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EMERGING TECHNOLOGY SERIES

NEW AND ADVANCED MATERIALS

3/1996

SPECIAL ARTICLE
Composite Materials Using Local Resources
by T.N. Gupta

COMPOSITES FROM LOCAL RAW MATERIALS - Overview

COMPOSITES FOR BUILDING MATERIALS

WOOD COMPOSITES

PLANT FIBRE COMPOSITES

UNIDO's *Emerging Technology Series - New & Advanced Materials* is established as a mechanism of current awareness to monitor developments in the materials sector and to inform governments, industry and academia, primarily in developing countries.
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DEAR READERS

In the fast changing scenario of the construction industry which requires a need to link the production of building materials to sustainable environmentally oriented development, the building materials industry in most developing countries is under pressure and unable to cope with the new demands from different sub-sectors of construction activities. This has led to a growing concern for developing and promoting alternative building materials based on renewable local raw material resources for housing and building construction.

One strong option is to promote the development and utilization of composite materials based on local resources, such as wastes from forestry, agriculture, horticulture or agro-based industries, natural fibres, plant materials, other biomass resources like thatches, grasses, reeds and other local resources from industrial wastes, which at present are not used properly. This type of industrial composite can provide very suitable alternatives, particularly in the face of universal concern for ecological degradation caused by continuing dependence on extracted minerals which are non-renewable in perceptible time frames.

At the same time, research and development undertaken on various scientific and engineering aspects of composites and their basic components during the past 2 to 3 decades have not only shown, but also reasonably demonstrated that many of these wastes and local resource-based materials can substitute traditional materials like cement, steel or wood. Some of such types of materials are even used in aircraft building industries.

Taking this into account, UNIDO and the International Centre for Science & Technology (ICS), have developed an international programme on the development, manufacturing and application of composite materials based on local resources and waste minimization, the implementation of which started in 1996. This publication will provide you will more detailed information on what is now happening in this area. We also hope that it will increase your interest in this particular type of new materials, as well as your willingness to participate in the UNIDO programme. Feel free to contact us for further information. Feedback on the "yellow pages" would be very welcome as well.

Vladimir Kojarnovitch
Technical Editor

CONTENTS

CONTENTS (continued)

A. SPECIAL ARTICLE

COMPOSITE MATERIALS USING LOCAL RESOURCES

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Abstract

This paper aims at presenting consolidated information on the research, development and application of composite materials for low-income group mass-housing in developing countries.

Composites based on high-cost and high-energy-consuming fibres such as glass fibre, Kevlar, carbon, boron etc., are not within the reach of people in developing countries and, therefore, those types of composites are not included in this paper. There are, however, two broad categories of composites which have the potential for very wide applications in buildings. These are: (1) natural fibre-polymer/cement composites—based mainly on locally available fibres (sisal, jute, mesta, cotton, coir, flax, kenaf etc.) and a polymer (polyester, epoxy, urea formaldehyde etc.) or cement as matrix. (Wood fibres have not been covered in this paper.) (2) Particulate/aggregate composites—based mainly on the utilization of inorganic wastes and by-products (fly ash, slag, mine tailings, lime sludges, by-product gypsum, red mud etc.) and a hydraulic binder (cement or lime pozzolana). The two categories of composites have been covered under sections A and B respectively.

This paper gives details of resources and composites, their physical and mechanical properties, pilot plant data and their potential for commercialization. Annex I gives some examples of several products which are being commercially produced in India.

The problems of technological developments and constraints in popularizing the use of composites in housing which must be carefully addressed by planners and builders have also been highlighted. A coordinated approach, including pilot-plant studies, strengthening the database on natural fibres, efforts for design, development and performance studies on building components, may form the scope of a UNIDO Shelter Programme. The emphasis in the programme could be on enterprise development and upgrading the existing know-how in the area of composites for buildings.

1. Introduction

Developing countries face multiple problems of low economic growth, absence of basic minimum services to a rapidly growing population, chronic unemployment and growing environmental degradation in rural and urban settlements. In attempting to solve the above problems most Governments and non-governmental organizations (NGOs) have found that the building materials and construction industry could play a very important role, particularly through self-help and reliance on local resources.

In spite of some well-meaning attempts during the last three decades, the people in developing countries still remain far from achieving even the modest targets of housing and infrastructural services. Yet there is almost a unanimity that the development of the building industry is the biggest force in pushing forward overall economic development through job creation on a large scale. In fact, considering the above background, the United Nations General Assembly adopted resolution 42/191 on the "Global Strategy for Shelter to the Year 2000", with the objective of providing shelter for all by the end of this century. It is UNIDO's aim to contribute and organize all possible technological and financial assistance to help to achieve the above objective.

Most developing countries have attempted to augment their requirements of cement, steel, brick and timber through imports, or through imported technologies in their production units. This approach has often failed to achieve the desired objectives and has not helped to achieve the goal of self-sufficiency. Many developing countries do not possess fossil fuels. This restricts the growth of building materials industries of the preferred types on the lines of those of the developed countries. Many projects of building materials industries in the developing world, based on imported technologies, closed down with colossal financial losses as they proved to be highly energy-intensive. In addition, imported technologies were not always found to be compatible with the state of development in most of these countries.

It has been fully recognized that developing countries must adopt building materials based on local mineral resources and industrial as well as agricultural wastes, residues and by-products. There has to be a consensus in developing indigenous technologies for building materials which could provide self-reliance and sustained housing growth. HABITAT-II (a follow-up of HABITAT-I, 1976), which concluded recently at Istanbul (Turkey), also addressed the issue and recommended that, in realizing the goal of adequate shelter for all, the utilization of local materials could make a crucial contribution. The promotion of the construction and building materials sector is an integral part of the global strategy for self-reliant and self-sustained development.

A major complementary role played by UNIDO in the field of building materials and construction is through the Shelter Programme, as part of their Chemical Industries Development. This Programme has three broad-based objectives:

- To transfer know-how to developing countries in order to enhance their capacities to exercise the most appropriate choice of technology and maximize operational efficiency;
- To improve product quality and enhance product diversification; and
- To promote the safe use of technology and products, including mitigation of subsector-specific adverse environmental effects and the recycling of the wastes of the industries covered by the programme.

With a view to meeting the above objectives, there are four levels of capacity-building with regard to:

(i) Policy and strategy;
(ii) Institutions;
(iii) Enterprises; and
(iv) Technology transfer and adoption, preferably among the developing countries themselves.

Thus the identification of suitable local building materials and technologies, their meaningful description and documentation have become the first priority. This paper makes an attempt in this direction with particular emphasis on the scope of utilization of all major local technologies, with particular reference to what is called "composite building materials based on local resources".

2. Local building materials and composite building materials

It is widely recognized that mud, stone and timber are some of the main local materials used for shelter since time immemorial. However, mud mixed with chopped straw to shape mud blocks; stone crushed into suitable sizes and mixed with cements as cast concrete blocks or slabs; and timber fragmented and reconstituted/laminated using a polymer resin into sheets and boards are the traditional materials technologies which can be called composite building materials.

There have been many noteworthy advancements in composite materials. Composites today are the final category of structural engineering materials which find varied applications in electronics, structural elements, high-speed tools, spacecraft, advanced ceramics etc., in which there is always a matrix such as cement, polymer, clay and certain reinforcing materials such as steel, polymer fibres, ceramic fibres and vegetable fibres. Thus, composites are combinations of two or more components. The key philosophy in defining composite materials is that they provide the "best of both worlds"; that is, they incorporate the best property of each component. A classic example of composite materials is FGRP (Fibre-Glass Reinforced Plastics), in which the strength of small diameter glass fibres is combined with the ductility of the polymeric matrix, to provide a product superior to either component alone.

3. Composite materials for mass housing

Even excluding the scope of such composites in which glass fibre, carbon fibre, Kevlar, polyamide etc., are used for highly sophisticated applications, there is a variety of composite materials which have great potential in housing for the masses. These composites include materials such as stabilized soil blocks, concrete blocks and asphalt roofing sheets. They could be broadly divided into two categories:

- Fibre-reinforced composites: mostly natural fibre (such as jute, coir, sisal, etc.), or steel fibre-reinforced products;
- Inorganic particulate composites: these include the utilization of mostly non-metallic minerals and their beneficiation or upgrading, which rejects tailings and by-products.

For the purposes of this paper, yet another category of composites exists, covering metals, alloys, industrial and structural ceramics and glass-ceramics, which are energy- and capital-intensive materials and usually not within the scope of usage in house construction for the poor, have not been discussed.

4. The UNIDO workshop on industrial composites—design and applications (30 October-5 November 1994, Trieste, Italy)

In the above-mentioned workshop, 16 papers were presented by eminent scientists and engineers. The themes included reviews of the scientific and technological progress made in the area of composites and future approaches.

The basic aspects of characterization of the fibres and binders, design developments, engineering properties, production technologies and application potentials were covered in various presentations made at the workshop.

From the detailed discussions held in the workshop, a consensus emerged that (a) natural fibre-reinforced composites materials have vast future potential as all developing countries have large renewable sources of such fibres; and (b) particulate (inorganic) composites are more universally applicable as mineral wastes and by-products are available in large quantities in almost all developing countries.

It is widely recognized that the development and application of particulate composite materials have reached a stage where mutual cooperation in technology transfer, upgrading and enterprises within developing countries themselves are achievable. On the other hand, natural fibre-reinforced composites, although explored extensively, still require meaningful schemes for strengthening and improving existing capabilities of the product development, upscaling model project reports through a network of cooperation among carefully selected research and development (R&D) institutions and NGOs.

Section A. Natural fibre composites

In the last 20 years there has been tremendous interest in the use of natural fibres for the manufacture of cement or polymer-bonded composites. There are examples of two well-established products: Tufnol 6F/45 (an epoxy-cotton composite made in the United Kingdom) and Trespa (a phenolic/wood fibre composite made in the Netherlands). Yet the somewhat poor strength properties of these two materials suggest that there is a need for further product optimization. At the same time, many claims have been made that on a weight-for-weight basis, the performance of the best plant fibre-reinforced composites is comparable with that of conventional glass-epoxy compositions.

Thermosetting polymer matrix and plant fibre composites find applications as electrical insulators (Tufnol Ltd.), semi-structural applications (Hoechst Holland) and wear parts (Tenmat Ltd.). In India, a certain jute-phenolic system has been used since 1994. With thermoplastic polymer matrix, sheet moulding component materials such as wood stock and Lignotoc (BASF AG) have recently been introduced as a sisal-reinforced composite. Mitsubishi in Japan have also introduced a polypropylene composite with 50 per cent reclaimed newspaper fibre. With substantial cuts in the expenditure in defence and aerospace programmes, some multinational companies are reorienting this product range from high-cost and high-performance composites towards more environmentally friendly and lower-cost plant fibre-reinforced composites.

With the above background it is interesting to look into the endeavours made recently, and future prospects for the production and uses of natural fibre-reinforced composites for use in housing solutions for the millions of poor people in the developing world.

A.1 Availability of natural fibres

Tables 1 and 2 show the natural fibres available in each country, and the annual production of natural fibres in the world, of which the major contributions are from the developing countries. In fact, many fibre samples from developing countries in Asia and Africa have been extensively studied. The following list shows some important fibres which were found to possess great promise in the manufacture of composites of low weight and high strength and their countries of origin.

Plant fibres vary widely in their chemical composition, structure and dimensions, as they originate from different parts of the plant. These variations are shown in tables 3 and 5. However, table 4 gives some comparative data on the specific strength properties of the plant fibres *vis-à-vis* those of glass, Kevlar and carbon fibres. In fact, many fibres are well known to the consumers of textiles, matting, ropes etc.; some of them are considered useful on the basis of their cellulose content. There is considerable interest in oil palm fruit fibres in Malaysia and elephant grass in some African countries and India. It is reported that there may be about 1,000 types to choose from, excluding wood and bamboo.

Tables 5 and 6 show important properties of dimension, density and mechanical strength which enables a direct comparison of the intrinsic values of plant-fibres and those of man-made fibres (glass, steel, boron, silicon carbide etc.)

Fibre density and dimensions are of specific interest to the manufacturers of composites. In terms of aspect ratio, most individual fibres have values in the range of 100-200. In summary, the advantages of plant fibres as reinforcements in polymer or cement-bonded composites are their acceptable specific strength, low cost, low density, high toughness, good thermal properties, reduced dermal and respiratory irritation (as compared to glass fibres) and their biodegradability. Moreover, plant fibres require very small energy inputs for processing. These advantages merit full attention in exploiting plant fibres for making composites. They actually meet the basic criteria of being locally available, of renewable production and having a proximity to nature.

Table 1. Fibres and country of origin

Abaca:	Bolivia, Malaysia, Philippines, Uganda
Coir:	India, Malayisa, Philippines, Sri Lanka
Flax:	Borneo
Hemp:	China, Yugoslavia
Jute:	Egypt, Ghana, Guyana, India, Jamaica, Malawi, Sudan, Tanzania
Kenaf:	Cuba, Iraq, Jamaica, South Africa, Tanzania, Togo
Ramie:	Honduras, Mauritius
Roselle:	Borneo, Guyana, Indonesia, Malaysia, Sri Lanka, Tanzania, Togo
Sisal:	Antigua, Bahamas, East Africa, India, Kenya, Tanzania
Sunn hemp:	Guyana, India, Nigeria, Sierra Leone

Table 2. Annual production of natural fibres and sources

Fibre source	World production (10^3 tons)	Origin
Abaca	70	Leaf
Bamboo	10 000	Stem
Banana	200	Stem
Broom	Abundant	Stem
Coir	100	Fruit
Cotton lint	18 500	Stem
Elephant grass	Abundant	Stem
Flax	810	Stem
Hemp	215	Stem
Jute	2 500	Stem
Kenaf	770	Stem
Linseed	Abundant	Fruit
Nettles	Abundant	Stem
Oil palm fruit	Abundant	Fruit
Palmirah	Abundant	Stem
Ramie	100	Stem
Roselli	250	Stem
Rice husk	Abundant	Fruit/grain
Rice straw	Abundant	Stem
Sisal	380	Leaf
Sunn hemp	70	Stem
Wheat straw	Abundant	Stem
Wood	1 750 000	Stem

Table 3. Chemical composition and moisture absorption of some natural fibres

Fibre	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Moisture regain at 65% R.H.	Transverse swelling in water (%)
Banana	60-65	6-8	5-10	10-15	16-20
Coir	43	<1	45	10-12	5-15
Cotton lint	90	6	-	7	20-22
Flax	70-72	14	4-5	7	20-25
Jute	61-63	13	5-13	12.5	20-22
Mesta	60	15	10	13	20-22
Palmirah	40-50	15	42-45	10-12	-
Pineapple leaf	80	-	12	10-13	18-20
Ramie	80-85	3-4	0.5	5-6	12-15
Sisal	60-67	10-15	8-12	10-12	18-20
Straw	40	28	18	-	-
Sunn hemp	70-78	18-19	4-5	10-11	18-20
Wood	45-50	23	27	-	-

Table 4. Specific strength, cost and energy contents of synthetic and natural fibres

Fibre	Sp. gr.	Specific tensile strength (GPa)	Specific tensile modulus (GPa)	Cost (US$/ton)	Energy content (GJ/ton)
Plant fibre	0.6-1.2	1.60-2.95	10-130	200-1 000	4
Glass	2.6	1.35	30	1 200-1 800	30
Kevlar	1.4	2.71	90	7 500	25
Carbon	1.8	1.71	130	12 500	130

Table 5. Mechanical properties of some natural fibres

Fibre	Length (mm)	Diameter (mm)	Density (kg/m³)	Young's modulus (GPa)	Tensile strength (MPa)	Elongation at break (%)
Bagasse	NA	0.2-0.4	1 250	17	290	NA
Bamboo	NA	0.1-0.4	1 500	27	575	3
Banana	NA	0.8-2.5	1 350	1.4	95	5.9
Coir	50-350	0.1-0.4	1 440	0.9	200	29
Elephant grass	NA	0.4	NA	5	178	5.6
Flax	500	NA	1 540	100	1 000	2.0
Jute	1 800-3 000	0.1-0.2	1 500	32	350	1.7
Kenaf	30-750	0.04-0.09	NA	22	295	NA
Mesta	NA	0.2	1 470	13	180-570	NA
Pineapple	NA	0.2-8.8	NA	14.5	413-1 627	NA
Sisal	-	0.5-2.0	1 450	100	1 100	-

Table 6. Mechanical properties of some fibres other than natural fibres

Fibre	Length (mm)	Diameter (mm)	Density (kg/m³)	Young's modulus (GPa)	Tensile strength (MPa)	Elongation at break (%)
Glass "C"	NA	NA	2 700	70	3 100	4.5
Glass "E"	NA	NA	2 900	72.5	3 400	4.8
Steel	5-200	0.1-0.4	7 860	207	700-2 100	3.5
Boron	NA	NA	-	410	3 800	2.8
SiC	NA	NA	-	430	240-2 400	-
Asbestos	<15	<0.2	2 550	159	210-2 000	7-18
Polymer (polypropylene)	NA	NA	900	6.8	590	210

A.2 Main problems in the design, development and application of plant fibre-reinforced composites

The design of a composite material based mainly on natural fibres depends upon reliable information on their technical properties. But the data available show wide variations even from one location to another in the same country. Therefore, there could not be one design based on the same fibre for a product which could be applicable for all countries producing that fibre. Thus, it is important to take care of this variability factor.

Natural fibres, in general, possess an elasticity modulus (Ef) lower than the elasticity modulus of the matrix (Em). Hence, the reinforcing effect is often not good and can only be increased as the Ef/Em increases. Such a difficulty can be overcome by the constant monitoring of the characterization data of all suitable plant fibres.

It is well understood that although the Young's modulus and tensile strength of a number of natural fibres are comparable to those of asbestos fibre (see tables 5 and 6), there is a poor interaction between natural fibres and cement matrix, unlike that of asbestos. Hence the cost-factor is not always attractive when a compatible polymer matrix is used, as it is costly and has to be imported in many developing countries.

Technological improvements suggest that natural fibre and cement composites, made with proper mixing, high pressure in mat-forming and other good quality control measures, make them fire-resistant, but those using polymer matrix do not fulfil this requirement, particularly for housing applications.

Almost all natural fibres show poor alkali resistance, resulting in unsatisfactory performance in cement matrix. Therefore, further R&D is in progress to improve the alkali-resistance of natural fibres by certain pre-treatments and the application of coatings on fibres. On the other hand, bond strength, which is just physical between polymer matrix and natural fibre, still cannot match that of asbestos fibre in cement, a bond which is physico-chemical.

Natural fibres show poor wetting in a cement matrix (e.g. glass fibre, Kevlar and carbon fibres) or even in a high-profile polymer resin like epoxy matrix. Also, many natural fibres, because of high water absorption, change their shape in a cement matrix and hence create difficulties in design developments for various building components. Therefore, there must be a constant vigil in ensuring long-range satisfactory bonding, resistance to deformation and delamination, resistance to attack by pests and termites and overall durability.

For making further progress in promoting natural fibre cement/polymer matrix composites as acceptable building materials, two major follow-up programmes need to be formulated carefully: (a) a coordinated database on the technical properties of natural fibres of different sources, and (b) backup of pilot plant studies in selected countries.

A.3 Development of plant-fibre composites for housing

Jute-epoxy, jute-polyester, jute-phenolic composites

Table 7 shows the comparative bonding properties of natural fibres and glass fibre composites in polymer matrixes. Jute fibre-epoxy composite shows bond strength nearest to that of glass fibre epoxy composite. In an earlier work, sisal-epoxy composite was found to possess nearly half the tensile strength to that of glass-fibre-epoxy composite, when both fibres were used in the same percentage per weight ratios. However, because of the low density of jute and sisal fibres their specific strength is comparable to that of glass fibre-epoxy composite.

In fact, jute fibre has adequate strength and is most compatible with a polymer matrix. These composites, in the form of panels, sheets, tiles, etc., are now the most recommended products for low-cost housing and also for grain storage bins. Although jute-fibre-polyester composites are now a commercial success, certain problems still need to be overcome. The difficulties of absorption and desorption by the composites, and a decrease in tensile strength up to 25 per cent, indicate their susceptibility to temperature and water-resistance and shear failure. The data on weathering properties after seven years' exposure, given in table 13, confirm the above observations. It is also recommended that a jute fibre and glass fibre "hybrid" composite may be used for better performance.

Coir-polyester composites

Many attempts have been made to make laminates and other products from coir fibre and unsaturated polyester. The results of one such experimental value, for using 9% per wt. of coir in polyester, are shown in table 8. Although several properties are satisfactory, the pull-out stress of the fibre from the sample was found to be very low, suggesting a poor bonding between the coir fibre and the matrix. Fibres with a higher lignin content may behave better.

Banana-cotton-polyester composites

The results of the various physical and mechanical properties of banana-cotton-polyester composites are given in table 9. It can be seen that satisfactory tensile and flexural strength and modulus of elasticity could be achieved if the fibre content was at least 14% per wt. However, in this composite the bond strength between the fibre and the matrix was poor.

Sisal-epoxy and sisal-polyester composites

Sisal is yet another natural fibre being extensively investigated; this low-cost fibre needs little effort in processing. Some of the properties of this fibre are given in table 5; the strength data of a sisal fibre-polyester resin composite, with or without a red mud (an aluminium industry waste) additive, are given in table 12. It is observed that the best results are obtained if the composite is made as a "hybrid" type using sisal fibre (about 35 per cent) and glass fibre (about 8 per cent) and red mud (about 20 per cent).

Sisal fibre-epoxy composites have also been advocated for application in roofing units and panel products. The mechanical properties of this epoxy matrix composite were found to be better than those of a polyester matrix composite. However, even only on a cost consideration, polyester matrix is considered preferable to epoxy matrix.

Many more natural fibres other than jute, sisal and coir have been evaluated, as shown in tables 2 and 3. The chief among them are mesta, bagasse, kenaf, sunn hemp and flax, in different matrixes—polymeric, bitumen cement and gypsum plaster. Wheat straw and rice husk have also been investigated.

A.4 Natural fibre-cement matrix composites

Polymers are definitely very costly as compared to Portland cement and gypsum plaster for use as a matrix in the development of natural-fibre-reinforced composites and for use as panelling, roofing and ceiling components in low cost housing. Even when both the matrixes are compared, on the basis of imported costs, it would be preferable to use cement in spite of some serious limitations in its combinations with plant fibres.

Many efforts have, however, been made in the development of roofing sheets and tiles using various natural fibres and cement. Technologies, plant and machinery designs of different types were developed. Components like large sheets and tiles were manufactured and used, and performance studies were carried out and data carefully compiled.

The results of all these attempts of cement-bonded natural fibre composites are given in table 11.

There have been preferences for making sheets—plain and corrugated—of a geometry similar to that of asbestos-cement roofing sheets. There has also been some recent preference for making tiles instead of sheets with certain advantages in overall costs and performance of the roofing structure. The net results are not encouraging and there may be endless academic discussions on cement versus polymers, sheets versus tiles, pressing versus vibration and lamination techniques, use of fibre surface-modifying chemicals and about a general agreement on the durability in terms of loading and exposure parameters. Several standard specifications have been brought out. Coir fibre and rice husk were found to be two compatible fibres/particles to suit cement matrix or vice-versa. There are some success stories, one among them is a rice-husk-cement composite. Some other composites commercially marketed and used are shown in table 14.

Table 7. Comparative bending strength properties of natural fibre and glass fibre-reinforced composites

Fibre/matrix	Sp. gr.	Bending strength (GPa)	Bending modulus (GPa)	Fibre volume fraction (%)
Random wood/phenolic	1.2	0.110	8.0	65
Woven jute/polyester	1.2	0.090	8.0	50
Filtered jute/polyester	1.2	0.100	10.0	60
Parallel jute/epoxy	1.2	0.450	43.5	70
Cotton/epoxy	1.5	0.170	8.0	55
Parallel kanef/epoxy	1.2	0.450	58.5	70
Pulruded glass/epoxy	1.7	0.690	43.0	70
Random glass/epoxy	1.9	0.172	10.5	70

Note: The above data refer to commercial products (sheets) produced in developed countries.

Table 8. Properties of coir-polyester composites with 9% per wt. coir

Density (kg/m^3)	1 160
Strength tensile (MN/m^2 flexural)	18.61
Strength flexural (MN/m^2 flexural)	38.51
Modulus of elasticity (GN/m^2)	4.045
Impact resistance (kg/m^2)	391.0
Water absorption (24 h) (%)	1.36
Dielectric strength (2.5 mm thick)	10 KV/min

Table 9. Properties of various fibre-polyester resin composites

Property	Type of fibre used in composite						
	Glass	Cotton fabric	Banana fabric	Coir	Banana cotton		
		Polyester % per wt. not known			Polyester % per wt.		
					8	14	18
Density (kg/m^3)	1 500-1 900	1 400	1 215	1 160	-	-	-
Strength							
Tensile	241-689	34.5-689	35.92	18.61	25.86	30.96	29.50
Flexural	344-662	62.1-124	50.60	38.15	52.38	61.24	60.40
Modulus of elasticity (GN/m^2)	6.9-41.4	2.76-4.2	3.33	4.05	1.36	2.03	1.80
Impact resistance (kg/m^2)	3 116-8 475	257.3-428	748.5	391	-	-	-
Water absorption (%)	0.2-1.0	0.8	1.93	1.36	-	-	-

Source: International Encyclopedia of Composites, volume 4, Editor Stuart M. Lee, VCH, New York.

Table 10. Mechanical properties of jute-fibre-reinforced composites

Resin used as matrix	Jute (% per wt.)	E-glass (% per wt.)	Ultimate tensile strength (MN/m^2)	Young's modulus (GN/m^2)	Ultimate flexural strength (MN/m^2)	Fracture strain (%)
Epoxy	32.9	-	104	15.04	150	0.69
Epoxy	18	40	157	25.41	445	0.62
Epoxy	-	68	429	44.30	938	1.04
Polyester	21.8	-	84	12.12	125	1.69
Polyester	10.1	38.5	200	18.15	229	1.10
Polyester	-	69.14	391	38.77	816	1.01

Note: Strength of basic materials when tested individually shows quite low values.

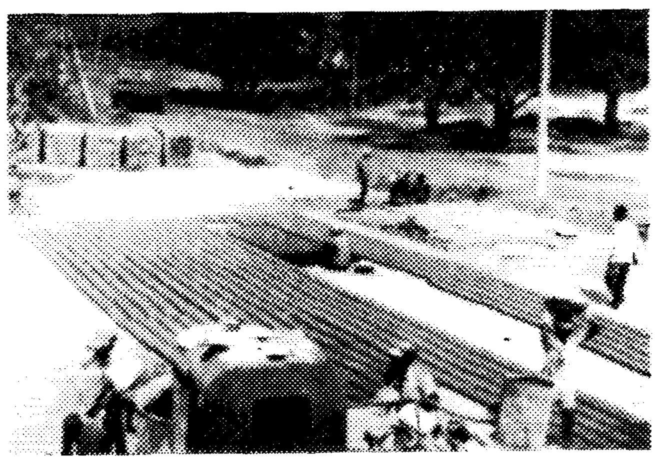
Table 11. Basic data on fibre (natural) reinforced cement roofing sheets and tiles

Country	Type of element	Dimensions (mm)	Cement:sand ratio	Type of fibre and length (mm)	Produced since	Fibre volume (%)	Type of compaction in manual/mechanical production
Africa							
Mozambique	Tile	240 x 500 x 7	1:2	Sisal 12	1985	1.7	Vibration
Zambia	Sheet	670 x 1 000 x 6	1:1	Sisal 10-20	1984	1.1	Tamping
Tanzania	Sheet	750 x 750 x 7.5	1:1	Sisal 20-50	1978	3.0	Vibration
Kenya (1)	Tile	Parry ITW tile	1:3	Sisal 12	1983	1.5	Vibration
Kenya (2)	Tile	" "	1:3	Sisal 12	1985	1.1	Vibration
Zimbabwe	Sheet	NA	1:1	Sisal 15-20	1979	0.9	Tamping
Ghana	Tile	760 x 1 000 x 10-15	1:1	Elephant 20-50	1985	NA	Vibration
Malawi	Sheet			Sisal 20-30	1980	NA	Tamping
Asia							
Bangladesh (1)	Sheet	790 x 1 000 x 6.5	1:08	Jute 18-25	1983	1.1	Tamping
Bangladesh (2)	Tile	Parry ITW tile	-	Jute 10-20	1983	1.9	Tamping
India (1)	Sheet	650 x 1 000 x 10	1:1	Coir 12	1982	1.9	Vibration + Pressure
India (2)	Sheet	1 000 x 2 000 x 7	1:0	Coir 100-200	1980	16	Tamping
Indonesia	Sheet	920 x 1 150 x 7	1:067	Ijuk 30	1983	3.4	Tamping
Sri Lanka	Sheet	390 x 1 000 x 10-15	NA	Coir 20-30	1984	NA	Vibration
South America							
Dominican Republic (1)	Sheet	750 x 1 350 x 6.9	1:1	Sisal 25	1984	1.2	Tamping
Dominican Republic (2)	Sheet	1 000 x 1 450 x 10-15	1:1	Sisal 50-75	1982	1.27	Tamping
Nicaragua	Sheet	840 x 1 000 x 6.9	1:1	Sisal 25	1984	3.5	Tamping
Soloman Islands	Tile	Parry ITW tile	1:3	Coir 20	1984	1.1	Vibration
Haiti	Tile	Parry ITW tile	2:5	Sisal 20	1984	NA	Vibration
Guatemala	Sheet	770 x 990 x 6.9	NA	Sisal 20-30	1981	NA	Vibration
Colombia	Sheet	610 x 1 140 x 10	1:2	Sisal 20-30	1982	0.6	Vibration

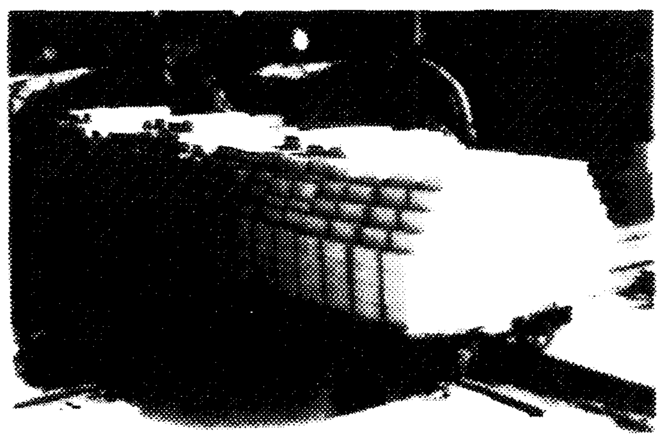
Source: SKAT, Switzerland publications.

