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Coconut Fibre – A Versatile Material and its Applications in Engineering

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ABSTRACT

This paper presents the versatility of coconut fibres and its applications in different branches of engineering, particularly in civil engineering as a construction material. Coconut fibre is one of the natural fibres abundantly available in tropical regions, and is extracted from the husk of coconut fruit. Not only the physical, chemical and mechanical properties of coconut fibres are shown; but also properties of composites (cement pastes, mortar and/or concrete etc), in which coconut fibres are used as reinforcement, are discussed. The research carried out and the conclusions drawn by different researchers in last few decades are also briefly presented. Graphs showing the relationship between different properties are also shown in this paper. Coconut fibres reinforced composites have been used as cheap and durable non-structural elements. The aim of this review is to spread awareness of coconut fibres as a construction material in civil engineering.

INTRODUCTION

Coconut fibre is extracted from the outer shell of a coconut. The common name, scientific name and plant family of coconut fibre is Coir, Cocos nucifera and Arecaceae (Palm), respectively.

There are two types of coconut 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. Coconut fibres are commercial available in three forms, namely bristle (long fibres), mattress (relatively short) and decorticated (mixed fibres). These different types of fibres have different uses depending upon the requirement. In engineering, brown fibres are mostly used.

According to official website of International Year for Natural Fibres 2009, approximately, 500 000 tonnes of coconut fibres are produced annually worldwide, mainly in India and Sri Lanka. Its total value is estimated at $100 million. India and Sri Lanka are also the main exporters, followed by Thailand, Vietnam, the Philippines and Indonesia. Around half of the coconut fibres produced is exported in the form of raw fibre.

Figure 1 show a coconut tree, coconut and coconut fibres [source: Wikipedia]. Figure 2 shows the structure (longitudinal and cross section) of an individual fibre cell.

Fig. 1. Coconut Tree, Coconut and Coconut fibres

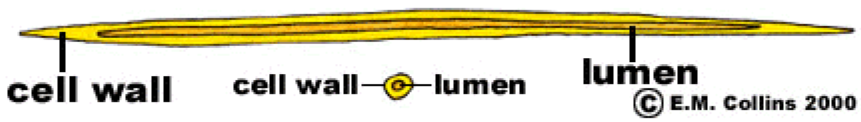


Fig. 2. Longitudnal and Cross-section of a Fibre Cell
[Afa Austin Waifielate Bolarinma Oluseun Abiola (2008)]

There are many general advantages of coconut fibres e.g. they are moth-proof, resistant to fungi and rot, provide excellent insulation against temperature and sound, not easily combustible, flame-retardant, unaffected by moisture and dampness, tough and durable, resilient, springs back to shape even after constant use, totally static free and easy to clean.

PROPERTIES OF COCONUT FIBRES

Physical and mechanical properties

The physical and mechanical properties of coconut fibres are presented in Table 1. The conditions specifically mentioned by the researchers are given at the end of table. Coconut fibres were investigated by many researchers for different purposes.

There is a huge difference in some properties, e.g. diameter of coconut fibres is approximately same and magnitudes of tensile strength are quite different, e.g. compare tensile strength of coconut fibres mentioned by Ramakrishna et al. (2005a) and Toledo et al. (2005) in Table 1.

Also, the range shown for a particular property is quite wide; e.g. Toledo et al. (2005) mentioned the density of coconut fibre as 0.67-10.0 g/cm^3. These values seem to be unrealistic, real values may be the 0.67-1.00 g/cm^3.

There are variations in properties of coconut fibres, and this makes it difficult for their frequent use as construction material. The purpose of compilation of data for the properties of fibres is to get a guideline, but after compilation, a huge variation is seen. There should be some standards for such variations, just like we have standards for sand and aggregates.

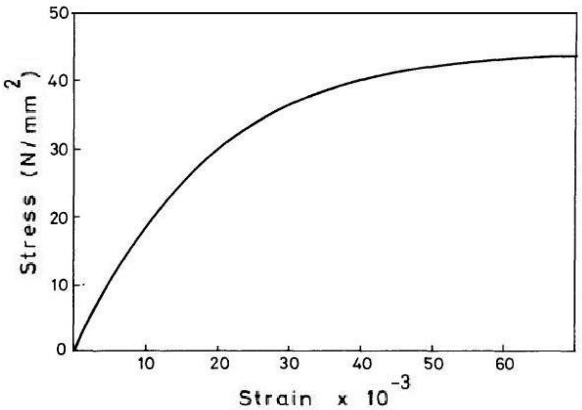
Figure 3 shows stress-strain relationship for coconut fibres as reported by some researchers. Coconut fibre is the most ductile fibre amongst all natural fibres. Coconut fibres are capable of taking strain 4-6 times more than that of other fibres as shown in Figures 3a and 3b.

