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UNITED NATIONS
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VEGETABLE-FIBRE CEMENT BOARD*

Prepared by the Institute for Material and Environmental
Research and Consulting (INTRON), on behalf of the
Ministry of Housing, Physical Planning and Environment of the Netherlands

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Preface

In the past two to three decades, significant progress and considerable research results have been registered in the field of low-cost building materials utilizing locally available raw materials.

The transfer of technology, however, has been rather slow in spite of a high demand for low-cost housing construction programmes in many developing countries. Technical literature on the subject is numerous but scattered, and one great difficulty, it seems, is the dissemination of technical know-how from one country to another through publications such as manuals, monographs, proceedings, technical papers etc.

This study on vegetable-fibre cement board, which was carried out by the Institute for Materials and Environmental Research and Consulting (INTRON) and financed by the Ministry of Housing, Physical Planning and Environment (VROM) of the Netherlands, was made available, free of charge, to the United Nations Industrial Development Organization (UNIDO). It is being issued as a UNIDO document as part of the Organization's effort to facilitate the transfer of technology in this important industrial field. It is hoped that it will contribute to the development of a natural-fibre-reinforced concrete boards industry in those developing countries where vegetable fibres and other suitable raw materials are in abundance.

SUMMARY

This investigation into vegetable-fibre cement board aims especially at the replacement of asbestos fibres in asbestos cement by native fibres of vegetable origin in developing countries.

Arguments to substitute asbestos by vegetable fibres are:

- health problems relating to asbestos;
- asbestos fibres have to be imported;
- appropriate vegetable fibres are mostly abundantly available in developing countries and can be produced also from waste vegetables products, such as rice straw, bagasse or waste wood;
- vegetable fibres are conformable to existing asbestos cement machines.

Vegetable fibrous material can be used in two ways:

- as bundles or strands
- as pulp.

Bundles or strands

Fibre bundles or strands are made from fibre-carrying leaves, basts or seeds by retting, decortication, carding, combing, etc.

These fibres still contain most of the original lignin and hemicellulose. The fibres are mostly long and are applied as continuous fibres or in chopped form.

There are a variety of fibres available. Mostly used in the world at the moment are sisal, abaca or manila hemp, and jute. In case the fibres are applied in a continuous form, a layer of continuous fibres or prefabricated mats of continuous fibres are embedded in a layer of mortar.

Subsequently a new layer of mortar is applied, followed by another layer of continuous fibres and so on. When chopped fibres are used a premix is made of chopped fibres and mortar which is subsequently poured in a mould. The continuous fibre sheets show higher strength and especially higher (pseudo) ductility.

Pulp

Pulp is made by chopping the raw material, which could be wood, bamboo, rice straw or bagasse etc., to pieces (chips) of some mm's or cm's.

The chips or pieces are subsequently pulped. The pulping processes applied vary from chemical to purely mechanical and thermomechanical.

To obtain a good quality of pulp for pulp cement board it has been ascertained that lignin and hemicellulose have to be removed to avoid negative effects of these constituents on the bonding of the fibre mortar and to improve the durability. Further it was found that collapsed fibres showing internal and external fibrillations in general have the best properties. The well-known kraft process appears to be in general suitable for producing these optimum quality pulps.

The pulp can be used in existing asbestos cement manufacture plants without major modifications. The most widely used machine in asbestos cement manufacture is the Hatschek apparatus, which preferably has to be a retrofitted to a so-called flow-on machine. This can be done with only minor costs. Even with the best pulp, pulp cement board made in the same way as ordinary asbestos cement, shows less good properties. Notably bending strength and especially the drying shrinkage wetting expansion behaviour are less favourable.

However, it has been shown that this can be improved by pressing the board and by autoclaving. For autoclaving ground quartz sand (silica flower) is used as raw material. In pressing, the board is compacted while water is removed. This leads to increased matrix strengths but, more important, substantially reduces the drying shrinkage/wetting expansion movements. Further it decreases the alkalinity and free lime content of the matrix. The latter appears to be important regarding durability.

Reinforcing mechanisms and durability

Theoretical models concerning the reinforcing mechanisms are discussed and phenomena influencing the durability of vegetable fibre cement board are considered.

For autoclaved pulp cement board it appears to be likely that Romualdi's fibre space fracture model can explain at least partially the reinforcing mechanism. For non-autoclaved pulp cement board the theory of Phan-Thien and Goh is useful, whereas for continuous fibre strands or bundles the Aveston-Cooper-Kelly theory can also be applied. Because of the changing conditions at the fibre interface in time the most likely models can also change in time.

Phenomena affecting durability are the alkaline degradation of lignin and hemicellulose in case of fibre strands or bundles and of the cellulose chains in non-autoclaved pulp cement board. For the latter material however, the rate of degradation appears to be lower than for the former. Also disposal of lime at the fibre-matrix interface (mineralization) has been observed and has been related to loss of impact strength.

Fibre treatment and matrix modification

A number of special treatments of fibres or modifications of fibres and mortars have been investigated. One of the most successful modifications of the matrix appears to be the use of a highly reactive silica powder such as silica fume and probably also rice husk ash. This silica reacts with the lime, which reduces alkalinity and the presence of lime. It has been shown to improve the long-term mechanical properties considerably.

Special additives are developed to enhance the processability of pulp fibres on existing asbestos cement machines.

Cost prices

Cost prices have been indicatively calculated for three plant sizes:
- village scale: applying a premix of chopped fibre mortars using very simple manufacturing tools, fully produced by hand;
- small-scale home industries: using pulp and pressing the sheets;
- large-scale industries: fully mechanised plants using flow-on machines, pressing and autoclaving.

The table below shows an overview of investments required, labour costs and production costs. Although the figures presented are only indicative and will differ from country to country and from area to area it is obvious that in general the total cost price will be similar for all three alternatives. However, it has to be stated that the quality of the product in general will be the highest for the large-scale industry and the lowest for the village scale industry.

The most striking difference regarding the production is the very much higher labour input required for the small-scale industry in comparison with the fully mechanised large-scale industry. This of course is of major importance for developing countries where unemployment is often high and labour costs are low.

	Unit	Village scale	Small-scale home industry	Large scale
Production	m^2/a	10,000	100,000	4,000,000
Capital investment	US $	10,000	250,000	10,000,000
Capital per unit of output	US $\$/m^2/a$	1	2.5	2.5
Jobs*	person	15	25	90
Jobs per thousand m^2 produced annually 0.022		1.5	0.25	
Jobs per 10^3 US $ invested		1.5	0.10	0.009
Cost price per m^2 of 5 mm	US $\$/m^2$	2.75	2.27	2.17

Training and quality

To manufacture vegetable fibres cement board on village scale and on small-scale home-industry level the skill of local people is of paramount interest. In general the quality of products made on village scale are lower than on industrial scale. Failures on large size, village made, vegetable fibre cement boards have made clear that production of small size products such as roofing tiles have to be preferred. Further a simple manufacturing manual and a standard for quality control based on simple tests can be helpful. Regarding the latter the report includes a Swedish recommendation.

CONTENTS

Appendices

1. INTRODUCTION

Fibres of vegetable origin as a reinforcement for building materials have a very long history. The use of straw for instance, to strengthen mud walls is probably as old as the use of clay for building.
The use of fibres to reinforce cement is of a much more recent date simply because cement has only been produced since last century. Fibrous Cement Board production started in the beginning of this century.
The fibre applied was asbestos, a natural mineral fibre. The production of asbestos cement has grown steadily. In the last twenty-five years it has become a major building material in many countries, notably in developing countries.

Efforts to replace asbestos fibres have increased in the last decades. The reasons are:

- Health problems relating to asbestos. Diseases such as asbestosis and the cancer type mesothelioma could be due to respiring of asbestos fibres (lit. 1)
- Asbestos fibres have to be imported from Canada, USSR or South Africa, which is especially unfavourable for developing countries with often negative trade balances and less hard currencies
- A shortage of asbestos fibres, which was likely in case the asbestos demand should continue to grow.

Attention was drawn to man-made fibres and to other natural fibres.
Man-made fibres however are:

- In general much more expensive than natural fibres (see table 1, lit. 2). Asbestos fibres costs in general amount to 30% of the production costs and costs for asbestos cement roofings in developing countries can account for up to 40% of the total costs. A substantial increase in fibre costs will therefore greatly increase fibre board costs
- Mostly not produced in developing countries
- Sometimes not durable, such as alkaline resistant glass fibres, or durable but then very expensive, such as polyaramide and carbon fibres
- Not applicable on the most common asbestos cement manufacturing machines, the Hatschek and Magnani machines, because of bad dispersability in water and poor felt forming properties.

Natural fibres of vegetable origin on the other hand:

- are mostly abundantly available in developing countries
- can often be produced from waste products such as ricestraw, bagasse or waste wood
- can be used, in particular when pulped, on asbestos cement machines.

Table 1. Assessment of fibres as possible replacements for asbestos in building boards (lit. 1).

Fibre	Dispersability in water ability	Felt forming	Alkali resistance	Autoclave temperature resistance	Flexural reinforcement	Toughness contribution	Costs (US $/ton)	Costs (US $/m^3)
Glass and ceramic								
E-glass	**	*	*	***	*	*	1800	4500
Cemfil	***	*	*	***	*	*	4000	10900
Kao-wool	*	*	*	***	*	*	5200	14200
Carbon fibres								
High modulus	*	*	***	***	***	****	22000	44500
Low modulus	**	**	***	***	**	***	3700	6500
Plastic								
Polypropylene	**	*	***	*	*	*	2000	1900
Rayon	**	*	***	*	*	**	1800	2300
Polyester	**	*	*	*	*	*	1900	2700
Nylon	**	*	***	*	*	*	1900	2200
Kevlar	**	**	***	***	***	***	11000	16200
Cellulose								
Wood pulp[1]	***	***	***	***	***	***	400	550
Mechanical pulp	***	***	***	***	**	*	250	350
Newsprint	**	***	***	***	**	*	75	100
Metal								
Steel	*	*	***	***	*	*	1900	14600
Asbestos	***	***	***	***	***	*	750	2300

* poor ** reasonable *** good **** very good (approximated prices, early 1981)

1) kraft

In the meantime the pulp cement board appeared to be most successful in asbestos cement substitution in the developing world, while other alternatives often make use of pulp fibres as one of the fibrous constituents.

The present report summarizes knowledge on cement board reinforced with natural fibres of vegetable origin with the emphasis on those developments that are of interest for developing countries. After a discussion of vegetable fibre composition and the various types of vegetable fibre the reinforcing mechanisms as far as specific for vegetable fibres will be described. Subsequently the pulp cement board will be considered, followed by the board made with continuous fibres. Finally a number of special matrix modifications and fibre treatments will be discussed.

2. FIBRE COMPOSITION AND STRUCTURE

Bundles of fibres, bound together by natural resins, gums and waxes, extend through the roots, stems and leaves of plants. They constitute the skeleton of the plant.

Some of these fibres are very rigid while others are flexible and very resilient. One thing they have all in common: they are based on cellulose. The natural polymer cellulose is formed by the plant from water and carbondioxide. It is a chain of anhydro-β-glucose units as shown in figure 1 (lit. 3). The number of these units can be a few thousand up to a few hundred thousands.

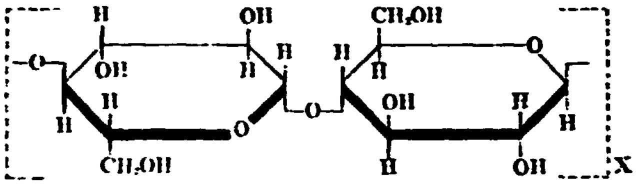


Figure 1. Anhydro-β-glucose units in cellulose polymer (lit. 3).

Although not completely established, it is thought that the cellulose polymer materials have a structure very much similar to some of the main artificial polymers e.g. crystalline areas alternated with amorphous areas, as shown in figure 2 (lit. 2).

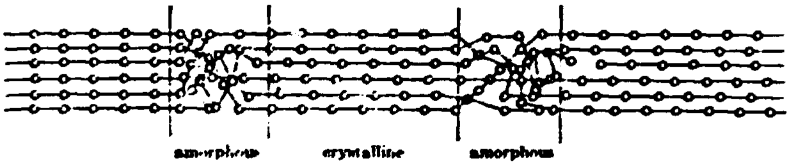


Figure 2. Chain structure of cellulose showing long chains forming crystalline and amorphous regions (lit. 3).

