Journal of Civil Engineering and Construction Technology Vol. 3(3), pp. 80-89, March 2012
Available online at http://www.academicjournals.org/JCECT
DOI: 10.5897/JCECT11.100
ISSN 2141-2634 ©2012 Academic Journals

Review

Natural fibres as construction materials*

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Accepted 20 February, 2012

This paper reviews the properties of different natural fibres. These natural fibres were investigated by different researchers as a construction material to be used in composites (such as cement paste, mortar and/or concrete). The different researches carried out and the conclusions drawn are briefly presented. The aim of this review is to compile the available data of different natural fibres evaluated in last few decades, and thus, it can be used as a reference/guideline for the upcoming research of a particular fibre. Natural fibres are used to increase the strength properties of the composites. But all properties cannot be improved at the same time because fibres have their own characteristics. So it is recommended that appropriate fibre should be used for a particular purpose. Also, there should be guideline/criteria for acceptance of natural fibres, because of variable properties of a particular fibre in different regions. No doubt, natural fibres can be used in a variety of manners, but still, there is a need of research for investigating the further properties of fibres.

Key words: Natural fibres, composites, cement paste, mortar, concrete.

INTRODUCTION

Fibres are thread like materials which can be used for different purposes. Fibres produced by plants (vegetable, leaves and wood), animals and geological processes are known as natural fibres. Researchers have used plant fibres as an alternative source of steel and/or artificial fibres to be used in composites (such as cement paste, mortar and/or concrete) for increasing its strength properties. These plant fibres, herein referred as natural fibres, include coir, sisal, jute, *Hibiscus cannabinus*, eucalyptus grandis pulp, malva, ramie bast, pineapple leaf, kenaf bast, sansevieria leaf, abaca leaf, vakka, date, bamboo, palm, banana, hemp, flax, cotton and sugarcane (Ramakrishna and Sundararajan, 2005; Agopyan et al., 2005; Paramasivam et al., 1984; Ramakrishna and Sundararajan, 2005; Li et al., 2007; Asasutjarita et al., 2007; Toledo Filho et al., 2005; Munawar et al., 2007; Rao and Rao, 2007; Li et al., 2006; Fernandez, 2002; Reis, 2006; Aggarwal, 1992; Satyanarayana et al., 1990; Corradini et al., 2006; Toledo Filho et al., 1999). Natural fibres are cheap and locally available in many countries. So their use as a construction material for increasing properties of composites costs a very little (almost nothing when compared to the total cost of the composites). Their use can lead to have sustainable development (Ramakrishna and Sundararajan, 2005). Another benefit may also include the easy usage/handling of fibres due to their flexibility, because the problem arises when high percentage of fibres is to be used as in case of steel fibres. But for use of very high percentage of fibres, there is a need to invent a methodology for casting. Volume fraction and fibre content are two terminologies used for expressing the quantities of fibres in a given composites (Ramakrishna and Sundararajan, 2005; Agopyan et al., 2005; Paramasivam et al., 1984; Ramakrishna and Sundararajan, 2005; Li et al., 2007; Asasutjarita et al., 2007; Toledo Filho et al., 2005; Li et al., 2006; Fernandez, 2002; Reis, 2006; Aggarwal, 1992; Satyanarayana et al., 1990; Corradini et al., 2006; Toledo Filho et al., 1999). Volume fraction can be the part of total volume of composite or the part of volume of any ingredient to be replaced. Fibre content can be the part of

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*Also presented in 11th International Conference on Non-conventional Materials and Technologies (NOCMAT 2009) 6-9 September 2009, Bath, UK.

total weight of composite or the part of weight of any ingredient to be replaced. Researchers have emphasized on the selection of optimum quantity of fibres along with the optimum fibre length (for example, matrix/composite with 3% volume fraction of fibres and 4 cm fibre length can achieved maximum strength, any further increase/decrease in volume fraction and/or fibre length may decrease strength of matrix/composite). Fibre reinforced composites can be used for many civil engineering applications including roofing tiles (Agopyan et al., 2005), corrugated slabs (Paramasivam et al., 1984), simple slab panels (Ramakrishna and Sundararajan, 2005), boards (Li et al., 2007; Asasutjarita et al., 2007; Aggarwal, 1992) and mortar (Toledo Filho et al., 2005) etc.

BRIEF DESCRIPTIONS OF SOME NATURAL FIBRES

Coir/coconut fibres

Coir fibre is extracted from the outer shell of a coconut. There are two types of coir fibres, brown fibre extracted from matured coconuts and white fibres extracted from immature coconuts. Brown fibres are thick, strong and have high abrasion resistance. White fibres are smoother and finer, but also weaker.

