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15371

Distr.
LIMITED

UNIDO/IS.600
17 January 1986

ENGLISH

UNITED NATIONS
INDUSTRIAL DEVELOPMENT ORGANIZATION

POTENTIAL APPLICATIONS OF COMPOSITE MATERIALS AND ASSOCIATED TECHNOLOGY IN DEVELOPING COUNTRIES*

by

E. Anderson**
B. Lux***

353

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V.86-50580

CONTENTS

Summary

The current status of composite material technology is reviewed in detail and the main characteristics of the composite materials described as well as the areas of their application. Among these areas the following subjects are discussed: advanced composite materials in energy production and energy storage; plastics in construction, different kinds of pipes, tanks and reservoirs, natural fibre composites. Discussion of each of these subjects includes aspects such as the state of development, raw materials used, design, manpower and energy requirements.

As a general conclusion the study states that composite material industry could be effectively introduced in developing countries, subject to the fulfillment of certain conditions, which are discussed in detail. Of all the composite materials the most suitable ones for introduction in developing countries are glass-fibre-reinforced polyester and natural fibre composites.

Preface

It is useful to study composite materials and the associated technology in the context of their potential application in developing countries for the following reasons:

- The materials and structures are artificially constructed from a wide variety of basic elements, so that suitable combinations (from the points of view of fabrication and use) for any given country and situation will surely be found;

- Energy savings may be achieved by choice of suitable materials and fabrication techniques;

- Many composite structure fabrication processes are labour-intensive, thus favouring their implantation in developing countries;

- Composite materials could be developed in the developing countries based on native resources: natural fibres such as coconut, bagasse, jute, cellulose and minerals such as asbestos, mica and silica;

- New industries could be set up to produce some of the raw materials: steel wire, cement, glass etc.;

- Composite materials already have a history of use in developing countries: wood, straw-reinforced building bricks, bamboo-structures, reinforced concrete, asbestos cement etc.;

- The technology and design procedures developed for glass fibre-reinforced plastics and advanced aerospace composites can be adapted to the optimization of materials and structures of prime interest in developing countries for key sectors, such as housing, water and sewage, transport and energy production;

Wood is the most wide-spread natural composite material: knowledge from synthetic composite design and utilization can be transferred to wood;

- Composites based on plastic matrices are generally corrosion-resistant and thereby maintenance-free--a big advantage in developing countries. Thus, even materials that are expensive to purchase could become advantageous on a life-cycle cost basis;

- In many cases, structures made of composite materials can be fabricated on site, thereby removing reliance of imports and eliminating transport costs. Examples are houses of fibre-reinforced cement or concrete and pipelines.

CHAPTER I. COMPOSITE MATERIAL TECHNOLOGY

A. Composite Materials

1. Definition of a composite material

A composite material is defined as a composition of two or more materials that provides an end-product with properties not available from one of the constituents in isolation. Such a definition is sweeping and covers many classes of materials such as:

1. Fibre-reinforced plastics
2. Fibre-reinforced inorganic materials
3. Fibre-reinforced metals
4. Pre-stressed concrete
5. Coated metals and plastics
6. Cermets

Within the context of defining materials for developing countries, composites of classes 1 and 2 will be treated in this paper since they represent the greatest potential interest from the points of view of their:

- Fabrication potential;
- Application potential;
- Production potential from indigenous raw materials;
- Potential to profit to the maximum from progress made in high-technology sectors.

2. Basic theory of reinforcement

Fibre-reinforced plastics and inorganic materials are of many types and compositions, which will be dealt with in section B of this chapter. The mechanism of reinforcement by fibres is different in the case of polymers and inorganic materials (i.e. cement in the context of this paper).

a. Polymeric matrix

The basic reinforcement equation for the polymeric matrix reinforced unidirectionally by fibres is the rule of mixtures: $E_C = E_F V_F + E_M V_M$.

In this equation, E_C is the resulting elastic modulus of the composite; E_F is the modulus of the fibre; E_M is the modulus of the matrix at the rupture of the fibre; and V_F and V_M are the volume fractions of the fibre and matrix, respectively.

The reinforcement results from the sharing of the load placed on the composite by the matrix and the fibre. The fibre is chosen in order to have a higher elastic modulus than the matrix (typically 10 to 100 times) and is effectively bonded to it such that, upon loading, the strains in both elements are equal, resulting in the fibre carrying the major share of the load. If the interfacial (shear) strength between the matrix and fibre is low, then the load-transfer from the matrix to the fibre is inefficient and the resulting strengths are very low. For each fibre-matrix combination there is an optimum interface, and much work is carried out on treatment of the fibres in order to obtain the best fabrication and property performance.

The same basic rule-of-mixtures equation holds more or less for the unidirectional properties of strength, thermal expansion, long-term strength etc. The properties in the direction transverse to the fibres are low. Only in very few cases, however, are the unidirectional (i.e. anisotropic) properties of the fibre-matrix combination useful. In order to be applied in real stress situations, the composite materials must be produced with properties that are either isotropic or engineered to satisfy the imposed stress conditions. As given in figure 1, the solutions available are:

- Multilayer laminates made of a stack of unidirectional laminae or fabrics bonded together and correctly oriented to provide isotropic properties.
- Randomly oriented fibres in the matrix.

In both cases, the characteristics of the material are lower than those of a purely unidirectional lamina, but may nevertheless be tailored to satisfy a multitude of stress situations. An example is given in figure 2.

Figure 1.

Effect of glass content and orientation on
the tensile strength of glass fibre-reinforced
plastics (GRP) laminates

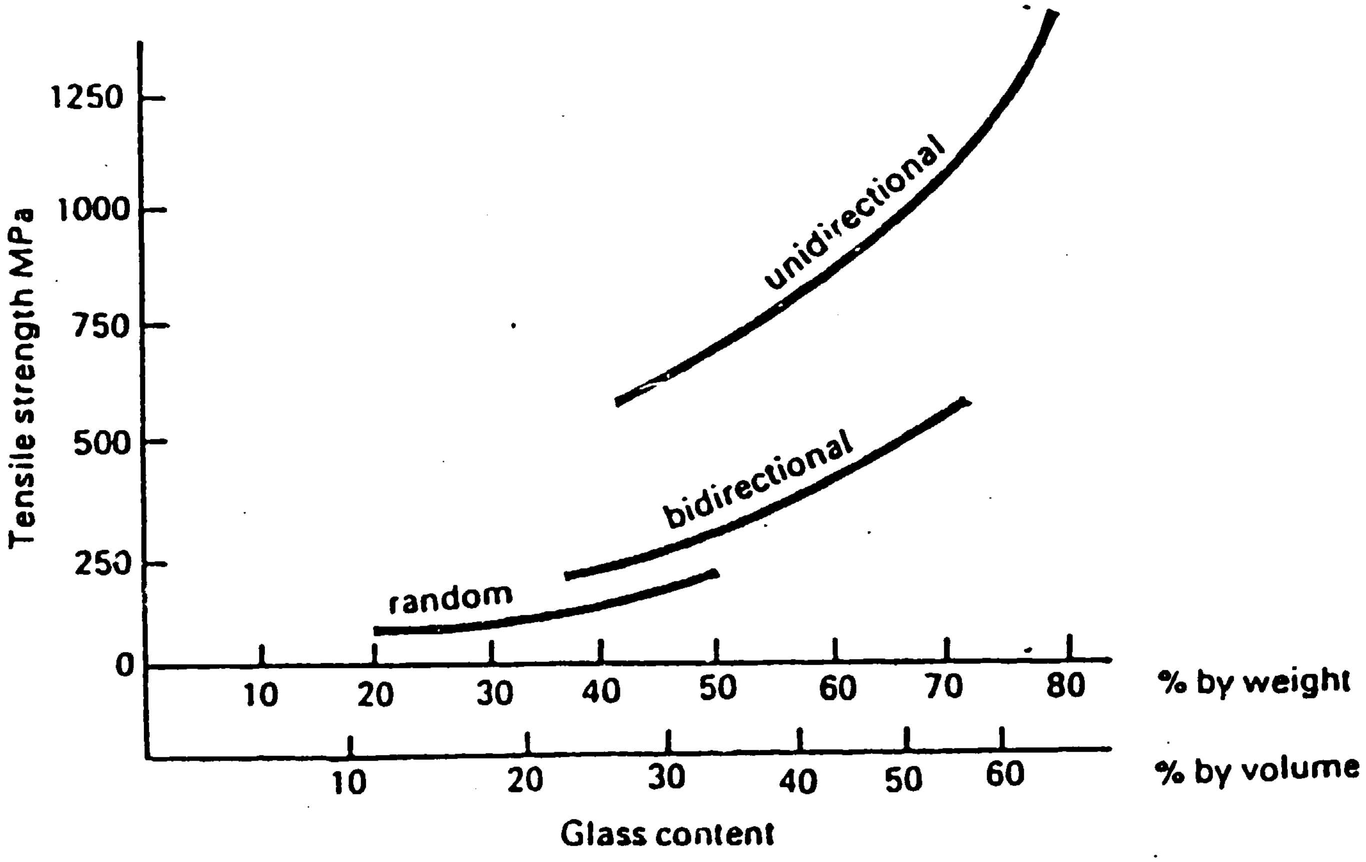
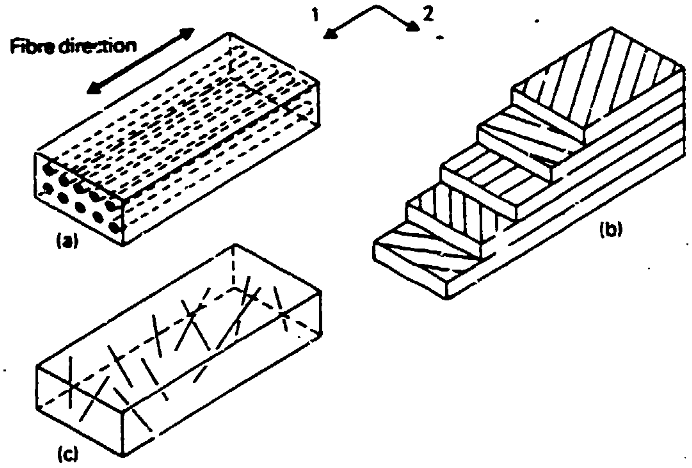


Figure 2.

Schematic representation of (a) unidirectional lamina,
(b) multilayer laminae and (c) randomly oriented short-fibre material



b. Inorganic matrix

The term inorganic covers cement, concrete, refractories and ceramics. In the context of the present paper, only the first two will be treated because of their potential interest.

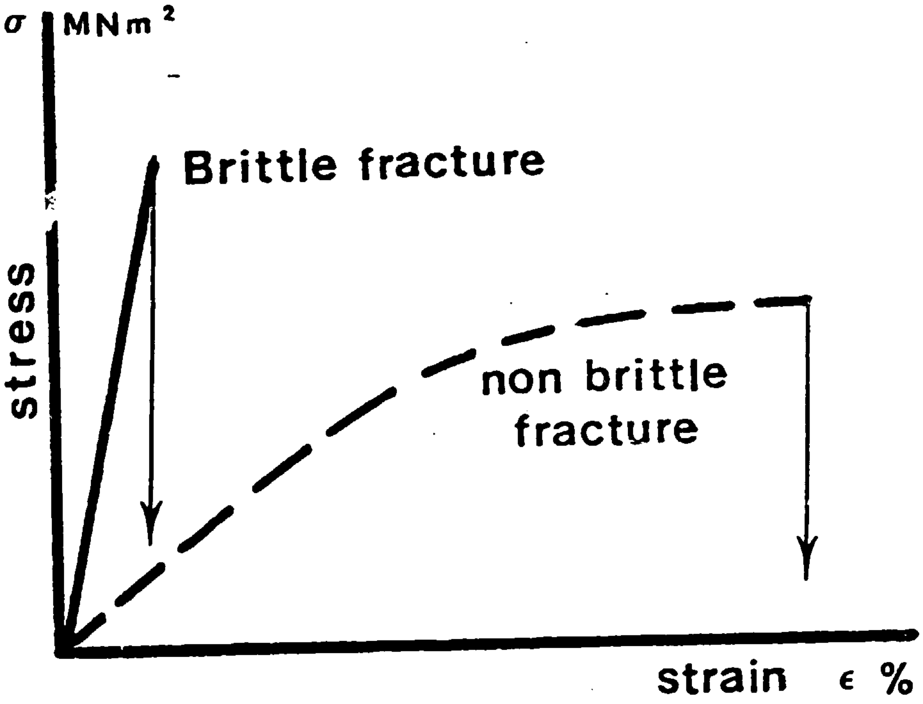
Reinforcement of such a matrix is effected by a ductilizing mechanism, as illustrated in figure 3. Cement and concrete are very weak in tension and already the stresses induced during drying and setting lead to cracking. The introduction of steel bars (pre-stressed or as reinforcement is a widely used macroscopic composite approach to reinforcement. The addition of a small amount (a few per cent) of short-length fibres (steel wires, asbestos, plastic, jute etc.) produces a similar reinforcing effect by:

- Preventing crack growth during drying;
- Limiting crack size at the setting stage and during utilization;
- Raising the failure strain of the cement or concrete matrix.

There is a certain amount of load-sharing involved, and it is necessary that the fibres be well bonded to the matrix (i.e. high interfacial shear strength) in order for them to limit crack extension by holding the crack faces together. In this paper, the general discussion of design, fabrication and properties will be limited to polymer-matrix composites since the variety and applications are wide. Inorganic matrix composites will be specifically dealt with in the presentation of examples in chapter II.

Figure 3.

Stress-strain curves of a typically brittle matrix and one ductilized by fibres



B. Current Technology

1. Classes of fibre-reinforced materials

The definition of reinforcement given in chapter I applies to a wide variety of combinations of materials. Laminates provide the highest strengths and stiffnesses and are fabricated from high-strength, continuous filaments in polymeric matrices. Typical properties of fibres are given in table 1. Matrices may be chosen from an almost infinite variety of polymers, but the ones most commonly used for laminates are epoxy, polyester, phenolic and vinyl, all of which are thermosetting (i.e. materials that cure upon heating and the process is irreversible). Typical properties of epoxy-matrix composites are given in table 2.

Short-fibre composites may have polymer (thermoset and thermoplastic) or inorganic (cement) matrices with chopped fibres, these being any of those given in table 1, or whiskers of natural fibres such as asbestos, jute, bagasse and sisal that have interesting reinforcing properties (see chapter II). The effect of different forms of glass-fibre reinforcement on the properties of polyester composites is illustrated in table 3.

A variation on the laminate structure, which also provides high-strength isotropic properties without complex layer lamination, is obtained by the use of woven fabrics consisting of either one fibre or a mixture (hybrids). The technology associated with such raw materials is very cost-effective. Although in theory any mixture of materials may be made, useful combinations are determined by:

- Properties obtainable;
- Fabrication possibilities;
- Cost.

In general terms, composite materials are divided into conventional and advanced. The advanced composites cover all metallic matrix materials and polymeric matrices containing advanced fibres such as carbon, aramid, boron, and even the advanced glasses such as S-glass. The major utilization sector is aerospace, with increasing incursions into sports goods and, due to large R and D efforts, into transportation and general engineering. Table 4 presents a short comparison of the major attributes and limitations of advanced fibres.

Conventional composites include inorganic and polymeric matrices containing glass or natural fibres, the most common examples of which are:

- Glass-fibre-reinforced polyester for buildings and pipes;
- Asbestos cement materials.

The latter have been utilized for many years in everyday applications, but the thrusts in aerospace have led to their improvement through utilization of design and fabrication technology developed for the advanced composites. The background knowledge is considerable, as evidenced by the multitude of references and conferences, examples of which are cited in references 1 to 6.

Table 1.

Physical properties of high-strength fibres

	DIAMETER (µm)	TENSILE STRENGTH (GPa)	TENSILE MODULUS (GPa)	DENSITY (G/cm^3)	1980 PRICE US$/kg
Carbon Fibre (HS)*/	7	3.7	240	1.8	40
Carbon Fibre (HM)/**	7	2.2	380 - 500	2.1	60-100
Aramid (Kevlar 49)	12	3.6	131	1.4	20
S (or R) Glass Fibre	9	3.6 - 4.5	86	2.5	5-22
Boron Fibre	140	3.2 - 3.5	365 - 400	2.2 - 2.6	≥300
Alumina		1.4 - 1.7	150 - 380	2.6 - 4	20-60
Silicon Carbide		2.4 - 3.3	180 - 428	2.5 - 3.5	800
E Glass Fibre	5-140	2.5	73	2.5	1

***/ High strength**
****/ High modulus**

Table 2.

Room Temperature Properties of Commercial Unidirectional Fibrous Epoxy Composites

FIBRE TYPE	E-GLASS	S-GLASS	ARAMID (Kevlar-49)	BORON/W 4 mil	THORNEL 300 CARBON	HMS CARBON
Fibre Volume (%)	60	60	60	50	60	62
Density (g/cm^3)	2.00	2.08	1.38	1.88	1.61	1.63
Longitudinal Properties:						
Tensile Strength (MPa)	1280	1620	1380	1280-1600	1610	830
Tensile Modulus (GPa)	39	59	76	204-220	148	193
Flexural Strength (MPa)	1380	1860	620	1690	2060	966
Flexural Modulus (GPa)	48	48	69	193	148	169
Compressive Strength (MPa)	620		280	3060-3180		380
Compressive Modulus (GPa)			72	242-545		107
Transverse Properties:						
Tensile Strength (MPa)			30	68-123		
Tensile Modulus (GPa)			6	21.8-27		
Interlaminar Shear (MPa)		97	60	11.7	117	55

Table 3.

Polymer-Matrix Composites

Typical physical properties of glass fibre-reinforced plastic (GRP) with different types of glass fibre-reinforcement

Properties	Unit	Chopped strand mat	Woven rovings	Satin weave cloth	Continuous rovings
Glass content	% weight	30	45	55	70
	% volume	18	29	38	54
Specific Gravity		1·4	1·6	1·7	1·9
Tensile strength	MPa	100	250	300	800
Tensile Modulus	GPa	8	15	15	40
Compressive strength	MPa	150	150	250	350
Bend strength	MPa	150	250	400	1000
Modulus in bend	GPa	7	15	15	40
Impact strength, Izod, unnotched*	kJ/m^2	75	125	150	250
Coefficient of linear expansion	$\times 10^{-6}/°C$	30	15	12	10
Thermal conductivity	W/m K	0·20	0·24	0·28	0·29

*Tested edgewise.

2. Advantages and limitations of composites

Composite materials are in general employed whenever the following advantages are sought:

- stiffness and/or strength, either in absolute terms or on a specific basis (i.e. stiffness per unit of weight), as in aerospace;
- weight savings, as in surface transport and automobiles, in particular;
- longer, maintenance-free utilization (corrosion, fatigue, impact etc.);
- cost-savings, either on an initial-investment basis or on an overall life-cycle cost basis.

Conventional composites such as glass-fibre-reinforced polyester are finding increasing applications due to these advantages.

Table 4.

Comparison of major advantages and limitations of currently available high-performance fibres

Fibre	Major advantages	Major limitations
Aramid	• Highest specific strength • High impact strength • Low cost	• Poor compressive strength • Difficult fibre to cut • Limited to resin matrix components
Boron	• High compressive strength	• High cost fibre • Low bending radius • Not suitable for complex shapes
Silicon Carbide (continuous fibre)	• High compressive strength • Inert towards molten metals	• Low bending radius • Relatively high cost
Carbon (PAN)	• Lowest coefficient of thermal expansion • Electrical conductor	• Brittle fibre • Relatively poor impact strength • Electrical conductor
Carbon (Pitch)	• Potentially lowest cost fibre	• Low tensile strength • High coefficient of variation
Aluminia FP	• Inert towards molten metals • Electrical insulator • Potential low cost	• Hi~h density resulting in low specific properties

Advanced composites, mainly chosen in aerospace for reasons of increased stiffness, can only be introduced in the industrial sector on the basis of cost-effectiveness. The direct material cost comparison with conventional materials is invariably unfavourable. This cost-effectiveness can be obtained through performance advantages, reduced manufacturing costs or by a combination of the two. In terms of performance, advanced composites may lead to more efficient operation (e.g. high stresses), lower maintenance and longer operating life. Also, direct moulding of complex structures (e.g. helicopter or windmill blades) reduces the number of (metallic) components and eliminates expensive machining. Limitations on composite usage remain:

- Predictability of properties. Although "simple" rules exist for small samples, the reproduction in larger production units is problematic and leads to sometimes severe penalties in terms of securing factors, which lead to heavier, costlier structures.

- Control of the quality of the basic components and of the structure that is produced, especially for critical, highly stressed structures, such as in aerospace or general engineering (pipes, tanks etc.).

- Engineering design specifically developed for composites. This problem applies more to general engineering than aerospace where complex solutions can be, and often are, employed.

- Education in composites at all levels of design, fabrication and utilization.

Discussion of composites from the viewpoint of their application in developing countries is presented in section C of this chapter.

3. Design

The important design aspects of composite materials are a function of end-utilization. For advanced composites and conventional composites in highly stressed structures such as pipes and tanks, continuous fibres in laminate or fabric form are invariably utilized. Design procedures are relatively well established for the stiffness (rigidity) of structures[7], whereas strength is not very well defined in large-scale structures and thus leads to rather heavy penalties in terms of safety factors.[8]

The effectiveness of the design depends to a large extent on the fabrication technique and its control. Optimum utilization of the reinforcing effect of the high-strength, high-modulus fibres is obtained through:

- Control of the interface, and
- Orientation and proportion of the fibres in the principal stress directions.

For random (short) fibre composites the major design criteria are:

- the homogeneous distribution of the fibres in two or three dimensions,
- the fibre content, and
- the fibre aspect ratio (length:diameter).

In the former case, the effectiveness of the reinforcing effect is mainly controlled by the fabrication process, while for the other two the design choice is the determining factor. Design with short-fibre composites is much more difficult than with continuous fibres, as will be seen later, and as such produces less spectacular end-effects and requires much more control in fabrication to obtain an optimum result. The advantage, however, is one of cost.

4. Fabrication techniques

Inorganic matrix composites may be made by any one of the normal techniques employed for the matrix itself : spraying, casting, press moulding, injection moulding etc. The fibrous reinforcement is invariably in the discontinuous, random form. Polymer matrix composite fabrication on the form of the product, its dimensions number etc. The major techniques are summarized in table 5 and illustrated in figure 4. Typical mechanical properties of E-glass fibre-reinforced polyester resin structures produced by the different techniques are given in table 6. A wide variety of properties are obtainable, the highest coming from those techniques where continuous filaments are employed under some form of pressure moulding. In filament winding, pressure is applied on the resin by the filaments themselves during the winding process.

The main advantages and disadvantages of the most wide-spread techniques are as follows:

a. Contact moulding

The fibres in the form of the pre-cut fabric or mat are placed in a mould and impregnated with resin that cures at relatively low temperatures. The advantages are simplicity of the moulds, low temperature and flexibility. Disadvantages include its limitation to relatively low-quality products and the wide-spread use of hand lay-up, which may be rather expensive and does not ensure reproducible quality. Mechanized lay-up can increase productivity dramatically (150 kg/man-hour compared with 2 kg/man-hour) for large series where the capital investment expense can be justified.

b. Compression moulding

The fibres are normally introduced in the mould in the form of a prepreg*/ or SMC**/ and compressed up to 200 degrees C to cure the resin and consolidate the part. Advantages are mainly that the properties are

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*/ Prepreg: Continuous, aligned fibres, chopped sheets or woven cloth or fabrics, preimpregnated with epoxy or polyester resin.

**/ SMC: Sheet moulding compounds consisting of a chopped strand mat impregnated with polyester resin.

Table 5.

Summary of moulding processes

	Contact moulding		
Process	*Hand lay-up*	*Spray lay-up*	*Vacuum bag/pressure bag*
Resin system	Liquid—polyester, epoxy, furane	Liquid—polyester, epoxy	Liquid—polyester, epoxy Prepreg—epoxy SMC—polyester
Reinforcements	Glass, carbon, other	Glass	Glass, carbon, other
Fibre content, glass (% by wt)	25–35	25–35	25–60
Normal laminate thickness (mm)	2–25, generally 2–10	2–25, generally 2–10	2–6
Typical cure temperature (°C)	Ambient to about 40	Ambient to about 40	Ambient to 50 for liquid resins, 80–160 for SMC and prepreg
Type of mould needed	Single—GRP, wood, etc.	Single—GRP, wood, etc.	Single—GRP, epoxy or metal
Moulding size limitation	In principle—none	In principle—none	Capacity of vacuum equipment or compressor, capacity of autoclave
Moulded in—ribs	Yes	Yes	Yes
—inserts for fixing	Yes	Yes	Generally no
—foam panels	Yes	Yes	Generally no
Equipment needed	Rollers and brushes	Spray and chopper gun, rollers	Hand/spray lay-up, automatic tape laying machine, autoclave/vacuum pump/compressor
Number of mouldings to justify mould cost	From one upwards	From one upwards	From one upwards
Production rate	Low	Low	Low
Labour content	High	High	High
Quality of moulding	Dependent on operator, one smooth surface	More dependent on operator, one smooth surface	Two smooth surfaces
Typical products	Boats, building panels, general	Boats, building panels, general	Aircraft sections, various panels, general

				Compression moulding	
Process	*Foam reservoir moulding*	*Resin injection/ resin transfer moulding*	*Vacuum impregnation*	*Cold press*	*Hot press*
Resin system	Liquid—epoxy, polyester	Liquid—polyester, epoxy	Liquid—epoxy, polyester	Liquid—polyester, epoxy	Liquid, prepreg, SMC/DMC—polyester
Reinforcements	Glass mat/open cell foam	Continuous strand mat	Glass, carbon, other	Glass, carbon, other	
Fibre content, glass (% by wt)	Variable	25–30	25–50	25–50	25–70
Normal laminate thickness (mm)	2 upwards	2–6	2–10	1–10	1–.0
Typical cure temperature (°C)	Ambient to about 50	Ambient to about 50	Ambient to about 150	40–50	100–170
Type of mould needed	Double GRP or light metal	Double GRP or light metal	Matched metal, GRP	Double GRP, metal	Matched metal
Moulding size limitation	Mould dimensions	Mould dimensions	Mould dimensions	Press size	Press size
Moulded in					
—ribs	Yes	Yes	Yes	Yes	Yes
—inserts for fixing	Generally no	Generally no	Generally no	Yes	Yes
—foam panels	Yes	Yes	Yes	Generally no	No
Equipment needed	Hand equipment	Resin injection pump	Vacuum pump	Hydraulic press	Heated press
Number of mouldings to justify mould cost	From one upwards	Generally 100–1000	Generally 100	100–1000	1000 upwards
Production rate	Moderate	Moderate	Low	High	High
Labour content	Moderate to high	Moderate	Moderate	Low	Low
Quality of moulding	Good, two smooth surfaces	Good, two smooth surfaces	Good, two smooth surfaces	Good All surfaces smooth	Excellent
Typical products	Automotive, furniture, various	Boats, various	Radomes, aircraft nose cones, various	Automotive, industrial, electrical	

Table 5. (continued)

Process	*Transfer moulding*	*Injection moulding*	*Filament winding*	*Centrifugal moulding*
Resin system	DMC —polyester, epoxy, other resins	DMC —polyester, epoxy, other resins	Liquid—polyester, epoxy Prepreg—epoxy	Liquid—polyester, epoxy
Reinforcements	Glass, carbon, others	Glass, carbon, others	Glass, carbon, other continuous fibres	Glass
Fibre content, glass (%by wt)	10–65	10–65	60–80	25–40
Normal laminate thickness (mm)	1–6	1–6	2–25	2–25
Typical cure temperature (°C)	155–170	Polyester 135–185, epoxy 160–220	Ambient to 170	Ambient to 50
Type of mould needed	Metal	Metal	Steel, plaster, etc.	Steel
Moulding size limitation	Machine capacity	Machine capacity	Machine size, generally 6 m diameter, 6 m long	Machine size, generally 6 m diameter
Moulded in—ribs	Yes	Yes	Externally, yes	No
—inserts for fixing	Yes	Yes	No	No
—foam panels	No	No	Yes	No
Equipment needed	Transfer moulding press	Injection moulding machine	Filament winding machine	Centrifugal moulding machine
Number of mouldings to justify mould cost	Over 1000	Over 1000	From one upwards	100 upwards
Production rate	High	Very high	Moderate	Moderate
Labour content	Low	Low	Medium	Low
Quality of moulding	Good, all smooth faces	Good, all smooth faces	Good, inside smooth	Good, both surfaces smooth
Typical products	Small-to-medium sized components	Small-to-medium sized components	Tanks, pipes and tubes	Pipes and tubes

Process	*Continuous sheet moulding*	*Pultrusion*
Resin system	Liquid—polyester, epoxy	Liquid—polyester, epoxy Prepreg—epoxy
Reinforcements	Glass	Glass, carbon, aramid
Fibre content, glass (% by wt)	25–35	60–75
Normal laminate thickness (mm)	2–6	600 x 250
Typical cure temperature (°C)	50–120	100–160
Type of mould needed	Metal rollers or sheet	Hardened steel die
Moulding size limitation	Width of machine	600 x 250 mm, die dimensions
Moulded in—ribs	No	Variety of cross-sections
—inserts for fixing	No	No
—foam panels	No	No
Equipment needed	Sheet moulding machine	Pultrusion machine
Number of mouldings to justify mould cost	Continuous output	Continuous output
Production rate	Up to 12 m/min	Up to 1 m/min
Labour content	Low	Low
Quality of moulding	Good	Good
Typical products	Roofing lights, etc.	Variety of cross-sections, rods, tubes, etc.

