The Fabrication, Testing and Application of Fibre Cement Boards

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INTRODUCTION

Fibre cement board (FCB) is a versatile green building material, strong and durable. It serves as a substitute for natural wood and wood based products such as plywood or oriented strand boards (OSB). The properties of FCB as a construction material make it preferable for use as a ventilated façade cladding for both newly built and renovated buildings, interior wall coverings, balcony balustrade panels, base course and chimney cladding, and enclosure soffit lining. FCB can be applied to unfinished, painted, or simply impregnated surfaces [1-3].

Fibre cement components have been used in construction for over 100 years, mainly as roofing covers in the form of corrugated plates or non-pressurized tubes. They were invented by a Czech engineer, Ludwik Hatschek (1856-1914) [4]. In 1900, he developed and patented a technology for manufacturing light, tough, durable, and non-flammable asbestos cement sheeting that he called "Eternit."

Fibre cement composite–compared to the components of concrete–shows improved toughness, ductility, flexural capacity, and crack resistance. A major advantage of the fibre reinforcement is the behaviour of the composite after cracking has started, as the fibres bridge the *matrix* crack (matrix-bulk material, in which the fibres are dispersed). Then, the stress is transferred to the high-resistance system of fibres, capable of withstanding the load. Post-cracking toughness allows the use of FCBs in construction. Moreover, the fibres can reduce the unwanted free plastic shrinkage within the structure, decrease the thermal conductivity, and improve the acoustic insulation and fire resistance.

For many years asbestos has been regarded as the most suitable material for reinforcing FCBs. White asbestos, a silicate mineral / $Mg_3(Si_2O_5)(OH)_4$ / naturally forms long and durable fibrous crystals with each visible fibre composed of millions of thin microscopic fibrils. It is found in many geological deposits throughout the world.

The fibres reinforce FCB components only when added in a specific quantity (approx. 10% wt.) and are uniformly dispersed throughout the cementitious matrix. A highly complex procedure is required to achieve this goal under efficient industrial conditions. Ludwig Hatschek solved the problem by inventing a machine with a rotating sieve and a vat containing a diluted fibre slurry, Portland cement, and mineral components. A thin film of an FCB is formed on a moving felt partially wrapped around the sieve, similar to the procedure used in paper sheet making. Starting in the early 1920s, the mass production of asbestos FCB expanded throughout the world. Corrugated roofing covers can still be found in many buildings, mostly in rural areas (see Fig. 1).

It is widely known that Ludwig Hatschek died from pulmonary disease. The death of an Englishwoman, Nellie Kershaw, in 1924 from pulmonary asbestosis was the first case to be described in the medical literature [5]. In the early 1970s, a global effort to legislate for the removal of asbestos from industrial products was initiated.

Fig. 1. Corrugated roofing made of asbestos FCB, now expected to be removed due to health risks.

Fibre cement was a major user of asbestos, and as such new reinforcing fibres were being sought as alternatives to asbestos in this class of building material. James Hardie and Coy Pty Ltd. started manufacturing asbestos cement products in Australia in 1917. The company extended production to New Zealand, Indonesia, Malaysia, and the US. In the mid-1940s, during the post-war years, when there was a shortage of asbestos, James Hardie commenced a research on replacing asbestos with cellulose fibres [6]. The fibres studied included bagasse, groundwood, wheat straw, cement bags, and brown paper. However, the work was discontinued when asbestos became more accessible. Regardless, the idea of using cellulose fibres was still considered by the company. Beginning in the 1960s, the company manufactured a product called “Hardiflex” containing 8% (wt.)

asbestos and 8% (wt.) wood fibres. In those days, no technology was available to maintain compatibility between the cellulose fibres and the matrix to create a product of sufficient quality. The considerable shortcomings of the organic fibres are due to their insufficient long-term durability in an alkaline environment compared to the cementitious matrix. Water absorption of the matrix could cause an *alkali attack* on the fibres resulting in volume variation, fibre fractures, pull-out resistance degradation, and mineralisation of the fibres.