Sisal fibres

Sisal fibres are stiff fibres extracted from an agave plant. These fibres are straight, smooth and yellow in colour. Strength, durability and ability to stretch are some important properties of sisal fibres.

Jute fibres

Jute fibre is produced from genus *Corchorus*, family Tiliaceae. It is a long, soft and shiny vegetable fibre having off-white to brown colour. High tensile strength and low extensibility are some key properties of jute fibres.

Hibiscus cannabinus (Kenaf) fibres

H. cannabinus (kenaf) is extracted from Malvaceae, a family of flowering plant.

Flax fibres

Flax fibre is extracted from the skin of the stem of flax plant. It is flexible and soft fibre.

Cotton fibres

Cotton fibre grows around the seeds of the cotton plant. It is soft and staple fibre.

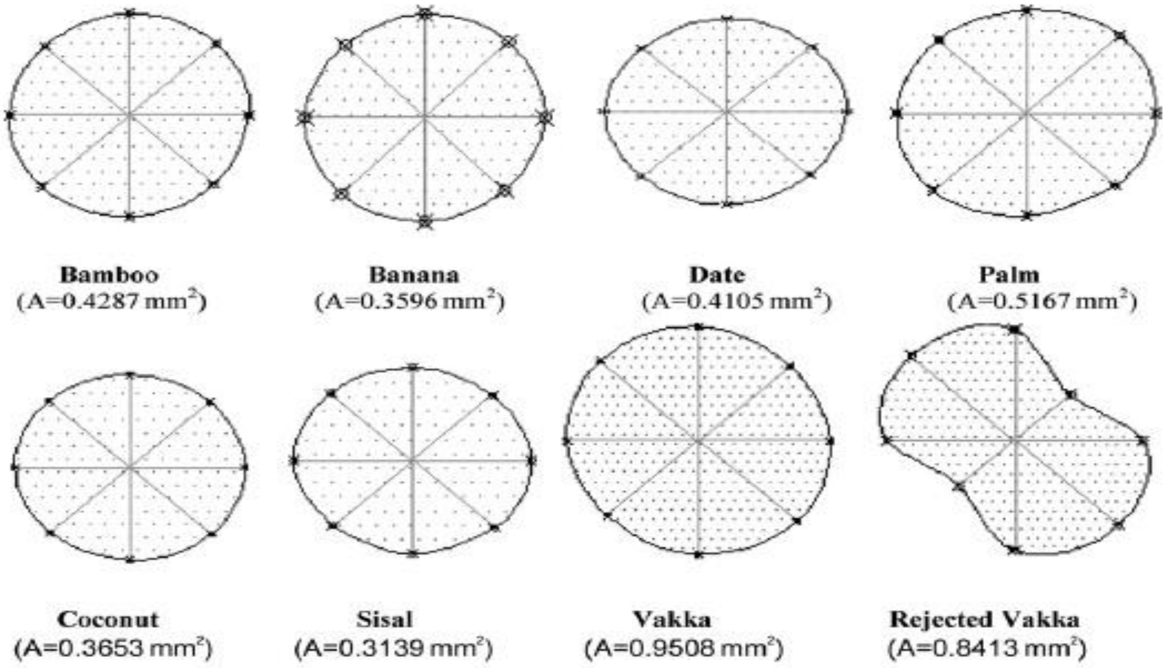
PHYSICAL AND MECHANICAL PROPERTIES OF NATURAL FIBRES

The cross sections of some natural fibres (Rao and Rao, 2007) are shown in Figure 1. The physical and mechanical properties of natural fibres are shown in Table 1. The conditions specifically mentioned by the researchers are given at the end of table. Some fibres like coir, sisal and jute were studied by many researchers for different purposes. There is a huge difference in some reported properties of a particular fibre, for example, diameter of coir fibres is approximately same and magnitudes of tensile strength are quite different, for example, compare tensile strength of coir fibres mentioned by Ramakrishna and Sundararajan (2005b) and Toledo Filho et al. (2005) as shown in Table 1. The reason could be the source of fibres from different regions of the world. Also range shown for a particular fibre is quite wide; for example, Toledo Filho et al. (2005) mentioned the density of coir and sisal fibre as 0.67 to 10.0 g/cm^3 and 0.75 to 10.7 g/cm^3, respectively. These values seem to be unrealistic, real values may be 0.67 to 1.00 g/cm^3 and 0.75 to 1.07 g/cm^3 for coir and sisal fibres, respectively. No doubt, there are variations in the properties of natural fibres, and this makes it difficult for their frequent use as construction material. That's why the purpose of current study is the compilation of reported data for the properties of fibres which can be used as a guideline. But after compilation, some huge variation is seen for example; compare diameter and tensile strength of coir fibres as reported by Ramakrishna and Sundararajan (2005b) and Reis (2006) as shown in Table 1. Such variations should be properly addressed and explained in the guidelines. Therefore, there should be guideline/criteria/code for the acceptance of a particular natural fibre for a particular purpose, as we have criteria/code for acceptance of bricks, steel, concrete etc. These criteria(s) may be at local, national and/or international level.