Figure 4.

Basic fabrication process for fibre-reinforced plastics

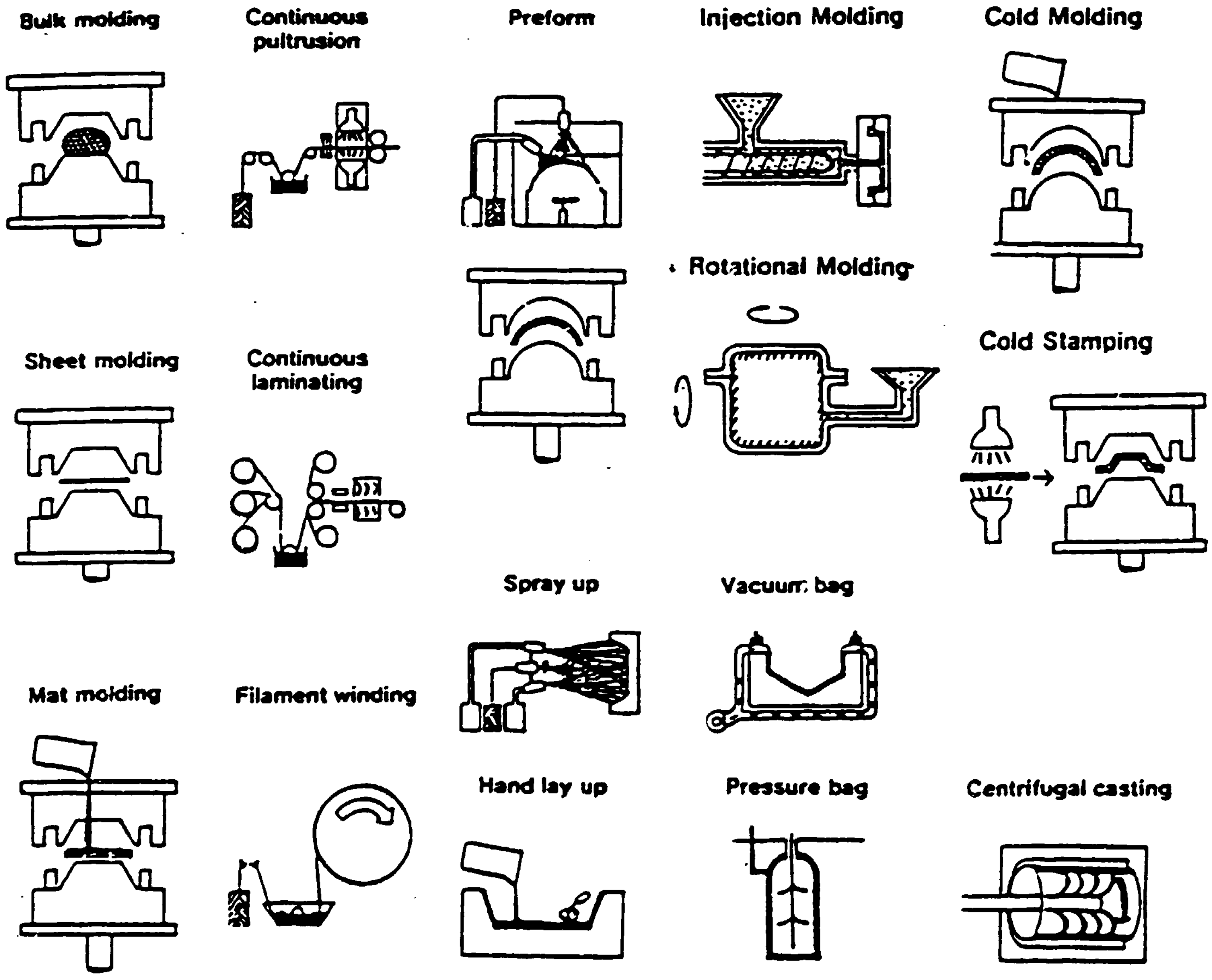


Table 6.

Mechanical properties of glass-reinforced polyesters made by different techniques

Moulding process	Reinforcement	Tensile strength (MPa)	Flexural strength (MPa)	Elastic modulus (GPa)
Contact moulding	Chopped strand mat	60- 150	80-120	5- 7
	Glass woven roving	150- 250	120-180	8-11
Vacuum-bag moulding	Chopped strand mat	80- 100	90-150	6- 8
	Glass woven roving	150- 250	150-200	9-12
Compression moulding at 10 bars	Woven roving	150- 250	200-400	15-25
Centrifugation	Chopped strand mat	80- 120	90-150	7- 9
Filament winding	Roving	600-1,500	1,000	25-60

good and reproducible. However, the tooling is expensive, the fabrication cycle is long and the process is limited to small-dimension parts. Hydraulic compression moulding can decrease moulding time to around five minutes for small parts at pressures up to 100 bars.

c. Autoclave moulding

Prepregs are draped on a former or are placed in a mould in the desired orientations, and then covered with a bag and placed in an autoclave for consolidation (typically 15 bars at 200 degrees C). Complex and large structures may be manufactured with rather cheap tooling, but the process is labour-intensive and limited to small series. This technique is widely used in the aerospace industry. The process is slow, requiring between 2 and 20 man-hours/kg of composite material (approximately US$30 to US$300/kg in industrialized countries). An autoclave costs more than US$250,000 and operating energy costs are high.

d. Continuous sheet moulding

The reinforcement, almost uniquely glass in the form of chopped strand mat or cloth, is unwound continuously, impregnated with resin (polyester or epoxy) and passed through rollers and a curing oven. The process is interesting for building and decorative panels that do not have to withstand high stress.

e. Filament winding

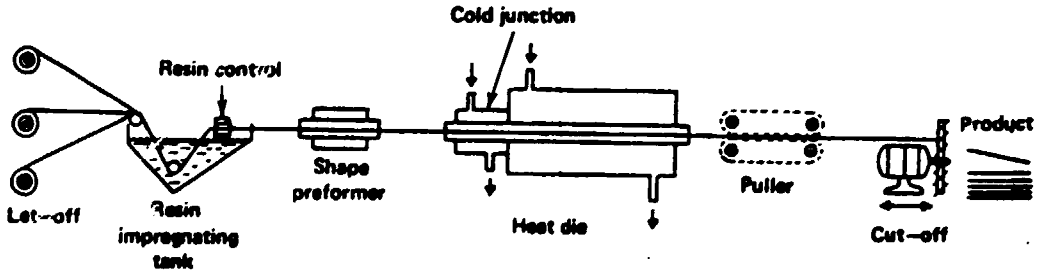
As the term implies the technique is used to produce pipes, tanks and spheres. The fibres may in the form of single tows, rovings of glass, carbon or aramid, or prepregs. Various processes are available and will be discussed in chapter II. Equipment may cost from anywhere between US$30,000 to US$120,000 per discontinuous machine. The semi-continuous Drostholm machines may cost upwards of US$500,000.

f. Pultrusion

The fibres are continuously impregnated with resin (or prepregs may be used) and pulled through a heated die during which the excess resin is removed, the cross-sectional shape of the part determined and the composite cured. Continuous fibre and fibre-reinforced products may be made mainly with polyester and vinyl-ester matrices. Pultrusion, for the production of low-cost composite profiles, is well established and provides high-quality, high-performance materials in a wide variety of cross-sectional shapes, such as tubes, profiles, rods. Mechanical performance is competitive with stock produced by other more expensive moulding procedures and enables the user to incorporate composites (advanced or conventional) into production components without the need for substantial investment (financial or technological) in complex processing procedures. The basic pultrusion process is illustrated below in figure 5.[9/]

Figure 5.

The basic pultrusion process: Intermittent pull, closed heated rigid die, complete cure.



Recent developments have shown that epoxy and (advanced) thermoplastics (polysulphone, polyetheretherketone) can be used as matrices in pultrusion, mainly for advanced composites. Equipment costs can run as high as US$400,000 for full automation and profiles up to 36 inches in size.

g. Reinforced reaction injection moulding (RRIM)[10/]

This technique is increasingly used for the rapid production of glass-filled elastomeric polyurethane thin-wall automobile components, such as bumpers and bonnets, and is gaining in interest for polyester matrices. The process consists of pumping separate streams of the polymer components (incorporating chopped fibres) into a heated, matched-metal mould and then polymerizing insitu. Rapid polymerization (less than 30 seconds) is essential in order to obtain an economic product. Costs for polyester parts are estimated at approximately US$1.60 per kg, competitive with other fabrication techniques for similar polyester products and cheaper than polyurethane parts. Property qualities are, however, lower.

5. Properties

Since such a wide variety of properties may be obtained with composite materials, it is impossible to discuss these properties without reference to specific systems and applications, as will be done later in chapter II. Neverthelses, in general terms, conventional composites (polymer and inorganic matrices) exhibit very interesting strength characteristics at reasonable cost due to the relatively low cost of the E-glass or natural fibres and the possibility to employ rather simple fabrication techniques without strict control measures. Stiffness (i.e. elastic modulus) is, however, not high, but may be improved by optimized design and strict control or by the addition of a limited amount of a stiffer, advanced fibre, such as carbon or aramid. The resulting improvement is illustrated in table 7, while figure 6 illustrates the various types of hybrids that can be produced.

Advanced composites possess exceptional stiffness characteristics, as illustrated in figure 7 and even more so on a specific basis as seen in figure 8. The further interesting feature of these figures is the high-strength characteristic of glass fibre composites.

6. Sectors of application

a. Advanced composites

The major fibres used in advanced composites are carbon and aramid, which in the last 15 years have moved from the research and prototype stage to wide-spread application. The current carbon fibre world market is around 1,000 tons, representing about US$70 million. Growth to a US$1 billion business by 1990 is forecast. Fifty per cent is used in aerospace, another 25 per cent in sports and leisure goods and 25 per cent in miscellaneous applications. Aramid fibres, of which the Kevlar$^{(R)}$ family is the best known, are of various types and a total of 7,000 tons are used annually in the United States of America, by far the major market : 2,200 tons of Kevlar 49 are employed in polymer composites, while 3,000 tons of Kevlar 29 are used in tyres.

Advanced composite materials find very wide utilization in a varity of industries:

Table 7.

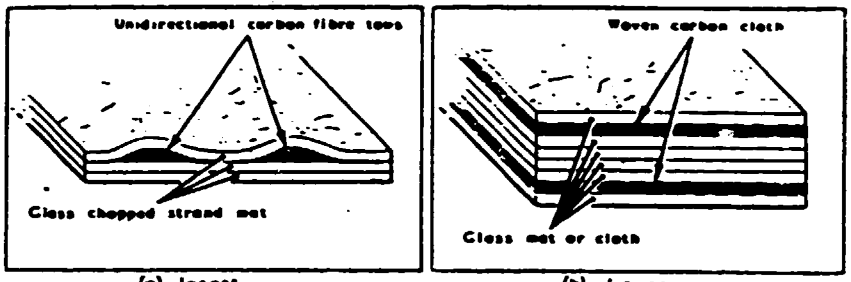
Mechanical properties glass/carbon hybrids

(Matrix resin-vinyl ester)

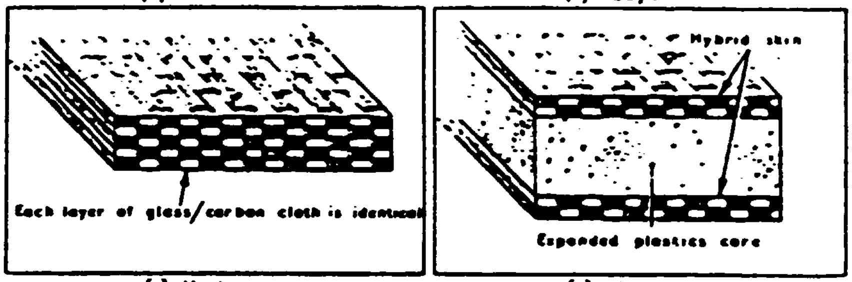
Warp Construction	V_f carbon at 60% total fibre content	Flexural strength MPa	Flexural modulus GPa	Interlaminar shear strength MPa	Tensile strength MPa	Tensile modulus GPa
All-glass	0.0	844	34.6	40	780	39.9
4:1	0.13	773	46.9	43	660	56.0
3:1	0.16	843	50.6	42	686	60.2
2:1	0.21	943	59.0	43	715	65.2
1:1	0.31	953	69.3	40	749	74.6
All-carbon	0.6	1240	101.2	38	1132	115.1

Figure 6.

Classification of hybrids



(a) Insert (b) Layer



(c) Uniform (d) Sandwich

Figure 7.

Tensile properties of materials of interest

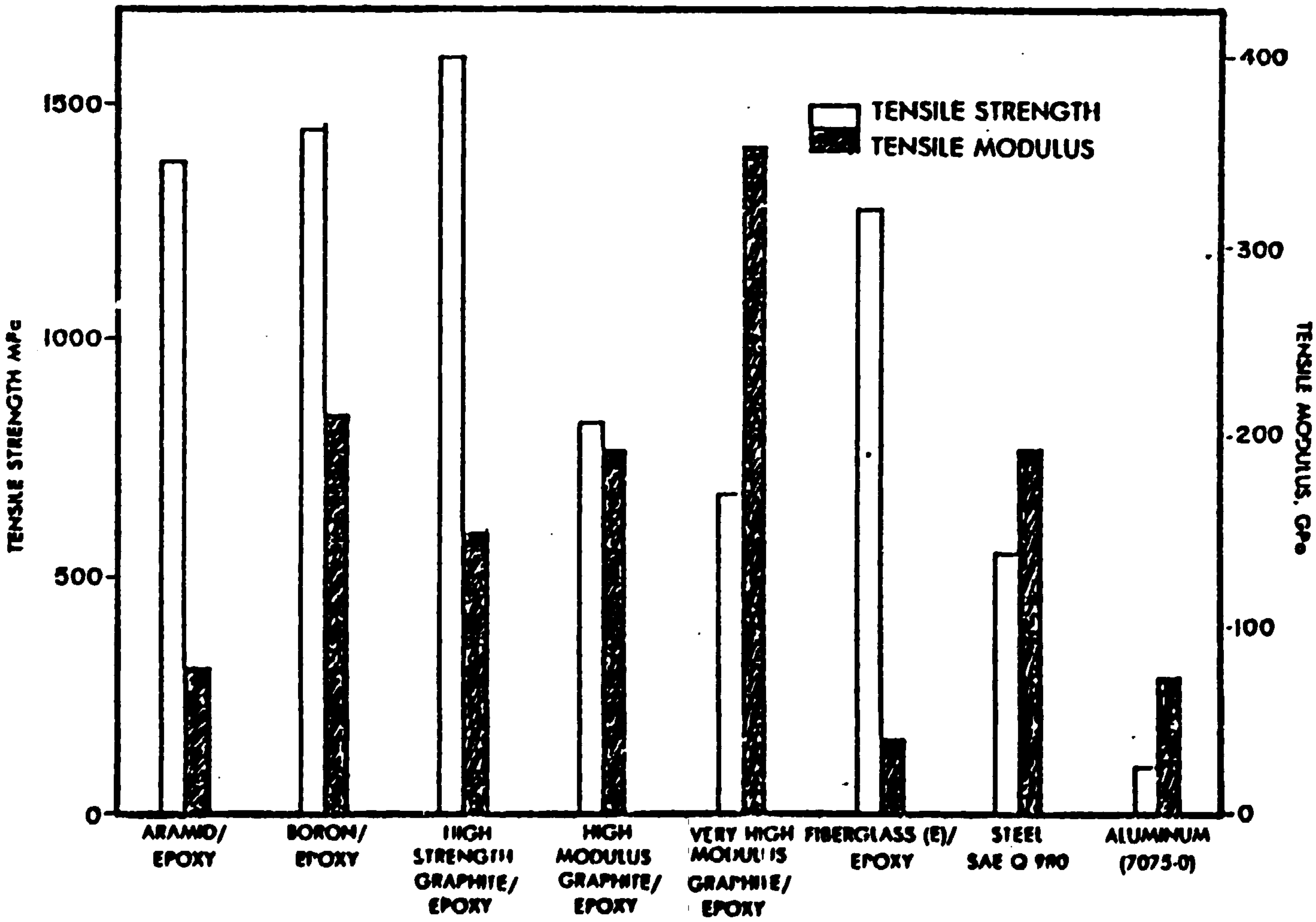
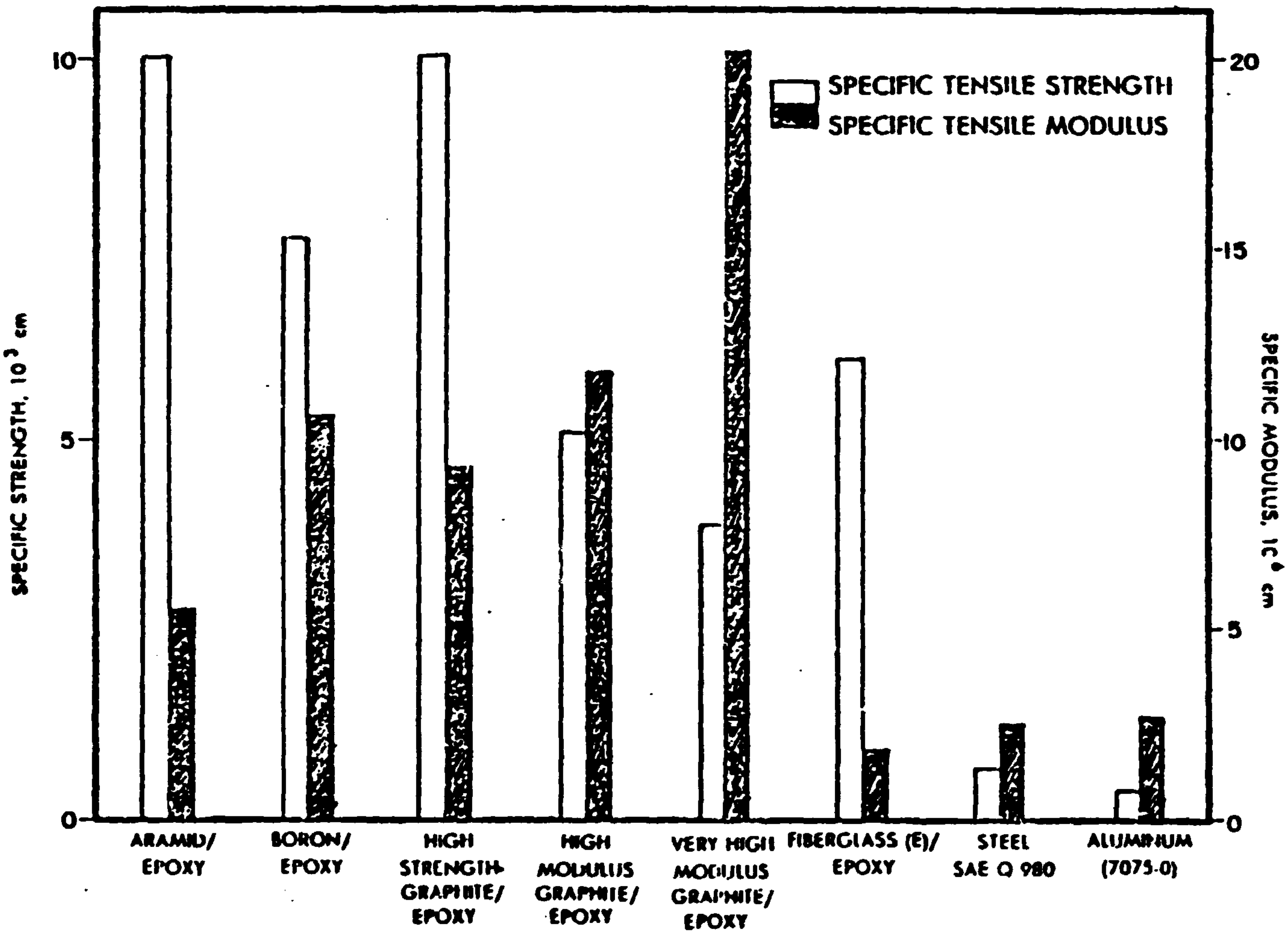


Figure 8.

Specific tensile properties of materials of interest



1. Military aircraft[1,11]/	Composite material	Weight/ aircraft (kg)	Weight of aircraft structural weight (%)
Horizontal stabilizer	boron/epoxy	85	0.8
Empennage	boron/epoxy	98	1.6
Empennage fin covers	graphite/epoxy	82	2.5
Upper and lower wing skins, horizontal surfaces, landing gear door etc.	graphite/epoxy	500	9.5

2. Helicopters[11,12]/
Rotor blades glass/epoxy or aramid/epoxy

3. Rockets[11]/

4. Space shuttles[11]/	Composite material	Weight savings compared with Al-alloys (kg)
Payload doors, maneuvering pods	graphite/epoxy	620
Thrust structure	boron/epoxy	410
Pressure vessel overwrap, piping	aramid/epoxy	290
Frame tubes	boron/aluminium	80

5. Flywheels, wind mills[13,14]/

Carbon/epoxy, aramid/epoxy and hybrids

6. Sports equipment[15]/

Golf clubs, tennis rackets, fishing rods, skis, canoes and kayaks etc.

7. Commercial and military boats[16,17]/

Many bybrids, incorporating glass for strength and toughness, and carbon or aramid for stiffness.

8. Commercial Aircraft[2]

After much testing and verification, advanced composites, including hybrids, are finding increasing utilization in commercial aircraft. The Lear Fan will be all plastic including much carbon or carbon/aramid,[18] which leads to 30 to 40 per cent weight saving over conventional construction.

The Boeing 767 uses around 3 tons of composites (approximately 3 per cent of the total structural weight) including one ton of carbon fibre composite on parts which reach over 10 metres in length.[11] The AIRBUS A-310 will similarly use large quantities of composites in rudders, vertical fins, ailerons, horizontal tail and elevators.

9. Automobiles[2,11]

The driving force for the utilization of advanced composites in automobile construction is weight-savings, to be translated into energy- and cost-savings. Table 8 summarizes the situation with respect to the Ford test car.[19] When completed in 1979, the car contained some 200 kg of carbon composites in approximately 160 different parts. The total weight savings of approximately 550 kg over the conventional steel LTD[*] was due partly to direct material substitution and partly to substitution of signle composite parts for multipart assemblies. The cost of the development car amounted to US$5 million.

Specific articles apparently on the point of being introduced are epoxy-glass/carbon hybrid springs (Rubery-Owen, GB), epoxy-carbon leaf springs (GKM, GB), epoxy-carbon lorry transmission drive shafts (Ciba-Geigy). Weights are around 25 per cent of the equivalent steel parts.

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[*] Conventional FORD car LTD model

10. Mechanical engineering[20]

Given their high specific stiffness and strength, carbon-epoxy composites are ideally suited for dynamic applications in textile machinery, printing presses and robotics. Advantages include increased speed, i.e. production, and reduced noise.

11. Sport activities

Kevlar fibre-reinforced epoxy structures have led to two record-making achievements in flying:

- the man-powered English Channel crossing on 12 June 1979 by Gossamer Albatros: the plane weighed 34 kg (and the pilot 64 kg!) and had a wing span greater than a DC 9[21];

- the first solar-powered flight of over 100 miles by the Solar Challenger on 7 July 1981.

Furthermore, gliders, yachts and airship gondola structures are using Kevlar and carbon fibres to achieve important weight savings, allowing rapid progress in performance.

Table 8. Comparison of the weights of conventional parts and carbon composite parts in the Ford test car[19]

Automobile part	Weight in steel (lb)	Weight in graphite (lb)
Body in-white (unfinished)	461	208
Frame	283	207
Front end	96	29
Hood	49	17
Deck lid	43	14
Bumpers	123	44
Wheels	92	49
Doors	155	61
Miscellaneous, e.g. brackets and seat frames.	69	36

b. Conventional composites: glass fibre reinforced[6,22,23]

The glass fibre-reinforced plastics industry is already over 30 years old and has grown continuously to reach around 950,000 tons in 1981 (excluding CMEA countries and the People's Republic of China, for which little information is available). The major markets remain in the industrialized nations of North America, Europe and Japan, while 9.3 per cent or 88,000 tons are consumed in Latin America (26,000 tons), Africa (10,000 tons), Western Asia (17,000 tons), other Asian countries and Indonesia (19,000 tons) and the Pacific (16,000 tons).

In the industrialized nations, there has been a dramatic change in the pattern of end-usage, with decorative fabrics practically disappearing and uses such as electrical and, not strictly, structural roofing and panels have grown dramatically, more than doubling in five years. The structural reinforced plastics represent between 40 and 60 per cent of the total market, with major applications in the United States being:

	Use of reinforced plastic (%)
Aircraft/aerospace	1
Marine	17
Construction	14
Electrical tubes	9
Corrosion resistance applications (tanks, pipes etc.)	18
Transportation	21
Appliances	5
Consumer goods	6

In Japan there are major use-pattern differences, with more usage in housing and marine, with low usage in transportation and consumer goods. Europe follows the pattern of the United States more closely.

The striking feature of recent years has been the dramatic growth of usages in Western Asia (from 2,000 to 17,000 tons in the five years to 1981) mainly for water and sewage (i.e. corrosion resistance). The utilization in the other developing markets has also grown (doubling in Africa), but at a much lower rate, more reminiscent of Japan than Western Asia. This lower growth and absolute utilization has been attributed to the fact that these countries do not have the same materials supply problems as the industrialized countries, so that substitution has not yet been necessary.

Glass fibre-reinforced plastics are also employed in advanced structures, such as helicopter blades12/ because of their light weight and excellent resistance to impact. Commercial aircraft, automobiles and boats represent important markets where the materials are used under high-stress conditions and where structural resistance optimization is possible by the composite technology approach. The petroleum industry also represents a growing market for glass fibre-reinforced plastics (GRP), mainly due to the increased corrosion resistance (reduced maintenance) and weight savings24/. The growth rates of reinforced plastics, both glass fibre-reinforced and advanced, are far in excess of those for conventional structural materials: steel, aluminium, zinc. However, composites still represent only less than one per cent of the total plastics consumption which themselves utilize only about ten per cent of the total petroleum consumed. Furthermore, advanced polymer matrix composites represent only 0.1 per cent of the conventional glass fibre-reinforced composites.