The cellular polymer appears to be helically wound around an open space: the lumen as shown in figure 3 for sisal fibres (lit. 4).

The fibre cell consists of a number of walls built up of fibrillae. In the outer wall (primary wall) the fibrillae have a reticulated structure. In the outer secondary wall S_1, which is located inside the primary wall, the fibrillae are arranged in the form of a spiral with a spiral angle of 40° in relation to the longitudinal axis of the cell. The fibrillae in the inner secondary wall (S_2) have a sharper slope, 18°. The innermost wall (the tertiary wall) is thin and has a reticulated arrangement of fibrillae.

The fibrillae are, in turn, built up of micro-fibrillae with a thickness of about 20 um. The micro-fribrillae are composed of cellulose molecular chains with a thickness of 0.7 um and a length of a few um.

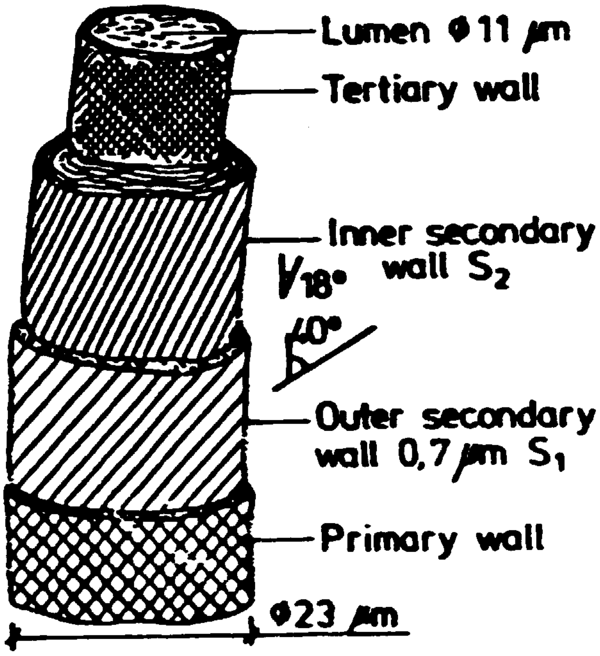


Figure 3. Schematic sketch of a fibre cell with the approximate dimensions indicated (lit. 4).

This structure gives the fibre its typical 'stress-strain' behaviour under axial tensile loads as shown in figure 4 (lit. 5). The fibre buckles (figure 5, lit. 5) at a certain load and after buckling initially shows a more elastic behaviour, followed by a renewed stiffer behaviour.

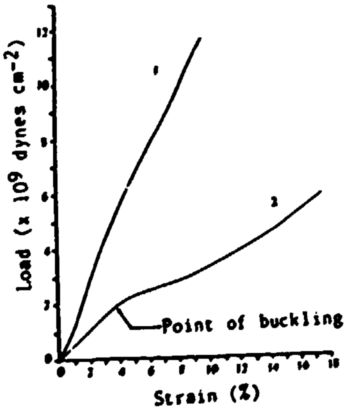


Figure 4. Stress-strain curves of sprucewood fibres.
1, a fibre that does not buckle
2, a fibre that buckles at the point indicated (lit. 5).

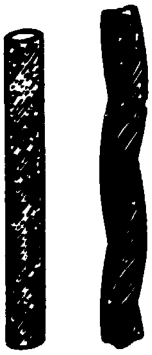


Figure 5. Left, spirally wound tube which, according to theory, buckles under axial tensile strain to the form indicated on right (lit. 5).

Figure 6. SEM-foto showing buckling under axial tensile strain of collapsed wood fibres.

Fibre cells which have been collapsed by beating or chemical treatments show a more ribbon-like structure without lumen and have a substantially linear stress-strain relation.

The fibre cells are linked together by means of middle lamellae, which are built up of hemicellulose, lignin and pectin. Figure 7 presents a schematic sketch of a fibre cell (lit. 6).

Hemicellulose (about 12%) consists of polysaccharides, mainly xylose. The degree of polymerization of hemicellulose lies between 50 and 200. The hemicellulose mainly occurs in the outer layer of the fibre wall, in other words the primary wall, and in the middle lamellae (lit. 4).

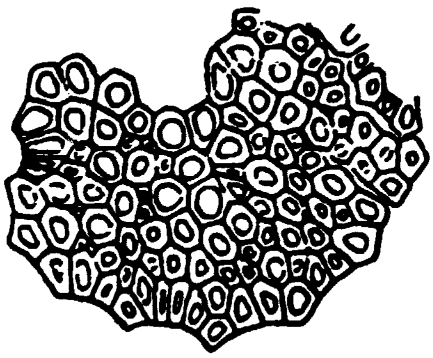


Figure 7. Cross-section through a sisal fibre (lit. 6).

The pectin (minor percentage) occurs in the middle lamellae and probably has a cohesive function.
The lignin mainly occurs in the middle lamellae. The middle lamellae contain up to 80% lignin which varies strongly from plant to plant. In plants cellulose is further found closely associated with fats and waxes of various kinds.

Pectin, lignin and hemicellulose influence the cement-water reaction and are known to affect the bonding of the fibre with the cement matrix negatively. Moreover these compounds are not alkaline resistant and degradation occurs in moist-hardened cement, see figure 8 (lit. 6).
The aromatic three-dimensional structure of lignin is easily broken down. Hemicellulose is also decomposed by the alkaline environment. End groups react and are unhooked from the molecular chain. The macromolecule is peeled off in this way. Because the polymerization degree of hemicellulose is rather low (50 to 200) in relation to the cellulose this peeling-off mechanism has a substantial effect on the characteristics of hemicellulose. Also the long cellulose molecules can be affected by the alkaline environment of the cement matrix. However this appears to occur only to a minor degree.

Unreinforced fibres of which the lignin and hemicellulose have not been removed therefore change their characteristics in a cement matrix, which is not the case, or hardly, with refined fibres such as pulp from the kraft process where lignin and hemicellulose have been removed.

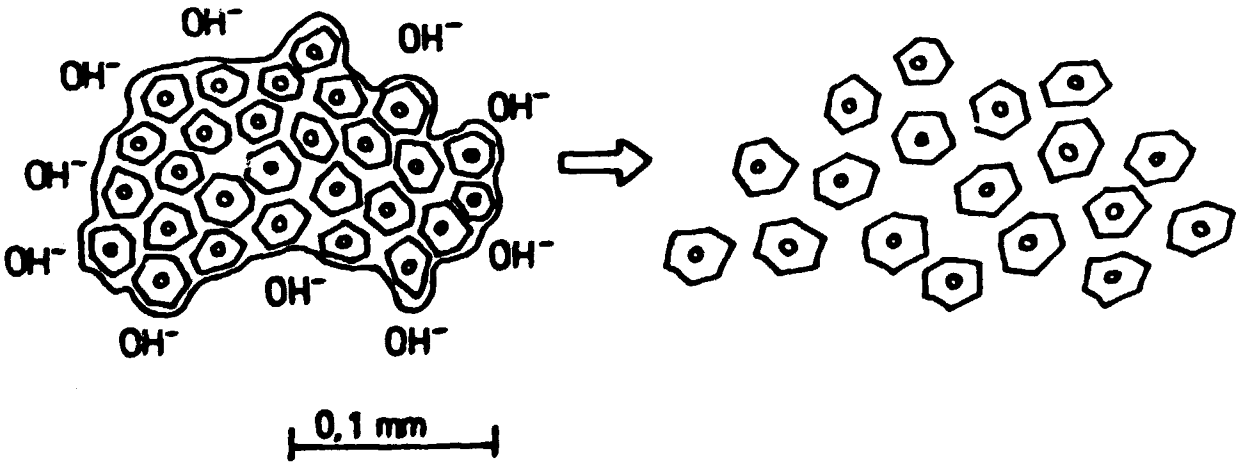


Figure 8. Schematic sketch of the decomposition of sisal fibres in concrete. The middle lamellae are dissolved by the alkaline pore water in the concrete (lit. 6).

3. FIBRE CLASSIFICATION

3.1. General

The cellulose fibres can be subdivided according to the part of the plant from which they originate (lit. 2,7,8,9). There are four main groups.

1) The bast or stem fibres, which form the fibrous bundles in the inner bark (bast) of the stems of dicotyledenous plants.
2) The leaf fibres which run lengthwise through the leaves of monocotyledenous plants.
3) The fibres of seeds and fruits including the true seed-hairs and the flosses.
4) Woodfibres made from the trunks of trees.

3.2. Bast or stem fibres

The bast fibres form bundles or strands that act as hawsers in the fibrous layer beneath the bark of dicotyledenous plants. They help to hold the plant erect.
On a tonnage basis jute is the most important of all the bast fibres, followed by flax and kenaf or hemp.
An overview of fibres with some properties is given in appendix 1. All of these fibres have been investigated for cement reinforcement, mostly in the form of strands of fibres. Most fibres lose some of their strength if embedded in a cement matrix, notably jute, which shows a loss of about 70% (lit. 12).

Most bast fibres are processed in a similar way: after harvesting they are submerged in water or kept wet, resulting in retting of the stalks.
The fermentation process frees the fibres from woody matter and cellulose tissue. Sometimes this process is accelerated by a chemical treatment.

After the retting process has been completed the fibre bundles are washed and dried and sent to the spinning mill. Sometimes the fibres are treated further, e.g. bleached.
Ramie stalks are processed in a different way. The fibres are removed from the stalks by the process of decortication. Mostly this is carried out by hand. Figure 9 shows a sketch of a decortication machine (lit. 13). The process consists in peeling and beating the bark and bast material from the stalk soon after harvesting.

The fibres are subsequently freed by soaking the bark in water and scarving with knives. The long strands of ramie fibre are then dried and bleached in the sun. Although ramie fibres are very strong and durable, large-scale production has never been put in practice due to difficulties to mechanize the fibre processing.

Other fibres investigated as cement reinforcement are reed and grass fibres. Elephant grass for instance and fibres derived from bagasse, the residual stalk of the sugar cane, and rice straw.
Rice straw and bagasse are waste products from the rice and sugar cane cultivation. Although there are various applications such as the use as a fuel or the production of boards (alternative for wood woolcement boards) there is still a large surplus in many countries.

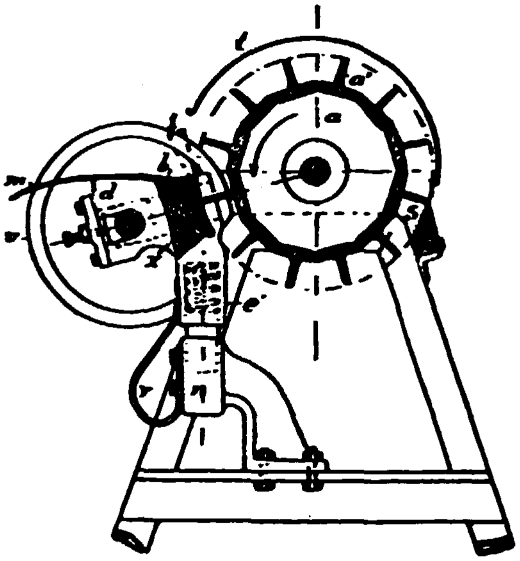


Figure 9. Fauré raspador for decortication (lit. 13).

3.3. Leaf Fibres

The leafs of monocotyledenous plants are supported by fibres which run through the length of the leaf. In general leaf fibres are coarser than the fibres which come from the bast of dicotyledenous plants, but some leaf fibres are on the contrary softer.

Properties of leaf fibres are given in appendix 1. Most important in terms of tonnage is sisal followed by another species of the agave family, Henequen. Both originate from Central America.

Quite a different plant is the musaceae family of which the species Musa textilis is the source of the abaca fibre or Manila Hemp. The fibrous leaves are arranged around the stem which they protect. It is grown mainly in the Philippines. Abaca is a high quality fibre which is used for ropes and cordage.
The fibres are extracted by decortication processes. The pulpy material is scraped away. Subsequently the fibres are dried or washed and dried in the sun.

Most of the leaf fibres behave rather well in cement matrices. All of them however, have to be evaluated for durability aspects. Sisal fibre reinforced cement, the most thoroughly investigated vegetable fibre cement board shows degradation in a hot wet environment.