The correlations between some mechanical properties of natural fibres are shown in Figure 2. The Figures 2a to 2d show the stress-strain relationship for different fibres. But the relationship for a particular fibre reported by different researchers seems to be a little bit different in these graphs, for example, compare stress-strain relationship for coir fibre in Figure 2b (Munawar et al., 2007), Figure 2c (Satyanarayana et al., 1990) and Figure 2d (Rao and Rao, 2007). Emphasis should be made to develop typical curves, not only for stress-strain relationship but also for other relationships. The variation of tensile strength and Young's modulus with fibre diameter is shown in Figure 2e and 2f, respectively. It can be observed that both decreases with increasing fibre diameter.

CHEMICAL COMPOSITIONS OF NATURAL FIBRES

Most of natural fibres contain cellulose, hemi-cellulose



Bamboo (A=0.4287 mm^2)

Banana (A=0.3596 mm^2)

Date (A=0.4105 mm^2)

Palm (A=0.5167 mm^2)

Coconut (A=0.3653 mm^2)

Sisal (A=0.3139 mm^2)

Vakka (A=0.9508 mm^2)

Rejected Vakka (A=0.8413 mm^2)

Figure 1. Cross sections of some natural fibres (Rao and Rao, 2007).

and lignin as major composition. The properties of natural fibres depend on its composition. The pre-treatment of natural fibres changes the composition and ultimately changes the properties of the natural fibres. Sometimes it improves the behaviour of fibres but sometimes its effect is not favourable. The chemical composition of natural fibres is shown in Table 2. The effect of pre-treatment of coir fibre was investigated by Asasutjarita et al. (2007). On the other hand, chemical composition may also change due to weather effect (Ramakrishna and Sundararajan, 2005b). These studies are further explained in next section.

BASIC RESEARCH ON NATURAL FIBRES AND RESULTING COMPOSITES

Ramakrishna and Sandararajan (2005b) investigated the effect of variation in chemical composition on tensile strength of four natural fibres (coir, sisal, jute and *H. cannabinus* fibres), when subjected to alternate wetting and drying, and continuous immersion for 60 days in three mediums (water, saturated lime and sodium hydroxide). Chemical composition of all fibres changed for tested conditions (continuous immersion was found to be critical), and fibres lost their strength. But coir fibres were reported best for retaining a good percentage of its original tensile strength for all tested conditions. Sisal retained 60 to 70% of their initial tensile strength after exposure in fresh water only.

Agopyan et al. (2005) studied the selected fibres (coir, sisal and pulp from eucalyptus) as replacement of asbestos in roofing tiles. Coir fibres were more suitable among the studied fibres.

Pramasivan et al. (1984), gave recommendations (about fibre length and volume fraction of coconut fibres) for the production of coconut fibre reinforced corrugated slabs along with the casting technique. Tests for flexural strength, thermal and acoustic properties were performed. For producing slabs with a flexural strength of 22 MPa, a volume fraction of 3%, a fibre length of 25 mm and a casting pressure of 1.5 atm were recommended. The thermal conductivity and sound absorption coefficient for low frequency were acceptable.

Ramakrishna and Sandararajan (2005a) performed the experimental investigations for measuring the resistance to impact loading on cement-sand mortar (1:3) slabs. The slab specimens (300 × 300 × 20 mm) were reinforced with natural fibres (coir, sisal, jute, *H. cannabinus*) having four different fibre contents (0.5, 1.0, 1.5 and 2.0% by weight of cement) and three fibre lengths (20, 30 and 40 mm). Composite with coir fibre content of 2% and a fibre length of 40 mm showed best performance by absorbing 253.5 J impact energy among all tested fibres. In general, the impact resistance was increased by 3 to 18 times for tested fibre reinforced mortar slabs than that of the unreinforced mortar slab. All fibres, except coir fibres, showed fibre fracture, at ultimate failure where as coir fibre showed fibre pull out failure.

Li et al. (2007) studied the fibre volume fraction (number of mesh layers) and the fibre surface treatment with a wetting agent for coir mesh reinforced

Table 1. Physical and mechanical properties of natural fibres.

