UNBLEACHED ETHANOLAMINE EMPTY FRUIT BUNCH (EFB) PULP AS PARTIAL SUBSTITUTION FOR PRODUCTION OF AUTOCLAVE FIBRE CEMENT COMPOSITE

YAM KOK PENG

UNIVERSITI SAINS MALAYSIA

2019

UNBLEACHED ETHANOLAMINE EMPTY FRUIT BUNCH (EFB) PULP AS PARTIAL SUBSTITUTION FOR PRODUCTION OF AUTOCLAVE FIBRE CEMENT COMPOSITE

by

YAM KOK PENG

Thesis submitted in fulfillment of the requirements
for the degree of
Doctor of Philosophy

August 2019

ACKNOWLEDGEMENT

I would like to show my sincere thank you to my academic supervisor, Professor Dr. Rozman Hj Din and Associate Professor Dr. Tay Guan Seng for his helpful guidance, suggestion and discussion. Besides, I would like to thank the management of Hume Cemboard Industries Sdn. Bhd. for giving me an opportunity to conduct my research at the Hume Cemboard Industries Laboratory and all the laboratory personals for their assistance and chance for using the equipment. Lastly, I would like to express my sincere thank you to my wife and family, for their supports, inspirations and cares that provided.

This project was the collaboration research between Hume Cemboard Industries Sdn. Bhd. and Universiti Sains Malaysia. The study fees were funded by the Ministry of Higher Education (MOHE) thru MyBrain15 program. The research was conducted at Hume Cemboard Industries Laboratories and some of the testing was conducted at Pusat Pengajian Teknologi Industri, Universiti Sains Malaysia (USM).

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

µm	micron meter
kton	kilo ton
wt%	Weight percentage

LIST OF ABBREVIATION

CCD	Charge-coupled Device
C-S-H	Calcium Silicate Hydrate
EFB	Empty Fruit Brunch
FQA	Fibre Quality Analysis
FRC	Fibre Reinforced Composite
GGBS	Ground-granulated blast-furnace slag
MOE	Modulus of Elasticity
MOR	Modulus of Rupture
OPC	Ordinary Portland Cement
OPF	Oil Palm Fibre
RMP	Refiner Mechanical Pulp
SEM	Scanning Electron Microscopes
SG_p	Specific Gravity of pulp
SG_T	Specific Gravity of Toluene
TMP	Thermomechanical Pulp

PULPA ETANOLAMINA TANDAN BUAH KELAPA SAWIT KOSONG (EFB) TIDAK TERLUNTUR SEBAGAI SUBSTITUSI DALAM PENGHASILAN KOMPOSIT SIMEN GENTIAN AUTOKLAF

ABSTRAK

Bahan-bahan mentah utama untuk AFCC adalah pulpa, simen Portland Biasa dan silika halus; dicampur menjadi buburan 10% kandungan pepejal dan kebanyakannya dihasilkan menggunakan mesin Hatschek. Peningkatan harga pulpa Radiata Pine (sehingga USD700/ton pada tahun 2015) telah memaksa pengeluar simen gentian untuk mencari sumber pulpa alternatif. Serat EFB sedia ada di Malaysia dan lebih murah. Proses pulping Etanolamina telah dipilih dalam kajian untuk serat EFB kerana keupayaan yang lebih tinggi untuk mengekalkan kandungan silika. Ciri-ciri gentian dan sifat fizikal komposit telah dianalisis, diuji mengikuti Standard Antrabangsa. Pulpa Radiata Pine mempunyai kualiti yang unggul dari segi panjang gentian, ketebalan, kehalusan, lebar gentian, kekuatan basah and kering zero span. Walau bagaimanapun, dari segi bilangan gentian dan indek makrofibrilasi, pulpa EFB mempunyai hasil ujian yang lebih baik. Daripada kajian difraksi sinaran-X (XRD), unsur silika dapat dikesan pada pulpa EFB. Resipi dengan 0 - 13% nisbah kandungan pulpa Radiata Pine dan C/S pada 0.2, 0.4, 0.6, 0.8 dan 1.0 dianalisis. Modulus Kepecahan (MOR) yang tertinggi dicapai pada 15.5MPa apabila menggunakan pulp 9% dan nisbah 1.0 C/S. Resipi seterusnya dengan selang 1% kandungan pulpa EFB untuk menggantikan pulpa Radiata Pine pada 9% dengan nisbah C/S pada 1.0. Nilai MOR tertinggi untuk keadaan kering (16.7MPa) dan basah (9.9MPa) diperolehi pada pulpa campuran antara 6% Radiata Pine dengan 3% EFB. Keputusan XRD menunjukkan bahawa puncak silika dikesan pada pulp EFB

dan membentuk lapisan kepingan kristal pada permukaan pulpa EFB selepas proses autoklaf. Oleh itu, pulpa EFB sesuai sebagai pengganti separa untuk AFCC.

UNBLEACHED ETHANOLAMINE EMPTY FRUIT BUNCH (EFB) PULP AS PARTIAL SUBSTITUTION FOR PRODUCTION OF AUTOCLAVE FIBRE CEMENT COMPOSITE

ABSTRACT

The major raw materials for AFCC are cellulose pulp, Ordinary Portland cement and grinded silica; mixed into slurry of 10% solid content and mostly produced using a Hatschek machine. The increasing price of Radiata Pine pulp (up to USD700/ton in year 2015) has force the fibre cement manufacturer to look for alternative pulp source. EFB fibre is readily available in Malaysia and cheaper. The unbleached Ethanolamine pulping process was selected in the study for EFB fibre due to higher ability to retain silica content on EFB pulp surface. Radiata Pine Pulp had superior quality in terms of fibre length, coarseness, fineness, fibre width, wet and dry zero span. However, in terms of fibre count and macro fibrillation index, EFB fibre showed better results. From x-ray diffraction study, silica element was detected on EFB pulp. Recipes with 0 – 13% Radiata Pine pulp content and Cement to silica (C/S) ratio at 0.2, 0.4, 0.6, 0.8 and 1.0 were analyzed. The highest modulus of rupture (MOR) was achieved at 15.5MPa using 9% pulp and 1.0 of C/S ratio. In addition, with the increment of pulp content, impact toughness and deflection of the composites were improved. Subsequent press sheet recipes with interval of 1% EFB pulp content to replace the Radiata Pine pulp at 9% with C/S ratio at 1.0. The results showed that the highest MOR values for both dry (16.7MPa) and wet (9.9MPa) condition were obtained for blended fibre between 6 % Radiata Pine pulp with 3 % EFB pulp. The XRD results showed that silica detected on EFB pulp and formed a flake layer of crystal on EFB pulp surface after autoclaving process. Thus, EFB pulp is suitable as partial substitution for AFCC.