3.4. Seed and Fruit Fibres

Hairs or fibres are often attached to seeds and fruits of plants. Cotton is the most important textile cellulose fibre in the world. It has also been used in experiments with cement reinforcement.
After harvesting the cotton fibres have to be separated from the seeds, which is done mechanically. Subsequently the cotton is subjected to various processes preliminary to spinning, such as baling, carding, drawing and combing. Cotton can also be treated (bleached etc.).
Coir is obtained from the coconut husk. The fibres are produced by soaking the husks in water for several days, crushing the wetted husk and combing it with spikes to separate out the larger coarse fibres. In this process short and long fibres are produced. The latter are used mostly for the production of cordage and ropes, but of course can also be used for reinforcement of cement.

3.5. Wood fibres

Cellulose fibre made from wood is in terms of quantity the most important in the world. The bulk of wood fibres is used for papermaking. But also production of viscose fibres is substantial. Fibres can be made of all kinds of wood. Mostly however pine trees are used. The process to produce fibres from wood will be described in section 4.2.

4. PULP

4.1. General

Wood pulp fibres so far have been most successful in replacement of asbestos. Pulp is used as:

- the single fibre in pulp cement board. The lower quality of the fibres, as compared with asbestos fibres, is enhanced by pressing the "green" sheets manufactured on the Hatschek or Magnani machines, autoclaving and/or matrix modification
- a carrier fibre together with man-made fibres such as polymer and (artificial) mineral fibres or with higher quality natural fibres of vegetable origin.

In this section the various pulping processes will be briefly discussed.

4.2. Pulping Processes

The method of removal of the cellulose fibres from wood, the pulping process, has a profound effect on the reinforcing properties of the fibres. Pulping processes vary from chemical to purely mechanical and thermomechanical. Mostly applied in pulp cement board manufacture are fibres produced by the alkaline kraft or sulphate process. About eighty percent of the world production of pulp is kraft pulp. Pulp of the acid sulphite process is less used.

In the fully chemical kraft process lignine and hemicellulose are separated from the fibre cells by cooking chips in a solution of sodium hydroxide and sodium sulphide. The kraft process has a low yield (less than 50%) and mostly produces collapsed ribbon like delignified fibres. Collapsed means that the lumen has been broken open, The ribbon form is well suitable for papermaking and also for use on Hatschek machines to produce fibre cement board. Figure 10 and 11 show Indonesian rice straw before and after pulping this rice straw using the kraft process.

Figure 10. Indonesian rice straw before pulping.

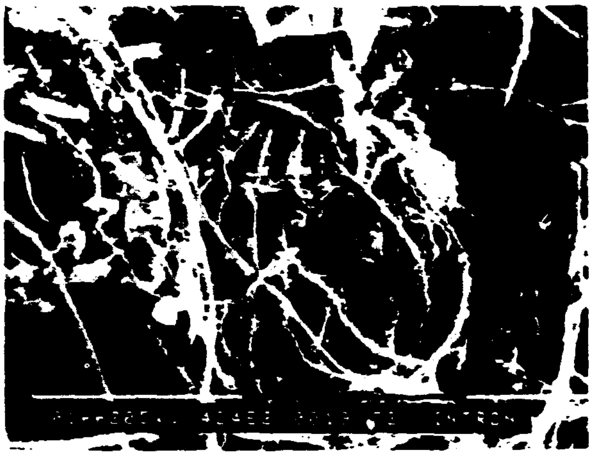


Figure 11. Indonesian rice straw after pulping.

Another alkaline process is the soda pulping process.
Alkaline processes are also appropriate to pulp seed and grass fibres, such as rice straw, bagasse, elephant grass, etc. whereas acid processes are not. Figure 12 shows a flow sheet of a pilot plant of such a process at the Institute for Research and Development of Cellulose Industries in Bandung, Indonesia. This pilot plant is specially set up to produce pulp from agro-wastes like rice straw and bagasse.

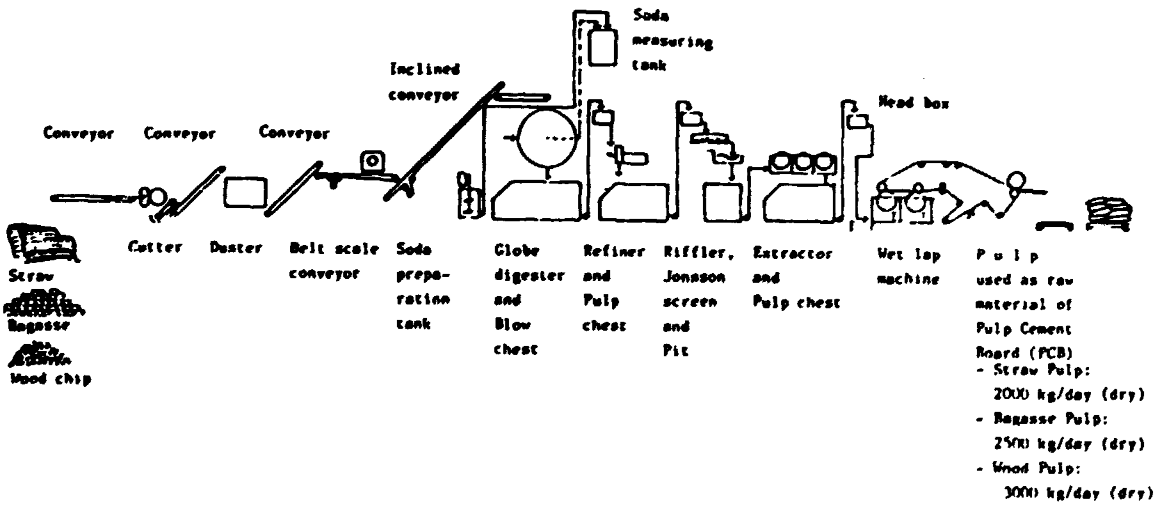


Figure 12. Flow-sheet diagram of pilot plant pulp making process. Institute for Research and Development of Cellulose Industries, Bandung, Indonesia.

An additional process step to reduce the lignin content of the fibres is bleaching.

Another process of which the pulp has been investigated for pulp cement board manufacture is high-temperature thermomechanical pulping (lit. 14,16). In this process the temperature is kept above the melting temperature of the lignin. The resulting fibre is lignin-coated and uncollapsed. The yield of the process is higher than for the chemical processes. These fibres appear to be less comformable on asbestos cement machines and their bonding behaviour to cement is inferior to that of kraft fibres.

Thermomechanically processed pulp can be improved regarding comformability by further refining e.g. Bauer disc refining etc., which yields pulp with a partially collapsed fibres.

Beating of fibres up to a certain degree improves properties of pulp and board, but beyond that degree the properties are reduced again (see figure 13, lit. 15).

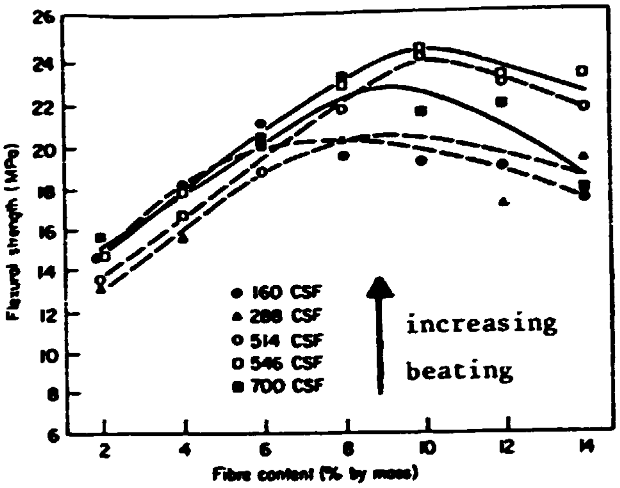


Figure 13. Effect of fibre content on flexural strength at various freeness values e.g. levels of beating (lit. 15).

The process of beating (or refining) cellulose fibres has three important effects:

- the fibres are shortened;
- external fibrillation occurs, causing partial or sometimes total removal of the primary wall and causing fibrils to form on the surface of the fibre; and
- internal fibrillation occurs, causing the fibre to become more conformable.

In terms of the Canadian Standard Freeness test in general optimum properties appear to be available at a freeness of about 500 CSF (ISO/DIS 5267/11). Further beating to a lower freeness value of the cellulose fibres is detrimental (lit. 15).
Typical fibre lengths applied are 0.5-3 mm for soft wood and 2.0-4.5 mm for hard wood.

Figure 14. Uncollapsed Indonesian rice-straw pulp.

Figure 15. Collapsed Dutch wood-fibre pulp.

The pulp is usually converted to paperboard and transported to the pulp cement board plant where the pulp board is repulped again.

For cement board manufacture pulp has been investigated manufactured from various types of woods, rice straw, bamboo, abaca, sisal, New Zealand flax and flax (lit. 17,18,33).

5. PULP CEMENT BOARD MANUFACTURE

The success of pulp of vegetable origin in substituting asbestos fibres in asbestos cement is to a major part due to its conformability to the orthodox asbestos cement manufacturing processes.

The main asbestos cement process is the Hatschek process; figure 11 shows the Hatschek machine schematically. A typical sheet manufacturing procedure for pulp cement board involves the following sequence of operations:

- The fibres, e.g. woodpulp, rice straw pulp or cotton are processed as far as necessary by pulping, beating and refining (in general to a freeness of 18-23°SR ISO 5267/1).
- The other constituents of the batch, i.e. cement, silica flower, other fibres if desired, and flocculating agents when required are mixed with the pulp to an aqueous slurry of 5 to 10% solids by weight.
- The water of the slurry, including some of the solids is drawn through the rotating permeable felt of the cilinder, as shown in figure 11. A film is formed on the surface of the screen which is taken over by a moving take off felt.
  Cellulose fibres allow higher film thickness than asbestos cement.
- The film is wound around a rotating drum (calender) and when the desired thickness of the sheet has been built up it is removed by cutting in the form of a flat sheet with a length of 1 to 4 metres.
- When desired the sheet is subsequently corrugated.

The film forming properties of the pulp are very important. In case of mixtures of fibres the cellulose fibres are often used as a carrier fibre (filter aid fibres or Prozess Faser), e.g. the cement particles adhere to the cellulose fibres and are not drawn off in the vacuum treatments on the rotating cylinder and on the moving felt belt.

Cellulose fibres are in general less appropriate for use on rotating screen cylinder machines such as the Hatschek than asbestos. More suitable are the so-called flow-on-machines such as the Magnani machine in which the pulp/cement mixture is brought directly on the felt band. Most Hatschek machines can be retrofitted easily and without much costs to a flow-on-machine (lit. 19).

Despite certain limitations the Magnani process is known for its simplicity and its ability to incorporate non-asbestos fibres and imposes fewer requirements on cellulose pulp. Because the fibres are less well orientated in the felt plane, the strength of the "green" sheet and hardened product in general is somewhat less than for the Hatschek machine.

In case only cellulose fibres are used the quality of the hardened pulp cement board is less than of asbestos cement e.g. the modulus of rupture is not very much higher than that of neat cement paste and the drying shrinkage/wetting expansion is much higher. In general the quality for outside application for roofing can be regarded as too low.

To compensate for this loss in properties the fibre cement board has to be pressed and/or autoclaved.
Conventionally pressing occurs in high hydraulic presses with many sheets stacked together. A typical pressing operation covers 5 minutes at 30 MPa. The compression has to be built up slowly to prevent any damage. Giant presses are common, e.g. 100.000 kN.