S/No.	Fibre	Diameter	Length	Tensile strength	Specific Tensile strength	Average Tensile Modulus	Specific Tensile Modulus	Tensile Strain	Elongation	Young's Modulus	Specific Young's Modulus	Toughness	Specific gravity	Permeable Void **	Moisture Content	Water Absorption Saturation *	Elastic Modulus	Density	Reference
1	Coir	0.40 - 0.10 mm	60 - 250 mm	15 - 327 N/mm^2	-	-	-	-	75.00 %	-	-	-	-	-	-	-	-	-	Ramakrishna& Sundararaja 2005b
		210 µm [a, b]	-	107 MPa [e]	-	-	-	-	37.7 % [d, e]	-	-	-	1104 - 1370 Kg/m^3	56.6 - 73.1 %	-	93.8 – 161.0 %	2.8 GPa [e]	-	Agopyan et al. 2005 [c]
		0.3 mm	-	69.3 N/mm^2 [f]	-	-	-	-	-	-	-	-	1.14	-	-	-	2.0 x 10^3 N/mm^2	-	Paramasivam et al. 1984
		-	-	50.89 MPa [g]	-	-	-	-	17.6 mm [g]	-	-	-	1.00	-	-	180 % [h]	-	-	Ramakrishna& Sundararaja 2005a [i]
		270 ± 73 µm	50 ± 10 mm	142 ± 36 MPa	-	-	-	-	24 ± 10 % [k]	-	-	-	-	-	10% [m]	24 % [l]	2.0 ± 0.3 GPa	-	LI et al. 2007
		0.11 – 0.53 mm	-	108.26 – 251.90 MPa	-	-	-	-	13.70 – 41.00 % [n]	-	-	-	-	-	-	85.0 – 135.0 %	2.50 – 4.50 GPa	0.67 – 10.0 g/cm^3	Toledo Filho at al. 2005
		121.3 ± 4.9 µm	-	137 ± 11 MPa	158 MPa	-	-	-	-	3.7 ± 0.6 GPa	4.2 GPa	21.5 ± 2.4 MPa	-	-	-	-	-	0.87 g/cm^3	Munawar at al. 2007 [0]
		-	-	500 MPa	0.4348 MPa / (Kg m^{-3})	2.50 GPa	2.17 MPa / (Kg m^{-3})	20.00 %	-	-	-	-	-	-	11.36% [p]	-	-	1150 Kg/m^3	Rao and Rao et al. 2007
		-	-	175 MPa	-	-	-	-	30.00 %	4.0 - 6.0 GPa	-	-	-	-	-	-	-	1.2 g/cm^3	Fernandez 2002
		0.1 - 0.4 mm	-	174 MPa	-	-	-	-	10 - 25 %	-	-	-	-	-	-	-	16 - 26 GPa	-	Reis 2006
		0.1 - 0.4 mm	50 - 250 mm	100 - 130 N/mm^2	-	-	-	-	10 - 26 %	-	-	-	-	-	-	130 - 180 %	19 -26 N/mm^2	145 - 280 Kg/m^3	Aggarwal 1992
		100 - 450 µm	-	106 - 175 MPa	-	-	-	-	17 - 47 %	4.0 - 6.0 GPa	-	-	-	-	-	-	-	1150 Kg/m^3	Satyanarayana et al. 1990

Table 1. Contd.