Note: The data of Table 11 are based on questionnaires and some personal contacts. This information needs updating.

Manual mixing of raw materials for production of clay-fly ash bricks



Manual casting of fly ash-lime-gypsum bricks at a small-scale unit



Sand lime fly ash bricks under autoclaving

House constructed with sand lime fly ash bricks

Table 12. Physio-mechanical properties of polyester-red mud-sisal fibre composites

Material	Red mud (%)	Sisal fibre (%)	Density (kg/m^3)	Water absorption (%)	Tensile strength (MPa)	Elongation (%)	E (GPa)	Flexural strength (MPa)
Unsaturated polyester (USP)	-	1 118	0.13	26.40	2.38	1.11	61.26	
Red mud-USP 20	-	1 130	0.23	17.30	1.49	0.97	58.79	
Sisal polyester (SP)	-	50	1 110	8.03	45.10	2.33	3.11	85.03
Sisal polyester (USP)	20	38	1 086	4.71	23.50	7.69	0.64	40.02
Sisal fibre-polyester (SP) (glass content 8%)	20	34	1 240	3.65	45.20	8.10	5.95	98.10

Source: B. Singh, Personal Communication.

Table 13. Physical properties of jute fibre and glass fibre-reinforced polyester composites before and after weathering for seven years

Property	Unweathered jute fibre-reinforced sheet	Weathered jute fibre-reinforced sheet	Unweathered jute fibre-reinforced sheet	Weathered jute fibre-reinforced sheet
Bulk density (kg/m^3)	1 160	1 025	1 300	1 250
Fibre content (%)	12-15	-	28-32	30-35
Water absorption (%) (24 h)	2.35	3.23	1.03	1.28
Flexural strength (MN/m^2)				
Dry	23	11.60	107	103
7 days soaking	34	19.10	74.10	
Tensile strength (MN/m^2)	24.20	9-20.6	76.00	63.00

Table 14. General properties of some commercial roofing sheets made from fibre-reinforced composites, in India

Property	Using waste paper board and asphalt	Pine shingle waste pulp and asphalt	Red mud waste and PVC	Cut steel wire and ccement
Density (kg/m^3)	700-1 100	900-1 100	200-400	
Dimensions (mm)	1 200 x 750 x4	400 x 150 x 10	2 000 x 1 000 x 3	1 500-1 800
Flexural strength (MPa)	80-85	15-20	50-60	1 200 x 750 x 10
Permeability of water	Nil	Nil	Nil	Trace
Water absorption (%)	8-10	8-10	0.2-025	5-10

Rice husk-polymer/cement composites

As already stated, particle boards manufactured from wood fibres are relatively costly, and much beyond the reach of poor people. Also, wood particle boards show poor performance when exposed to the atmosphere in tropical climates. Asia and Africa produce about 100 million tons of rice husk per year. Rice husk as it comes from the mill has a bulk density of about 120 kg/m^3. A whole range of rice husk boards with a density of 300 kg/m^3 to 1,300 kg/m^3 is now manufactured commercially. The bonding resin is phenolformaldehyde or a blend of phenolformaldehyde and cashew nut shell liquid resin. Portland cement is also a compatible matrix material for rice husk.

Rice husk contains about 18 per cent silica, which makes the boards totally resistant to termites, wood-boring insects and rodents. The boards can be used for wall panelling, ceilings, partitioning etc. Rice husk boards can be used in damp and humid locations such as bathrooms, without a fear of crumbling by decay. Rice husk board does not show flaming combustion but only smolders slowly when ignited. It resists flame propagation and also flame penetration. The board has very good water resistance.

Rice husk-polymer composites (boards) are at present manufactured with a density 500 kg/m^3 to 900 kg/m^3. They show water absorption 3.5 to 10 per cent and swelling in thickness 3 to 10 per cent. Lower-density rice husk boards are easy to nail and screw; they have a better nail-holding property and also show better thermal and acoustic properties than wood particle boards.

Rice husk, although an agricultural product, is available throughout the year. The cost of rice husk is not expected to increase beyond the cost of fibre wood, and this factor favours it for a variety of uses as wall panels, door shutters, ceiling tiles and furniture. The technology of the production of rice husk-polymer/cement bonded boards, on a small or large scale, has been developed at the Indian Plywood Industry Research and Training Institute (IPIRTI), and is available through the National Research Development Corporation of India, 20-22 Jamroodpur, Kailash Colony Extension, New Delhi-110 049, India.

Rubber wood composites

Wood substitutes have a national priority in resource mobilization in housing, as many Governments have totally banned the use of traditional timber in housing and other uses.

Rubber wood is the only sustainable supply of plantation wood world-wide, and particularly in the tropical zone countries of Asia, Africa and South America. Seasoning and preservative treatment make rubber wood free from some of its inherent defects. Further engineering technologies in lamination of splint lumber, with a polymer (PF type) make it an ideal substitute for wood lumber. Some of the comparative properties are shown in tables 15 and 16.

The Building Materials and Technology Promotion Council (BMTPC) of India has recently promoted this innovative technology. The rubber wood laminated splint lumber could be an excellent material for doors and windows. The product has good market potential and can be sold at a very attractive price.

The BMTPC has also promoted technological processes for the utilization of yet another plantation timber called "Poplar". The technology includes densification, fabrication and application as wood substitutes in buildings. The properties of "Poplar" veneer lumber as compared to those of teak wood are shown in table 17.

Table 15. Comparative engineering properties of rubber wood and teak

	Source of rubber wood			
	India	**Malaysia**	**Sri Lanka**	**Comparative teak (India)**
Moisture content (%)	12.0	17.20	12.0	12.0
B.D. (kg/m^3)	624	690	582	696
Maximum crushing strength (kg/cm^2 parallel to grain)	374	329	396	532
Screw withdrawal power (kg)	296	-	-	399

Source: BMTPC, New Delhi, India, Internal Report, 1995.

Table 16. Mechanical and physical properties of laminated rubber splint lumber

Property	**Average value for LSL**	**Value for solid rubber wood**
Sp. gr.	0.56	0.5 to 0.66
Volumetric shrinkage (%)	5.21	N.A.
Modulus in rupture (kg/cm^2)	720	570
Modulus of elasticity (kg/cm^2)	70 800	72 000
Compressive strength parallel to glue line (kg/cm^2)	326	320
Compressive strength perpendicular to grain (kg/cm^2) (parallel to glue line)	80	N.A.
Shear strength parallel to glue line (kg/cm^2)	119	N.A.
Screw holding strength (kg) (parallel to glue line)	165	176
Nail holding strength (kg) (parallel to glue line)	98	93

Source: BMTPC, New Delhi, India, Internal Report, 1995.

Table 17. Mechanical properties of "poplar" wood veneer lumber and teak

	Poplar wood	Teak
Moisture content (%)	8.2	12
Sp. gr.	0.704	0.551
Compressive strength perpendicular to grain (kg/cm^2)	183	83
Maximum shear strength (kg/cm^2)	176	92
Modulus of elasticity (kg/cm^2)	870	665
Screw holding power (kg)	260	N.A.
Nail holding power (kg)	200	N.A.

Source: BMTPC, New Delhi, India, Internal Report, 1995.

Section B. Particulate composites (inorganic types)

Particulate composites are essentially the materials which are formed by the aggregation of the particulates or particles of two or more components. Concrete is an excellent example of a particulate composite. Since agglomeration or aggregation of the particles is the basic feature, the resultant products are also called "aggregate" composites.

The matrix in almost all inorganic particulate composites is cement or lime-pozzolana. However, there could not be a very rigid demarcation as even the cement matrix-properties are modified, for better results, by the incorporation of small inorganic as well as organic admixtures. Surface modifier, setting time regulators, workability aids, plasticiser and superplasticiser or early/ultimate strength developing additives are often organic materials. Nevertheless the bulk in the inorganic particulate composites is the inorganic materials (see table 18).

Stabilized-soil block is another classic example of particulate composite in which soil and cement or lime are the two major components. A small quantity (1-2 per cent) of chopped fibres is also added which contributes to the adhesive strength and durability of the blocks.

Today, inexhaustible information is available on the utilization of a variety of industrial wastes and by-products for the manufacture of walling, partitioning, roofing and flooring materials. Pulverized fuel ash (fly ash), blast furnace slags, stone processing waste, laterites, ore beneficiation tailings, gypsum by-products, lime sludges have been considered as excellent alternative aggregate materials which, combined with cement or lime-pozzolana or another alternative matrix material, produce many new aggregate composites.

Extensive data on the various physical, chemical, mineralogical and mechanical properties of industrial wastes and by-products have been compiled. These data provide a high degree of confidence in designing tailor-made composite materials suitable for highly cost-effective construction technologies. Utilization of waste materials effect savings in naturally occurring rocks and minerals, a reduction in the use of cement, and pollution abatement through profitable and safe disposal of the wastes.

B.1 Resources of waste materials for use in particulate composites

Fly ash (pulverized fuel ash)

Fly ash is the residue from thermal power stations using pulverized coal in the boilers. Fly ash is evaluated for its chemical composition which is almost in the same range as of calcined clay-pozzolana. The specific surface of many fly ashes is about 4,000 cm^2/g (Blaine's) and residual carbon content is 0.5 to 5% per wt. Dry fly ash as collected from the chimneys of boilers is highly reactive with lime to produce a hydraulic (cementitious) binder composite material. Hence the reactivity of fly ash towards lime is very important. Fly ashes contain about 60 per cent silica (SiO_2), most of which is reactive.

Today the annual world consumption of coal in thermal power stations is about 2,500 million tons which on burning generate about 250-300 million tons of fly ash per year. There are, however, only a few developing countries which have enough coal to burn and produce fly ash. China and India are major fly ash producing developing countries. It is, therefore, natural that these two countries are the most advanced in finding a number of uses for fly ash as construction materials. The major uses found are fly ash-blended cements, called Portland-fly ash pozzolana cement, in mass concrete in the construction of dams, precast concrete products, light weight sintered aggregate and fly ash-lime (sand-lime type) bricks and blocks.

China and India have so far carried out outstanding research and development in the utilization of fly ash. Yet, unfortunately, because of many logistic and administrative bottlenecks not even 10 per cent of the 80 and 50 million tons of fly ashes, produced yearly in China and India respectively, are actually utilized. Among African countries, South Africa is the foremost in presenting fly ash-based technologies for various composite materials. When the production of fly ash in some of the developing countries is likely to touch still higher figures by the end of the century, huge efforts are required to accelerate the utilization of fly ash. Perhaps it would be useful to obtain information from the UNIDO assisted project on fly ash utilization carried out in the Shanghai Research Institute of Building Sciences, CPR.

Table 18. Industrial, mining and mineral waste having potential for utilization in the production of composites

Sl. No.	Type of waste	Source	Type of particulate composites in which utilized	Appropriate technology available (country)
1.	Fly ash/pulverized fuel ash	Thermal power stations using pulverized coal as fuel	Portland-pozzolana cement (using up to 20% of fly ash) cement concrete, lime-fly ash mortar, plaster, cellular concrete, brick and tiles, fly ash-sand-lime bricks, stabilized soil bricks (using lime or cement and fly ash)	India China UK Russia
2.	Blast furnace slag	Steel plants		
	(a) Air cooled type	" "	As dense aggregate replacing natural stone aggregate in concrete.	
	(b) Foamed type	" "	As light weight aggregate in concrete and concrete products	India China South Africa UK Russia
	(c) Granulated type	" "	As part replacement in Portland cement for Portland-blast furnace slag cement; in super sulphated cement	
3.	By-products gypsum	Ammonium phosphate fertiliser, hydrofluoric acid and boric acid industries	As replacement of natural gypsum in making fibrous gypsum plaster boards, blocks, composite mortar etc.	India UK Russia
4.	Mine tailings	Beneficiation of the zinc, copper, iron, gold, feldspar, fluorspar, bauxite ores and minerals	As part replacement in composite mortar, concretes, masonry cement, cellular concrete, sand-lime bricks, as replacement of sand.	India China Germany Russia
5.	By-product lime sludges	Sugar, paper, acetylene, tannery fertilizer industries	After calcination used in composite mortars, plaster and lime-pozzolana composites.	India Indonesia
6.	Laterite wastes	Cutting and dressing of laterite blocks	For stabilized laterite bricks/blocks using cement or lime as stabiliser and a fibre as reinforcement.	Ghana India
7.	Red mud	Aluminium industry	For blended cement, bricks/tiles compositions and fibre-reinforced panel products.	India Russia
8.	Basic or acidic metallurgical slags	Metals and alloys industries	Masonry cement compositions and in cement-concrete replacing natural aggregates, cementitious binders etc.	India China UK
9.	Broken glass and ceramics	Glass and ceramic industries	Insulating bricks and tiles, flooring tiles, decorative panels	China India Russia
10.	Inorganic ashes of plants	Incineration (in boilers) of rice husk type materials	Replacement of natural or clay pozzolana in lime-pozzolana composites, pozzolana cement, bricks etc.	India Sri Lanka Malaysia
11.	Wastes from mica, slate, vermiculete etc.	In the mining of the respective mineral	Utilization after calcination in lime-pozzolana	India

In India, the emphasis is on the development of technologies for the stabilization of fly ashes in their collection ponds and then to develop selective forming and forests which could provide much needed cellulosic materials for reconstituted wood products. Another promising way could be to manufacture fly ash-lime bricks, either steam-cured or using cement for adequate compressive strength of the bricks. A third major application could be in road construction. It is almost certain that in India not more than 5 per cent of fly ash produced could be absorbed in cement and concrete products.

Table 19 shows the range of chemical composition and mineralogical constituents of Indian fly ashes. Table 20 shows some important uses of fly ash in inorganic composite materials.

Table 19. Chemical analysis and mineralogical constituents of Indian fly ashes

Constituent	% by wt.
SiO_2	37.15-66.75
Al_2O_3	18.30-28.90
Fe_2O_3	3.2-21.90
TiO_2	-
CaO	1.3-10.80
MgO	0.8-5.25
SO_3	0.94-2.91
$Na_2O + K_2O$	0.04-1.30
Loss on ignition	0.05-16.60

Mineral composition

Quartz, mullite, glassy phase, ferrous oxide (FeO), magnetite (Fe_3O_4), haematite (Fe_2O_3)

The table 19 shows the wide variability of fly ash composition which does not have any control as the quality of coal varies and power production parameters also vary. The mineralogical make-up also differs considerably. These factors restrict the general application of fly ash as a building material.

By-products of blast furnace slags

The developing countries which have large steel plants also produce slags. Slags, if air-cooled are suitable as dense aggregates for cement-concrete; foamed-type slag finds use in lightweight concrete products and granulated-type slag for Portland blast furnace slag cement. These materials are based on well-established technologies. However, recent research and development work has shown that slags, fly ash and by-product chemical gypsum (from ammonium phosphate and fluorine industries) could be blended and interground to produce a hydraulic binder for making concrete blocks, bricks and as mortar and plaster. Again, most of the developing countries do not have steel plants and therefore no slags; and even if they have iron ores suitable for steel production they do not have the fuel resources to meet the demand of large steel plants. Hence fly ash and slags are important resources only for a few developing countries.

Table 21 shows the chemical composition of blast furnace slags. Table 22 describes the constituents, factors and suitability of slags for building materials. Blast furnace slag produced in any country has similar characteristics and uses.

Thus, suitability and processing of slags are important factors. Most of the technical aspects have, however, been resolved. Slags are also used for making ceramic composites for wall cladding; one name given for it is "Slag Cital".

Coal washery rejects

Depending upon the coal deposits and their quality, many high ash coals need washing, in large washeries, producing huge quantities of rejects. Coal washery reject is usually silicious-argillaceous in composition with about 15-20 per cent coal particles. The Indian experience is to utilize the washery rejects for blending with clays, moulding into bricks and then burning in small or large kilns.

Mine tailings

Unlike the limited scopes of availability and utilization of fly ash and slags in the majority of developing countries, there are enormous quantities of mining operation rejects available for profitable utilization. Upgrading and beneficiation of ores of copper, zinc, tin, gold, silver, nickel etc., produce tailings which are either silicious or calcareous-dolomitic depending upon the composition of the parent rocks containing the ores. These tailings have found application in several aggregate composites—such as fine filler in concrete, admixture in mortar and plaster, for blending with Portland cement to produce masonry cements and in the production of lime-stabilized bricks, sand-lime type autoclaved bricks and cellular concrete units. These composites have been fully evaluated for their performance and service life.

Table 23 shows the physical, chemical and mineralogical properties of 10 types of mineral tailings including coal washery rejects. The main uses of these tailings in the production of alternative/new building materials are also indicated. Mine and mineral tailings can feed the requirements of large or small-scale manufacture of sand-lime type calcium silicate bricks and cellular concrete and thus contribute to the saving of precious primary minerals and also energy.

Table 24 presents data of pilot-plant production of sand-lime-type calcium silicate bricks and table 25 for cellular concrete.

Table 26 gives results of masonry cement produced by using tailings and Portland cement, by intergrinding.

All the above-mentioned materials (calcium-silicate bricks, cellular concrete and masonry cement based on the utilization of mine-mineral tailings) conform to international standard specifications.

Red mud

Red mud is the name given to the waste material thrown in the manufacture of alumina from bauxite. Composition of red mud depends upon the overall chemical constituents in bauxites. Red mud is red coloured slime with a high iron oxide (Fe_2O_3) and titanium dioxide (TiO_2) content and small quantities of aluminium oxide (Al_2O_3) and silica (SiO_2). Red mud has been used in several cement plants as flux material, in making bricks and tiles of high strength, and in composites with a polymeric matrix reinforced with natural or man-made fibres, into shapes of boards, roofing sheets, tiles, cladding materials and door and window shutters. However, difficulties in the collection, washing, processing, drying and grinding are some of the constraints in major consumption of red mud as composite materials for housing. Some red muds were also suspected to be mildly radioactive but this has not been corroborated after detailed testing.

Table 20. General uses of fly ash in inorganic composites

Material	Description
Aggregates (for concrete and concrete products)	Production of light weight aggregate of sp. gr. <1 is carried out by palletization and sintering at 1,050°-1,100° C. The residual carbon content of fly ash on burning provides energy for sintering and thus the process needs very little energy.
Cement (as Portland-fly ash pozzolana cement for concrete and also as raw mix)	Fly ash finds a substitute for clay or other argillaceous material in cement manufacture; particularly where high MgO containing limestone is used. In ordinary Portland cement, the blending proportion again depends on the fineness, carbon content (low percentage preferred) and lime-reactivity. These properties also govern fly ash application in roads and stabilized blocks.
Cellular concrete and other concrete	Fly ash is an excellent material as the substitute for ground sand in the manufacture of sand-cement/lime based light weight cellular concrete for structural as well as filler and insulation grades. Fly ash is also a replacement for sand in concrete.
Bricks (Calcium-silicate sand-lime type—steam cured, and clay-fly ash burnt brick type)	Fly ash-sand-lime bricks are as good as other sand-lime bricks, in the former fly ash replaces sand up to 70 per cent. Fly ash is also blended with plastic clays for burnt-clay bricks where it works as opening materials reducing drying shrinkage cracks and providing saving in coal for firing.

Table 21. Chemical composition (percentage) of blast furnace slag

Source	**CaO**	**SiO_2**	**Al_2O_3**	**MgO**	**Feo**	**MnO**	**S**
British	48	31	10	3	1.0	0.5	1.5
German	45	35	12	4	0.5	0.5	2.0
Indian	40	35	18	5-8	0.5	1.0	1.5

Table 22. Constituents, factor and suitability of slags

Constituents	**Factor**	**Suitability for**
High SiO_2 or high Al_2O_3	Cools to glassy granulated form easily	Slag wood composites
High CaO and low Al_2O_3	Makes suitable composition but tends to dust	Portland blast furnace slag cements but not aggregates
High MgO or high MnO	Makes unsuitable composition	Not so good for slag cement

Table 23. Ore beneficiation tailings and their uses

Chemical analysis constituents (%)	**Zinc tailings**	**Copper tailings**	**Gold tailings**	**Iron tailings**
Loss on ignition	14.75	2.24	5.31	3.58
SiO_2	60.63	59.42	61.63	58.53
AL_2O_3	0.54	12.06	11.63	9.21
Fe_2O_3	3.02	19.82	9.85	21.08
CaO	12.68	2.11	10.36	4.08
MgO	7.27	1.86	2.32	2.76
NA_2O+K_2O	-	-	-	-
Physical properties				
Fineness modulus	0.342	0.637	0.103	0.416
Sp. gr.	2.85	2.95	2.85	3.04
Bulk density (kg/l)	1.51	1.45	1.56	1.60
Specific surface (Blaine's) (cm^2/g)	3 500	3 500	4 000	3 500
Mineralogical constituents	Quartz and dolomite	Quartz and biotite	Quartz and calcite	Quartz and haematite
Recommend utilization in building materials	Cellular concrete	Cellular concrete	Cellular concrete	-
	Calcium silicate bricks	Calcium silicate bricks	Calcium silicate bricks	Calcium silicate bricks
	Masonry cement	Masonry cement	Masonry cement	Masonry cement
	Mortar	Mortar	Mortar	Mortar
	Fine filler in concrete	Fine filler in concrete	Fine filler in concrete	Fine filler in concrete
	Filler in bitumen mastics	Filler in bitumen mastics	Filler in bitumen mastics	-
	-	As opening material in brick making	-	Burnt clay bricks
	-	Filler in acid resistant cement	-	Filler in acid resistant cement

Table 23 *(cont'd)*

Chemical analysis constituents (%)	Feldspar tailings	Fluorspar tailings	China clay waste tailings	Coal washery tailings	
				Burnt	Unburnt
Loss on ignition	1.30	0.85	11.20	01.8	16.90
SiO_2	63.84	73.00	50.30	57.60	60.40
Al_2O_3	18.32	5.70	32.70	31.30	18.10
Fe_2O_3	1.42	7.00	2.37	3.86	7.03
CaO	1.45	1.30	0.07	0.36	0.66
MgO	0.50	-	0.35	0.92	0.44
Na_2O+K_2O	12.13	-	0.59	2.73	2.35
Ca_2F_2	-	12.80	-	-	-
Physical properties					
Fineness modulus	-	0.4-0.8	0.56	-	-
Sp. gr	2.53	2.75	2.85	2.66	2.40
Bulk density (kg/l)	1.45	1.8	2.63	1.32	1.25
Sp. surface (Blaine's) (cm^2/g)	2 550	2500	2 800	2 200	1 900
Mineralogical constituents	Feldspar quartz	Calcium fluoride quartz	Quartz feldspar	Quartz, albite, feldspar	
Recommended utilization in building materials	Burnt-clay brick, calcium silicate bricks, ceramics concrete blocks	Calcium silicate bricks aerated concrete, concrete blocks	Ceramics tiles, bricks, calcium silicate bricks	Burnt clay bricks, sintered light-weight aggregate, concrete blocks	

Table 24. Properties of calcium silicate bricks made by using tailings 70-90 per cent, sand 10-20 per cent and lime 7-10 per cent

Forming pressure	160-240 kg/cm^2
Steam autoclaving	6, 8, 11 and 14 kg/cm^2 pressure
Duration of autoclaving	3-6 hours
Compressure strength of bricks	115-140 kg/cm^2 based on variations in forming pressure and steam-curing parameters
Drying shrinkage of bricks	0.01 to 0.055% of length
Thermal conductivity of 11.5 cm thick wall	9.3 to 9.7 gram-cal/cm^2/h/° C/cm
Water absorption	15-20% by weight

Table 25. Results of cellular concrete produced on pilot-plant using tailings 50-80 per cent, cement/lime 30-50 per cent, gypsum 5-1 per cent, aluminium powder 0.05 per cent

Process parameters	Autoclaving at 10 kg/cm^2 steam pressure for 10 hr
Compressive strength of cellular concrete blocks	36-60 kg/cm^2
Drying shrinkage (%)	0.05 to 0.08
Thermal conductivity	0.35 gram-cal/cm^2/h/° C/cm
Fire resistance	Good

Table 26. Results of masonry cement composite using tailings 60 per cent + Portland cement 40 per cent (pilot-plant data)

Fineness (cm^2/g) (Blaine's)	5,600
Setting time (minutes)	Initial 150 Final 480
Compressive strength of 1:6 masonry cement-sand mix, (kg/cm^2)	7 days 28 28 days 52
Water retention (%)	72
Soundness La'chatelier expansion	1 mm

Table 27 gives the chemical composition and table 28 gives the physical and mineralogical constituents of red mud from different countries.

From the chemical composition it is seen that in some red mud samples precious titanium dioxide is wasted. Some samples are rich in an iron oxide or have a very high alkalinity (Na_2O). Red mud has to be processed to remove alkalies so as to render it suitable for making bricks and tiles in combination with fly ash and/or fibres. Red mud is causing serious pollution problems because it is being stocked and its toxic soluble constituents are flowing into ground water, lakes and rivers.

Red mud presents difficulties in settling and its colloidal suspended particulates continue to float for a long time. The particle-composition related properties of red mud are given in table 28. Table 29 presents data on red mud fly ash bricks.

The mineralogical composition shows the suitability of red mud from Russia for use in cement—raw meal composition as its iron oxide content is quite low. Other red muds are more suitable for ceramics.

By-product gypsum

Substantial quantities (about 2.5 million tons per year in India) of by-product high grade gypsum (chemically 99 per cent $CaSO_4\ 2H_2O$) are produced from ammonium phosphate fertilizer, fluorine/hydrofluoric acid and boric acid production plants; and accordingly they are designated as "phosphogypsum", "fluorogypsum", and "borogypsum". This gypsum, after washing to remove its acidic impurities, is calcined to produce gypsum plaster which, as a matrix, in turn, is reinforced with vegetable fibres or glass fibres to produce composites such as boards, blocks, tiles, door shutters, etc. Extensive R&D and industrial production experience have been acquired in several Indian institutions.

Gypsum plaster is soluble in water and therefore it is not suitable for outdoor applications. By-product gypsum, after necessary neutralization of acidity, purification and upgrading, is classified to determine its suitability for various uses. In several countries, including India, by-product phosphogypsum, fluorogypsum, and borogypsum have now found use in the preparation of a water resistant binder using fly ash, granulated blast furnace slag and small quantity of lime or cement. Table 30 gives the physical properties and table 31 gives the chemical properties of this binder.

The binder referred to in tables 30 and 31 can be used for plastering and also for building blocks—solid and hollow—for load bearing and non-load bearing applications.

Glass fibre-reinforced gypsum binder (water-resistant) has been prepared, using an E-type glass fibre. This glass fibre has a diameter (of the fibre filament) of 8-10 μm; the number of filaments in a strand is about 200, tensile strength of the fibre is 17,500 kg/cm^2 and its Young's modulus is 68,900-76,000 kg/cm^2. Composites using the binder in a 67 per cent consistency and in a thickness of 5 mm are made, using chopped glass fibre, about 4% per wt. The typical properties of glass fibre-reinforced gypsum binder-composite are given in table 32.

Miscellaneous lime-sludge wastes

Waste lime-sludge in large quantities is obtained from sugar, paper, tanning, fertilizer and acetylene gas industries which consume high grade lime in their production processes. Most of the waste lime-sludges are in the form of calcium carbonate ($CaCO_3$). On briquetting and calcination the sludge produces lime (CaO) which mixed with calcined clay, or fly ash, or natural pozzolana, makes low-cost mortar/plaster materials. This lime could also be used for producing stabilized—soil bricks and sand-lime type bricks or in road construction.

Lime sludge from calcium carbide-acetylene plant is obtained as calcium hydroxide [$Ca(OH)_2$], which, if kept protected from atmospheric carbonation by storage under water, can be an excellent material for direct blending with a natural or artificial pozzolana or rice husk ash for making lime-pozzolana composite mixtures.

The lime-pozzolana mixtures must be protected from atmospheric carbonation during storage, by packing in waterproof bags. A summary of the lime-pozzolana mixtures, using calcined lime sludge and a pozzolana, for 28 days (wet curing) compressive strength of 1:3 mortar (ILP:3 sand), is given in table 33. These alternative binders are, although in use for many years, one of the best locally available alternatives to cement-binder. They, however, need further technological support in standardization as well as fiscal incentives like those given for the use of fly ash or red mud or any other waste.

In addition to the major groups of industrial wastes mentioned above, many others find use in composite building materials. The major advantages in the utilization of the waste materials are well known and hence the emphasis should be on future planning on the following lines:

(a) **Planned construction project:** Large public sector construction projects should be undertaken in which the use of industrial wastes has an integral component.

(b) **Removal of logistic difficulties:** Wastes continue to be accumulated, in spite of all available knowledge about the benefits of their utilization, because of a lack of proper infrastructural facilities and roads as well as unplanned storage systems. These difficulties must be removed to have proper access to solid waste management.

(c) **Identification of well proven technologies and their dissemination:** Correct sources of technologies must be identified and mutual cooperation among developing nations should be encouraged, instead of looking towards only import from the developed world.

(d) **Standards, validation and certification:** For these regulatory measures there is a need to constitute one central agency in each country for processes based on waste materials.