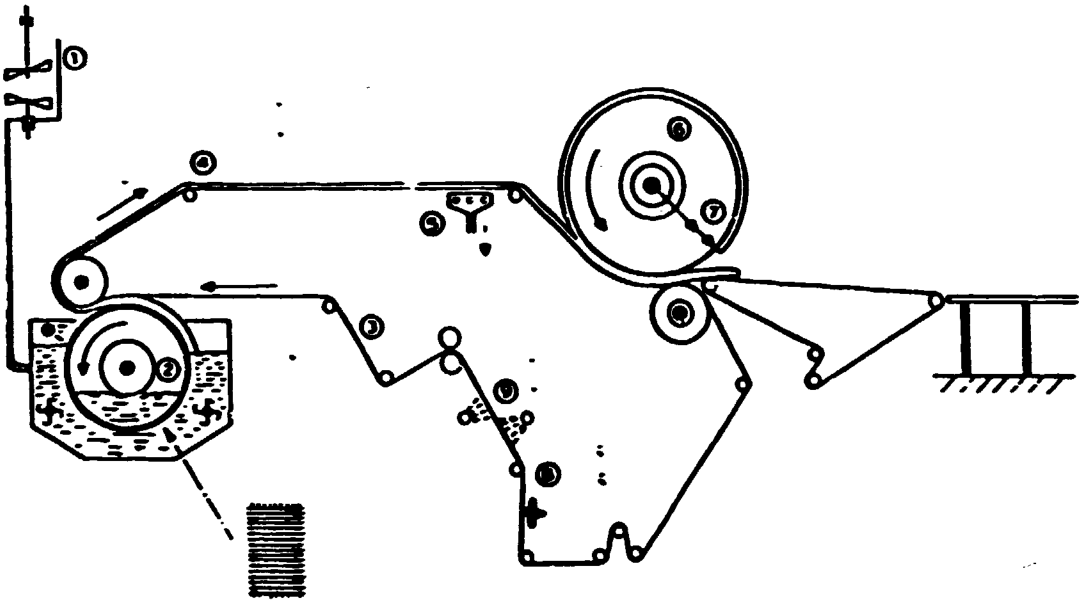
The stackpresses are not appropriate for corrugated sheets manufacture. However to meet the quality of corrugated sheets of asbestos cement pulp cement board has to be pressed. Therefore a special single sheet press with a very short pressing time of only 14 s has been developed in the Federal Republic of Germany. The pressures applied are between 15 and 18 MPa. Sieve sheets are used for dewatering during pressing (lit. 19).

Typical autoclaving is effected at 0.85 MPa steampressure and with varying periods, but usually longer than 6 hours, mostly 8 to 10 hours. Before autoclaving the sheets need a dormant period otherwise the strength development will be affected negatively.
The temperature during autoclaving is usually higher than 150°C, the temperature above which cellulose is known to decompose quickly. The reason why this does not happen in cement is not clear at the moment (lit. 2).

In case of use of a second fibre of high quality there is a possibility to leave out the pressing or autoclaving operation.
Man-made fibres used in West European countries are Dolanit$^{(R)}$ a polyacrylnitril fibre, Kuralon an acetalized polyvinyl alcohol fibre, or mineral fibres especially the ZrO_2-containing glass fibre (Cem-Fil$^{(R)}$).

Further processing after the manufacture of the hardened basis sheets such as sawing etc., is not different from ordinary asbestos cement manufacturing.

A modified Hatschek process is known from patent literature in which it is claimed that a variety of fibres can be applied (lit. 20). The process has a modified screen cylinder tank and the slurry has been modified by adding a clay and/or water-soluble polymer e.g. polyethyleneoxide homopolymer which improves the cement retention on the cylinder (see section 8.2.).



1: Mixer, agitator
2: Screen cylinder
3: Felt band

4: Ply of asbestoscement
5: Dewatering
6: Calender

7: Cutter
8: Beater
9: Sprayer

Figure 16. The fabrication of asbestoscement sheets by the Hatschek process.

6. PULP CEMENT BOARD PROPERTIES

6.1. General

In this section reinforcing mechanisms and properties of pulp cement board will be discussed. Only those aspects will be regarded which are specific for pulp board. Concerning the reinforcing mechanisms reference is made to general theories such as the rule of mixtures of Hooke, the Aveston Cooper Kelly (ACK) Multiple Cracking theory, and Romualdi's and Balson's fibre spacing fracture mechanism approach, which are discussed in literature 21.

6.2. Behaviour in tensile loading

In the development of pulp cement board the tensile strength and modulus of rupture of the board have been gradually improved. Major steps forward have been the pressing and autoclaving of the boards. Without these improvements the tensile strength and the modulus of rupture achieved would not be very much better than for neat cement paste.

Figure 17 (lit. 22) shows typical bending load - deflection curves for pulp cement board. Autoclaved pulp cement board is stronger than non-autoclaved board, but the latter has a higher fracture energy. Boards made with fibres which are collapsed and are fibrillated show in general higher strength than uncollapsed fibres without fibrillation.

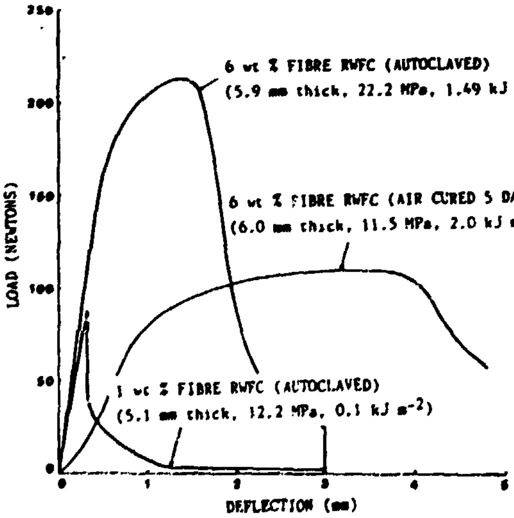


Figure 17. Typical load deflection curves for wood pulp cement composites (lit. 22).

Pressing and autoclaving increases the modulus of rupture considerably. Figure 18 (lit. 15) shows the modulus of rupture (flexural strength) as a function of fibre content for autoclaved pressed pulp cement board following various preconditioning treatments. The wet material is less strong but shows a higher fracture energy (figure 19)

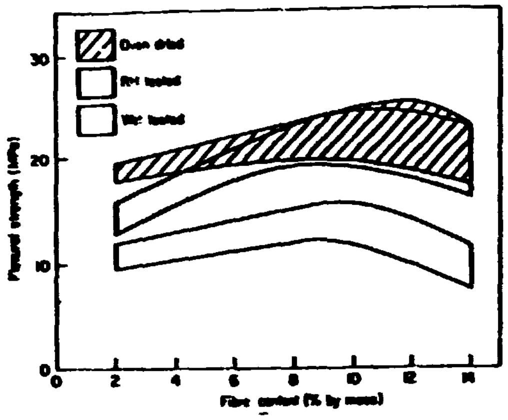


Figure 18. Effect of fibre content on flexural strength of autoclaved pulp cement board following various preconditioning treatments (lit. 15).

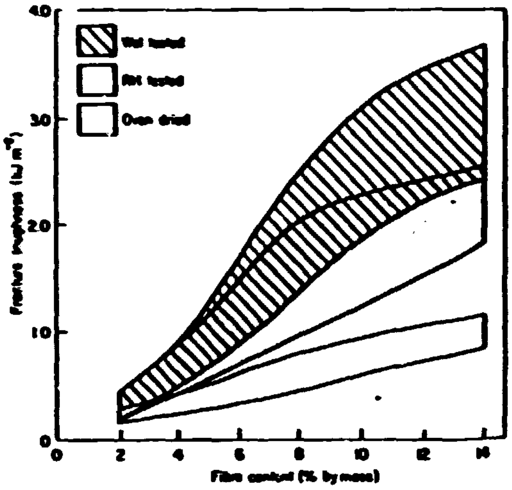


Figure 19. Effect of fibre content on fracture thoughness following various preconditioning treatments (lit. 15).

It has been observed that in dry pulp cement board mostly fracture of the fibres occurs, especially in the autoclaved pressed boards, while in wet board pull out of fibres prevails. Figure 20 shows some photographs of pullout and fracture. Fibre pull out in wet board is most likely to happen in the fibre itself. The outer part of the fibre remains in place but the inner core is pulled out. The cause is probably water which renders the inter cellulose polymer chains bonding weaker. This interchain bonding is based mainly on hydrogen bonding (lit. 22).

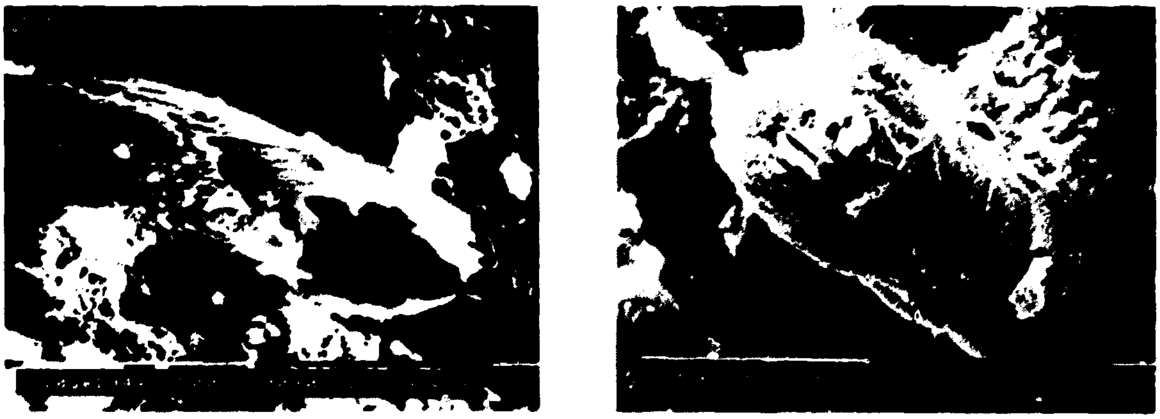


Figure 20. (a) SEM showing Fibre pullout on wet board
(b) Fracture of the fibre in dry pulp cement board.

6.3. Reinforcing mechanisms

Many models have been proposed to explain the behaviour of pulp cement board in mechanical loading. Obviously the stress transfer between fibre and cement and the way this is changed during loading is crucial in the tensile load behaviour.
It has been shown that the theory of Phan Thien and Goh (lit. 23) is useful to describe the stress transfer between fibre and matrix in pulp cement board (lit. 24). An expression is provided for the force required to displace an embedded uniform fibre from an elastic matrix and for the corresponding interfacial shear stress in case the fibre is long and slender and its Young's modulus is not much higher than that of the matrix. These are conditions likely to be present in pulp cement board.

The formula given by Phan Thien and Goh for the interfacial shear stress in a fibre pull out test is:

$$\tau(x) = \frac{P}{\pi R^2} \; \frac{1}{(1 + x^2 / R^2)^{3/2}} \left[2 - \nu - \frac{1.5}{(1 + x^2 / R^2)} \right]$$

Where τ (x) = interfacial shear stress a location x from the surface
P = the load
ν = poisson ratio of the matrix
x = distance from surface
R = fibre radius

Figure 21 shows for a wood pulp fibre with a fibre radius R of 20 um the shear stress as a function of the distance from the surface. After a maximum at a distance from the surface of about 0.7 of the fibre radius the shear stress drops rapidly.

When the force P equals the debonding or fibre fracture force (Pm) debonding or fracture occurs.

$$\tau_m = \frac{P_m}{\pi R^2} \left[\frac{2\,(2-\nu)}{5} \right]^{5/2} \qquad \text{or for } \nu = 0.2 \qquad \tau_m = 0.44 \; \frac{P_m}{\pi R^2}$$

In case the fibre is longer than the distance at which the maximum shear stress should occur, the occurrence of fibre fracture or fibre pull out will totally depend on the strength of the fibre.

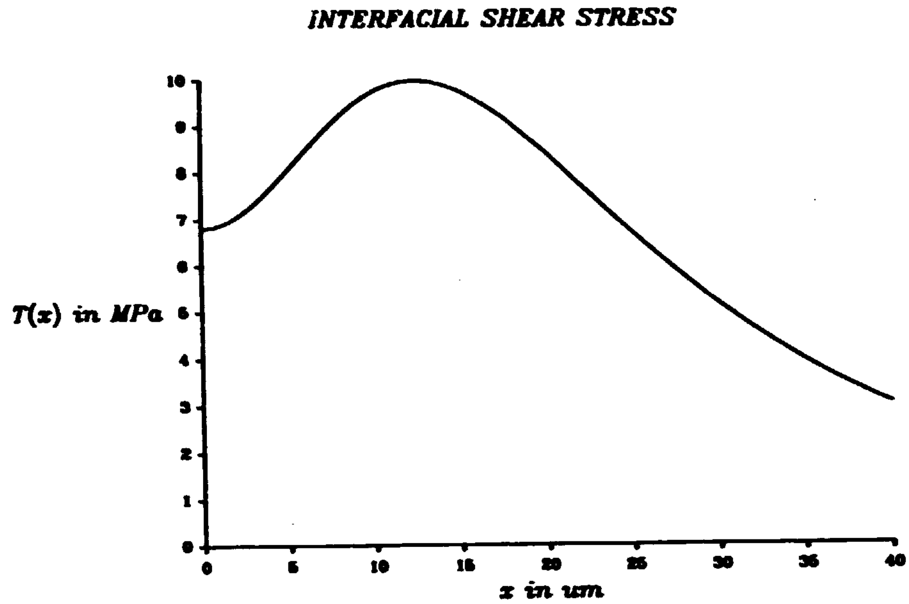


Figure 21. Interfacial shear stress along fibre in a fibre pull out test according to the Phan Thien and Goh model (lit. 21).
assuming υ = 0,2 (poisson ratio) P = 0,0285 N (force)
R = 20 um (fibre ratio) x = 0 is surface

Another similar formula is given in literature 25.

$$\tau_m = \left[\frac{1}{2 \ln p} \; \frac{Gm}{Ef}\right]^{\frac{1}{2}} \cdot \left[\frac{Pm}{\pi R^2}\right]$$

In which p = the ratio of inter-fibre distance to fibre radius
Gm = shear modulus of the matrix
Ef = fibre modulus of elasticity

This formula deviates from the previous one only by the constant. It also shows that by decreasing p, τ_m increases. An estimate of τ_m based on the above formula and pull out test results is of the order of 10 MPa.
Higher values are unlikely for reinforcement of a neat cement paste, because the shear strength of the matrix will then be lower.
It has to be noticed that a measurement of fibre-matrix bond strength in the case of wood pulp fibres is rather difficult to make as fibre dimensions render pull-out tests extremely difficult.