An effective method to lower the alkalinity of the matrix was the addition of pozzolanic components in the form of fine-ground quartz sand containing amorphous silica. Pozzolanic silicate in the presence of alkaline calcium hydroxide produces a hydrated calcium silicate, a substance with lower alkalinity [7]:

$$3Ca^{++} + 2H_2SiO_4 + 2OH^- + 2H_2O \rightarrow Ca_3[H_2Si_2O_7](OH)_2 \cdot 3H_2O$$

In the late 1980s, asbestos fibres were successfully replaced in the following products: flat sheet, corrugated roofing, and moulded products by the leading manufacturers, including James Hardie [6] and Cembrit [2]; however, other manufacturers, mostly in Eastern Europe and Asia, continued the use of asbestos until the first decade of the 2000s.

A mass production of green FCB was made possible after the optimal source of the reinforcing fibres was determined. Nowadays, a kraft lap pulp derived from hardwood, e.g., *Pinus radiata* or *Red Cedar*, is used. Cellulose is the main component of the kraft pulp (>50% wt.). This polymeric substance has the ability to form long and hard to break linear chains made out of alternating pairs of dehydrated glucose / $C_6H_{10}O_5$ / as shown in Fig. 2.

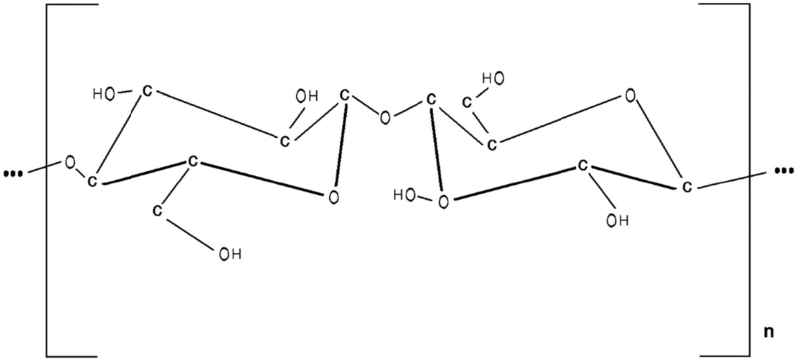

Fig. 2. Single polymer molecule–a basic component of the linear chain in cellulose.

Multiple hydroxyl groups in the glucose from one chain form the hydrogen bonds with oxygen atoms in adjacent chains, thus forming microfibrils with high tensile strength. The microfibrils have a diameter of approx. 100 nm and, in turn, form thicker (30-40 µm) fibres. The microfibrils can be positioned at a different angle in relation to the longitudinal axis of the fibre. At small angles, an increase in fibre stiffness compared to the fibres made out of microfibrils positioned at larger (40-50°) angles can be observed [8]. The elasticity/stiffness of the fibres can thus be controlled by choosing the source of cellulose or by the mechanical processing of the *kraft pulp* (the most common industrial source of cellulose fibres).

Coutts in [9] has reported that there is a cellulose–cement compatibility in the sense that the matrix hardening is not affected by the presence of a certain amount of cellulose. Optimal interfacial bond between the fibre and the matrix can be established. Excessive bond strength would result in material embrittlement, while a weak bond would reduce the composite strength. Since cement is an alkaline material it contains metal (Ca, Si, Al, Fe) hydroxyl groups. Cellulose fibres contain hydroxyl groups and carboxylic groups. These groups form covalent bonds capable of producing efficient fibre–matrix bonds. Therefore, the cellulose matrix composite can show both high flexural strength and fracture toughness that should be balanced by the optimal amount of components.

The methods of investigation into the mechanical (and other) properties of a variety of FCB products will be discussed in Chapter 2. Many manufacturers also add 3-5% synthetic fibres, e.g., polyvinyl alcohol (PVA, PVOH) fibres to FCB.