C. History of composites and reasons for expanded utilization in developing countries

Fibre-reinforced composite materials, in the broadest sense of the defintion, have been manufactured and utilized in the presently designated industrialized and developing countries for thousands of years. In ancient Egypt, chopped straw was added to bricks to prevent them from cracking upon drying. This principle was also used until quite recent times in Western Europe. Similarly, the Incas and Mayas put plant fibres into their clay for pottery manufacture. In these two examples, the fibres act less as a reinforcement of the final product than as a reinforcement of the drying clay. Nevertheless, the composite materials' principles discussed earlier apply to modern, high-technology composites.

In the case of inorganic matrices, the objective of adding fibres is rather one of increasing their resistance to cracking than a strictly strengthening mechanism (this is a secondary effect). Ordinary cement, concrete, or even pre-stressed concrete will invariably crack upon drying, the cracks opening up as a function of time, exposure, stress etc. If a small proportion of steel, asbestos or other natural fibres is added, crack initiation frequency is reduced and their propagation suppressed or modified to such an extent that no large, catastrophic cracks result, and the structure may support reasonable tensile stresses.

Some of the most impressive uses of the above reinforcing principle were in ancient Greece where the marble gateway to the Acropolis, the Propylaea, was reinforced by six-foot-long iron rods concealed within the spans, thus enabling spans of up to 20 feet to be made, whereas around eight feet was a limit with unreinforced marble.

The road to present-day reinforced concrete passed through many phases until in the mid 1800s it was discovered that Portland cement did not corrode iron bars. Previously all attempts to copy the Greeks had been doomed to failure due to rusting of the reinforced bars in the climates of the industrialized countries.

The principle of using fibres of high stiffness and high strength, either alone or in bundles in order to reinforce weaker matrices by the stress transfer mechanism rather than that of crack-stopping, has also been practiced since ancient times. In many cases the fibres served the purpose of providing a base or foundation for the matrix, which would have been otherwise useless for the required purpose. In contrast to the previous category which involved ductilizing of brittle matrices with small amounts of fibres, here large proportions of fibres are required which necessitate adding the matrix to the fibres or providing the fibres in a form such that fracture of one does not lead to immediate fracture of the structure. Common examples are paper, paper maché, hemp ropes, coir-coconut fibre rope, laminated wood structures.

In past ages, coir was used in the Arabian Gulf and along the coast of the Indian Ocean to bind wood together in ships that sailed to Africa and Asia. A recent project of the Sultan of Oman[25/] reproduced such a ship, which demonstrated the already advanced usage of common, natural fibres to construct structures that resist high stresses.

Thus, experience in the use of fibres and confidence in the resulting structures is part of the heritage of many developing countries, and the introduction of more advanced materials and advanced technology to produce composite materials would not seem out of place. There is a need for solutions to critical problems in the sectors of energy, housing, transport, environment, water etc. The advanced technology developed for composites can be used to optimize structures in the developing countries and help build up an industry that can satisfy both local needs and even offer export possibilities.

CHAPTER II. POTENTIAL MANUFACTURE AND APPLICATIONS IN DEVELOPING COUNTRIES

The basic needs of all economies remain food, housing, energy, health and sanitation to be attained and maintained by efforts (labour, investment, operation cost etc.) that are realistic within the context of each nation. Materials-development, in general, and composites, in particular, can, and already do, play a role in improving conditions with respect to the above. In some cases, the impact will be more direct and important than in others, and these will be the theme of the examples presented herein. For developing countries, the need will be to choose labour-intensive technologies and fabrication techniques of composite manufacture. The examples chosen to illustrate the potential of composite material manufacture in developing countries are presented in the following pages.

A. Advanced composite materials in energy production or energy storage[26]

Advanced polymeric matrix composites containing S-glass, carbon, aramid fibres or mixtures of these (hybrids) represent the highest specific strengths (per unit weight) and stiffnesses of all materials. They have been under development for 15 years or more and are now quite widely utilized in aerospace, military and commercial aircraft, and sports goods. A wide variety of materials and structures are produced in the industrialized countries. The sector has been the subject of innumerable research and development projects, both of military and commercial applications, and the level of efforts is illustrated by the large number of technical publications and specialist conferences (see the references at the end of this paper).

1. Materials and the technology

A composite (epoxy plus 60 per cent volume of carbon fibres) is, at equal weight, five times stiffer and more resistant than a low alloy steel. Taken at face value, this statement is exciting and opens up views of unlimited applications. However, the fact that this has not transpired is due to:

- The increased properties are only along the axis of the fibres, so that laminates or woven structures have to be used in real applications, thus reducing the gains, at equivalent weight, to around two.
- The epoxy matrix is limited in operating temperature and both epoxy and other thermosetting resins are sensitive to U.V..
- The design of composite structures for stiffness is well established but not yet for strength since there can be rather wide variations and defects in the structure whose effect is not yet understood. Thus, heavy security factors are often placed on composites in high-stress, critical applications.
- The long-term reliability and life-time is not fully understood or predictable.
- The cost of materials, manufacture and control is very high so that only applications where the added value is high--large weight-savings are to be gained or complex machining can be avoided--can be satisfied by advanced composites.

2. Stage of development : windmill blades[27]

An example of an advanced composite structure used in energy generation will serve the purpose of evaluating the potential of advanced composite production and utilization in developing countries. A windmill blade contains many of the features where composites are at an advantage without actually entering into areas of advanced technology, such as in aerospace whose immediate introduction in developing countries is doubtful.

Advanced composite blades and even glass fibre or hybrid reinforced ones are interesting for the following reasons:

- Light weight blades can be made which allow the blade to rotate under low wind velocity (2-3m/s), thus increasing its efficiency.
- Large blades can be made which result in large energy gains.
- The blades have high fatigue-resistance, thereby withstanding vibration and strong winds.
- The corrosion-resistance of the blades makes them applicable in coastal, high-humidity regions, resulting in low maintenance requirements.

Several projects are underway in Denmark, the Netherlands and the United States of America where the largest blade is 25 m in length. As yet, however, no industrial application is known.

3. Potential application in developing countries

a. Raw material supply

The highly stressed nature of the application implies the use of high quality components: epoxy resin matrix and glass or glass/carbon hybrid laminates or woven cloth. Prepregs are a perfect raw material. Until a local glass fibre production can be installed, all the raw materials must be imported.

b. Design

The design procedures are under study in industrialized countries and can be readily transferred. The outer skin of the blade is made from a composite with an inner core of foamed plastic or honeycomb.

c. Manufacture

Manufacture is by hand lay-up or oriented laminate or woven cloth prepregs in a mould. The honeycomb or machined foam is added, the top skin is laid-up in the same manner and the whole structure is cured and consolidated either in an autoclave or by pressure or vacuum-bag moulding. In the former case, investment is required in a very large autoclave. The latter technique does not require large investment but the product quality may be lower (but nevertheless sufficient for some smaller blade applications). Smaller windmill blades, for small individual dwelling units, for example, have been made by pultrusion and prove to be highly performing and cost-effective.

d. Manpower requirements

The requirements are of the rather skilled to semi-skilled variety for the lay-up. Developments are underway to filament wind structures such as windmill (and helicopter) blades, thus decreasing the need for skilled labour while increasing productivity and structural reliablity.

e. Energy and infrastructure requirements

Most composite (and plastic) manufacturing technologies are low-energy consuming and do not require large factories to be profitable. The structures are light, so that no heavy handling equipment is required.

f. Quality control

In highly stressed components, such as windmill blades, the quality is all important. In industrialized countries it poses a problem both from the point of view of cost and assurance. In developing countries, advanced composite manufacture will have to depend on imported equipment, know-how and personnel, which will make production costs extremely high.

g. Flexibility of technology

Equipment investment and manpower training for windmill blade manufacture could be equally applied to aircraft wing structures, helicopter blades and airship components[29/], all of which (with the possible exception of the latter) are not, however, of immediate interest for developing countries and which require even stricter quality control than windmill blades.

h. Utilization

A cost-effective source of energy would be of great interest for housing needs, irrigation etc. in developing countries with no indigenous fuel sources except a steady wind. In the United States, application in Hawaii is far along the evaluation stage while Nigeria is also benefiting from some research.[27]

Use of carbon fibre composites in corrosion-resistant applications will not be great until the fibre price drops well below the US$20/kg mark. Introduction as hybrids with glass is, however, an interesting approach to producing large, stiff structures such as tanks.

4. Conditions for implantation

It is felt that, if the investment in equipment can be made, labour can be trained to a sufficient level of skill to allow windmill blades to be manufactured. The problem, however, lies in the fact that the blade is only part of a wind-power generating plant and blade manufacture on-site will probably only have a very small influence on the cost of the whole plant or on the cost of electricity production. Estimates for construction cost are US$2-4/kW, and for power generation US$0.2-1/kW. These must be compared with current electricity charges of around US$0.07/kWh. Wind-power generation plants must, however, at least be of interest for countries with little indigenous energy sources, especially for isolated villages in mountains or islands.

The first condition for implantation of widespread composite blade wind-power in a developing country must be that the whole plant, not only the composite blade, be manufactured locally from imported parts and materials eventually. The second condition is that the plant be as maintenance-free as possible, and this can be ensured by high-quality mechanical and electrical equipment together with composite housings which could certainly be manufactured by techniques akin to those used in the blade manufacture. Furthermore, the technology could be used to produce composites for other sectors of industry and public consumption (buildings).

In order to install a profitable and worthwhile wind-generation plant, at least 20 plants per year should be envisaged, which means around 40 composite blades. With a blade production cycle (including mould preparation, lay-up, curing, final inspection) of around ten days, this represents work for a team of about 20 semi-skilled and four skilled staff on two moulding and one curing station (to limit investment). Further manual labour would be required for handling. Management and quality control would require high (imported) expertise and cost.

5. Limitations on implantation

The limitations on the implantation of the fabrication of windmill blades (or other advanced composite structures for that matter) are:

- in most instances, the advanced composite is part of a larger structure or equipment that is chosen in order to make the whole system more efficient (economically or technically). Examples are aerospace and automobiles. Thus, in order for composites to be effectively introduced, there must be a need for the whole structure or system and justification for its adoption and local manufacture. Thus, the composite does not entirely stand or fall on its own merits but is part of a larger decision.

- advanced composite uses in individual, consumer-type articles are limited to luxury, leisure activities such as skiing, tennis, golf and fishing that are not needed in great numbers in developing countries.

- reinforcement by advanced fibres must really be extremely worthwile in order to overcome the price differential with ordinary E-glass (US$40/kg for carbon compared with around US$1/kg for glass).

- product control is a very important part of the manufacturing cycle and, since the composites are used in increasingly severe conditions, the controls increase in number, severity and complexity. Highly skilled personnel then become necessary.

B. Glass-fibre-reinforced plastics (GRP) in construction

Background

Of those established markets in industrialized countries, the most promising and exciting for developing countries is in construction where profit could be taken from the experience gained in the optimization of composites for load-bearing applications in order to design and construct cost-effective structures. The list of potential applications in the building industry that is reproduced in table 9 is taken from a background paper published by UNIDO.[30] The present analysis arrives at very much the same conclusions so it is worthwhile to present the results of that previous evaluation.

1. Material and technology

The basic material in question is glass fibre-reinforced polyester made by contact moulding--either hand or spray lay-up--into panels. Depending on the utilization and operating conditions of stress and environment, the structure will be anywhere from 2 to 10 mm thick and consists of several laminate layers, as illustrated in figure 9. Sandwich panels may also be produced to provide higher stiffness (see figure 10). The structures produced by this technique may be both large and small for boat hulls, vehicle bodies, building panels and cladding, ducts and tanks or small dimension mouldings.

A single mould (made of GRP, wood, plaster of Paris or metal) is used so that a moulding with only one smooth surface is produced. The mould surface is coated with a silicon-free wax and a mould-release agent, such as polyvinyl alcohol is applied before each moulding operation. Between 500 and 1,000 releases can be obtained with careful treatment of the mould. Details on the technology are presented widely in the literature, reference 31 providing an excellent introduction.

Table 9.

Potential applications of fibre-reinforced composite 31/

Application	Form of basic material	Advantages	Disadvantages
Rooflights	Corrugated or flat sheet	Stronger than glass, lower weight, easier to install	Light transmission less than glass. Deterioration of light transmission due to aging
Domelights	One piece moulded or fabricated components	Low weight; easy to install	As above
Domes and other roof structures	Modular components, single or double skins	Low weight, easy to erect	Stiffening with metal or timber may be necessary
Internal partitions	Corrugated or flat sheet	Convenient. Special decorative effects can easily be incorporated	Limited use because of cost
Cladding	Flat or profiled unsupported sheet or as surface "skin" to concrete or asbestos	Low weight, range of decorative effects, versatility for individual design	Fire performance limitations and adverse effects of prolonged weathering
Sectional buildings	Modular components, often double-skinned with "sandwich" construction	Low weight and ease of handling	As above
Bathroom units	Assembled modules	As above	No specific disadvantages
Tanks and cisterns	One or two piece press mouldings	Low weight, no corrosion, low thermal conductivity	No specific disadvantages
Pipes and ducts	Continuous profiles or as cladding on concrete or PVC pipe	Strengthens concrete pipes and protects them from chemical attack. Increases temperature range for PVC pipe	No specific disadvantages
Window frames	Assembled press moulded components or as sections for cladding timber	Reduces maintenance associated with most other materials	Less suitable than timber for non-standard dimension
Concrete moulds	Mouldings generally made by hand lay-up, but sometimes by press moulding	Low weight. Gives concrete of high quality and excellent finish. Provides a new medium for architectural designs on concrete	Low stiffness means that additional support is often necessary

Figure 9.

Typical laminate construction

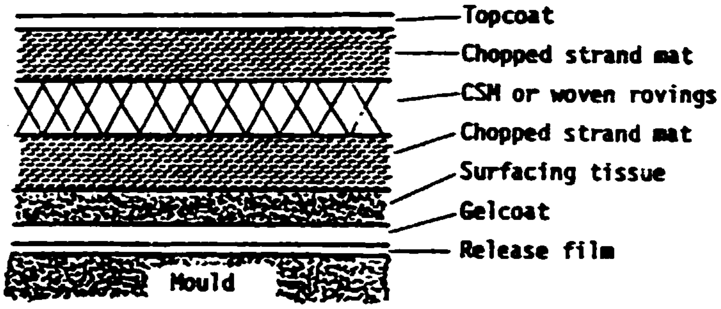
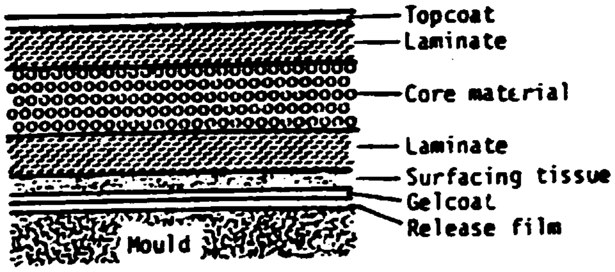


Figure 10.

Typical sandwich construction



As seen in chapter I, table 6, the properties of GRP made by the contact moulding technique are not the highest but, for large structures, they compare very favourably with other techniques and thicknesses can be very readily increased to give the required stiffness and strength.

Once the technology has been mastered for one type of structure, e.g. building panels, there is no problem to applying it to others by only changing the mould. The structure is cured either in an oven for small parts or with infrared for larger structures. The use of GRP in construction may be completed by the fabrication of the framework by pultrusion of GRP rods, tubes or profiles. Even advanced composites could be used in the framework or as structural panels in order to provide increased stiffness.

2. Stage of development[32/]

The uses of reinforced plastics in the construction industry are fairly general to all industries. Cladding panels, ceilings, roofing, domes and sanitary ware are common applications. There is hesitancy, however, to use these materials in load-bearing situations, indicating a degree of ignorance on the part of the builders and designers. The construction industry is still heavily restrained by official legislation and standards for materials in building. In the countries that have shaken free from these restrictions, the industry has shown healthy advances. The problem does not appear to be insoluble but the main stumbling block is still the fire hazard. Test conditions are critical in assessing materials for building construction and as yet no test seems to be satisfactory, short of building the project and burning it down. Flame-spread and smoke-emission tests are useful but not adequate.

Although many developing countries have a great demand for low-cost housing, very little was done to alleviate this pressing need. It may be noted here that work in the United States on low-cost plastic housing using jute-reinforced polyesters has gone past the experimental stage and 100 prefabricated houses can be turned out a day. Roofing is an extremely interesting application for GRP, as in the Argenteuil (Paris) market, the Agadir market and many covered sports stadiums.

Concrete form work still accounts for a large proportion of consumption in this field. No legislation on fire risk is operable here and reinforced plastic forms for precast or on-site casting of concrete have many advantages over wood or steel. With reinforced plastics it is possible to obtain complex shapes which are unattainable economically with other materials. A reinforced-plastics former may average 150 castings, whereas complex wood forms average between 30 and 40 and steel is about 25 per cent more costly. Other benefits of reinforced plastic forms are that they are easy to detach from the concrete and maintain their shapes, give a smooth finish, are strong and light and do not dent or rust.

3. Potential application in developing countries

Raw material supply. The raw materials are polyester and mainly chopped strand mat. The latter is a material that could very well be produced in some developing countries. Since the fibres are short, however, there is high potential for using natural fibres, such as jute (this will be treated in a later section), while still using composite material technology.

Design. Design is well-established for building panels, but there is certainly room for specific designers to satifsy specific local conditions. For example, building panels that incorporate (foamed) insulation against heat and cold, panels incorporating some form of heat storage for cold countries etc.

Manufacture. The contact moulding process is quite straightforward and should be readily introduced in developing countries. Attention should be paid to provide adequate ventilation since health may be affected by over-exposure to resin vapour. The pultrusion technique requires rather sophisticated equipment (manufactured in industrialized countries) together with the associated technology. However, since one considers this as an addition to the basic moulding manufacture, the experience gained should be invaluable in any extension to more complex technologies.

Energy/manpower. The energy cost involved in the contact moulding process is negligible compared to the materials cost and the cost of manpower. Thus, the process and the resulting products are well-suited for implantation in developing countries. Manpower requirements will be in the semi-skilled category. The pultrusion technique requires more sophisticated knowledge of the equipment itself and the product. Skilled labour is required, but attypical production rates of one metre per minute, the labour costs will be minimal in such an operation. The burden will be capital cost of the equipment and its maintenance.

Installation. Assembly of the panels will be by mechanical means, so no special skills are required. The eventual pultruded GRP frame may require special fixtures, which have been developed for loaded structures.[33/] In other cases bolting may be applied.

Utilization. The panels should be maintainance free, but must be protected against heavy impacts or high stresses over a long period. Exposure to some industrial, acid-containing environments may lead to degradation, which can be a problem in load-bearing applications. Fire remains a hazard for any structural application of GRP (for obvious reasons) and for cladding and ceilings because of flame-spreading and smoke-emission. Chemicals may, however, be added to the polymer matrix to act as fire retardants.

Tooling costs and factory space. The costs of a hand lay-up facility are in the order of US$50,000 to US$80,000 for a production capacity in the order of US$300,000 to US$500,000 square meters of product. Corresponding factory space is in the order of 2,000 square metres. To the above must be added the mould costs, which need not be excessive for initially non-load-bearing building panels.

4. Conditions for implantation

The conditions that must be fulfilled in order to consider implantation of an industry to produce building panels are as follows:

- There must be a large and well-established need for buildings--housing, commercial, school and industrial--to be supplied by a component or modular approach. This approach allows rapid construction and its success depends on the availability of factory-made components in a limited range of dimensions. GRP corresponds to this demand.

- The predominance of manual labour demands light-weight building components, again an advantage for GRP.

- Satisfaction of a large housing demand by prefabricated components can only really be met by local production.

- The country's climatic conditions must lend themselves to the component, panel approach. In the residential sector in the United States, for example, about 50 per cent of houses are built by the component approach on a light wooden frame. The panels are also predominantly wooden. In developing countries, the panels could be of GRP and the framework of wood or even pultruded GRP sections.

- National legislation is necessary on product quality and its utilization from structural, load-bearing and fire-retardant points of view.

5. Limitations to introduction of GRP building products

The number of limitations is that the matrix is polyester, and based on the petrochemical industry. If the market is sufficient, however, polyester can be imported in bulk form at perhaps competitive prices to alternative building materials, e.g. wood, brick, concrete etc.

The replacement of petrochemical-based by biomass-based resins is not for the immediate future (for economic, not technical reasons), but the (probably) imported glass fibres could be replaced by natural fibres if this proves to be a problem.

Quality of the product must be ensured and this might require the presence of more (imported) skilled labour at the outset than might be deemed desirable. The further disadvantages listed in table 9 are not unique to developing countries and can be overcome with the necessary product quality and design/construction practices.

6. Conclusion

The production of building components, principally panels, could be a very interesting industry in developing countries, and its introduction could be followed by the flourishing of a GRP industry in the following manner:

- GRP building panels made by the contact moulding process;
- Production of other housing-related products by the contact moulding process, e.g. ducts and tanks;
- Production of pultruded GRP rods or bars that could be used as the building framework, where wood is scarce or too expensive.

The contact moulding process can be further employed to cost-effectively produce:

- Forms for concrete casting of larger, industrial buildings;
- A variety of consumer products, e.g. furniture.

C. Asbestos-cement (AC) pipes

1. Pipeline demand and supply

Closely linked to the growth of product transport in general, transportation by pipeline will in the future increase in importance on a world-wide scale. Specifically, in certain Western Asian and developing countries which are currently accelerating industrialization programmes, as well as expanding housing water supply and irrigation systems, there will be a growing need for transportation of larger and larger quantities of water, natural gas, sewage, and eventually solids in the form of slurries (e.g. mineral ores).

This growing demand for pipe materials will have to be satisfied in the immediate future by the materials shown in figure 11. However, the conventional materials exhibit problems and drawbacks in developing countries from the technical, supply, transport and economic points of view, such that new solutions are required, especially in the large-diameter, medium-pressure sector which includes long-distance water transport and irrigation. Composite design and fabrication technologies already provide an answer to some of the problems in the form of asbestos-cement and glass fibre-reinforced plastics (GRP), and have further allowed a new solution to be developed in the form of a steel-plastic composite pipe.

Figure 12 illustrates schematically the approximate ranges of application of various pipe materials as a function of diameter and operating pressure. In the range from 10 to around 30 bars pressure and in diameter above about 12 inches, there is a definite gap which requires filling either by upgraded GRP pipes (possible by improved composite technology as discussed in the relevant chapter) or by the pipe material (issue of a new composite technology: steel-plastic).

Figure 13 presents a comparison of pipe prices in Saudi Arabia for 1978 but shows that for six bars operating pressure, ductile iron is the cheapest but is almost invariably imported into developing countries. Asbestos-cement and glass-reinforced plastic are seen to be highly competitive because they are fabricated in the country itself. Imported pipes would be anywhere from 20 to 50 per cent more expensive due to transport and import duty.

Of all the fabricating processes for pipes of wide potential utilization, the composite approach for asbestos-cement (AC), glass fibre-reinforced plastics (GRP) and steel-plastic are the most interesting ones for developing countries because of:

- Relatively low capital investment;
- A small-scale operation is possible;
- Local labour, supervised in some cases by skilled foremen, can be used;
- The technologies are well-developed;
- Design bases exist that can be adapted to developing country needs both for fabrication and installation.

Figure 11.

DEMAND & SUPPLY OF PIPES

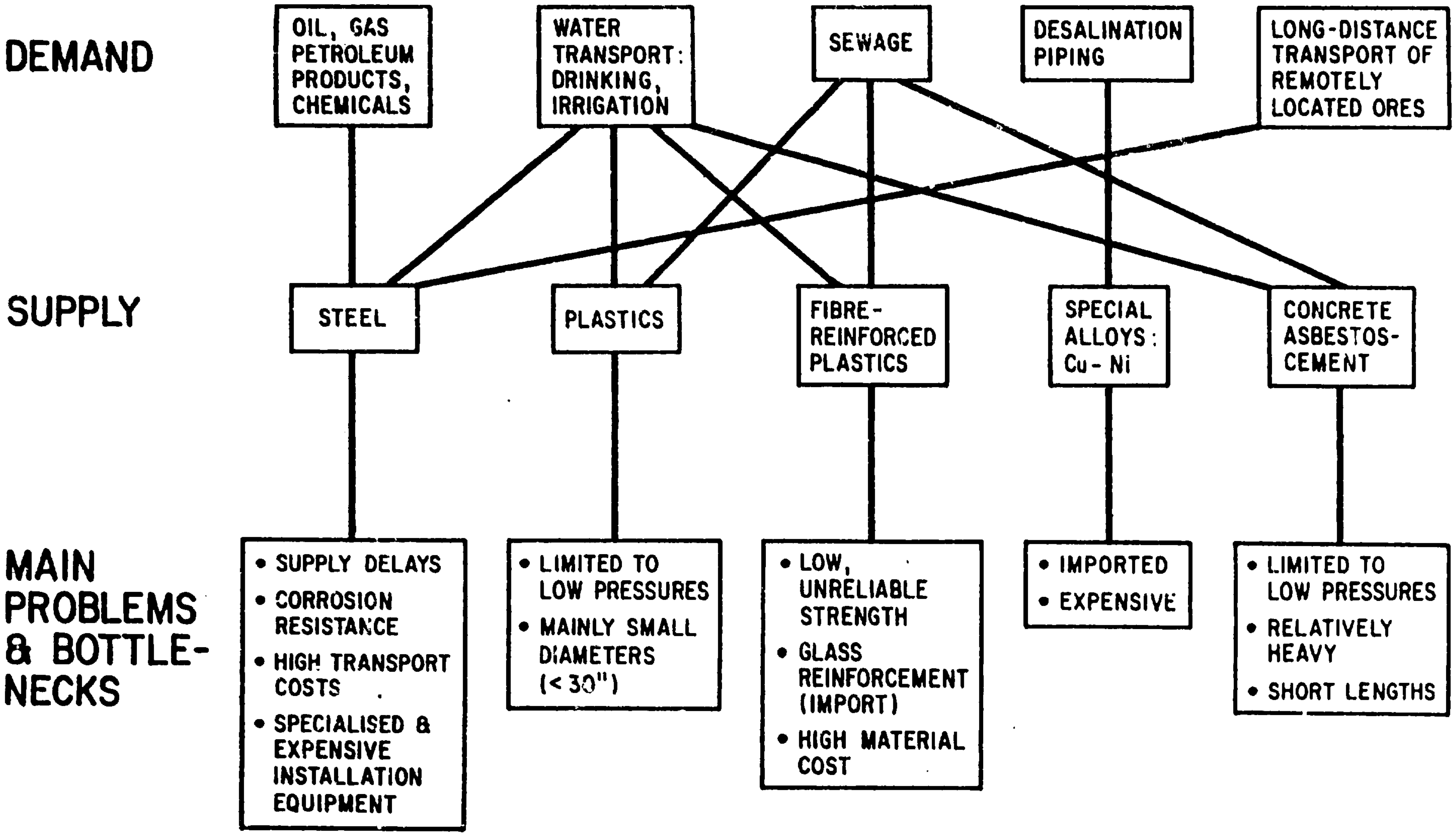


Figure 12.