Table 1. Physical and Mechanical Properties of Coconut Fibres

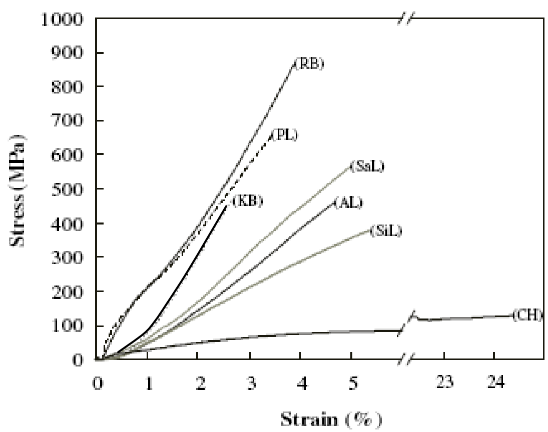
Diameter (mm)	Length (mm)	Tensile strength (MPa)	Specific Tensile strength (MPa)	Average Tensile Modulus (GPa)	Specific Tensile Modulus (GPa)	Tensile Strain (%)	Elongation (%)	Young's Modulus (GPa)	Specific Young's Modulus (GPa)	Toughness (MPa)	Permeable Void (%) **	Moisture Content (%)	Water Absorption Saturation (%) *	Elastic Modulus (GPa)	Density (Kg/m^3)	Reference
0.40-0.10	60-250	15-327	-	-	-	-	75	-	-	-	-	-	-	-	-	Ramakrishna et al. (2005a)
0.21 [a, b]	-	107[e]	-	-	-	-	37.7 [d, e]	-	-	-	56.6-73.1	-	93.8-161.0	2.8[e]	1104-1370	Agopyan et al. (2005) [c]
0.3	-	69.3[f]	-	-	-	-	-	-	-	-	-	-	-	2.0	1140	Paramasivam et al. (1984)
-	-	50.9 [g]	-	-	-	-	17.6[g]	-	-	-	-	-	180 [h]	-	1000	Ramakrishna et al. (2005b) [i]
0.27± 0.073	50± 10	142± 36	-	-	-	-	24 ± 10 [k]	-	-	-	-	10 [m]	24 [l]	2.0 ± 0.3	-	Li et al. (2007)
0.11–0.53	-	108-252	-	-	-	-	13.7–41[n]	-	-	-	-	-	85.0-135.0	2.50-4.50	670-1000	Toledo et al. (2005)
0.12± 0.005	-	137± 11	158	-	-	-	-	3.7± 0.6	4.2	21.5 ± 2.4	-	-	-	-	870	Munawar et al. (2007) [0]

Diameter (mm)	Length (mm)	Tensile strength (MPa)	Specific Tensile strength (MPa)	Average Tensile Modulus (GPa)	Specific Tensile Modulus (GPa)	Tensile Strain (%)	Elongation (%)	Young's Modulus (GPa)	Specific Young's Modulus (GPa)	Toughness (MPa)	Permeable Void (%) **	Moisture Content (%)	Water Absorption Saturation (%) *	Elastic Modulus (GPa)	Density (Kg/m^3)	Reference
-	-	500	0.43[q]	2.50	2.17[q]	20	-	-	-	-	-	11.4[p]	-	-	1150	Rao et al. (2007)
-	-	175	-	-	-	-	30	4-6	-	-	-	-	-	-	1200	Fernandez (2002)
0.1-0.4	-	174	-	-	-	-	10 - 25	-	-	-	-	-	-	16-26	-	Reis (2006)
0.1-0.4	50-250	100 - 130	-	-	-	-	10-26	-	-	-	-	-	130 - 180	19-26	145-280	Aggarwal (1992)
0.10-0.45	-	106 - 175	-	-	-	-	17-47	4-6	-	-	-	-	-	-	1150	Satyanarayana et al. (1990)