In consequence of above, it therefore appears to be unlikely that improvements of the bond e.g. by coupling agents will bring very much improvement. Test results with coupling agents indeed do not show a significant increase in strength.

However it is likely that improvements in bond together with improvements of the matrix will be advantageous regarding strength.
Autoclaving and pressing improve the fibre-matrix bond and matrix strength. Modification of the matrix with silica fume shows similar improvements, as will be discussed in section 8.4.

Further it has been shown by Hannant et al (26,27) that the reinforcing mechanism of pulp cement board could be explained by Romualdi's fibre space fracture mechanism approach. In principle this means that in case the inter fibre distance is decreased and becomes smaller than the largest fault in the neat matrix, the matrix strength is increased, which leads to a higher bending over point e.g. the first failure of the matrix recognizable by the deviation in the tensile-strain curve of linear elastic behaviour.
In this concept higher fibre content and finer fibres therefore lead to an increased strength, regardless of the quality of the fibres as long as they are well bonded (only required in case of two- or three-dimensional arrangement of the fibres) and stronger than the matrix.

In fact both the Phan Thien - Goh and the fibre space fracture mechanism theories appear to be applicable to dry autoclaved pressed pulp cement board. This material shows an almost linear elastic behaviour which cannot be explained by the ACK multiple cracking or other theories. This brittle behaviour suggests that the cement matrix and the fibre are failing at almost the same moment.

For non-autoclaved pressed boards and wet boards the fibre pull out is a phenomenon which is of much more importance. Typical fibre pull out behaviour is shown in figure 22 (lit. 24).

As shown by Morissey et al (lit. 24) it is likely that this behaviour can be explained by the Phan Thien and Goh model combined with the fact that cellulose fibres, especially the refined collapsed chemically treated ones, are of a non uniform,but on the contrary, highly irregular form.

After initial debonding, the fibre is pulled out partially but it gets grip again on the matrix due to a mechanical anchorage.
Eventually the fibre can be loaded to an even higher level than before initial debonding (case b in figure 22) which can lead to fibre fracture instead of debonding or to a renewed debonding.

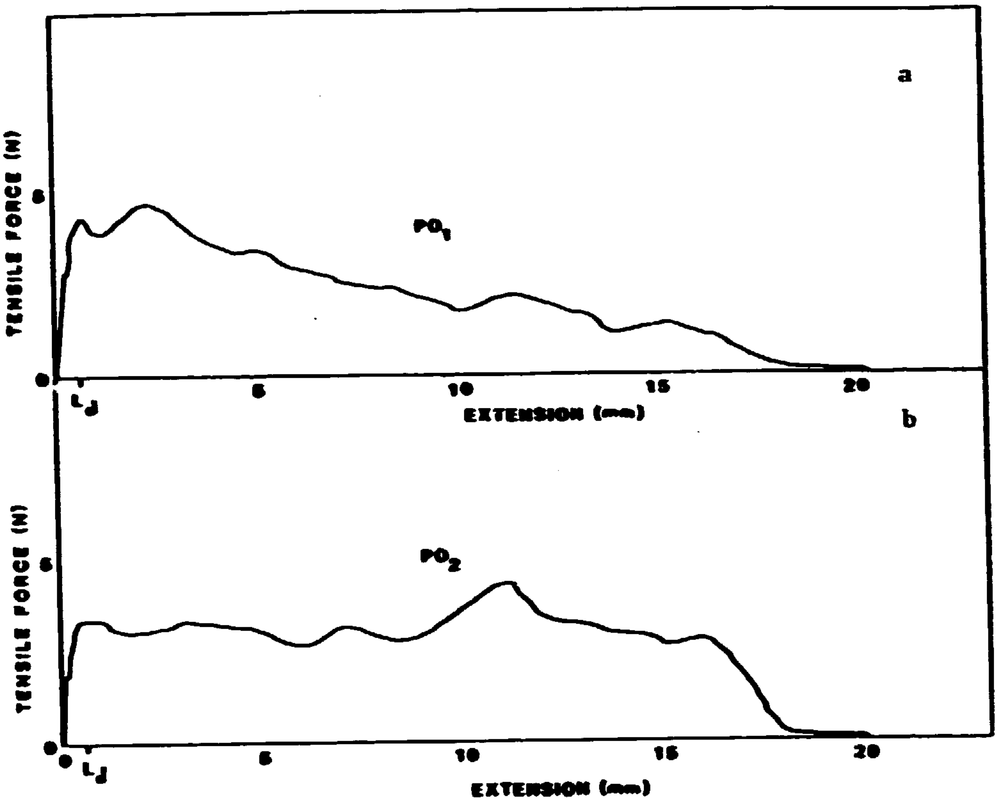


Figure 22. Load-extension diagrams of embedded sisal slivers that pulled out of the matrix (lit. 24)
a apparent conventional pull-out (PO_1)
b pull-out after force fluctuation (PO_2)

6.4. Durability

The durability of fibre cement boards replacing asbestos cement is a main topic in research. Five potential ageing mechanisms for cellulose-fibre reinforced cement are described in literature. These are:

- Alkaline degradation of the fibre
- Increase in fibre-matrix bond due to fibre mineralization and precipitation of lime around the fibre
- Moisture stressing of the cellulose fibres
- Carbonation
- Micro biological attack.

Results regarding pulp cement board are rather confusing.

Non-autoclaved boards

For a pressed kraft pulp cement board Gram reported a considerable loss in modulus of rupture and fracture energy upon exposure in his climate cubicle. The strength ranges from initially 21.5 MPa to not more than about 10 MPa after 60 cycles; fracture energy reduced even more (lit 4,28).
Gram but also Davies et al (lit. 4,16,28) suggest that the cellulose fibre is mineralized by precipitation of lime compounds at the fibre surface and in the fibre lumen. The boundary layer between cement paste and the fibre gets denser with time. This results in an improved bond between the matrix and the mineralized less flexible cellulose fibre. Although this phenomenon is known to decrease tensile strength, modulus of rupture and strain capacity for glass fibre reinforced cement it is not clear why in the case of pulp cement board strength should be affected.
It is known that pulp cement board roofing shingles which have been produced in Germany during the World Wars have lasted a very long period without major damage. Asbestos cellulose cement board produced in Australia does not show any sign of deterioration of the cellulose fibre after 13 years in service. However a saw dust cement floor did show mineralization only after 30 years (lit. 14).

Autoclaved boards

For autoclaved pressed pulp cement board a rather stable behaviour is reported from accelerated ageing tests (lit. 2,29). During immersion in water of 50°C, which exposure is used for predicting the durability of glass fibre reinforced cement, it does not show significant loss in strength after 350 days.

Also severe wetting - drying - freezing tests were survived without significant damage. Carbonation does not negatively effect mechanical properties but on the contrary shows some improvement in tensile strength. However moisture movement is increased by carbonation where asbestos cement shows a decrease. This can lead to moisture movement of pressed autoclaved pulp cement board of a factor two times higher than for non-autoclaved non-pressed asbestos cement (lit. 29). Table 2 shows results presented in literature 29.

Table 2. Summary of results showing trends determined by linear regression analysis (lit. 29).

Fibre type	Accelerated test method	Mechanical test method	Modulus of rupture	Tensile strength	Internal bond strength	Impact strength	Moisture movement	Modulus of elasticity
Wood	wet-dry-freeze cycling	perp.	0	0	0	(-)	0	0
		para	0	0		0	0	0
	50°C soak	perp.	0	0	0	0	0	0
		para.	0	(+)		0	0	0
	carbonation	perp.	0	(+)	+	(+)	+	(+)
		para.	(+)	(+)		(-)	+	0
Asbestos	50°C soak	perp.	0	0	0	0	(-)	0
		para.	0	0		0	(-)	0
	carbonation	perp.	+	+	0	0	-	0
		para.	+	+		0	-	0

0 = no change
+ = increase
- = decrease
(): significant at 95% level of confidence
no brackets: significant at 95% level of confidence
perp. = test load applied perpendicular to principal fibre direction
para. = test load applied parallel to principal fibre direction

Biological degradation appears to be prevented by the alkaline environment and the dense matrix. After neutralization by carbonation, however, exposure in a so-called fungal cellar does show decrease in mechanical properties, although no biological degradation of the fibre was observed.

At exposure in wheatherometers,autoclaved pressed pulp cement board is reported to behave stably. Maybe the relatively good behaviour in exposure tests of autoclaved pulp cement board in comparison with non-autoclaved product could be explained by the fact that after autoclaving the matrix is much less alkaline than when hardened at ambient temperature. The lime etc. has reacted with the added silica. Therefore there will be less alkaline attack. Because of the reduced availability of free lime there will also be a reduced precipitation of alkaline substances at the fibre surface.

7. UNREFINED FIBRE CEMENT BOARD

7.1. General

Pulp is used in general for large-scale production although small-scale production is not excluded.

Pulp however has to be produced in rather sophisticated factories which are difficult to implement in many developing countries, especially in rural areas.

For those areas attention has therefore been drawn to the use of non-pulped fibres of vegetable origin for small-scale (village-scale) production.

7.2. Production

In general there are two ways of production. These are hand lay up using continuous fibre strands, and premix casting, applying chopped strands.

For small-scale production in case of continuous fibres an usual procedure is to lay down alternating layers of mortar and fibres in a mould. After each fibre layer the composite is compacted with the aid of handrollers. Finally a thin layer of mortar is placed on top of the laminate and the upper surface is made even and smooth by means of handtools. The fibre strands should not be twisted into twine but applied individually.

Instead of laying strands also networks can be prepared which are applied as mats.

Figure 23 shows the various process steps (lit. 30).

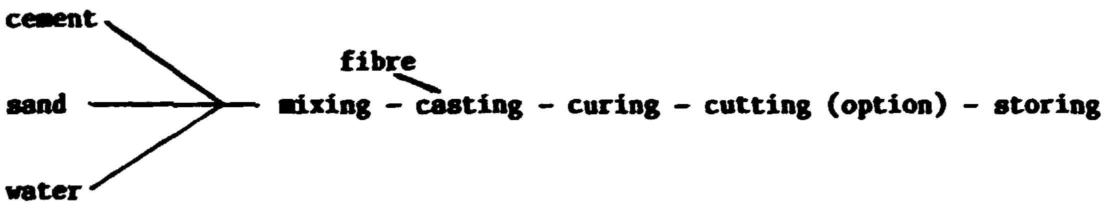


Figure 23. Material flow with continuous fibres (lit. 30).

When chopped fibres (10-50 mm) are used the various constituents are mixed. A number of mixing sequences have been developed. Mostly the dry constituents - cement, sand and fibre - are mixed first, subsequently water and additives are added. After thorough mixing the fibrous mortar is poured into a mould and compacted by rolling, tamping and/or vibration. Figure 24 (lit. 30) shows the process steps involved. The quantity of chopped fibres which can be incorporated in the mortar is rather low (up to 3% by volume) because at increasing fibres percentages:

- the tendency to ball up of the fibres increases; see figure 25 (lit. 30)
- the workability decreases faster in time. The fibres, when dry, absorb water; this stiffens the mix, consequently more water is needed to maintain the required workability; see figure 25 (lit. 30).

