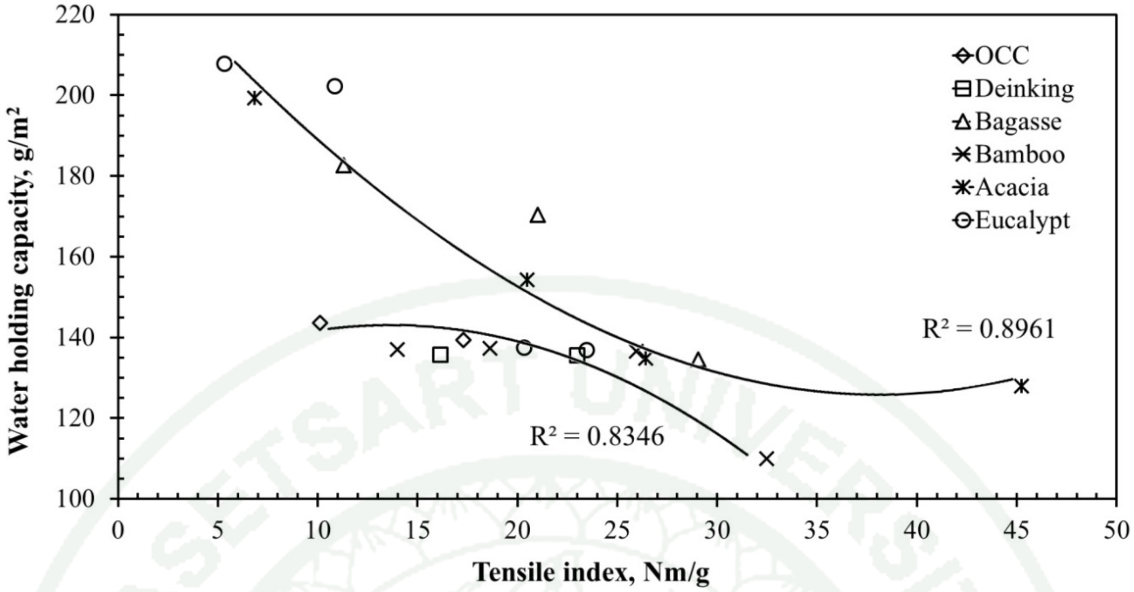


Figure 44 Water holding capacity of creped sheets produced by various types of pulp materials as a function of tensile strength.

CONCLUSION AND RECOMMENDATION

Conclusion

The modification of laboratory testing methods was found that the methods could be used to determine the properties of commercial tissues and the laboratory sheets. The four main properties were generally categorized as tensile strength, softness, liquid absorption speed and water holding capacity.

A wet creping method could be developed in the laboratory and the creped sheets were engineered to improve their softness and liquid absorption. The result showed that changing the crepe sheet properties causes breaking of the fiber bonding in the creped structure and creates small pores in the creped sheets. The breaking bonding is particularly important for softness and liquid absorption, whereas it is adversely for the strength property.

The quality of the creped sheets was dependent on degree of refining, pressing pressure and basis weight of the base sheets. The creped sheets at higher pressing pressure and higher degree of refining also raised density and tensile strength but reduced the softness, water holding capacity and liquid absorption speed while the creped sheets at higher basis weight improved the tensile strength and the water holding capacity but it reduced the softness and the liquid absorption speed.

The application of this creping method to the evaluation of industrial pulp determined that the eucalypt, acacia and bagasse pulp produced creped sheets with a higher softness and water holding capacity. The bamboo pulp had a lower water holding capacity similar to the OCC and deinked pulp, but produced high strength creped sheets. The results of various types of pulps was found a utilization of other type of pulps to produce tissue paper could be used at lower degree of refining of eucalyptus pulps that used in industrial.

Recommendation

This study is focus mainly on modification of laboratory testing methods for measuring the tissue properties, the effect of creping condition, development of laboratory creping technique to examine the quality of industrial pulps and the effect of fiber morphology while the effects of chemical additives and creping chemicals are removed. However, the chemical additives and creping chemicals are very important in the tissue production. In further research, it should be studied.

