IOP Conference Series: Materials Science and Engineering

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To cite this article: N Bakar *et al* 2020 *IOP Conf. Ser.: Mater. Sci. Eng.* **736** 052017

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IOP Conf. Series: Materials Science and Engineering **736** (2020) 052017 doi:10.1088/1757-899X/736/5/052017

# A review on physical, mechanical, thermal properties and chemical composition of plant fibers

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**Abstract.** In recent years, research on natural fiber composites increased owing to their light-weight, easy availability and improved mechanical characteristics. Natural fiber is also an environmentally friendly material, which produces less pollutant during its production. Therefore, extensive research has been carried out on natural fibers as they constitute an interesting alternative to traditional synthetic fibers, especially for composite materials. This paper presents a comprehensive review on the physical, mechanical and thermal properties as well as chemical composition of natural fibers. Comparison between different natural fibers regarding the aforementioned properties and composition are presented and discussed. This review will provide a useful guide on the performance of natural fibers in natural fiber reinforced composites for other applications such as structural strengthening.

## 1. Introduction

The use of natural fiber gained a significant attention in the recent decade due to their promising properties which makes them as an alternative to replace the expensive and non-environmentally friendly synthetic material, i.e., fiber reinforced polymer (FRP). Plant fiber is one of the varieties of natural fibers obtained from stems, leaves, roots, fruits and seeds of plants [1]. The prominent advantages of natural fibers include acceptable tensile properties, low cost, high toughness, bio-degradable, fully sustainable, and environmental friendly in nature [2–4]. The use of natural fiber is more economical as it consumes less energy, leading to lower production cost compared to artificial fiber. In addition, natural fibers are non-carcinogenic and safe during handling and processing. Natural fibers can be obtained easily from available plant-based natural resources such as kenaf, jute, coir, bamboo, pineapple leaf, hemp, sugar cane baggase, sisal and flax. There are hundreds of lignocellulosic fibers that can be found in temperate and tropical zones around the world [4]. All the lignocellulose-based natural fibers consist of cellulose micro-fibrils in an amorphous matrix of lignin and hemicellulose which run along the length of the fiber whereby each fibril is similar to that of a single wood fiber [1].

However, natural fibres also exhibit some undesirable characteristics. High moisture absorption, low thermal resistance and highly anisotropic properties are some of the disadvantages associated with natural fibers. Plant based fiber is hygroscopic by nature and hence easy to absorb moisture (Celino et al., 2014). Plant fiber is mainly made of cellulosic material which has a degradation temperature of about 270 ºC, which is very low compared to other thermal material such as ceramic (Chin et al., 2019). In addition, plant fiber is not uniform throughout because the properties at the trunk and crown

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of a plant is not similar. Knowledge and understanding of the physico-chemical properties as well as mechanical behaviour of natural fibers is important in order to optimize the composite performance. Past investigations mainly carried out studies on the fiber composition and the effect of the treatment process on their mechanical characteristics [1,5,6]. The mechanical characteristics of the natural fibers are influenced by parameters such as the crystal-structure, the degree of crystallinity, the spiral angle of the fibrils, the degree of polymerization, the porosity content, the size of the lumen (center void), and the chemical composition. Furthermore, many problems occur at the interface due to incompatibility when natural fibers are used as reinforcement in composite materials. Therefore, surface modification of the natural fibers (treatment) is required to improve compatibility and interfacial bond strength. Hence, it is noteworthy that chemical treatment of the fibers can either increase or decrease the strength of the fibers [7]. On the other hand, the hydrophilic nature of natural fibers, limited thermal stability during melt processing, and poor dispersion characteristics within the non-polar thermoplastic matrix are major concerns in the fabrication of natural fiber-reinforced thermoplastic composite with desired attributes [8].

Hence, the aim of this paper is primarily to review past investigations on the physical, mechanical, and thermal properties as well as chemical composition of various natural fibers. The output from this review provides a useful guide on the performance of various natural fibers for fabrication into natural fiber reinforced composites to be used for structural strengthening applications.

## 2. Natural fibers

Natural fibers are subdivided on the basis of their origin, such as plants, animals, and minerals [9,10] as shown in figure 1. Plant fibers are also known as cellulose fibers since they are composed of cellulose fibrils and lignin matrix [10]. Cellulose fiber can be classified based on their origin such as seed, leaf, bast, fruit and stalk [9]. Generally, the plant fibers used for composites are cellulosic fibers, such as sisal, flax, hemp, jute, bamboo, kenaf, and wood [2,10].