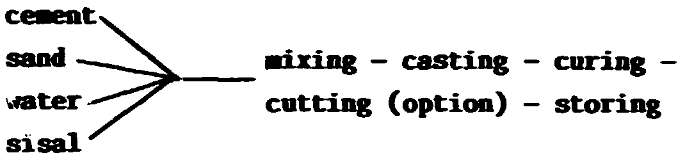


Figure 24. Material flow with chopped fibres (lit. 30).

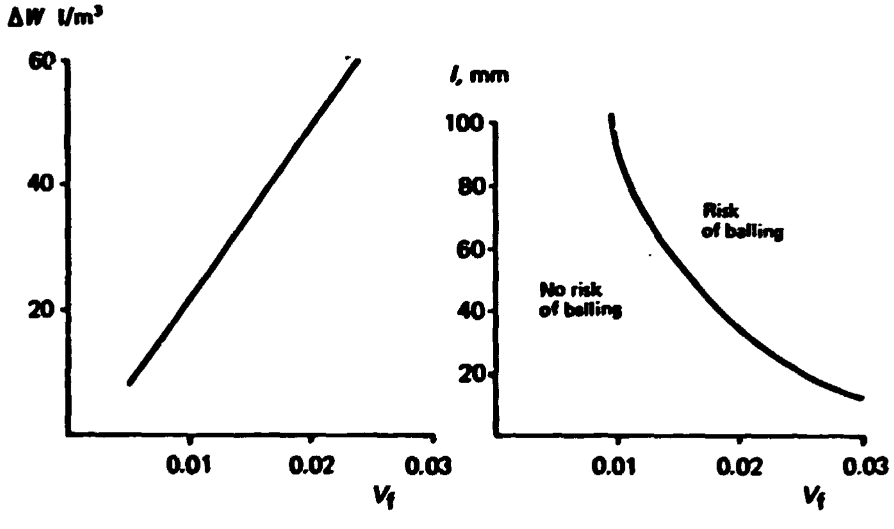


Figure 25. Extra water needed (Δ W) to keep a constant workability and tendency to ball as visually examined (lit. 30).

In a more advanced way of production the green fibre cement boards are covered with a scrim or filter cloth placed on top of the board. Mould-bottom, green board and filter cloth are subsequently pressed. A pressure of a few MPa is maintained for some minutes to some hours.

The figures 26 to 30 do show photographs of the various process steps including filter pressing in a small-scale factory in Malang, Indonesia. This plant manufactures flat ceiling sheets. In the press fifty sheets are pressed together. The filter pressing improves the quality of the fibre cement board substantially.

Figure 26. Hand spreading and compaction.

Figure 27. Burlap.

Figure 28. Transport of 50 sheets to press.

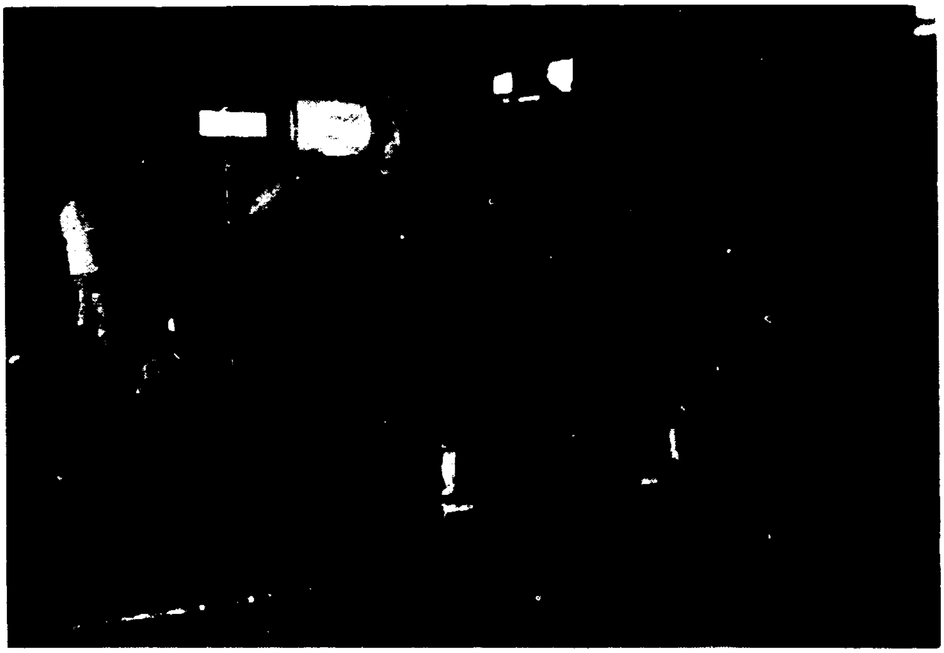


Figure 29. Filter pressing.

Figure 30. Endproduct.

After production of the green boards the boards have to be cured well. This can be done by covering the board with wet burlap, plastic foil or by keeping the sheets in a waterbasin after preliminary hardening. Alternatively the sheets can be stacked between the bottom moulds or between carrying plates. The required time of curing depends on many factors but has to be at least 7 days.

7.3. Properties

In case of continuous fibres the tensile strength reinforcement is much more effective than for chopped fibres; see figure 31 (lit. 30). Mainly because of the more efficient fibre orientation but also because of the larger aspect ratio. The latter is especially important at young ages when the bonding is very small due to retarding effect of lignin at the fibre surface on cement hydration but also because the individual fibres in the strands are not completely surrounded by the matrix. Later the importance of the aspect ratio decreases. Also short chopped fibres then mostly have lengths larger than the critical length.

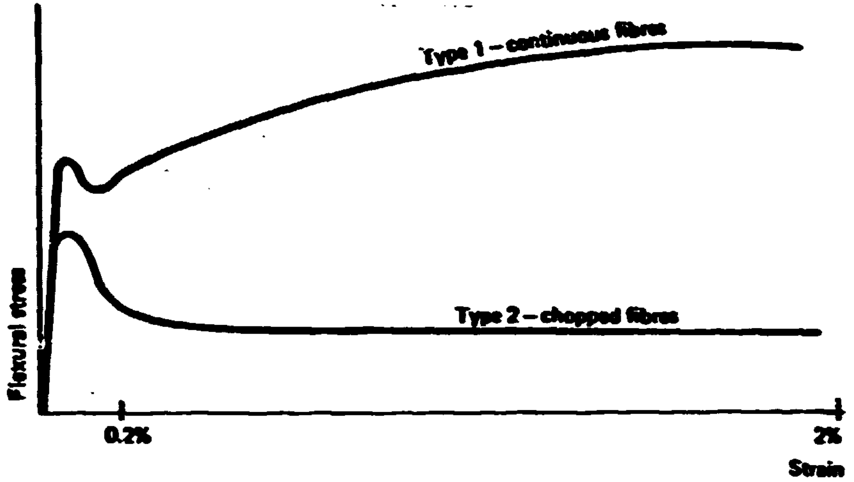


Figure 31. Typical stress-strain curves for concrete with different types of sisal-fibre reinforcement (lit. 30).

Regarding durability the test results are conflicting. In accelerated tests mostly a strong decrease in fracture energy and strain capacity is reported and a smaller decrease for strength; see e.g. figure 32 (lit. 6).

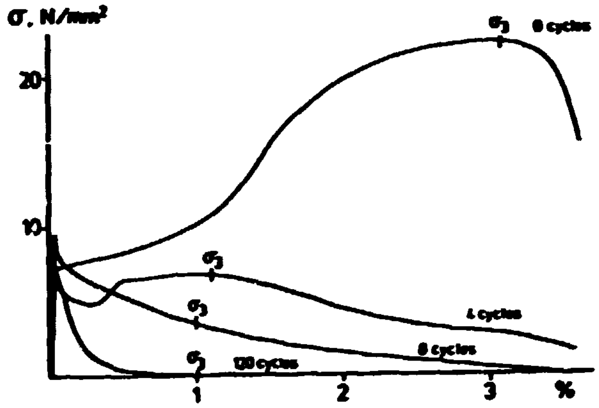


Figure 32. Stress-strain curves for specimens of sisal fibre concrete aged 0, 4, 8 and 120 cycles in a climate cubicle (lit. 6).

In practice deterioration appears to be more moderate. Although in tropical areas natural weathering results are in line with the accelerated weathering tests.

Gram (lit. 4) explains the deterioration as the result of lignin and hemicellulose dissolution and the break-down of cellulose chains.

But also the improved fibre-matrix bond (mineralization) will contribute to the loss in the energy of fracture and strain capacity.

An appraisel by Appropriate Technology International (lit. 34) of vegetable fibre cement roofings produced with village scale techniques since the late 1970's showed that up to 47% of the roofing sheets suffer visible cracking within a few years. The cracking was due to:
- deterioration of the fibres
- difficulties in achieving the recommended water/cement ratio and curing régime
- loss of rigidly of the wooden moulds applied.

Based on these finding it was concluded that these roofing sheets are not suitable for rural housing and facility construction (lit. 34).

7.4. Standard requirements

In literature 34 a draft standard has been prepared for corrugated sheets of fibre cement board for use in developing countries.

The standard comprises requirements and test methods on dimensions, strength and water tightness. It is attached as appendix 2 to this report.

8. SPECIAL TREATMENTS/MODIFICATIONS

8.1. General

Various attempts have been made to improve manufacture and properties of vegetable fibre cement board. Those concern:

- the retention of cement and filler on the Hatschek machine, including too rapid waterdrainage;
- the bond between fibre and matrix;
- the durability of the fibre cement board by means of fibre treatment and/or modification;
- the modification of the matrix in such a way that autoclaving and/or pressing is not necessary;
- improvements of the matrix.

In this section the above subjects will be discussed briefly.

8.2. Retention of cement and filler

It has been reported that the affinity of cellulose fibres for cement and silica filler is less good than for asbestos fibres. On the Hatschek screen cylinder too much cement and silica flower is drawn through the screen. Furthermore water sometimes is drained too rapidly, preventing the right settlement of fibres and cement.
It is claimed (lit. 20) that these problems can be overcome by applying water soluble polymers in the suspension, such as polyethylene oxide with large molecular weights (up to 5.10^6).
It is further claimed that especially a combination of a swelling clay and such a water soluble polymer is advantageous. Also the addition of a flocculating agent can improve felt formation. Figure 33 (lit. 20) shows a flow sheet of a process with these additives. These additives not only improve the retention of the solid particles but also decrease the speed of water drainage.

In developing countries there could be an opportunity to realize this kind of water retention improvements by using native natural water soluble polymers such as arabic gum.

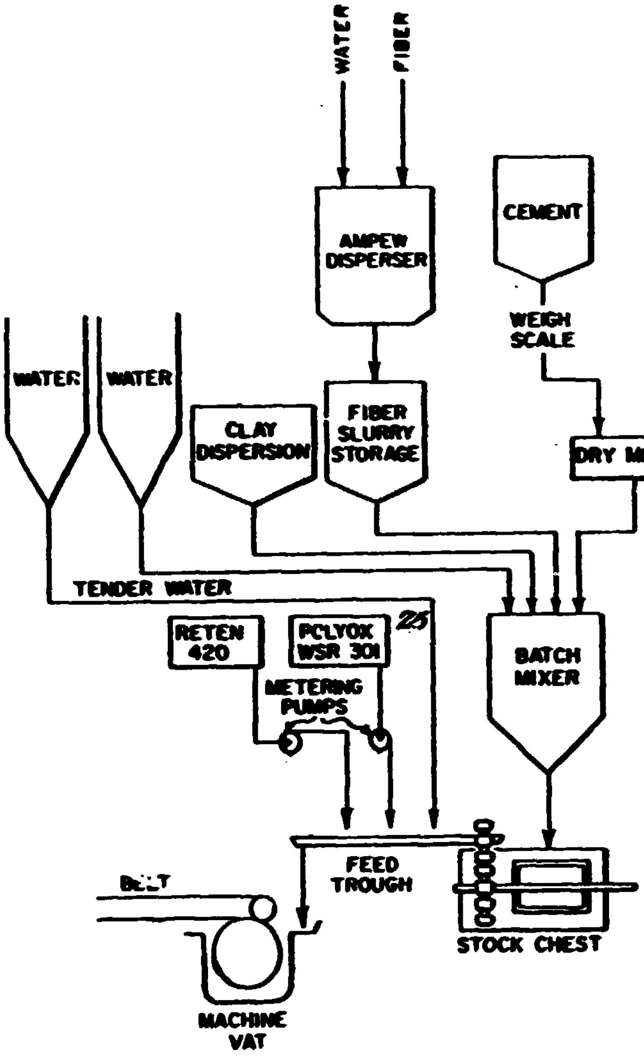


Figure 33. Flow-sheet of patented fibre cement board process applying soluble polyethylene oxide polymer (Polyox), clay and flocculating agent (Reten) (lit. 20).