CHAPTER 1

INTRODUCTION

Autoclave fibre cement composite (AFCC) is not a new building material that was recently developed; instead it has been in the market for centuries. Researches were being conducted in many developed countries such as Australia, United Stated, Brazil and Europe. Majority of them are using locally available raw materials from their country. There are three major raw materials in producing AFCC such as cement, fine sand and cellulose pulp. Both cement and fine sand are easily available in Malaysia but a comprehensive study on this area has yet to be conducted. In Malaysia, production of Fibre Cement Composite was started in around year 1960 but during that time it was using asbestos fibre, Air-cured technology (by Malex Industry and United Asbestos Company). In 1990 Hume Cemboard Industries (newly established) and United Asbestos Company (UAC) were moving forward to produce AFCC. However, this was a joint venture (JV) with foreign investors [Coutts (2005)].

Coutts (2005) reviewed and mentioned that much research data is locked away in the archives of companies and not much research are being done outside of Australia. Therefore, in ASEAN countries, there is a lack of research study in AFCC. Local manufacturers have yet to fully comprehend the fundamentals behind it. Although many studies have been conducted in fibre cement composite manufacturer's laboratory, the studies are mainly looking at short term solutions and the results are not recorded intensively nor published [Coutts (2005)]. To compete or sustain in this industry, it has to move forward to understand the fundamental of fibre cement composite technology which will open up opportunity to further develop new products, new raw materials, new applications and new specifications.

Temperate countries such as Europe, United State and Oceania have widely used or utilized the fibre cement composite due to its superior durable properties. Studies such as sisal fibre, eucalyptus pulp, Brazilian waste fibre and slash pine fibre have been made on the fibre cement composites which are suitable to their weathering conditions and their locally available pulp or raw materials. Fibre cement composite will be the future building materials for developing countries such as Malaysia and it is a matter of time before the art of utilizing fibre cement composites can be mastered as building material. Again, it needs an in depth study on how the three main raw materials such as cement, fined sand and cellulose fibre react towards the composite's final properties impact [Savanstano (2005), Flavio (2009), Tonoli (2010), Tonoli (2009a), Morton (2010)].

Recipes with 0 – 13% Radiata Pine pulp [Savastano (2005), Coutt (1995), Onuaguluchi (2017)] with cement to silica C/S ratio of 0.2, 0.4, 0.6, 0.8 & 1.0 [Shaw et al. (2000)] was initiated and test results were conducted and explained in this research.

To be more competitive and sustainable in the market, pricing plays a crucial part in fibre cement composites. When fibre cement composite manufacturers looked into the cost impact for fibre cement composite, pulp contributed more than 50% of the raw materials cost with only 8-10% pulp usage. Thus, a replacement or partial substitution of the current unbleached softwood Kraft pulp is important to lower down the cost but still maintain the composite's properties. All this can be achieved if manufacturers are able to find locally available wood or non-wood pulp. The recent review of oil palm fibre (OPF contains about 43-65% of cellulose and 13%-25% lignin content [Shinoj (2011)]. Towards green technology and awareness, 15.8 million tons of empty fruit bunch (EFB) fibres that will be thrown away yearly [Malaysia Palm Oil Board (2016)] are available to be utilized as replacement for unbleached softwood kraft pulp.

There are various studies on EFB pulp in wood composites (such as oil palm fibre composites by Shinoj, 2011) and paper industry (such as oil palm fibres as papermaking material by Wan Rosli, 2011), but very less or none of the research had been done on the usage of EFB pulp in AFCCs. In this research, EFB pulp morphology, interaction and bonding towards cement to silica (C/S) ratio will be explained. Besides, the suitable blended ratio of EFB pulp and Radiata Pine pulp will be shown. Unbleached Ethanolamine pulping was selected for EFB pulp for AFCC as the study conducted by Labidi (2008) shows the highest percentage of silica retention when compared with kraft pulping process.

The Star Properties Malaysia reported that the usage of fibre cement in developed and mature markets like Europe, Australia, New Zealand and South Korea, among others has increased significantly. It is certain that there will be a spill over into Malaysia in the near future. Besides, the rise in green buildings, green townships and green cities has become significant in most developed countries in recent years. Fibre cement board is not only versatile, but an eco-friendly material that can be used to substitute bricks in the building and construction industry. Developers, architects and the main or subcontractors have started to look into the Industrialize Building Solution (IBS) introduced by CIDB Malaysia. In addition, with the foreign labour shortage currently faced in the country, the fibre cement board and its application system should be considered as an alternative to speed up construction work [Puspadavi (2013)].

To compete or sustain in this industry, ones must move forward to understand the fundamentals and be able further develop new products, new raw materials, new applications and new specifications to be used locally. Thus in Malaysia, the focus should be to develop locally available pulp use into AFCC. The emphasis should be on using our locally available raw materials such as EFB pulp, sand and cement. If the EFB pulp suitable to substitute the Radiata Pine pulp, its open another door to utilize the EFB waste in Malaysia. Besides, it will be another breakthrough research development in AFCC industry, not to mention the reduction of cost.

The objectives of this project are:

(i) To characterize of the Empty Fruit Bunch pulp and Radiata Pine pulp.

(ii) To study the effect of different percentage of pulp (Radiata Pine pulp & Empty Fruit Bunch pulp) and cement to silica ratio on Autoclave Fibre Cement Composite properties.

(iii) To determine the optimum Radiata Pine pulp and Empty Fruit Bunch pulp ratio for Autoclave Fibre Cement Composite production.

CHAPTER 2

LITERATURE REVIEW

The current available literature review on cellulose and EFB pulp characteristics, alternative wood and non-wood pulp on AFCC, pulping process, composite matrix distribution and bonding will be reviewed in this part. Many types of additives, production process and materials retention have been studied for their respective benefits in improving the properties of air-cured and AFCCs. However, the focus of this research was on optimum AFCC recipe with different pulp and cement to silica (C/S) ratio; and substitution of EFB pulp. Thus, the literature discussed here will be limited to those AFCC incorporated with wood and non-wood pulp fibres.