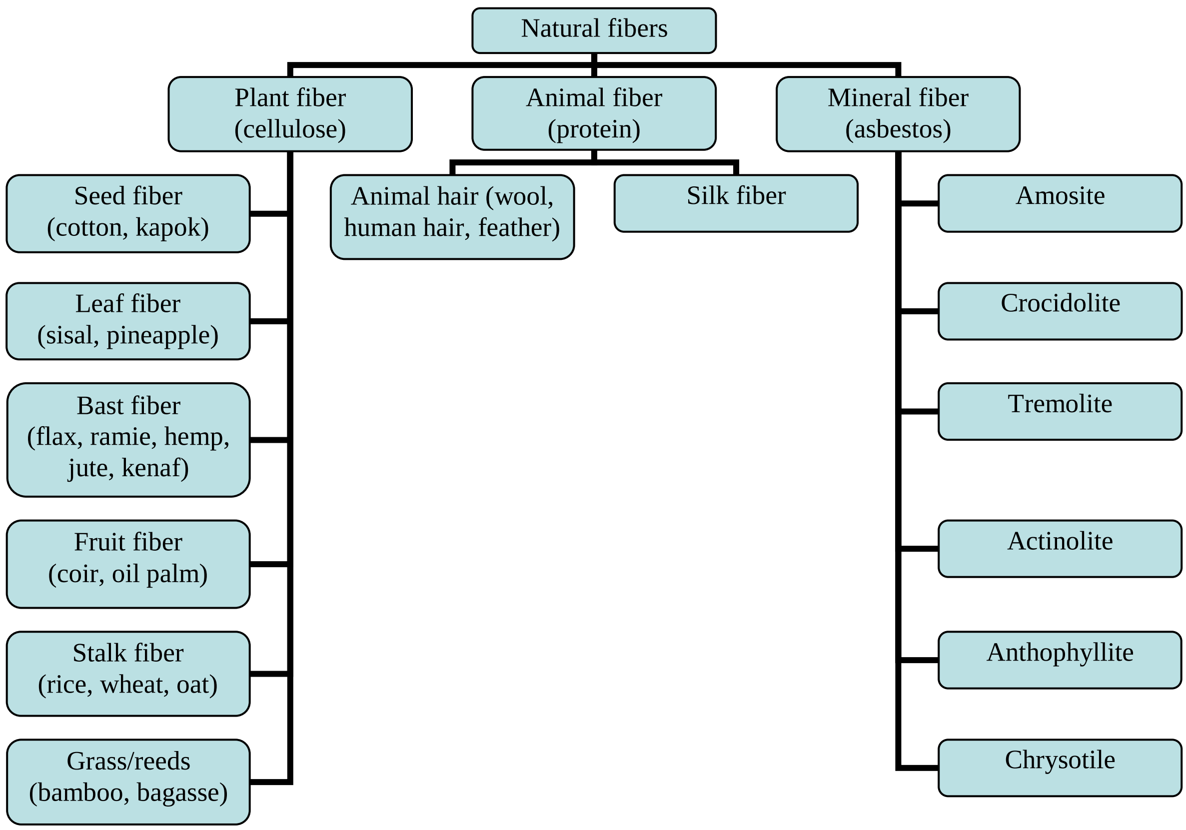


**Figure 1.** Classification of natural fibers [2,9,10].

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The strength and stability of the plant fiber depends on its cellulosic content. The hemicellulose contained in plant fiber give the fiber characteristic structure and strength [9]. The cellulosic content can be determined using an x-ray diffraction and Fourier transform infrared analysis. Figure 2 shows several example of plant fiber source such as bamboo, jute and sisal. The plant must undergo several processing steps before the fiber can be obtained. Example of plant-based fibers in the processed form is shown in figure 3.