APPROXIMATE RANGES OF APPLICATION OF VARIOUS PIPE MATERIALS (SHOWING GAP FILLED BY STEEL-PLASTIC)

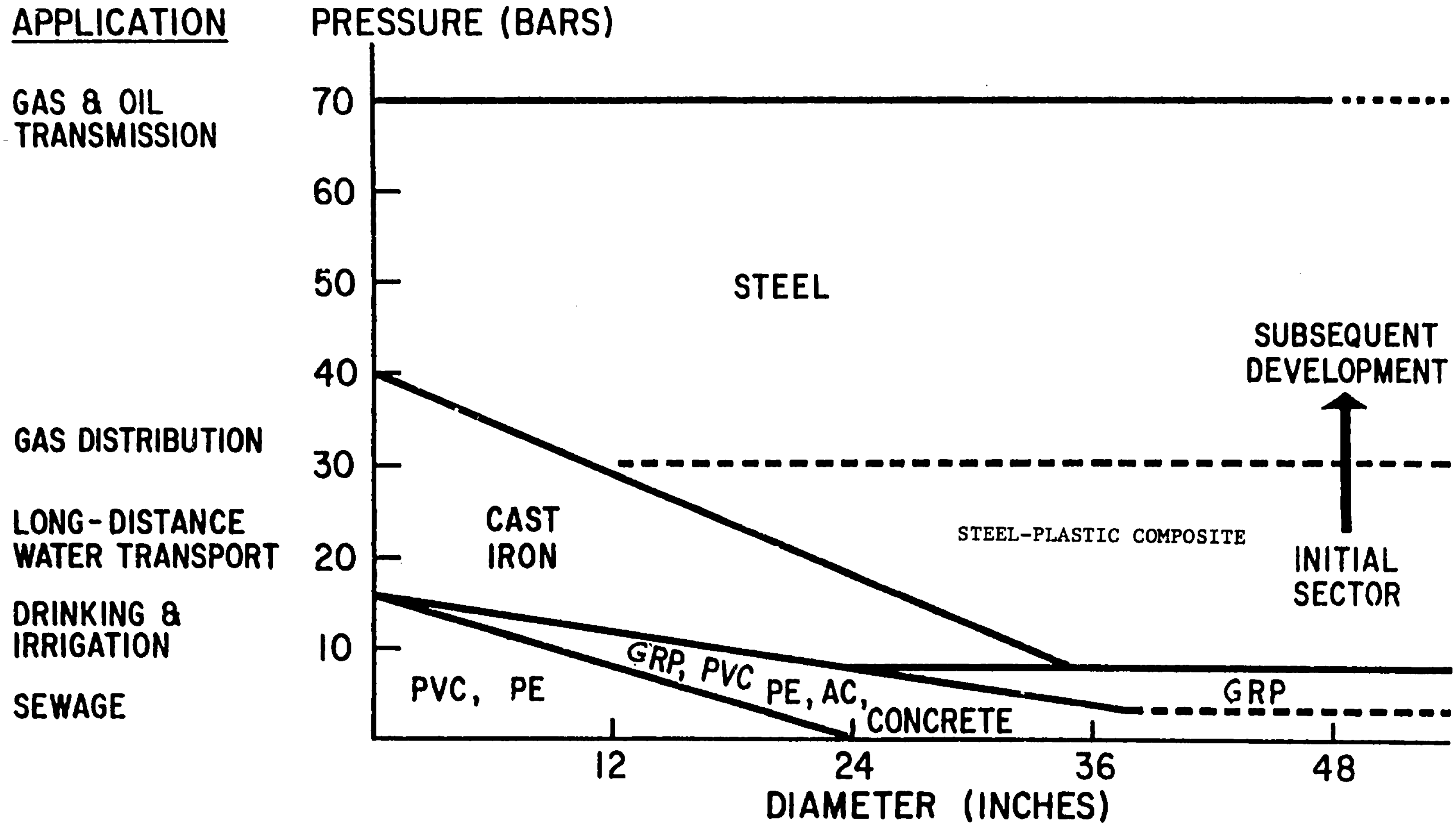
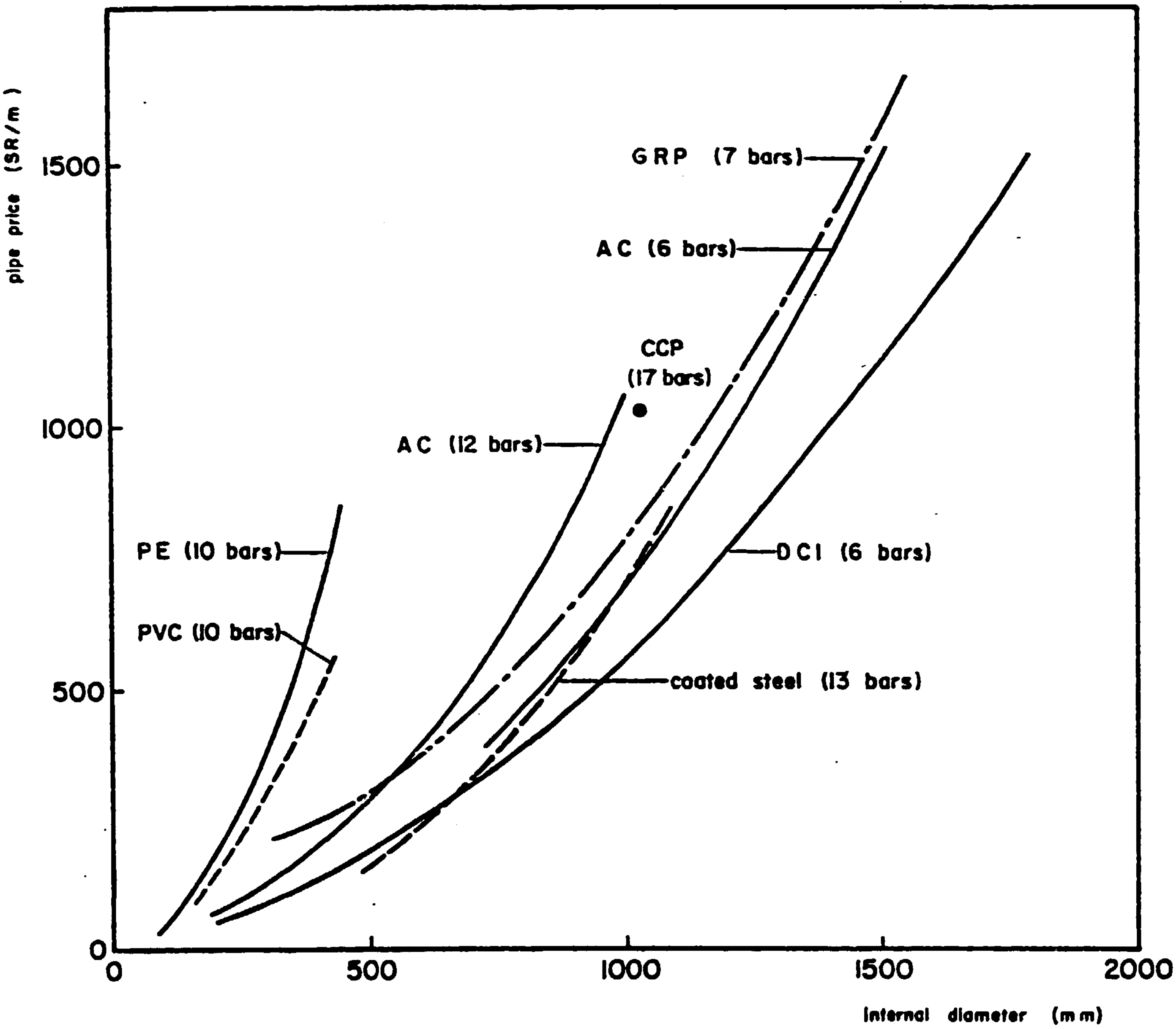


Figure 13.

Pipe material prices for medium-pressure water pipelines
quoted for Saudi Arabia in 1978



2. Material description

a. Basic materials

Asbestos-cement (AC) pipes--an already traditional pipe material in many countries--represent a real composite material, where the asbestos fibres are the reinforcing material and the cement is the matrix (about 85 per cent weight). The asbestos fibres are by virtue of the fabrication process mainly aligned in the circumferential pipe direction but also partially along the pipe axis. Despite this anisotropy in the orientation of the asbestos fibres, the mechanical properties are relatively homogeneous in the circumferential and axial directions (not in the radial direction, however), so that in view of pipe applications asbestos cement can be regarded as a quasi-isotropic material.

Asbestos-cement pipes are composed of:

- Asbestos fibres, mainly of two types: chrysotile and crocidolite asbestos. Chemically speaking they are hydrated metal silicates. These fibres are very thin, with diameters less than 0.03 μm , their lengths are in the order of 3-70 mm. They have exceptional high strengths up to 5 GPa and a modulus of about 180 GPa.

- Cement, mainly of the Portland variety.

- Water, which is consumed in the cement hardening process.

b. Properties

Some typical relevant properties of AC pipes are presented in table 10, which shows that their strength is not very high despite the fact that the reinforcing asbestos fibres are very strong. This is due to the multiple orientation of the fibres, their short length and low volume percentage. However, as far as short fibre composites are concerned, they represent the most wide-spread example.

Table 10.

Some typical properties of asbestos-cement pipes

Mechanical properties	
E-modulus (circumferential)	33 GPa
crushing strength	50-70 MPa
compressive strength (axial)	40-50 MPa
tensile strength (circumferential)	25-30 MPa
Poisson's ratio	0.17 - 0.2
impact strength	0.136 mkp/cm^2
Other properties	
density	~ 1.9 g/cm^3
porosity	up to 23%
water absorption	up to 12 - 18 weight %
thermal expansion coefficient (radial)	$1.67 \cdot 10^{-5}\ {}^{o}K^{-1}$
(axial)	$1.25 \cdot 10^{-5}\ {}^{o}K^{-1}$
heat conductivity	0.58 - 0.35 kcal/m.h.°C
long time temperature resistance	$\leq$ 300°C

As with other materials which harden by chemical reactions, and in particular with cements, there is an increase of up to 15 per cent in some of the mechanical properties over an initial period of one to two years due to post-hardening processes. AC pipes are rather resistant against the abrasion by sand/water mixtures, such as found in sewage lines. It has been shown that the abrasion-resistance is mostly due to the asbestos fibres.

The corrosion resistance of AC pipes is very high in neutral or slightly alkaline conditions, which is generally the case for drinking water and domestic sewage. In acid conditions (pH below 6), the pipes may be affected, especially in industrial sewage or in sewage systems with low flow rates. In stagnant sewage, sulphate producing bacteria lead to degradation of the cement and either special cements have to be employed, the pipes coated or other materials used, such as GRP.

c. Health hazards in connection with the fabrication and use of AC pipes

It is recognized that asbestos fibres present a health hazard when inhaled in significant amounts into the lungs over prolonged periods of time. This imposes the corresponding restrictions on the fabrication of the AC pipes, especially concerning the preparation of the materials mixture.

Concerning the possibilities of introducing asbestos fibres into drinking water by the use of AC pipes, it has been stated variously that the probability of risk to health is small, approaching zero. However, additional evidence on this subject is still desirable in order to arrive at a studied, reasonable conclusion. On the other hand results exist showing that the asbestos content of water in AC pipes is no higher than background asbestos content of water extracted from the rocky terrain. On the other hand certain countries, Scandinavia especially, are banning all use of AC pipes for water transport.

d. Fabrication[34/]

AC pressure pipes are generally produced by two different methods: the Mazza and the Magnam procedures. The most widely employed technique is the Mazza procedure that uses a continuous winding process. The mixture of asbestos fibres, cement and water is applied as a thin film to an endless belt which carries the film to a rotating steel mandrel. The mandrel picks up the film and each lamination is consolidated under pressure up to the final wall thickness.

Some hours after the winding of the pipe the mandrel is removed and the pipes are either hardened in water (about a week) or with steam (about 24 hours). The final hardening of the AC pipes takes up to six weeks. Only then is final testing of the pipes carried out--30 seconds at twice the international service pressure--and delivery can follow.

3. Stage of development

AC pipes are already made in many developing countries, representing a very cost-effective answer to pipeline transport of mainly water (drinking and irrigation), drainage and sewage. The technology is well-established and readily transferable.

AC pipes are normally made in lengths of up to 5 m, with diameters between 50 and 1,800 mm. Maximum diameters are up to 2,500 mm. The smaller pipes are produced in shorter lengths because of thin wall flexural problems. It is a rather light pipe. For example, an AC pipe, one meter long with 400 mm internal diameter and for a service pressure range of 10 bars weighs about 90 kg, whereas a corresponding cast iron pipe weighs about 158 kg.

AC pipes are standardized for pressures of 2.5 to 16 bars. The upper pressure limit is in general about 10 bars. The pressure limits of AC pipes are given by their properties and are not, it seems, dictated by the efficiency of the joints. The matching of different pressure ranges is made in the case of the AC pipes, as with most other pipe materials, by increasing the wall thickness.

4. Potential application in developing countries

a. Raw material supply

The use of asbestos-cement products (building, pipes etc) represents around 30 million tons world-wide. Its qualities of durability and non-combustibility linked to low cost make it a very attractive structural material. The health hazard is mainly associated with asbestos handling; proper care in fabrication and utilization of asbestos-cement products is effective in removing risks. Several western countries have already banned the use of asbestos cement, but it will certainly continue to be used in many other industrialized and developing countries until a material that is reliable and equivalent in price is found.

b. Design

AC pipe design is well-established by national and international codes that are readily applicable in developing countries. Typical pipe classes established by Saudi Arabian Standards SAS 5/1396 H (1976) are given below in table 11.

Table 11.

Pipe classification according to the internal pressure tightness test, providing that the working pressures do not exceed the values indicated

Class	Internal hydraulic tightness test pressure		Maximum working pressure	
	MPa	kgf/mm^2	MPa	kgf/mm^2
Class 6	0.6	0.06	0.3	0.03
Class 12	1.2	0.12	0.6	0.06
Class 18	1.8	0.18	0.9	0.09
Class 24	2.4	0.24	1.2	0.12
Class 30	3	0.30	1.5	0.15
Class 40	4	0.40	2	0.20
Class 50	5	0.50	2.5	0.25

c. Manpower equipment

The fabrication technique is so well-developed that equipment is normally fully automated, thus requiring few skilled workers for actual production. Skilled workers would be required for management, equipment maintenance and product quality control representing a total of around five.

The advantage of entering the AC-pipe-production sector is that other products, such as for building can also be made with different equipment, but with essentially the same basic technology and manpower.

d. Utilization

Pipe utilization and installation are straightforward and represent no major problems. For long-distance-pipeline transmission, the pipes are normally buried and joined by mechanical couplings, typical ones being Reka which are also made of AC and produced by the same process, and incorporate rubber sealing rings to ensure easy alignment and leak-proof performance. Their installation is predominantly labour-intensive with skilled manpower required for supervision and testing.

5. Conditions for implantation

The conditions that must be fulfilled in order to consider implantation of an industry to produce AC pipes are as follows:

- There must be a well-established need for water, irrigation and sewage piping so as to justify investment.
- There should, if possible, be local construction companies capable to install the pipes with little investment.
- National legislation on product quality and utilization is not a prerequisite for introduction since initially standards of other countries may be followed.
- Strict care will have to be guaranteed during fabrication, handling and installation to remove any health hazards.
- Locally available raw materials, i.e. cement production and asbestos, would lead to a more rapid introduction, but are not indispensable if they can be cost-effectively imported.
- Transport capabilities (trucks, road infrastructure) for pipes which are rather heavy and sensitive to damage.

6. Advantages and limitations

The well-documented advantages of AC pipes and their main disadvantages are listed below in table 12.

Table 12.

Advantages and main disadvantages of AC pipes

Advantages	Main disadvantages and their consequences	
1. Reasonably cheap	1. Relatively low strength	a. Pressure limitation
2. Simple joining		b. Thick wall pipe
3. Good corrosion resistance under normal circumstances with sulphate-resisting cement		c. Heavy pipes for pressure applications
	2. Quite brittle	a. Careful handling b. Exfoliation at cut ends
4. Large experience in Western Asia and elsewhere	3. Mechanical joining	a. Limits pressure
5. Smooth bore	4. Short pipe lengths • production technique for large diameter • bending design for small diameter	a. Rather slow laying on cross-country lines
	5. Eventual health hazard: • pipe itself • manufacture • on-site cutting	a. Difficult to assess

The fabrication techniques of asbestos cement products can, with limited and inexpensive equipment modification, be applied to glass fibre-reinforced cement (GRC) products (pipes, sheets etc). Such a drive to replace asbestos is taking place because of the health question, but no commercial breakthrough has yet taken place mainly because of cost and, as far as glass fibres are concerned, long-term stability problems in the akaline cement.

A great deal of money and R and D effort has gone into finding replacements for asbestos using AC fabrication techniques. However, properties of alternatives such as cellulose-reinforced cement, polypropylene-reinforced cement and glass-reinforced cement are generally inferior to those of asbestos cement, except when made by a different technique such as spray lay-up for GRC.[35,36] A recent development utilizing an acrylic fibre appears to have promise,[37] but is not yet an industrial proposition. Such alternative composite materials for structural purposes have penetrated the developing countries, as exemplified by joint ventures by a leading European glass fibre producer in Western Asia.

7. Conclusion

Asbestos cement pipe and building material production can be introduced in developing countries without excessive technical or skilled manpower problems. Raw materials supply may be local or bulk-imported. Fabrication in the country reduces expensive transport costs and import duties.

The health hazards may be removed by appropriate care in fabrication and utilization. Replacement of asbestos is not foreseen on a large scale, although composite material design principles may be applied, because of cost and reliability questions. Replacement is taking place, and will continue, by other completely new products such as glass-fibre-reinforced plastic, already established in many pipe sectors.

D. Large diameter fibre-reinforced plastic pipes (GRP pipes)

Background

Glass-fibre-reinforced plastic pipes (GRP) are composed of resin and fibreglass reinforcements. The resins used are nearly all of the thermosetting type, the most important for GRP pipes being the polyesters and epoxies. Among these, many resin systems are available that provide a wide range of chemical resistance and mechanical properties.38/

The most critical factor in the design of GRP pipes is the resin since, although any loads on the pipe will be supported by the glass fibres, the resin must distribute the loads to the fibres and various laminae. For this reason it is very important that the resin be flexible enough to avoid premature micro-cracking under load. At the same time it must also provide corrosion protection for the fibres.

The strength properties of GRP pipes are, of course, related to the choice and arrangement of the glass fibres. The glass fibre reinforcement (normally E-glass) for GRP pipes can be used, depending on the pipe design and the manufacturing technique, in different forms:

- Continuous rovings. These consist of a multiplicity of parallel (without twist) glass fibre strands. In filament winding they are impregnated with the resin system and wound on a mandrel;
- Fabrics or tapes;
- Mats;
- Chopped fibres.

Without continuous rovings and fabrics the strength properties obtained are directed by the choice of winding geometry. With mats and chopped fibres, isotropic properties are obtained.

1. Materials and technology

The basic properties of glass fibre-reinforced plastics depend strongly on the type of reinforcement (rovings, fabric, chopped mat etc.) and its volume content in the structure. Typical properties for different reinforcement geometries have been presented earlier in this paper. The general properties offered by GRP pipes can be summarized as follows:

- High strength-to-weight ratio
- High resistance against internal and external attack
- Good durability
- Low thermal conductivity
- Medium range of temperature resistance
- Light weight coupled with easy handling and installation.

The properties (both strength and corrosion) of GRP pipes vary from producer to producer and depend strongly upon the foreseen application. This is understandable since GRP pipes are truly composite pipes, which can be tailor-made to meet the specific requirements. Also, standardization work on GRP has not yet progressed sufficiently, though in many countries appropriate standards have already appeared or are in the drafting stage.

GRP pipes are made in diameters as small as 50 mm up to very large (3,000 mm or more). They are made in various lengths, e.g. 6 meters, 12 meters or even in semi-continuous lengths. Working pressures of GRP pipes vary with pipe diameter. The smaller the pipe diameter the higher the design pressure, up to about 140 bars. The typical pressure range is between 20 and 40 bars.

GRP pipes are designed with [illegible] security factors ranging from 6 to 10.[39] These security [illegible]ied either against the short-time weeping strength or [illegible] strength, depending on the wall structure of the GRP pipe[illegible] GRP pipes with a high glass-fibre content the design re[illegible] is the "weeping" strength. With low glass-fibre contents (40 per cent) the design reference is the burst strength. The pressure for proof testing is 1.5 times that of the design pressure.

2. State of development

There exist different types of GRP pipes and, correspondingly, the fabrication techniques also vary. The most important among them are filament winding and centrifugal casting.40/

a. Fabrication

Filament winding. Filament-wound pipes are normally produced by winding specifically oriented resin-impregnated glass fibre rovings on to a mandrel. Figure 14 shows a schematic representation of basic filament-winding machines. The most common fabrication techniques involve:

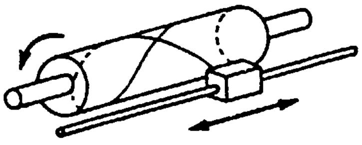
- Biaxial winding. The rovings are applied in the hoop and longitudinal directions. The longitudinal reinforcement can also be provided by hoop-winding large fabric tapes with the main reinforcement direction parallel to the pipe axis. The longitudinal reinforcement can also be achieved by a pultrusion equipment section, combined with the hoop-winding technique. This concept has been proposed for continuously manufacturing pressure pipes. The biaxial winding can also be adapted to semi-continuous and fully continuous machines.

- Helical winding. This method is applied only on discontinuous machines, which could be modified, conventional lathe-type machines. Mandrels can be either solid or callapsible. The hoop and longitudinal pipe strength are determined by the helix angle. With this type of manufacture the joint profiles may be moulded integrally with the pipe.

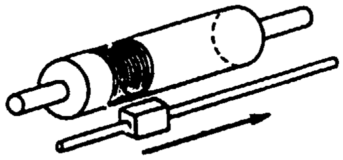
The application of the resin can be carried out either by using preimpregnated rovings or immediately prior to the winding of the rovings on the mandrel (wet impregnation). For the manufacture of GRP pipes, virtually only the latter technique is applied because it involves lower cost, although the preimpregnated technique has some advantages, such as closer control of the filament percentage and higher winding speeds.

Figure 14.

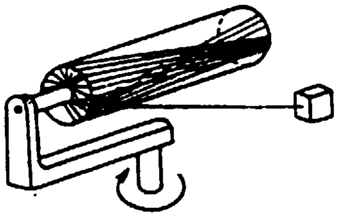
Schematic representation of basic methods and types of filament placement



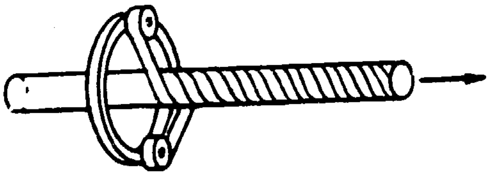
A. CLASSICAL HELICAL WINDER



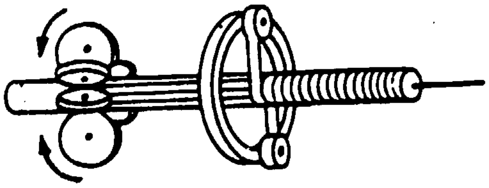
B. CIRCUMFERENTIAL WINDER



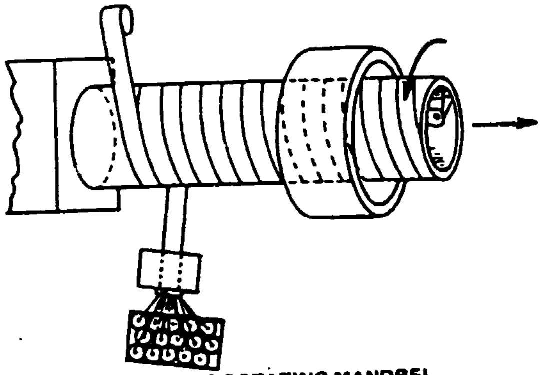
C. POLAR WINDER



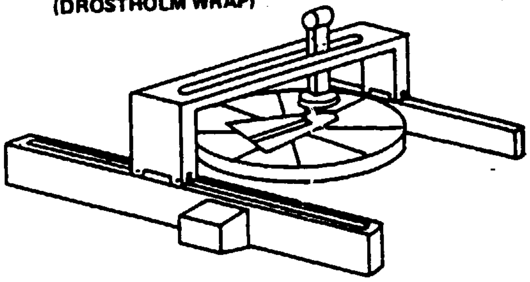
D. CONTINUOUS HELICAL WINDER



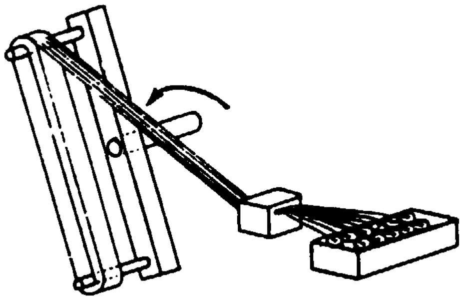
E. CONTINUOUS NORMAL-AXIAL WINDER



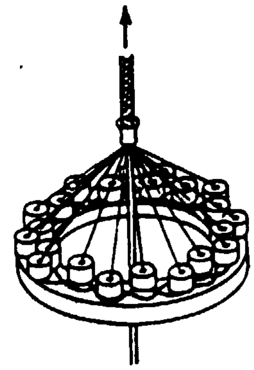
F. CONTINUOUS ROTATING MANDREL
(DROSTHOLM WRAP)



G. FIBER-PLACEMENT MACHINE



H. LOOP-WRAP WINDER



I. BRAID-WRAP WINDER

Continuous fabrication techniques. The biaxial filament winding technique is well suited for continuous GRP pipe manufacture and has been applied in semi-continuous machines, characterized by the fact that they can produce much longer pipe sections than the discontinuous ones. To this category belongs the Drostholm machine which cannot be regarded as a truly continuous machine because the mandrel rotates, as illustrated in figure 15.41/ The mandrel is in this case a continuous steel band supported in a cylindrical shape by discs which are interchangeable to produce pipes of various diameters. As the discs rotate, friction pulls the band around allowing it to move longitudinally. Production rates can vary from 6 meters per hour for large diameters (approximately 3 m) up to 20 m per hour for the smaller diameters.

The basic machine principle is shown in figure 16, the manner of material application producing a pipe structure illustrated in figure 17 for low pressure applications. For high-pressure pipe (10 bars), the sand filler is not present.

b. Joining

There exist different commercial joining techniques for GRP pipes depending on the pressure range of application and the manufacturing technique employed.42/

c. Application

GRP pipes constitute one of the most versatile pipe material classes since they cover both pressure and non-pressure pipe work over a wide range of diameters beginning at about 25 mm and going up to 4,800 mm with current production equipment.43,44/ Although of relatively recent introduction on the market, GRP pipes already have proved themselves, in competition with existing pipe materials, in several traditional markets, such as water distribution, sewage and effluent disposal and chemical process work. The required properties in these and other applications which favour the use of GRP are:

Figure 15.