2.1 Background of Fibre Cement Composite

In the late 19th century an Austrian by the name of Ludwig Hatschek invented fibre cement composites. The first recipe of fibre cement composite was a mix using 10% asbestos fibres added with 90% cement and water. The mixture was run through a cardboard machine, forming strong thin sheets. Initially, asbestos was used as reinforcing fibres and it was commonly used as siding or cladding in house buildings due to its superior quality such as fire-resistance, light weight, good water tightness properties and of course its cost efficiency. However, in the 1970s asbestos became widely known and World Health Organization (WTO) accepted that exposure to asbestos is very harmful to health. It leads to a number of capable of causing death diseases such as pleural mesothelioma (lung), asbestosis and peritoneal mesothelioma (abdomen). Therefore, the use of asbestos was gradually banned and introduction of safer reinforced fibre alternatives such as cellulose were expanded to allow on-going development of fibre cement [Coutts (2005)].

Fibre cement products contained significant amount of asbestos fibre material. The asbestos fibres are bonded strongly to the cement and to be inactive in the cement matrix and therefore less chance to be released or suspended in the environment or inhaled into the lung. Loose asbestos fibre were used in thermal insulation application or as flocking materials are more harmful as it can be easily suspended in the air. However, asbestos fibres were certainly exposed during the cutting of the asbestos fibre cement composites. Besides, long-term abrasion of the asbestos fibre cement composites after it has been subjected to atmospheric natural weathering and corrosion, which causes the bonded cement composite to degrade and asbestos fibre freely in bonded [Coutts (2005)].

The first country in the world to be completely free of asbestos material in fibre cement composite production was Australia and then followed by New Zealand which accepted this technology immediately. Since 1987, James Hardie Industries have been manufacturing asbestos free fibre cement products including non-pressure pipes and moulded products. In view of the success in James Hardie's technology, it has further motivated two main fibres cement product's producers in Australia of using planted cellulose fibre reinforced cement products to start operations, the CSR and BGC Fibre Cements. In the past years, James Hardie has successfully expanded their asbestos-free manufacturing process technology further abroad to North America, New Zealand, and other Asian countries such as Malaysia [Coutts (2005)].

In the past few years, Green building materials are among the most widely discussed topic in the world, which sparked interest in scientists globally to conduct more researches on the building material's sustainability and renewability by using recycle materials. Researches have been studied in using renewable vegetable sources to obtain non-wood fibres which will be developed into fibre cement composites. Mechanical and physical properties are the main concern towards the development of non-wood fibre substitution as fibre is the reinforcement material in fibre cement composites. Non-wood fibres exhibited important benefits in fibre cement composite such as relatively low cost, non-hazardous to environment, bio-renewability and biodegradability, recyclable, zero carbon foot print and other interesting properties [Savastano et al. (2000), Tonoli et al. (a, 2010) & Ardanuy et al. (2015)].

In order to cope with the current global demand for more energy efficient construction materials which is sustainable and energy efficient, extensive research has been conducted to produce more environment friendly fibre cement composite. The fibre cement composites are mainly applied for non-structural, envelopes for building, flat sheets for ceiling, pre-manufactured components and roofing tiles. The non-wood fibre can be found easily in a wide variety of fibre morphologies such as length, diameter, aspect ratio, width, coarseness and fines which are mainly from strands, fibres or staple where they are suitable reinforcement materials. One of the major advantages of Cellulosic fibre is due to its easily modified surface to have more hydrophobic, hydrophilic characteristic or to attach other functional group. Some of the studies exhibited improvements in composite ductility, toughness, bending capacity, crack resistance and impact resistance compared with non-fibre-reinforced cement based composite. The major advantage of fibre reinforcement composite is the behaviour of the composite after initial cracking started. The fibre bridges the composite matrix and distributes the load. Cellulosic fibres provide sufficient strength, stiffness and mechanical bonding to cement based matrix. Besides, cellulosic fibre is capable to reduce free plastic shrinkage properties, improve acoustic properties performance and reduce thermal conductivity performance. It can also increase sound absorption, density and specific damping properties of the composite [Ardanuy et al. (2015)].

Fibre reinforced composite (FRC) contains short fibres that randomly dispersed into the matrix and in the aligned strands or textile structures. The FRC reinforcement depends on the type and amount of fibre used, fibre geometry such as length, width, aspect ratio; and its adhesion and distribution to the matrix. The main reason for the selection of cellulose pulp generally used by paper industries was due to its fibre strength properties and it is readily available. Besides, it also can easily be dispersed in water which is the main basic of the preparation of fibre cement composite preparation. Intensive researches had been conducted on a wide range of fibres from different forms and sources that used to reinforce the fibre cement composite and pulp forms are the most common. The majority fibres used to reinforce the fibre cement composites are from wood resources and mainly obtained from Kraft pulping process. Sisal with the botanical name as Agave Sisalana and crop plant from agricultural waste such as banana, fique and cotton has also been an interest in the fibre cement composite research due to its low prices and availability. Apart from the suitability of pulps using crop plant as reinforcement on fibre cement composites, the preparation and characterization of cementitious composites also were the area of interest being studied [Coutts (2005), Ardanuy et al. (2015)]. Table 2.1 shows the type of cellulose fibres being used as reinforcement for fibre cement composite.

Table 2.1:
Cellulose fibres used as reinforcement for cement composites [Ardanuy et al. (2015)].