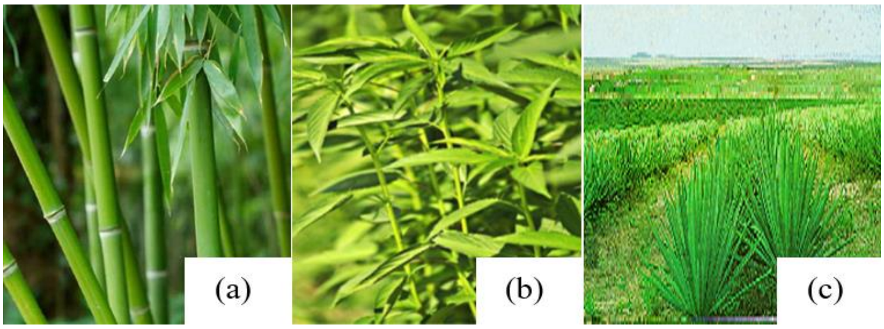


**Figure 2.** Plant source of natural fiber. (a) bamboo plant [11], (b) jute plant [2] and (c) Sisal plant [11].

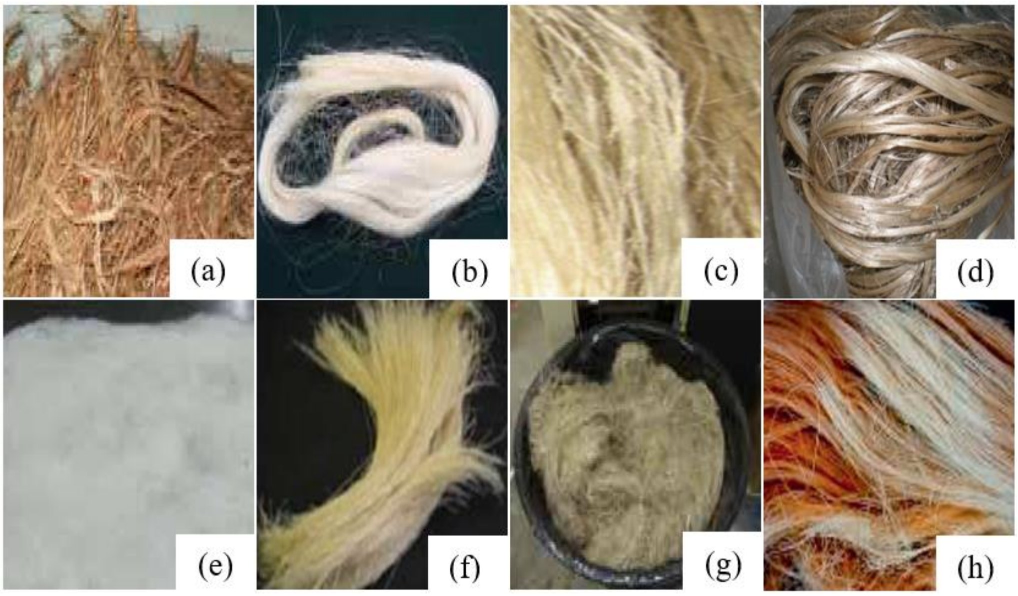


**Figure 3.** Natural fibers. (a) Coir fiber [12], (b) Sisal fiber [12], (c) Unidirectional jute fiber [2], (d) Kenaf fiber [13], (e) Cotton fiber [12], (f) Bamboo fiber [14], (g) Hemp fiber [12], (h) Pineapple fiber [15]

### *2.1 Coir*

Coir fiber is a lignocellulosic fiber extracted from the husk and outer shell of a coconut. Coir is the fibrous material found between the hard, internal shell and the outer coat of a coconut. The colour and the smoothness of the fiber depends on the time the coil was harvested. The advantage of coir fiber is due to its floating behaviour in water because coir is water resistant and resistant to salt water damage. Brown coir (ripe coconut) fiber are stronger than white coir fiber but less flexible [9,16]. Coir possess tensile strength in a range of 95 -118 MPa with modulus elasticity of 8 GPa, Most of the coir fibers can be found in India, Sri Lanka, Philippines and Malaysia [11].

*2.2. Sisal*The botanical name of sisal is *Agave sisalana* [17]. The fiber of agave plant is straight, smooth and yellow in colour. The fibers are extracted from the leaves of sisal plants. This hard fibers have strength, durability, ability to stretch and resistance to deterioration in saltwater. Sisal retains 60% to 70% of their initial tensile strength after exposure to fresh water only [16]. Sisal fiber is commonly used to make ropes and twines which are widely employed for marine, agricultural, and general industrial use. The fiber contains mainly cellulose, lignin and hemicelluloses. Tensile strength of sisal fiber are in the range of 347-378 MPa with modulus of elasticity about 15 GPa. It is available in countries such as East Africa, Bahamas, Antiqua, Kenya, Tanzania and India [11].