8.3. The bond between fibre and matrix

In the early days of pulp cement board development the modulus of rupture attained was fairly low, not very much higher than of neat cement paste. One of the possibilities to increase the strength looked for was the improvement of the bond between fibre and matrix.

The use of coupling agents was investigated. Coupling agents are well known from glass fibre reinforced plastics.

For pulp cement board research has been done with silanes and organometal compounds like cyclopentadienyl halides. Figure 29 shows an example of such a coupling (lit. 32).

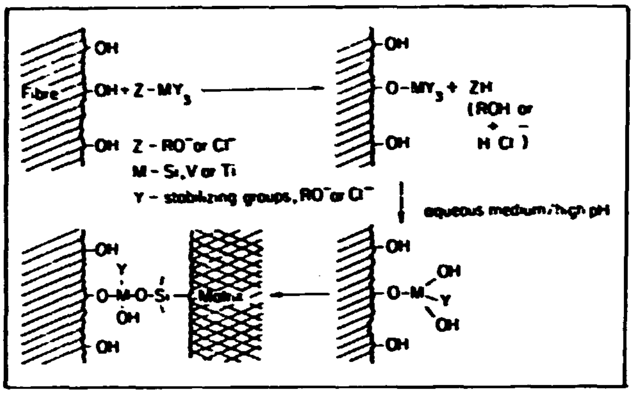


Figure 34. Possible coupling mechanism with organometal coupling agents (lit. 32).

The results with those coupling agents however were rather poor.

The reasons why these bond improving agents do not very much contribute to strength are likely to be those described in section 6.3.

Another cause could be that during loading the fibre is contracted more than the matrix after the latter has been cracked, so that stress transfer from matrix to fibre and vice versa is reduced. This could be especially the case when fibres are applied with open lumen, i.e. uncollapsed.

For polyalkyl fibres, e.g. of polyethylene and polypropylene, experiments with coupling agents do not show improvements either.

Better results than with coupling agents regarding the stress transfer from matrix to fibre have been obtained by using collapsed fibres showing microfibrillation. These fibres have a lower effective contraction, a higher aspect ratio and better mechanical bonding (see section 6.3.).

8.4. Improvements regarding durability

Fibre impregnation

Gram (lit. 6) has carried out experiments with sisal fibres impregnated with formine, stearic acid, potassiumnitrates, sodium chromate, borax, chromium stearate and fluorine-carbon-hydrogen-stearate. Table 3 shows results. The durability is in general improved, but the initial modulus of rupture decreases, probably because of poor bonding.

These impregnating compounds are water repellent and sometimes interfere negatively with the cement hydration. Therefore bonding is reduced and the rate of mineralization is decreased.

Table 3. Values for σ_3 after a different number of cycles in the climate box for specimens reinforced with sisal fibres which have been impregnated (lit. 6).

Impregnating agent	Number of cycles and σ_3 (N/mm^2)			
	0	12	60	120
Unimpregnated sisal	32.8	2.8	0.9	0.4
Boric acid and PVC_2	0	-	-	-
Borax and chromium stearate	16.1	-	-	3.3
Formine and stearic acid	16.7	-	7.7	4.2;6.3
Formine and stearic acid	17.4	3.8	7.2	5.3
Formine and stearic acid	13.6	9.7	9.5	5.6
Potassium nitrate and stearic acid	14.0	-	6.4	3.0;4.1
Magnesium sulphate and PVC_2	4.8	-	0.8	0.6
Sodium chromate and fluorine-carbon-hydrogen-stearate	18.2	-	3.9	3.7

σ_3 = maximum stress in pseudo-ductile area or 1% strain stress whatever is the largest

Matrix modification

Gram (lit. 6) did experiments with wax beads. These beads are mixed into the matrix. After hardening the fibre cement board is heated. The wax melts and blocks the pores so that transport of water and ions is reduced.

A more practical matrix modification is the use of silicafume or other reactive pozzolans. Gram (lit. 4) obtained a substantial improvement by adding silica fume with a percentage of more than 20% of the binder mass, as shown in figure 35.
Silica fume is a waste product of the silicon and ferrochrome production. It consists of fairly pure silicium dioxide. It has a spherical shape with diameters between 90 and 1000 nm. It is very reactive with lime and because of its fineness and rounded shape it fills up well the interstices between the relatively coarse cement particles (average about 30 um).

According to Gram the improved durability is due to the decrease of the pH which can go down from 13 to as far as 12. However, also the lime bonding capacity and the consequently lower deposit of lime around the fibre can contribute.

For developing countries it could be interesting to investigate rice husk ash as an alternative for silica fume. Rice husk burnt under controlled conditions can give a very reactive silica.

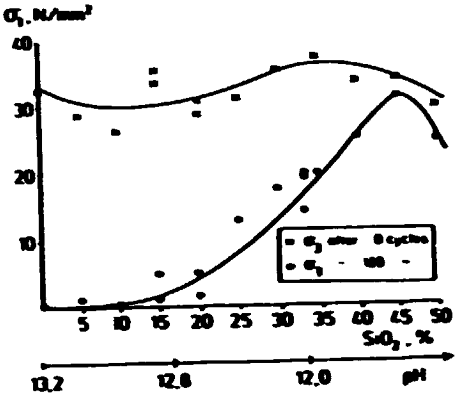


Figure 35. The stress σ_3 (mean value for three specimens reinforced with sisal fibres) after 0 and 120 cycles in the climate box as a function of the percentage silica fume of the binder weight (lit. 4).

9. PRODUCTION COSTS

9.1. General

The production costs of vegetable fibre cement boards will vary from country to country and from process to process.
Even more varying is the capital required for the various processes.
Village scale production by premix of chopped fibre strands will demand much less capital than highly automated pulp cement board manufacturing.
Regarding the costs for labour it is just the opposite. Low-cost labour is abundantly available in developing countries. In developing countries capital in general is scarce and expensive.
Although these facts should make a decision regarding the kind of process to be implemented in a particular country rather simple, in reality this is not so. This is because for pulp cement board we have to deal in many countries with an already existing asbestos cement industry.
In some developing countries such as Indonesia there is large-scale asbestoscement production while also the share of fibre cement board manufactured by small-scale home industries is substantial.

To cover the range of scales of existing plants, three processes will be discussed in this section. Those are:
- premix of chopped fibre strands on village scale
- pulp cement board manufacture on a semi-mechanical scale
- large-scale pulp cement board manufacture using Hatschek machines with pressing and autoclaving.

It is assumed that all plants are producing sheets with an average thickness of 5 mm and that all use the same percentage of fibre e.g. 7 % by mass.
Investments and production costs will be assessed.

The figures mentioned should only be used in an indicative sense. In any actual situation a feasibility study has to be made taking into considerations differences:
- in quality of the product manufactured
- in costs for transport
- in requirements on the substructure for the boards

etc.

9.2. Some Key Items in Plant Set-Up

Village scale

The set-up of the plant is shown in figure 36 (lit 30). The investments without land are low and are estimated at US $ 10,000.- for a production of 10,000 m^2 per annum. The fibre content (strands) is 7% m/m and the rest of the dry material consists of cement and filler in a ratio of 1 to 2. The filler consists of fine sand. The apparent dry density of the board is 1400 kg/m^3. The factory employs on average 15 persons.

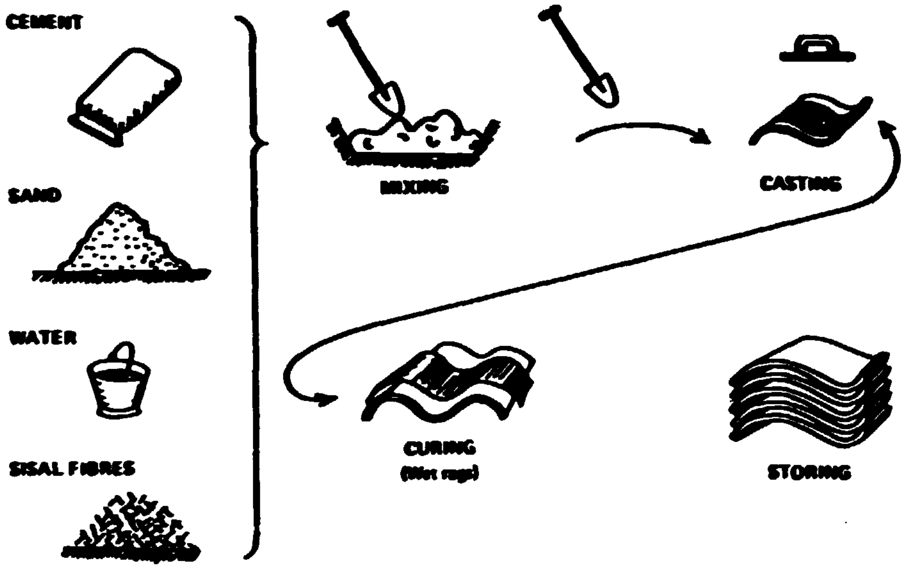


Figure 36. Production at the village level when chopped fibres are used (lit. 30).

Small-scale home industry

The plant consists of:
- a mixer to repulp the fibres supplied by a pulp manufacturer
- a roll mixer
- moulds of plywood
- handtools for compacting, cutting, etc.
- a hydraulic press of 150 tons

The capacity is 100,000 m^2 per annum. The factory employs 25 persons. The board contains 7% by mass of fibres (pulp) and the cement to filler ratio is 1 to 2. The filler is a ground limestone. The apparent dry density of the board is 1600 kg/m . The total investment without land is put at US $ 250,000.-.

Large-scale production

A factory is estimated to produce 4 million m^2 per annum. The sheets are pressed and autoclaved.

The plant consists of:
- slurry preparation
  storage tanks, repulping mixer, various mixers, etc
- green sheet production
  Hatschek machine: three vat cylinders, 120 to 180 tons a day
- hydraulic press of 10,000 tons
- autoclave, 15 m long
- cutting devices
- moulds
- handling and transport devices

The boards contain 7% m/m of fibre (pulp) and cement and filler in a ratio of 1 to 2. The filler is ground quartz sand. The apparent dry density is 1600 kg/m^3. The plant employs 90 persons. The total investments without land required are estimated at US $ 10 million.

The key items of these plants are summarized in table 4.

Table 4. Investments and Labour in vegetable fibre board manufacture (prices 1987)

	Unit	Village scale	Small scale home industry	Large scale
Production	m^2/a	10,000	100,000	4,000,000
Capital investment	US $	10,000	250,000	10,000,000
Capital per unit of output	US $/($m^2$/a)	1	2.5	2.5
Jobs*	person	15	25	90
Jobs per thousand m^2 produced annually	person/ (m^2/a)	1.5	0.25	0.022
Jobs per 10^3 US $ invested	person/ 10^3 US $	1.5	0.10	0.009
Fibre price	US $/kg	1.0	1.5	1.5
Cement price	US $/ton	90**	80	60
Filler	US $/ton	1	5	10

* including sales office, etc.

** prices cheaper for plants close to cement plants than in rural areas.

9.3. Costs estimate

On the basis of the plants described in the previous paragraph a rough cost estimate has been made.

Further assumptions made for the estimate are given in table 5. The results are as follows:

Village scale	Small-scale home industry	Large industry
2.75 US \$/m^2	2.27 US \$/m^2	2.17 US \$/m^2

The differences are rather marginal. It has however to be emphasized that this calculation is only valid under the assumptions made. When the figures are compared the difference in the quality of the boards has to be taken into account. Obviously the quality of the large industries boards is higher than the village scale boards. The small scale home industry product quality will be somewhere between. On a price-quality basis the board of the large industry will therefore be cheapest. But, costs for land have been left out but will apparently be higher for large-scale industry in an industrial area than in rural areas for village-scale production. Further transport costs will be in average higher for products of the large-industries than of village scale manufacture. The cost price for the village-scale production and small-scale production is very sensitive regarding labour costs. An increase in labour costs of 25% for instance increases the production costs as follows:

Village scale	Small-scale home industry	Large industry
13 %	2.5 %	0.8 %

Heierli and Stulz (lit. 35) calculated a costprice of US \$ 4.90/m^2 for a unit of 24 workers in a plant in Peru with a production capacity per worker of 82.5 m^2 per month. At a productivity per worker of 150 m^2 per month the costs reduce to US \$ 2.90.