Fibre Source	Fibre form	wt%
Softwood (pinus)	Pulp (chemical-kraft)	4-12
Crop plant (bast fibre)	Pulp (chemical-kraft)	1-5, 8 & 10
Crop plant (leaf fibre)	Pulp (kraft)	4-12
	Staple	4
	Strands (18-60mm)	3 & 10
Crop plant (leaf fibre)	Staple	4
Crop plant (leaf fibre) banana	Pulp (chemical-kraft)	4 & 8
Crop plant (leaf fibre) fique	Pulp	2-3
Crop plant (leaf fibre) coir	Staple	3-4
	Pulp	2.5
Crop plant (seed fibre) cotton linters	Pulp	4
Agricultural waste: sugar cane stalk	Pulp (mechanical)	2-4
Agricultural waste: wheat straw	Pulp (mechanical)	2-4

A review done by Ardanuy et al. (2015) showed that fibre properties not only depend on the different fibre source but also depend on the types of pulping process. Table 2.2 depicts fibre properties obtained from different sources and different pulping processes. In general, the mechanical properties of the fibre cement composites contributed by type of fibres, fibre length, diameter, coarseness, kappa number and aspect ratio. The use of fibres has contributed two-dimensional and homogenous fibres distribution in the fibre cement composites. Only a few works were conducted on fibre strands in fibre cement composites. It is widely known that long fibres study has only been made by Toledo Filho and co-worker [Flavio (2009), Flavio (2013), Ardanuy (2015)]. The long fibre is to give a structural reinforcement of the composite and subsequently improved the composite's mechanical properties. However, the feasibility of machine capability and manufacturing process needs comprehensive study as the dispersion and homogenous distribution is not easy to obtain [Ardanuy et al. (2015)].

Table 2.2:

Pulping process and fibre properties on different cellulose fibre type [Ardanuy et al. (2015)]

Fiber Type	Process	Length, mm	Witdh, µm	Aspect Ratio
Sisal	Thermo-mechanical	2.25	10.2	221
Sisal	Chemical-thermomechanical	2.46	12.7	194
Sisal (by-product)	Chemical-thermomechanical	1.61	10.9	148
Sisal	Kraft	1.65, 1.66	13.5, 22.2	122, 75
Sisal	Kraft + beating	1.13	18.7	60
Sisal	Kraft + geating	0.79	20	40
Pine	Bleached kraft (surface treated)	2.94	31.4	94
Pine	Kraft	2.7 - 3.05	29.3 - 34.1	84 - 94
Pine	Chemical-thermomechanical	1.71	32.4	90
Banana	Kraft	1.95	15.3	127
Banana	Chemical-thermomechanical	1.99	20.1	99
Cotton linters	Thermo-mechanical	0.79	20	40
Eucalyptus	Kraft	0.66	10.9	61
Eucalyptus	Pulping waste	1.12	480	2
Bagasse	Pulping waste	1.303	348	4
Wheat	Pulping waste	1.238	345	4

Even though the advantages of using non-wood fibre is studied and proven, but, it is limited by its long term durability. This issue of long term durability is due to an increase of fibre fracture, migration of the hydration materials to lumen and space it has decreased in the number of fibre pull out; and high water absorption. However, this has caused the material to reduce its toughness and post-cracking strength of the fibre cement composite. The importance of cellulosic fibres was to create reinforcement and have interfacial bond in between fibre and matrix. [Ardanuy et al. (2015)]. Most studies exhibited the mechanical bonding as the fibre pull out surfaces were smooth [Coutts (1985), Katz (1996), Coutts (2005), John (2005), Tonoli et al. (a, 2010), Ardanuy et al. (2015)].

2.2 Basic Fibre Cement Composite Raw Material

2.2.1 Type of Natural Fibres

Cellulose, hemicellulose and lignin are the major components of cellulosic fibres. It is also composed of minority components such as proteins, peptides, water and other inorganic compounds. Natural vascular plants of all types can be used as cellulosic fibres and it can be derived from wood and non-wood sources. Lignocellulosic fibres have higher lignin content compared to non-wood fibres. Non-wood fibres can be classified into four major types. It is depends on the type of plant used to extract the fibre. Bast fibres consist of hemp, kenaf, ramie jute and flax. Stalk fibres consist of straw rice, wheat and barley. Reed fibres consist of bamboo and grass. Seed fibres consist of cotton and coir. Typically, wood sources supplies about 93% of the world’s virgin fibre. Non-wood sources provide the remainder and mainly on bagasse, kenaf, bamboo and eucalyptus [Smook (1992)].

The cellulosic fibres can be classified by function of their form or shape. Thus, cellulose fibres can be found as strand consist of long fibre with length between around 20 to 100cm. Staple fibres consist of short fibre length which can be spun into yarn. Lastly, pulp is a very short length fibre around 1 to 10mm which can be dispersed into water easily. The strand or staple fibres are obtained from wild plants or crop and directly from the after a water retting process or raw plant. The physical and chemical properties of the vegetable fibres often depend on the harvesting, source, processing methods and cultivation [Ardanuy et al. (2015)]

In general, woods are classified into two major groups. The gymnosperms are normally called softwood or conifers such as Radiata Pine, Douglas fir, cedar and hemlock. The angiosperms are hardwood or broad-leafed trees such as birch and beech. The significant difference between softwood and hardwood with respect to volume and weight percentages is the various types of fibre cell. Another major difference between softwood and hardwood is the length of the fibres. Softwood fibre length is more than twice as long as hardwood fibres. In general, softwood contain lower portion of holocellulose and more lignin content compared to hardwood, but lesser extractives content [Smook (1992)].

2.2.1(a) Softwood

The world's production of timber consists of 80% softwood and mainly produced from North America, Scandinavia, Russia and China. The vertical structure of conifers is consisting of long, tapering cells called tracheids. The horizontal structure is consisting of narrow rays with single cell width but several cells high. Ray cells are divided into two specialized types. Ray tracheids are present in only certain softwood species. Ray parenchyma occurs in all softwood species. Parenchyma cells are alive at maturity. The function of parenchyma cells are photosynthesis, storage, vascular tissues and as the bulk of ground. The tracheids cell is dead and empty at functional maturity. Tracheids serve for upward conduction of water, support, dissolved minerals and are the only elements in conifers and ferns [Smook (1992)].

Plant growth is based on the end of the annual ring with denser band of tracheids. Summerwood also known as latewood has different properties from the earlywood also known as spring wood tissue. Earlywood is less dense than latewood, only approximately one – half or one third of latewood density value. The wall of a typical tracheid is composed of several layers. The middle lamella separates two neighbouring tracheids with very high in lignin content. Primary wall consists at each tracheid and tracheid has a three layered secondary wall with specific alignment of microfibrils. Microfibrils are bundles of cellulose molecules and their orientation can influence the characteristics of a pulp fibre. Radiata Pine, Douglas-fir, Cedar, Redwood and Spruce are an example of softwood trees [Smook (1992)].