*2.3. Jute*

Jute is known as the 'Golden Fiber' due to its golden brown colour. It is from the family of flowering plants called *Tiliaceae*, produced from genus *corchorus* which have long, soft, shiny vegetable fibers that changes colour from off-white to brown. Jute can grow 2 m to 3.5 m in height and are very brittle, with a low extension to break because of the high lignin content (up to 12-16%). Jute fibers extracted from the ribbon of the stem have less resistance to moisture, acid and UV light [2]. The specific modulus of jute fiber approaches that of the glass fiber and it remains stable up to a temperature of 200˚C without any damage to its properties [9]. A single jute fiber composed mainly of cellulose, hemicelluloses and lignin with little amounts of protein, extractives and inorganics. Jute fiber has a tensile strength of 400 – 800 MPa with a specific gravity of 1460 kg/m$^3$. Jute can be found in countries including India, Eqypt, Guyana, Jamaica, Ghana, Malawi, Sudan and Tanzania [11].

*2.4. Kenaf*

Kenaf, better known as *Hibiscus cannabinus*, is a plant in the family of flowering plants called *Malvaceae* [4] which shows good potential for usage as reinforcement in composite products. The stem of kenaf is divided into two separate parts, the bark (bast) containing relatively long fibers and the stem containing short fibers, called the core (wood) [13] which have gained the interest of utilizing kenaf as fiber source [18]. Kenaf fibers contain 60 – 80% cellulose, 5 – 20% lignin (pectin), and up to 20% moisture. Hemicellulose is responsible for biodegradation, moisture absorption and thermal degradation of the fibers. Lignin is thermally stable (pectin) but responsible for the UV degradation of the fibers [19]. The average tensile strength of kenaf fibers range from 157 – 600 MPa. Diameter of kenaf fiber in the range of 0.15 – 0.30 mm has a density of 1500 kg/m$^3$ [20].

*2.5. Flax*

Flax is a 80 cm high plant which possesses strong fibers throughout the stem whereby the fiber is extracted from the skin of the stem [21]. These fibers from eco-friendly system have wide applications especially in the automobile industries. Flax fiber consists of 64.1 – 71.9 ($\%_{wt}$) of cellulose, 16.7 – 20.6 ($\%_{wt}$) of hemicellulose, 2 – 20.6 ($\%_{wt}$) of lignin, , 8 – 12 ($\%_{wt}$) of moisture content, , 1.8 – 2.3 ($\%_{wt}$) of pectin, and 1.5 – 1.7 ($\%_{wt}$) of wax [22]. The fibers are known for its low density (1.5 g/cm$^3$), high aspect ratio (700 – 2000), high tensile strength (1500 GPa) and stiffness (90 GPa) [21].

*2.6. Cotton*

Cotton which belongs to the genus Malvacae is a cellulosic fiber which are soft and fluffy staple. It is made from the seeds of the cotton plant. Cellulose is the main component of cotton which consists of 94% of 100%. Other components comprise of protein, pectic acid, mineral substances, acids, sugars, pigments and waxes. Although cotton is produced in various countries of the world, however the chemical composition varies depending on the geographical condition. Cotton possess tensile strength from the range of 287 – 597 MPa with specific Young's modulus of 5.5 – 12.6 GPa. [16].

*2.7. Bamboo*

There are about 10 bamboo species found worldwide namely *Bambusa*, *Dinochloa*, *Yushania*, *Chusquea*, *Gigantochloa*, *Phyllostachys*, *Dendrocalamus*, *Racemobambos*, *Thyrsostachys* and *Schizostachyu* [14]. Bamboo is a composite material consists of cellulose fibers with an average tensile resistance of 700 MPa. The cellulose fibers are immersed in a lignin matrix [11]. Higher tensile strength is a key property of bamboo fibers owing to its higher silica content [23]. The tensile strength of bamboo fiber ranges from 73 MPa to 600 MPa. Bamboo fiber density is about 0.6 g/cm$^3$ - 0.91 g/cm$^3$ [9,11,16]. Most of the bamboos are available in India, Sri Lanka, Eqypt, Guyana, Jamaica, Philipines and Malaysia [11].

### *2.8. Hemp*
Hemp is an annual herbaceous flowering plant from the *Cannabis* plant species. For industrial purpose, hemp fiber can be derived into varieties of products including paper, textiles, clothing, biodegradable plastics, paint, insulation, biofuel, food, and animal feed. Hemp fibers are extremely strong and durable and they can be seen in the manufacture of ship canvas sails, rigging and nets because of their strength and resistance to salt water [9]. The tensile strength of hemp falls within the range of 550 – 900 N/mm$^2$, modulus elasticity of 15 – 45 GPa with a density of 1480 g/cm$^3$ [11].