For a village scale production in Peru they came to a.o. the following conclusions:

- The main cost factor is labour not capital.
- The cost of equipment is not important.
- The main capital investment is for building and land.
- To compete with other roofing products the productivity must be increased.
- Investments in machinery and equipment could increase 5 to 10 fold without affecting the cost price negatively.

Table 5. Assumptions for production costs estimate

	Unit	Village scale	Small scale home industry	Large scale
Depreciation period	years			
main machinery		5	10	10
moulds and tools		3	3	3
Working capital	% of investment	60	40	20
Interest	%	10	10	10
Energy requirements				
Electricity	kWh/m^2	-	0.15	1.5
Steam	10^{-3} tons/m^2	-	-	24
Energy costs				
Electricity (0.07 US $/kWh)	US $/m^2		0.01	0.11
Steam (0.15 US $/kWh)	US $/m^2	-	-	0.26
Labour costs	US $/ person/a	1000	1000	3000*
Maintenance costs**	% of investment	20	15	6

* higher qualified personnel required in industrial areas

** excluding labour e.g. comprised in labour costs

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Appendix 1. Vegetable fibres and some properties

Tradename	Plant species	Origin	Dry density (kg/m³)	Tensile strength (N/mm²)	Modulus of elasticity (GN/m²)	Elongation at break (%)		Alkali resistance	Lit.*
						dry	wet		
Bast or stem fibres									
- Jute	Corchorus	S. Asia	1500 (1020-1040)	217 (250-350)	26-32	1.7	1.5		6,7,9
- Flax	Linum usitatissimum	Europe, Russia, Asia	1540	340 (1000)	100	1.8	2.2	good	6,7,9
- Hemp	Connabis sativa	Europe, Asia	1480	309 (385)		1.8			6,7,10
- Kenaf	Hibiscus cannabinus	S. Asia, Africa, U.S.		180		1.7	2.1		6,7
- Ramie	Boehmeria nivea, Boehmeria tenacissema	China, Russia, S. Europe, US, S. America Philippine		292					6,7
- Sunn (Indian hemp)	Crotalaria juncea	India, Pakistan		282					6,7
- Urena	Urena Lobata	S. Africa, Brazil		122		1.3	0.9		6,7
- Roselle				187					7
- Bagasse		Tropics, Sub-Tropics	1240	20					7
- Elephant grass			300	180	4.9	3.6			7,9
- Bamboo	Dendrocalamus strictus		1500	350-500	33-40				9

* see section 10

Appendix 1. (continued)

Tradename	Plant species	Origin	Dry density (kg/m^3)	Tensile strength (N/mm^2)	Modulus of elasticity (GN/m^2)	Elongation at break (%)	Alkali resistance	Lit.*
Seed and fruit fibres								
- Cotton	Gossypium family	U.S., Russia, China, S. Asia, S. America, S. Europe, Africa, C. Europe	1540 1350	280-840	5.6-11.2	5-10	excellent	6,10
- Coir	Cocas nucifera	Tropics	1330	72				6,7
- Tree cotton	Bombaceae family	Tropics, Brazil, West Indies						6
- Java kapok	Ceiba pentandra	Malaga, Indonesia						6
- Balsa fibre	Ochroma pyramidale	West Indies						6
- Kumbi	Cochlospermum gossypium	India						6
- Chorisia speciosa		Brazil						6
- (Strophanthus spp.)								6
- Beaumontia grandiflora								6
- Milk weeds	Asclepias syriaca Asclepias incarnata	U.S.						6
- Calotropis floss (akund)	Calotropis gigantea Calotropis procera	S. Asia, Africa, S. America, West-Indies						6
- Cattail fibre (typhaceae)	Typha latifolia Typha angustifolia	U.S						6

Appendix 1. (continued)

Tradename	Plant species	Origin	Dry density (kg/m³)	Tensile strength (N/mm²)	Modulus of elasticity (GN/m²)	Elongation at break (%)		Alkali resistance	Lit.*
						dry	wet		
Leaf fibres									
- Sisal	Agave sisalana	East Africa, S. America, C. America, Mexico	1480 1200-1300	830 278	15-19	2,9 2,6	 2,9		6,7,9, 10
- Henequen	Agave fourcroydes	Cuba, Mexico		205		4,9	6,0		6,7
- Abaca (Manila hemp)	Musa textilis	Philippines C. America		428		2,1	2,4		6,7
- Canton	Musa species	Philippines							6
- Pacol	Musa species	Philippines							6
- Cantala	Agave cantale	Philippines, India Indonesia, Mexico		120					6,7
- Letona	Agave letona	El Salvador							6
- Mauritius fibre	Furcraea gigantea	Mauritius							6
- Phormium (New Zealand flax)	Phormium tenax	New Zealand, S. Africa, S. America		231					6,7
- Sansevieria	Sansevieria species	Africa, India Mexico		287					6,7
- Caroa	Neoglasovia variegata	C. and S. America							6
- Pineapple fibre	Ananas comosus	Philippines, India Indonesia, Hawai.							6

Appendix 1. (continued)

Tradename	Plant species	Origin	Dry density (kg/m^3)	Tensile strength (N/mm^2)	Modulus of elasticity (GN/m^2)	Elongation at break (%)	Alkali resistance	Lit.*
Leaf fibres								
- Pita floja	Aechme magdalenae	C. and S. America						6
- Bromelia	Bromelia species	C. and S. America Mexico						6
- Palma	Samuela carnerosana	Mexico						6
- Fique (cabuya)	Furcraea macrophylla	Colombia						6
- Piassava	Bahia piassava (attalia funifera)							
	Para piassava (leopoldinia piassaba)	Brasil						6
- Raffia		Madagascar						6

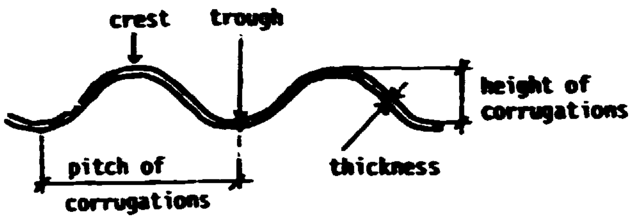
* see section 10

Appendix 2

DRAFT STANDARD FOR CORRUGATED SHEETS OF FIBRE CONCRETE USING TEST METHODS SUITABLE FOR USE IN DEVELOPING COUNTRIES (lit. 28)

SCOPE This standard relates to corrugated sheets of fibre concrete for roof covering, wall cladding, etc. The shape of the sheet is shown in FIG.A.

FIG.A. The shape of corrugations



DIMENSIONS

Requirement Permissible dimensional deviation in mm:

length	+ 5 -10
width	+10 - 5
thickness	+ no limit -0.5

The requirements relating to length and width apply only to sheets produced on an industrial basis.

Testing For each sheet, the length and width shall each be determined at two points to the nearest whole millimetre.

For each sheet, the thickness shall be determined at six points to the nearest tenth millimetre. Measurements shall be made at two crests, two troughs and two transition points.

The results shall be given as the mean length and width of the sheet to the nearest whole millimetre. The mean thickness of the sheet shall be given to the nearest tenth millimetre. This value shall not, however, exceed the least measured value by more than 0.5 mm.

STRENGTH

Requirement The term strength refers to the loadbearing capacity of the sheets at the limit of proportionality, and is expressed as a load per metre width of the sheet.

The load at the limit of proportionality shall be at least 150 kgf/m.

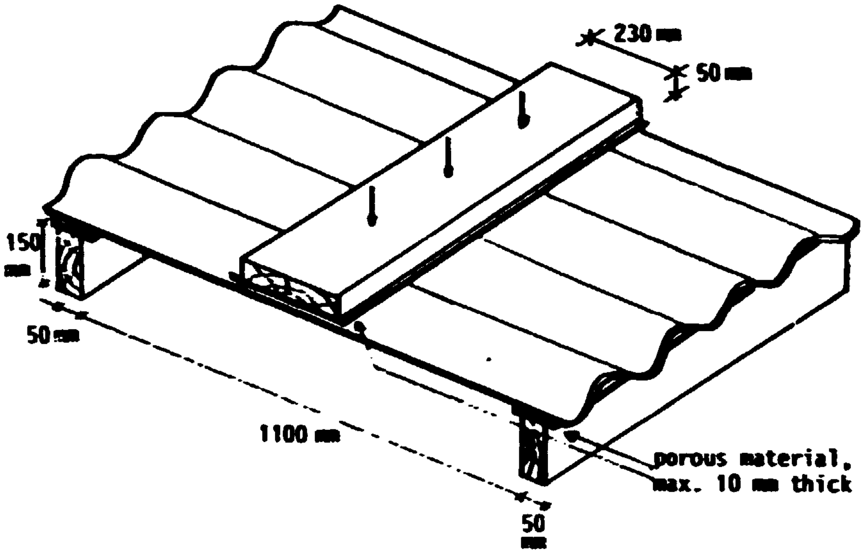
Testing The sheets should be stored in a closed room for 5 days prior to the test.

During the test, the sheets are to be placed on two flat rigid horizontal supports of 50 mm width and at least the same length as the width of the sheets. The clear span between supports shall be 1100 mm.

The sheets shall be loaded at the midsection, perpendicular to the corrugations, with a rigid spreader board of e.g. wood, of 50 mm thickness. The width of the board shall be 230 mm and its length at least the same as the width of the sheet. The edges of the spreader board shall be rounded.

Between support and sheet and between sheet and spreader board, there shall be placed a pad of porous material, for instance wood fibre board, of about 10 mm thickness. See FIG.B.

FIG.B. Equipment for bending test.

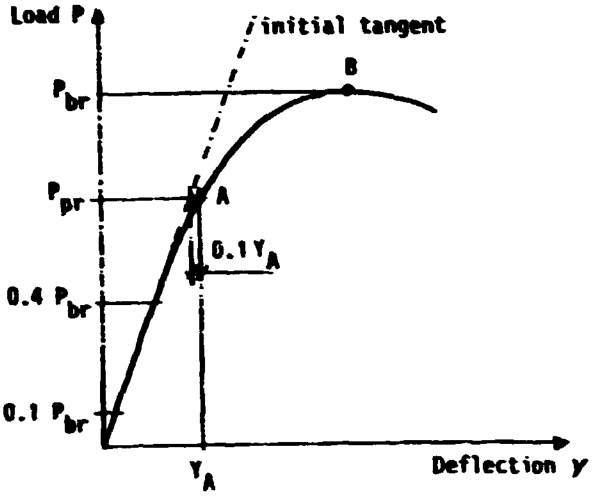


Application of load shall continue until failure occurs.

Results: The loadbearing capacity at the limit of porportionality, to the nearest whole kgf (N), shall be divided by the width of the sheet in m to three decimal figures. The load at the limit of porportionality shall be given to the nearest whole kgf (N) per metre.

With regard to calculation of the load at the limit of proportionality, see FIG.C.

FIG.C. Schematic load-deflection diagram



The load at the limit of proportionality = P_{pr}.

The limit of proportionality is that point on the load-deflection diagram at which the deflection, measured from the initial tangent, is 0.1 times the total deflection at the same point (point A in FIG.C.)

The initial tangent is the straigth line drawn through the points 0.1 and 0.4 times the ultimate load P_{br}.

WATERTIGHTNESS

Requirement The term watertightness refers to the ability of the sheets to resist the action of 250 mm high water column for 24 hours.

At the end of the 24 hours, there shall be no water drops on the bottom face of the sheet. Moist patches may however occur.

Testing Testing shall be carried out in a room in which the movement of air is limited.

A tube of 35 mm internal diameter, about 30 cm long, shall be used for the test. One end of the tube shall be shaped so as to fit into a corrugation trough. The sheets shall be placed on horizontal supports in such a way that the bottom face can be inspected. The tube shall be placed in a trough. The joint between tube and sheet shall be sealed with a suitable sealing compound. Water to a height of 250 mm above the bottom of the trough shall be poured into the tube. The bottom face of the sheet shall be subjected to visual inspection after 24 hours.

FIG.D. Equipment for watertightness test.