The mandrel of a Drostholm machine

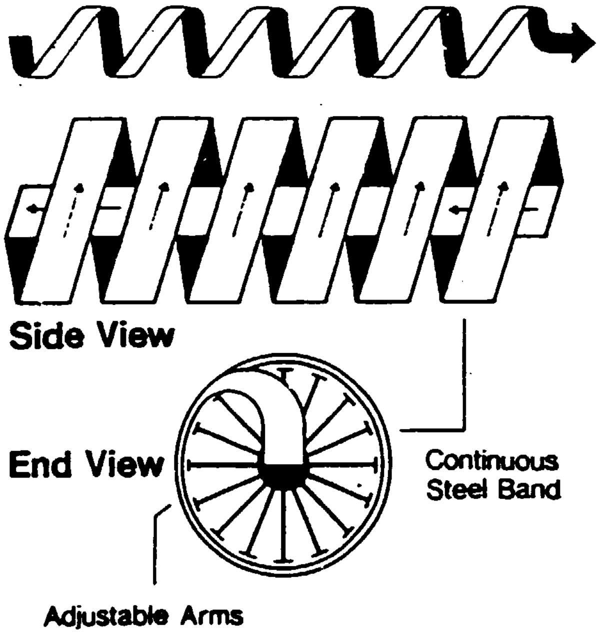
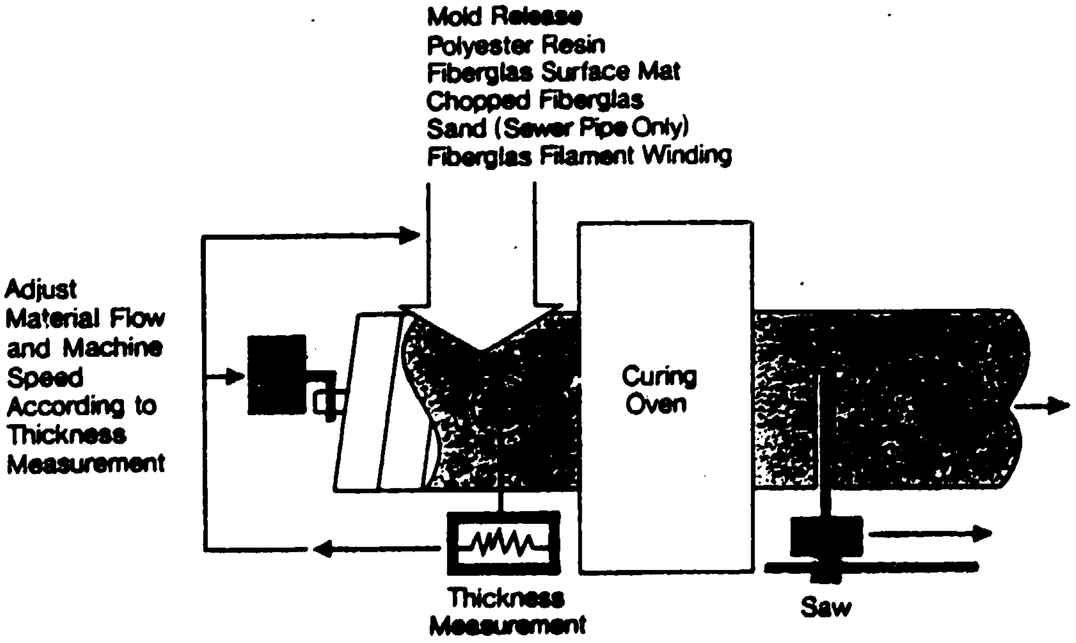


Figure 16.

Basic machine principle of continuous fabrication

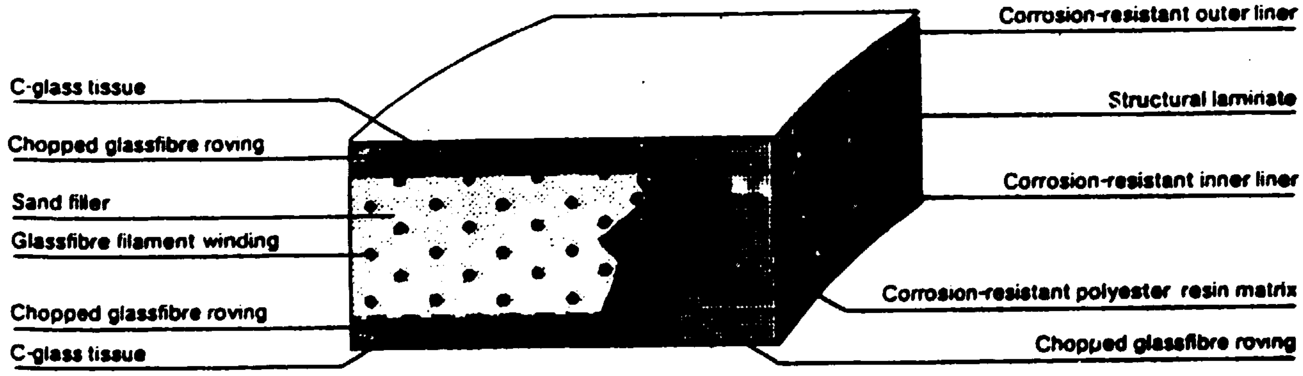


- Corrosion resistance to external attack of aggressive soil conditions.
- No contamination of the transported products: no tendency to support the growth of yeasts, fungi or bacteria.
- Corrosion resistance to internal attack by aggressive products being transported.
- Resistance to internal pressure.
- Resistance to external loads such as backfill, wheeled traffic etc.

Concrete examples of application of GRP pipes are in the chemical industry for brine lines, waste effluent lines, process piping, condensate lines and pickling lines; in the petroleum industry for salt water lines, condensate lines and waste treatment lines; in the pulp and paper industry for wood-fibre slurries, waste liquor, paper stock, chlorine solutions, dyes etc.

Figure 17.

Sketch of sewerage pipe and 0-6 bars pressure pipes



3. Potential application in developing countries

a. Raw material supply

The glass fibres could eventually be fabricated in some developing countries. The basic raw material, namely, silica is the main component of sand, but sand composition varies widely throughout the world, thus necessitating special developments to produce glass-quality sand. The glass fibres made from sub-quality sand are not suitable for reinforcement, producing only glass-wool (insulation product). Thus, initially at least, glass fibres would have to be imported.

The resin used exclusively for the large diameter water and sewage pipes is polyester, which again would have to be imported except in countries possessing a petrochemical industry. If the market exists, importation of the above-mentioned materials in bulk should be much more cost-effective than importing the ready-made pipes. The sand for low pressure pipes can be local quality, suitably cleaned and treated to provide a good finished product.

b. Design

Pipe material design according to composite material principles is very well established so that pipes can be readily manufactured to meet specific operating conditions. The American Society for Testing and Materials (ASTM) has developed many standards and codes which can be used for specifying, testing and installing GRP pipe, as seen from the list in table 13.

Buried GRP pipes are classed as flexible conduits and as such differ fundamentally from rigid conduits, such as asbestos-cement or concrete. They rely on a soil-pipe interaction to carry loads imposed by the backfill.[45] Thus, installation technique is of almost as much importance to performance as the pipe properties, so control must be strictly exercised.

Table 13.

Glass fibre-reinforced plastic pipes
(United States Standards and Codes)

STANDARDS AND CODES

Raw Materials	
ASTM C581	Test for Chemical Resistance of Thermosetting Resins used in Glass Fiber Reinforced Structures.
ASTM D633	Test for Tensile Properties of Plastics.
ASTM D648	Test for Deflection Temperature of Plastics Under Load.
ASTM D671	Test for Flexural Fatigue of Plastics by Constant-Amplitude-of-Force.
ASTM D790	Test for Flexural Properties of Plastics.
ASTM D2343	Test for Tensile Properties of Glass Fiber Strands, Yarns, and Rovings Used in Reinforced Plastics.
Finished Products	
ASTM D695	Test for Compressive Properties of Rigid Plastics.
ASTM D1598	Test for Time-to-Failure of Plastic Pipe under Constant Internal Pressure.
ASTM D1599	Test for Short Time Rupture Strength of Plastic Pipe, Tubing, and Fittings.
ASTM D2105	Test for Longitudinal Tensile Properties of Reinforced Thermosetting Plastic Pipe and Tube.
ASTM D2143	Test for Cyclic Pressure Strength of Reinforced Thermosetting Plastic Pipe.
ASTM D2290	Test for Apparent Tensile Strength of Ring or Tubular Plastics by Split Disc Method.
ASTM D2310	Classification for Machine Made Reinforced Thermosetting Resin Pipe.
ASTM D2412	Test for External Loading Properties of Plastic Pipe by Parallel Plate Loading.
ASTM D2517	Specification for Reinforced Epoxy Resin Gas Pressure Pipe and Fittings.
ASTM D2583	Test for Indentation Hardness of Plastics by Means of a Barcol Impressor.
ASTM D2992	Test for Hydrostatic Design Basis for Reinforced Thermosetting Resin Pipe and Fittings.
ASTM D2996	Specification for Filament Wound Reinforced Thermosetting Resin Pipe.
ASTM D2997	Specification for Centrifugally Cast Reinforced Thermosetting Resin Pipe.
ASTM D3262	Specification for Reinforced Plastic Mortar Sewer Pipe.
ASTM D3517	Specification for Reinforced Plastic Mortar Pressure Pipe.
ASTM D3567	Method for Determining Dimensions of Reinforced Thermosetting Resin Pipe and Fittings.
NSF Std.15	Thermoset Plastic Pipe, Fittings, Valves, Tanks, Appurtenances, Joining Materials and Thermoset Potable Water Supply Systems.
ASME Case 1792	Fiberglass Reinforced Thermosetting Resin Pipe (Section III, Division 1/Nuclear Power Plant Components/Cases of ASME Boiler and Pressure Vessel Code).
NBS PS16-69	Custom Contact - Molded Reinforced - Polyester Chemical - Resistant Process Equipment.
API Spec.5LR	Reinforced Thermosetting Resin Line Pipe (RTRP).
API Spec. RP5L4	Care and Use of Reinforced Thermosetting Resin Line Pipe.
Mil-P-22245 A (Docks)	Military Specification - Pipe and Pipe Fittings, Glass Fiber Reinforced Plastic.
USAF	Reinforced Plastic Mortar Pipe (RPMP).
SCS432G	Irrigation Pipeline - Reinforced Plastic Mortar.
UBC	Glass Fiber Reinforced Plastic Pipe.
USBR C380	Reinforced Plastic Mortar Pressure Pipe.
Standards in the Preparation or Approval Process	
AWWA	Standard for Glass Fiber Reinforced Thermosetting Resin Pipe (RTRP and RPMP).
ASTM X-23.10-8-14	Standard Recommended Practice for Underground Installation of Flexible Reinforced Thermosetting Resin Pipe and Reinforced Plastic Mortar Pipe.
ASTM X-23.10-17-2	Specification for Large Diameter Filament Wound Reinforced Thermosetting Resin Pipe.
ASTM X-23.11-4-3	Specification for Reinforced Plastic Mortar Sewer and Industrial Pipe.
ASTM X-23.13-9-7	Test for Determining the Chemical Resistance Properties of Reinforced Thermosetting Resin Pipe in a Deflected Condition.
ASTM X-23.14-14-4	Specification for Reinforced Plastic Mortar Pipe Fittings for Non-Pressure Applications.
ASTM X-23.14-15-5	Specification for Bell and Spigot Reinforced Thermosetting Resin Pipe Joints Using Flexible Elastomeric Seals.
ASTM X-23.16-2-8	Specification for Glass Fibre Reinforced Polyester Manholes.

Source: The American Society for Testing and Materials

c. Manufacture

In the area of water and sewage and eventually slurry pipes discussed here, the resin matrix will be polyester and fabrication either by filament winding or centrifugal casting for both pressure and non-pressure pipe. The centrifugal casting technique has the advantage of being relatively simple, using fully automated equipment for resin, fibre (and sand) feeding, but the equipment itself is rather expensive. Filament winding can be done manually on suitable diameter mandrels or automatically on discontinuous or semi-continuous equipment, the cost of which is in the order of US$500,000 to 1 million.

For many of the initial applications in developing countries, the working conditions will not be too severe so that hand lay-up pipes could be employed. Subsequently, however, quality will have to be ensured by automatic equipment such as the Drostholm machine. In fact, developing countries which have had an activity in glass fibre-reinforced plastics for some 10 or more years (India and Mexico, for example) rely heavily on hand lay-up technology and utilizations lie in corrosion-related activities (pipes, tanks etc.), transport (trucks) and construction. However, countries such as the United Arab Emirates and Saudi Arabia, which more recently have come on the composite scene, already utilize filament winding (i.e. low manpower utilization) for pipe production.

d. Manpower

Manpower requirements are quite high for hand lay-up pipes. For one winding machine, approximately three skilled foremen and nine semi-skilled workers are required for raw materials control, manufacture and quality-control tasks, and around 10 labourers for handling etc. For automatic equipment the skilled labour will have to be increased to around five (to include the machine maintenance), while the total of semi-skilled workers and labourers can be reduced to around 10.

e. Energy infrastructure

As with most plastics-related fabrication, the energy requirements are low and should represent no problem for most developing countries. Equally, the plant lay-out is relatively simple and requires no special facilities or precautions apart from careful work.

f. Applications

The actual use pattern of pipe materials depends on the local environmental conditions and the pipe materials being offered (and their price). All things being equal, glass fibre-reinforced plastics find their largest markets in applications where pipes are exposed to corrosive environments: either externally such as in aggressive soil, or internally from sewage and industrial effluent, chemical process piping. They are also utilized in water transport and distribution where they maintain the purity and allow no bacterial growth. Land reclamation projects in Pakistan have also used GRP pipe.

In Western Asia, for example, in the smaller diameter range (approximately 400 mm), they are not economically competitive with thermoplastics except at higher pressures (16-25 bars) or high temperature operation (industrial effluents, for example). Above this diameter, they find competition with vitrified clay in sewage transport until about 600-800 mm but stand virtually alone above this diameter at the moment.

Apart from a chemical plant that is a large and a growing market for high-quality filament wound pipes mainly with epoxy resin matrices (see section F), the water and sewage area has seen many applications of polyester resin pipe, and their use in gravity or low pressure water and sewer pipelines would seem to be so well proven in Europe and the United States that their acceptance in new areas of the world should be no problem, as already shown in Western Asia[46/], as long as:

- The specific local environment is taken into consideration in material choice and design.

- Testing is carried out with pipes in conditions stimulating those to be found in practice.
- Certain modifications in installation technique may be possible due to the local situation.
- The manufacturer is in more-or-less complete control of the commissioning.

As far as pressure pipes are concerned, there is again a considerable practical experience in Europe and the United States and this can certainly be transferred to other countries with the above provisions even further reinforced, especially as far as material testing and evaluation is concerned.

An important step in the right direction was taken in 1975 with the construction of a dual 1600-1700 mm, 29 km water pipeline in Iran using GRP (Owens Corning). The choice was based mainly on the ability of the GRP pipe to withstand the corrosive soil conditions in the Persian Gulf area. The line transports water as part of a pipeline-canal system from the Karun River near Ahwaz in southwestern Iran to Bandar Shahpour, a coastal city on the Persian Gulf. The water, which will be carried at 3 bars, is used for commercial, industrial and residential purposes. The pipe runs directly through the Persian Gulf flood plain, which has an extremely high salt content, but which has no effect on the GRP while others would be corroded.

The biggest problem in extrapolating GRP to wide usage, for example, in Western Asia, is that there are so many material variables involved that standard products can only be offered after a certain amount of local experience has been obtained. Increasingly, however, GRP pipes are proving themselves indispensable in developing countries in certain land reclamation projects, sewage schemes (200 km in 1977 in Western Asia alone) and irrigation schemes in the Savanna Belt.

Special points to be looked at for GRP application in warm countries concern the high temperatures; both ambient and of the products transported. These are in part overcome by the use of appropriate resins a, ' suitable design factors.

4. Conditions for implantation

The conditions for implantation of glass fibre reinforced plastic pipe production capacity in a developing country are as follows:

- A well-established market must exist for water and sewage pipe;
- The raw material can be obtained locally or imported at competitive prices;
- Skilled or semi-skilled labour must be available;
- Initial know-how will have to be imported for hand lay-up on a relatively simple filament winding equipment;
- Investment will have to be available for more complex and automated filament winding or centrifugal casting equipment;
- The pipe quality offered must be guaranteed to be high and reproducible;
- Technical assistance must be offered on how best to install and utilize the pipe;
- A technical collaboration must be set up with a well-established pipe producer, at least in the initial stages. A joint-venture is also a valid manner in which to introduce this new technology to developing countries;
- The pipe material must be cost-competitive from the final installed cost point of view.

5. Limitations

Table 14 lists some of the major advantages and limitations of using GRP pipes. With respect to developing countries, the most severe disadvantages will be the cost and the fact that the material is relatively new compared to steel, vitreous clay or asbestos cement. They should not, however, prove to be insurmountable except in very remote countries where any local investment would be hampered by lack of infrastructure or basic semi-skilled labour.

Table 14.

Glass fibre-reinforced plastic

Advantages	Main disadvantages and their consequences	
1. Excellent corrosion resistance	1. Long-term behaviour difficult to predict	a. High safety factors b. Pressures limited c. "Higher than necessary" costs
2. High strength-to-weight ratio	2. Relatively expensive	Limitation on areas of application
3. Light weight	3. Production steps not completely controlled	Structure defects
4. Low thermal conductivity	4. Delicate laying	a. Stricter specification on backfill and handling than on AC b. Introduction of damage
5. Low flow resistance	5. Wide variety of producers	Choice of pipe difficult
	6. Standards not yet harmonized	Choice of pipe difficult

6. Conclusions

Glass fibre-reinforced plastic pipe production for local consumption is suitable for introduction into developing countries provided that the economics are correct: including resin and glass fibre, fabrication, transport and installation. The techniques of fabrication are well-established and a variety of pipe diameters and pressure ratings can be produced by simply changing the mandrel.

No excessive investment or requirement of many skilled workers is involved. Profit may be drawn from many years of experience world-wide, and improving designs and manufacturing techniques are becoming available as fall-out from the high-technology, advanced composite material sector.

E. Steel-plastic composite pipes

Because of some of the problems, listed previously in table 10, and the fact that a pipeline market sector between about 10 and 30 bars pressure at diameters above 12 inches is relatively poorly satisfied, a pipe material and a manufacturing process have been recently developed, which furthermore satisfy the product requirements listed below:

- Maximum cost effectiveness;
- Ease of fabrication, transport and installation;
- Possibility of on-site fabrication;
- High reliability during operation;
- High corrosion-resistance;
- Good, predictable strength characteristics;
- Possibility of wide variation in characteristics and dimensions to satisfy wide market.

1. Material and technology

The composite material, currently produced by Dunlop, is manufactured by the helical winding of several layers of high-strength steel sheet (thickness around 0.5 mm) in an epoxy of polyester resin matrix. The main advantage of using steel sheet from the fabrication point of view is that a high-strength pipe can be obtained by a simple, continuous process neither requiring high investment, such as for steel pipes nor the sometimes complex winding machines for certain glass fibre-reinforced plastic (GRP) pipes.

The structure of the pipe walls ensures a high, reproducible and predictable strength while the resin provides the necessary corrosion resistance. Different combinations of steel and resin lead to a whole variety of pipes to satisfy various service conditions. Normally 25 to 50 per cent volume of steel is employed and typical characteristics are presented in table 15 for production pipes.

Table 15.

Steel-plastic composite pipe production data[47]

Standard pressure classes	6, 10, 16 and 25 bar
Maximum operating temperature (standard pipes)	80 degrees C
Ultimate tensile strength (hoop)	200 MPa/min
Ultimate tensile strength (longitudinal)	108 MPa/min
Specific stiffness	60 GPa/min
Coefficient of linear expansion	12×6^{-6} per degree C
Hazen-Williams "C" value	150
Chemical resistance	typical of conventional epoxy systems

2. Stage of development

The status of the development of the steel-resin composite pipe has reached the stage where pipes from 20 to 200 cm diameter are produced industrially in lengths up to 12 meters for uses in water and sewage transmission, slurry transport (phosphates, China clay, clinker etc.), chemical plant, tankers and boats etc.

Currently, opportunities of local, on-site manufacture are being researched in order to reduce transport and labour costs. Further development work is oriented towards continuous fabrication which would lead to decreased manufacturing costs and/or increased productivity, together with the potential for truly on-site, over-the-ditch manufacture--a tremendous advantage for difficult, remote terrains.

Raw materials remain steel sheet (carbon steel, hot rolled) and epoxy resin. Further developments will tend to a replacement of the epoxy resin by cheaper resins, such as polyester or acrylics. The cost structure is strongly dominated by the labour cost so that there is a large potential for developing countries in this respect.

3. Potential interest of this technical development for developing countries

In certain developing countries the large distance involved in transporting products such as crude oil, gas and water (and mineral ores in the future) means that the ideal mode of transport, given the required tonnage level, is by pipeline, which, once installed, is:

- Economical to run, requiring only automatic control;
- Invisible since normally burried;
- The mode of transport which has least accidents and leads to the lowest pollution with respect to the service given;
- Not subject to disruption by weather etc.

In addition, the large urbanization and industrialization efforts in developing countries mean that many pipes are required for water supply and sewage disposal.

In phosphate and ore extraction, corrosion/erosion resistant piping systems are also at a premium; the steel-resin pipe is particularly advantageous since it provides a long, maintenance-free lifetime under these demanding conditions.

It has been shown previously that many pipe materials exist, but all of them entail problems. The composite pipe, with its numerous advantages is considered extremely interesting from the points of view of environment, geography and industry for the following reasons, which are shown schematically in figure 18:

- Development of new pipe materials to replace some other imported ones (steel, fibre-reinforced plastics, asbestos cement) or pipes, on which royalties are paid for production.

- Solution of current problems of corrosion etc. in pipelines, such as oil gathering, sewage, water and ore transport.

- On-site, or at least within the country, pipe fabrication, which reduces import and transport costs and leads to lower priced pipes for water transport etc.

- Possibility to develop a locally-based industry and to diversify uses of the pipes and of pipeline transport in order to stimulate national development (e.g. mineral ore transport from remote locations, saline water over long distances, underwater desalination, off-shore pipelines).

- Use of petroleum derivatives: epoxy, polyester in pipe manufacture together with eventually locally available filler materials, such as mica, sand and other minerals.

- Eventual installation of a line for the production and treatment of steel strips which could be employed in other sectors such as building and construction.

- Export of pipes to other neighbouring countries which are also dependent on pipeline transport.

- Finally, those fields of application which have been evaluated as most promising for the composite pipe are:

  (1) short-term irrigation and drinking water, as well as sewage, and
  (2) high-pressure pipelines for crude oil and natural gas, together with chemical and desalination plant piping and well casings for corrosive wells in the longer term. These are the areas where developing countries have a considerable need.

A major factor which enters into the choice of a pipe material is, of course, the cost of installation, even in the event that the mechanical and chemical performance can be improved. Comparison of calculated installed costs of the steel-resin pipe with those of steel and glass filament-reinforced plastic pipe are presented in figure 19 for water transport under pressure. The immediate conclusion is that the steel-resin pipe is a serious competitor for GRP and steel pipe. Manpower, energy and infrastructure requirements are about the same as for glass fibre-reinforced plastic pipes. Design techniques are also similar to those of GRP and the pipe can be installed and joined in a similar manner. Given the presence of the steel strips, the pipe is less subject to impact damage.

The cost of transport is a big factor in the final installation cost of a pipeline, and a calculation is presented in table 16 for steel and the steel-resin pipes to be employed in water transport. This table brings out the big advantage of the steel-resin pipe: reduction in transport costs due to the possibility of on-site or within-the-country fabrication for equivalent, or even improved mechanical and chemical performance.

Figure 18.

POTENTIAL INTEREST OF THIS TECHNICAL DEVELOPMENT

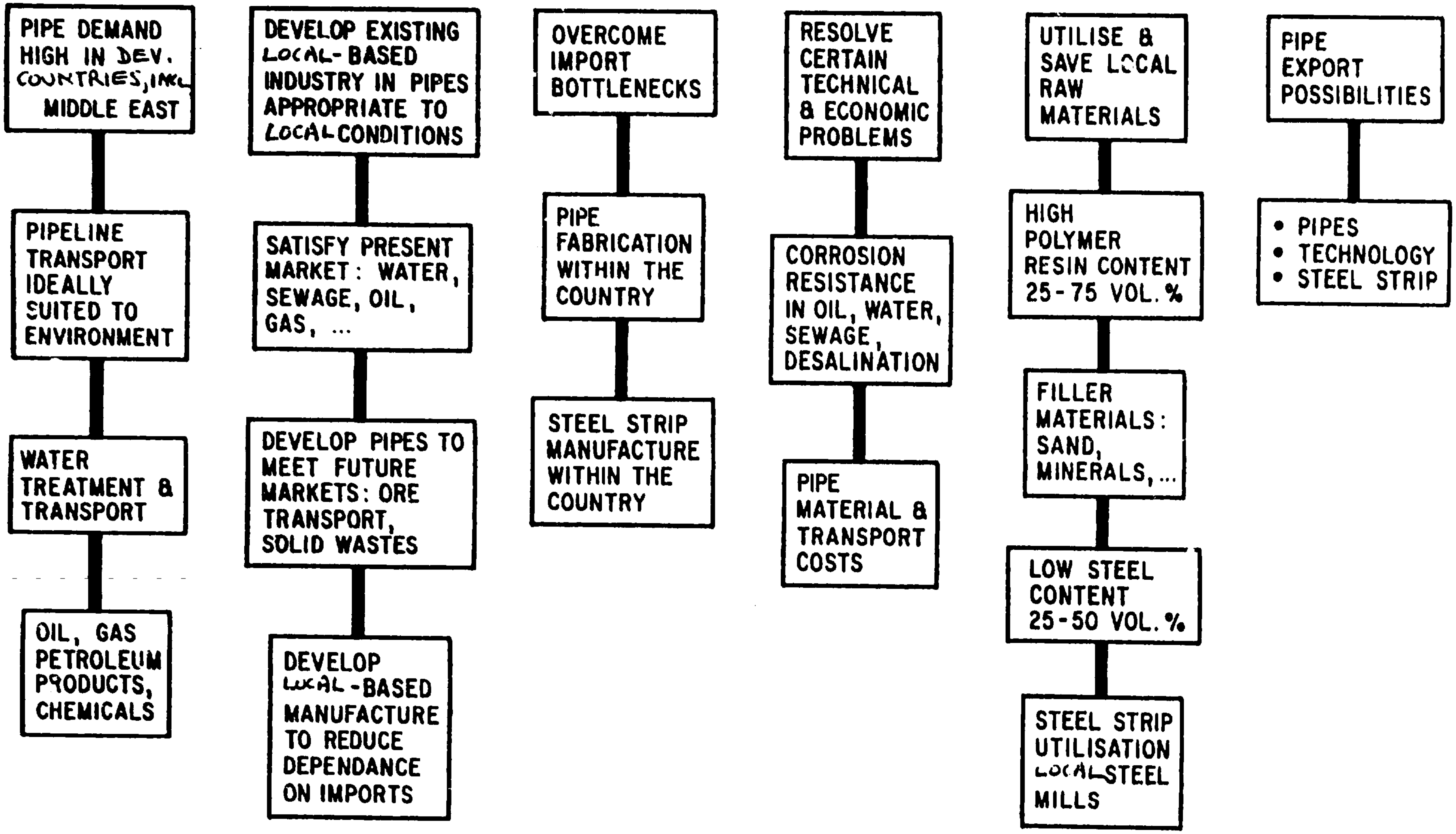


Figure 19.