### *2.9. Baggase*
Baggase is the fibrous residue from the remains of crushed sugarcane stalks after the juice is extracted. Baggase fiber are categorized as natural fiber products which biodegrades in 25 – 65 days. These fibers are the bast fiber like banana fibers which consists of water, fibers and small amounts of soluble solids [24]. This dry fiber has been used as biofuel material and in the production of pulp in the paper industry [9]. The tensile strength of baggase fibers falls in the range of 180 – 290 MPa with Young's modulus, 15 – 19 GPa [24].

### *2.10. Pineapple leaf*
Pineapple fiber is produced by pulling or splitting away from the pineapple leaf. Tonnes of pineapple leaf fibers are being produced every year but only very small portions are being used in the feedstock industry and energy production. The fiber is white in color, smooth and glossy, medium length fiber with high tensile strength. Countries such as India, China, Java, Philippines and Malaysia are the countries that produce pineapples. The pineapple leaves fiber exhibits a modulus range from 34.5 – 82.51 GN.m$^{-2}$, tensile strength ranges from 413 to 1627 MN.m$^{-2}$, and an elongation at breakpoint ranges from 0.8 to 1.6% [25].

## 3. Physical and mechanical properties of natural fiber
Details of physical and mechanical properties of different plant fibers such as coir, sisal, jute, kenaf, flax, cotton, bamboo and hemp are summarized in Table 1. Referring to the table, it was found that flax, jute, kenaf and hemp exhibit high tensile strength compared to other types of fibers. Flax possess the highest tensile strength, 345 – 2000 MPa with a density of 1.5g/cm$^3$. Bamboo fiber exhibited the lowest density, 0.6 – 1.1 g/cm$^3$. Meanwhile, coir fiber can withstand maximum elongation at break of 17 – 47% at density of 1.2g/cm$^3$.

## 4. Chemical composition of natural fiber
Most plant fibers are composed of cellulose, hemicellulose, lignin, waxes and water-soluble compounds. The percentage of composition for each of these components varies for different fibers. During biological synthesis of plant cell walls, polysaccharides such as cellulose and hemicellulose are produced simultaneously. Lignin fills the space between the polysaccharide fibers, cementing them together hence the cellulose is protected from chemical and physical damage [12]. The chemical composition of natural fibers varies depending upon the type of fibers. Hemicellulose is responsible for biodegradation, moisture absorption and thermal degradation of the fiber as it shows the least resistance, whereas lignin is thermally stable but prone to UV degradation (Lawrence and Collier, 2005). A common method to remove non-cellulosic materials from plant cellulose fibers is through chemical treatment using sodium hydroxide (NaOH) to remove pectin, lignin, water and alkali-soluble hemicelluloses. A summary for chemical composition of various plant fibers such as coir, sisal, jute, kenaf, flax, cotton, bamboo, hemp, baggase as well as pineapple is shown in Table 2. From the table, it was found that jute contains the highest cellulose, hemicellulose and lignin compared to other fibers.