The formation of compression wood on the underside of leaning trees and branches are called softwood growth. Tissues of softwood can be found in every tree but the amount and severity varies from one tree to another. Compression wood is identified by high density rounded tracheids, high lignified secondary wall, large fibril angles and spiral checks in the cell wall which contributes to the different results in pulp manufacturing process. Compression wood fibres generally do not react well to beating or refining. However, with severe mechanical treatment, the thick layer of the secondary wall becomes unravelled into very long fibrils [Smook (1992)].

Softwood pulp fibre properties gave important rules in paper making as well as in fibre cement composite. The two most important factors in determining the properties of paper are the cell wall thickness and fibre length. Minimum length is required to have a good interfibre bonding and also corresponding to its tear strength. In general, softwood tracheids (red cedar species) with comparatively thin cell wall collapse readily into ribbons during paper sheet formation. This principle also can be applied to fibre cement composites manufacturing process. Tracheids with thick cell walls (Radiata Pine and Douglas fir species) resist to collapse and do not contribute to interfibre bonding to the same degree with thin cell walls. The thicker cell wall fibres tend to produce bulky sheet with low tensile or burst strength but better tearing resistance. Within same species, earlywood tracheids with thin-walled are more flexible while the latewood tracheids are less conformable due to having 60 to 90% of their volume in cell wall materials [Smook (1992), Swamy (1988)]. The structure of a tracheid is illustrated and explained in Figure 2.1 and composite softwood block illustrating in Figure 2.2. Figure 2.3 shows microfibrillar textures in cell wall organization.

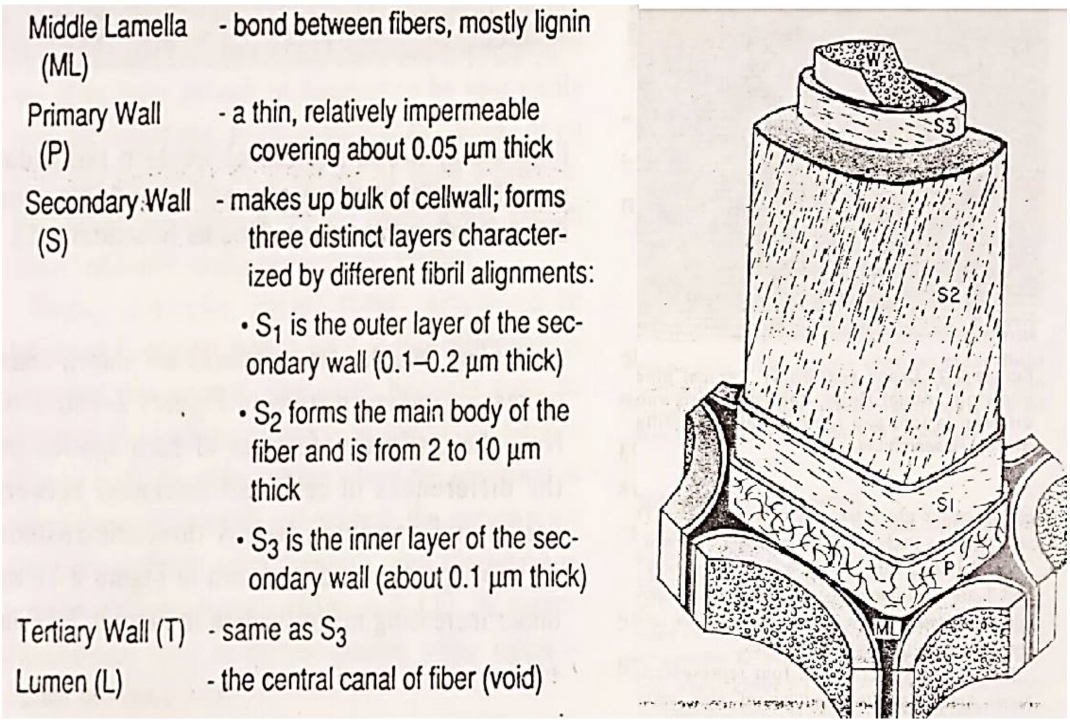

Figure 2.1: Layers of softwood tracheid (20-40 microns diameter) [Smook (1992)]

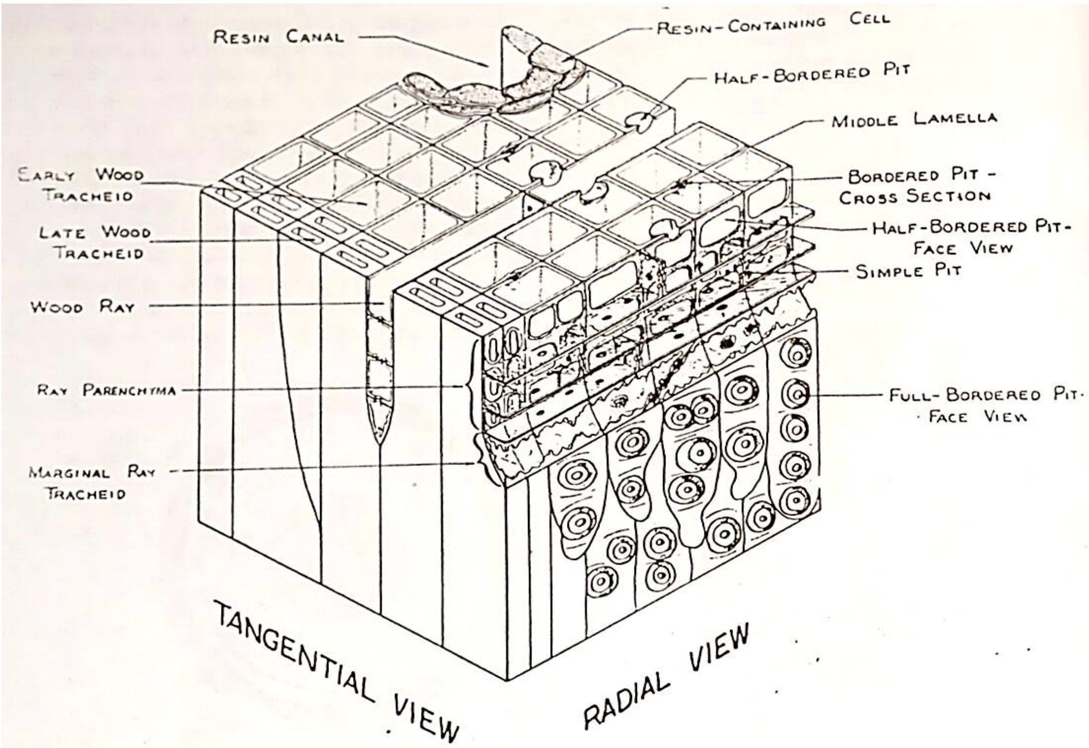

Figure 2.2: Transverse view of the composite wood block illustrating the structural features of softwood [Smook (1992)].