COMPARISON OF INSTALLED COSTS OF PIPES OF 1.0 DIA. FOR USE AT 13 BARS PRESSURE IN IRRIGATION

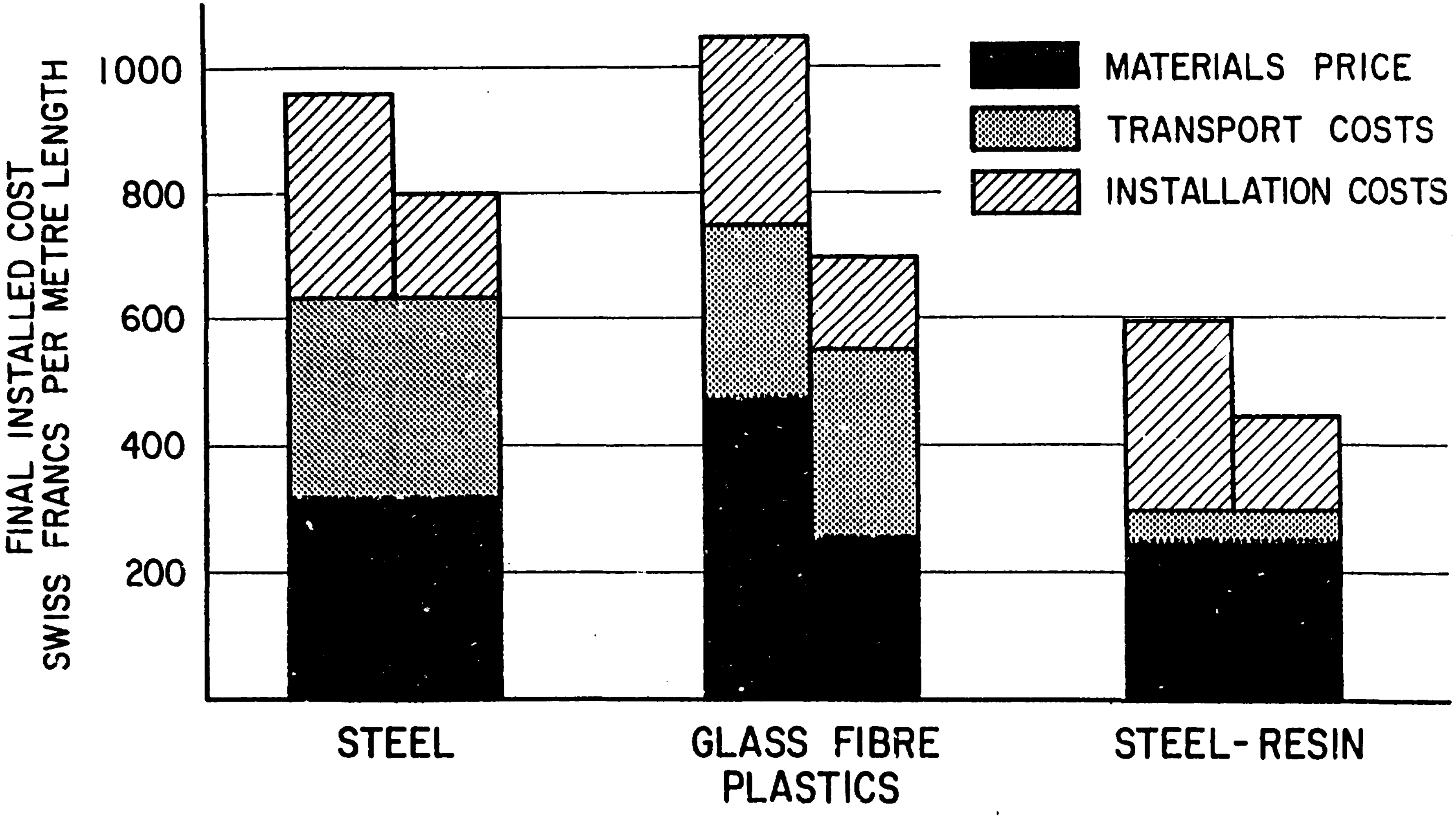


Table 16.

Transport costs per meter completed pipe
(1.0 m diameter)

Pipe	Place of manufacture	Shipping cost (US$)	Inland transport cost (US$)
Steel	Europe	120	5
Composite	Near East		
	- port	13	5
	- on-site	13	2

4. Conditions for implantation in developing countries

In order that developing countries gain maximum sociological, economic, environmental and technical benefits from the technology, the composite pipe fabrication, properties and industrial infrastructure should be developed to meet the specific local needs and conditions so as to avoid any technological transfer problems in the future. In this manner the steel-resin pipe could help develop an industry appropriate to local conditions. The various steps in the pipe production and installation would be as shown in figure 20, along with the main features and market possibilities.

Figure 20.

Envisaged industrial realization in developing countries linked to the composite pipe

Product/Operation	Main features	Market possibilities
Steel strip	• Import • Local production • Steel mill product	• Use in buildings/ transport • Export
Resin: epoxy, polyester	• Petroleum Derivative • "Biomass" derivative	• Use in glass fibre structures • Adhesives • Export
Machine manufacture	• Industrialized country • local	• Licencing Technology • Export
Pipe production	• Low investment • In factory • On-site of installation	• Wide range of pipelines • Export
Pipe Installation	• Small Crews • No heavy equipment	• Remote regions • Urban development
Pipe maintenance	• High corrosion resistance • As at present	• Desalination piping • Sour gas and oil

5. Conclusions: advantages and limitations

The main conclusions of the analysis are presented in table 17. The pipe would seem to meet many of the requirements for implantation in developing countries and, in addition, the development of a manufacturing capability and a pipeline infrastructure will assist in other important sectors of future local industy, including:

- Water saving: transport over long distances of saline water in corrosion-resistant pipes.
- Integrated water transport and distribution by means of large-scale interconnecting networks.
- New technologies such as desalination.
- Mineral industry, including long distance or transport from remote locations, ore handling etc.

Table 17.

Main conclusions concerning the composite pipe

Advantages	- Meets growing need for pipe materials in medium-pressure range
	- High corrosion resistance
	- Relatively simple fabrication
	- On-site or within-the-country fabrication
	- Low transport costs
	- Low installed cost compared to competitive materials
	- Raw materials could be produced within the country: resin, filler and steel
	- High export potential
	- Would seem to meet demands of the local market

Application	- Short-term in water treatment and transport, and slurries - Longer-term in energy product transport, well casings, chemical plant piping etc.
Outstanding problems	- Development of suitable continuous fabrication techniques - Product of suitable continuous fabrication techniques - Product optimization for various chosen applications - Relatively new pipe material, so confidence of users has to be gained

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F. Small diameter glass fibre-reinforced plastic (GRP) pipes

Background

The manufacture of small diameter GRP pipes (6 inches) is effected in the same general manner as for the larger diameter pipes already discussed above. However, centrifugal casting is not favoured and two varieties of filament winding are employed:

- Discontinuous or fixed length mandrels (figure 21)
- Semi-continuous either in a modified version of the Drostholm machine or by pultrusion.

The pipes are mainly produced either with a polyester or epoxy matrix (vinyl esters are also employed) and may have an inner lining of a thermoplastic to provide increased corrosion resistance and sometimes to facilitate manufacture. The pipes are employed in conditions where corrosion resistance is important, such as in:

- Chemical and petrochemical industry
- Waste water treatment
- Long-distance district hot-water heating
- Mining
- Energy extraction (e.g. tubing in oil and geothermal wells)
- Oil and gas gathering lines.

1. Description of material and technology

The basic method for the manufacture of small diamter GRP pipe is the filament winding process. The pipe is formed by first applying a resin-rich surface veil to the rotating steel mandrel to provide a smooth interior surface and corrosion protection. Depending on the design requirements, one or two layers of chopped fibre reinforcing material may be applied prior to winding the structural wall. The next step is to fabricate the structural wall. This is accomplished by winding filaments onto the mandrel under controlled tension. This is typically done with a helix angle of between 55 degrees and 65 degrees to the longitudinal axis of the pipe. The composition of this layer consists of roughly 45 per cent glass fibre, by weight. The glass fibres used for this layer have an ultimate strength of 1,400 MPa. The final step is to wind a resin-rich postcoat onto the structural wall that contains an ultraviolet screen. This provides protection of the exterior surface from corrosion and ultraviolet degradation of the structural wall.

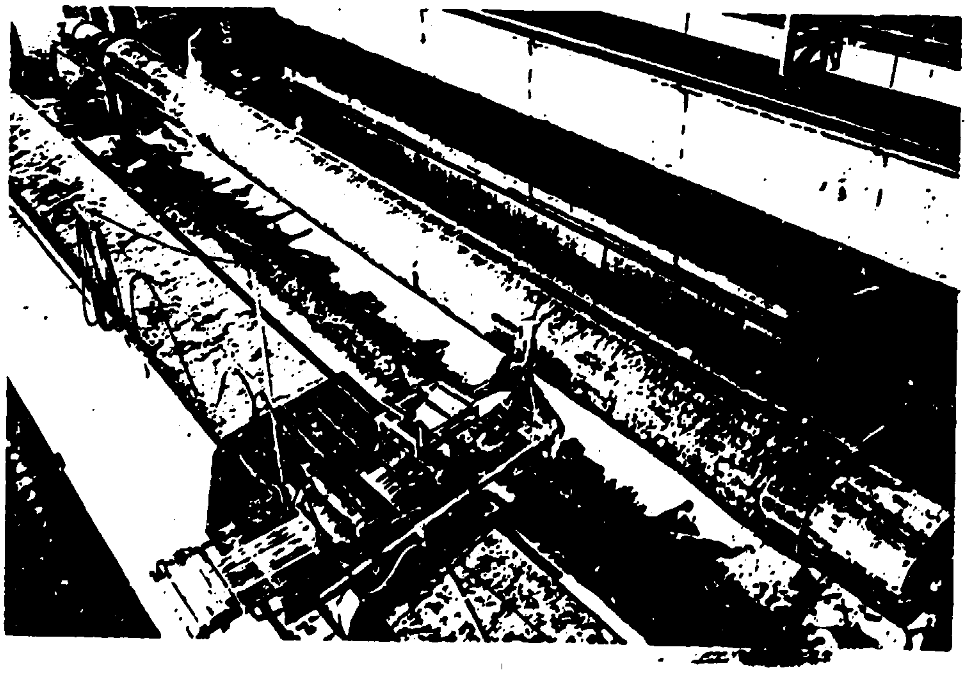
For fittings and special pipe configurations, the open-mould method is used. This method utilizes fibreglass mat placed onto the mould, and/or spray application of chopped strand fibreglass and resin. The type of resin chosen depends mainly on the corrosive environment that the pipe will face, and in general the cheapest resin is chosen that satisfies the imposed working conditions. One advantage of the composite structure, which is built up on a mandrel by the addition of layers of the various components, is that the inner surface (normally termed "gel coat") and external surface layers may be (and often are) different from the matrix that holds the fibres together. These resins are thus chosen for optimum corrosion resistance.

The amount and type of fibreglass (E-glass, S-glass, continuous mat, chopped etc.) depends on the strength requirements and again many possibilities exist. For high-strength, high-quality piping applications, continuous E-glass filaments are mainly required, although chopped strand mat pipes could present some interest. For continuous glass filaments, filament winding is employed to manufacture the pipes. On discontinuous machines helical winding gives high quality pipes of usually smaller diameter than those produced by biaxial (circumferential and axial reinforcement) or purely circumferential winding on semi-continuous machines of the Drostholm type. The chosen quality control possible on the discontinuous machines means that such pipes are more suitable for corrosive piping as replacement for stainless steel, for example. In such areas epoxy resins are also employed to give higher strength capability and, of course, result in higher cost.

High quality GRP pipes in diameters of approximately 16 inches with epoxy resins for service up to 150 degrees C and 20 bars or higher are available from companies such as Ameron (Bondstrand series), Ciba-Geigy, and are used, for example, in corrosive piping and in the petrochemical industry in fire-fighting systems.[48]

Figure 21.

Discontinuous helical winding of GRP pipe



2. Stage of development

The stage of development of the materials and associated manufacturing technology may be dealt with in terms of the utilization of the GRP pipes.

a. High pressure, corrosive applications

The pipes have invariably an epoxy matrix and are manufactured by automatic helical filament winding on fixed-length mandrels to provide high strength. The pipe ends may be plain (i.e. same diameter as the body) or one end may be bell-shaped so as to provide a bell-and-spigot joint. In tubing applications (for oil, water or geothermal wells) the pipe ends are threaded (machined on thickended ends) for easy installation and dismantling.[48] Other "rapid" installation mechanical joining systems are available which allow cost effective systems to be built of GRP.[48]

The technology is well developed and the pipes find increasing utilization in sectors where the lifetime of steel pipes is too low to be cost-effective, e.g. chemical and petrochemical plant piping, fire-fighting pipe systems, oil and gas gathering lines, oil wells and mining slurry pipelines. The structures are optimized composites with typical specified minimum properties specified by API Spec. 5LR, as follows for use in oil and gas systems. The properties vary, depending on temperature (23 degrees C and 65 degrees C) and grade (R-40 to R-60), as follows:

- cyclic (150 x 10^6) pressure strength, long term:	29 - 43 MPa
- cyclic (750) pressure strength, short term:	108 - 145 MPa
- static (10^5h) pressure strength, long term:	79 - 145 MPa
- short-term rupture strength:	216 - 360 MPa
- ultimate axial tensile strength:	54 - 81 MPa

This API specification holds for pipe diameters in the range of 2 to 12 inches. Pipe lengths are up to 12 meters and more.

GRP pipes are designed with rather high security factors ranging from 6 to 10. These security factors are applied either against the short-term weeping strength or against burst strength, depending on the wall structure of the GRP pipes. In "pure" GRP pipes with a high glass fibre content, the design reference is the "weeping" strength. With low glass fibre contents (40 per cent), the design reference is the burst strength. The pressure for proof testing is 1.5 times that of the design pressure. Working pressures of GRP pipes vary with pipe diamter: the smaller the pipe diameter the higher the design pressure, up to about 140 bars. The typical pressure range is 20 to 40 bars.

b. Low pressure, corrosive applications in the chemical industry etc.

The pipes in this case are either epoxy or polyester matrix made by a hand lay-up winding process. The fibre orientation and content are not as controlled as in filament winding so that the pipes are not suited to high pressures. However, they are widely used in gravity piping for corrosive effluents or low pressure piping for process water, chlorine, caustic etc. Another technique used for the lower pressure range pipes is pultrusion of GRP on an extruded thermoplastic pipe. This requires little labour and is readily automated.

(i) Costs.

The high-pressure pipes based on epoxy are high-cost pipe materials to be used only in the most extreme conditions. The low pressure types are in the same cost category as discussed previously under section D.

(ii) Fittings.

In piping systems, the fittings such as flangers, reducers, T-pieces and elbows are manufactured by various techniques, either on PVC or polyethylene forms: compression moulding, hand lamination or filament winding.

(iii) Joints.

The pipes may either be joined by flanges, bell and spigot (formed on the pipes), adhesive bonding or rubber sealing with a sleeve, or by conventional couplings such as Viking Johnson or Straub.

(iv) Installation.

Installation is readily carried out since the pipes are light.

3. Potential fields of application in developing countries

a. Raw materials: glass and petrochemical-based resins.

In developing countries the cheaper, lower pressure polyester matrix pipes are initially introduced because the higher pressure applications require high guaranteed quality with (expensive) epoxy resins. They represent, due to their cost, a rather select product, manufactured by relatively few companies at very high standards: e.g. Ciba-Geigy, Ameron and Keramchemie.

b. Design

Design is done according to composite technology but for low pressure applications there are no hard and fast rules or codes. Each company follows similar design and fabrication practices so that qualities are similar but rarely standardized. In developing countries, some conventional, proven design should be chosen, based on established practice.

c. Manufacture/manpower

Hand lay-up helical winding on a mandrel is a perfect technique for developing countries, requiring low capital investment and being labour-intensive. On the average, two skilled workers per machine are required plus around 10 semi- or non-skilled workers for the lay-up, handling, cutting etc. One winding machine can make several diameters by simply changing the mandrel. The latter, often made of wool or steel in segments or tapered to allow pipe removal, will represent the largest investment at around US$5,000 for a 12 inch diameter by 6 m long mandrel. A typical production plant lay-out is illustrated in figure 22.

d. Energy

As with most plastic manufacturing techniques, energy requirements are low and readily satisfied by electrical power in almost all countries.

e. Infrastructure

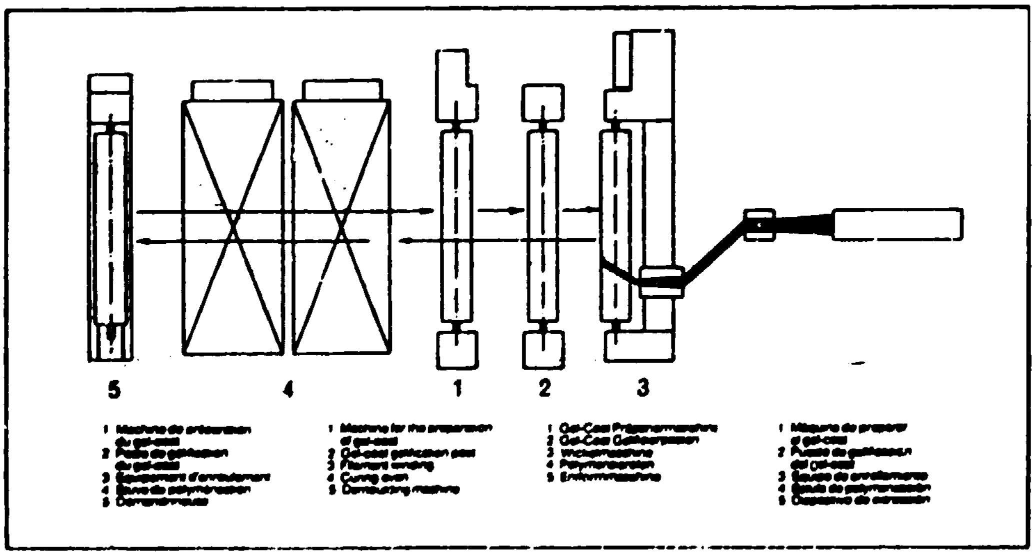
If piping systems are to be produced, capacity for the manufacture of fittings must equally be installed. The methods involved for fittings are normally labour-intensive and the costs are around five times that of the straight pipes on a weight basis. In developing countries, fittings production could be very interesting, even for export if their quality is guaranteed.

f. Installation

Installation of GRP piping systems does not require heavy equipment, but does require high quality workmanship in alignment, joining and final commissioning.

Figure 22.

Lay-out of typical GRP filament winding plant



4. Conditions for implantation

The conditions for implantation of small diamter GRP pipe production facilities in a developing country are as follows:

- There must exist an estabished or growing market in one of the sectors: (corrosive) oil and gas field development (gatnering lines and down-hole tubing), chemicals or petrochemicals (piping systems, waste water pipelines etc.), mineral extraction (piping and pipelines for slurries and corrosive fluids), food industry (waste water transport etc.);
- The raw materials can be locally obtained or imported cost-effectively;
- GRP pipes have already been used (or have been considered for use) in these sectors or experience has been gained in other sectors such as large diameter pipes;
- Skilled or semi-skilled labour must be available;
- Initial know-how will have to be imported for hand lay-up on a relatively simple filament winding equipment;
- Investment will have to be available for more complex and automated filament winding or centrifugal casting equipment;
- The pipe quality offered must be guaranteed to be high and reproducible;
- Technical assistance must be offered on how best to install and utilize the pipe;
- A technical collaboration must be set up with a well-established pipe producer, at least in the initial stages. A joint-venture is also a valid manner in which to introduce this new technology to developing countries;

- The pipes must be cost-competitive with similar imported products or alternative materials (e.g. stainless, coated steel or plastic);
- Local engineering and construction companies must be capable of accepting and installing the pipes.

5. Advantages/limitations

The advantages of GRP piping systems over conventional materials are the results of the properties of the material and the design flexibility of the material and manufacturing process. Some of these advantages are the following:

- Relatively low investment costs
- Labour-intensive manufacture
- Versatile technique
- Built-in corrosion resistance
- Light weight
- Lower transportation costs
- Fast joining
- Low maintenance costs
- Reduced support requirements.

These advantages can lead to significant cost savings. For instance, since the GRP pipe is lightweight, lighter handling equipment and less manpower are required to position and join the pipe sections. Again, due to the light weight, several segments of pipe may be joined prior to burial or submersion, providing further cost reduction. Also excavation costs are reduced due to narrower trench and less stringent bedding requirements. Another advantage of the light weight of the GRP pipe is a major reduction in shipping costs. This becomes even more important as the fuel costs for transportation rise.

Major limitations to their production and utilization in developing countries are:

- Material is relatively unkown;
- Quality control must be high. Therefore skilled labour is required;
- Cost;
- Legislation and codes vary from country to country. Therefore confidence of designers, users and authorities must be gained;
- Joining may require skill and careful workmanship;
- The small diameter, higher quality pipes may be imported more effectively than the larger diameter pipes (or tanks) because of quality requirements and lower transport costs;
- The market may not (yet) be so large.

6. Conclusions

Small diameter, high quality glass fibre-reinforced plastic pipes may be manufactured in developing countries from the investment, energy and manpower points of view. Market opportunities and therefore demand might not be there immediately, except in industrializing countries, so that an initial introduction of large diameter pipes is seen as offering more opportunities.

G. Glass fibre-reinforced tanks and reservoirs

In many developing countries, there are very important mineral and chemical resources which, when developed, require considerable investments in equipment if the industry is not to remain simply an extraction one, without refining or production of upgraded products. Many of the processes involve highly corrosive chemicals that have to be stored and transported and which are ideally suited to GRP applications as tanks and piping. (The piping will be similar to that discussed in the previous chapter). Examples are salt extraction from Sabkha or highly saline water, phosphate extraction and chlorine production. Furthermore, water treatment and water storage facilities for industry and housing as well as petrol storage in especially warm developing countries expose materials to severe corrosion, which can be alleviated by GRP storage tanks and reservoirs. Grain or other food stuffs or crops storage has also to be effected in very large silos (quite frequently of GRP).

Currently, steel is the widest used material for storage tanks, and in some cases (salts) it is of the very expensive stainless variety. All are imported and many already in the fabricated form, especially stainless tanks, often several meters in diameter and height. The high material and transport costs involved can be readily imagined. In many instances, although the exact choice depends on working conditions, GRP tanks can be and are employed. However, transport is more delicate (and hence expensive) so that there is a very strong case for local fabrication of GRP tanks.

Small-diameter tanks are also currently manufactured from composite materials for use in high pressure gas bottles. For questions of security, the bottles consist of an aluminium core overwrapped by either glass or Kevlar$^{(R)}$ in an epoxy matrix. The bottles, which can hold four times the volume of gas of a steel bottle at equivalent weight are now used in ambulances, fire fighting equipment and are foreseen for automobiles (liquid petroleum gas as fuel). Application in developing countries could be interesting in the latter context, but is not felt to be for the immediate future. The subsequent sections of this chapter deal with large diameter tanks.

1. Material and technology description

Four principal techniques are available for tank manufacture, the material invariably consisting of polyester reinforced with glass fibres:

- Hand or spray lay-up with chopped glass fibres for non-pressurized water or fuel storage tanks for housing or small industrial plants.

- Filament winding as described in section D for pipes, but of course on large diameter mandrels. The ends are fabricated by moulding and are joined by adhesive bonding. Capacities from 45 liters onwards up to 3,800 litres are readily fabricated, and dimensions up to around 200,000 litres are made by specialist companies.

- On-site filament winding either on rotating horizontal mandrels up to 6 m diameter and 20 m long[49] or on vertical mandrels up to 25 m diameter around which the winding heads turn.[50] Capacities up to 5,000 m^3 have been constructed, economics being said to compare favourably with coated steel above 600 m^3.

- On-site assembly of preformed GRP sheets, assembled together with polyester putty and the joints reinforced with pultruded rods and spray lay-up. Tanks up to 900 m^3 have been constructed.[51]

2. Stage of development

Glass fibre-reinforced tanks and reservoirs are widely used in industrial countries in the food industry, agriculture, pulp and paper industry, caustic and chlorine plants, water treatment and storage etc. Design codes exist, as illustrated below in table 18 and experience is very positive. Typical design data for large diameter filament wound tanks containing 70 per cent glass in the structure are as follows:

	MPa
Hoop tensile strength	400
Hoop tensile modulus	36×10^3
Flexural modulus	22×10^3

As well as stationary tanks, glass fibre-reinforced plastics have been applied, for transport purposes, as corrosive materials on railways, the biggest being 3 m diameter by 15.5 m length by filament winding. The development of high quality tanks and the equipment to manufacture them

Table 18. - Main design elements in various standards for GRP pipes, vessels and tanks

	BS 4994: 1973 (vessels and tanks)	BS 5480 Part 1 : 1977 (pipes)	ANSI/ASME BPV Sect. x, July 1, 1977	AD - Merkblatt NI
Maximum internal pressure (bar)	5	≥ 64	≥ 210	none
Strain limitation under external load	none	none	none	in preparation
Temperature range (°C)	0-100	≥ 30	-54 -65	-30 -50
Design factors:	$K = 3 \times k_1 \times k_2 \times k_3 \times k_4 \times k_5$			$= S \times G_1 \times G_2 \times G_3 \times G_4$*)
. Strength factor	3	not given, but stated as in preparation to be similar to BS 4994	not given	$S = 2.7$
. Method of manufacture rovings, machine	$K_1 = 1.4$			$G_3 = 1.2$
. Long-term performance	$K_2 = 1.2 - 2.0$ depending on experience			$G_1 \leq 2.0$
. Temperature	K_3 (see Fig. 2.12)			$G_2 = 1.4$ for corrosion
. Cyclic loading	K_4 (see Fig. 2.13)			-
. curing	K_5			-
. Material inhomogeneity	-			$G_4 = 1.2$

*) $S\Sigma G$ should never be less than 6 and $\Sigma G \leq 3.7$

BS = British Standard

has benefitted enormously from advanced composite applications in missile tanks. The Minuteman rocket is partly filament wound. Design practices and the filament winding programmes developed are applicable to more everyday structures, such as water storage tanks.

3. Potential fields of application in developing countries

a. Raw material supply

As in the case of the large diameter glass fibre-reinforced pipes, the raw materials are E-glass fibre and polyester, and the analysis presented previously applies equally for tanks and reservoirs.

b. Design

Again, design can follow the procedures and codes discussed for pipes.

c. Manufacture

Factory manufacture is by hand lay-up or filament winding and requires the same equipment as discussed above. Mandrels are, of course, larger in diameter and require heavier equipment. For on-site manufacture, special imported equipment is required, together with transportation.

d. Manpower

As with the large diameter pipes, skilled labour will have to be employed for the factory manufacture, while the on-site operations will require a larger percentage of manual labour.

e. Energy/infrastructure

Energy requirements are low, but for on-site fabrication require mobile generators that are not too difficult to obtain and operate. Plant lay-out will have to be larger than for pipes, but again presents no particular problems.

f. Applications

Application sectors in developing countries will be in the storage of grain, cereals, milk, wine; caustic; salts extraction; sewage treatment; water storage; mineral extraction and treatment (i.e. not just a mining activity), fertilizer storage etc.

4. Conditions for implantation

The conditions for implantation of glass fibre-reinforced tank production in a developing country are as follows:

- A well-established market must exist, either within the country or in neighbouring countries where the products can be cost-effectively exported;
- The raw materials can be obtained locally or imported at competitive prices;
- Skilled or semi-skilled labour must be available;
- Initial know-how will have to be imported for hand lay-up on a relatively simple filament winding equipment;
- Investment will have to be available for more complex and automated filament winding or centrifugal casting equipment;

- The tank quality offered must be guaranteed to be high and reproducible;

- Technical assistance must be offered on how best to install and utilize the tank;

- A technical collaboration must be set up with a well-established tank producer, at least in the initial stages. A joint venture is also a valid manner in which to introduce this new technology to developing countries;

- The tanks must be cost-competitive with similar imported products and with alternative materials such as lined steel and stainless steel;

- Local engineering and construction companies are capable of accepting and installing the tanks, i.e. have confidence in the new material.

The drive to introduce tank manufacture will depend on local conditions and requirements. Specifically, in countries with important resources of salts, for example, serious thought should be given to setting up a very small, labour-intensive factory for the fabrication of hand lay-up glass fibre-reinforced plastic tanks and pipes, which could be a most cost-effective manner to solve corrosion and maintenance problems.

5. Advantages/limitations

The advantages of the glass fibre-reinforced plastic tanks are:

- High corrosion-resistance;

- Low maintenance compared with lined steel both inside and outside (weathering);

- Light weight for factory built tanks which facilitate transport and handling;

- Rapid on-site installation of the larger tanks. For example, an 11 m diameter by 5 m high demineralized water tank in six weeks on a concrete foundation;

- Fabrication in the country will keep costs down and make the structures more cost-competitive with imported steel tanks*/;

- The fabrication process is versatile and the large diameter tanks (without the ends) can also be used as pipes (see section D) or chimneys in factories (the largest here is 160 m high by 2.8 m in diameter, situated in Japan).

Major limitations to their utilization are:

- Cost;

- Lack of rigidity in large dimensions, so a reinforcing structure is required;

- Legislation: not so severe on non-pressure applications;

- Lack of qualified personnel;

- Quality assurance;

- Joining.

These limitations are more severe for mobile tanks than for stationary ones.

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*/ A typical project involving 26 on-site GRP silos for wheat flour storage, each 6 m in diameter and 20 m high, cost approximately US$500,000 and took six weeks to complete.

6. Conclusions

Glass fibre-reinforced plastic tank production for local consumption is suitable for introduction into developing countries if the products can be fabricated and installed cost-effectively. Factory fabrication is similar to that used for large diameter pipe and versatile enough in a first step to satisfy the most demanding markets. On-site manufacture may be applied, but probably by a specialized company on a one-off basis for special projects.