**Table 1.** Physical and mechanical properties of different plant fibers.

| Fiber | Density ($g/cm^3$) | Tensile strength (MPa) | Elongation at Break (%) | Young's Modulus (GPa) | Reference |
|---|---|---|---|---|---|
| Coir | 1.2 | 175 | 17-47 | 4.0-6.0 | [9] |
| | 1.25 | 220 | 15-25 | - | [26] |
| | 1.2 | 175 | 30 | 4.0-6.0 | [27] |
| | - | 95-118 | - | 8 | [11] |
| | 1.2 | 131-220 | 15-30 | 4-6 | [28] |
| Sisal | 1.5 | 468-700 | 3.0-7.0 | 9.4-22 | [9] |
| | - | 80-840 | - | 9-38 | [29] |
| | 1.33 | 600-700 | 2-3 | 38 | [14] |
| | 1.35-1.45 | 468-100 | 0.4-24 | 0.6-22 | [12] |
| | 1.34 | 600-700 | 2-3 | - | [26] |
| | 1.5 | 511-635 | 2.0-2.5 | 9.4-22 | [27] |
| | - | 347-378 | - | 15 | [11] |
| | 1.3-1.5 | 507-855 | 2.2-2.5 | 9.4-28 | [28] |
| Jute | 1.3 | 393-800 | 1.16-1.5 | 13-55 | [9] |
| | 1.46 | 400-800 | 1.8 | 10-30 | [14] |
| | 1.3-1.46 | 345-1500 | 7.8-8.0 | 2.7-12.6 | [12] |
| | 1.47 | 400-800 | 1.8 | - | [26] |
| | 1.3 | 393-773 | 1.5-1.8 | 26.5 | [27] |
| | - | 400-800 | - | 10-30 | [11] |
| | 1.3-1.5 | 393-800 | 1.5-1.8 | 10-55 | [28] |
| Kenaf | 1.45 | 157-930 | 1.6 | 22.1-60 | [2] |
| | 1.45 | 930 | 1.6 | 36.5 | [8] |
| | 1.2-1.4 | 433.1 | 1.8 | 26.9 | [9] |
| | - | 129 | - | 12.5 | [13] |
| Flax | 1.5 | 345-2000 | 1.2-3.2 | 15-80 | [9] |
| | - | 300-1500 | - | 24-80 | [29] |
| | 1.29-1.5 | 345-1100 | 1.5-5.0 | 27.6-160 | [12] |
| | 1.5 | 345-1035 | 2.7-3.2 | 27.5 | [27] |
| | 1.5 | 345-1830 | 1.2-3.2 | 27-80 | [28] |
| Cotton | 1.5-1.6 | 200-597 | 6.0-8.0 | 5.5-12.6 | [12] |
| | 1.51 | 400 | 8-25 | - | [26] |
| | 1.5-1.6 | 287-597 | 7.0-8.0 | 5.5-12.6 | [27] |
| | 1.5-1.6 | 287-800 | 3.0-10 | 5.5-13 | [28] |
| Bamboo | 0.6-0.91 | 193-600 | 1.4 | 20.6-46.0 | [9] |
| | 0.6-1.1 | 140-230 | - | 11-17 | [14] |
| | - | 73-505 | - | 10-40 | [11] |
| Hemp | 1.48 | 550-900 | 1.6 | 26-80 | [9] |
| | - | 310-900 | - | 30-70 | [29] |
| | 1.48 | 550-900 | 1.6 | 70 | [14] |
| | 1.48 | 690 | 1.6 | 30-60 | [27] |
| | - | 550-900 | - | 15-45 | [11] |
| | 1.5 | 550-1110 | 1.6 | 58-70 | [28] |
| Pineapple | 1.07 | 126.6 | 2.2 | 4.4 | [9] |

**Table 2.** Chemical composition of natural fiber.

| Fiber | Cellulose (wt %) | Hemicellulose (wt %) | Lignin (wt %) | Waxes (wt %) | Reference |
|---|---|---|---|---|---|
| Coir | 32-43 | 0.15-0.25 | 40.45 | - | [30] |
| Sisal | 65 | 12 | 9.9 | 2 | [30] |
| | 43-78 | 10-14 | 3.75-10 | 2 | [12] |
| Jute | 61-71 | 14-20 | 12-13 | 0.5 | [30] |
| | 61.1-71.5 | 13.6-20.4 | 12-13 | 0.5 | [12] |
| Kenaf | 72 | 20.3 | 9 | - | [30] |
| Flax | 71 | 18-20 | 2.2 | 1.5 | [30] |
| | 71 | 18.6-20.6 | 2.2 | 1.7 | [12] |
| Cotton | 85-90 | 5.7 | - | 0.6 | [12] |
| Bamboo | 26-43 | 30 | 21-31 | - | [30] |
| Hemp | 68 | 15 | 10 | 0.8 | [30] |
| Bagasse | 55.5 | 16.8 | 25.3 | - | [30] |
| Pineapple | 81 | - | 12.7 | - | [30] |
| | 81.27 | 12.31 | 3.46 | - | [11] |

## 5. Conclusions

A review on the physical and mechanical properties as well as the chemical composition of natural fibers was conducted. In comparison to other types of fibers, it was found that flax and jute exhibited the highest tensile strength in excess of 1500 MPa, hence suitable for use as construction material. It was found that all plant fiber are primarily made of cellulose, hemicellulose and lignin.

**Acknowledgement**

This research is supported by the internal grant of Universiti Malaysia Pahang RDU 180349 and RDU 1803105. The authors would like to acknowledge the Center of Excellence for Advanced Research in Fluid Flow (CARIFF) and the Faculty of Civil Engineering a& Earth Resources, Universiti Malaysia Pahang for the equipment and facilities provided.

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