2	Sisal	0.10 - 0.50 mm	180 - 160 mm	31 - 221 N/mm^2	-	-	-	-	14.8 %	-	-	-	-	-	-	-	-	-	Ramakrishna& Sundararaja 2005b
		227 µm [a, b]	-	458 MPa [e]	-	-	-	-	4.3 % [d, e]	-	-	-	1117 - 1165 Kg/m^3	60.9 - 77.3 %	-	110.0 – 240.0 %	15.2 GPa [e]	-	Agopyan et al. 2005 [c]
		-	-	58.16 MPa [g]	-	-	-	-	6.0 mm [g]	-	-	-	1.17	-	-	200 % [h]	-	-	Ramakrishna& Sundararaja 2005a [i]
		0.08 – 0.30 mm	-	227.80 – 1002.3 MPa	-	-	-	-	2.08 – 4.18 % [n]	-	-	-	-	-	-	190.00 – 250.00 %	10.94 – 26.70 GPa	0.75 – 10.70 g/cm^3	Toledo Filho et al. 2005
		128.6 ± 6.4 µm	-	375 ± 38 MPa	493 MPa	-	-	-	-	9.1 ± 0.8 GPa	12.1 GPa	10.7 ± 1.2 MPa	-	-	-	-	-	0.76 g/cm^3	Munawar et al. 2007 [o]
		-	-	567 MPa	0.3910 MPa / $(Kg\ m^{-3})$	10.40 GPa	7.17 MPa / $(Kg\ m^{-3})$	5.45 %	-	-	-	-	-	-	9.76 % [p]	-	-	1450 Kg/m^3	Rao & Rao 2007
		-	-	511 - 635 MPa	-	-	-	-	2.0 - 2.5 %	9.4 - 22.0 GPa	-	-	-	-	-	-	-	1.5 g/cm^3	Fernandez 2002
		50 - 200 µm	-	568 - 640 MPa	-	-	-	-	3 - 7 %	9.4 – 15.8 GPa	-	-	-	-	-	-	-	1450 Kg/m^3	Satyanarayana 1990
		0.15 - 0.26 mm	1200 - 1500 mm	297.83 MPa	-	-	-	-	-	-	-	-	0.69		11.00 %	119.0 %	11.37 GPa	-	Toledo Filho 1999
3	Jute	0.04 - 0.35 mm	128 - 1525 mm	29 - 312 N/mm^2	-	-	-	-	19.00 %	-	-	-	-	-	-	-	-	-	Ramakrishna& Sundararaja 2005b
		-	-	60.14 MPa [g]	-	-	-	-	13.10 mm [g]	-	-	-	1	-	-	281 % [h]	-	-	Ramakrishna& Sundararaja2005a [i]
		-	-	393 - 773 MPa	-	-	-	-	1.5 - 1.8 %	26.5 GPa	-	-	-	-	-	-	-	1.3 g/cm^3	Fernandez 2002
4	*Hibiscus cannabinus* (or Kenaf Bast)	0.04 - 0.16 mm	163-1527 mm	18 - 180 N/mm^2	-	-	-	-	12.4 %	-	-	-	-	-	-	-	-	-	Ramakrishna& Sundararaja 2005b
		-	-	76.04 MPa [g]	-	-	-	-	6.70 mm [g]	-	-	-	0.71	-	-	285 % [h]	-	-	Ramakrishna& Sundararaja2005a [i]
		68.5 ± 3.4 µm	-	476 ± 46 MPa	361 MPa	-	-	-	-	25.1 ± 2.0 GPa	19.2 GPa	5.2 ± 0.7 MPa	-	-	-	-	-	1.31 g/cm^3	Munawar et al. 2007 [o]

Table 1. Contd.

5	Eucalyptus grandis pulp	10.9 μm$^{a, b}$	-	-	-	-	-	-	-	-	-	-	1609 Kg/m^3	89.2 %	-	643.00%	-	-	Agopyan et al. 2005 [c]
6	Malva	-	-	160 MPa [e]	-	-	-	-	5.2 %[d, e]	-	-	-	-	-	-	-	17.4 GPa [e]	-	Agopyan et al. 2005 [c]
7	Ramie Bast	49.6 ± 3.6 μm	-	849 ± 108 MPa	615 MPa	-	-	-	-	28.4 ± 3.6 GPa	20.6 GPa	16.0 ± 2.4 MPa	-	-	-	-	-	1.38 g/cm^3	Munawar et al. 2007 [o]
		-	-	400 - 938 MPa	-	-	-	-	3.6 - 3.8 %	61.4 - 128 GPa	-	-	-	-	-	-	-	-	Fernandez 2002
8	Pine-apple leaf	57.5 ± 3.9 μm	-	654 ± 46 MPa	494 MPa	-	-	-	-	27.0 ± 2.3 GPa	20.5 GPa	9.5 ± 0.8 MPa	-	-	-	-	-	1.32 g/cm^3	Munawar et al. 2007 [o]
		20 - 80 μm	-	413 - 1627 MPa	-	-	-	-	0.8 - 1 %	34.5 – 82.5 GPa	-	-	-	-	-	-	-	1440 Kg/m^3	Satyanarayana et al. 1990
9	Sanse-vieria Leaf	88.0 ± 4.3 μm	-	562 ± 36 MPa	631 MPa	-	-	-	-	14.4 ± 0.9 GPa	16.2 GPa	12.5 ± 0.9 MPa	-	-	-	-	-	0.89 g/cm^3	Munawar et al. 2007 [o]
10	Abaca Leaf	122.1 ± 6.2 μm	-	452 ± 34 MPa	545 MPa	-	-	-	-	12.9 ± 0.9 GPa	15.6 GPa	10.0 ± 1.9 MPa	-	-	-	-	-	0.83 g/cm^3	Munawar et al. 2007 [o]
11	Vakka	-	-	549 MPa	0.6778 MPa / (Kg m^{-3})	15.85 GPa	19.56 MPa / (Kg m^{-3})	3.46 %	-	-	-	-	-	-	12.09 % [p]	-	-	810 Kg/m^3	Rao & Rao 2007
12	Date Leaf	-	-	309 MPa	0.3121 MPa / (Kg m^{-3})	11.32 GPa	11.44 MPa / (Kg m^{-3})	2.73 %	-	-	-	-	-	-	10.67 % [p]	-	-	990 Kg/m^3	Rao & Rao 2007
13	Date amplexicaul	-	-	459 MPa	0.4781 MPa / (Kg m^{-3})	1.91 GPa	1.99 MPa / (Kg m^{-3})	24.00 %	-	-	-	-	-	-	09.55 % [p]	-	-	960 Kg/m^3	Rao & Rao 2007
14	Bamboo-mechanically extracted	-	-	503 MPa	0.5527 MPa / (Kg m^{-3})	35.91 GPa	39.47 MPa / (Kg m^{-3})	1.40 %	-	-	-	-	-	-	09.16 % [p]	-	-	910 Kg/m^3	Rao & Rao 2007
15	Bamboo-chemically extracted	-	-	341 MPa	0.3831 MPa / (Kg m^{-3})	19.67 GPa	22.10 MPa / (Kg m^{-3})	1.73 %	-	-	-	-	-	-	10.14 % [p]	-	-	890 Kg/m^3	Rao & Rao 2007