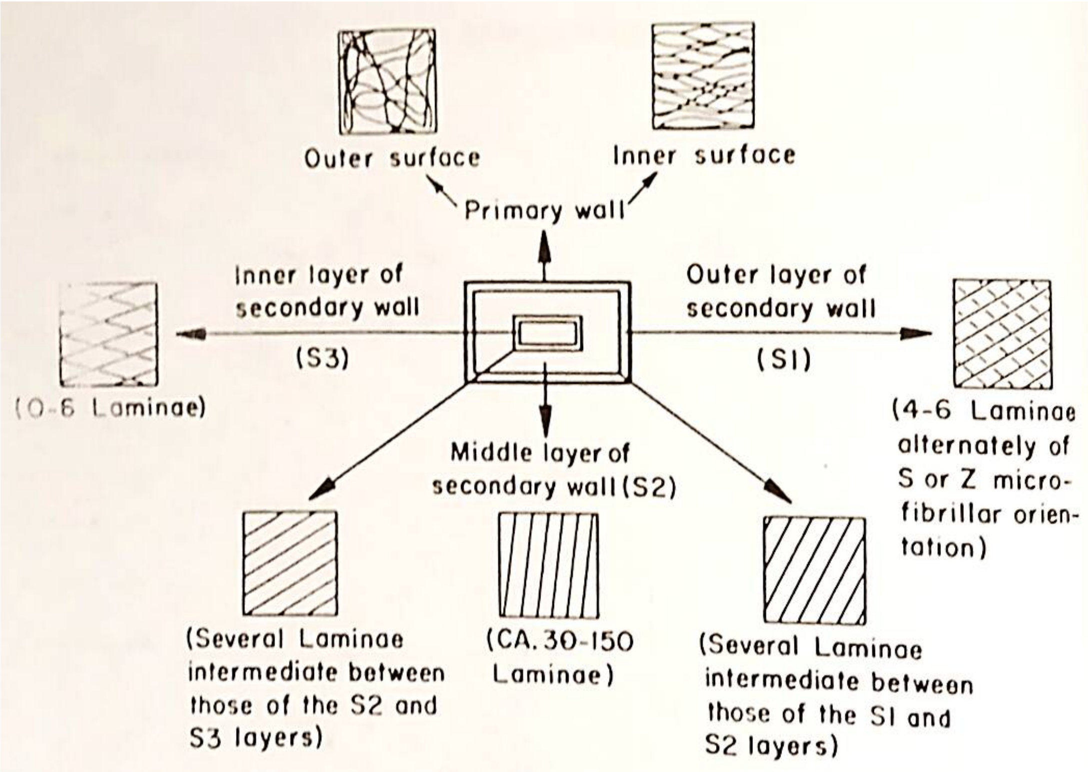

Figure 2.3: Cell wall organization showing microfibrillar textures [Smook (1992)].

2.2.1(b) Hardwood

Hardwood has a more complex structure compared to softwoods. The main different characteristic differentiate hardwoods from softwoods is the existing of vessels or pores. The hardwood vessels may show significant variation in size, perforation plates shape and structure of cell wall such as spiral thickenings. The main structural features of hardwood are illustrated in Figure 2.4. Libriform fibres are the vertical structure of hardwoods which composed of both relatively long and narrow cells. Vessels are those shorter and wider cells. Hardwood vessels sample are usually can be noticed easily in cross section pores or a series of long grooves on the vertical surfaces. Horizontal or vertical ray parenchyma systems also exist in Hardwood. Hardwood vessel diameter varies from earlywood to latewood within an annual ring. The termed ring-porous becomes easy to notify. The annual rings are more difficult to be seen if the gradation in vessel diameter is small and this wood is termed as diffuse-porous [Smook, (1992)].

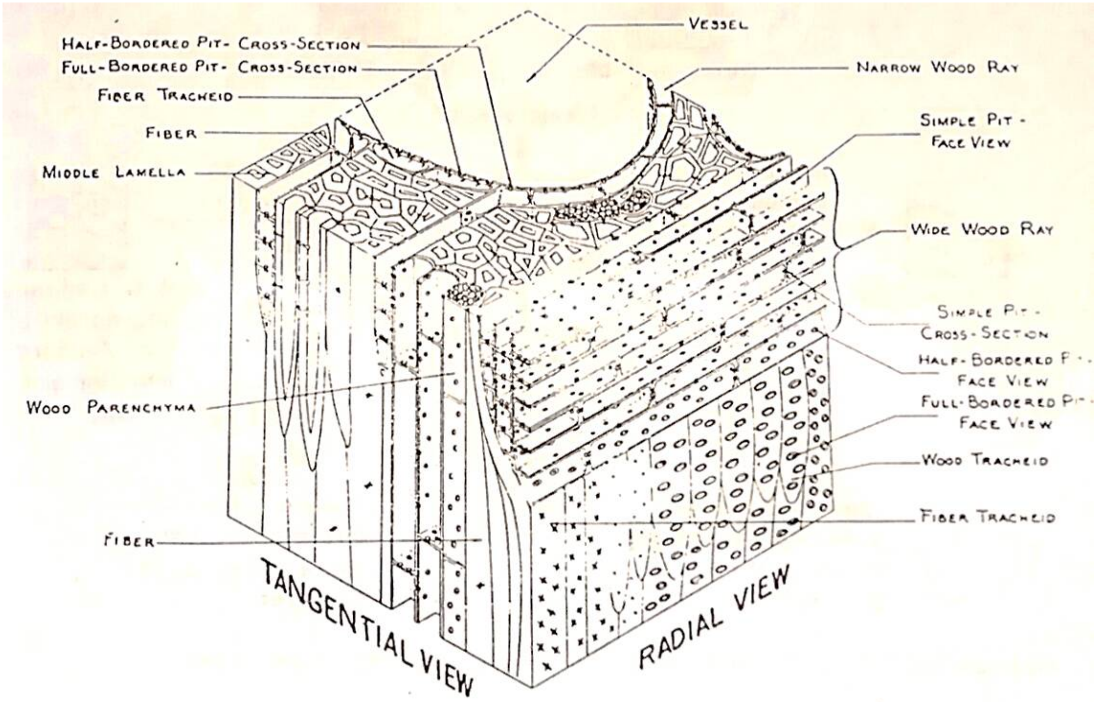

Figure 2.4: *Transverse view of the composite wood block illustrating the structural features of a hardwood [Smook (1992)].*