Profit may be gained from experience in the industrialized countries in advanced tank manufacture, as well as the technologies applied for advanced composites. Any investment in tank manufacture should probably be preceded by a pipe production capability, given that demand will probably be higher in the pipe sector, thus justifying the initial investment. Labour requirements are similar for the two products and may be satisfied at least initially by some assistance from the originators of the technology.

H. Natural fibre composites

As mentioned in chapter I, section B, composites based on natural fibres have been employed in construction since early history. It was recognized that fibres obtained either as the by-product of food cultivation, such as coir (from coconut fibres), or specifically from fibrous plants, such as cotton and jute, could provide strong structural materials either as cloth, rope or, when added to mud, for bricks. Apart from matting and textiles, however, natural fibres are not widely employed in structures as reinforcements. Their utilization is often as a filler, without thought being given to optimizing their effect on the mechanical properties of the structure.

Serious thought is being given to developing composites based on natural fibres[52,53] in polymers, cement and clay matrices, mainly because they are relatively low in cost, compared with synthetic fibres, as illustrated below:

	US$/kg
carbon fibres	40
stainless steel	0.6
E-glass	1
pineapple leaf	0.7
hemp	0.6
palmyra	1
sisal	0.8
coir	0.5
asbestos	0.2
polypropylene	1.2

Also, local fibrous materials are produced in large quantities world-wide. For example the 1979 figures were as follows:

	India (tons)	World (tons)
coir	160,000	280,000
bagasse	14,000,000	-
banana	160	100,000
sisal	3,000	600,000
palmyra	100	not available
jute	1,500	not available

The advantage of developing an industry based on local natural resources would be inestimable and worth examining in more detail from the point of view of more specific materials and utilizations.

1. Description of material and technology

Because its excellent inherent structural characteristics are sometimes poorly utilized due to deficiencies linked to its strength variability and its sensitivity to moisture and organic decay, wood has long been the` target for improvement by artificial means such as polymer impregnation.[53/] The properties are improved significantly, but the approach is not strictly a composite one since the strength is still determined by the original wood (artificial composite) structure.

Natural fibres, such as wood, cotton, sisal, jute and hemp are, however, used to reinforce cement on an industrial scale. Their major properties are compared in table 19 with other fibres used for reinforcing cement. (The properties of typical matrices, Portland cement and polyester resin are included for comparison purposes). On a specific stiffness basis, the natural fibres and polypropylene fall far below asbestos or glass but compare well on a specific strength basis--important for cement reinforcement where crack stopping is the predominant strengthening mechanism. Reinforcement of polymers by the natural fibres given in table 19 is also practised in countries, such as India.

2. Stage of development

The use of natural fibres to reinforce cement and thereby provide useful structural materials to fulfill the same purposes as asbestos-cement, e.g. in stressed applications, such as panels, roofing, piping etc., faces severe handicaps due to degradation by moisture and organic attack. Lower stressed applications, such as building bricks remain valid.

The more novel and interesting composite approach to utilizing natural fibres is as reinforcement for polymeric matrices, and therefore is that which will be treated from the point of view of its introduction into developing countries.

Although no large industrial application is as yet known of natural fibres in polymer-based structural composite materials, the fibres are widely employed in ropes, textiles, clothes, particle boards and panels, paper etc. Their incorporation into polymeric matrices has also been studied with a view to producing laminates and useful materials for

Table 19.

Properties of fibres used for reinforcing cement

Fibre	Typical diameter (mm)	Max. length (mm)	Tensile strength (MPa)	Elastic Modulus (GPa)	Specific Gravity	Elongation at break (%)
E-glass	9-15	cont.	2100-3500	77	2.56	2-3.5
Crocidolite (blue) asbestos	0.1-20	100	3500	196	3.37	2-3
Carbon	7.5	cont.	2450-3150	345-415	1.99	1.0
High tensile steel	5-500	cont.	1050	210	7.84	4.0
Polypropylene	>4	cont.	400	7.7	0.91	8
Cotton	10-20	63	280-840	5.6-11.2	1.35	5-10
Coir	100-450		530	2.5-13	1.15	15-40
Sisal	7-48	1200 (Strand)	840	9-15	1.48	3-7
Hemp	11-50	1800 (Strand)	385	-	1.48	1.8
Portland cement	-	-	3-14	7-28	2.5	0.05
Polyester resin	-	-	42	2	1.3	3

consumer articles,[52] such as helmets, cases, frames and roofing. Strength properties of the composites are, however, not yet sufficient and require development work. Furthermore, jute is considered to be the most promising reinforcing fibre because of its properties, availability and cost.[54] Sisal-epoxy tubes have been successfully made by winding and found to be similar in specific properties and cost to glass-epoxy composites.[45]

3. Potential application in developing countries

a. Raw materials

The main driving force for considering the use of natural, locally found fibres is the lack of an indigenous supply of asbestos or the ready, cost-effective production capacity for glass. Most developing countries have resources of some of the natural fibres listed in table 19 and use them in one form or another in everyday life.

A major problem for their introduction in structural applications will be the initial collection and selection/sorting of those fibres most suitable for reinforcement from the dimension and quality points of view. The matrix would be polyester (for its high cost effectiveness) or a polymer also based on local biomass resources, as described in section I or a potential specific material development. Generally speaking polymeric resins are the most expensive matrices that can be considered for natural fibre composites (polyester cost $\simeq$ 5 times bitumen cost $\simeq$ 20 times cement cost), but the properties are invariably superior, processing easier and the products that can be manufactured are infinitely more varied.

b. Design

Natural fibre composite design follows the rules laid down for glass composites with two basic reinforcement forms:

- discontinuous, short fibre mats
- yarns, cloths made up of short fibres.

Optimum use of the fibres, and hence suitable design and reliable operation, depends on effective bonding between the fibres and the matrix. No ready-made answer to the bonding problem exists, but solutions are to be found in fibre surface treatment.[52/]

c. Manufacture

Techniques that may be used on an industrial scale (and that have been on a laboratory scale) for composite manufacture are the same as for glass fibre-reinforced plastics, being mainly hand lay-up for mats and eventually filament winding for cloths.

d. Manpower

The requirements will be the same as for hand lay-up GRP construction materials as described previously in section B.

e. Energy and infrastructure

No high energy requirements or special infrastructure are required for the manufacture of composites. On the other hand, the collection and sorting of the natural fibres will have to be organized, requiring unskilled manpower in the first case and unskilled and skilled in the second, as well as (complex) automatic equipment to sort out fibres of suitable dimensions.

4. Conditions for implantation

There mainly remains further development work to be done in order to determine the potential of introducing technology based on natural fibre composites. The sequence of execution of the the work consists of the following tasks:

a. Determination of the properties of local, natural fibres, and sensitivity to dimensions, form (mat or cloth) and surface quality.

b. Fabrication of composites and determination of their properties, both short-term and long-term exposure to the environments likely to be encountered.

c. Tests to improve/optimize the properties either by better adapted fabrication techniques or by improvement of the bonding (by coating).

d. Cost evaluations of the best composites produced and extrapolation to future production capacity.

e. Comparison with other structural materials and in particular composites based on imported fibres.

In parallel with the foregoing test programme, a detailed evaluation must be made of fibre production capacity and localization, collection procedures (as well as their cost and manpower requirements), sorting requirements etc. Finally, evaluation of available manpower and required investments must be made before arriving at a final decision to introduce the technology. As with all other (composite material) technology, the decision will not be universal since it depends on local conditions, perhaps to an even greater extent than composite technologies based mainly on imported materials.

Initial applications will be those not subjected to high operating stresses (because of the lack of knowledge of the material properties), such as furniture, housing panels (not structural), roofing, household articles, containers etc. Development of improved properties will extrapolate applications to structural housing panels, transportation uses etc.

5. Advantages and limitations of natural fibre composite technology

The immediately evident advantage is the possibility to use local resources to replace imported materials. In some cases, it may be that (initially at least) the effort and cost to be put into collection and sorting may offset the local advantage, but the tangible and intangible benefits of developing a local industry must not be overlooked. For example, increased employment, reduced import bills and eventual export of the goods. In cases where the composites would replace other conventional materials, light-weight, durability, low maintenance etc. would be further advantages.

Limitations are mainly linked to the fibres themselves: (1) relatively low and variable dimensions, strength and modulus, therefore difficult to guarantee product quality, and (2) water absorption as well as decay and attack by fungi, as well as to the composites: (1) low strength and stiffness due to non-optimized bonding between fibre and matrix, (2) wide variety of natural fibres available, so composite testing and design must be repeated many times, and (3) the prescribed matrix is a petroleum-based polymer, although possibilities of using a biomass-based polymer exist, as discussed in section I below.

6. Conclusions

Natural fibres are interesting enough to be considered for incorporation into polymer matrices to produce "local" composites. A wide variety of fibres can be employed and are found in considerable quanities in many developing countries. Examples are jute, hemp, sisal, cotton, coir and bagasse. The major hurdle to be overcome is product quality due to problems of initial fibre quality (hence collection and sorting are key factors) and poor bonding to the matrix. Research and development are required to solve the problem, but even then the solution may be as expensive as imported glass, or even more so. The natural fibre-composite material design and fabrication would be the same as practised for glass fibre-reinforced polymers. The matrix would have to be (imported) polyester or locally produced polymer based on biomass as illustrated in the following section for some lower quality composites not exposed to high stresses.

I. Composites based on natural fibres in a biomass-based polymeric matrix

Polymeric materials may be produced from biomass, which is simply a source of carbon chains in the same manner as petroleum, natural gas or coal. However, in almost all cases, the extraction from straw or other products is much more expensive than processes from fossil fuels. Thus, unless petroleum increases spectacularly in the coming years, no large-scale biomass industry will be developed. In certain cases, and certainly in the future, biomass will become a source of useful polymers and the following is a short description of one possible development.

1. Material and technology: Furfural and structural boards from bagasse[56]

The majority of sugar-cane producing nations find themselves confronted with the problem of what to do with the resulting bagasse, the fibrous waste product which remains after the extraction of the sugar. The removal of the sugar from the cane leaves large quantities of bagasse for which there is no single given end use. In fact, over the years several possibilities have been tried in order to use these large quantities of bagasse, but each have met with various problems.

2. Stage of development

Examples of uses tried are:

- Combustion
- Paper pulp
- Agriculture
- Boards: the use of bagasse fibres in panel and board production in the largest sense of the term (i.e. hard particle boards, fibre boards, insulation panels etc.) would seem to be the most interesting end-use application of the bagasse, thus exploiting the fibrous quality of the material. However, in this application a synthetic binding agent is required and the

majority of countries with bagasse must import this synthetic resin, which obviously reduces the economic viability of this application.

3. Potential application in developing countries

For the reasons outlined above it would seem interesting to develop this last mentioned use (bagasse boads) in the following new manner. Instead of using a synthetic binding agent this resin would be obtained from the bagasse itself. In this way the bagasse would be the source of both the elemental fibrous structure required for the board and the binding agent.

One could, for example, use the residue obtained following the separation of the fibres as the starting material for the binding agent. This is the non--or only slightly--fibrous portion of the bagasse containing essentially the chemical compounds pentosanes, which on reaction with dilute sulphuric acid, gives furfural. Furfural is known for its condensation reaction with phenols, accompanied by an opening of the double bonds leading to a cross-linking (a property used for improving phenol-formaldehyde resins). Thus, we have the binding agent provided by the fufural which reacts with the phenolic groups of the lignin of the fibres. In this way it should be possible to produce the boards or panels using only the bagasse waste product resulting from the sugar extraction. The bagasse itself would thus be providing both the structural material (fibres) and the binding material (furfural).

4. Conditions for implantation

The conditions for implantation follow exactly those outlined in section H, being applied to the specific case of bagasse fibres.

5. Advantages and limitations of the technology

The advantage for bagasse-producing countries is obviously to develop an industry based on local resources and reduce imports. The major limitations are in:

- The relatively low strength of the composites, which may place it in competition with even cheaper materials, e.g. wood, wood chips, cardboard;
- The need to develop a biomass-matrix production and master the "new" composite technology.

6. Conclusions

As a first step natural fibres, including bagasse, should be employed in composites with conventional matrices such as polyester. Opportunities and advantages to be gained are numerous. The passage to a biomass-based matrix will have to wait till the first step has been mastered.

CHAPTER III. CONCLUSIONS

A. Criteria for production/manufacture and application of composite materials in developing countries

1. Technology flexibility

Composite material developments have in recent times been stimulated by weight-reduction requirements in the aerospace industry, made possible by the invention and production of the so-called high performance fibres: S-glass, carbon, aramid, boron etc. The older industry of glass fibre-reinforced composites has also grown rapidly in the same period in weight-saving sectors (transportation) and in sectors where the corrosion resistance, low maintenance and rapid installation characteristics could be taken full advantage of. The reasons why composite materials will be of interest to developing countries will almost certainly not be weight savings in aerospace nor in mass transportation nor in allowing leisure-luxury goods to be developed. The reasons will be more down to earth, such as cost-effectively solving basic needs of the population with or without local raw materials and local labour.

These reasons will be considered subsequently but the immediate interest of composite materials technology for developing countries, and the major reason for examining them, is that since both the materials and the resulting structures are artificially constructed from a wide variety of basic elements, suitable combinations (from the fabrication and utilization points of view) will be found for any given country and local situation, i.e. the flexibility of the technology.

The previous chapters have presented an overall picture of composite material, highlighting the various types and current applications. Any particular country may find its strength lying in one or more of the steps involved in composite technology:

- Raw materials availablity
- Fibre extraction (natural) or production
- Matrix production
- Semi-product (mats, fabrics, prepreg, SMC etc.) manufacture
- Design, testing etc.
- Fabrication, processing of composite material
- Composite structure manufacture.

The composite material industry is currently characterized by a few specialized (large) fibre producers, a similarly limited number of polymer matrix material producers (cement is of course different), several specialized semi-product manufacturers (sometimes the same as the fibre producers), followed by a vast number of (sometimes small) industries that produce a wide variety of composite materials, articles and structures. The fabricators range in size from Hercules (aircraft structures) down through Owens Corning Fiberglass (glass fibre-reinforced pipes) to a multitude of moulders, filament winders etc.

Thus, upon deciding to enter the composite materials sector, a developing country will probably be more tempted to (initially at least) start at the fabrication and, using imported basic components and technology. As experience grows, steps upward in the chain through original design (for local environments) to semi-product manufacture and even matrix production may be profitable. The ultimate step of being able to produce suitable fibres or widely apply locally available fibres should be within the grasp of many developing countries.

The criteria for considering production/manufacture, on the one hand, and utilization on the other are not necessarily the same since many products may be imported instead of locally produced, if the price is right, and there is no advantage in introducing the corresponding technology into the country, at least at an initial stage.

The two aspects will be dealt with separately in the following pages on a general level. Specific examples have been presented in chapter II.

2. Production/manufacture

a. Criteria for introduction of the technology

(i) The first criterion for composite materials to be manufactured in developing countries is to satisfy an important local utilization need or to improve the quality of life. One can safely say that in all countries (industrialized and developing) there exist needs for materials with the combination of properties offered by composites. These are in housing, surface transport, communications, provision of water and energy, sanitation and sewage transmission industry. Furthermore, the utility of certain composite materials in some developing countries is already established in housing, water and sewage transmission, and to a certain extent, production is local. The supply of the need by local production has to be made and justified on a cost-effective basis, even if in some instances taxes and tariffs are introduced to artificially favour local production. Here the notion of profitable market size is contained, which, of course, varies from product to product and from country to country. In instances where capital investment is high, a large initial secure and growing market has to be guaranteed, such as in the consumer sector or housing-related sectors. In labour-intensive manufacturing processes an initial small market is sometimes sufficient to justify start-up of a new business.

(ii) The second criterion is the use of local raw materials to produce composites for internal or even external consumption. Here one can consider cement, organic fibres, mineral fibres, biomass-polymers, petroleum- or coal-derived polymers, steel or glass fibres. At the present time the production of the latter three materials is in the hands of the industrialized countries but, given the right set of local conditions, there is nothing against producing such materials in energy-rich developing countries. The problem is that, unless the local raw material source is cheaper, little economic advantage will be gained by local production since the processes are highly automated and of proprietary nature (belonging to the industrialized countries).

(iii) The third criterion is the more cost-effective on-site/local fabrication of the composite material or structure from the imported basic components. In this context the imported price plays a major role: this consists of the factory price plus transport plus taxes (if any). For many large structures, such as pipes and tanks, transport costs per kg or metre length of useful product are high since mainly empty space is being moved.

(iv) The fourth criterion is to provide jobs to the indigenous labour force by manufacturing composite materials or structures that replace either already imported composites or substitut other local or imported materials. Here the manufacturing technology is important and the labour-intensive ones, such as moulding, in particular. Small finished articles are being increasingly produced by automated processes but larger ones, such as (some) pipes and tanks, boats, panels etc. could be advantageously made in developing countries for local consumption. Labour-intensive products could also be exported to neighbouring countries and even to industrialized countries, under certain conditions of quality control.

(v) The fifth criterion for considering a local composite material or structure production would be if a specific problem could only be solved by a composite material and that importation was impossible because of dimensions or the nature of the application. Here one can think of very large storage tanks that have to be manufactured on-site.

(vi) The sixth criterion is that the basic material and associated manufacturing and application technology is well-proven in industrialized countries. Local R and D could be oriented towards adapting the technologies, whereby new or modified materials might be introduced to take advantage of local conditions. The obvious examples here would be the use of natural fibres instead of glass in some structures.

(vii) A seventh criterion, that is purely political in nature (at least at the outset), is that a composite material industry must be developed in the developing country itself in order to create jobs and establish an advanced industry in that country. The decision may or may not be based on technical or financial arguments and the resulting products may be forced on the market at artificially low prices. This choice is very rare but must be considered since even the industrialized countries have undertaken high-technology ventures with a view to increasing prestige. Even although the initial decision might have been valid on a technological market and cost basis, projects have been continued beyond the profitability stage for mainly political reasons.

(viii) The eigth and final criterion, or rather sine qua non for introducing composite material production in developing countries, is the availability of finance for

- factory space
- equipment investment
- technology aquisition
- raw materials procurement
- wages

The initial financing for a composite material venture may be possible from the World Bank, local investors, industrialized country banks and investors, or most probably through a joint venture with companies involved in the relevant technology.

b. Advantages

A distinct advantage for its introduction is that composite materials technology does not require very large markets and hence no very large production capacity investments to justify its introduction. Neither does it involve very large factories/heavy equipment (such as the steel industry), individual factories may be kept small (for specialized products), and many may be situated in different parts of the country to satisfy local markets. The labour force may also be kept small thus limiting large population movements.

In general terms, further advantages for the introduction of composite material production in developing countries are:

- Profit may be drawn from the large amount of R and D undertaken in the industrialized countries;
- Design procedures are relatively straightforward for normal utilizations that would be envisaged initially;
- The basic components are for the most part very cost-competitive for importation.

c. Limitations

Limitations and handicaps for the introduction are:

- Technology will almost certainly have to be initially imported in at least some of the smaller countries, and technical assistance will be necessary;
- In some cases joint ventures will have to be negotiated;
- Although not very labour-intensive, a skilled or semi-skilled work force is required since the quality of the final product is highly dependent on the care during manufacture. For highly stressed components, this will be a severe handicap to be overcome (initially at least) by the presence of highly skilled engineers in the work force;
- New handling and installation techniques (and philosophy) will have to be mastered that differs from those practised for metal or wood;
- The engineering consultants and construction companies will have to be persuaded to use (a) a composite material, in addition, (b) a locally produced composite material.
- Ingrained tradition and confidence in new solutions are involved here and should not be underestimated in their negative or

positive impact on the introduction of composite materials. As a temporary initial measure, codes of construction and local legislation may be introduced to assist in forcing through composites which will then succeed or fail on their own merit.

- Manufacturing and utilization specifications will have to be written and put into effect, initially based on those used in the industrialized countries;
- Cost comparison may be unfavourable when compared with alternative or similar imported products.

3. Utilization

a. Criteria/advantages

The criteria for justifying utilization of composite materials, independent of their provenance, are:

- Cost-effective satisfaction of a local need (as under production above) or improvement of the quality of life;
- Accomplishment of some task that would be otherwise impossible or difficult (e.g. salt extraction);
- Improvement of the efficiency or cost-effectiveness of certain processes by increasing life-time (e.g. sewage pipes);
- Reducing the need for maintenance (e.g. through improved corrosion resistance) and often costly technical expertise.

Currently, the utilization of composites in developing countries is mainly in corrosion-resistant applications involving pipeline transport of water, sewage and corrosive media. The (only!) major reason for utilization is cost-effectiveness and in many instances where the market is large, local production capacity has been introduced. This is the case in Saudi Arabia and the United Arab Emirates. In other instances, a local production facility has been temporarily set up for the duration of a specific project.

b. Limitations

The major limitations and arguments against the utilization of composite materials and structures in developing countries are essentially the same as those discussed under production:

- Expensive imports unless locally produced;
- Semi-skilled and skilled labour required for installation;
- Inexperience of engineering consultants and construction companies;
- Confidence;
- Lack of satisfactory specifications that ensure homogeneous and regular quality of both product and installed structure;
- Cost.

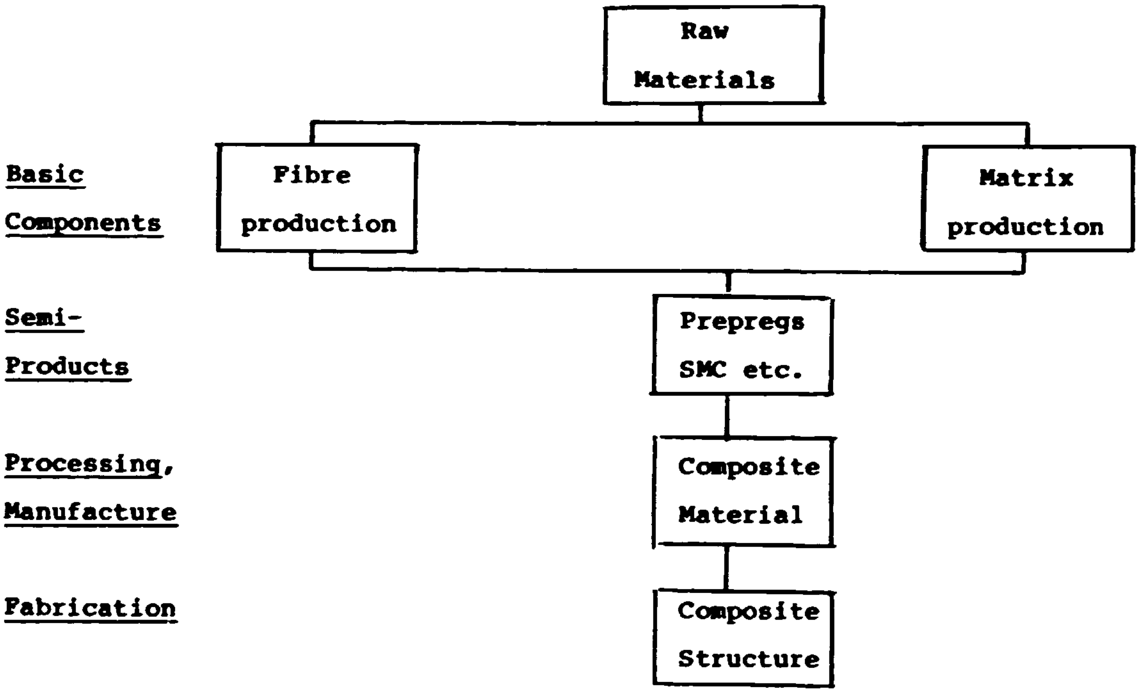
B. Potential manufacture and applications for developing countries

In this section, various composite materials and structures chosen on the basis of the criteria presented in chapter I are discussed from the standpoints of their potential manufacture and applications in developing countries.

The manufacturing process, as discussed in chapter II, involves a series of operations all the way from the basic component production through to the final material product or structure, as illustrated in figure 23. The moment at which any individual country or company enters the process depends on many parameters and will vary from case to case.

Figure 23.

Composite material and structure production flow-diagram



Regarding specific examples, an analysis of each step of the general production flow-diagram is presented from the viewpoint of potential importance to, and implantation in, developing countries. All types of composite material are covered, from those involving natural fibres through the most wide-spread glass fibre-reinforced plastics up to the advanced composites.

1. Composite material and structure production

a. Basic components production

The wide variety of possible basic components opens up many potential avenues for developing countries to become involved in composite fabrication through firstly basic component production either for subsequent local consumption or even export.

b. Natural organic composites

Incorporating both fibres and matrix, natural organic composites are among the most widely used construction materials, e.g. wood (lignin reinforced with cellulose fibres) and bamboo. Optimum utilization of wood is through lamination of sheets of highly anisotropic natural wood = plywood. Attempts are also made to extract the cellulose fibres and to reconstruct artificial composites (paper, reinforced cement etc.). These composites do not represent anything new in comparison with artificial composites, but a combination of the two sometimes leads to interesting, more efficient and cost-effective structures.

2. Specific fibre production

a. Natural organic fibres

These exist in most developing countries and are more or less already utilized for clothes, textiles, ropes etc. The most common ones are cotton, jute, hemp, coconut fibres and bagasse. Extraction if often the by-product of another process, e.g. sugar cane = bagasse, but the collection and selection often have to be improved so that the fibres can be utilizable as effective reinforcements.

b. Minerals

Asbestos is the most widely used mineral fibre, but is not found in all countries. Two types--chrysotile and crocidolite--are employed for reinforcement purposes, and the latter requires strict security/health measures in handling and treatment. If these are followed, however, asbestos-reinforced products--principally cement--are of great value in the housing and pipeline sectors.

Mica is equally a very interesting natural reinforcement material, existing in flake form which provides directly a two-dimensional reinforcement. Technologies of incorporation (surface treatment, bonding etc.) are not yet far advanced so as to take full advantage of the reinforcing effect of mica, but it exhibits high potential. For example, it can considerably increase thermoplastic resin properties: stiffness x six; flexural strength times two; heat resistance by 50 per cent, while also reducing warping or demoulding.57/

c. Metal wires

The best known are steel wires produced mainly by wire drawing (or from the melt) and which are employed widely in the reinforcement of rubbers (natural and synthetic): tyres, hoses and concrete. Others, such as tungsten are employed in special circumstances to reinforce high temperature, turbine blade alloys.

d. Whiskers

These are small diameter (approximately 10 μ), short, high purity fibres of metals, oxides (e.g. sapphire) or nitrides (Si_3N_4) that are grown from the melt or the vapour phase. They have very high strength and stiffness, but are expensive and difficult to handle.58/ Silicon carbide whiskers are produced by high temperature (1,800 degrees C) treatment of rice hulls: 100 kg milled rice gives 20 kg rice hulls. Whisker reinforcement is of most interest in metal matrix composites.

e. Glass fibres

Five main types are on the market for reinforcement purposes; their compositions are given in table 20. E-glass (electrical glass) is the most frequently used type since it is the most cost-effective; it was originally developed for electric insulation purposes. Presently, it constitutes the standard reinforcement for all kinds of plastics. Recently, E-glass has been increasingly used for mixed-fibre, hybrid reinforcement.

C-glass (chemical glass) is known for its chemical durability, which is better than that of E-glass. It is used for reinforcement in corrosive environments (e.g. batteries). A-glass (common soda-lime glass) is made from soda-lime scrap glass and is usually blown into insulating wool. Its use for reinforcement has been reduced drastically because E-glass is more cost-effective. It is still used for reinforcing pitch-based or impregnated materials.

Table 20.