Table 1. Contd.

16	Palm	-	-	377 MPa	0.3660 MPa / (Kg m^{-3})	2.75 GPa	2.67 MPa / (Kg m^{-3})	13.71 %	-	-	-	-	-	-	12.08 %[p]	-	-	1030 Kg/m^3	Rao & Rao 2007
17	Banana	-	-	600 MPa	0.4444 MPa / (Kg m^{-3})	17.85 GPa	13.22 MPa / (Kg m^{-3})	3.36 %	-	-	-	-	-	-	10.71 %[p]	-	-	1350 Kg/m^3	Rao & Rao 2007
		0.154 mm	-	384 MPa	-	-	-	-	5.20 %	-	-	-	-	-	-	-	20 - 51 GPa	-	Reis 2006
		80 - 250 µm	-	54 - 754 MPa	-	-	-	-	10.35%	7.7 – 20.0 GPa	-	-	-	-	-	-	-	1350 Kg/m^3	Satyanarayana et al. 1990
18	Hemp	23.15 ± 17.60 µm[j]	-	900 MPa	-	-	-	-	-	-	-	-	1.50 g/mm^3	9.40 ± 0.53 %	85 -105 %	-	34 GPa	-	Li et al. 2006
		-	-	690 MPa	-	-	-	-	1.60%	-	-	-	-	-	-	-	-	-	Fernandez 2002
19	Flax	-	-	345 - 1035 MPa	-	-	-	-	2.7 - 3.2%	27.6 GPa	-	-	-	-	-	-	-	1.50 g/cm^3	Fernandez 2002
20	Cotton	-	-	287 - 597 MPa	-	-	-	-	7.0 - 8.0%	5.5 -12.6 GPa	-	-	-	-	-	-	-	1.5 - 1.6 g/cm^3	Fernandez 2002
21	Sugar Bagasse	0.2 - 0.4 mm	-	170 -290 MPa	-	-	-	-	-	-	-	-	-	-	-	-	15 -19 GPa	-	Reis 2006
22	Palmyrah	70 - 1300 µm	-	180 - 215 MPa	-	-	-	-	7 - 15%	4.4 – 6.1 GPa	-	-	-	-	-	-	-	1090 Kg/m^3	Satyanarayana et al. 1990
23	Talipot	200 - 700 µm	-	143 - 263 MPa	-	-	-	-	2.7 - 5 %	9.3 – 13.3 GPa	-	-	-	-	-	-	-	890 Kg/m^3	Satyanarayana et al. 1990

[a] Coefficients of variation frequently over 50% - [b] Determinations of thickness by scanning electron microscopy - [c] Brazilian Standard NBR-9778 - [d] Elongation on rupture – [e] Authors took other researchers data - [f] Ultimate value - [g] Maximum Value and it do not agree with the general accepted value which may be due to the test conditions adopted by [4] – [h] In 24hrs – [i] In natural dry condition - [j] width - [k] At break - [l] Water absorption ratio (100% humidity) - [m] Moisture content (20ºC) - [n] Strain at failure – [o] Data for mechanical properties are given as averages and 95% confidence interval - [p] Percentage moisture present on weight basis at normal atmospheric condition **By Vol. *By mass.

mortar (CMRM) using nonwoven coir mesh matting. They performed four-point bending tests on slab specimens. They concluded that the composites reinforced with three layers of coir mesh having fibre content of 1.8% resulted in a 40% improvement in the maximum flexural stress. These were 20 times higher in flexural ductility and 25 times stronger in flexural toughness and toughness index.