Hardwood is the formation of tension wood on the upper side of leaning stems and branches. The slightly denser tension wood is characterized by a relative absence of vessels and fibres having a distinct gelatinous inner layer composed of highly crystalline cellulose. Although chemical pulping yields are higher for tension wood, the fibres are difficult to beat and exhibit poor interfibre bonding. Tension wood is found to some degree in every hardwood trees, but the amount and severity depends on the growing habit of the particular tree. The hardwood fibre length is much lower than softwood and thus has lower interfibre bonding and tear strength. In general, hardwood tracheids with relatively thick cell walls are more difficult to collapse and less conformable during sheet formation. This will be the draw back for fibre cement composite manufacturing process [Smook (1992) & Swamy (1988)].

2.2.1(c) Non-wood

Globally, non-wood fibres are consider insignificant part of raw material supplied to pulp and paper industries as well as to fibre cement composites industry. However, in many other countries, non-wood fibres still widely used and are quite important in terms of percentage or amount of total pulp supplied. In the Asia and Pacific regions, manufacturers have invested substantial resources and time into the pulping process of non-woods fibre. Countries such as India and China are the leaders in the optimization of non-woods fibre for papermaking. In North America, Europe, Latin America, Africa and Russia, the use of non-wood fibres has been restricted due to easily available of their softwood. As of now, the most commonly used of non-wood fibre is straw, which contributed for up to 44.4% of total production. This is followed by bamboo at 21.4% and bagasse at 14.3% of the total production. Other non-wood fibres such as kenaf, sisal, cotton and hemp are also becoming more significant in manufacturing of pulp and paper. Countries where the softwood recourses are limited and non-wood (annual plant) are plenty, the utilization of non-wood fibres for the paper industry can only continue to grow [Zhong et al. (2018)].

In papermaking industries, some non-wood fibres used as raw materials have high annual yields per hectare. Example the Kenaf average annual yield per hectare is twice that of fast-growing softwoods. Table 2.3 shows the non-wood pulp yield from different fibre materials from 2006 to 2015 in China. Non-wood fibres generally have lower lignin content and thus it is easier to delignify as compare to wood and also lower activation energies. Manufacturing paper from non-wood fibres can actually help to reduce the use of pulpwood from natural forests or large-scale plantations. This will definitely help out in the global effort to reduce wood fibre usage. Non-wood fibre may be a substantial alternative to tree plantations under certain climatic conditions. The sustainable supply of fibre is a main concern for paper mills is the only disadvantages of the non-wood fibre. Large storage capacity is needed to ensure a constant supply as most non-woods are annual plants. This is further complicated that most non-wood fibre sources are low in density and high in volume as compared with wood. In general, most small non-wood paper mills do not have proper chemical recovery facilities to manage large volumes of silica content that must be removed from the non-wood fibre. Growing non-wood fibre is also very time consuming, As such, serves as another disadvantage [Pierce (1998) & Bobalek at al. (1989)].

Table 2.3:

Total non-wood pulp yield in 2006-2015 in China. [Zhuming et al. (2017)]

Unit: Thousand Tons

	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Reed pulp	144	144	150	144	156	158	143	126	113	100
Bagasse pulp	74	90	97	98	117	121	90	97	111	96
Bamboo pulp	95	120	146	161	194	192	175	137	154	143
Straw pulp	908	849	808	676	719	660	592	401	336	303
Others	69	99	97	97	111	109	74	68	41	38

Table 2.4 shows the average dimensions of various non-wood plant fibres versus wood fibres. The data shows wide different in the fibre characteristics between wood and non-wood fibres. Plenty of the non-wood fibres are similar to hardwoods which obtained shorter fibre length, while others non-woods fibres are so long and must be shortened in order to be used in the papermaking process. In

general, the overall fibre diameter of the non-wood fibre is small and subsequently resulting in lower fibre coarseness. In pulp and papermaking, the fibre dimensions and properties serve as a guideline on the usefulness of pulps. If non-wood fibres mixed with wood fibres, it can be used in any grade of papers with an appropriate combination from the technical and quality viewpoints. Table 2.5 shows some chemical properties of various non-wood fibres. In some of the non-wood plant, the presence of silica is to protect the non-wood plant from the environment. A tree uses bark is for protection, which acts as a ‘skin’ for the plant and high pentosan levels increased black liquor viscosity.

Table 2.4:

Non-wood plant fibre raw material (Hurter et al. (2001)]

Common name	Scientific name	Fibre length [mm]	Fibre diameter [µm]
Straw & stalk fibres			
Cereal straw		1.5	23
Wheat straw	Triticum aestivum	1.0-1.5	13
Corn straw		1.0-1.5	18
Rye Straw	Secale cereale	1.5	13
Oat straw	Avena sativa	1.5	13
Barley straw	Hordeum vulgare	1.5	13
Rice straw	Oryza sativa	0.5-1.4	8-10
Corn stalk	Zea mays	1.0-1.5	16-20
Sorghum stalk	Andopogon bicolor	1.0-1.7	20-47
Cotton stalk	Gossypium hirsutum	0.6-0.9	20-30
Reed & grass fibres			
Common reed	Phragmites communis	1.5-2.5	20
Giant reed	Arundo donax	1.2	15
Papyrus	Cyperus papyrus	1.5	12
Reed canary grass	Phalaris arundinacea	1	20
Elephant grass / Miscanthus	Miscanthus sinensis	1.2	20
Esparto	Stipa tenacissima	1.1-1.5	9-12
Sabai	Eulaliopsis binata	2.1	9
Switch grass	Panicum virgatum	1.4	13
Cane fibres			
Bagasse / Sugarcane	Saccharum officianarum	1.0-1.7	20
Bamboo		2.7-4	15
Bast fibres			
Flax	Linum usitatissimum	25-30	20-22
Hemp	Cannabis sativa	20	22
Sun hemp	Crotalaria juncea	2.5-3.7	25
Kenaf	Hibiscus cannabinus	2.6	20
Jute	Corchorus capsularis	2.0-2.5	20
Core fibres			
Kenaf	Hibiscus cannabinus	0.6	30
Leaf fibres			
Abaca / Manilla hemp	Musa textilis	6	20-24
Sisal	Agave sisalana	3.0-3.5	17-20
Seed hull fibres			
Cotton staple	Cossypium hirsutum	20-30	20
Cotton linters	Cossypium hirsutum	0.6-3.0	20
EFB (oil palm empty fruit bunch)	Elaieis guineensis	1	20
Tree-based fibres			
Softwood (coniferous)		2.7-5.0	32-43
Hardwood (deciduous)		0.7-3.0	20-40
Eucaluptus		0.7-1.3	20-30