Table 27. Chemical composition of red mud

Constituent %	Red mud samples from aluminium plants of: India: Hindalco	India: Indalco	India: Alcorpon	Australia	Hungary and Yugoslavia	Jamaica	Suriname
Loss on ignition	9-10	10-12	10-13	13-15	10	13	13
SiO2	6.8-7.7	6-8	6-8	14-18	60	-	12
Al_2O_3	18-20	25-29	24-26	24-28	20	15	19
Fe_2O_3	33-35	24-27	22-25	18-22	48	52	25
TiO_2	18-20	22-25	18-21	6-8	5	5	12
CaO	4-4.5	-	-	7-10	3	5	3
Na_2O	5-5.75	4-5	-	8-10	5	-	10
Cr_2O_3	-	-	-	0.1-0.2	0.3	-	-
V_2O_5	0.24-0.26	-	-	0.07-0.1	0.2	-	-
P_2O_5	0.26-0.28	-	-	0.08-0.1	0-2	-	-

Hindalco: Hindustan Aluminium Co., Renukoot, (UP) India
Indalco: Indian Aluminium Co., Alwaye, Kerala, India
Alcorpon: Aluminium Corporation, Asansol, West Bengal, India

Table 28. Physical and mineralogical properties of red mud

Sp. gr	2.6-3.1
pH	11.7-12.3
Bulk density (g/cm^3)	1.1-1.3
Initial solids in mud slurry (%)	7.8-35.9
Settling rate (cm/kg)	0.014-0.015

Mineralogical constituents of red mud

Indian	European	Russian
Quartz	Natrolite	Alkali-alumino silicates
Gibbsite	Boehmite	Kaolinite
Goethite	Goethite	Halloysite
Rutile	Haematite	Feldspar
Unatase	Unatase	Limonite

Table 29. Properties of red mud-fly ash bricks

Composition	Compressive strength range (kg/cm^2), Temp. of firing: 1 000° C	Compressive strength range (kg/cm^2), Temp. of firing: 1 050° C	Water absorption (%), Temp. of firing: 1 000 °C	Water absorption (%), Temp. of firing: 1 050 °C
Fly ash-red mud (50:50)	175-210	240-275	18.5-19	16.5-17
Fly ash-red mud-clay (50:30:20)	185-225	380-425	17.5-18	16.0-17

Table 30. Physical properties of water-resistant gypsum binder

Fineness (cm^2/g)	3 200
Setting time (minutes)	Initial 75 Final 155
Bulk density (kg/m^3)	1 200
Compressive strength (28 days) (kg/cm^2)	350
Soundness (La'chatelier) (mm)	1.6
Water absorption (%)	6
pH	11.5

Table 31. Chemical properties of water resistant gypsum binder

Constituent	% per wt.
Loss on ignition	4.11
SiO_2 + insoluble in HCL	8.5
Al_2O_3	9.00
CaO	37.30
MgO	1.80
SO_3	39.65
P_2O_5	0.15
F	0.09

Table 32. Properties of glass fibre-reinforced gypsum binder composite

Property	Gypsum-binder composite (E glass 4%)	Gypsum plaster composite (E glass 4%)
Bulk density (kg/m^3)	1.628	1.20
Consistency (%)	65	81
Flexural strength (kg/cm^2)		
3 days	121.7	49.7
7 days	132.1	49.8
28 days	220.0	49.6
Tensile strength (28 days) (kg/cm^2)	180	27.5
Impact strength (28 days) (kg/cm^2)	186	102.0
Thermal conductivity (Kcal/mh°C)	0.09	0.12

Note: There is progressive increase in strength of the "binder" as it is hydraulic due to its fly ash, slag and lime/cement content.

Table 33. Recommended lime-pozzolana mixtures as alternative to cement binder

Blend	Cementitious material (%) OPC	Lime	Pozzolana	Total aggregate	Recommended use
OPC-pozzolana	50	-	50	9-12	Low-strength concrete
	50	-	50	4-8	Mortars and plasters
	66	-	34	6-10	Medium-strength concrete and concrete blocks
	75	-	25	6-8	Structural concrete
Lime-pozzolana	-	34	66	6-8	Low-strength concrete and concrete blocks
	-	34	66	3-6	Mortars, plasters and load bearing blocks
OPC-lime-pozzolana	20	-	60	6-9	Medium-strength concrete and concrete blocks
	10	25	65	6-8	Low-strength concrete and concrete blocks
	5	30	65	4-7	Mortars and plasters

Source: UNCHS, A Compendium of Information on Selected Low-Cost Building Materials, UNCHS (Habitat) Nairobi (Kenya) p.39

Concluding remarks

Aggregate composites, based on inorganic industrial wastes, and natural fibre-reinforced composites are materials for cost-reduction in housing and a possible answer to meeting the requirements of building materials for millions of shelters to be constructed in all developing countries.

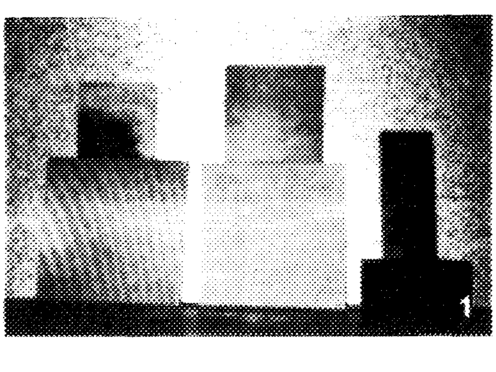
Some of the composites, like fly ash-lime, Portland-slag cement, gypsum plaster fibre board, are now well proven. So is the indicator in the manufacture of jute fibre-polyester, red mud-PVC and rice husk-cement boards and blocks (see annex I). Yet there are several gaps in the scientific and technological developments of natural fibre based composites, using polymer or cement matrix—perhaps more problems with the latter matrix.

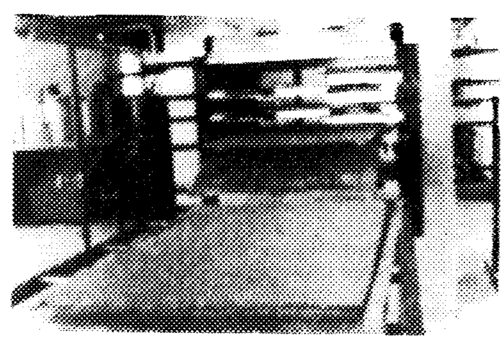
There could be some well-defined projects for the collection and compilation of data on wastes and natural fibres. There appears to be a need for improving manufacturing technologies in fly ash-lime bricks, laterite blocks and phosphogypsum boards. Also, to improve the performance of natural fibre composites, a database is needed on the aspects of the technological properties, improvements in lamination and sandwiching of fibres, recycling processes, use of additives for improving bond strength of fibres in cement matrix and studies on the durability of building products. These are the key areas for future research and development and engineering design of the products.

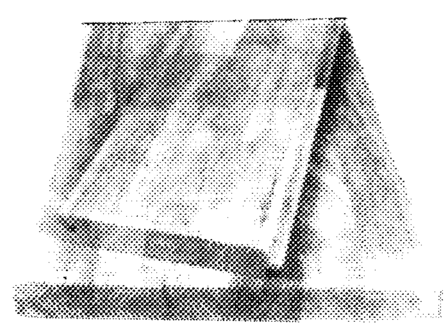
Names of some organizations disseminating information on composites

GATE—German Appropriate Technology Exchange, Germany.
ITDG—IntermediateTechnologyDevelopmentGroup, UK
SKAT—Swiss Centre for Appropriate Technology, Switzerland
CRATerre—International Centre for Earth Construction, France
BMTPC—Building Materials and Technology Promotion Council, India
NRDC—NationalResearchDevelopmentCorporation, India
SRIBS—Shanghai Research Institute of Building Science, Shanghai
UN-ESCAP, UN-ECLAC, UN-ECA, UNCHS, UN-ESCWA, FAO, UNIDO

1. Red mud polymer composites for door/window shutters
2. Manufacture of risk husk boards
3. Laminated splint lumber from rubber wood for manufacture of door/window shutters







Annex I

COMMERCIAL PRODUCTS OF SOME COMPOSITES IN INDIA

S. No.	Name of the composite	Composition of the composite % per wt.	Type of building material	Name and address of the manufacturer in India
ORGANIC COMPOSITES				
1.	Red mud-PVC jute fibre	Red mud, PVC fibre	Corrugated roofing sheet panels	Lotus Roofing Pvt. Ltd. Sedurapet P.O. Pondicherry 605 101
2.	Jute fibre-polyester	Polyester, jute fibre	Panels	Jupiter Board Industries 93, Pilkhana Road Berhampore, Mushidabad 742 101 (WB)
3.	Red mud-polyester-sisal-glass fibres	Red mud, polyester, sisal	Panels, tiles, roofing sheet	Neolux India Ltd. 75, Altanta, 7th Floor 209, Nariman Point Bombay 400 021
4.	Bitumen bonded paper fibre or pulp	Paper fibre, felt, bitumen	Corrugated roofing sheet	Light Roofing Ltd. No. 2/87, GST Road Chettipunniyam 603 200 Chengai, MGR, Dist Tamil Nadu
5.	Bitumen-pine needle fibre	Pine needle fibre, bitumen	Shingles for roofing	Light Roofing Ltd. No. 2/87, GST Road Chettipunniyam 603 200 Chengai, MGR, Dist Tamil Nadu
6.	Gypsum plaster-fibre jute/sisal and glass	Sisal/glass fibre, gypsum plaster	Partitions, door shutters	Ganesh Agro Industries Pvt. Ltd. 636, Mundka, Delhi 110 041
7.	Borotik	Rubber wood	Door shutters, partitions	Borox Morarji Ltd. Jolley Bhawan No. 2, New Marine Lines Bombay 400 020 (India)
8.	Coir-oxychloride composite	Coir fibres, magnesium oxychloride cement	Ceilings, partitions, panels	Anutone Boards (P) Ltd. Bangalore (India)
9.	Rice husk board	Rice husk, synthetic resin	Wall panelling, false ceiling, partitioning, door/window shutters, roofing panels, flooring	Padmavathy Panel Boards Pvt. Ltd. 114, 4th Cross 1st, N Block Rajaji Nagar Bangalore 560 010 (India)
10.	Bagasse board	Baggase, synthetic resin	Wall panelling, false ceiling, partitioning, door/window shutters, flooring, furniture	Western Bio system Ltd. ECO HOUSE 65/1-A, Akarshak Opp.Nal Stop Karne Road Pune 411 004
11.	Cement bonded particle board	Cement 62% Wood (e.g. eucalyptus and casurine) 28%	Partitioning, wall lining, false ceiling, roofing, flooring, doors, panelling	NCL Industries Ltd. 7th Floor, Raghava Ratna Towers Chirag Ali Lane Abids Hyderabad 500 001
12.	Medium density fibre board	Cotton plant scantling, wood fibre, resin	Chaukhats, doors, mouldings, furniture, partitioning, panelling, flooring, ceiling	NUCHEM Limited E-46/12, Okhla Industrial Area Phase-I New Delhi 110 020

S. No.	Name of the composite	Composition of the composite % per wt.	Type of building material	Name and address of the manufacturer in India
13.	Stramit board	Dry unpulped straw and paper	False ceiling, doors, partitions, non-load-bearing walls, flooring, roofing, wall cladding	Ballarpur Industries Ltd. Thapar House 124, Janpath New Delhi 110 001
				INORGANIC COMPOSITES
14.	Elatomation bonding plant	Technology for cement/polymer bonded boards	Roofing sheet, partition, panelling, door shutter and frames	Synergy International B-17, Defence Colony New Delhi 110 024(India)
15.	Fly ash-red mud polymer composite	Fly ash, red mud and polyester	Door shutter	Dual Build Tech (P) Ltd. Madras (India)
16.	Clay fly ash bricks	Fly ash 30-40% Clay 60-70%	General-purpose building bricks	Calcutta Mech. Brick (P) Ltd. Calcutta 700 020 (India)
17.	Fly ash-sand-lime bricks	Fly ash 70% Sand 20% Lime 10%	General-purpose bricks	Damodar Valley Corporation DVC Power Plant Baria, Durgapur West Bengal (India)
18.	Fly ash-sand-lime bricks	Fly ash 70% Sand 10-20% Lime 7-10%	General-purpose bricks	Pulver Ash Ltd. Bundel West Bengal (India)
19.	Fly ash cellular concrete	Fly ash cement/lime gypsum Aluminium powder	Light-weight blocks and slabs	Ballarpur Industries Ltd. Palval Haryana (India)
20.	Fibre-reinforced phosphogypsum composite	Purified phosphogypsum plaster and glass fibre or coir	Walling, roofing panels and blocks	IDL Salzbau Visakhapatnam Andhra Pradesh (India)
21.	Sand-lime bricks and fly ash-lime brick	Sand 90% Lime 10% Fly ash 10-90% Lime 35-40%	General-purpose, white and coloured bricks, hollow blocks	Sand Plast India Ltd. Behroor, Alwar Rajasthan (India)
22.	Clay-fly ash bricks	Clay 60-65% Fly ash 35-40%	General-purpose bricks	Kolaghat Power Station Kolaghat West Bengal (India)
23.	Fly ash-lime gypsum brick (Fal-G)	Fly ash 60% Lime 10-20% Gypsum 10-20%	Bricks of medium-range strength	Bhadrachalam Paper Board Ltd. Bhadrachalam Andhra Pradesh (India)
24.	Fly ash cement brick/blocks	Fly ash 60-80% Lime/Cement 10-20%	Walling, foundation etc.	Gujarat Electricity Board Fly ash Company Ahmedabad Gujarat (India)
25.	Fibre-fly ash cement boards (E Board classic)	Agro waste fibres Cement 65% Fly ash 30%	Roofing, partition and panels	Everest Roofing ""Eternit" Ltd. Bombay (India)

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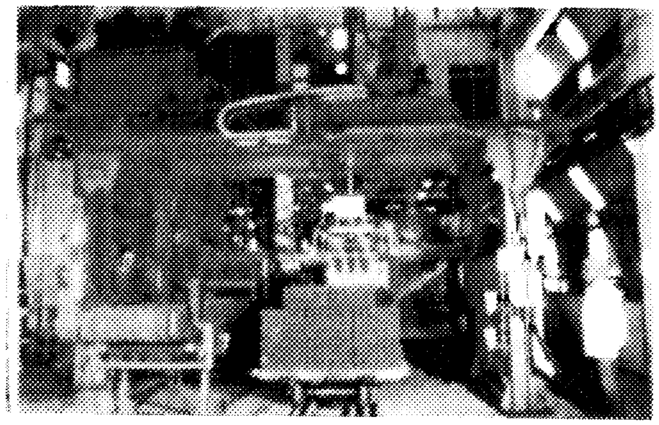
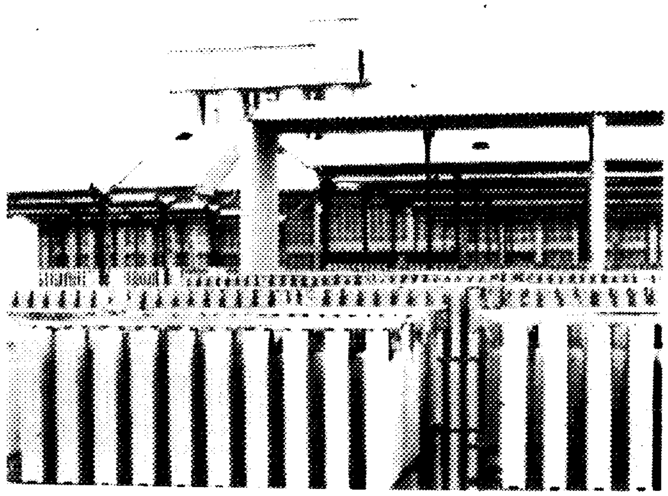
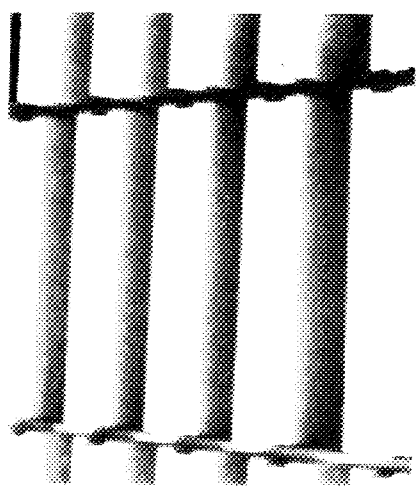
Production of fly ash-sand-lime bricks



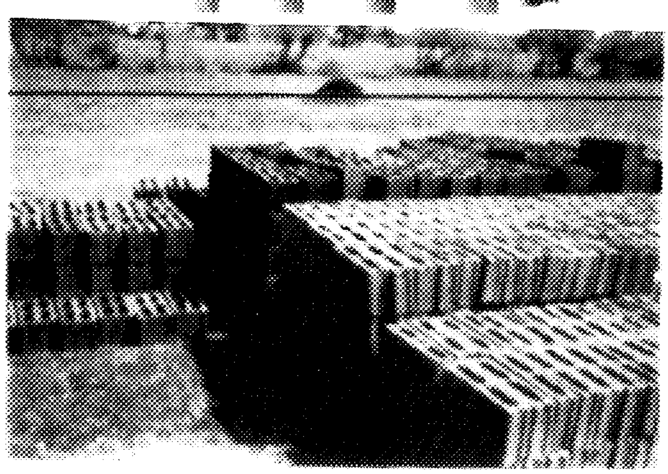
Production of phospho-gypsum panels



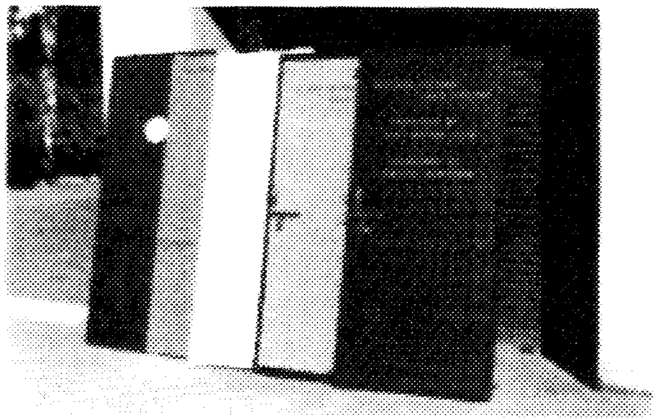
Phosphogypsum panels for walling and partitioning



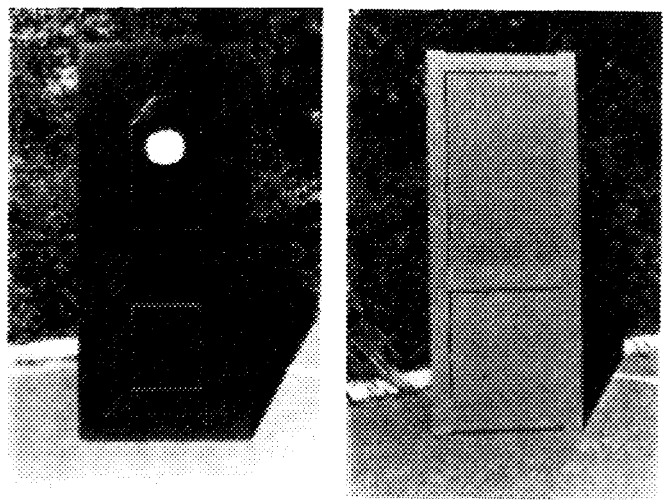
Production of fly ash-lime-gypsum-cement-concrete hollow blocks. The coloured blocks are manufactured by adding red-oxide pigment



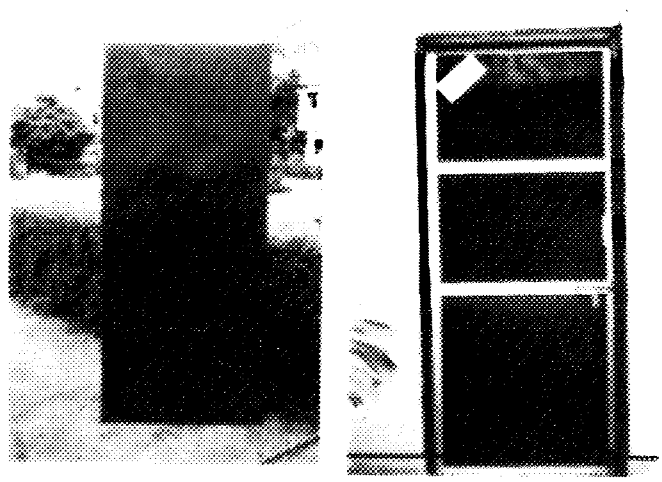
Door-shutters from agro-industrial wastes



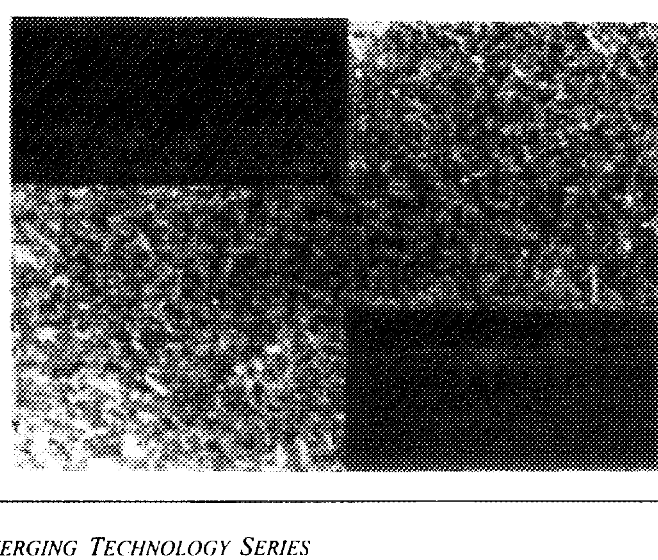
Medium-density fibre (MDF) door shutters



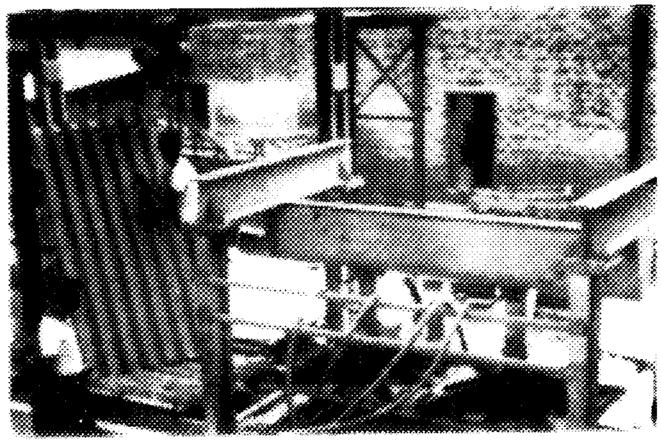
Red mud-polymer (RMP) door shutters



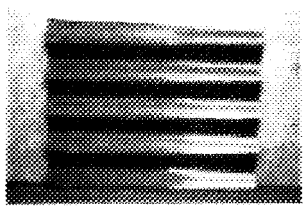
Bagasse boards for false ceiling, panelling, etc.

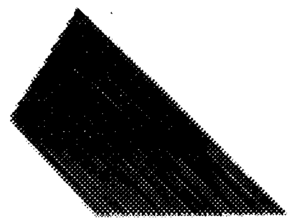


Production of red mud-polymer (RMP) roofing sheets

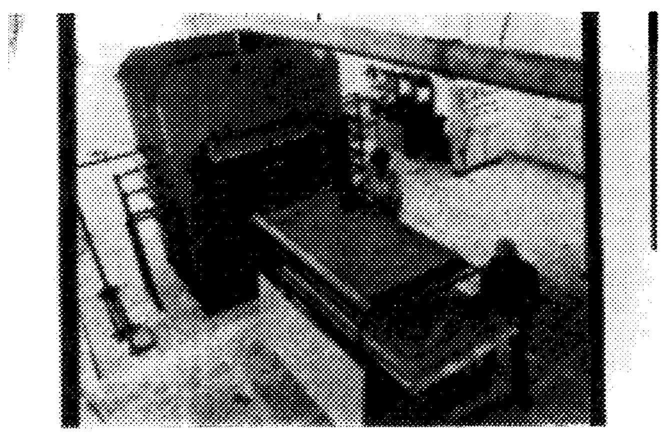


Red mud-polymer roofing sheets





Production of rice husk boards



Laminated splint lumber from rubber wood

B. COMPOSITES FROM LOCAL RAW MATERIALS — OVERVIEW

COMPOSITE MATERIALS FROM LOCAL RAW MATERIAL RESOURCES

By Pradeep Rohatgi

1. Science and technology of polymer natural fibre composites: an example of composites from local raw materials

There has been unprecedented growth in polymer matrix composites containing fibres. These composites provide unique combinations of properties, including high specific strengths and moduli and can therefore substitute for other conventional materials. The fibres that can be incorporated in polymers include: glass, carbon and boron which are man-made, or natural fibres such as jute, cotton, ramie, sisal, banana, sunn hemp and coir, which are renewable and inexpensive.

Natural fibres like jute, coir, banana, sisal and others, are abundantly available in developing countries such as India, Sri Lanka, Thailand, Indonesia, the Philippines and African countries, but are not optimally utilized. At present, these fibres are used for conventional uses such as for the production of yarns, ropes, mats and mattings, as well as in making fancy articles like wall hangings, table mats, handbags and purses. Fibres like banana and pineapple are also used in making cloth in addition to their use in the paper industry. However, in recent years, many of these conventional uses for natural fibres are threatened by plastics and synthetic fibres, like glass and nylon fibres. Hence, there is a need to develop new uses for these fibres. In addition, natural fibres have recently attracted the attention of scientists and technologists recently in view of the following advantages:

(i) These fibres, despite their low strength, can lead to composites with high specific strengths due to their low density. For example, wood flour, used as 50 per cent filler in thermosetting phenolic resin, is found to improve the specific strength and impact resistance of the resin.

(ii) They are an abundantly available renewable resource, and in recent years several simple techniques have been used to extract these fibres and fabricate composite materials using these resources.

(iii) Natural fibres are non-toxic.

(iv) Scientific data on the chemical composition, structure and properties of some of these fibres is now more readily available.

Natural fibres are generally ligno-cellulosic, consisting of helically wound cellulose microfibrils in a matrix of lignin and hemicellulose. These fibres consist of several fibrils which run along the length of the fibre; the cellulose content and the microfibril angle determines their mechanical properties.

Preparation and properties of selected polymer-natural fibre composites

1. Sisal-epoxy composites

One of the earliest natural fibre-polymer composites was attempted by incorporating sisal fibres in an epoxy matrix. The fabrication process used included winding and lamination. The winding of cylinders with longitudinal or helical and hoop reinforcements was successfully carried out. It was found that the fabrication of these composites was easy and the cost of the production of samples was quite low. Tensile strength of the sisal-epoxy composites was found to be 250 MN/m^2 to 300 MN/m^2 which is nearly half the strength of fibreglass-epoxy composites of the same amount of glass. However, due to low density of sisal fibre, the specific strength of sisal composites was comparable to that of glass composites. The unidirectional modulus of sisal-epoxy composites was found to be about 8.5 GN/m^2. This study indicated the feasibility of developing composites from one of the abundantly available natural fibres to be used for consumer goods, low-cost housing and civil structures.

2. Cotton-phenolic resin composites

Phenolic resin composites with cotton fabric incorporated into their matrices have been used as bearings, substituting for phosphor bronze bearings in the roll necks of steel and non-ferrous rolling mills. This substitution resulted in energy savings of up to 25 per cent.

3. Jute-epoxy-polyester phenol formaldehyde composites

In view of the better strength properties of jute fibre and its compatibility with polymers, research has been carried out to fabricate jute-epoxy, jute-polyester and jute-phenol-formaldehyde composites/laminates for uses such as low cost housing materials, silos for grain storage and small fishing boats.

Recently an attempt has been made to overcome the high resin consumption, absorption and desorption of moisture in jute-polymer composites by coating the fibre with lignin and ethylene diamine (EDA) respectively before incorporation into the matrix. Lignin treatment was given by soaking the fibres in 10% per wt. lignin solution for 30 minutes, followed first by drying for 24 hours at ambient temperature and then at 80° C for two hours.

It was reported that the resin wastage during fabrication of treated fibre incorporated composite was considerably reduced, whereby the resin consumption was found to be half of that required for untreated fibres. Similarly, EDA treatment of fibres reduced moisture absorption by composites. Unidirectional composites were then fabricated by winding lignin treated EDA coated fibres on a flat plate using a general purpose polyester resin, and curing the composite between flat plates at a pressure of 0-28 MN/m^2 (40 lb/sq. in.). The EDA treatment seems to bring down the moisture absorption of the fibres in the composites without significantly affecting the tensile strength and modulus of the jute polyester composites. Now, acetylation treatment is being developed for natural fibres to improve their properties.

Attempts have also been made to prepare hybrid composites using jute and glass fibres in polyester resin. Up to 20 per cent of jute fibres and up to 40 per cent of glass fibres have been used to prepare hybrids. It was found that both the tensile strength and the modulus of the hybrids were higher than the jute containing composites due to the higher modulus of glass fibres. The hybrids containing a small amount of glass fibres seem to fail as a result of the rupture of jute fibres, followed by the failure of the glass fibres. However, during compression testing, the failure of the hybrids seemed to be by delamination. The tensile strength and modulus of the hybrids after accelerated weathering decreased by 5-23 per cent and 10-15 per cent respectively, while with polyester resin the percentage reduction is insignificant (0.5 to 1.1 per cent). It was therefore concluded that jute fibre could be used as low cost filler where the strength and modulus requirements of the components were not very high. It was also concluded that the longitudinal compressive strength of the hybrid composites depends on the ratio between the thickness of core (jute) reinforcement and the thickness of the shell (glass) reinforcement.