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APPENDICES

Appendix A

Data analysis of commercial tissues

Appendix Table A1 Average data of various types of commercial tissues

Types	Thickness (µm)	Basis weight (g/m^2)	Density (g/cm^3)	Tensile index (Nm/g)		Softness (1/g)	
				MD	CD	MD	CD
Bathroom tissue	60.10	17.28	0.288	9.06	3.35	32.30	19.87
Kitchen towels	65.50	21.12	0.322	16.46	9.32	6.27	2.15
Table napkins	50.37	15.72	0.316	10.18	4.84	24.16	14.60
Facial tissue and handkerchiefs	56.95	13.95	0.245	7.54	2.65	71.69	44.19
Paper towels and industrials wipes	54.40	16.30	0.300	4.85	2.06	33.35	17.49
Making from recycled paper	55.70	17.80	0.320	12.05	3.47	19.92	8.90

MD is machine direction, CD is cross machine direction and SD is standard deviation

Appendix Table A2 Data of tensile index and softness value of commercial tissues

Types	Thickness (µm)	Basis weight (g/m^2)	Density (g/cm^3)	Tensile index (Nm/g)				Softness (1/g)			
				MD	SD	CD	SD	MD	SD	CD	SD
A1	60.40	15.83	0.262	5.438	0.475	2.991	0.150	40.317	6.360	23.428	2.929
A2	59.80	18.72	0.313	12.688	1.195	3.705	0.270	23.201	2.220	16.311	3.331
B1	70.00	22.91	0.327	21.006	1.539	11.678	1.414	4.307	1.070	1.743	0.259
B2	61.00	19.33	0.317	11.919	0.863	6.964	0.529	8.079	0.830	2.559	0.376
C1	60.60	17.84	0.294	13.393	1.145	5.498	0.514	21.505	3.240	11.619	2.744
C2	37.40	12.88	0.344	6.311	0.438	3.273	0.232	99.724	10.040	44.004	7.970
C3	53.10	16.49	0.310	10.847	1.305	5.762	0.326	28.594	5.940	17.583	2.724
D1	57.80	13.88	0.240	6.854	0.602	2.648	0.092	68.510	10.820	53.852	5.185
D2	56.10	14.03	0.250	8.223	0.619	3.823	0.175	78.223	8.010	40.439	6.130
E1	56.70	17.55	0.310	5.462	0.484	2.568	0.286	39.487	5.500	18.579	3.952
E2	52.10	15.04	0.289	4.241	0.260	1.545	0.111	27.214	7.279	16.400	3.725
F1	53.40	17.90	0.335	14.755	1.132	3.050	0.421	6.977	3.092	3.699	0.826
F2	58.00	17.69	0.305	9.342	1.323	3.886	0.322	19.919	3.519	14.104	2.296

A is bathroom tissue, B is kitchen towel, C is Table napkins, D is Facial tissue and handkerchiefs, E is Paper towels and industrials wipes, F is Making from recycled paper, WHC is water holding capacity, MD is machine direction, CD is cross machine direction, ND is non-direction and SD is standard deviation

Appendix Table A3 Data of absorption speed and water holding capacity of commercial tissues

Types	Liquid absorption speed (mm/s)				Water holding capacity (g/m^2)	
	MD	SD	CD	SD	ND	SD
A1	0.1456	0.0488	0.5894	0.0422	112.960	7.320
A2	0.0452	0.0116	0.1318	0.0353	91.408	7.287
B1	0.0265	0.0113	0.0691	0.0112	137.857	8.384
B2	0.2308	0.0392	0.2244	0.0423	138.644	8.969
C1	0.0802	0.0184	0.1186	0.0326	92.738	3.256
C2	0.0526	0.0183	0.0672	0.0251	77.645	4.719
C3	0.0987	0.0187	0.1015	0.0167	80.264	6.176
D1	0.4047	0.1435	0.4831	0.1032	97.959	3.970
D2	0.1620	0.0395	0.2396	0.0265	91.714	4.375
E1	0.0983	0.0197	0.1414	0.0315	108.856	4.479
E2	0.3881	0.0942	0.2166	0.1374	98.321	4.856
F1	0.0151	0.0022	0.0227	0.0170	93.010	4.691
F2	0.0564	0.0114	0.0743	0.0221	97.002	8.138

A is bathroom tissue, B is kitchen towel, C is Table napkins, D is Facial tissue and handkerchiefs, E is Paper towels and industrials wipes, F is Making from recycled paper, MD is machine direction, CD is cross machine direction, ND is non-direction and SD is standard deviation.