Asasutjarita et al. (2007) determined the physical, mechanical and thermal properties of coconut coir-based light weight cement board after 28 days of hydration. The parameters studied were fibre length, coir pre-treatment and mixture ratio. Boiled and washed fibres with 6 cm

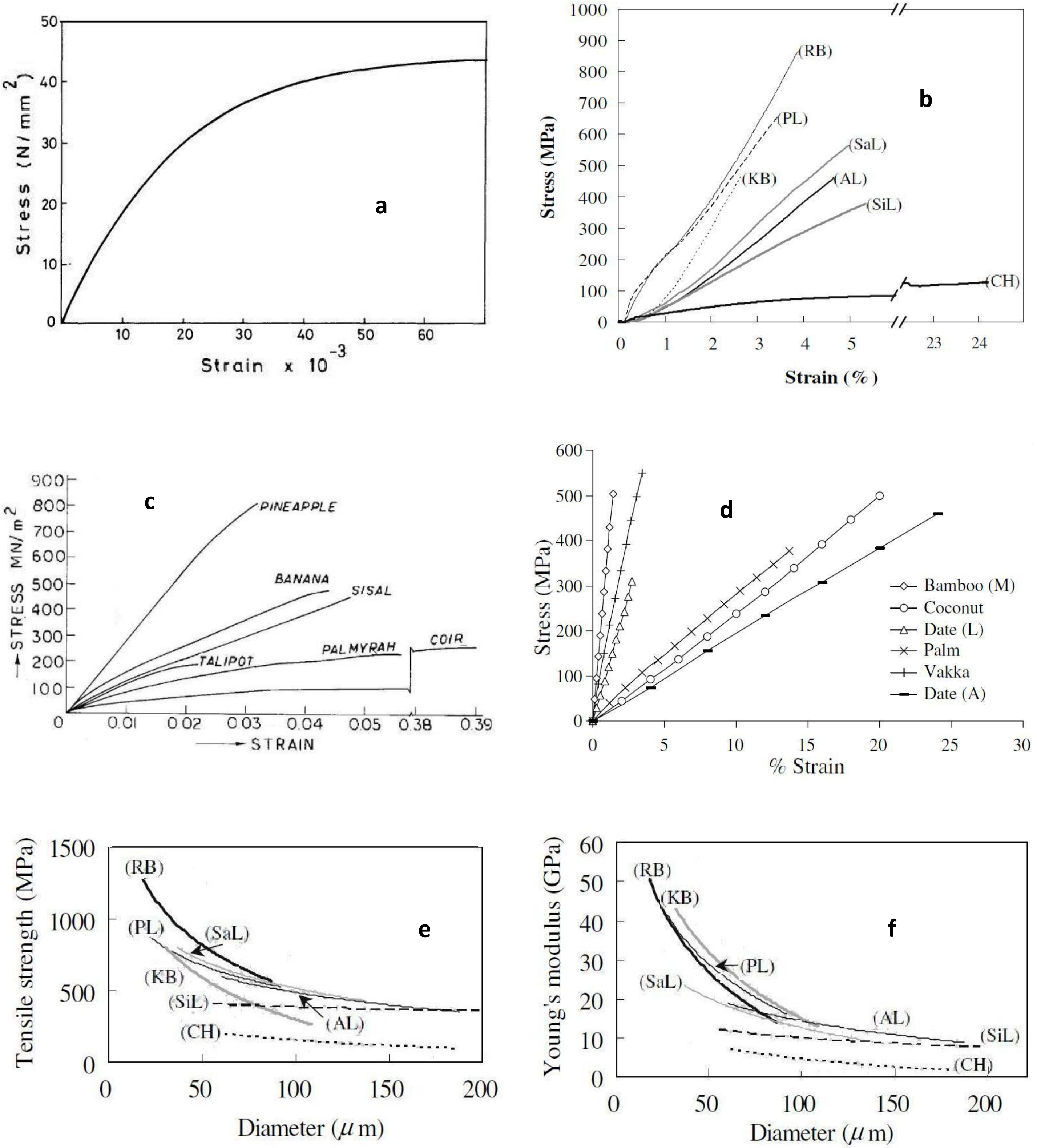


Figure 2. Correlations of mechanical properties for natural fibres. **a,** Mean stress-strain curve for coconut fibre (Paramasivam et al., 1984); **b,** typical stress-strain curves for the non-wood plant fibre bundles (Munawar et al., 2007)*; **c,** stress-strain curves of natural fibres (Satyanarayana et al., 1990); **d,** stress versus percentage strains of various fibres (Rao and Rao, 2007); **e,** relationship between diameter and tensile strength of non-wood plant fibre bundles (Munawar et al., 2007)*; **f,** relationship between diameter and Young's modulus of non-wood plant fibre bundles (Munawar et ai., 2007)*. (*Note: RB, Ramie bast fibre; PL, pineapple leaf fibre; KB, kenaf bast fibre; SaL, sansevieria leaf fibre; CH, coconut husk fibre; AL, abaca leaf fibre; SiL, sisal leaf fibre).