4. Bagasse-phenol formaldehyde composites

Bagasse fibres (80-90 per cent by volume) have been incorporated in phenol formaldehyde (pf) resin and the composites were prepared by varying moulding pressures. In one of the studies carried out, the specimens were prepared by: (a) random orientation of short bagasse fibres of 61% per wt. of fibre in 30 per cent pf resin and remaining other constituents resulting in flat specimens, while in method (b) corrugated sheets were prepared with about 78% per wt. of fibre with 4.14 per cent pf and 17 per cent other constituents. The values of strength and modulus for these two types of specimens were found to be 28.4 MN/m^2 and 4.89 GN/m^2, or random orientation, and 7.78 MN/m^2 and 1.72 GN/m^2 for corrugated sheets at right angles to the direction which contained 10 per cent bagasse fibre in one direction and 90 per cent randomly oriented fibres. It was also found that both the tensile modulus and strength increased with the density of the composite. A linear relationship was found to exist between the modulus and tensile strength for boards of varying fibre-to-binder ratios. Applied pressure was found to control the end properties of these composites. The increase in strength properties was attributed to fibres acting as crack arresters as well as to reinforcement of pf resin. These studies have clearly shown the possibility of fabricating newer composites using natural fibres like bagasse with polymers for applications such as roofing materials.

5. Coir-polyester composites

Attempts have been made to incorporate retted coir fibres with general purpose polyester resin to prepare laminates and some consumer articles by a manual lay-up process. In one study, up to 9% per wt. coir could be incorporated into polyester in the form of laminates. Mechanical properties, including UTS modulus, flexural and impact strengths, and selected electrical properties of these composites have been listed. Single fibre pull-out tests carried out on coir fibres embedded in polyester resin showed very low pull-out stresses, suggesting poor bonding between the fibre and the matrix.

Articles like helmets, post-boxes and equipment housings were made from polyester coir composites using the manual lay-up technique. These components showed no measurable degradation when they were subjected to indoor and outdoor weathering over a one-year period.

Further studies of fibre surfaces were carried out using a scanning electron microscope, to understand the causes for poor bonding between coir fibre and polyester. It was found that the surface of the fibre has a non-polar waxy coating, called "cuticle" of an aliphatic origin, which is likely to be non-compatible with polyester, thus resulting in the poor bonding of coir fibre surface with the polyester. This suggested that the surface of the fibre should be modified by either coatings (including multiple coatings with materials which have compatibility with polyester resin), or leaching out the cuticle layer to improve the compatibility between the fibre and polyester.

In one such attempt, 1.5 to 5.0 μm thick continuous coatings of copper were deposited over the fibre by electrolytic coating process. The properties of the coated fibres, and of composites containing equal amounts of both uncoated and coated fibres were evaluated. It was found that composites containing coated fibres (up to 0.23 v.f. by volume) showed a considerable increase in tensile and flexural strength, as well as in electrical conductivity over those containing the same amount of uncoated fibre. The increase in electrical conductivity of composites containing copper coir fibre could lead to applications in electro-magnetic interference shielding.

Other approaches to achieve compatibility between coir fibre and polyester resin include soaking or leaching the fibres in various concentrations of an alkali solution similar to the mercerization of cotton. Coir-polyester composites using alkali-treated fibres showed a 90 per cent increase in pull-out stress, and a 40 per cent increase in mechanical properties when alkali-treated coir fibres were incorporated with polyester resin. This was probably due to improved bonding between the fibre and polyester resin.

Further, longitudinal ultrasonic velocity and sound attenuation measurements were carried out on these composites containing alkali-treated coir fibres. It was observed that longitudinal ultrasonic velocity decreased with an increase in the fibre content for both untreated and alkali-treated fibres containing composites, with a predominant decrease in composites containing untreated fibres. This is an indirect indication of a better bonding between alkali-treated coir and polyester. Similarly, ultrasonic attenuation (α) values increased with a fibre content for both treated and untreated fibre containing composites. Higher values of α in composites containing treated fibres, for the same volume fraction of fibres as untreated fibres, indicate higher porosity in untreated fibres. This study also indicated the potential of these inexpensive composites for sound absorption applications.

Preliminary studies on coir-glass fibre hybrid composites have also been conducted. A 3.5 m^2 size roofing was fabricated by a manual lay-up process using hybrid composites. This roofing withstood natural weathering for several years without showing any degradation.

Studies with jute and coir fibre with surface modifications or hybridization with high modulus inorganic fibres (glass fibres) suggest that: (a) it is possible to increase the volume fraction of natural fibres in composites, particularly with jute fibres; and (b) it is feasible to utilize natural fibres to fabricate useful composites.

6. Banana-cotton-polyester composites

Banana-cotton fabric, with banana in the weft direction and cotton in the warp direction, has been incorporated with polyester resin in various proportions from 9% per wt. to 25% per wt. fibre. A simple manual lay-up technique was used in fabricating both laminates and simple consumer articles, using banana-cotton fabric and polyester resin. It was found that up to 14% per wt. fabric could be incorporated by the process without applying any load. Mechanical properties like Young's modulus, tensile strength, impact and flexural strengths of these composites have been evaluated. A decrease in UTS and flexural strength of the composite, as compared to the polyester matrix, has been attributed to the poor bonding between the fabric and the matrix and confirmed by optical and SEM studies.

Laminates and consumer articles like castings for voltage stabilizers, 16 mm projector covers, mirror casings and scooter boxes have been fabricated and exposed to indoor weathering conditions. No degradation has been observed in these components on exposure to weathering. Periodic testing of laminates for strength properties and non-destructive testing of laminates and consumer articles showed no degradation even after a year of indoor exposure.

7. Wheat straw-polyester composites

Recently work on wheat straw-polyester composites has been reported on. Here, a composite for potential use as a building material has been developed. It was found that up to 50% per wt. straw fibre could be incorporated into polyester resin. The process involved in making the composite is: (i) combining straw fibre and resin with a catalyst in an open mould and a close-fitting plunger; (ii) alternate layers of fibre and resin built in the mould and subjected to a pressure of 1 MN/m^2 for about 18 hours and (iii) postcuring for about two hours at 80° C before removing the mould. A higher amount of fibre (50% per wt.) caused difficulties in removing the composite from the mould. It was also found that a pretreatment of the straw fibre was necessary to remove the silica-rich layer on the epidermis of the straw fibres in order to obtain a good bonding with the polyester resin.

A mechanical method was adopted wherein the fibres were split longitudinally and rolled flat before mixing with resin. This treatment was found to result in a better bonding between the fibres and the resin used. It was found that as the fibre content increased up to 0.21 per cent volume fraction, values of flexural strength and flexural modulus decreased from 32 MN/m^2 to 25 MN/m^2, and 4.4 GN/m^2 to 2.7 GN/m^2; the flexural properties steadily increased to a maximum of 0.61 per cent v.f. to flexural strength of 40 to 56 MN/m^2 and flexural modulus of 4.7 to 6.2 GN/m^2. However, the tensile modulus was found to steadily increase with an increase in volume fraction of fibre up to 0.61 per cent from 3.3 GN/m^2 to 8 GN/m^2. The stiffness of the composite containing 0.61 per cent v.f. of fibres was found to be 0.99 m x 10^6 which is 2.5 times greater than that of pure matrix in contrast to 2 m x 10^6 for soft wood and glass fibre-reinforced plastics and 2.7 m x 10^6 for high-tensile steel. The value of work of fracture (10 kJm^{-2} for 0.7 per cent volume fraction) of the composite indicates that this material is quite tough.

8. Sunn hemp fibre-polyester composites

Unidirectionally aligned continuous sunn hemp-polyester composites with varying fibre volume fractions have been prepared using a modified manual lay-up technique for low-volume fractions, and a pultrusion technique for high-volume fraction composites.

The tensile strength and Young's modulus of sunn hemp fibre were 389 MPa and 35.4 GPa respectively. Tensile strength and linear elastic modulus of composites were found to increase linearly with the volume fraction of fibres (up to 0.4 volume fraction) in accordance with the rule of mixtures. The work of fracture, as measured by the Izod test, also increased linearly with the volume fraction of fibres, and was 21 KJm^{-2} at 0.24 v.f., indicating high toughness in these composites. The high toughness of these natural fibre composites is attributable mainly to the fibre pull-out work, and the creation of a new surface as the fibre-matrix interface.

In summary, considerable work has been done on structure and properties of abundant and renewable natural fibres and polymer-based composites made using these fibres. The strength of particular fibres depends upon their cellulose content and microfibril angle of cellulose fibres. The properties of polymer natural fibre composites depends upon the properties of the particular fibre, its volume percentage and distribution in the composite, and the surface treatment of the fibre which effects bonding. These polymer natural fibre composites have great potential in lightweight applications requiring high toughness and sound absorption.

2. Barriers in the commercialization of composites utilizing local resources

One of the major barriers to the commercialization of natural composites is the limitations on individual scientists and policies in developing countries, with regard to working in an area, which is required, but not yet commercialized in developed countries. Most of the scientists in developing countries follow the lead of the scientists in developed countries and work in these areas. In all likelihood, these scientists may not have worked on local resources, and no developed country would have generally commercialized products based on the local resources of developing countries. As a result, these areas remain neglected in terms of research, development and commercialization, even in developed countries.

The scientific and industrial community in developing countries have not allocated major resources and deployed their best brains to work on composites from local resources. Even in countries like India, with a well-developed scientific infrastructure, the resources devoted to composites required by defence, space technology and consumer requirements are greater than the resources devoted to composites made from local resources to meet the basic needs of the people. A new value system needs to be inculcated in the scientists, industrialists and policy makers of developing countries, whereby they take pride in working on composites based on local resources. They should realize that developing composites from local resources represents a greater challenge in scientific innovation and creativity than merely reproducing the work on synthetic composites which has already been done in developed countries several years ago. The reward and peer recognition system in the developing countries should recognize the work done on composites made from local raw material resources, especially if they find applications in meeting the basic needs of people, such as housing.

A major barrier is the misconception that work on developing composite materials from local resources is a low-level science and technology. This misconception prevents the best trained scientists and technologists from working in these areas of greater relevance to developing countries, and thus reduces Government support for these activities. Even in a country like India, which recognizes the imperative for technologies to meet the basic needs of people, at one time the Government considered closing down the regional research laboratories working on composites from local resources, while research funds for defence research were being increased.

Another major barrier in the development of new composite materials from local resources is the fact that frequently the availability of these local resources and their properties have not been adequately characterized. Considerably more data on the characteristics of much smaller resources for composites manufactured in developed countries are available in developing countries, than the data on the much larger resources of developing countries, which can have a larger impact on living standards in these countries.

In addition to the attitude problem, some of the other barriers in the large-scale manufacture of composites using local resources, especially natural fibres, include the following:

(a) These are scattered resources which have widely variable properties from one location to the other;

(b) These fibres are generally low in moduls and strength compared to synthetic fibres like carbon;

(c) These fibres have a tendency to absorb moisture and change their shape, and they tend to decay under attack by bacteria and pests;

(d) The natural fibres and the polymer-based composites made from these fibres are flammable; this is a problem in housing applications;

(e) There is no comprehensive database on either the properties of fibres or composites, suitable for design, especially using computers;

(f) There are no obvious industries making composites from natural fibres to emulate;

(g) There are very few project reports, if any at all, on setting up industries in the organized sector using these resources;

(h) Financing is not readily available to set up industries to manufacture composites from natural fibres, since it is not an established industry, and therefore it represents a high risk.

3. *Implications of the new and emerging field of biomimetics on synthesis of composites using local materials*

There is considerable interest in the new and emerging field of biomimetics, which is trying to create and synthesize new materials which have a hierarchical architecture similar to biological materials. This will greatly increase the knowledge base on the structural property relationship of materials with structures similar to biological materials, including biological renewable resources for composites. This new knowledge base, including cellular materials, must be applied to understand and improve the properties of local resources like natural fibres to make them more suitable for use in the synthesis of composites, and to improve the properties of composites made from these resources.

Natural fibres for plastic reinforcement

Plant fibres have a strength per unit weight similar to those of man-made fibres. Although plant fibres are successfully used in a limited number of composite products at the moment, the advantages of plant fibres, and the diverse fibre properties provided by nature, are such that plant fibres are likely to become more important in lower-cost composites in the future.

In recent years there has been mounting interest in the use of natural fibres for the reinforcement of plastics. Figure 1 shows the tensile strength of a number of prototype materials, as well as that of two products that have a well-established market: Tufnol 6F/45 (an epoxy/cotton made in the UK) and Trespa (a phenolic/wood fibre made in Holland). The comparatively poor strength of the prototype products suggests that some product optimization is still required.

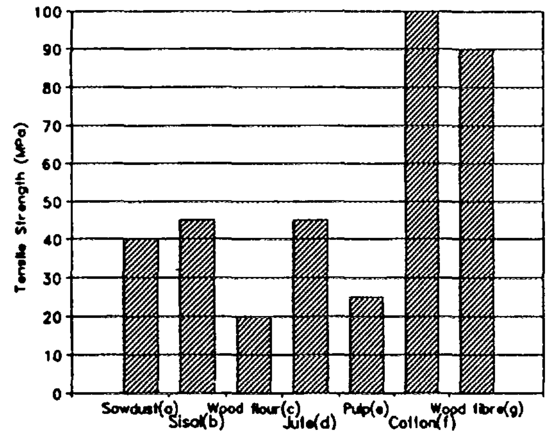


Figure 1. Tensile strengths of some prototype and commercial plant fibre-reinforced composite materials. (a) Sawdust/polystrene composite (30% fibre volume fraction and matrix tensile strength = 36 MPa). (b) Sisal/polyester composite (40% fibre volume fraction). (c) Masterwood wood flour thermoplastic composite (50% wood flour volume fraction). (d) Jute/phenolic composite (fibre volume fraction not given). (e) Aspen pulp/polyethylene composite (30% fibre volume fraction and matrix tensile strength = 16 MPa). (f) Tufnol: Commercial woven cotton/epoxy (fibre volume 35%). (g) Trespa: Commercial wood fibre/phenolic (fibre volume fraction not given) [7,9,23-25].

In table 1 below, the bending strength and modulus of the same two commercial products are compared with some experimental materials, as well as with data for conventional glass epoxy composites. Here, some of the experimental materials show performance several-fold better than those of Tufnol and Trespa. Further, on a weight-for-weight basis, the performance of the best plant-reinforced systems is comparable with that of the conventional glass epoxy composites.

Already, the range of commercial applications for products reinforced with plant fibres is extensive. With thermosetting matrix materials, the list includes electrical insulation (Tufnol Ltd.), semistructural applications (Hoechst Holland NV), and wear parts (Tenmat Ltd.). The first pultruder was sold to India in 1994 for use with a jute/phenolic system. With thermoplastics, the list includes well-established sheet moulding compound materials such as Woodstock and Lignotoc. BASF AG has recently launched a sisal-reinforced equivalent, whereas Mitsubishi in Japan has introduced Papia on the market, a polypropylene compounded with 50 per cent reclaimed newspaper fibre for use in injection moulding and the thermoforming of vehicle components. Following retrenchment in aerospace/defence expenditures, it is interesting to note that some multinational companies are reducing their commitment to the highest cost and performance composites, and showing great interest in more environmentally friendly, lower cost, plant fibre-reinforced materials.

With this background, the present article reviews the kinds of plant fibres that are available for composite

Table 1. Bending strength properties of natural and glass fibre-reinforced composites

Fibre matrix	Specific gravity	Bending strength (GPA)	Bending modulus (GPA)	Fibre volume fraction
Random wood/phenolic*	1.2	0.11	8.0	65%
Woven jute/polyester	1.2	0.09	8.0	50%
Felted jute/polyester	1.2	0.10	10.0	60%
Cotton/epoxy*	1.36	0.17	8.0	35%
Parallel jute/epoxy	1.2	0.45	43.5	70%
Parallel kenaf/epoxy	1.2	0.42	39.0	70%
Pultruded glass/epoxy	1.7	0.69	42.0	70%
Random glass SMC/epoxy	1.9	0.17	10.3	?70.0

* Commercially available materials.

production, looks at their advantages and disadvantages relative to synthetic fibres, and examines the potential for the development of novel materials reinforced with plant fibres.

The fibre types available

Definitions

Although animals produce fibre, there has been only limited interest in the use of such fibres in composites. This possibility should perhaps be explored further in view of the present glut of wool on the market.

Plant fibres vary widely in chemical composition, structure, and dimensions, and originate from different parts of the plant. There is considerable confusion in nomenclature: the plant anatomist refers to certain specific cell types as fibres; the industrialist (such as a paper maker) refers to any cell, or part of a cell, in a process as a fibre (although operations such as depithing may exclude short cells from a raw material stream entering the process); bundles of cells extracted largely intact from some plants are referred to as fibres in the textile and cordage industries. In the present discussion, the term "fibre" is used to describe a single cell, or part of a cell, whether or not it is a true fibre in the botanical sense. The term "fibre bundle" is used to describe intact groups of fibres.

Sources

The largest fibre resource is wood, although at least 65 per cent of this is used as fuel or in a solid form. Most of the remainder is used in the production of particleboards, fibreboards, pulp and paper. Many end-users of these products will not be aware of the fibrous character of the materials composing them. As with bamboo, most of the material is presently used in cane form rather than as fibres or fibre bundles.

In contrast, many of the other commercially important fibres and fibre bundles are well known to consumers in the fibrous form of textiles, cordage, matting, etc. (e.g., cotton, flax, jute, hemp, coir, sisal), even if the origin of the material is not fully appreciated. In some cases the markets are shrinking and depressed (jute, coir, sisal), whereas in others the land area under cultivation is increasing (flax, hemp) in anticipation of increased utilization in composites and other industrial applications. To reduce costs for non-textile applications, novel ways of extracting fibre bundles from these plants are being developed.

To this list must be added many other potential sources of useful fibre. Banana fibre (*Musa cavendishi, M. sapientum*) is already produced in small quantities, but there is potential for annual production in excess of 200,000 tons. The fibre quality is similar, though slightly inferior, to abaca. Many species of palm could provide fibre derived from the stem, leaves or fruit; there are prototype products being made from the fibrous residue of oil palm fruit in Malaysia. Members of the Asclepiadaceae family also show potential: milkweed floss (*Calatropois procera*) was used as an alternative to kapok to provide buoyancy in life jackets during the Second World War. Other established sources of plant fibre include urena (*Urena labata*), henequen (*Agave fourcroydes*), New Zealand flax (*Phormium tenax*), and pineapple (*Ananas comosus*).

In Europe, there is much interest in elephant grass (*Miscanthus sp.*), nettles (*Urtica sp.*) and broom (*Cytisus sp.*). The first of these is seen primarily as a high producer of biomass; however, the mean cell length may be too short for use in composites. Nettles may yield a longer, stronger fibre. Broom fibres have been used commercially in the past, and have already been incorporated into a prototype composite car part.

At the same time, there is a growing awareness of the fibre content of waste streams. Examples of these are the straw residues derived from grain, linseed and oilseed rape production. Linseed fibres (*Linum usitatissimum*) are as long and strong as those of flax; only the fibre bundle length (crucial mainly in textile manufacture, but not in composite production) is lower.

In summary, the plant kingdom offers a wealth of potential candidates for composite production. One author suggests that there may be as many as 1,000 types to choose from, excluding wood and bamboo. It is unlikely that the volume available will act as a constraint to their use in composite production.

If anything, one of the present problems is an embarrassment of choice: the properties of fibres from different species are so diverse that it is difficult to be certain that we are focusing on the most promising. Research effort to date has tended to concentrate on those that have traditionally been produced for other end-users (e.g. textiles: flax, jute, cotton) or that are available as a by-product of another major crop (coir), or that have been selected on the basis of biomass production (*Miscanthus*). These criteria may not lead to the selection of the most cost-effective plant fibres for the reinforcement of the various grades of plastic products.

Strength properties

Strength data allowing selection of other fibre types for plastic reinforcement on a more quantitative basis are available for only a few species. Average values are shown below in table 2. In comparing these with data for synthetic fibres, the much lower specific gravity of plant fibres should be remembered. Plant fibres are tubular structures. The wall specific gravity is about 1.5. Depending on the ratio of wall thickness to fibre diameter, the effective fibre specific gravity is typically in the range of 0.15 (e.g., balsa) to 1.2 (e.g., lignum vitae,- the timber used to make bowls). On processing, thinner walled cells can collapse, giving an effective density in industry much higher than that in the plant. In the context of composite product, the issue is further complicated by uncertainty as to whether all the voids within individual fibres will be accessible to matrix, and whether, if they are not, such contained voids will reduce composite properties.

For these reasons, although it can be said with certainty that plant fibres will in most cases have an effective specific gravity in the range of 0.6-1.2, the benefits of this in terms of improved strength per unit weight (specific strength) will be less certain. If *specific strengths* are calculated, plant fibres and plant fibre bundles come out with values not dissimilar to those of synthetic fibres. It should be noted that the work to fracture of solid wood is approximately $10^4 J/m^2$, which is comparable to that for many man-made composites. Each individual plant fibre is itself a composite. The implication of this is that plant fibres should be less susceptible than some man-made fibres to length reduction on compounding or recycling.

Dimensions

Fibre dimensions are of key interest to the composite manufacturer. The diameter of individual fibres is usually in the range of 15-35 μm. The length of fibre bundles is dictated largely by the part of the plant from which they are derived. Thus, coir (originating from a fruit) has bundles only 0.15-0.28 m long; sisal (originating from a leaf) has bundles 0.6-1.0 m long; jute (originating from a stem) has bundles 1.5-3.6 m long. In terms of aspect ratios, most individual fibres have values in the range of 100-200. Notable exceptions are hemp (550), flax (1,500), cotton (2,000), and ramie (4,000). The aspect ratio of fibre bundles varies from about 100 to in excess of 4,000, depending to some extent on the damage inflicted on them during extraction from the plant. By careful selection of the fibre type, it should therefore be possible to find both short plant fibre for reinforcement of moulding compounds and injection mouldings, and longer fibres for use when anisotropy is desired in the product. Because chemical modification offers a route for the creation of a desired density of strong covalent bonds between plant fibre and matrix, it is possible that the aspect ratios deemed essential in reinforcement of plastics with synthetic fibres may not be required with plant fibres.

Table 2. Typical strength data for plant fibres and fibre bundles

	Tensile strength (GPa)	Tensile modulus (GPa)
Single fibres		
Cotton	3.54	5.0
Straw	4.43	17.0
Wood	7.48	21.6
Hemp	8.95	25.1
Kenaf	11.91	60.0
Flax	20.00	85.1
Fibre bundles		
Sunn hemp	1.52	
Coir	1.52	5.2
Jute	5.38	8.0
Sisal	6.14	12.7
Abaca	6.41	23.4
Pineapple	10.00	60.0

Note: Hemp and flax are available as fibre bundles as well as single fibres. Conversely, single fibre strength data could be obtained for the materials listed as fibre bundles. The values of single fibres tend to be for cells carefully separated out from the plant in the laboratory. Industrial separation processes can significantly reduce strength properties: industrial flax fibres can have only 55 per cent of the tensile strength of laboratory extracted fibres, and their tensile modulus may be reduced by as much as two thirds. [Sources: *The BioComposites Centre*].

Advantages and disadvantages of plant fibres in composites

The advantages of plant fibres as reinforcements for composites are: acceptable specific strength properties, low cost, low density, high toughness, good thermal properties, reduced tool wear (cf. glass fibres), reduced dermal and respiratory irritation (cf. glass fibre), low energy content, energy recovery possible, and biodegradability. Of these, the density and environmental issues merit further comment. Because of the low density of plant fibre, a plant fibre-reinforced product will always be thicker than one reinforced with the same mass of glass fibre. (The same mass will generally be required because the *specific* strength properties, not the *real* strength properties, are comparable for the two fibre types.) When the product design is stiffness-limited, as is frequently the case, rather than failing stress-limited, a thicker product could be stiffer and still acceptably strong for the same mass. This can make cheaper and/or stiffer products possible, provided that the design can tolerate the increase in thickness.

The environmental issues are sometimes more political than logical. However, the attractiveness of using materials provided by nature cannot be denied. Plant fibres are carbon dioxide neutral in their production and require only small energy inputs for processing. The possibility of recovering some of the Sun's energy stored in the plant fibre at the end of product life is appealing. The glass fibre-reinforced product cannot be burned at the end of product life to recover energy, and must therefore be sent to landfill unless otherwise reused. The superior toughness of plant fibre suggests that the number of cycles possible in the re-utilization of reinforced thermoplastics may be greater than with glass fibre.

The dermal and respiratory irritation issue is more controversial. The question of whether fibreglass is linked to lung disease remains open. What is clear is that plant fibres are more *pleasant* to work with than glass, and because their diameter is much higher than the 1-5 μm threshold regarded as the hazard limit for carcinogenicity, it seems that they will be *safer* to work with as well.

The disadvantages of plant fibres are their water reactivity, polarity, finite length and large diameter and variability.

The potential for new plant fibre-reinforced products

It is noteworthy that, of the existing commercial plant fibre-reinforced products, one of the strongest (Tufnol) is made with the weakest and most expensive fibre (cotton). Some of the potential for the improvement of plant fibre composites is evident. Still greater advances can be expected following further improvement of fibre/matrix compatibility. We can therefore anticipate greater use of plant fibres in products ranging from dough mouldings, to injection mouldings and resin transfer mouldings, and to pultrusions. In some cases, this will be driven by cost advantages; in others, it will be by environmental benefits.

With thermoplastic matrix materials, the polarity of the plant fibre has often presented problems. The poor wetting of the fibre surface leads to limited specific adhesion, with the result that the fibre acts as a nonreactive filler rather than a reinforcement. It is possible that these difficulties can be overcome through the use of a fibre coating or sizing.

In many cases, however, the water reactivity of the composite remains a problem. Even if the product does not immediately fail on exposure to water or a humid environment, the resultant swelling or "movement" may be unacceptable in the product. Where the encapsulation approach is unsuccessful or deemed too risky, the best solution is chemical modification. This involves replacement of a significant proportion of the hydroxyl groups in the plant cell wall by other groups less attractive to water. Although considerable research has been carried out in fibre modification in the textile industry over the past 50 years, much of this is not applicable to composites for a variety of reasons.

Firstly, if the modifying group reacting with the hydroxyl is only monofunctional, there is a risk that it will be subsequently difficult to form a strong adhesive bond with the modified surface. This difficulty has arisen, for example, in the acetylation of wood and fibre. Secondly, it is not desirable that the modification reaction should be dependent on the presence of free radical initiators, since the continued generation of free radicals after product manufacture will cause product degradation and aging. Much of the work on the formation of graft copolymers with cellulose is not readily applicable to plant fibres containing lignin because the lignin scavenges the free radicals, thereby inhibiting the reaction. The lignin concerned can then act as a free radical buffer, causing product degradation and aging. Thirdly, it is important that the modifying reaction does not depend on the presence of, or lead to production of, strong acids or alkalis, since these can degrade plant cell wall polymers after product manufacture. Finally, to give modifying groups access to the hydroxyl groups readily accessible to water in the cell wall, it is important to react the plant material in a partially swollen condition. Pre-swelling can have so large an effect on the rate of reaction that it can effectively be considered to be part of the catalysis system. However, too much penetration of the wall can damage its structure; careful control of the degree of swelling is therefore necessary.

C. COMPOSITES FOR BUILDING MATERIALS

Promotion of composite building materials

by N. Biering, Chemical Industries Branch, Industrial Sectors and Environment Division, United Nations Industrial Development Organization (UNIDO), for the Advanced Workshop on Industrial Composites Design and Application, Trieste, Italy, 30 October-4 November 1994

Abstract

The paper focuses on the role of UNIDO in promoting the manufacture and use of composite materials in the housing and construction sector in developing countries and on the methodologies employed to ensure the widest possible application of the technologies in question.

In order to place the topic of the paper in a broader perspective, an overview is presented of UNIDO's building materials programme in general and of the policy elements which determine the strategy adopted, including basic priority issues such as environmental sustainability, local raw material utilization, employment generation and private entrepreneurship development.

A presentation will be made of the range of composite building materials which are being promoted by UNIDO in the context of its technical assistance activities. Particular focus will be placed on the efforts to introduce cement stabilized soil blocks and fibro cement roofing tiles to a number of African countries and on the promotion of fly ash use in lightweight concrete and other structural applications.

Through selected case stories the various approaches employed in order to achieve an effective transfer of R&D results and technologies made available through other channels will be illustrated with emphasis on the adaptation of the products to the market demands and the achievement of financial viability of the manufacturing operations. In this context reference will also be made to UNIDO's potential role as technology broker thanks to its close contacts to holders of advanced composite technologies as well as to the potential users of these technologies in the developing countries.

Finally a case will be made for the important role to be played by the composite building materials as means for achieving a higher level of ecological sustainability—through the reduction of energy consumption in the production process and increased utilization of agricultural and industrial wastes.

The building materials programme

The main characteristic of the building materials sector of the majority of developing countries is its overwhelming dependence on high priced, imported products and products manufactured from imported raw materials. This has a number of negative effects on the national economy:

- A major drain on the scarce foreign exchange reserves;
- High construction costs in the formal and semi-formal sectors;
- Underutilization of domestic raw material resources;
- A loss of the potential contribution of the sector to job creation and increased economic activity.

Most severely affected by the lack of appropriately priced building materials is the housing sector, where this problem is compounded with a very limited availability of resources and mechanisms for housing financing. The cumulative effect is that, currently, a large and growing proportion of the population and especially the rural families and the urban poor are living under unsatisfactory and deteriorating shelter conditions.

By providing these materials locally, the countries increase their self-reliance and reduce their dependence on imports. Furthermore, by constructing cheap housing, local authorities can absorb the growing population pressures that will build up in urban and rural areas after the turn of the century.

Developing the local production of building materials and prefabricated components is likely to encourage investment in the building industry.