Appendix B

Testing results of creped sheets at the different creping conditions

Appendix Table B1 Testing results of physical properties of uncreped and creped sheets at 20% and 30% dryness

Types			Thickness	Basis weight	Density
Degree of creping	Dryness	basis weight (g/m^2)	(µm)	(g/m^2)	(g/cm^3)
Creped	20%	30	123	30.02	0.244
		40	163	41.41	0.254
		50	194	53.55	0.276
	30%	30	124	31.56	0.255
		40	161	41.88	0.260
		50	181	50.75	0.280
Uncreped	20%	30	99	30.33	0.306
		40	112	40.51	0.362
		50	142	51.75	0.364
	30%	30	87	30.70	0.353
		40	108	40.96	0.379
		50	134	51.05	0.381

Appendix Table B2 Data of tensile index and softness both crepe and across crepe direction of creped sheets at 20% and 30% dryness

Types		Tensile index (Nm/g)				Softness (1/g)			
Dryness	basis weight (g/m^2)	Crepe direction	SD	Across crepe direction	SD	Crepe direction	SD	Across crepe direction	SD
20%	30	25.95	4.44	13.129	1.65	0.676	0.107	3.551	0.750
	40	31.714	6.33	13.645	1.02	-	-	3.094	1.038
	50	41.389	4.94	13.825	0.67	-	-	1.038	0.211
30%	30	27.536	3.99	16.935	1.18	0.244	0.036	3.359	0.524
	40	36.274	4.75	17.168	2.20	-	-	2.334	0.632
	50	41.423	2.08	24.150	3.19	-	-	0.746	0.174

SD is standard deviation.

Appendix Table B3 Data of absorption speed and water holding capacity both crepe and across crepe direction of creped sheets at 20% and 30% dryness

Types		Liquid absorption speed (mm/s)				Water holding capacity (g/m^2)	
Dryness	basis weight (g/m^2)	Crepe direction	SD	Across crepe direction	SD	Non direction	SD
20%	30	1.0909	0.2740	0.4565	0.0511	161.033	10.447
	40	0.8876	0.2086	0.3483	0.0672	172.798	4.547
	50	0.7477	0.1291	0.2283	0.0222	200.007	9.284
30%	30	0.8596	0.1371	0.2801	0.0580	142.534	2.730
	40	0.7143	0.1247	0.2198	0.0368	161.983	5.906
	50	0.5859	0.1760	0.2108	0.0130	186.213	8.803

SD is standard deviation.

Appendix C

Results of uncreped and creped sheets at the different degree of refining

Appendix Table C1 Testing results of physical properties of uncreped and creped sheets

Types		Thickness	Basis weight	Density
Degree of creping	Degree of refining (ml,CSF)	(µm)	(g/m^2)	(g/cm^3)
Uncreped	500	118	31.75	0.269
	400	110	30.17	0.274
	300	99	30.33	0.306
	200	99	30.51	0.308
Creped	500	193	32.77	0.170
	400	155	31.58	0.204
	300	123	32.00	0.260
	200	106	30.37	0.287

Appendix Table C2 Data of tensile index both crepe and across crepe direction of uncreped and creped sheets

Types		Tensile index (Nm/g)					
Degree of creping	Degree of refining (ml, CSF)	Non direction	SD	Crepe direction	SD	Across crepe direction	SD
Uncreped	500	12.36	0.97	-	-	-	-
	400	17.32	2.31	-	-	-	-
	300	38.36	4.04	-	-	-	-
	200	38.86	3.93	-	-	-	-
Creped	500	-	-	7.981	0.95	2.704	0.76
	400	-	-	14.106	1.43	7.634	1.31
	300	-	-	25.95	4.44	14.747	3.77
	200	-	-	31.27	4.18	15.696	2.31

SD is standard deviation.

Appendix Table C3 Data of softness both crepe and across crepe direction of uncreped and creped sheets

Types		Softness (1/g)					
Degree of creping	Degree of refining (ml, CSF)	Non direction	SD	Crepe direction	SD	Across crepe direction	SD
Uncreped	500	0.813	0.158	-	-	-	-
	400	0.745	0.092	-	-	-	-
	300	0.625	0.085	-	-	-	-
	200	0.378	0.071	-	-	-	-
Creped	500	-	-	2.555	0.392	17.188	2.761
	400	-	-	0.892	0.136	7.042	0.849
	300	-	-	0.676	0.107	3.551	0.750
	200	-	-	0.398	0.034	2.737	0.364

SD is standard deviation.