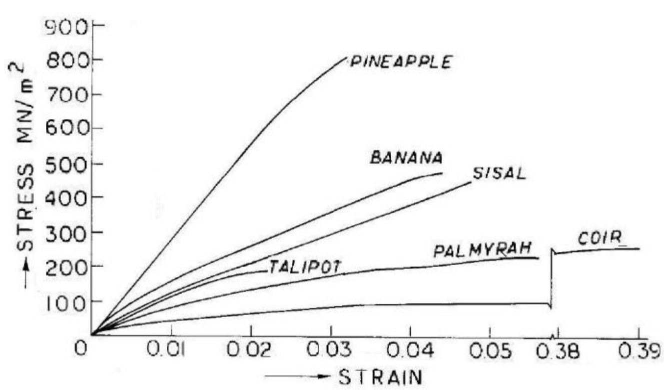
*[a] Coefficients of variation frequently over 50% - [b] Determinations of thickness by scanning electron microscopy - [c] Brazilian Standard NBR-9778 - [d] Elongation on rupture – [e] Authors took other researchers data - [f] Ultimate value - [g] (Unit: mm) Maximum Value and it do not agree with the general accepted value which may be due to the test conditions adopted by [4] – [h] In 24hrs – [i] used natural dry condition of fibres - [j] width - [k] At break - [l] Water absorption ratio (100% humidity) - [m] At 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 – [q] MPa / (Kg m^{-3}) **By Vol. *By mass*



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)]

Fig. 3. Correlations of Mechanical Properties for Natural Fibres

(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)

Fibre dimensions of the various individual cells are said to be dependent on the type of species, location and maturity of the plant. The flexibility and rupture of the fibre is affected by the length to diameter ratio of the fibre and this also determines the product that can be made from it. The shape and size of central hollow cavity, lumen, depends on (i) the thickness of the cell wall and (ii) the source of the fibre. The hollow cavity serves as an acoustic and thermal insulator because its presence decreases the bulk density of the fibre [Flower et al. (2006) as cited by Afa Austin Waifielate Bolarinma Oluseun Abiola (2008)].

Afa Austin Waifielate Bolarinma Oluseun Abiola (2008) evaluated the mechanical properties (load-extension curves, stress-strain curves, Young's modulus, yield stress, stress and strain at break) of inner and outer coconut fibres experimentally, and the results were verified by finite element method using a commercial software ABAQUS. The author found that the inner coconut fibre had a higher mechanical strength as compared to that of outer fibre, but the outer coconut fibre had a higher elongation property which could makes it to absorb or with stand higher stretching energy as compared to the inner coconut fibre.

Chemical properties

Coconut fibres contain cellulose, hemi-cellulose and lignin as major composition. These compositions affect the different properties of coconut fibres. The pre-treatment of fibres changes the composition and ultimately changes not only its properties but also the properties of composites. Some-times it improves the behaviour of fibres but sometimes its effect is not favourable.

The chemical composition of coconut fibres is presented in Table 2.

Table 2. Chemical Composition of Coconut Fibres

Sr. No.	Fibre	Hemi-cellulose (%)	Cellulose (%)	Lignin (%)	Reference
1	Coir	31.1 [a]	33.2 [a]	20.5 [a]	Ramakrishna, et al. (2005a)
		15 - 28 [b]	35 - 60 [b]	20 - 48 [b]	Agopyan, et al. (2005)
		16.8	68.9	32.1	Asasutjarit, et al. 2007
		-	43	45	Satyanarayana, et al. (1990)
		0.15 – 0.25	36 - 43	41 - 45	Corradini, et al. (2006)

[a] *The compositions are % by weight of dry and powdered fibre sample*
[b] *Chemical compositions are % by mass and author took other researchers data*

Ramakrishna and Sandararajan (2005b) investigated the variation in chemical composition and tensile strength of four natural fibres (coconut, sisal, jute and hibiscus 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 coconut fibres were reported best for retaining a good percentage of its original tensile strength for all tested conditions.

The effect of pre-treatment of coconut fibres is investigated by Asasutjarit, C., et al., 2007 for light weight cement boards.

PROPERTIES OF COCONUT FIBRE REINFORCED COMPOSITES

Cement paste

Aziz et al. (1981) cited the work of Das Gupta et al. (1978 and 1979) who studied the mechanical properties of cement paste composites for different lengths and volume fractions of coconut fibres.

The authors concluded that the tensile strength and modulus of rupture of cement paste increased up to a certain length and volume fraction; and further increase in length or volume fraction decreased the strength of composite.