The building industry is not the final destination. Upstream and downstream, it generates a host of small and medium-sized enterprises (SMEs), whose activities overlap with the informal sector and lend strength and vitality to the fabric of national and regional economies. These businesses ensure workers stable and substantial sources of income and serve as schools in which vocational skills are acquired and knowledge is passed on, thus contributing to diversify and further the human resource development process.

Through their economic and social functions, the industrial enterprises of the building materials and construction sector lend full effect and meaning to the policy of UNIDO for the promotion and development of human resources, particularly the integration of women into the industrial development process at all levels of responsibility. In this context, it must be emphasized that the sector offers a wealth of opportunities for the employment of women, to which the achievements of the Organization's field projects bear evident witness.

The practical experience of UNIDO's technical assistance activities also clearly demonstrates how the enterprises in the private sector concerned with construction and housing are excellent entry points for new technologies and techniques that are easy to master and thus, in turn, easy to disseminate to a wider range of end-users.

Objective and target areas of the programme

The development objective of the programme is to permit the needs of a country for housing but also, since the sectors are closely interlinked, for other types of buildings and engineering structures to be satisfied without undue delay and at a cost/quality ratio which represents the optimum for each specific country.

Although the programme addresses the needs of the overall building materials and construction industry sector, it focuses particularly on the housing needs of the lower to middle segments of the urban population and is based on the belief that any meaningful strategy for the provision of low-cost shelter must include a resolute shifting of present housing production methods to a more intensive use of indigenous resources and to a more labour-intensive basis without ignoring minimum standards of durability and comfort of dwellings.

The overall objective of the programme is, thus, on a country-by-country basis to ensure the adequate availability in terms of quality, quantity and cost of a full range of locally-produced building materials suited for application in the local construction sector and of compatible construction techniques and appropriate public policies, regulations and support mechanisms.

The programme contributes to the achievement of ecologically, financially and technologically sustainable shelter development through the promotion of the following priorities, which can be considered at three distinct target levels of policies and strategies, institutional support and enterprise operation.

Composite building materials

In conventional terminology, composite materials evoke the concepts of high technology and use of specialized components satisfying strict quality requirements. Products such as carbon fibre products, special polymers and advanced ceramic products come to mind.

However, strictly speaking even such basic products as mud-bricks improved through the addition of straw and cow dung qualify as composite materials, and a wide range of building materials in daily use in the developing countries can be said to belong to the group.

In the context of this paper, composite building materials are defined as products which in their manufacture incorporate more than one raw material which typically are of different origin. The raw materials can roughly be divided into three basic categories:

- Non-metallic minerals and mineral products such as clay, sand lime, cement, natural stone, etc.;
- Materials of plant origin including wooden particles, straw, vegetable fibres, agricultural wastes (husks and shells), etc.;
- Manufactured materials such as artificial aggregates (expanded clay and fly ash pellets), polymers, mineral fibres (glass, ceramics, carbon) and metallic components.

The possibilities for combinations of such basic raw materials, whereby their physical and chemical characteristics supplement or reinforce each other, are only limited by the imagination of the technologists. And while some of the composite building materials (CBMs) which result are considered traditional and hardly recognized as CBMs, such as the above-mentioned mud blocks and standard concrete blocks and elements, others have only very recently appeared on the market despite their basic and easily accessible ingredients.

Some CBM technologies are still at the level of laboratory research but hold great potential for the housing sector of the developing countries. They include new and sometime sophisticated products, based on basic local raw materials and linked to appropriate structural systems, which eventually are expected to play an important role, due to their excellent performance characteristics and low cost, as well as their contribution to environmental sustainability.

UNIDO is in touch with R&D institutions and/or commercial enterprises involved in this research and is actively encouraging the work carried out. The Organization also keeps a close eye on new developments regularly presented at congresses and symposia and other scientific gatherings in keeping with its mandate to monitor and promote a global process of technology transfer.

Fly ash cement composites

Paper presented by S.S. Rehsi (Chandigarh, India) at: Advanced Workshop on Industrial Composites Design and Application, October/November 1994, International Centre for Science and High Technology (ICS), Trieste, Italy

Abstract

Fly ash cement composites have been a subject of considerable interest with R&D scientists in various countries, where fly ash is available. In India, R&D work on these materials was taken up in the 1960s and was continued over the next two decades. Fly ash samples collected from different thermal power plants in the country and ordinary Portland cement (OPC) were used to produce fly ash cement composites. The materials were subjected to different physico-chemical tests, X-ray diffraction and microscopic (SEM) examination. Various aspects, such as:

(i) Fly ash characteristics and their influence on the properties of fly ash cement composites;
(ii) Mechanism and kinetics of hydration reactions;
(iii) Morphology of reaction products on curing at normal and elevated temperatures;
(iv) Performance and durability under different environmental conditions;
(v) Use of locally available pozzolanic materials such as calcined clay and rice husk ash, in place of fly ash;
(vi) Fibre-reinforced fly ash cement composites; and
(vii) Appropriate/intermediate technologies for the production of fly ash cement composites and allied materials, were investigated. The important findings are summarized below:

1. There is a wide variation, from sample to sample, in the physical properties, chemical and mineralogical compositions of fly ash. As compared to fly ashes produced elsewhere, Indian fly ashes contain relatively high amounts of SiO_2 and Al_2O_3, unburnt carbon and lower amounts of Fe_2O_3 and SO_3. In mineralogical composition, they contain 45-80 per cent spheroidal silicious, aluminous and ferruginous glassy particles, the rest being irregularly shaped, angular as well as rounded black particles of unburnt carbon, and crystalline phases consisting of quartz, mullite, haematite and magnetite.
2. Lime reactivity, also called pozzolanic activity, which determines the suitability of fly ash for use as pozzolana in fly ash cement composites, is greatly influenced by the physico-chemical properties and mineralogical composition of the fly ash. It increases with an increase in the: (i) fineness of fly ash as determined by the per cent passing through a 45-micron sieve; (ii) content of SiO_2+ Al_2O_3; and (iii) content of spheroidal glassy particles.
3. The kinetics of pozzolanic reactions between silicious and aluminous constituents in the fly ash and lime produced by hydration of cement in fly ash cement composites are slow at normal temperatures. Consequently, the rate of strength development in fly ash cement composites is slower than corresponding OPC composites, at early stages in particular. The pozzolanic reactions produce calcium silicate hydrate (CSH) and hydrated calcium alumino-silicate (C_2ASH), which add to the strength of fly ash cement composites. On continued hydration, the fly ash cement composites and corresponding OPC composites have, more or less, similar strength later.

4. The kinetics of pozzolanic reaction and cement hydration are acceleratedat elevated temperatures. The morphology of the hydration products changes from a poor crystalline form at normal temperature to a good crystalline form at an elevated temperature of 100° C and above. The conversion of poor crystalline hydration products into a good crystalline form reduces the volume changes in fly ash cement composites on wetting and drying. The fly ash cement composites also develop higher strength *vis-à-vis* OPC composites on curing at elevated temperatures.
5. The fixation of lime by pozzolanic reactions and incorporation of the additional CSH so formed renders the fly ash cement composites more water impermeable, more heat resistant and more resistant to sulphate attack. These reactions also impart soundness, i.e., volume stability in fly ash cement composites prepared with high magnesia Portland cement (MgO content: 10 per cent).
6. Fine powders of locally available clay, calcined at an optimum temperature suiting its clay mineral, and rice husk ash obtained by incinerating rice husk at 600-700° C, possess high pozzolanic activity. These reactive pozzolanic materials are suitable for use, in place of fly ash, in fly ash cement composites.

Appropriate/intermediate technology packages have been developed for the production of the following construction materials for use of the building industry:

(i) Natural fibre reinforced fly ash cement bonded roofing sheets;
(ii) Fly ash cement concrete walling, roofing and flooring units;
(iii) Reactive pozzolanic materials from locally available clay and rice husk;
(iv) Small-scale production of cement in a mini cement plant of capacity ranging from 20 to 200 tons per day;
(v) Hydraulic binder from industrial, mining and agricultural wastes.

Fly ash characteristics

(a) Physico-chemical characteristics

Fly ash is a finely divided powder thrown out at thermal power plants using pulverized coal for raising steam in the boilers. It contains spheroidal glassy particles (solid or hollow particles called cenospheres), irregularly shaped (angular as well as rounded) black particles of unburnt carbon, and crystalline phases.

The fly ash is lighter than OPC. Its specific gravity generally ranges between 2.05 to 2.45, the higher value being associated with higher Fe_2O_3 content in the fly ash. The specific gravity of OPC ranges between 3.1 to 3.15.

(b) Mineralogical composition

The mineralogical composition of fly ash varies according to the quality and fineness of the pulverized coal, the type and amount of mineral matter associated with it, the method of burning, flame temperature, oxidation conditions and control of the combustion systems. The principal groups of minerals present in the coal are (i) hydrated aluminium silicate group, e.g., kaolinite, montmorillonite, illite; (ii) carbonate group, e.g., calcite, siderite; (iii) sulphide group, e.g., pyrite, marcasite; and (iv) accessory minerals group, e.g., quartz, feldspar, apatite, etc. On instantaneous combustion at high temperature in the boiler, these minerals undergo thermal changes to produce crystalline phases like mullite, magnetite, haematite, quartz, tridymite and an amorphous phase consisting of silicious, aluminous and ferruginous glasses.

(c) Lime reactivity

The level of lime reactivity, also called pozzolanic activity, forms the basic criterion to judge the suitability of fly ash for use as pozzolana in fly ash cement composites. It is determined by lime reactivity and compressive strength and Fratini tests. According to IS:3812-1981, fly ash is considered suitable for use as pozzolana if its lime reactivity is not less than 4 N/mm^2, and the compressive strength of the fly ash cement mortar is not less than 80 per cent of the strength of the corresponding plain cement mortar. In the Fratini test, the point representing concentration of lime vs. alkalinity should fall below the solubility isotherm at 40° C for $Ca(OH)_2$ in the presence of alkalis.

The reactivity of fly ash with lime can be enhanced by treatment with acid, addition of alkalis or some trace chemicals. Other methods found effective are grinding, sieving, recalcination, and addition of certain chemical admixtures along with plasticizers.

Mechanism and kinetics of hydration reactions

Hydration of fly ash cement composites leading to strength development consists of (i) hydration of Portland cement and (ii) pozzolanic reactions between silicious and aluminous constituents in fly ash and the lime released by hydration of the Portland cement. While the mechanism of hydration of Portland cement is well established, the mechanism of pozzolanic reactions is still not fully resolved. Microscopic studies show that the pozzolanic reactions involve the following stages:

(i) Migration of ions from aqueous phase to reaction sites at the surface of the particles;
(ii) Precipitation of $Ca(OH)_2$;
(iii) Reaction between $Ca(OH)_2$ and vitreous phase of fly ash particles leading to the formation of CSH, C_4AH_{13} and C_2ASH_8.

The viterous phase shows heavy etching and many particles up to 1 to 2 micrometers are consumed within 28 days. The crystalline phases in fly ashes remain inert and do not take part in pozzolanic reactions.

The kinetics of pozzolanic reactions between silicious and aluminous constituents in fly ash and the lime released by cement hydration in fly ash cement composites are slow at normal temperatures. Fly ash also retards the hydration of C_3S, which is the main cement compound contributing to strength in early stages. Consequently, the rate of strength development in fly ash cement composites is slower than corresponding OPC composites, at early stages, in particular. The pozzolanic reactions produce calcium silicate hydrate (CSH), which add to the strength of fly ash cement composites. On continued hydration, the fly ash cement composites and the corresponding OPC composites have, more or less, similar strength at later stages. The fly ash cement composites, therefore, require extra measures such as an extended period of wet curing and/or use of a slightly richer mix, to obtain a satisfactory and comparable level of strength development, particularly under low ambient temperature conditions (about 10° C). There is no problem in strength development under tropical conditions with temperatures of 30° C and above. However, under hot and dry conditions with an ambient temperature above 40° C, problems like a rapid evaporation of water, accelerated setting, and increased tendency to crack, may arise.

Morphology of reaction products at normal and elevated temperature

The calcium silicate hydrate, which is the main cementing product formed by hydration of C_3S and β-C_2S in Portland cement and by the pozzolanic reactions in fly ash cement composites is in the form of a poorly crystalline, near-amorphous gel, at normal temperature. It is subdivided into CSH(I) and CSH(II). The CSH(I) has a crumpled foil type structure. Its Ca/Si molar ratio is below 1.5 (0.8-1.5 to be more specific). The CSH(II) looks like fibres, or as fibres having a distinctly corrugated or fibrous texture. Its Ca/Si molar ratio is 1.5-2.0.

The gel has an inherent tendency to shrink and give off some of its water. On drying the set cement for the first time, it undergoes irreversible shrinkage and reduction in water content and changes into a more stable form. On subsequent wetting and drying, the volume changes become reversible.

The fixation of lime by pozzolanic reactions and incorporation of additional CSH so formed renders the fly ash cement composites more water impermeable, more heat resistant and more resistant to sulphate attack. These reactions also impart soundness, i.e. volume stability, in fly ash cement composites when prepared using OPC having high MgO content (up to 10 per cent). It is well known that the presence of MgO beyond a certain amount in OPC causes unsoundness, i.e. volume instability. The standard specifications on OPC all over the world have, therefore, placed a maximum limit on its content which ranges from 4 to 6 per cent.

Reactive pozzolanic materials for use in place of fly ash

Under situations where fly ash is not available, other pozzolanic materials such as (i) fine power from a locally available clay, calcined at optimum temperature suiting its clay mineral, and (ii) rice husk ash obtained by incinerating rice husk at 600-700°, can be used.

Calcined clay pozzolana

Raw clays are essentially a group of hydrated aluminium silicates. On heating, they first give off their surface and inter-layer water. Further heating brings about the loss of the hydroxyl ions in the structure; later the collapse of the structure occurs, yielding a very intimate mixture of the amorphous oxides (SiO_2, Al_2O_3 and Fe_2O_3), which is highly reactive with lime. Further heating results in the interaction of these oxides to form non-reactive crystalline mullite, spinels, etc.

The optimum temperature of calcining raw clay to produce reactive pozzolana, is presumed to be that temperature at which the crystal structure of the clay mineral just collapses and the oxides of silicon, aluminium and iron are in reactive amorphous form. The optimum temperatures of calcining different clays for maximum reactivity have been found to be:

For montmorillonite type of clay	600 to 800° C
For kaolinite type of clay	700 to 800° C
For illite type of clay	900 to 1,000° C

Rice husk ash

Rice husk ash contains 90-95 per cent silica, the rest being minor amounts of calcium, magnesium, potassium, sodium, phosphorous and sulphur, along with trace amounts of aluminium, manganese and iron which vary according to the soil and manures used. The silica in rice husk is mostly present in an amorphous state. Microscopic (SEM) examination and X-ray diffraction of the rice husk ash obtained under different conditions of heat treatment show that while the amorphous state of silica is predominantly retained in thermally treated samples up to 700° C, samples obtained above 800° C show an increased crystallinity of silica (mostly present as cristobalite and tridymite). Crystal growth gradually increases with a rise in time and temperature of the thermal treatment. In fact, crystallization of silica occurs in samples if retained at 700° C for more than 1½ hours. Rice husk ash obtained from rice husk fired boilers contain a high proportion of crystalline silica. As stated earlier, only amorphous silica is pozzolanic. Therefore, rice husk ash obtained at 600-700°C or less is suitable for use as pozzolana.

Appropriate/intermediate technology packages

Appropriate/intermediate technology packages have been developed for the production of construction materials for use by the construction industry. A brief account of the technology packages is given below.

1. *Natural fibre reinforced fly ash cement bonded roofing sheets*

Fly ash cement is suitable for use in all situations where OPC is usable under normal conditions. In addition, the alkalinity of the fly ash cement matrix is lower (pH about 12.0) than that of OPC matrix (pH about 12.5 or more). Natural fibres of vegetable origin such as coconut coir, sisal, jute, sugar-cane bagasse, banana, palms, flax, akwara, elephant grass, etc., which get embrittled and lose strength due to an alkali attack in the OPC matrix over a period of time, suffer comparatively less damage in fly ash cement matrix.

An appropriate technology package has been developed to manufacture fly ash cement bonded corrugated coir fibre roofing sheets. In the manufacturing process, coir fibre is first soaked in mineralized water for one to two hours. The free water is drained off the fibre, which is then mixed with dry cement in the ratio of 1:5 by weight. The corrugated roofing sheet is made from this wet matrix of cement-coated fibres either by a manual process or a semi-mechanized process. In the manual process, a mat of suitable thickness is formed on a corrugated mould and pressed under a uniformly distributed load to exert a pressure of 1.5 to 2 kg/cm^2. It is held under pressure for four to eight hours, then demoulded and cured in the shade and dried. In the semi-mechanised process, the cement-coated fibre matrix is uniformly spread on the drag (or bottom part) mould. The cope (or top part) mould is placed in position on the loaded drag mould. The assembled mould is pressed down hydraulically to press the raw materials to the required pressure. Wedges are then inserted in the slotted pins of the drag mould to hold the cope mould in position so that the formed sheet is kept pressed during its setting period. The wedged mould assembly is then rolled out of the press and transported on a trolley to the curing yard. After three to four hours, the sheet is demoulded, removed from the mould and kept in the shade for natural curing in vertical stacks for a period of about eight days. After curing, a cement-wash is applied on both sides of the sheet. A coat of waterproofing paint is finally applied on top side of the sheet and the painted sheet is ready for use. The sheet can be nailed and used like an asbestos cement sheet. It can be produced in the size 2 m x 1 m and of 6 to 8 mm thickness. Its breaking load at a span of 60 cm is similar to that of asbestos sheet at a span of 100 cm.

2. *Fly ash cement concrete walling, roofing and flooring units*

Fly ash cement can be used in place of OPC to produce a variety of precast construction materials, such as building blocks (dense/lightweight concrete blocks (solid or hollow), stone masonry blocks for walling, RCC lintels and sills for brickwall, RCC frames for doors and windows, RCC planks, RC ribbed slabs, L-pan units, channel units, cored units and waffle units for roofing/flooring, and autoclaved cellular (foamed) concrete products for walling, roofing and flooring. Some of these construction materials have been in use in building construction in India for many years.

The use of these construction materials ensures quality control, reduces wastage of resources and speeds up construction.

3. *Reactive pozzolanic materials from locally available clay and rice husk*

(i) Reactive pozzolana from locally available clay

For the production of a reactive clay pozzolana, locally available raw clay is calcined in an oil-fired rotary kiln at the optimum temperature suiting its clay mineral. The capacity of the rotary kiln could vary from 5 to 20 tons per day or more depending upon requirements. Various operational parameters, such as size of feed, rate of feed, inclination of the rotary kiln, speed of kiln rotation, control of flame temperature, retention time in the calcination zone, etc., need to be adjusted and fixed to suit the particular kiln installed. The calcination of raw clay can also be done in a down-draught kiln. The controls are, of course, better in rotary kilns.

The calcined clay is ground in a ball mill to the desired fineness to obtain a highly reactive pozzolanic material, conforming to IS:1344-1981 "Specification for calcined clay pozzolana".

(ii) Reactive rice husk ash

A highly reactive rice husk ash is produced by incinerating rice husk at 600-700° C in a specially designed incinerator. A 2-4 tons per day unit is considered to be economically viable in areas where there are rice husk hulling units with potentials of processing about 10,000 tons of paddy per annum.

As an alternative to specially designed incinerators, an open clamp can be used to incinerate rice husk. For this purpose, a mixture of rice husk and clay in the proportion of 1:1 by weight is prepared. It is moistened with water and shaped into balls or cakes which are dried in the sun and then fired in an open clamp kiln or a trench made from burnt clay bricks. Any clay or soil with a clay fraction of more than 20 per cent is suitable for use. The fired product is soft and brittle and then ground in a ball mill to obtain a highly reactive pozzolana.

4. *Small-scale production of cement*

Small-scale cement plants based on vertical shaft kiln technology have been developed. The capacity of these plants range from 20 to 200 tons per day.

The process of cement manufacture by the vertical shaft kiln technology involves the grinding of raw materials, consisting of limestone, clay, coke breeze and corrective materials (if any), to a fineness of at least 90 per cent passing through a 90-micron sieve. The ground raw meal, prepared by mixing raw materials in the required proportions, is homogenized in a silo with compressed air. The homogenized raw meal is then nodulized in a pan nodulizer with the help of a fine spray of water. The nodules (6-10 mm diameter, with a moisture content of 10-12 per cent) are then fed into the vertical shaft kiln at a uniform rate for firing. In their downward fall in the kiln, the green nodules counter hot flue gases of increasing temperature flowing counter-current to the nodules. In the process, the nodules are dried, dehydrated, decarbonated, and finally clinkered with the formation of cement minerals. The cement clinker comes out of the kiln at the bottom through the periphery of a rotary discharge grate. On cooling, the clinker is ground in a ball mill with about 4 per cent gypsum, by weight, to a fineness of not less than 2,250 cm^2/g (Blaine's) to obtain Portland cement conforming to IS:269-1989 "Specification for ordinary Portland cement (4th revision), 33 Grade".

The raw materials to be used in the manufacture of cement in vertical shaft kilns need to conform to the following specifications.

(a)	**Limestone**	
	SiO_2	12 per cent, max.
	Al_2O_3	4 per cent, max.
	Fe_2O_3	2-4 per cent, max.
	CaO	45 per cent, min.
	MgO	2.5 per cent, max.
(b)	**Clay/shale/fly ash**	
	SiO_2	60-66 per cent
	Al_2O_3	12-18 per cent
	Fe_2O_3	5-9 per cent
(c)	**Coke breeze**	
	Calorific value	6,000 kcal/kg, min.
	Ash content	30 per cent, max.
	Volatile matter	8 per cent, max.
(d)	**Gypsum**	
	$CaSO_4.2H_2O$ content	80 per cent, min.

5. *Hydraulic binder from industrial, mining and agricultural wastes*

Hydraulic binder conforming to IS:3466-1988 "Specification for masonry cement (2nd revision)" and suitable for use in masonry work can be produced from non-conventional materials such as waste lime sludge from acetylene generators, paper and sugar mills, fly ash, blast furnace slag, phosphogypsum, tailings from gold, copper and zinc mines, and rice husk, as described below.

(a) A raw mix is prepared by mixing together 13.6 kg dry lime sludge from an acetylene generator and 5 kg fly ash per batch, and then pelletized in a pan pelletizer. The pellets are sintered at about 1,150° C in a sintering hearth. No additional fuel is required for sintering if the fly ash contains about 7 per cent unburnt carbon, as determined by loss on ignition. After sintering and subsequent cooling, the sintered material is crushed and ground in a ball mill to a fineness of 15 per cent maximum retained on a 45-micron sieve.

(b) An intimate mixture of dried and powdered lime sludge and rice husk in the proportion 1:1 by weight is prepared. It is wetted with water and shaped into balls which, after drying in the sun, are fired in open trench/clamp kilns. The fired material, after cooling, is ground in a ball mill to a fine powder to obtain the hydraulic binder.

(c) Binder conforming to IS:3466-1988 and suitable for masonry work can be produced by intergrinding the following mixtures:

(i) 2 parts of fly ash, 2 parts of lime and 1 part of OPC, by weight.

(ii) 2 parts of fly ash, 3 parts of OPC and 5 parts of granulated blast furnace slag with a suitable quantity of gypsum and an air entraining admixture.

(iii) 40 parts of gold mine tailings and 60 parts of OPC by weight. Tailings from copper and zinc mines can be used, in place of gold mine tailings, with suitable adjustment in the mix proportions.

(iv) 75 parts of phosphogypsum hemihydrate, 15 parts of granulated blast furnace slag or fly ash, 10 parts of OPC and suitable amounts of a retarder.

(v) 50 parts of phosphogypsum anhydrite, and 50 parts of granulated blast furnace slag with suitable amounts of OPC and an accelerator.

Laterites as construction materials for rural housing

Paper presented by A. Ayensu, Department of Physics, University of Cape Coast, Cape Coast, Ghana, at the Advanced Workshop on Industrial Composites Design and Application, October/November 1994, International Centre for Science and High Technology (ICS), Trieste, Italy

Abstract

Laterites and other lateritic materials have been used as building materials since pre-historic times. Unfortunately, the performance and reliability of lateritic structures have not been satisfactory from the point of view of durability and the high cost of maintenance. These drawbacks are primarily due to human factors such as poor design and/or lack of proper building codes coupled with environmental factors such as rainfall erosivity, soil erodibility and excessive ponding. In this paper, the chemical and mechanical properties of laterites have been evaluated to determine the appropriate standards or criteria for selection of lateritic materials for housing construction in rural communities where laterites are abundant and can be excavated cheaply. There is an acute demand for cheap and affordable houses and rational use must be made of laterites as building materials.

To classify and differentiate lateritic materials as wormhole, pellet, soft-doughy type or latosol, the processes of laterization and induration which determine the quality of laterites are explained in detail. A ternary phase diagram of SiO_2, Al_2O_3 and Fe_2O_3 system is presented, from which the parameter, K_1, is calculated:

$$K_1 = \frac{SiO_2/60}{Al_2O_3/102 + Fe_2O_3/160}$$

K_1 distinguishes laterites and non-laterite materials.

Laterite behaviour in relation to moisture content is discussed with special reference to the Atterberg limits. To be used as a building material, the liquid limit of selected laterite should be within the range of 30-40 per cent, the plastic limit must be 10-20 per cent and the volumetric shrinkage must be $\leq$ 20 per cent. The factors which control the strength and compaction such as grain size distribution in relation to the composition of gravels, sand and clay minerals are also discussed.

It is recommended that laterites must be processed at minimal cost with minimum energy input into products such as latcrete and bricks. Appropriate building codes are required for rural laterite housing schemes. Since the major defects of laterite buildings are crack formation due to shrinkage and erosion, precautionary measures such as water-proofing by plastering walls, extended eaves on roofs to cover foundations, gutters and platforms around the buildings have become essential requirements. When reinforced with cement, the compressive strength of the latcrete must be $\geq$1.38 MPa when wet, and ~2.76 MPa when dry.

1. Introduction

Even though laterites often possess less than desired properties compared to other civil engineering materials such as granite, concrete and steel, they are often used as construction materials because they are economical. For most applications, laterites must be stabilized, reinforced or modified to improve their engineering properties.

1.1 Terminology

The generic name "laterite" is applied to describe naturally occurring "materials" possessing certain chemical characteristics which, after desiccation, harden irreversibly; or residual soil produced *in situ* by weathering of igneous rocks in the humid tropics. Laterite is a porous, indurated and concretionary material which is usually red to reddish brown in colour, and commonly referred to as "brick earth". The three types of laterites found in the tropics and characterized by their physical appearance are wormhole or hardpan (crust), pellet (gravel) and "soft-doughy" laterite. Wormhole is a massive concretionary formation with an iron-rich matrix and of slaggy appearance. Pellet laterite consists of fine grains which are cemented by iron oxide into pellet-shaped grains which may be loosely consolidated or not. All three laterite types harden irreversibly upon exposure to alternate wetting and drying. Laterites are widely distributed in tropical regions lying between 35° N and 35° S.

Laterite is often confused with lateritic soil (latosol) simply because their physical appearance and chemical properties are similar. Latosols vary in type from poorly graded sands to highly plastic clays, in colour from red to reddish brown and exhibit some secondary iron cementation between the mineral grains. Although lateritic soils harden upon drying, they soften readily upon wetting. An important physical difference between laterite and lateritic soil is that a laterite has a gravel component. The differences in behaviour of laterites and lateritic soils are significant and erroneous classification could lead to serious construction failures. Latosols are typically found either above laterite deposits or alone on younger and moderately dissected terrain.

1.2 Laterization

The production of laterite by weathering is referred to as laterization. Physico-mechanical weathering by temperature changes and erosion cause disintegration of rocks; and chemical weathering decomposes rock minerals by oxidation, reduction and carbonation. Colloidal and other soluble products are leached to lower horizons or removed altogether, but hydrated oxides of aluminium and iron are concentrated by evaporation. Laterization of kaolinite can be represented by chemical equation of the form:

$$\underset{\text{(Kaolinite)}}{Al_2O_3.2SiO_3.2H_2O} + H_2O \rightleftharpoons \underset{\text{(Gibbsite)}}{Al_2O_3.3H_2O} + \underset{\text{(Quartz)}}{2SiO_2} + O_2$$

Such a chemical reaction causes a continual rifting of silica from the sesquioxides leaving alumina available for concentration at the site of deposition. The placement, concentration and type of chemical compounds determine the physical properties of the primary concretion, and the ultimate product of laterization is either haematite or bauxite. Laterites in a residual soil are identified by the relative amounts of SiO_2, Al_2O_3, and Fe_2O_3 as shown in table 1.

Table 1. Identification of laterite, lateritic soil and non-lateritic material by the parameter, K_r

$$K_r = \frac{\%SiO_2/60}{\%Al_2O_3/102 + \%Fe_2O_3/160}$$

Material	K_r
Non-lateritic	>2.00
Lateritic soil	1.33 - 2.00
Laterite	<1.33

1.3 Induration

Laterite may harden *in situ* or may later harden when exposed to air. Induration is the most significant property of laterite, and understanding of this process is essential for selection and use of laterite. Laterite material will indurate irreversibly when the water of hydration is mechanically removed from the sesquioxides, changing them from compounds lacking an affinity for water to material which might be induced at a later time.

A high concentration of silica inhibits induration. Fe_2O_3 is a superior, cementing agent and its presence in concentrations exceeding 25 per cent is conducive to induration. In addition, the removal of CO_2 during desiccation could produce the necessary valency change to catalyse hardening. The factor most responsible for hardening is generally thought to be the degree of iron-salt concentration at the point of desiccation.

2. Properties of laterites as building materials

2.1 Composition and chemical properties

The range of the chemical composition is shown in table 2.