Table 2. Chemical composition of natural fibres.

S/No.	Fibre	Hemi-cellulose (%)	Cellulose (%)	Lignin (%)	Reference
1	Coir	31.1[a]	33.2[a]	20.5[a]	Ramakrishna and Sundararajan (2005b)
		15 - 28[b]	35 - 60[b]	20 - 48[b]	Agopyan et al. (2005)
		16.8	68.9	32.1	Asasutjarita et al. (2007)
		-	43	45	Satyanarayana et al. (1990)
		0.15 - 0.25	36 - 43	41 - 45	Corradini et al. (2006)
2	Sisal	26.0[a]	38.2[a]	26.0[a]	Ramakrishna and Sundararajan (2005b)
		10 - 21[b]	43 - 88 [b]	20 - 48[b]	Agopyan et al. (2005)
		12.0	65.8	9.9	Fernandez (2002)
		-	67	12	Satyanarayana et al. (1990)
		10 -14	67 - 78	8 -11	Corradini et al. (2006)
3	Jute	22.7[a]	33.4[a]	28.0[a]	Ramakrishna and Sundararajan (2005b)
		12.0	64.4	11.8	Fernandez (2002)
		13.6 - 20.4	61 - 71.5	12 - 13	Corradini et al. (2006)
4	*H. cannabinus*	25.0[a]	28.0[a]	22.7[a]	Ramakrishna and Sundararajan (2005b)
5	Eucalyptus bleached kraft	-	89[b]	0.5[b]	Agopyan et al. (2005)
6	Malva	-	76[b]	10[b]	Agopyan et al. (2005)
7	Ramie	13.1	68.6	0.6	Fernandez (2002)
8	Flax	16.7	64.1	2.0	Fernandez (2002)
9	Cotton	5.7	82.7	-	Fernandez (2002)
10	Banana	-	66	5	Satyanarayana et al. (1990)
11	Pineapple leaf	-	81	12	Satyanarayana et al. (1990)
12	Palmyrah	-	40 - 52	42 - 43	Satyanarayana et al. (1990)
13	Talipot	-	67 - 68	28 - 29	Satyanarayana et al. (1990)

[a],The compositions are percentage by weight of dry and powdered fibre sample and only the salient features are indicated; [b], chemical compositions are percentage by mass and authors took other researchers data.

fibre length gave better results. On the other hand, optimum mixture ratio by weight for cement : fibre : water was 2:1:2. Also, the tested boards had a lower thermal conductivity than that of commercial flake board composite.

Munawar et al. (2007) characterized the morphological, physical and mechanical properties of the non-wood plant fibre bundles (ramie, pineapple, sansevieria, kenaf, abaca, sisal and coconut fibre). The larger the diameter of the fibre bundles, the lesser will be the density, tensile strength and the Young's modulus.

Rao and Rao (2007) determined the tensile properties of natural fibres [vakka, date, bamboo {mechanically and chemically extracted}, sisal, banana, coconut and palm fibres] under similar conditions. It was noted that the ultimate tensile strain of different fibres increased in the sequence of mechanically extracted bamboo (bamboo-M), chemically extracted bamboo (bamboo-C), date leaf, banana, vakka, sisal, palm, coconut and date. They concluded that the increase of ultimate tensile strength of different fibres was in the order of date leaf, bamboo-C, palm, date, coconut, bamboo-M, vakka, sisal and banana. But the ascendance in the tensile modulus of different fibres was in the order of date, coconut, palm, sisal, date leaf, vakka, banana, bamboo-C and bamboo-M.

Reis (2006) investigated the mechanical characterization (flexural strength, fracture toughness and fracture energy) of epoxy polymer concrete reinforced with natural fibres (coconut, sugar cane bagasse, and banana fibres). Fracture toughness and fracture energy of polymer concrete can be increased by using chopped coconut fibre and sugar cane bagasse fibre in concrete. And flexural strength can be slightly increased by using coconut fibre only.

CONCLUSIONS

The use of natural fibres, as reinforcement of composites (such as cement paste, mortar and/or concrete), are economical for increasing their certain properties; for example, tensile strength, shear strength, toughness and/or combinations of these. Since, variations exist in properties of natural fibres; therefore, such deviations should be properly addressed as we have categorized the gradation of aggregates. For all these, natural fibres need to be properly tested and results should be published in a systematic manner that is, there should be a guideline for using the specific fibres as construction material.

ACKNOWLEDGMENTS

The careful review and constructive suggestions by the anonymous reviewers are gratefully acknowledged.

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