Appendix Table C4 Data of absorption speed both crepe and across crepe direction of uncreped and creped sheets

Types		Liquid absorption speed (mm/s)					
Degree of creping	Degree of refining (ml,CSF)	Non direction	SD	Crepe direction	SD	Across crepe direction	SD
Uncreped	500	1.167	0.1474	-	-	-	-
	400	0.8086	0.1968	-	-	-	-
	300	0.4449	0.0465	-	-	-	-
	200	0.2695	0.1104	-	-	-	-
Creped	500	-	-	1.5625	0.4161	1.0676	0.2185
	400	-	-	1.0870	0.2272	0.8547	0.1799
	300	-	-	0.7087	0.3010	0.4565	0.0511
	200	-	-	0.6369	0.0786	0.1894	0.0154

SD is standard deviation.

Appendix Table C5 Data of water holding capacity both crepe and across crepe direction of uncreped and creped sheets

Types		Water holding capacity (g/m^2)	
Degree of creping	Degree of refining (ml,CSF)	Non direction	SD
Uncreped	500	188.017	15.369
	400	159.223	18.717
	300	131.206	8.866
	200	121.071	10.516
Creped	500	207.711	18.510
	400	193.811	3.100
	300	156.644	17.385
	200	136.840	10.904

SD is standard deviation.

Appendix D

Testing results of various types of pulp

Appendix Table D1 Testing results of physical properties of various types of pulp

Types		Thickness	Basis weight	Density
Types of pulp	Degree of refining (ml,CSF)	(µm)	(g/m^2)	(g/cm^3)
Deinking	300	170	31.29	0.184
	200	148	27.76	0.188
OCC	300	122	28.01	0.230
	200	112	28.09	0.251
Bagasse	400	174	34.09	0.196
	300	164	32.78	0.200
	200	144	34.12	0.237
Bamboo	500	133	27.94	0.210
	400	130	28.62	0.220
	300	116	29.82	0.257
	200	115	29.67	0.258
Acacia	500	174	31.82	0.183
	400	147	30.86	0.210
	300	111	29.39	0.265
	200	103	30.12	0.292
Eucalypt	500	193	32.77	0.170
	400	155	31.58	0.204
	300	123	30.02	0.244
	200	106	30.37	0.287

Appendix Table D2 Percentages of pulp fractionation of six types of pulp

Types of pulp	% Fractionation							
	R50	SD	R100	SD	R150	SD	P200	SD
Deinking	48.86	1.177	21.78	1.076	5.65	0.228	23.72	0.127
OCC	47.13	0.658	20.70	0.408	5.59	0.136	26.58	0.115
Bagasse	34.86	0.288	29.68	0.513	14.22	0.258	21.23	1.060
Bamboo	49.92	0.842	9.75	0.096	3.21	0.047	37.12	0.699
Acacia	55.84	1.136	22.92	0.957	5.17	0.018	16.08	0.161
Eucalypt	46.70	2.933	30.72	2.426	5.95	0.496	16.63	0.011

R50 fraction (mesh opening 0.297 mm), R100 fraction (mesh opening 0.149 mm) and R200 fraction (mesh opening 0.074 mm), P200 is the fraction that passes through the 200 mesh wire and SD is standard deviation.

Appendix Table D3 Data of water retention value of various types of pulp

Types of pulp	Degree of refining (ml, CSF)	WRV (g water/g)	SD
Deinking	300	1.0100	0.0362
	200	1.1631	0.0068
OCC	300	0.8073	0.0249
	200	1.0395	0.0223
Bagasse	400	1.4815	0.0214
	300	1.5736	0.0624
	200	1.7404	0.0461
Bamboo	500	0.8981	0.0303
	400	1.1654	0.0112
	300	1.2286	0.0054
	200	1.3123	0.0022
Acacia	500	0.8471	0.0364
	400	1.2453	0.0468
	300	1.4488	0.0477
	200	1.8355	0.0728
Eucalypt	500	0.7588	0.0009
	400	0.9845	0.0702
	300	1.4125	0.0625
	200	1.7584	0.0356

WRV is water retention value and SD is standard deviation.

Appendix Table D4 Data of tensile index both crepe and across crepe direction of various types of pulp

Types		Tensile index (Nm/g)			
Types of pulp	Degree of refining (ml, CSF)	Crepe direction	SD	Across crepe direction	SD
Deinking	300	20.98	3.25	11.30	1.27
	200	28.85	2.89	17.145	2.35
OCC	300	12.54	2.43	7.73	0.87
	200	20.57	2.11	14.05	0.87
Bagasse	400	14.14	2.15	8.45	1.24
	300	26.99	4.44	15.09	1.68
	200	39.84	5.96	18.27	1.81
Bamboo	500	15.83	2.81	12.17	2.01
	400	20.93	3.22	16.35	1.98
	300	31.14	4.99	20.76	2.04
	200	41.22	2.50	23.78	1.70
Acacia	500	8.41	0.71	5.29	0.82
	400	28.70	4.13	12.29	1.38
	300	37.95	3.67	14.93	0.84
	200	67.76	6.43	22.76	2.91
Eucalypt	500	7.98	0.95	2.70	0.76
	400	14.11	1.43	7.63	1.31
	300	25.95	4.44	13.13	1.65
	200	31.27	4.18	15.70	2.31

SD is standard deviation.