Table 2. Major chemical composition of laterite

Chemical comp.	*Average (%)*	*Low (%)*	*High (%)*
SiO_2	16.6	0.6	49.8
Al_2O_3	20.1	2.7	38.7
Fe_2O_3	47.5	20.7	81.9

In general, laterite has a lower base-exchange capacity and higher pH than lateritic soil. Kaolinite is the predominant clay mineral in laterite as compared to a latosol where all three clay minerals, kaolinite, illite and montmorillite are present.

2.2 Mechanical properties

The mechanical properties and degree of laterization serve to determine the suitability of laterites as construction materials. The experimental methods and standards used to differentiate permanently indurated materials from those which soften under load and/or moisture conditions are sieve analyses, Atterberg limits, Proctor's compaction test, California Bearing Ratio test, slaking test, submergence test, abrasion test, shrinkage and swelling tests. The percentage of components of laterite and their gradation are shown in table 3.

Table 3. Components of laterite and their gradation

Laterite	*Gravel (%)*	*Sand (%)*	*Fines (%)*	*Clay (%)*
Wormhole	40	30	<30	-
Pellet	40	10	50	-
Latosol	-	40-50	30-40	20-30

It must be emphasized that the strength of laterite at a location is a function of density and moisture content. Table 4 below gives values of some mechanical data for laterite, and materials of low liquid limit (LL <50 per cent), low plastic limit (PL <25 per cent) and low per cent swelling can be considered to be suitable for building.

Table 4. Mechanical data for lateritic materials

Laterite type	*Specific gravity*	*Hardness (MOH scale)*	*Dry density x 10^3 kgm^{-3}*	*Optimum moisture content (%)*	*Liquid limit (%)*	*Plastic limit (%)*	*Plastic index (%)*
Wormhole	2.76-3.50	3	2.08-2.40	8-12	30-50	10-20	20-30
Pellet	2.76-3.50	3	2.08	10-14	30-50	25-35	5-25
Latosols	2.73-3.12	-	1.76-1.92	12-16	40-70	25-50	15-20

2.3 Design considerations

To design structures made of laterites, a major consideration must be to prevent local ponding, structural softening and erosion during heavy storms, and buildings must therefore be elevated from the ground. In addition, adequate drainage ditches, culverts and interceptor ditches must be provided to handle the intense run-off. This is a key factor in ensuring the long-term use of the structures. The annual values of rainfall erosivity indices are high in the tropics, and the estimates for Ghana are 935 $Jm^{-1}h^{-1}$ on the EI_{30} index, and 1.38 x 10^4 Jm^{-2} on KE >25 index.

2.3.1 Grain size distribution and texture

The engineering properties of laterites are strongly dependent on grain sizes, shapes and distribution. Laterite particles range from boulders, cobbles or gravels to sand.

2.3.2 Atterberg limit

The presence of water in the voids is probably the most important factor affecting the behaviour of laterite. Atterberg limits indicate different boundaries of mechanical response in terms of water content, and it is possible for laterite to exhibit mechanical behaviour ranging all the way from a brittle solid to a liquid depending on the water content w. When w >LL, laterite can support no static shear stress. When PL < w < LL, laterite behaves as plastic or Bingham solid; and this range is called the plastic index (PI = LL - PL). At w < PL, laterite behaves as a semi-solid or even brittle material. Below the shrinkage limit (SL), no further decrease in volume occurs as drying continues.

3. Stabilization and compaction of laterites

Since the engineering properties of laterites are usually poor, their economic uses in fills and buildings require some form of modification or stabilization to increase the strength, preserve homogeneity, provide water-proofing and prevent dusting.

3.1 Mechanical stabilization

During mechanical stabilization or compaction, densification and particle rearrangement occur because air is expelled from the voids without a significant change in the water content. The strength is increased and the detrimental effects of shrinkage and swelling can be ameliorated. Compaction of laterites reduces permeability from 2 x 10^{-4} - 2 x 10^{-2} cm/s to a range of 1 x 10^{-7} - 1 x 10^{-6} cm/s; and compressibility from 100 x 10^{-3} to 3 x 10^{-3} sq. ft/ton.

Compaction is a function of density, water content, laterite type and applied mechanical energy. In Proctor tests, samples of the same laterite and of different water contents are compacted with the same compactive effort. A plot of the bulk dry density against water content shows a characteristic parabolic curve. The water content corresponding to the maximum dry density (MDD) is called the optimum water content (OMC). Typical values of MDD are within the range 1.6 - 2.4 x 10^3 kgm^{-3}, while the OMC ranges between 10 and 20 per cent. Even at very high water content and high compaction energy, the compaction curve never reaches the 100 per cent saturation line; however, more energy will increase the MDD and decrease the OMC.

3.2 Stabilizing with cement

Chemical stabilization of laterite is best done with about 4 to 8 per cent dry weight of cement. Stabilization of lateritic soil is best accomplished with 4 to 10 per cent of quick lime. The curing period for laterite-cement is one to three days, while a minimum of seven days is required for lime. The cement or lime is mixed with the dry material, water is added and the mixture is immediately compacted to obtain high dry density.

Cement stabilized laterite with unconfined compressive strength of 0.8 to 1.4 MPa and good resistance to wetting-drying cycles have been produced. Only the specified amount of cement must be used, since the free lime of the cement is used up in secondary reactions with the laterite or absorbed by the primary hydration phases, and the pH of the water phase is reduced by expansive clay so that hardening is inhibited.

3.3 Surface protection with plaster

Sand-cement mortar of density 2.07 x 10^3 kgm^{-3}, compressive strength 9.21 MPa, wetting expansion 0.10 per cent, and drying shrinkage of 0.07 per cent can be used to plaster the exterior and interior walls of laterite buildings to minimize water penetration and abrasion wear of the background material. A 2 cm thick plaster can be used to ensure compatibility of thermal shrinkage of laterite and mortar, since any differential movement between them will cause cracking. Weakly prepared plasters have greater flexibility and can accommodate shrinkage of laterite better than strong mortars.

4. Lateritic materials for rural housing in Ghana

In Ghana, the inhabitants have been building with laterite since historic times. Unfortunately, the effects of rainfall erosivity and soil erodibility have reduced the prospects of building with laterites, as the structures tend to collapse during heavy storms. However, the adoption of cement as a substitute building material is becoming very expensive, and therefore, the traditional knowledge of using laterite must be improved to make laterite more competitive and acceptable.

4.1 Availability of laterites

Up to 1960, 94 per cent of all rural houses and 53 per cent of all urban houses were built of lateritic materials, and only 8 per cent of all houses in the country were built of cement blocks. Present estimates indicate that of all the houses built in the rural areas, about 30 per cent are built from raw lateritic materials, 50 per cent of laterite bricks, and 20 per cent of sandcrete blocks.

4.2 Indigenous building techniques

In the rural areas, there are no building codes or zoning requirements. The building site is usually located at the outskirts of the town, or an area which served as a garbage dump, and only the barest minimum site preparation is done. A traditional compound house is a "swish, mud or Atakpame" building of six to ten rooms, with a patio, kitchen and toilet facilities, all enclosing a central open yard for natural ventilation.

4.2.1 Monolithic swish house

A swish house is constructed from latsols or laterites which are placed in monolithic position when in plastic state. Dug out laterite is mixed with water, rammed with the feet, cured for two to three days and made into globules of 15 to 20 cm in diameter. The foundation which is required to establish a relatively solid non-moving contact between the structure and the ground is poorly constructed.

The builder normally judges the texture of the laterite by "feel" and prefers highly plastic materials which contain a large amount of clay that can be worked easily, but which unfortunately exhibit large volume shrinkage. The walls are built up in courses and each course is allowed to dry before the next course is built. The wall thickness varies from 20 to 30 cm and each course is about 30 to 45 cm high.

4.2.2 Failure categories

Principal non-performance or failure categories of laterite walls are water penetration, inadequate structural behaviour and crack development due to high ambient temperatures and changes in the moisture content of the building materials. In addition to the difficulties of alignment, bonding and compaction of adjacent layers, the major defects associated with the traditional building methods are:

(a) Rain or water penetration of the walls, causing cracking as a result of cyclic wetting and drying accompanied by expansion and shrinkage of the laterite. The moisture cycling leads to structural instability, ultimate failure as evidenced by shorter life spans of most houses (typically under 100 years).

(b) Erosion of the building foundation as a result of poor design, site selection and excessive ponding. Animals rub their bodies against the unprotected walls, fragment the laterites and open up cracks. This reduces the thickness and strength of the base walls which causes the heavier upper course walls to tumble.

These defects can be overcome if appropriate building methods are adopted. The artisans or builders must be trained in site preparation, foundation work, materials selection and methods of stabilizing latsols. The swish houses can also be plastered to provide additional protection. The doors and window frames must be installed during construction. The floors must be filled with rammed earth, topped with concrete and screed finished with cement.

4.3 Application of appropriate technology

Appropriate methods have been developed to process and stabilize laterites into resistant and durable building materials:

(a) Sun-dried bricks, produced by the "soft-mud process" is the moulding of wet laterites into bricks of various dimensions. The laterite is made up into a softer plastic material by adding 1-2 per cent water above the OMC. The bricks are formed by ramming the soft laterite into wooden moulds and sun-drying for up to 14 days. The method produces bricks of compressive strength of 0.62 - 1.03 MPa, with random distribution of crystalline phases and pores without laminations. In buildings, the bricks show least tendency of cracking, have aesthetic value, and correct vertical and horizontal alignment can be achieved. The door and window frames are fitted during construction and mortar of 1 cm thickness can be used to give strong bonding to adjacent layers. The walls can be plastered easily without adding a subgrade.

(b) Latcrete blocks produced by "press and extrusion method" of a mixture of cement, sand and low-grade laterites. A cement content of <5 per cent dry weight is recommended and after casting, the blocks are air-dried under shade for 24 hours to cure, and are ready for use after 21 days. The minimum compressive strength obtained is >1.38 MPa when wet and >2.76 MPa when dry. Large-scale and low-cost rural housing schemes, such as the Habitat Programmes, use latcrete and laterite bricks in building construction.

(c) Burnt bricks are made from latosols of very high clay content which is processed with cement and fired at high temperatures. Burnt brick buildings are much more durable and require minimum maintenance and protection, but the high cost of production makes these bricks unpopular.

Binders for cellulose materials and their derivatives: clean fuels and building materials for the future

Paper presented by E. LaMont-Gregory, School of Anthropology, Oxford University, United Kingdom, at the Advanced Workshop on Industrial Composites Design and Application, October/November 1994, International Centre for Science and High Technology (ICS), Trieste, Italy

Abstract

It is part of conventional wisdom that the next major advance in the standard of living in the so-called "developing world" will come about as a result of improvements in social and economic conditions. Sustainable sources of clean fuel for cooking and heating and locally produced building materials that are not derived from forest resources may play an important part in this effort.

Wood is a vital source of energy for most of the population in many countries. Wood is also an important source of building material, household furnishings, and fuel for brick drying and bakeries. Forest resources are increasingly cleared to grow more food for expanding populations. As more food is grown, more crop residues are accumulated. It is these materials, crop residues, that present an opportunity to meet fuel and building material needs in the future.

To use crop residues for building materials—panel boards—requires binding technology. The use of straw for panel boards has become feasible, but due to the high cost of current binders, straw panels cannot successfully compete with other residue panel board products.

A binder derived from cellulose materials may help to overcome the limitations of straw board production. However, in the opinion of the author, the best use of the cellulose derived binder may be in the production of smokeless cooking and heating fuels. Clearly, one fourth of the world's population is dependent on wood and other biomass residues for cooking and heating purposes.

When wood, crop residues or dung are burned in their natural state, respirable particulates and other pollutants are emitted which readily accumulate in poorly ventilated homes and enclosed courtyards. These pollutants exceed recommended human exposure levels established by the World Health Organization by factors of 10 or more. Prolonged or chronic exposure to raw biomass smoke is a significant cause of human health problems, such as acute respiratory infections in new-born babies and children, chronic lung disease and cancer, and is associated with several eye problems.

Although any organic material may be carbonized, however, when crop residues are carbonized, carbon dust or fines are produced which must be briquetted into a usable solid fuel.

Carbon dust derived from carbonized crop residues properly bound together into solid smokeless carbonaceous briquettes could help to alleviate not only the health problems associated with raw biomass smoke, but could also help to assure a supply of cooking and heating fuel from a renewable and sustainable source in countries with scarce forest resources but which have abundant crop residues. If carbonization is carried out in a way which permits by-product recovery, important petrochemical replacements result, such as wood preservatives which will extend the life of panel boards derived from either wood or alternative building materials.

Cement composites based on pozzolanic clays

Paper presented by V.T.L. Bogahawatta, National Building Research Organization, Colombo, Sri Lanka, at the Advanced Workshop on Industrial Composites Design and Application, October/November 1994, International Centre for Science and High Technology (ICS) Trieste, Italy

In most developing countries, the only binder used in the construction sector is Portland cement. Its limited supply and high cost have meant that the cost of construction has escalated or that investments are restricted. It is known that when some clay materials are calcined at optimum temperatures they become pozzolanic. Previous studies in this area were mainly concerned with the investigation of strength characteristics of indigenous materials.

The present study was concerned with a technique of improving the pozzolanic activity of the final product by pulverizing and fractionating the starting material before heat treatment. The optimum firing schedules favourable for imparting pozzolanic activity to the clay materials under investigation were also established.

An initial survey was made to identify and characterize geomaterials of different paedogenesis which possess potential activity. Fifteen earthy materials including residual (lateritic) soils, clays and minerals collected from different localities were subjected to activation trials and subsequent strength tests. The material possessing the required characteristics was then fractionated and subjected to a series of pre-determined firing schedules. A combination of 10 firing temperatures and five isothermal holding times were employed. The optimum size fractions and firing schedules appropriate to the material were thus established. Standard mortar cubes were prepared. An accelerated curing test was designed to moist cure the specimens. Pozzolanic activity of cements was determined as an index. The tests on the specimens indicated a marked improvement in compressive strength when critical size fractions are heat treated according to a schedule established in the investigation.

The strength of specimens showed a further increase at low concentrations of additives. The resulting cement had a pozzolanic activity index above 100 indicating that it is comparable with OPC in strength characteristics. The residual (lateritic) soils and clays which are amenable for transformation into pozzolanic materials have been characterized mineralogically. The investigation provides a basis of manufacturing cement composites based on activated residual (lateritic) soils.

Composites cure corrosion in concrete

The setting may be traditional, but the bridge which spans the small river that passes through this typical rural picture is anything but. A break-through in materials engineering, Fidget's Footbridge on the outskirts of Chalgrove in the UK is claimed to be the world's first concrete bridge reinforced with plastic composite rather than steel bars. The only metal in the bridge can be found in the four steel lifting sockets.

The project, which began at the end of 1993, involves partners from the UK, France, Holland, Norway and Switzerland. According to the consortium leaders EuroProjects (LTTC), the aim is to develop more durable reinforced concrete structures.

UK participants included Sheffield University, responsible for structural testing, designers Sir William Halcrow & Partners, GEC Reinforced Plastics which supplied the synthetic reinforcement, with help from Allied Steel and Wire, Vetrotex, DSM and DuPont.

The project aims to give the industry an alternative route to corrosion-resistant concrete that has been properly benchmarked against other techniques. It will have application in any structure where road salt is present, or where there are other corrosive factors—such as in a marine environment. (Source: *Advanced Materials News*, November 1995)

D. WOOD COMPOSITES

Wood, composite material and fibre source

By: C. Birkinshaw, University of Limerick, Ireland.
(Paper presented at the *Advanced Workshop on Industrial Composites Design & Application*, October-November 1994, ICS, Trieste Italy)

Introduction

Wood is both the most abundant composite material and fibre source. Many countries in both temperate and tropical regions have significant economic dependence on timber production and conversion to wood-based composite materials. The historically important position of wood in almost all societies is a testimony to its extraordinary balance of mechanical properties, in particular its combination of stiffness, strength and toughness at low weight. This desirable mix of properties has only been equalled by synthetic composites in the past few years and whilst some of the newer materials achieve higher specific strength and stiffness, when properties are related to cost, then wood is still a most attractive engineering material. If the environmental aspects of wood production are sensitively managed, then wood or wood composites will continue to be the first choice material for many structural applications.

However, a number of factors are altering the economic and technical climate for these materials, and are forcing a more critical property appraisal and changes in utilization. Some of these factors are:

Reduced availability of commercially important species. This is having an impact throughout most production areas but is particularly important with the tropical hardwoods used for high value products such as furniture. Environmental concern is increasingly important as a further limitation to the exploitation of the remaining high quality forest timbers. The changing patterns of use of tropical timbers will be commented on later, but natural resource attrition is not only a problem of the rain forests as current North American experience shows. There, very large areas of forest are no longer capable of producing their traditional high volumes of commercial timbers as the end of harvestable old growth is approached.

Changes in building and structure design towards larger unsupported spans which present problems of dimension for solid wood. This is further exacerbated by the reduced availability of large-sized trees and many engineering applications now demand structural members of such length that only laminated products will suffice.

Changes in construction technology away from traditional on-site preparation of timber components towards the use of modular units prepared by factory assembly from standard materials.

Tighter structural specifications as, driven by a combination of technical and commercial considerations, building codes become more stringent whilst at the same time increased competition from alternative technologies cuts financial margins for the timber industry. This tends to force the structural engineer and wood scientist to look more closely at how efficiently materials are used.

The overall effect of these changes is to move the wood-based industries away from solid wood towards wood-based composites. These can be made using wood species and qualities which would be unacceptable for solid use and yet produce materials of uniform engineering properties in standard sizes. In this way the scarce supplies of high-grade hardwoods can be utilized to the greatest effect as veneers, etc. and glu-lam and laminated veneer lumber can be used to meet the need for large-span engineering units with wood particle or fibre panel products supplying the building industry's cladding needs.

These changes demonstrate the other role of wood as a source of fibre materials for manufactured composite systems. The oldest wood fibre-based industry—and commercially still the most important—is paper, but the last 20 years have seen a steady rise in other wood fibre and wood particle products. The major process limitation at the moment is the batch nature of almost all panel processes, products being press moulded as discrete components, and a significant technological challenge will be to follow the lead of the synthetic composites industry and make shaping processes continuous.

However, despite the inevitable increase in the relative position of wood composites, solid wood will continue to be of importance as a structural material for smaller buildings and building components and although there is a long history of use, there are still areas of structure-property relationships in wood that are not well understood. Some of these are critical to efficient engineering use.

In many respects, the structure-property relationships of the modern synthetic composites are better understood than those of wood because they are much simpler systems in which the roles of the constituents can be defined with precision. Wood is complex at all levels of definition and much more responsive to its environment. The profoundly important role that water has to play needs to be examined in detail, as it controls the ways in which wood can be utilized. Lack of proper appreciation of the effects of the interaction of wood with its environment continues to be responsible for many product failures. At present the topic of greatest importance to wood engineering is the nature of the deformation and creep mechanisms, particularly those processes which occur when moisture content is changing. All moisture-dependent properties are clearly important because in almost all applications wood is exposed to cyclical humidity change; yet engineers demand stable or predictable materials.

Summary of mechanical properties

The cellular and porous nature of wood means that it is well suited to resist bending and deformation and the degree of resistance varies according to the total amount of cellular material present and its distribution between the various cell wall components.

To a first approximation strength can be related to specific gravity by a power law of the form: $S=k\ (p)^n$ where S is the strength property of interest, k is a proportionality constant for the particular property, p is the specific gravity and n is the exponent defining the shape of the curve. For compression parallel to the grain, n is approximately unity and for compression perpendicular to the grain, n is around 2.25; k is particularly sensitive to moisture but n shows little change between wet and dry wood.

However, ultimate strength properties are of limited value as in most engineering applications wood is exposed to much lower stress levels than those which cause rupture. Typically, structural members might be operating for many years at stresses between 10 per cent and 80 per cent of the ultimate failure stress and therefore stiffness and the ability to endure load are the characteristics of prime importance.

The shear and compressive force resistance of wood is not particularly good. High point loads associated with fixing and joining often present problems as cell wall buckling and collapse can occur. Correlations have been established between embedding strength of fasteners, density and crushing strength [for example, Koponen & Absetz, 1993. Cruz, 1994]. One practical way of improving performance may be to use densified veneer wood as reinforcement in high-stress joint situations, for instance where dowel-type fasteners are used [Leitjen 1994].

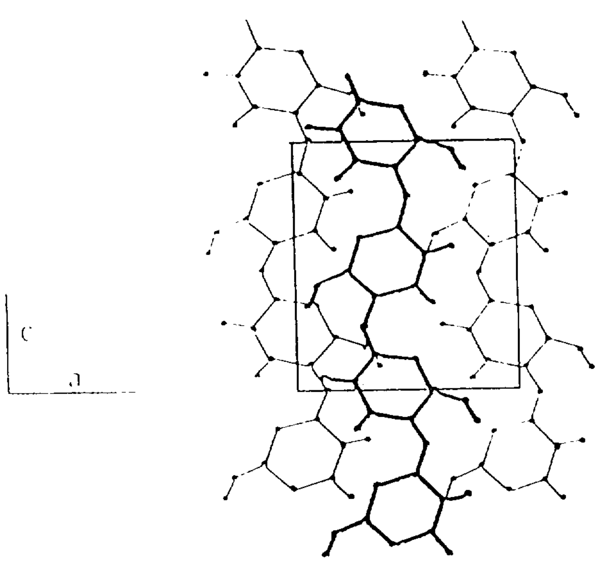
The fatigue properties of wood are excellent, probably because of plastic deformation of the matrix.

Characteristics of the constituent polymers and their response to moisture

In natural celluloses, cotton, wood, ramie and other fibrous plant materials cellulose always occurs in the cellulose I form, which has the two chain monoclinic unit cell shown in figure 1. The diffraction pattern is generally interpreted as indicating a parallel chain structure in which the corner and centre chains of the unit cell possess the same orientation along the c-axis. The chains are disposed within sheet-like arrangements parallel to the b-c plane of the crystal lattice and hydrogen bonding occurs between units within each sheet. Chains in the sheets which contribute the corners of the unit cell are offset by 1/4 c from those which contribute the centres. Hydrogen bonding occurs within the sheets, but in cellulose I there is no hydrogen bonding between sheets. Usually the degree of polymerization is between 10,000 and 15,000. The glass transition temperature of dry cellulose is around 230° C.

Figure 1

Unit cell of cellulose I



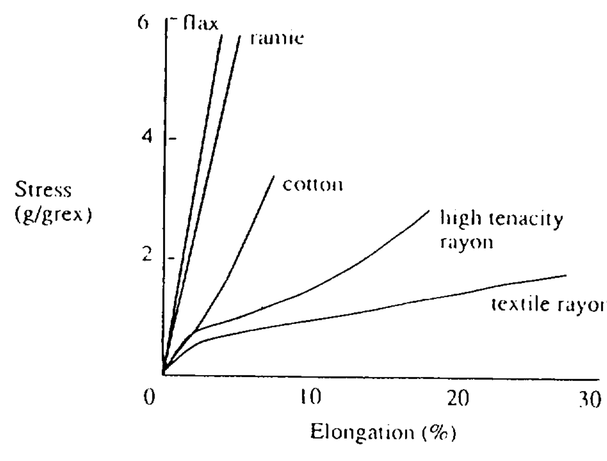
The β linkage imposes a rotation of 180° on alternating glucose residues and as a result the chains are stiff and straight, forcing crystallization in an extended chain fashion. Most synthetic polymers crystallize in folded chain arrangements and when stressed a progressive loss of fold structure can occur with an apparent overall plastic deformation. Figure 2 compares the stress-strain properties of various types of cellulose fibres. Synthetic fibre can often be deformed by large-scale crystal rearrangement but such a stress relief mechanism is not available to the cellulose crystals where crystal deformation can only occur through slip plane formation. As a result, fracture occurs at relatively low strains although the elastic modulus is relatively high.

In addition to the highly developed intermolecular forces the cellular chain is conformationally restricted and so the entropy change on melting would be small. Both enthalpy and entropy factors combine to give a theoretical melting temperature which is higher than the thermal decomposition temperature of around 300° C. Cellulose, like all polysaccharides, has mechanical, physical and chemical properties which are dominated by the effects of hydrogen bonding and chain rigidity.

The degree of crystallinity of wood celluloses is between 60 per cent and 90 per cent but uncertainties remain about the detail of the crystallite structures. Cellulose molecules vary from 2,500 to 5,000 nm in length but the crystal regions are much shorter, typically 60 nm long, arranged in something resembling the fringed micelle model. There are suggestions that a hierarchy of structures exists.

Figure 2

Stress strain behaviour of different forms of cellulose fibre measured at 65 per cent relative humidity and 20° C



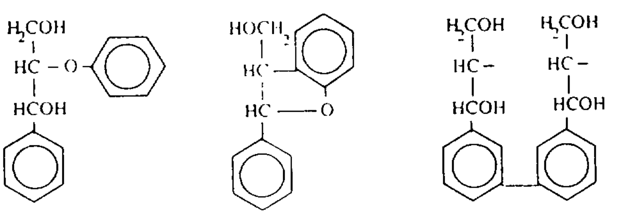
The precise fibrillar and sub-fibrillar structures are still the structure of much debate, particularly with respect to the arrangement of ordered and disordered regions.

The composite matrix materials, hemicelluloses and lignin are chemically variable and many structures have been published. Figure 3 shows the major inter-unit linkages of lignin [Alder, 1977]. As larger-scale deformations involve plasticity of the lignin and hemicellulose-rich cell components, the thermal and hygroscopic behaviour of these materials is important. They are also potentially important as polluting by-products from pulping operations. The reported glass transition temperatures for extracted dry lignins typically lie in the range 140-177° C [e.g. Young, 1978, & Hatakyamo &

Nakano, 1790)], but extracted materials must be presumed to be of lower molecular weight and structurally different in the *in situ* polymer. Glass transitions for whole wood to lignin are reported to be between 60° and 90° C [Salmen, 1984, Kelley et al., 1987, Young, 1978, Atack & Heitner, Vikstrom & Nelson, 1980] with precise values depending upon wood type and experimental conditions, particularly on moisture content.

Figure 3

Major inter-unit linkages in lignin



Lignin variability is high, both from species to species, and within a species. Chemical heterogeneity exists between heartwood and sapwood lignin [Parameswaran et al., 1975] and even between that in different cell wall layers [Hardell et al., 1980] and it must be assumed that this makes some contribution to variability in response to water. However, in a comparison of axial and transverse viscoelastic behaviour of water-saturated wood, it has been shown [Salem, 1986] that although a slight difference existed in softening behaviour, analysis of results using a free volume approach lead to the same activation energy, implying that lignin can be treated as a mechanically homogeneous matrix.

The hemicelluloses are also structurally heterogeneous and, if dry, display glass transition temperatures in the range 138° to 217° C [Goring, 1963, Irvine, 1985, Cafferty et al., 1964]. Again many structures have been published, [for example, Fengel & Wegener, 1989] and all proposed structures are notable for high concentrations of hydroxyl groups which offer opportunity for both inter- and intra-molecular hydrogen bonding. Plasticization by water is sufficient to bring softening temperatures close to ambient [Kelley et al., 1987, Irvine, 1984, Erikson et al., 1980]. While evidence has been presented [Erikson et al., 1980] for primary bonding between hemicellulose and lignin, the clear separation of the softening events suggests little interpenetration. As water cannot penetrate the crystal regions of the cellulose microfibrils, at any given overall moisture content, the actual concentration in the amorphous hemicelluloses will be appreciably higher than in the wood as a whole.

A fourth group of compounds, loosely referred to as extractives and consisting of terpenoids, flavonoids, stilbenes and lignans have only limited effect on mechanical behaviour, but are central to the natural protection of the wood against biological attack. Their greater concentration in hardwoods often mean that these timbers can be used without preservatives. However, the bio-cide action of extractives can present an environmental problem in the waste streams from wood processing plants. Extractives are central to one of wood's more traditional applications and that is as a container for maturation of alcoholic beverages. Extraction of tannins and vanillins from timbers such as oak is vital to the development of flavour in wine and whiskey. It is difficult to see synthetic composites having anything to offer in this application.

Response to long-term loading

The problem

Despite the extensive knowledge available about the structure and chemistry of wood, problems still exist in satisfactorily explaining the long-term behaviour under load. Short-term stiffness and strength and fracture processes are reasonably well understood through the theories that have been developed for orthotropic synthetic composites, but difficulties still arise in trying to explain time-dependent and humidity-dependent properties.

Creep in wood is unlike creep in other polymeric solids and composites in two important respects. Firstly, it shows a rather complicated dependence on changes in moisture content (mechano-sorptive effect) and secondly, under the right conditions of moisture and temperature, a very high level of creep recovery is possible. The problem lies in arriving at valid microstructural explanations and correlating these with predictive mathematical models.

Mechano-sorptive creep

Mechano-sorptive creep in wood is the acceleration in creep deflection under load during change in moisture content. The effect has been known for a long time, as the results of Hearmon and Paton show. Similar effects are observed with composite panel products [Dinwoodie et al., 1991]. The acceleration in creep occurs whether the moisture content is increasing or decreasing, and maximum deflection change occurs during the drying part of the cycle, confirming that the mechanism is not simple plasticization. The effect is observed at low loads, typically around 10 per cent of the breaking strength of wood under dry conditions, and the net increase of deformation per cycle diminishes when the number of moisture cycles increases. Creep recovery can also be increased by moisture cycling, and compared with synthetic polymers, extremely high levels of recovery are possible.

It is difficult to relate creep to molecular mobility and cell wall mechanics, probably because of the number of possible mechanisms involved, depending upon strain level, orientation and moisture content. From a chemical point of view, it seems reasonable to assume that visco-elastic and mechano-sorptive creep arise from the same molecular and structural processes but phenomenological observations, particularly the differences in recovery behaviour, contradict this. With mechano-sorptive creep, recovery is related to change in moisture content, whereas with viscoelastic creep, recovery is time dependent and partial.