Table 3 shows the tensile strength and modulus of rupture of cement paste composite reinforced with different volume fractions of 38 mm long coconut fibres ranging from 2 % to 6 %.

Table 3: Mechanical Properties of Coconut Fibre Reinforced Cement Paste Composites
[Das Gupta et al. (1978 and 1979) as cited by Aziz et al. (1981)]

Fibre volume fraction (%)	Tensile Strength (MPa)	Modulus of Rupture (MPa)
2	1.9	3.6
3	2.5	4.9
4	2.8	5.45
5	2.2	5.4
6	1.5	4.6

It can be easily observed that 4 % volume fraction of coconut fibres had given the highest mechanical properties amongst all tested volume fractions.

With 4 % volume fraction, the authors also studied the tensile strength of cement paste reinforced with different lengths of coconut fibres. The reported tensile strengths were 2.3, 2.8 and 2.7 MPa with lengths of 25, 38 and 50 mm, respectively.

Thus coconut fibres with a length of 38 mm and a volume fraction of 4% gave maximum strength of cement paste composite.

Cement sand mortar

Research 1

Slate (1976) investigated mechanical properties of coir fibre reinforced cement sand mortar. The researcher tested two different design mixes (cement sand ratio by weight), first was 1:2.75 with water cement ratio of 0.54 and second was 1:4 with water cement ratio of 0.82.

Fibres content was 0.08, 0.16 and 0.32% by total weight of cement, sand and water. The mortars for both design mixes without any fibres were also tested as reference.

Cylinders having size of 50mm diameter and 100mm height and beams having size of 50mm width, 50mm depth and 200mm length were tested for compressive and flexural strength. The curing was done for 8 days only.

It was found that all strengths were increased in case of fibre reinforced mortar as compared to that of plain mortar for both mix design with all fibre contents. However, a decrease in strength of mortar was also observed with an increase in fibre content.

Research 2

Li et al. (2006) studied untreated and alkalized coconut fibres with two lengths of 20 mm and 40 mm in cementitious composites as reinforcement materials. Mortar was mixed in a laboratory mixer at a constant speed of 30 rpm, with cement: sand: water: super plasticizer ratio of 1: 3: 0.43: 0.01 by weight and fibres were slowly put into the running mixer.

The resulting mortar had better flexural strength, higher energy absorbing ability and ductility, and lighter than the conventional mortar. Good results were achieved with the addition of a low percentage of coconut fibres and chemical agents in cementitious matrix.

Concrete

Research 1

Reis (2006) investigated the mechanical characterization (flexural strength, fracture toughness and fracture energy) of epoxy polymer concrete reinforced with natural fibres (coconut, sugarcane bagasse and banana fibres).

Fracture toughness and fracture energy of coconut fibre reinforced polymer concrete were higher than that of other fibres reinforced polymer concrete. And flexural strength was increased up to 25 % with coconut fibre only.

Research 2

Baruah and Talukdar (2007) investigated the static properties of plain concrete (PC) and fibre reinforced concrete (FRC) with different fibre volume fractions ranging from 0.5% to 2%. Fibres used were steel, artificial and natural fibres (jute and coir fibres only). Here, discussion is limited only to PC and the coir fibres reinforced concrete (CFRC).

The mix design (cement: sand: aggregates) for plain concrete was 1: 1.67: 3.64 with water cement ratio of 0.535. Per cubic meter of concrete mix was cement = 350 kg, fine aggregates = 568.40 kg, coarse aggregate = 1239.40 kg and water = 182 kg. The maximum size of aggregates was 20mm. Coir fibres having length of 4cm and diameter of 0.4mm with volume fraction of 0.5, 1, 1.5 and 2% were added to prepare CFRC.

The sizes of specimens were (1) 150 mm diameter and 300mm height for cylinders (2) 150 mm width, 150 mm depth and 700 mm length for beams, and (3) 150mm cubes having a cut of 90 mm X 60 mm in cross-section and 150 mm high for L-shaped shear test specimens. All specimens were cured for 28 days.

The investigated properties, compressive strength (σ), splitting tensile strength (STS), modulus of rupture (MOR) using four point load test and shear strength (τ), are shown in Table 4 for PC and CFRC. It can be noted that CFRC with 2 % fibres showed better results amongst all volume fractions.