Components of continuous-filament fibreglass*/

(Percentage)

Component	Type				
	Common soda-lime (A)	Electrical (E)	Chemical glass (C)	Alkali resistant (AR)	High-strength (S)
SiO_2	72.0	54.3	64.6	60.9	65.0
$Al_2O_3 + Fe_2O_3$	0.6	15.2	4.1	0.27	25.0
CaO	10.0	17.3	13.4	4.8	--
MgO	--	4.7	3.3	0.1	10.0
Na_2O	14.0	0.6	7.9	14.3	--
K_2O	--	0.6	1.7	2.7	--
B_2O_2	--	8.0	4.7	--	--
BaO	--	--	0.9	--	--
TiO_2	--	--	--	6.5	--
ZrO_2	--	--	--	10.2	--
SO_3	0.7	--	--	0.2	--
As_2O_5	trace	--	--	--	--
F_2	--	0.1	trace	--	--

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*/ Continuous glass fibres are made by three processes: the marble melt process, the direct-melt process, and the Pochet process.

S-glass (high-strength glass) has a high tensile strength and elastic modulus fibre developed essentially for military application. Being considered as a strategic material, its use is strictly controlled. A similar but lower cost high strength fibre named S-2 glass is now on the open market. Typical uses are aircraft floorings, helicopter components, compressed gas tanks etc. (R-glass has similar properties as S-glass). AR-glass (alkali-resistant glass) has been developed principally for reinforcing cement and concrete. This glass is supposed to be resistant to alkaline matrices.

A comparison is given below of the properties of the two major reinforcing types of glass fibre, indicating that the most interesting glass for developing countries is the E-glass.

	Tensile strength (GPa)	Elastic modulus (GPa)	US$/kg (1982)
E-glass	2.5	73	1.1
S-glass S 2	3.6	86	5.2
S 1	4.5		22.0

Glass fibre production involves passing the molten glass through a platinum bushing consisting of several hundred holes. The freshly drawn continuous filaments (10 μ diameter) are protected by a chemical agent and stored in the form of strands and yarns. For incorporation into composites, the glass fibres are made into continuous filament rovings and mats, chopped strand mats and chopped fibres and woven cloth.

Major glass fibre manufacturers are Owens Corning Fiberglass, PPG, Pilkington and St. Gobain. The technology is highly advanced and certainly transferable to any country desirous of investing in glass fibre-reinforced composite fabrication. In addition, a new low-energy method for producing short glass fibre has been developed[59/] which works with a variety of raw material glass: scrap, bottles, a wide range of mineral glass etc. Quantities down to 1,500 t/year can be processed.

f. Carbon fibres

Carbon fibres were first used for electric lamp filaments by Edison in 1880, and carbon fabrics made from graphitized rayon cloth have been available for many years. However, only recently have fibres of strengths and moduli of interest for reinforcement purposes been produced.60/

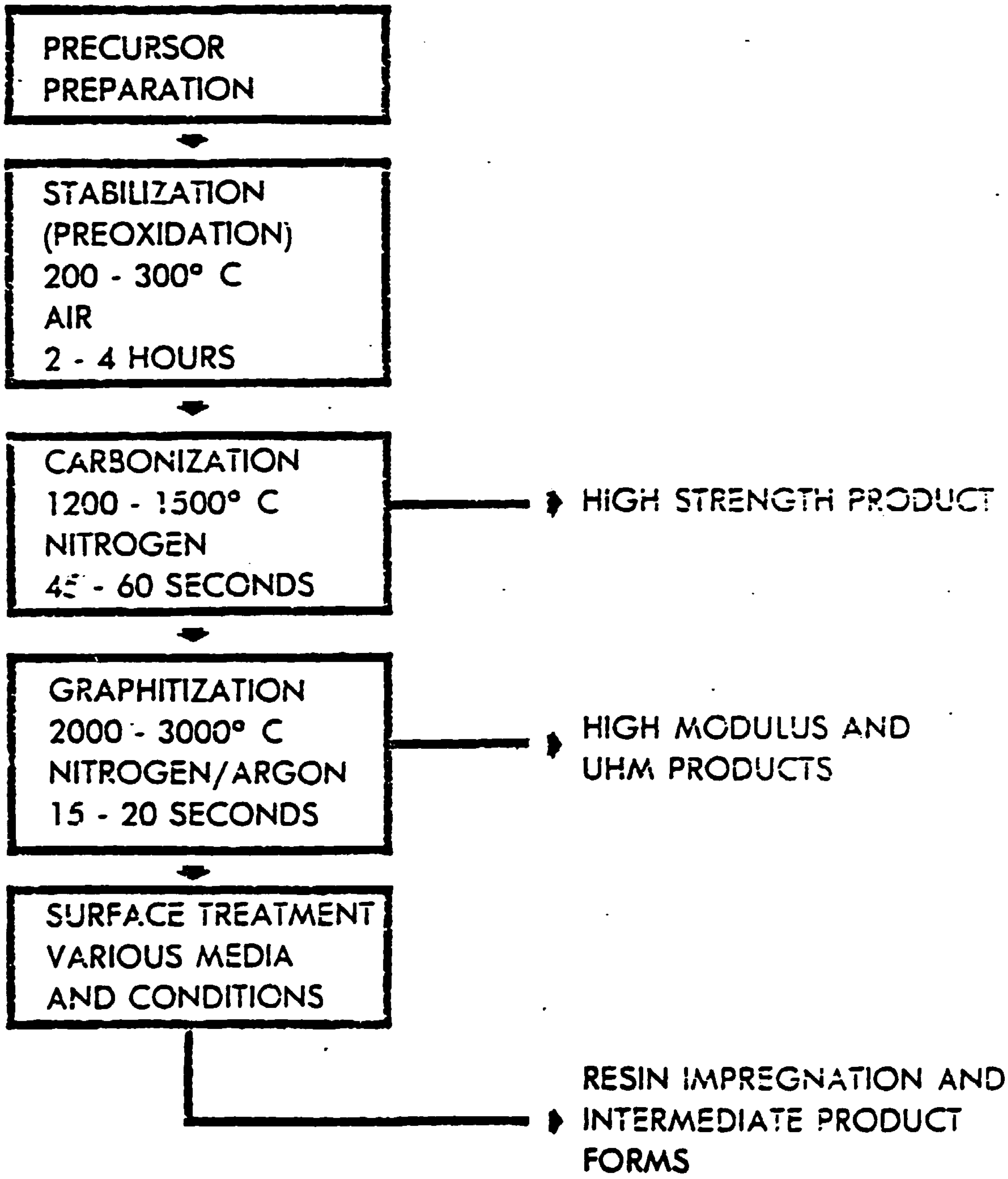
The fibres are made by pyrolitic degradation of a fibrous organic precursor (i.e. heated under tension to very high temperature in an inert atmosphere) so as to drive off the volatile components and orient the carbon atoms. The main precursors are rayon (now discontinued), polyacrylonitrile (PAN) and pitch fibres, i.e. all petroleum- or coal-derived chemicals. The interest in pitch is its low initial cost, but much preparation is required to obtain a grade suitable for fibre extrusion. Figure 24 presents an outline of the carbon fibre production process.

The carbon fibres are produced in tows of between 1,000 and 160,000 individual fibres (each about 12 μ in diameter). The process parameters control the properties of the final fibre, and in general the higher the temperature the higher the modulus. However, the strength decreases with increasing modulus. As with glass, the carbon fibre tows are surface-treated for protection and subsequent compatability with resins, and then wound on spools or woven into cloth or chopped into mat.

Energy requirements are estimated to be in the order of 40 kW/kg of carbon produced. Current annual world production capacity (installed or planned) is in the order of 3,500 tons, which is far in excess of present-day requirements (approximately 1,000 tons). The established companies in Japan (Toray, Kureha), the United Kingdom (Courtaulds) and in the United States (Hercules, Union Carbide, Celanese etc) will soon be joined by three newcomers: RK Textiles (Great Britain), ELF and PUK (both in France) representing around 450 tons per annum. Investments required are in the order of US$100,000 per ton of carbon fibre produced annually and manpower requirements are around 30 people per 100 tons/annum.

Figure 24.

Graphite fibre process outline



Current prices of carbon fibres are around US$40/kg and upwards, and major applications remain in aerospace or luxury/leisure goods. Prices have dropped considerably in the last five years, but US$20 is considered to be about the minimum possible based on present raw materials and production process. Fibre production is highly automated and requires only a small number of skilled workers to produce 150 t/year.

g. Aramid fibres[61]

At the moment, only one commercial aramid fibre exists: KEVLAR R of E.I. Du Pont de Nemours, introduced in 1977. Manufacturing details are not available, but the basic process involves the spinning at high temperature (260 degrees C) of a poly-p-benzamide polymer. It is a member of the polyamide (e.g. nylon) fibre family.

Three types of fibre are currently available: Kevlar for rubber tyres, hoses and belts, Kevlar 29 for ropes, cables and protective clothing and Kevlar 49 for the reinforcement of plastics. The latter represents around 30 per cent of the total Kevlar fibre production, or around 2,000 tons per annum, and sells at between US$18 and US$22/kg. The actual markets for Kevlar 49 fibres are in aerospace (40 per cent), marine applications (40 per cent), miscellaneous (20 per cent).

h. Boron filaments[62]

These very special, high-price filaments (US$300 to US$1,000 per kg depending on the diameter) are used uniquely in aerospace and military applications to reinforce aluminium or plastics. They are manufactured in a continuous form on a heated tungsten or carbon filament by chemical vapour deposition from a boron trichloride/hydrogen mixture. Application in everyday sectors is unthinkable at the present price, which is not expected to decrease much in the near future.

i. Planar reinforcements[63]

The use of planar reinforcements, such as flakes and ribbons, provide reinforcement in two directions. Current composites using this principle include mica-based polymers,[64] and metal-ribbon-reinforced pipe[66] and sheet[66]. Reinforcement principles are similar to those for filaments and the materials represent interesting opportunities for using either local resources (mica) or relatively conventional industrial products, such as steel sheet as discussed earlier.

3. Specific matrix production

a. Cement and concrete

The basic raw materials for the production of cement and concrete exist in almost every country in the world. There is often a question of quality but compromises may be made in order to optimize the use of local resources.

b. Polymers[67]

The principal raw material for polymers today is petroleum. The petrochemicals necessary for polymer production (organic acids, bases, ethers, esters, olefins etc.) can also be synthesized from other organic substances (coal, natural gas and biomass). The reliance on petroleum is mainly economic. The total quantity of petroleum-based chemicals produced represents only about 2 per cent of the oil consumption. Also, substituting a polymer for a glass, ceramic or metallic component more often than not results in fossil fuel savings due to a reduction in processing energy.

Most polymeric materials, either alone or in the reinforced form, have further additions of fillers (carbonate, mica, talc etc.) that may improve fabrication and the final properties, as well as significantly reducing cost. Useful properties that give polymeric materials advantages in certain applications include:

- Good formability;
- High strength-to-weight ratio in many forms;
- Unique viscoelasticity;
- Low density in general;
- High corrosion resistance to aqueous and many organic systems;
- Electrical conductivity (low to high);
- Low thermal conductivity;
- Good joinability;
- Wide range of permeability to gases and liquids.

Two other characteristics of polymer application also provide advantages:

- Energy-efficient production methods;
- Little dependence on scarce materials.

Properties that limit the application of polymers include:

- Poor aging creep response;
- Low upper temperature limit (200 to 400 degrees C);
- Low resistance to environmental organics, ultraviolet radiation, ozone and radioactivity;
- Poor flame retardance;
- Relatively poor reproducibility of properties (principally due to inadequate processing control).

An additional significant disadvantage of polymers arises from their by-products. The chemical wastes resulting from polymer fabrication and synthesis are in a few cases highly toxic and may be non-biodegradable. Furthermore, disposing of polymer products at the end of their useful life generates severe environmental problems. The magnitude of these problems is only now being realized and will receive more attention in the future.

The manufacture of plastic resins for utilization in fibre-reinforced composites is a major industry as shown in Table 21. Expoxy production in 1982 was 135,000 tons in the United States, 30,000 of which was in reinforced plastics, i.e. accounting for 80 per cent of the increased tonnage. Of these 30,000 eight-thousand were used in advanced composites.

In the presence of a catalyst, heat and/or pressure thermosets undergo an irreversible chemical reaction (cure) to give rather high strength polymers that are noted for their excellent adhesion characteristics to reinforce fibres. Phenolics, polyesters, epoxies and vinyl esters account for 90 per cent of the reinforced matrix market. Thermoplastics account for the remainder and, as the name implies, they are reversibly transformed by heat from highly stable solids at room temperature to highly viscous liquids which can be readily worked.

Table 21.

Reinforced resin consumption in the United States of America in 1977

	Reinforced plastics (1000 metric tons)	Total consumption (100 metric tons)
Thermosetting Resins		
Epoxy	22	125
Phenolic	41	638
Polyester Unsaturated	370 (700[a])	477
Urea-Melamine	15	514
	448	1,754
Thermoplastic Resins		
Nylon	17[a]	110
Polyacetal	2[a]	42
Polyester, Thermoplastic	15[a]	21
Polyethylene, H.D.	2[a]	1,620
Polyprophylene	30[a]	1,247
Styrenics[b]	13[a]	2,110
Other[c]	9[a]	150
Total	88[a]	5,300

a/ includes reinforcement material
b/ Polystyrene, ABS and SAN
c/ includes Noryl, polycarbonate, polysulfone, fluroplastics, polyphenylene sulfide etc.

Epoxy resins are predominantly used in advanced composites and in situations of high stress, the curing temperature increasing with required operating stress and temperature. They are also the most expensive, varying from US$1.50 to US$22 per kg, or between 2 and 30 times the price of polyesters, which are by far the most widely used resins for glass fibre-reinforced composites and are starting to be examined as matrices for the lower stressed advanced composites.

Thermoplastic resins, such as nylon are employed as matrices for composites containing short (glass) fibres that are widely used in friction applications (gears). Advanced (and rather expensive) thermoplastic matrices, such as polyethersulphone (PES) and polyetheretherketone (PEEK) are currently under investigation for advanced composite utilization.

4. Semi-products manufacture

Under semi-products are included fibre tows, roving fabrics, tissues, mats and chopped fibres as well as thermoset resin preimpregnated products (prepregs), sheet moulding compounds (SMC), and thermoplastic compounds. All the fibre forms are produced in order to facilitate incorporation into a matrix for the optimum fabrication of the finished product.

The fibre tows, rovings, mats and chopped fibres are normally produced directly by the fibre producer, whereas fabrics and tissues are the work of companies with textile experience. The fabrics may be of one fibre or a mixture (hybrids) and the weaving of glass (or glass and carbon, for example) is within the capabilities of many textile companies.

Thermoset resin preimpregnated (prepreg) products consist of a preformulated mixture of fibres and partially cured resin that requires no further processing other than:

- Cutting to shape;
- Laying up in correct form in a mould;
- Curing under specified conditions of temperature, pressure and time.

Prepregs may contain non-woven (unidirectional) or woven fibres, and their use is the standard mode of advanced composite manufacture. Resins may be epoxy or polyester.

The main advantage of prepregs is their limited shelf life (i.e. duration of storage without alteration). For example, an epoxy prepreg shelf life is six months at minus 18 degrees C and 14 days at 21 degrees C. Therefore refrigerated transport and storage are necessary. Prepregs of carbon fibre are also rather expensive: about two to three times the cost of the fibre contained in the material.

a. Sheet-moulding compounds (SMC)(69)/

Sheet-moulding compounds (SMC) of polyester and glass fibre are widely used for moulding furniture as well as bumpers, hoods, fenders etc. in the automobile industry. SMC is made by depositing chopped fibres (10 to 50 mm long) on a layer of resin carried as a continuous paste or film. The fibres are sandwiched by a second layer of resin and pressed to remove excess resin. The resulting sheet is wound under tension and stored. Basic SMC machines cost from US$30,000 to US$150,000 and require four to six operators.

b. Thermoplastic compounds

Thermoplastic compounds consist of mixtures of between 10 to 40 per cent weight of short fibres (mainly glass but also carbon[70/] for the more expensive resins) and are compounded with the resin (often nylon) in screw extrusion equipment. They are used as feedstock in injection-moulding machines.

5. Composite processing manufacture

The techniques have been described previously in chapter 1. The choice of technique obviously depends on the product that has to be produced. From the choice criteria presented in section A of this chapter, the products that present the most interest for developing countries, and thus define the technique(s) to be used, are as follows:

Modular buildings	Contact moulding
Pipes/ducts	Centrifugal casting Filament winding (manual or mechanized)
Tanks, cisterns	Filament winding (manual or mechanized)
Energy production - related structures	Pressure moulding, hand lay-up

Products in these categories are discussed in detail in chapter II.

In many instances, the composite structure produced must be machined or joined to other similar elements or to another structure in order to provide a useful structure. In the majority of the cases discussed from the viewpoint of the developing countries, final fabrication will involve either mechanical joining (in buildings and pipes) or adhesive bonding (pipes, tanks).

C. Specific suggestions

1. Analysis of applications

Table 22 presents the results of the analysis carried out in chapter II for the different composite materials and applications as they meet the criteria for introduction of composite production in developing countries, which were presented in section A of this chapter.

2. General conclusions

The analysis conducted in this paper allows the following general conclusions to be drawn:

- In general terms, a composite materials industry could be effectively introduced in developing countries, subject to the fulfillment of certain conditions;

- Unless adequate local capabilities for R and D and commercialization exist, the developing countries may find it advantageous to use what exists in the way of:
    - Technology
    - Design
    - Manufacturing techniques
    - Installation techniques.

  Applications may, however, be new and unique to each country and adaptations may be necessary.

- Raw materials should initially be those proven elsewhere to give satisfactory performance. The utilization of local raw materials as replacement for imported products or as a source of new products should be studied in parallel with production of standard materials;

- The most suitable basic material is glass fibre-reinforced polyester, which has a large background of experience in design, fabrication, installation and operation that can be readily transferred to developing countries;

- There exist manufacturing techniques for products of primary importance to developing countries, which are heavily dependent on manpower that is readily available in developing countries. The new skills to deal with composites are, however, quickly acquired and can be accelerated by appropriate instruction. The skilled labour required could be imported in the initial phases mainly for quality control at all stages of production;

Table 22.

Evaluation of composites on the basis of choice criteria for developing countries

CRITERIA	Raw Materials production		Windmill Blades	GRP in construction	Large Diameter Pipes			Small diameter GPR pipes	GPR tanks	Natural fibre composites
	glass fibre	polymere matrix			AC	GRP	steel-plastic			
Flexibility of technology	Na	Na	+	++	+	+	+	+	+	++
Satisfy local need	o	o	o	++	++	++	++	+	+	++
Improve quality of life	o	o	+	+	+/o3)	++	++	+	o	++
use local raw materials	o	-1)	o/-	+/o2)	+/o	-	o4)	-	-	+
Economic local production	o	o	o	+	+	+	+	+	+	+
Provide employment	+	-	+	++	++	++	++	++	++	++
Solve specific problems	Na	Na	+	++	++	++	++	+	+	++
Technology is proven	+	+	+	++	++	++	+	++	++	o
Financement available	o	-	o/-	+	+	+	+	o	o	-
Quality control straight forward	-	-	-	+	++	+	++	+	+	o
Introduction of new technology (political)	++	++	++	++	o	++	++	+	+	++
skilled labour requirement low	-	-	-	o	+	o	o	-	o	o

Key

++	No doubts on criterion fulfilment
+	Under certain circumstances the criterion is fulfilled
o	No definite answer
-	Does not meet criterion, or only with much development and expense.

1) Readily met only in oil/gas/coal producing countries.
Biomass source requires R and D.
2) In low stress applications, natural fibres may be employed.
3) Health questions still outstanding.
4) Where a steel mill is available.

- Plant investment and energy requirements are not excessive in the initial phases of introduction of the industry;
- Glass fibre-reinforced plastics for construction panels and pipes require no special research and development effort or personnel.

3. Specific suggestions

Of all the composite materials, along with their basic components, that have been analyzed, the most suitable for introduction in (selected) developing countries are:

(i) Initially glass fibre-reinforced polyester, because a great deal of experience exists already. It is a proven success in many sectors and is highly cost-effective.

(ii) Natural fibre composites because of the supply, economic and local expertise development opportunities.

a. Introduction of the material will be recommended where there is an established, and growing, need for:

- housing
- water transportation
- sewage removal
- energy development
- minerals treatment.

It is specifically suggested that glass fibre-reinforced polyester be introduced in the following manner:

(i) Establishment of a local company for the fabrication of hand or spray lay-up, contact moulding of GRP panels with short fibre mats for construction purposes and mouldings for tanks, baths, furniture etc. The know-how and training of personnel should be introduced through a commerical arrangement with a specialized company. The main advantage of the hand lay-up technique is that it is highly versatile and, once the basic know-how is assimilated, this technique can be used to fabricate a large variety of consumer products. A parallel investment could be made in pultrusion (also a relatively simple technology) where plans exist to develop the construction industry (i.e. the pultruded profiles will served as the framework).

(ii) In the case of a large country, several smaller companies may be set up at the same time in order to satisfy more local markets.

(iii) Design and fabrication techniques should follow the already established and well-tried procedures. Local personnel should be continuously trained.

(iv) Once fabrication and operating experience has been gained, or as a parallel operation depending on the market situation, the production range should be expanded to hand-wound pipes and tanks which will be stressed more highly than the previous products but which can still not be classified as being highly stressed. At this stage one is moving into areas where quality control is of utmost importance and the need for skilled labour increases.

(v) Introduction of automated equipment for the utilization of woven rovings and filament winding equipment for highly stressed products. At present, the composite approach to product development is reaching the sophisticated stage and may require further assistance from specialized countries. In some instances (and countries) the introduction of sophisticated technology may be justified at a very early stage because of the market profile and investment availability.

(vi) The final profile of the composites industry will vary from country to country, but two extremes are possible:

- One large, fully integrated company
- A multitude of small fabricating companies of a relatively low level of technology: manual, artisan moudling.

b) Natural fibre composites render products which may be termed low-stress, yet useful, everyday applications of considerable interest to developing countries, e.g. furniture, utensils, travel containers, packaging etc. Extension of such structures to housing panels has been done in certain countries and is extremely interesting.

The recommended general approach to the introduction of a natural fibre composite industry is as follows:

(i) <u>Analysis of the local situation</u>

- Evaluate potential raw material supply and distribution, manpower availability, finances etc.
- Identify the most promising products and their competitors.

(ii) <u>Specific developments</u>

- Market analysis of selected products
- Feasibility study on the chosen materials and products
- Research and development for the most suitable materials, their treatment and fabrication; search for new fibres and local matrix materials; and appropriate design methods
- Semi-industrial development: licenses, marketing, sales, factory implantation (e.g. one large or many small ones).

4. Impact analysis in developing countries

a) Impact on structural materials

Introduction of composites (mainly/only GRP) will reduce demand for (eventually imported) steel and cement. Introduction of advanced composites will probably lie in a new field, so of no influence on current materials usage.

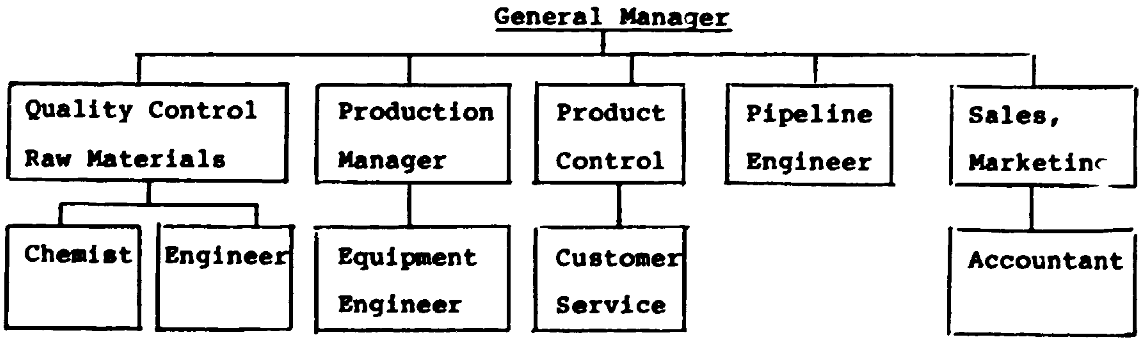
b) Impact of raw materials supply

No problem can be foreseen from the raw materials supply side if composites are more widely introduced in developing countries.

c) Labour

Labour requirements may be extrapolated from the situation in France where for an annual GRP production of 120,000 tons, approximately 30,000 people are employed, 5 per cent or 1,500 of whom are engineers. Typical companies manufacturing construction panels and hand lay-up pipes employ around 40 people and produce in the order of 200 tons per annum.

In developing countries, a typical small (approximately 200 ton capacity) company for pipe production could employ initially around 100 people, of whom 10 should be skilled, as given in the following organizational chart:



No development activity should be envisaged in the initial stage.

d) Energy

The specific energy content of GRP is much lower than in the case of steel or aluminium. Therefore introduction of GRP manufacture instead of steel saves energy. Advanced composites, such as carbon fibre-reinforced polyester, are equivalent to steel. The direct transformation energy, and therefore the costs associated with composite manufacture, are negligible for small series such as are produced in contact moulding, projection, low pressure injection or pressing. The costs represent only around 0.2 per cent of the total; raw material, labour and capital costs dominate. In hot pressing and thermoplastic injection this amount rises to between 1 and 6 per cent.

e) Transportation

Large gains are to be made by introducing light weight materials into automobiles, trucks, trains and aircraft. The developing countries will benefit from this in imported goods, but there will probably be little impact on structures manufactured within the country itself.

f) Health

The potential impacts on health by the introduction of composites all tend to be negative because:

- The small dimensions of the fibres may, if no precautions are taken, lead to lung damage. The hazard potential is considered to be less than that of asbestos, coal dust or quartz.
- The flammability of the reinforced plastics.
- Resin handling: prescribed procedures must be adhered to.

g) Water and air quality

Water and air quality might improve if composites lead to the introduction of more water treatment plants or scrubbing towers in chemical plant.

h) Solid wastes

Solid wastes resulting from scrapped composites are difficult to recycle. Current use is in land fill.

i) Product reliability issues

In the initial phase of introduction of composites in developing countries, uses should be restricted to non-critical structures or components where no major problems, such as involving loss of life, pollution, etc. can result. This is because product and installation quality are the sine qua non for reliable operation, and perhaps these cannot be guaranteed immediately in order to allow critical, often highly stressed structures to be produced and utilized in developing countries. The industrialized countries already spend vast sums of R and D money to resolve this situation without yet arriving at a satisfactory conclusion unless strict control is placed on all production and installation stages (i.e. at a high cost and with skilled personnel).

j) Technology advances

The advances in composite technology in industrialized countries, mainly in the areas of manufacturing and product quality, will be of direct benefit to developing countries. Unlike more traditional industries, there is large scope for innovation by all parties to develop products "fit for purpose". Thus, developing countries can have a considerable impact on the advancement of composite technology from the viewpoint of design for wide utili[illegible], especially in the natural fibre composites sector.

k) Research & development and education

The area of composite materials is one where considerable innovative work can be done in both developed and developing countries. Thus, introduction of composite materials manufacture and utilization will stimulate R and D activities in universities and research establishments on materials science, chemistry, chemical engineering, structural engineering etc. By the same token, the teaching of subjects related to materials technology at universities will be greatly enhanced because of their relevance to national activities.

GLOSSARY OF TERMS

ABS	acrylonitrile butadiene styrene
AC	asbestos cement
Boron/W	boron on tungsten filament
GPA	(giga Pascal) 1 GPa = 10^9Pa
GRP	glass-fibre reinforced plastic
HM	high modulus
HS	high strength
kgf	kilogram force
kJ/m^2	kilo Joules per square meter
µm	micron
MPa	(mega Pascal = 10^6Pa = 1MN/m^2 (mega Newton per sqare meter)
PE	polyethylene
Prepregs	Continuous, aligned fibre, chopped sheets or woven cloth or fabrics, preimpregnated with epoxy or polyester resin
PVC	polyvinyl chloride
RRIM	Reinforced reaction injection moulding
SAN	styrene acrylonitrile
SMC	Sheet moulding compounds consisting of a chopped strand mat impregnated with polyester resin

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