The stress strain properties of wood in tension parallel to the grain are linear almost to failure, but in compression parallel to the grain non-linearity occurs at stress levels above about 50 per cent of the ultimate failure stress. This implies differences in the deformation mechanisms and may provide an indication of a possible explanation of mechano-sorptive creep. Electron microscopy has demonstrated that compression parallel to the grain causes slip planes in which a section of fibrils undergo a partial transverse shift. Creep tests are usually performed in bending mode with slip planes occurring on the compression side of the neutral axis.

Slip planes often form immediately below or above a ray crossing which acts as a point of stress concentration and there are suggestions that local inhomogeneity may be responsible for slip plane formation at relatively low stress.

It is also possible that stresses caused by moisture change may reduce the onset stress.

According to Young and Hilbrand [1963] the onset stress for slip plane formation is a function of time of application of stress—in one experiment slip planes occurring at 55 per cent of ultimate strength with a rapid loading ramp of 5 min and at one third of the ultimate strength when the loading period was increased to one month. Slip plane failure may also be important in wood dried under compression [Armstrong & Kingston, 1962].

As stress levels are increased, slip planes coalesce to form kink bands. Up to 66 per cent of residual compression strain can be accounted for by kink bands. As stress is further increased, kink bands link up to form compression creases followed by extensive cell wall buckling before failure.

Slip plane intensity is a measure of accumulated damage in structural timber and is semi-nondestructive as only small samples need to be removed to determine accumulated damage. Development of standardized observation procedures may allow utilization in residual service life assessment.

When the wood is initially loaded a limited number of slip planes will occur, depending upon the stress applied and the duration of load. On initial wetting more slip planes will develop rapidly in response to inhomogeneous moisture stress, assisted by the fact that slip planes form more easily anyway at a higher moisture content.

During the drying phase deformation increases due to the increased shrinkage associated with the slip planes. Local moisture stresses may again cause further slip plane formation.

Wetting may result in a decrease in deformation, as the additional deformation associated with new slip planes is less than the longitudinal shrinkage of those already present. At higher loads, the formation of new slip planes may predominate, giving an increase in deformation.

Wetting may result in an increase in deformation, as the additional deformation associated with new slip planes is less than the longitudinal shrinkage of those already present. At higher loads, the formation of new slip planes may predominate, giving an increase in deformation.

The validity of the theory has been tested by comparison of changes in moisture-induced longitudinal swelling with microscopic observation of slip plane intensity. Because the formation of slip planes effectively superimposes a transverse shrinkage component on the longitudinal one, wood containing slip planes will have a much greater longitudinal moisture movement than slip plane-free material. Thus, in a specimen subject to bending, there will be a difference between wood on either side of the neutral axis.

However, if slip planes are the explanation of mechano-sorptive creep, problems exist with some of the common models. Complete recovery from mechano-sorptive creep implies that for any given stress a creep limit will exist. Such an idea is attractive because it carries with it two important consequences for structural engineering use of wood:

1. In defining the designed deflection of a structure under any conditions of time and humidity change.
2. In allowing material grading according to creep limit. However, to use this it would be necessary to correlate the creep limit with some other more easily measurable parameter such as elastic modulus.

Conclusions

The structural engineer expects wood to display strength and stiffness over a long period of time under varying conditions of humidity, temperature and contact with potentially aggressive chemical and biological agents. Because of the very great effect that moisture has, and because cellulose and lignin are biodegradable, prediction of property retention can be problematic. However, taking the overall balance of properties, wood fares well in comparison with metals and cement materials. Beams and columns of solid wood or laminates, and stressed skin construction using laminates represent very efficient engineering solutions to many structural problems. Wood components are usually lighter and cheaper, have a low energy content and can often be made from local materials.

Wood and the environment

By: C. Birkinshaw, University of Limerick, Ireland.

(Paper presented at *Advanced Workshop on Industrial Composites Design & Application*, October-November 1994, Trieste, Italy)

Introduction: levels of analysis

Wood is in dynamic equilibrium with its environment and in analysing any dynamic phenomenon it is necessary to define the boundaries of the system. With wood, the interactions can be analysed on the micro-scale, by defining the system in terms of isolated samples of timber exposed to environmental action, or alternatively on larger and larger scales until the relationship of wood and the wood industries with the global environment are being considered. In the first case, the prime tools are biochemistry and micromechanics, while in the second case, subjects as diverse as economics and climatology must be involved. The micro-scale can be handled with precision and objectivity, but the broader analyses bring in important but unverifiable models and value judgements.

The intention here is to look at different levels of analysis. In the first example, current knowledge about direct environmental action on timber will be reviewed, paying particular attention to fungal decay processes as these have enormous economic consequences. Options for wood protection will also be considered. In the second case, turning to a larger-scale analysis, some of the environmental factors important to the pulp and paper industry will be reviewed. The third example moves further away from direct technical considerations and looks at the application of the life cycle inventory methods to analysis of the energy content of wooden products. Finally, moving closer towards economics, current trends in tropical hardwood production are reviewed and the implications for wood composites development considered.

Environmental impact of the wood industries

Introduction

In the past ten years the environmental consequences of the wood-based industries have been the focus of increasing attention. Whilst individual industrial operations have always had the capacity to provoke local environmental concern—usually through poor management of effluent—environmentalists and politicians are now looking at the broader picture. This interest takes two forms: firstly, increased public concern at the ecological loss resulting from exploitation of natural forests; and secondly, worries within those countries that have significant economic dependence on timber, as the consequences of over-exploitation start to reduce income.

A comprehensive review of the environmental, economic and technical interactions of the wood industries is not possible here, but an examination of three diverse and important areas can be attempted as case studies typical of some of the issues to be faced. The areas addressed are pulp production, the energy content of wood components and utilization of tropical hardwood. Pulp operations are the worst ecological offender of all wood-processing operations and so are clearly an area worth attention. In materials selection processes, energy utilization is now recognized as a major decision parameter and therefore comparison of the energy requirements of wood with that of competitive materials is interesting. Rapid depletion of tropical hardwood reserves is of concern to all, and changes in forest management policy are now occurring which will have far-reaching consequences for the location of wood composite production.

Pulping

Pulping is the conversion of solid wood to a loose fibrous mass, sometimes with digestion of lignin to leave almost pure fibres. Most pulping is done for the paper and board industries, although some pulp is used as feedstock for the production of regenerated cellulose fibres. Papers and boards are composite materials in which the binder is not usually continuous; for many applications satisfactory papers can be produced which are almost entirely composed of cellulose fibres. The fibres are usually collapsed and mechanical strength comes mainly from entanglement and secondary bonding. The amount of wood used for pulp production for the paper and board industries is approximately equal to that used in lumber and other constructional products, but pulp production is potentially far more environmentally damaging than other wood processes. There are two main problems, a high energy requirement and problem wastes arising from the release of extractives and from the chemically aggressive process liquors. The increasing use of hardwoods, residues from other wood processes and whole trees may be a more efficient use of the natural resource, but it increases the potential for chemical waste production.

Whilst there are numerous individual processes, pulps can be divided into two main groups. Mechanical pulp, including thermomechanical pulp (TMP), is produced by stone grinding or refiner grinding and is effectively finely divided wood. It is used for the cheaper papers, such as newsprint. Much mechanical work must be done to separate the fibre bundles from the matrix and many energy reduction strategies have been used. For instance it has been shown that the excess steam from a TMP operation can supply the energy requirements of a newsprint mill. The major chemical environmental problem is usually disposal of effluent containing bark extractives toxic to aquatic life.

Chemical pulp, in which the cellulose lignin ratio is usually altered, is used for most other paper and board applications. It can be subdivided into three further categories.

Soda process pulp obtained by treatment of wood with caustic soda.

Sulphate or kraft process pulps in which sodium sulphate is added to the caustic liquor and reduced by the carbon present to the sulphide which is a digesting agent.

Sulphite process pulp obtained by digestion with a solution of magnesium, ammonium or calcium disulphide containing sulphur dioxide.

Residual lignin is present in all pulps and bleaching is used to reduce its optical effects. Many bleaching systems have been evaluated, but the most environmentally challenging situations are probably presented by the chlorine and caustic soda systems used with kraft pulps. The chlorine alters or removes the chromophoric lignin groups with the subsequent alkali treatment allowing removal of the residue.

Table 1 [Gullischen, 1993] compares the gross environmental demands of thermomechanical pulping and chemical pulping— in this case, a bleached softwood kraft pulp. Thermomechanical pulping requires a considerable energy input but makes much more efficient use of wood. However, with kraft pulps, if wastes can be burned, there is an energy surplus. Paper recycling is increasingly encouraged and is energetically attractive, but as some fibre degradation always occurs, the process has restricted application.

Table 1

Comparison of energy and wood demands of pulping operations

Requirement	Bleached softwood kraft pulp	TMP	De-inked recycled newsprint
Wood (ton/ton)	2.1	1.0	0
Electric energy (kWh/ton)	-300	2,200	300

Although the energy requirements of chemical pulping are low, there is no doubt that such operations present considerable environmental risks. Because of lignin heterogeneity and the range of pulping conditions, numerous reactions are possible, but the overall intention is depolymerization of the lignin. The easiest bonds to break are the a-anyl ethers and the resulting phenolics, including quinone methides, are environmentally problematic. Figure 1 is a schematic representation of an alkali pulping process with some of the environmental problem areas identified.

Work continues on the two major problems of general clean-up of process water before release and removal of organochlorines. Closed circuit water systems, ultrafiltration and multi-stage evaporation are all possible solutions, but each brings new problems. However, the organochlorine problems can be removed if non-chlorine bleaching procedures are used, but this requires market acceptance of lower brightness products. Again the advantages of recycling are obvious, but the process depends upon an extensive waste-collection facility. Additionally, as pulp types are not interchangeable use will remain restricted.

Bio-pulping and bio-bleaching, in which purified ligninases are used, are now under investigation as environmentally acceptable pulping processes. However, enzyme costs are high and present indications are that bio-bleaching may be more realistic than bio-pulping.

Figure 1

Unit cell of cellulose 1

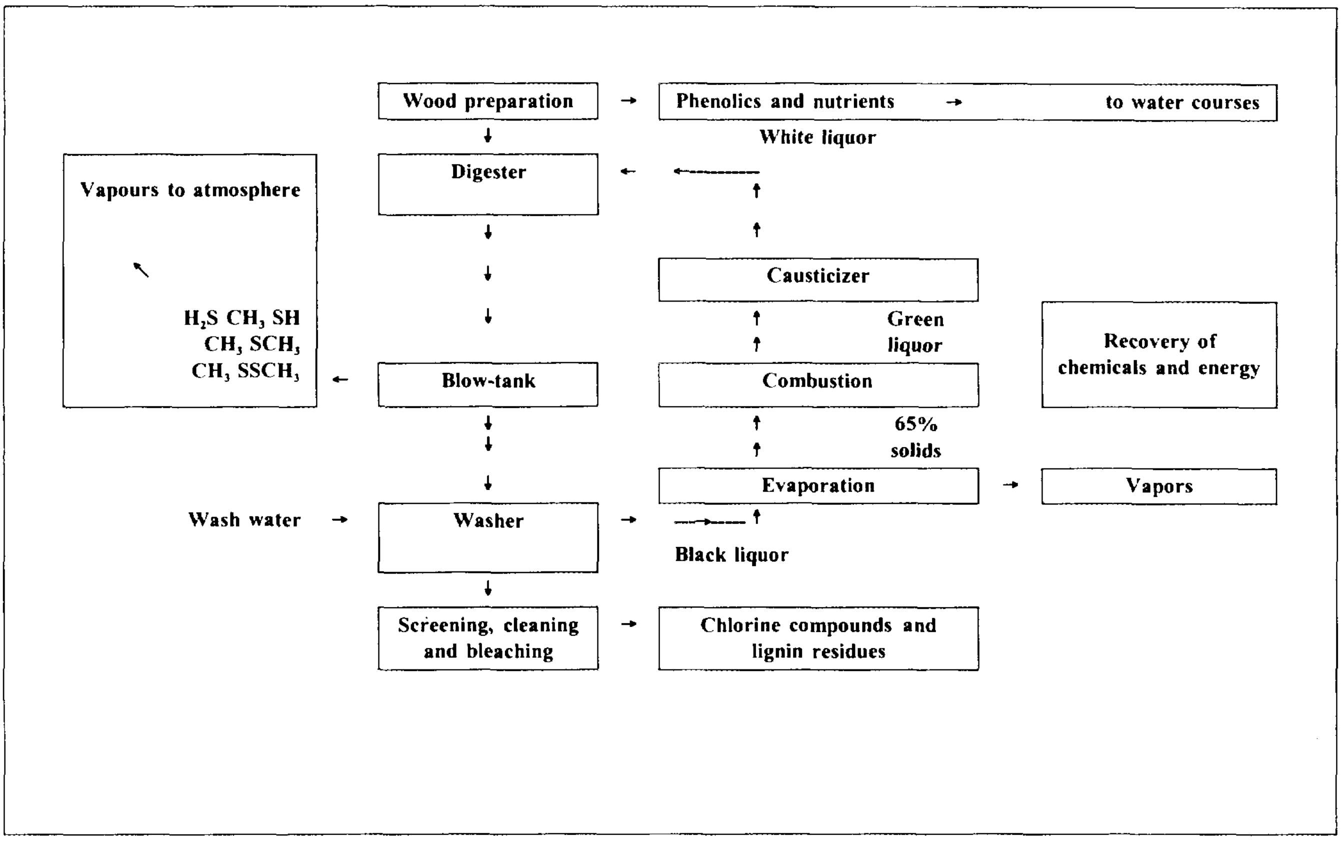
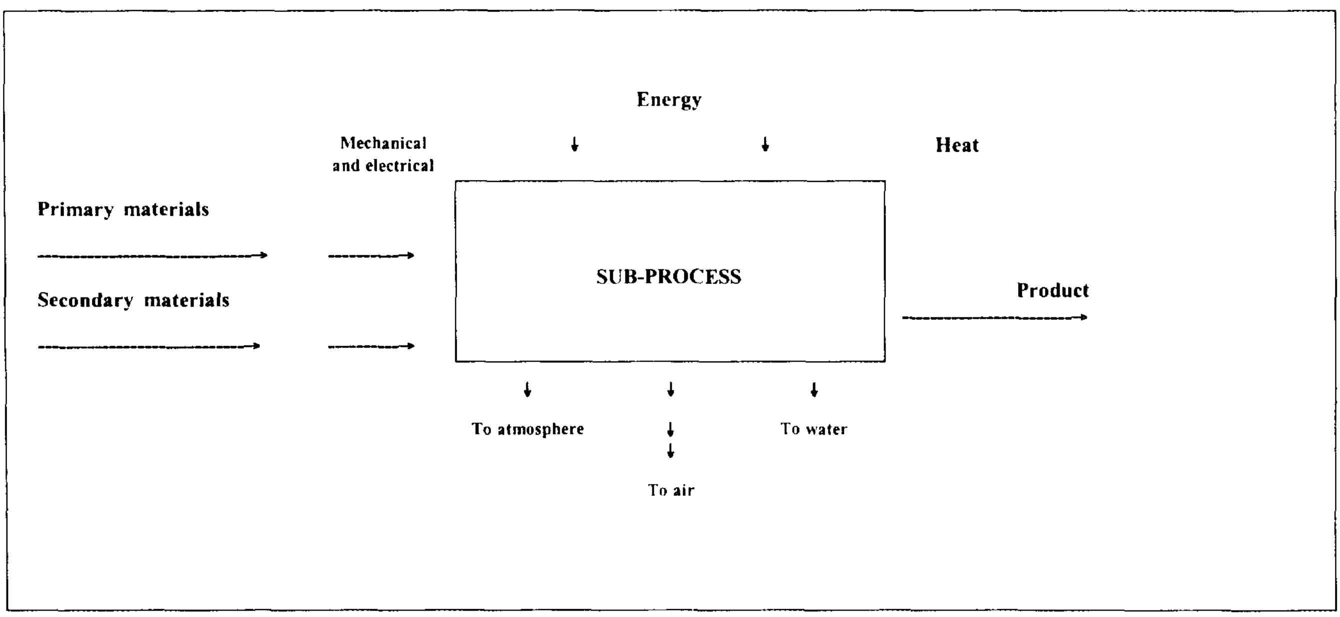


Figure 2

An analysis module used in the life cycle procedure



Energy content of wooden component

In materials selection processes, environmental concerns influence choices in both direct technical ways and indirectly through consumer perception or prejudice. Although wood utilization is often attacked on environmental grounds, it can be shown that if total energy use is adopted as the prime environmental criterion, then wood is the optimum material choice. The Finnish Technical Research Institute, VTT, in examining the energy content of floor surfaces by life cycle analysis, concluded that wood products typically consumed less than 20 per cent of the energy of some of the alternatives [Mali, 1994].

Life cycle analysis is concerned with measuring the cumulative effects that a product generates from the moment the materials and energy necessary for the product's manufacture are extracted from nature, until the last remnants of it are returned to earth. All stages that the material passes through—raw material production, product fabrication, transport, in-service, disposal and recycling— can be quantified as modular sub-processes. These are combined to show the complete balance of materials and energy consumed, and products and wastes generated.

How the various parameters are then ranked for decision-making will depend upon a range of economic, technical and social factors. The objective of the analysis may be selection of a material for a particular engineering application or a comparison of several alternative process routes to the same product.

With wood products, conversion and processing energy inputs include mechanical work in cutting, shaping and finishing, heat in drying, transport of both raw materials and finished product, and the energy content of the secondary materials such as finishes and preservatives. In general, these are small compared with alternative materials.

The previously mentioned study [Mali, 1994] of flooring materials focused on energy balance and some of the results are shown in figure 2 above. An identified deficiency which illustrates some of the problems of LCA is that although allowance is made for differences in substructures beneath the floors, no allowance is made for lifetime maintenance. This would clearly modify the detail of the outcome. However, the results do show that wood can be an energetically favourable material choice compared with alternatives.

Tropic hardwood utilization: the pattern of change

The overall patterns of hardwood production and conversion in any geographical region are subject to continual change in response to political, environmental and economic pressures, but nevertheless it is possible to identify a general increase in the importance of composites. Exploitation of tropical hardwood reserves continues to be one of the most emotive environmental issues, but examination of the data shows that producers have already recognised the benefits of a move towards more efficient usage and conversion to higher added value products.

It is possible to identify particular pressures operating within the individual economies summarized in table 2 below.

Indonesia has accessible forests and reasonable geographical proximity to the Japanese market. Hardwood accounts for 14 per cent of export earnings and the high density of commercially valuable trees producing timbers of the lighter colours has resulted in severe felling pressure in the past, but recent forest exploitation policy has acted as a stimulant to technical improvement in the production of wood-based composites. Annual fellings are now limited to $31.4 \times 10^6\ m^{-3}$. Initially, a strategy of encouraging production of higher value products increased forest depletion due to the use of inefficient machinery, but this has focused attention on production technology. Some improvements have now occurred with production of hardwood plywood up to $10.3 \times 10^6\ m^{-3}$. Continuing technical development should permit current levels of output to be maintained despite the declining log supply.

Brazil continues to be the main hardwood reserve with nearly 20 per cent of the world's tropical forest resource, but it is likely that increased timber production over the next five years will be the result of increasing softwood and composite production. Particleboard and hardboard are showing strong growth with newly operating mills.

The Philippines illustrates the consequences of past unrestrained production. A current ban on logging and other production constraints suggest that the outlook for all wood products is poor.

Thailand has also suffered from overproduction with forest area dropping from 53 per cent in 1961 to 28 per cent in 1993. Hardwood materials output is now partly dependent upon imported logs.

Korea is a complex situation. Hardwood output is falling quickly but extensive plantings of softwood took place in the 1960s and 1970s. However, the species used—red pine—is only suitable for fuel or fibre use.

Prediction of future trends is difficult but some of the more obvious pressures can be identified. Deforestation rates are of concern, but are improperly understood by most commentators.

An important consideration is the amount of new plantation wood that is going to become available. Much of this is fast growth softwood; fibre and particle products offer a means of exploitation. There is an important planning difficulty here with the maturity time of the fastest-growing trees being longer than industrial relocation time in response to economic change. Within the next 10 years several major plantings, for instance radiata pine and eucalyptus in Chile, will become available, changing emphasis away from hardwood lumber production towards fibre, pulp and composites. One of the principal engineering challenges is going to be in finding effective ways of using this lower-quality timber in products with sufficient added value to ensure continued industrial commitment. It is here that wood composites will play a central role.

The nature of wood composite production, with its requirement for a steady supply of a raw material of reasonable consistency, encourages planned forest utilization and reafforestation policies. Composite manufacture also increases local labour opportunities and multiplies the value of indigenous raw materials by large factors. Properly planned and managed production operations offer an environmental balance to check unsustainable use of raw materials.

Table 2

Output details of the main tropical hardwood producing countries for 1991, 1992 and 1993 (estimated)

[Taken from USDA FAS World Agricultural Production, November 1993]

Country	Commodity	Production (1 000m^{-3})			% change
		1991	1992	1993	1991-1993
Brazil	Tropical hardwood logs	33 000	33 200	34 800	+5
	Tropical hardwood lumber	8 000	8 600	9 100	+13
	Tropical hardwood veneer	210	220	245	+17
	Hardboard	446	460	510	+14
	Particleboard	420	505	670	+60
Philippines	Tropical hardwood logs	1 561	619	500	-68
	Tropical hardwood lumber	726	452	400	-45
	Tropical hardwood veneer	54	54	50	-8
	Tropical hardwood plywood	321	256	225	-30
Thailand	Tropical hardwood logs	232	110	100	-67
	Tropical hardwood lumber	1 238	1 343	1 400	+13
	Tropical hardwood veneer	45	42	44	-2
	Tropical hardwood plywood	395	411	427	+8
Taiwan	Tropical hardwood logs	24	15	15	-38
	Tropical hardwood lumber	806	582	548	-32
	Tropical hardwood veneer	630	620	610	-3
	Tropical hardwood plywood	530	486	450	-15
	Hardboard	446	460	510	+30
	Particleboard	90	109	110	+22
	Softwood logs	24	15	15	-38
	Softwood lumber	42	50	52	+24
Malaysia	Tropical hardwood lumber	8 924	9 300	10 260	+15
	Tropical hardwood veneer	705	1 200	1 400	+99
	Tropical hardwood plywood	1 670	2 100	2 400	+44
	Particleboard	90	109	110	+22
Indonesia	Tropical hardwood logs	27 000	26 500	26 500	-2
	Tropical hardwood lumber	8 500	8 300	8 200	-4
	Tropical hardwood veneer	50	55	60	+20
	Tropical hardwood plywood	9 600	10 100	10 300	+7
	Particleboard	320	350	380	+19
South Korea	Tropical hardwood lumber	1 158	1 142	600	-48
	Tropical hardwood plywood	1 134	948	800	-29
	Hardboard	58	48	50	-16
	Particleboard	155	276	300	+94
	Softwood logs	1 006	903	900	-16
	Softwood lumber	3 897	3 698	3 900	0

Manufacture of low matrix composites from wood and non-wood materials

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(Paper presented at *Advanced Workshop on Industrial Composites Design & Application Conference*, October-November 1994, ICS, Trieste, Italy)

Each year, 3,500 million cubic metres of wood are produced world-wide. The total annual world production of wood-based panels is currently around 125 million cubic metres, with an estimated worth of approximately $US 10,000 million. Some 31 million cubic metres of the annual production is traded internationally.

The major products are: plywood, particleboard (chipboard), fibreboards (dry and wet process), and oriented strandboard (OSB and waferboard). These all use small amounts of organic resins (e.g. urea formaldehyde, phenol formaldehyde or isocyanate resins). There is also a growing interest in inorganic matrix composites (e.g. cement bonded particleboards). Due to raw material problems and technical innovations, there is a gradual move away from plywood to particle and fibre products.

Manufacture of low matrix composites from wood are relatively simple processes: wood is machined into an engineered piece; the piece is dried and resinated; a mattress of pieces is laid and the mattress is pressed into flat panels or moulded shapes. The advantages of these composites over solid wood are: reduced variability, width of products, engineered product and the use of lower-grade raw materials.

In some areas of the world, wood is either a scarce resource or is extensively used for other purposes. In these areas alternative raw materials should be considered. It has been shown that wood can be wholly or partially replaced with agricultural residues (e.g. straw, bagasse (sugar-cane waste)) or with common indigenous materials (e.g. flax shive, jute stick, papyrus, etc.).

E. PLANT FIBRE COMPOSITES

Development of sisal fibre reinforced plastics

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Abstract

Plant fibres provide strong, low-cost, lightweight alternatives to man-made fibres. In addition, plant fibres have the advantages of having a very reactive surface chemistry and a high work fracture. The fibres are recyclable or can be designed to be combustible to allow recovery of their energy content, unlike man-made fibres such as glass fibres. Other potential advantages over man-made fibres include reduced tool wear and safer handling and working conditions. In addition to these technical advantages, there are also the significant environmental advantages of using fibres which come from a continually renewable resource and which utilize atmospheric carbon dioxide rather than carbon from mined resources.

The most common current source of industrial plant fibres is wood. Wood fibres have the advantage of being uniform, readily available and well known, but have the disadvantage of being short (mean fibre length 2.7 mm). However, this is not the only possible source of plant fibre. Tanzania has an abundant resource of sisal, coir, kapok, cotton, bamboo and straw. These fibres are readily available in large quantities and offer longer individual fibres (e.g. sisal fibre bundle, up to 1,200 mm).

These plant fibres have proved suitable for reinforcement of thermoset and thermoplastic polymeric matrices. The fibres improve both the strength and toughness of polymeric resin such as epoxy, polyester and phenolic. There exists a large range of polymeric matrix materials on the market. These are however very expensive, as they are extracted from petroleum products. It has been found that there exists in tropical countries a wide range of natural resins from plants, some of which are already being exploited commercially. These include cashew nut shell liquid (CNSL) and tanning wattle. However, the export value of these products is still very low compared with the end-uses that derive from them, most of which come back to us in the form of varnishes, paints, brake-linings and clutch facings, phenol-formaldehyde products, etc. at high prices.

In this paper, the structure and mechanical properties of sisal fibre are presented. An evaluation of their effectiveness as a reinforcement of epoxy resin is made with some emphasis on the effect of chemical modification of the fibre surface. Finally, the end-use application of sisal fibre-CNSL composites as building materials is presented. The research priority areas in the development of composite technology in developing countries are proposed.

1. Introduction

Sisal is a hard fibre extracted from the leaves of the sisal plant (*Agave sisalana*). The agavaceae are a family of monocotyledonous fibre producing plants. The genus agave is made up of about 300 species, nearly all of which are native to tropical and subtropical North and South America. By the beginning of this century, some of these species had been introduced to a large number of other tropical countries in Africa, the West Indies and the Far East. This was largely due to an expansion in demand for hard fibres in the industrialized countries of Western Europe, America and Japan.

The market value of sisal and its demand suffered damage following the introduction of synthetic fibres in the fibre markets. The synthetic fibres were being deployed in applications that had been previously dominated by the natural vegetable fibres, and were relatively cheaper, until after the 1973 oil crisis.

Many plant fibres have been successfully used as reinforcements for polyester and epoxy resins for the production of low-cost composite materials. This alternative use of plant fibres comes at a time when new end-uses of these fibres are being sought, to improve the economies and quality of life in the developing countries where they are produced. Ideally, attractively cheap and commercially useful composite materials are sought which exploit the strength and stiffness of natural cellulosic fibres as a reinforcement to polymeric materials.

Plant fibres have the following advantages over man-made synthetic fibres and certain mineral fibres:

(i) They are cheap and require less energy to produce.
(ii) It is easy to dispose of them because they are biodegradable.
(iii) They are very light, and result in composites with good specific properties.
(iv) Due to the polymeric nature of cellulose, they are compatible with most polymeric plastics.
(v) They are non-toxic, and do not cause cancer.
(vi) They possess moderate strength and stiffness to merit use as reinforcement materials to plastics.

However, these fibres have certain limitations. These include high water and moisture absorption which causes swelling and results in dimensional instability. The fibres undergo biodegradation, hence they have a limited lifespan. It has also been reported widely that they undergo degradation under the influence of ultraviolet radiation. It is well established that the mechanical and physical properties of most plant fibres are variable, and non-uniform, making the prediction and resulting properties of composites difficult.

Table 1 illustrates the properties and cost of some synthetic and plant fibres. The cost of sisal fibre is about 10 per cent that of glass fibre.

2. Structure and properties of sisal fibre

A sisal plant produces about 200 to 250 leaves before flowering, each of which contains 1,000-1,200 fibre bundles. The leaf is composed of 4 per cent fibre, 0.75 per cent cuticle, 8 per cent dry matter and 87.25 per cent water. The sisal leaf contains three types of fibres: mechanical, ribbon and xylem fibres.

Table 1. Representative properties of some fibres

Fibre	Density (kgm^3)	Tensile strength (MPa)	Tensile modulus (GPa)	Max. strain (%)	Cost (US$/kg)
Carbon	1 880	2 400	400	-	200
Stainless steel	7 850	1 200	200	8	30
Glass	2 540	1 700	70	4.8	3.25
Sisal	1 450	640	15	6.8	0.36
Jute	1 450	530	13	2.0	0.30
Coir	1 150	175	5	30	0.25

Table 2. Effect of structure and composition on the mechanical properties of some plant fibres

Fibre	Cellulose content (%)	Microfibrillar angle (Degrees)	Initial modulus (GPa)	Ultimate tensile strength (MPa)	Elongation max. (%)
Coir	43	30-49	4-6	106-175	17-47
Banana	65	10	7.7-20	54-754	10
Sisal	67	10-22	9.4-15.8	568-640	3-7
Pineapple	81	8-14	34.5-82.5	413-1627	0.8-1.6
Palmyra	40-52	29-32	4.4-6.1	180-215	7-15
Jute	63	7-9	2.5-13	533	1-2

The mechanical fibres are mostly found around the periphery of the leaf. They have a more or less thickened horseshoe shape and seldom divide during extraction processes. They are the most predominant and their fineness dictates the grading and general commercial usefulness of sisal fibre. Ribbon fibres occur in association with the conducting tissues in the median line of the leaf.