The compressive strength, splitting tensile strength, modulus of rupture and shear strength of coir fibre reinforced concrete with 2% fibres by volume fraction were increased up to 13.7, 22.9, 28.0 and 32.7 %, respectively as compared to those of plain concrete. It is also noted from their research that all these properties were also improved for CFRC with all other tested volume fractions of fibres (0.5, 1 and 1.5 %). These properties were increased up to only 1.3, 4.9, 4.0 and 4.7 %, respectively for CFRC with 0.5% fibres by volume fraction.

Table 4: Properties of Coconut Fibre Reinforced Concrete (CFRC)
[*Baruah and Talukdar (2007)]*

Fibre volume fraction (%)	Compressive Strength (MPa)	Split Tensile Strength (MPa)	Modulus of Rupture (MPa)	Shear Strength (MPa)	Toughness Index, I_5	Toughness Index , I_{10}
-	21.42	2.88	3.25	6.18	1.934	1.934
0.5	21.70	3.02	3.38	6.47	2.165	2.270
1.0	22.74	3.18	3.68	6.81	2.109	2.773
1.5	25.10	3.37	4.07	8.18	2.706	4.274
2.0	24.35	3.54	4.16	8.21	2.345	3.452

APPLICATIONS IN CIVIL ENGINEERING TECHNOLOGY

Plaster

John et al. (2005) studied the coir fibre reinforced low alkaline cement taken from the internal and external walls of a 12 year old house. The panel of the house were produced using 1:1.5:0.504 (binder: sand: water, by mass) mortar reinforced with 2% of coconut fibres by volume.

Fibres removed from the old samples were reported to be undamaged. No significant difference was found in the lignin content of fibres removed from external and those removed from internal walls.

Roofing material

Research 1:

Cook et al. (1978) reported the use of randomly distributed coir fibre reinforced cement composites as low cost materials for roofing. The studied parameters were fibre lengths (2.5 cm, 3.75 cm and 6.35 cm), fibre volumes (2.5, 5, 7.5, 10 and 15%) and casting pressure (from 1 to 2 MPa with an increment of 0.33 MPa). Different properties like bending, impact, shrinkage, water absorption, permeability and fire resistance were investigated.

They concluded that the optimum composite was a composite with a fibre length of 3.75 cm, a fibre volume fraction of 7.5 % and cast at pressure of 1.67 MPa. Cost comparison revealed that this composite was substantially cheaper than the locally available roofing materials.

Research 2:

Agopyan et al. (2005) studied coir and sisal fibres as replacement for asbestos in roofing tiles. Coir fibres were more suitable among studied fibres.

Slabs

Research 1:

Paramasivam et al. (1984) conducted a feasibility study of making coir fibre reinforced corrugated slabs for use in low cost housing particularly for developing countries. They gave recommendations for the production of coconut fibre reinforced corrugated slabs along with casting technique.

Tests for flexural strength, thermal and acoustic properties were performed. For producing required slabs having a flexural strength of 22 MPa, a volume fraction of 3 %, a fibre length of 2.5 cm and a casting pressure of 0.15 MPa (1.5 atmosphere) were recommended. The thermal conductivity and sound absorption coefficient for low frequency were comparable with those of locally available asbestos boards.

Research 2:

Ramakrishna and Sandararajan (2005b) performed the experimental investigations of the resistance to impact loading were carried out on cement sand mortar (1:3) slabs. The slab specimens (300 mm x 300 mm x 20 mm) were reinforced with natural fibres (coconut, sisal, jute and hibiscus cannabinus fibres) having four different fibre contents (0.5, 1.0, 1.5 and 2.5% by weight of cement) and three fibre lengths (20, 30 and 40 mm).

A fibre content of 2% and a fibre length of 40mm of coconut fibres showed best performance by absorbing 253.5J impact energy among all tested fibres. All fibres, except coconut fibres, showed fibre fracture, at ultimate failure where as coconut fibre showed fibre pull out failure.

Research 3:

Li et al. (2007) studied fibre volume fraction and fibre surface treatment with a wetting agent for coir mesh reinforced mortar using nonwoven coir mesh matting. They performed a four-point bending test on a slab specimen.

They concluded that cementitious composites, reinforced by three layers of coir mesh (with a low fibre content of 1.8 %) resulted in a 40 % improvement in the maximum flexural stress, were 25 times stronger in flexural toughness, and about 20 times higher in flexural ductility.