Appendix Table D5 Data of softness both crepe and across crepe direction of various types of pulp

Types		Softness (1/g)			
Types of pulp	Degree of refining (ml, CSF)	Crepe direction	SD	Across crepe direction	SD
Deinking	300	0.298	0.032	5.808	0.618
	200	0.290	0.015	3.693	0.645
OCC	300	0.611	0.083	5.395	0.407
	200	0.601	0.117	3.082	0.509
Bagasse	400	0.339	0.094	3.637	0.678
	300	0.300	0.034	2.686	0.269
	200	0.227	0.025	1.406	0.169
Bamboo	500	0.532	0.169	2.864	0.416
	400	0.274	0.049	2.416	0.379
	300	0.249	0.045	2.102	0.299
	200	-	-	1.344	0.425
Acacia	500	0.701	0.181	7.961	0.691
	400	0.199	0.010	4.769	0.581
	300	0.185	0.016	3.078	0.668
	200	-	-	2.394	0.557
Eucalypt	500	2.555	0.392	17.188	2.761
	400	0.892	0.136	7.042	0.849
	300	0.676	0.107	3.551	0.750
	200	0.398	0.034	2.737	0.364

SD is standard deviation.

Appendix Table D6 Data of absorption speed both crepe and across crepe direction of various types of pulp

Types		Liquid absorption speed (mm/s)			
Types of pulp	Degree of refining (ml, CSF)	Crepe direction	SD	Across crepe direction	SD
Deinking	300	0.5290	0.2032	0.2351	0.0396
	200	0.5198	0.1736	0.1208	0.0115
OCC	300	0.3171	0.0641	0.2160	0.0759
	200	0.1606	0.0331	0.0839	0.0130
Bagasse	400	0.7584	0.2928	0.4190	0.0606
	300	0.5367	0.0784	0.2358	0.0489
	200	0.4376	0.2302	0.0767	0.0154
Bamboo	500	1.0870	0.1230	0.7042	0.1752
	400	0.9585	0.2474	0.4831	0.0974
	300	0.6369	0.2845	0.2536	0.0180
	200	0.5871	0.1530	0.1364	0.0201
Acacia	500	1.3514	0.2305	0.7673	0.0903
	400	1.0676	0.3238	0.3974	0.0813
	300	0.7576	0.0790	0.2639	0.0123
	200	0.5837	0.1820	0.0626	0.0030
Eucalypt	500	1.5625	0.4161	1.0676	0.2185
	400	1.3333	0.1684	0.8547	0.1799
	300	1.0909	0.2740	0.4565	0.0511
	200	0.7042	0.0364	0.1894	0.0154

SD is standard deviation.

Appendix Table D7 Data of water holding capacity both crepe and across crepe direction of various types of pulp

Types		Water holding capacity (g/m^2)	
Types of pulp	Degree of refining (ml, CSF)	Non direction	SD
Deinking	300	135.66	11.321
	200	135.52	7.639
OCC	300	142.08	9.247
	200	138.14	9.810
Bagasse	400	182.64	11.449
	300	160.35	3.386
	200	134.42	11.146
Bamboo	500	139.75	3.266
	400	137.19	7.384
	300	136.50	7.589
	200	109.94	10.741
Acacia	500	199.22	9.969
	400	165.61	8.769
	300	134.76	8.053
	200	127.84	11.718
Eucalypt	500	210.10	8.871
	400	193.81	3.100
	300	161.03	10.447
	200	136.84	10.904

SD is standard deviation.

CURRICULUM VITAE

NAME : Miss Preeyanuch Anukul

BIRTH DATE : December 20, 1988

BIRTH PLACE : Bangkok, Thailand

EDUCATION :

YEAR	**INSTITUTE**	**DEGREE/DIPLOMA**
2011	Kasetsart University	B.Sc. (Pulp and Paper Technology)

SCHOLARSHIP : Graduate Thesis Scholarship for Internationalization publish, The Graduate School Kasetsart University

Trainee Scholarship, Wood and Paper Industrial Technology, Department of Forest Products, Faculty of Forestry Kasetsart University