The structure of the ribbon fibre gives them considerable mechanical strength. They are also the strongest fibres and unlike mechanical fibres, they are readily split longitudinally. Xylem fibres form part of the composite fibre bundles at the median line of fibre. They are composed of thin-walled cells and are therefore easily broken up and lost during the extraction process.

Generally, the strength and stiffness of plant fibre depends on the cellulose content and the spiral angle which the bands of microfibrils in the inner secondary cell wall make with the fibre axis.

High values for the tensile strength and Young's modulus are always associated with a higher cellulose content and lower microfibrillar angle. On the other hand, high liquid contents and high microfibrillar angle lead to high strains to fracture. These trends are clearly evident in table 2, showing the mechanical properties with respect to structure of various plant fibres.

McLaughlin et al. postulated that the fibre bundle behaved like a composite material composed of a strong crystalline phase of cellulose and a tough amorphous phase constituting the matrix. It was first assumed that the microfibrillar spiral angle θ of the inner secondary wall in a particular cell is constant. The second assumption was that the cells within a particular species are identical.

If we assume the Young's moduli for the crystalline and non-crystalline phase to be 45 and 3 GPa respectively, then the predicted value of the Young modulus for the six fibres would be as shown in table 3.

Table 3. Predicted values of the Young's modulus using McLaughlin's model

Fibre	Young's Modulus (GPa)
Coir	13
Banana	29
Sisal	28.15
Pineapple	35.6
Palmyra	17
Jute	28.9

The values for most of the fibres shown are higher than the experimental values shown in table 2 above.

3. Chemical modification of the fibre surface

The external surface of sisal fibre cell is covered by a layer of waxy lignin/hemicellulosic materials with which the cell is bonded to its adjacent neighbours in the fibre bundle. When a sisal fibre bundle is polished, a loosely attached scale-like substance—the cuticle—comes off exposing the shiny, smooth and waxy surface. The presence of the cuticle and the waxy surface inhibit the formation of chemical or mechanical bonds at the fibre-matrix surface. In most cases, they prohibit direct contact of the resin to the fibre surface. Additionally, wetting or spreading of the wet resin on the fibre surface is inadequate due to high surface smoothness.

The wetting and spreading phenomena of a liquid on a solid surface can be understood by considering the equilibrium conditions at the boundary of a liquid drop in contact with a solid surface.

The work of adhesion can be increased only by increasing the surface roughness and the solid surface tension. The latter is affected by chemical modification on the surface such as to create more transactive surface molecules that would readily form chemical bonds with, or diffuse into the liquid.

The large amount of hydroxyl groups which occur throughout the structure of cellulose is largely responsible for the hydrophillic nature of most plant fibres, as water is easily attracted and held through hydrogen bonding. This, in turn, reduces the interfacial strength between fibre surface and a polymer resin where chemical or mechanical bonding would be expected. The philosophy behind surface modifications is therefore to improve compatibility and bonding characteristics by creating compatible surface energies and formation of chemical as well as mechanical bonds. The desired surface modification is that which additionally alters the water or moisture uptake and enhances rot and mildew resistance, thus resulting in imported mechanical and physical properties.

The bond strength can be improved through one or more of the following:

(a) Cleaning the surface by dissolving the fatty substances and the layer of cuticle. This additionally roughens the surface and increases the capillarity or surface tension of the fibre surface;

(b) Reacting the fibre with reagents that could make it hydrophobic, through the elimination of the hydroxyl groups on the cellulose chain while grafting a polymer group compatible with the resin matrix. These are referred to as interfacial agents.

Mercerization is one of the oldest techniques for cleaning textile fibres. The treatment consists of soaking of the fibre in a caustic soda solution, then rinsing in water before drying. The mercerization treatment improves the fibre surface's adhesive characteristics by removing natural and artificial impurities from the surface. X-ray examination of native and mercerized cotton fibre has shown that mercerization changes the form of cellulose crystallites, increasing the amount of amorphous cellulose at the expense of crystalline cellulose. The surface tension, hence wettability, of mercerized fibres is higher. This results in better bonding through a form of mechanical interlock between the matrix and the roughened fibre surface. Mercerization also results in fibre bundle fibrillation, that is, breaking down the composite fibre bundle into smaller fibres. Fibrillation in turn results in increased effective fibre surface area available for contact with the wet matrix. Interfacial complying agents are used on glass fibre in order to improve the interfacial bond with polymeric matrices in glass fibre-reinforced composites. These form stable covalent bonds with both the mineral surface and the resin. Silane coupling agents are the most common. These have been found to work quite well on sisal and other cellulose-based materials. All commercial silane coupling agents are of the general structure $X_3S_i(CH_2)_nY$, where n= 0-3, X is a hydrolysable group on silicon, and Y is an organofunctional group, selected for compatibility with a given resin. The hydrolysable groups are essential for generating intermediate silanols.

4. Experimental work

4.1 Chemical modification of sisal fibres

High-grade sisal fibres were supplied by the Tanzania Sisal Authority (TSA). The fibres were subjected to the following treatments:

(i) **Dewaxing:** Fibres were soaked for 24 hours in a solution of benzene and methylated spirit 1:1 in a sealed glass vessel. They were then rinsed in distilled water and then dried in an oven at 100° C.

(ii) **Mercerization:** Dewaxed samples were mercerized by soaking them in a 1.0M solution of sodium hydroxide for about 72 hours, rinsed in distilled water and then dried as above.

(iii) **Silane treatment:** An organofunctional silane—A 1100—was supplied by Union Carbide (UK) Ltd. Some mercerized sisal fibres were treated in a 100 per cent silane solution for one hour, while others were treated for 24 hours in a 5 per cent solution of silane in methanol.

A 0.1M solution of ceric ammonium nitrate (CAN) was used as a catalyst and all reactions were carried out at room temperature—20° C—and atmospheric pressure.

4.2 Evaluation of moisture resistance

Fibre samples in the original "as received", dewaxed, mercerized and silane-treated (100 per cent) conditions were used. Fibre samples of about 1 g were obtained from each group of treated fibres. They were first dried in a vacuum chamber, then weighed using a sensitive electronic balance (±0.0001 g), then exposed to moisture in a controlled humidity chamber at 65 per cent RH-20° C. Weight changes were monitored after short intervals.

4.3 Moulding of composites

Unidirectional composites were produced from an epoxy resin system—Araldite LY 1927GB—supplied by Ciba Geigy Plastics, using two compression moulds meant for rectangular section and round section unidirectional composites. The composites were allowed to gel at room temperature for about 24 hours while under pressure. The composites were then extracted from the moulds and cured at 60° C for two hours, at 80° C for another two hours, and then at 100° C overnight as specified by the resin manufacturer. Unidirectional composites were manufactured using fibres in the "as received", mercerized and silane-treated conditions.

4.4 Mechanical testing

4.4.1 Compression tests

The tests were carried out on dry and wet composites according to BS2782 Part 3: Method 345A: 1979. The specimens were in the form of right cylinders 12 mm in diameter and 18 mm in height. An Instron 1122 machine was used and all tests were performed at a cross-head speed of 1 mm/min. The wet composites had been soaked in distilled water for five days.

4.4.2 Flexural tests

Three-point loading bend tests were performed on wet and dry composites in accordance with ANSI/ASTM D 790-71 (1978) on an Instron 1122 machine. Test specimens, 125 mm long, 12.7 mm wide and about 5 mm thick were used at a loading span of 80 mm.

Table 4. Mean mechanical and physical properties of sisal-expoy composites of 40 per cent fibre volume fraction

Material/treatment	Compressive strength (MPa)	Flexural strength (MPa)	Flexural modulus (GPa)	Water absorbed (0%) after 72 hours soaking	Density
Epoxy resin (unreinforced)	120.0	95.0	3.1	-	1.17
Untreated dry composite	148.0	266.5	15.93	-	1.14
Mercerized dry composite	183.1	262.1	17.63	-	1.24
Silane dry composite	184.8	244.5	17.36	-	1.25
Untreated wet composite	62.53	221.7	9.15	15.6	-
Mercerized wet composite	75.83	200.7	10.12	9.0	-
Silane wet composite	98.53	237.2	12.33	5.0	-

5. Experimental results and discussion

The moisture gain as a percentage of sample dry weight was plotted against time, for the samples tested in section 4.2. Silane treated fibres have the best moisture resistance.

The effect of fibre treatment on the comprehensive strength showed that untreated composites produce composites with significantly less strength than treated fibres, but in each case a consistent variation with fibre volume fraction is observed.

The mean compressive strength, flexural strength and flexural modulus have been evaluated for composites containing 40 per cent fibre volume, and these are shown in table 4. These data show that sisal fibre generally improves the overall mechanical properties in composites. Regarding strength and stiffness see table 4.

Mercerization is observed to improve the mechanical properties of the composite. This is thought to be due to improved mechanical and chemical bonding, following the removal of the waxy surface, leaving behind a rougher surface that leads to the improvement of wettability as predicted by the Wenzel's equation.

The flexural properties of wet silane treated sisal-epoxy composites are superior to those not treated in silane. It was observed that chemical modification of sisal fibres using the silane coupling agent gave significant improvements to the composite properties under wet conditions. Also, the compressive strength of wet composite was increased by a further 30 per cent. As expected, the flexural properties (strength and modulus) increased linearly with fibre volume fraction almost in accordance with the rule of mixtures. These results affirmed the useful advantage of fibre chemical modification in terms of resistance to moisture and water absorption and improved mechanical properties of the composite. Further work is however required to establish cheaper chemical modification reagents because silanes are very expensive.

6. Development of sisal-CNSL composites for roofing applications

There is an ever-increasing demand for roofing materials in developing countries due to the rise in population and the desire to improve the existing housing conditions. Traditional materials such as grass, coconut and palm leaves still account for more than 90 per cent of the materials used for roofing in rural tropical Africa. Given the prevailing tropical environment of high rainfall and humidity, and the high incidence of pests, insects and micro-organisms that feed on cellulosic materials, the life span of such roofing materials is limited to just a few years.

In modern times, materials such as corrugated iron and aluminium, and ceramic tiles have been widely adopted to replace the traditional thatch. However, these new materials are still quite expensive for the majority of the rural population. A recent innovation is the introduction of natural fibre reinforced cement tiles, reinforced by asbestos and/or sisal fibre. Despite the widely acknowledged carcinogenic effects of asbestos fibre, in developing countries like Tanzania, a small amount of asbestos-cement corrugated and plain sheets are still being manufactured and sold locally. The total replacement of asbestos by sisal and other plant fibres is seen as the best option, and sisal-cement tiles are now being produced on a small scale in Tanzania. However, these materials are usually heavy and fragile, and therefore not suited to the rudimentary forms of transportation and materials handling obtainable in rural areas of Africa and most other developing countries. These materials sometimes require advanced skills of workmanship in roof construction, which is not readily available in rural areas. Hence, they are still not well accepted and metal sheets are still the rural people's choice.

The use of vegetable fibre-reinforced plastics offers a solution to the technology and handling problems restricting the use of ceramic materials for roofing. It has been demonstrated that plant fibres and polymeric resins can be combined to produce engineering materials with moderate properties. The existing industrial polymers available on the market—such as epoxy, polyester and phenolics, are however too expensive to merit such low technology applications. However, there exists, in some tropical countries, natural polymers from plants which can be easily harnessed to serve as binder matrices for plant fibres in making useful engineering composites. Cashew nut shell liquid (CNSL), is one such plant-based natural polymer.

CNSL is a blend of naturally occurring phenol-based monomers, which is extracted from the shell of a cashew nut. Additionally, CNSL is known to give adequate protection against dry wood termites and other pests and is therefore an outstanding preservative. Laboratory tests on sisal-CNSL corrugated composites have shown that the composite possesses adequate strength and rigidity to merit application as a roofing material. They are light, easy to cut, and may be joined in the same manner as other wood products. They are also tough and therefore can be transported without the any risk of breaking. It has also been reported that the material is almost 50 per cent cheaper than the corrugated iron sheets. The future of composite materials technology transfer to developing countries therefore depends on these countries' ability to utilize existing indigenous materials in developing useful engineering composites, as demonstrated by this potential use of sisal-CNSL composites for roofing applications.

7. Potential areas for further research

In most tropical developing countries, there exists a wide variety of plant fibres which have not been exploited. These include pineapple leaf fibre, banana fibre, kapok or silk cotton and coir. There is a need to explore methods to harness these fibres into modules suitable for polymer reinforcement. There are also other potential natural polymers from plants that are available, and which could be further developed to yield useful binding matrices for the plant fibres. Development of geo-textiles from plant fibres for soil conservation in both urban and rural areas is another potential area for research. National and international research institutions need to make collaborative efforts in addressing these potential areas of research, which provide the developing countries with the opportunity to reap direct economic benefits from their natural resources.

8. Conclusions

The following conclusions can be made from this work:

- Sisal fibres can be chemically modified using organofunctional silanes to produce composites with improved mechanical properties and resistance to moisture.
- The mechanical properties of unidirectional sisal-epoxy composites are directly proportional to the sisal fibre volume fraction.
- The transfer of composite technology to less developed countries can be achieved through use of available fibre and resin resources.

From this presentation, it can be generally concluded that sisal fibres and many other plant fibres may be employed as reinforcement to plastic materials to yield composite materials with useful engineering applications. The utilization of natural instead of synthetic polymers as matrix materials in such composites will make possible the transfer of composite technology to tropical developing countries.

Development of friction dust and brake linings from cashew nut shell liquid (CNSL) sisal composites

By N. Tibanyenda
Department of Chemistry
University of Dar es Salaam, Tanzania
(Paper presented at: *Workshop on Industrial Composites Design and Applications*, October-November 1994, International Centre for Science and High Technology, Trieste, Italy)

As prices of derivatives from oil are increasing steeply, it is high time that use of natural raw materials is also made in the production of finished goods. Cashew nut shell liquid (CNSL) is one such natural raw material, which is a by-product derived from raw cashew when the cashew is processed to obtain cashew kernels, the main product.

The active constituent of CNSL is a meta-substituted phenol with a long hydrocarbon side chain which, on account of its unique molecular structure, imparts to CNSL many useful properties leading to its manifold uses in the manufacture of resins, varnishes, clutch facings and brake lining compositions.

A modified process has been developed to process frictional material, either from CNSL directly, or from residue obtained while refining CNSL to manufacture cardanol. The friction dusts are characterized by a toughness and flexibility not usually associated with common phenolaldehyde resins. They possess, in addition, good stability at elevated temperature and very good solvent chemical resistance. The modified process for the production of CNSL-sisal-based frictional materials solves the pollution problems for asbestos-based materials, formalin and other toxic vapours evolved from the reactants are condensed.

A comparison of plant fibre properties

By David Robson and Jamie Hague
The BioComposites Centre
University of Wales
Bangor, Gywnedd
(Paper presented at: *Workshop on Industrial Composites Design and Applications*, October-November 1994, International Centre for Science and High Technology, Trieste, Italy)

In order to understand the properties and behaviour of plant fibres and behaviour of plant fibres and derived chemicals, it is necessary to describe their fine structure (ultrastructure). Most published work on plant fibre ultrastructure is on wood fibres and cotton because of their commercial significance. This brief review of plant fibre structure describes wood fibre structure. Very little work has been done on the comparative ultrastructure of different plant fibres.

Nature has spent several million years perfecting plant molecular structure. Each cell and each plant part can be considered as a composite material at a molecular level, at a cell wall level and at a cell level. This composite structure gives some plant fibres and plant fibre bundles excellent strength and stiffness. For example, on a weight-for-weight basis, flax fibres are as strong as and stiffer than glass fibres.

A comparison of fibre physical and chemical properties of plant fibres shows that non-wood plant fibres (cells) can be 30 times longer than wood fibres, twice as strong as wood fibres and three times as stiff as wood fibres. The physical properties of plant fibres are not usually reflected in their price.

Entrepreneurs harness the strength of straw

The Alternative Agricultural Research & Commercialization (AARC) Center, an independent agency of the US Department of Agriculture, is dedicated to commercializing industrial (non-food, non-feed) uses of agricultural materials. Based in Washington, D.C., the centre provides financing on a partnership, payback basis to private firms to bring new, environmentally friendly products made from renewable resources to the marketplace.

Several centre projects focus on alternatives to conventional structural materials, as follows:

Sign posts: Xymax Inc., Mankato, KS, will manufacture a composite material—called Bondomass—made by extruding wheat straw with post-consumer plastics. The composite will first be used to make posts for highway signs. Future uses are said to include railroad ties, fence posts, decks, docks and window and door frames.

Bondomass is reportedly cheaper than lumber, will not warp or split like wood, and does not need to be painted.

Houses: A stress-skin panel building system—incorporating straw—for single-family, multi-family, and commercial construction will be made and marketed by Agriboard Industries, Fairfield, IA.

The compressed core of the panels is extruded entirely from residual wheat straw. On each side of the core is a skin made of oriented strand board.

Particleboard: Wheat straw and a non-toxic binder will be used by PrimeBoard Inc., Wahpeton, ND, to produce a high-quality substrate for the panel industry.

The product costs less to produce than traditional particleboard, is stronger (fibres are cross-linked), and is water resistant. It competes with conventional panels that use a toxic, urea formaldehyde binder. One side of the board will be laminated to finish the product.

Details: For more information about these and other programmes, contact AARC Center, US Department of Agriculture, 0156 South Building, 14th & Independence Ave. SW, Washington, DC 20250-0400; Fax: (202) 690-1655. (Source: *Advanced Materials & Processes*, March 1996)

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Judging from the feedback we occasionally receive from our readers, it seems as though the work we try and do is appreciated. A BIG thank you to all those who returned our questionnaire. We enjoy what we do, hearing from readers throughout the world is great! What we'd like to do now, is take it a bit further.

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- Looking for a particular technology or want to invest somewhere in something specific? Contact us for our "Yellow Pages"! PLUS - we pass it on to our worldwide network of Investment Promotion Service Offices, AND it is considered for inclusion on the UNIDO Internet Home Page under 'Business Opportunities'. (***http://www.unido.org*** - check it out!);
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UNIDO welcomes any comments, requests, offers, suggestions and the like. We are a service organization - here to *promote sustainable industrial development through harnessing the forces of government and the private sector to foster competitive industrial production, develop international industrial partnerships and promote socially equitable and environmentally sustainable industrialization.*

Send your correspondence to: *Ms. J. Roetzer-Sweetland, UNIDO, Industrial Information Section, Vienna International Centre, P.O.Box 300, A-1400 Vienna, Austria. Fax: +43 1 21131 6843. E-mail: jroetzer-sweetland@unido.org*

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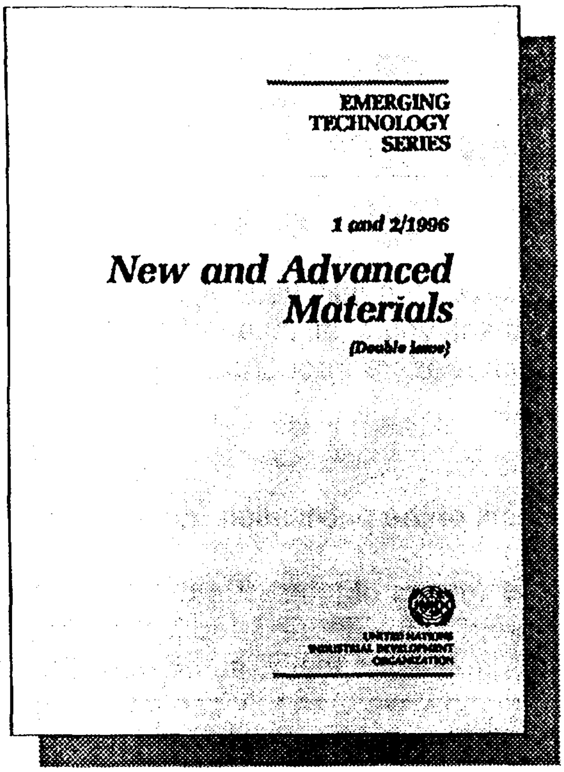

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TECHNOLOGY AND INVESTMENT OPPORTUNITIES

TECHNOLOGY OFFERS

Decorticator for Natural Fibres

A decorticator has been developed for on-farm use to extract fibre from plants, particularly from linseed straw, a waste product from oilseed production which has useful properties for industrial textiles. Potential applications include mats to control soil erosion, pollution absorption, sound insulation and as a filter for paper or composites.

CONTACT: Mr. H. Gilbertson, Manager, Natural Fibres Organization, Wrest Park, Silsoe, Bedford, MK45 4HS, United Kingdom FAX: (+44) 1525 862 095

Non- Metallic Heating Element

A company has developed a new technology for the encapsulation of a non-metallic heating element into a thermosetting plastic. The patented storage heater comprises six heated plates wired in parallel, which are located in a casing with a fan to draw in cold air. An adjustable vent controls the air flow at the heater exit.

The company offers the technology under licensing agreements.

CONTACT: Mr. D. Badami, NIMTECH, Alexandra House, Borough Road, St. Helens WA10 3TN, United Kingdom. FAX:(+44) 1744 453 377. Email:helpdesk@nimtech.u-net.com Quote Ref. TO161

Cement Bonded Chipboard Production

Company offers both technology and equipment for cement bonded chipboard production line. Capacity ranges from 600.000 to 1.000.000m^2 per annum. Raw materials available: Chips from spruce or fir trees; Portland cement; water of standard technical quality; water glass; separating oil. If laboratory and pilot plant experiments are positive, another wood species and plant can be used. The chipboards are used in the production of internal and circumferencial walls. The concrete mixture is poured into a double wall cover that consists of two individual boards connected with steel clips. The chipboards can also be used for the production of ceiling and wall panels, as well as insulating floor fillings.

Preliminary budget estimate of total project cost is US$3 million.

Company offers equipment, licensing agreements and turn-key operations.

CONTACT:Slovak Chamber of Commerce & Industry, Regional Chamber Trencin, Dolny Sianec 1, 91101 Trencin, Slovakia. FAX: (+42) 831 521 023. Quote Ref.:9.1

Plastic Processing

Know-how, design, engineering and complete production lines for extrusion and blow moulding available. Also, equipment for shredding, grinding, milling and agglomerating plastic waste as well as controlling facilities. Products include 1- or multi-layer films, bottles and containers having up to 30 litres capacity.

CONTACT: Metalchem Torun, c/o UNIDO IPS Warsaw, Ms. D. Pokrzywnicka, POBox 1, Warsaw 12, Poland. FAX:(+48) 391 21 772

Cold Hardening Adhesive

Russian company offers technology for a cold hardening adhesive which can be used for bonding together metals and non-metallic metals; for manufacturing composite joints (adhesive and riveted, adhesive and threaded). Technology is suitable for operating in temperature range of -60^C to +80^C over an extended period. The adhesive has a proven high water resistance of adhesive joints under tropical conditions. If adhesive and riveted joints are used, the adhesive can improve their strength and local carrying capacity.

CONTACT: InterTec, Brahmsplatz 8/3, A-1040 Vienna, Austria. FAX:(+43) 1 504 40 94. Email:info@intertec.co.at

TECHNOLOGY REQUESTS

Machines
Manufacturer of ball valves, rotational tableting machines and production lines for plastic tubes and foils seeks a joint venture partner offering modern constructional solutions and technology, licenses and market access.
CONTACT: Metalchem Annopol, c/o UNIDO IPS Warsaw, Ms. D. Pokrzywnicka, POBox 1, Warsaw 12, Poland. FAX:(+28) 3912 1772

Zinc Alloy Balls
Swedish company wishes to obtain technology to produce zinc alloy balls with a diameter of 2-4 mm. They anticipate producing tens of millions per annum.
CONTACT: Mr. D. Badami, NIMTECH, Alexandra House, Borough Road, St. Helens WA10 3TN, United Kingdom. FAX:(+44) 1744 453 377. Email: helpdesk@nimtech.u-net.com Quote Ref. TR16

Soap Manufacture
Modern soap manufacturing technology and equipment is required for the production of laundry and toilet soaps from locally available and imported raw materials such as: tallow, palm oil, caustic soda and pigments. Estimated project cost: US$800,000. Preferred Mode of Cooperation: Joint venture, equipment supply and finance.
CONTACT: Mr. Masunoor, Managing Director, Masunoor Enterprises Ltd., POBox 8, Dodoma, Tanzania. FAX:(+255) 61 24201

Coconut Products
Technology is required for the production of various products, such as desiccated coconut, coir mats and coconut water, utilizing every part of the coconut tree. It is anticipated that the product will meets the needs of a strong export market (80%). Technology requirement: Product/process know-how, packaging and equipment.
Preferred Mode of Cooperation: Joint venture, equipment supply and technical services.
CONTACT: Ms. K. Mandalia, Managing Director, East African Mercantile Corp. Ltd., POBox 914, Dar-Es-Salaam, Tanzania. FAX:(+255) 51 26911.

Finishing Operations for Agglomerate Materials and Materials Based on Natural Wood
Technology and equipment are required for the production of: (1) precisely cut sizes and contour milling of edges (round, key and groove), preliminary capacity is 500,000m^2 per annum in two shifts; (2) surface finish (bonding and varnishing with active substances for UV hardening), preliminary capacity is 300,000m^2 per annum in two shifts; and (3) wrapping into contracting foil. A production line solution is not possible and needs to be an independent workplace in one location.
CONTACT: Slovak Chamber of Commerce & Industry, Regional Chamber Trencin, Dolny Sianec 1, 91101 Trencin, Slovakia. FAX:(+42) 831 521 023. Quote Ref.3.8

Upgrading Wood Working Machinery
A private company manufacturing wooden components for engineering applications, including furniture, trusses, doors and windows for construction projects requires modern high precision equipment to supplement or replace present equipment. They seek to computerize production and to identify processes for recycling sawdust. Raw materials are available locally. Know-how, patents, design, maintenance, packaging, equipment, quality control and environmental advice are sought under a joint venture.
CONTACT: Managing Director, Classy Green Enterprises, POBox 35020, Dar-Es-Salaam, Tanzania. FAX: (+255) 51 43085.

ESTABLISHMENT OF THE INTERNATIONAL MATERIALS ASSESSMENT AND APPLICATION CENTRE (IMAAC)

The establishment of the International Materials Assessment and Application Centre (IMAAC) is part of an extensive programme of the Investment & Technology Promotion Division of UNIDO aimed at establishing and networking international technology centres in the field of new technologies.

It is acknowledged world-wide that materials technology is a key which enables technology for a wide range of industrial sectors and can have a major impact on the economic and industrial competitiveness of a country. The further development and support of new materials are so important precisely because very sizable impetus and spill-over effects on virtually all sectors of the processing industry can result from them

The problem confronting industrialization and economic development strategies in the late 1990s and beyond, will be how developing countries can absorb and utilize the new scientific and engineering insights and practice so as to upgrade their traditional and existing materials capabilities to meet higher specifications and quality requirements in users national, regional and global markets.

The speed of technological change, the enormous complexity and multi-disciplinary, trans-sectoral aspects of materials science and engineering clearly highlight that not only are we living in an "information age", but are entering a "materials science age", upon which information technologies, including telecommunications, micro-electronics and biotechnology find themselves heavily dependent.

In this context, the IMAAC is expected to raise the level of understanding throughout the materials related industry of the importance of materials transition and help developing countries mobilize the necessary resources for sustainable development and competitiveness. The Centre will provide an international forum for managing specific techno-economic aspects of materials science and engineering in an integrated, multi-disciplinary and trans-sectoral manner.

UNIDO is starting the implementation of the pilot activities of the IMMAC project which is aimed at laying down the basis for its full operation and functioning. The Republic of Brazil, under a Trust Fund Agreement with UNIDO, has provided IMAAC with its initial funding and will host the Centre in Rio de Janeiro.

For more information, contact: Managing Director, Investment & Technology Promotion Division, UNIDO, P.O.Box 300, A-1400 Vienna, Austria. FAX: (+43 1) 21131 6809.

UNIDO AND NIMTECH (UK)

LAUNCH INVESTMENT PARTNERSHIP SCHEME

Following the signing of an agreement to provide support for British firms, a window of opportunity for British investment and technology has been opened.

At the official launch, NIMTECH's Chief Executive Officer said that the two-year project would "give UK firms a head start, enabling them to capitalize on new overseas business opportunities generated by UNIDO technical cooperation projects, which amounted to more than US$100 million in 1996."

UNIDO's representative said that the project represented a major step towards helping private firms in developing countries meet new business partners in the United Kingdom.

The project builds on the success of an initial 12-month cooperative arrangement between UNIDO and NIMTECH, begun last year to promote British partnership in investment and technology in developing countries and economies in transition. It aims to sharpen the focus of commercialization of new and emerging technology for which viable markets - estimated to be worth more than US$1,000 million - have been identified. Emphasis so far has been on cleaner production techniques, biotechnology and nanotechnology.

UNIDO is the specialist United Nations agency that promotes sustainable industrial development in countries with developing and transition economies. It harnesses the forces of government and the private sector to foster competitive industrial production, develop international industrial partnerships and promote socially equitable and environmentally sustainable industrialization.

For further information, please contact: Stuart Heaman-Dunn, Investment and Technology Promotion Division, UNIDO, P.O.Box 300, A-1400 Vienna, Austria, (Fax: +43 1 21131 6809; E-mail: sheaman-dunn@unido.org), or Paul Richardson, NIMTECH, Alexandra House, Borough Road, St. Helens, WA10 3TN, United Kingdom, (Fax: +44 1744 453 377; E-mail: helpdesk@nimtech.co.uk).

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Light Engineering

Textiles

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