Boards

Asasutjarit 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 6cm fibre length gave better results. On the other hand, optimum mixture ratio by weight for cement: fibre: water was 2:1: 2. Also, tested board had lower thermal conductivity than commercial flake board composite.

Wall paneling system

Mohammad Hisbany Bin Mohammad Hashim (2005) tested wall panels made of gypsum and cement as binder and coconut fiber as the reinforcement. Bending strength, compressive strength, moisture content, density, and absorption were investigated.

Coconut fibres did not contribute to bending strength of the tested wall panels. Compressive strength increased with the addition of coconut fibres, but the compressive strength decreased with an increase in water content and density was increased. There was no significant change of moisture content with coconut fibres. However, moisture content increased with time. There was also no significant effect to water absorption on increasing coconut fibre content.

House construction

Some researchers (Luisito J Peñamora, Neil J Melencion and RolendioN Palomar - 2005) of PCA-Zamboanga Research Center, San Ramon, Zamboanga city invented coconut fibre boards (CFB) for different applications as shown in Figure 4. According to them, CFB can replace construction materials such as tiles, bricks, plywood, and asbestos and cement hollow blocks. It is used for internal and exterior walls, partitions and ceiling. It can also be used as a component in the fabrication of furniture, cabinets, boxes and vases, among others.

Fig. 4. Applications of Coconut Fibre Boards in House Construction and Other Utilities
[Luisito et al. (2005)]

Slope stabilization

Coir erosion fabrics provide firm support on slopes and unlike other natural fibre alternatives like cotton or jute, do not degrade until 5 years. They have the necessary strength and come in a number of forms such as matting, rolls and logs and are used for soil stabilization.

Coconut fiber finds applications in slope stabilization in railway cutting and embankments, protection of water courses, reinforcement of temporary walls and rural unpaved roads, providing a sub base layer in road pavements, land reclamation and filtration in road drains, containment of soil and concrete as temporary seeding etc, highway cut and fill slopes, control of gully erosion and shallow mass waste.

APPLICATIONS IN OTHER ENGINEERING TECHNOLOGIES

Bullet proof vest

Yuhazri, M.Y. and Dan, M.M.P. developed a unique bullet proof vest made of coconut fibre, which provides all the protection that can be found in a regular vest. It is not only economical but also lighter.

A normal bullet-proof vest costs about RM 16, 000/- and weighs 9 kg, but this vest is only 3 kg and cost RM 2, 000/-. The test proved that the vest was capable of stopping 9mm caliber bullets at a 5 m range.

Yuhazri, M.Y. and Dan, M.M.P. (2008) also tested high impact hybrid composite material with coconut fibres as reinforcement for ballistic armor, and satisfactory results were reported.

Motorcycle helmet

Yuhazri, M.Y. and Dan, M.M.P. (2007) utilized coconut fibres in the manufacturing of motor cycle helmet. They used epoxy resins from thermo set polymer as the matrix materials and coconut fibres as the reinforcement. After the development of helmet shells fabrication method, mechanical testing (dynamic penetration) was performed on this composite material to determine its performance.

The result in the mechanical performance showed that coconut fibres performed well as a suitable reinforcement to the epoxy resin matrix.

Car parts

A team of Baylor University researchers is trying to develop a technology to use coconut fiber as a replacement for synthetic polyester fibers in compression molded composites.
Their aim is to use the coconut fibers to make trunk liners, floorboards and interior door covers on cars.

General use

Apart from applications in engineering, coconut fibres are also used in yarn, ropes, mats, mattresses, brushes, sacking, caulking boats, rugs, geo-textiles, insulation panels and packaging.

CONCLUSIONS

The versatility and applications of coconut fibres in different fields is discussed in detail. Coconut fibres are reported as most ductile and energy absorbent material. It is concluded that coconut fibres have the potential to be used in composites for different purposes. Various aspects of many coconut fibres reinforced composites have already been investigated; and the economical and better results are achieved as reported by many researchers. Since the use of coconut fibres has given some marvellous products, there is still possibility of the invention of new products containing coconut fibres with improved results. In civil engineering, coconut fibres have been used as reinforcement in composites for non-structural components. There is a need of investigating the behaviour of coconut fibre reinforced concrete to be used in main structural components like beams and columns.

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- http://en.wikipedia.org/wiki/Coconut
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- http://coirboard.nic.in/about_coirfiber.htm
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