Table 2.5:

Chemical properties of various non-woods (Kinsella 2004)

Fibre/Source	Cellulose (%)	Lignin (%)	Pentosans (%)	Ash (%)	Silica (%)	Pulp yield (%)
Jute	57	16-26	15-26	0,5-2,9	< 1	42
Kenaf	53	15-18	21-23	2-5	4	46
Flax	70	10-25	6-17	2-5		
Abaca	61	9	17	1	<1	
Sisal	43-56	8-9	21-24	0.6-1	<1	
Cotton	80-90	3-3,5		1-1,2	<1	
Bagasse	55	18-24	27-32	1.5-5	0,7-3	45- 65
Bamboo	52-68	21-31	15-26	1.7-5	1.3-3	38-45
Wheat straw		16-21	26-32	2.5-10	3-7	39-62
Esparto		17-19	27-32	6-8	2-3	
Reed		22	20	3-4	2	45
Soft wood	57	26-34	7-29	<1	<1	45-70
Hard wood		23-30	19-26	<1	<1	45-70
EFB	37	19		2.3	2.3	39-54

Non-wood plants are categorized by differences in plant size and composition due to differences in cultivation environment. These plants are more likely than trees to abnormalities in seasonal weather such as droughts, floods, environment changes, soil and storage period variation from days to years at the pulp mill. The storage time variation requires tight quality control, and thus supplier has a higher insecurity that bales will be rejected when compare in cases of a wood fibre. However, with a proper quality control system in place for non-wood fibres, this variation is manageable.

There are four types of different categories of sources for the non-wood fibres (sometimes compacted to three):

a) Crops that are grown specifically for paper fibre (on-purpose or dedicated) such as kenaf, hemp, jute, bamboo and flax.

b) Harvesting or field or agricultural residues are materials left behind in an agricultural plantation after the crop has been harvested. These remainders include corn, stalks, sorghum, cotton and straw. It is renewable in immediately, while commercial pulpwood required at least seven years (required at least seven years) renewal time. The cost of such plant fibre has been pre-calculated by the production and existing farm machinery can be used to process it. Crop remainders can be used as animal fodder, bedding, as an energy source and soil amendment. Agricultural by-products are characterized by moderate quality and low raw material cost [Finell et al. (2004)]

c) Industrial residues or process residues from the agricultural wastes are those materials left over after the processing of the plant into usable resources. Agricultural Processing Waste is the wastes after agricultural products are processed. They include hemp residue, peanut crust, hemp, bagasse, rice husk, cotton linters, flax residue from oilseed and cotton or linen scraps from clothing production. This type of raw material is easy to collect and transport because it is ready stock piled in the factories. Industrial plants can produce high quality pulp but it is more expensive. [Finell et al. (2004)]

d) Naturally occur uncultivated crops from natural stands are available such as sisal, papyrus, wild grasses, bamboo and reeds [Kinsella (2004)].

2.2.1(d) Chemical Composition

The chemical composition of wood normally consists of carbohydrates (cellulose and hemicellulose), lignin and extractives. Cellulosic fibre exhibits a number of properties which will fulfil the requirement of papermaking. The same concept is applied on the fibre cement composite. In general, the best balance of papermaking properties occurs when most of the lignin is removed from the fibres while retaining substantial amount of hemicellulose [Smook (1992)].

2.2.1(d)(i) Cellulose

Cellulose is a carbohydrate composes of oxygen, carbon and hydrogen, which the situated two elements in the same proportion as in water. Cellulose is a polysaccharide contains many sugar units. The chemical formula for cellulose is $(C_6H_{10}O_5)n$, where n is the degree of polymerization (DP) or the number of repeating sugar units. The value of 'n' varies with the treatment received and different cellulose sources. The structure of cellulose is shown in Figure 2.5. Cellobiose unit is the recurring unit of two consecutive glucose anhydride units. The chains form in extended form during the cellulose synthesis from the polymeric linkages. Cellulose molecules set tightly together over long chains and thus increase forces that contribute to the great strength of cellulosic materials [Smook (1992)].

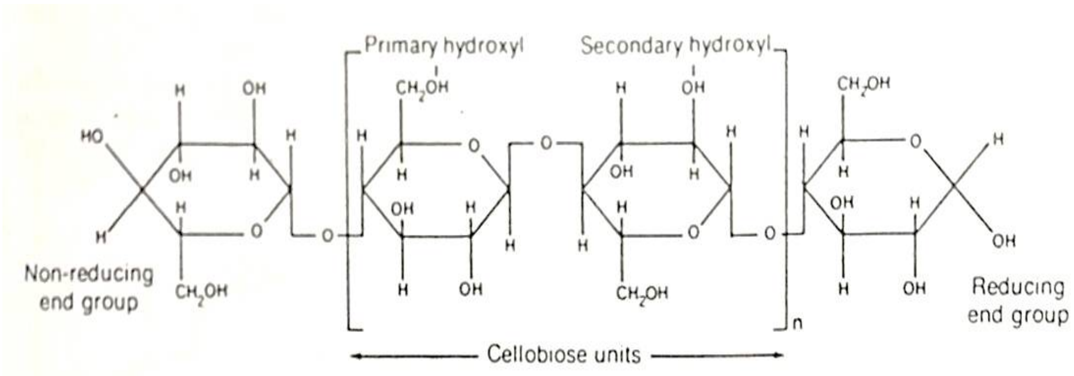

Figure 2.5: Cellulose Structure [Smook (1992)]