The technology is used for several reasons [10]. The added fibres are non-toxic and feature high tensile strength and flexibility. PVA is hydrophilic and is capable of forming strong bonds between the hydroxyl group and the cement matrix in the presence of water. The material is cheap and widely available. It is used in FCB in the form of fibres 30-50 µm in diameter. Fig. 3 shows the PVA polymer molecule.

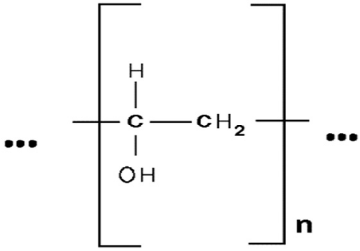

Fig. 3. Formation of polyvinyl alcohol (PVA).

Introducing the two aforementioned types of fibres allows better control of their length distribution within the matrix, while the mechanical strength of the composite is roughly proportional to the fibre aspect ratio, i.e., to the diameter/length coefficient. It also eliminates the common problem of thin fibre "curling" together when dispensed into the slurry [11], and at the same time allows the fibres to be enveloped by cement and filler particles. Fig. 4 shows two polarized light micrographs of FCB containing 6% (wt.) kraft cellulose fibres and 2% (wt.) PVA fibres.

Figures 4, 2-31, 2-32, 2-33, 2-34, 2-35, 2-36, 2-37, and 3-14 are reproduced in the centrefold in colour for improved readability.

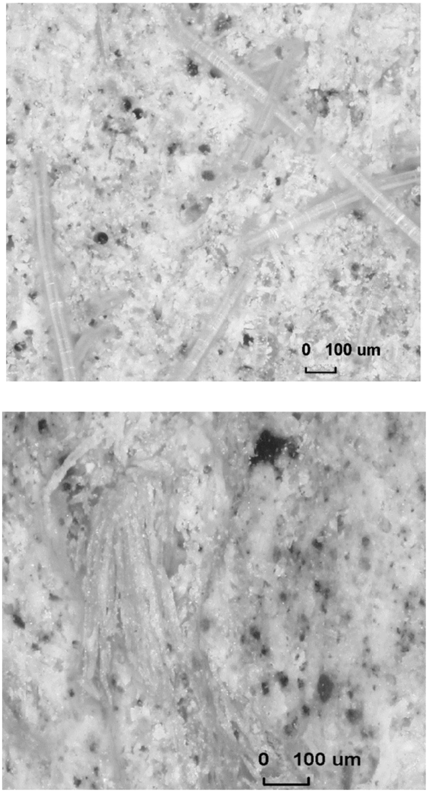

Fig. 4. Micrographs of the fibre cement board containing 6% (wt.) of kraft cellulose fibres and 2% (wt.) PVA fibres. Top micrograph shows PVA fibres and bottom micrograph shows small strand of cellulose fibres.

CHAPTER ONE

FABRICATION OF FIBRE CEMENT BOARDS

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Introduction

A modern process of FCB fabrication consists in laying thin paper-like films on top of each other until a desired sheet thickness is obtained [13, 14]. The process distributes the reinforcing fibres in planar uniformity, taking the best advantage of the reinforcing fibres to increase the in-plane strength of the sheet. Thus, the strength of sheets made using this process is approximately 50% greater than the sheets formed to full thickness in a single action using a filter press or the extruding processes. In a process detailed below, a thin film formed from a diluted fibre slurry is usually 0.25-0.4 mm thick and each FCB comprises a stack of these films. Thus, the final sheet consists of approx. 20-30 or more thin films. A large number of layers partially suppresses the imperfection of the considered method: the films formed on a sieve are not uniform in composition but due to sedimentation they have a fibre-rich side and a fibre-poor side. Additionally, 2.5-3 mm long fibres bridge the sieve holes, slightly blocking the feed of other particles and forming a fibre-rich layer. The portions formed last can be relatively fibre-poor. On this account, an advanced fibre orientation and distribution devices have been developed and introduced into the actual chain of FCB fabrication.

Fig. 1-1 shows a flowchart of a sample fibre cement board production process. The particular sub-processes named in the flowchart are detailed below.

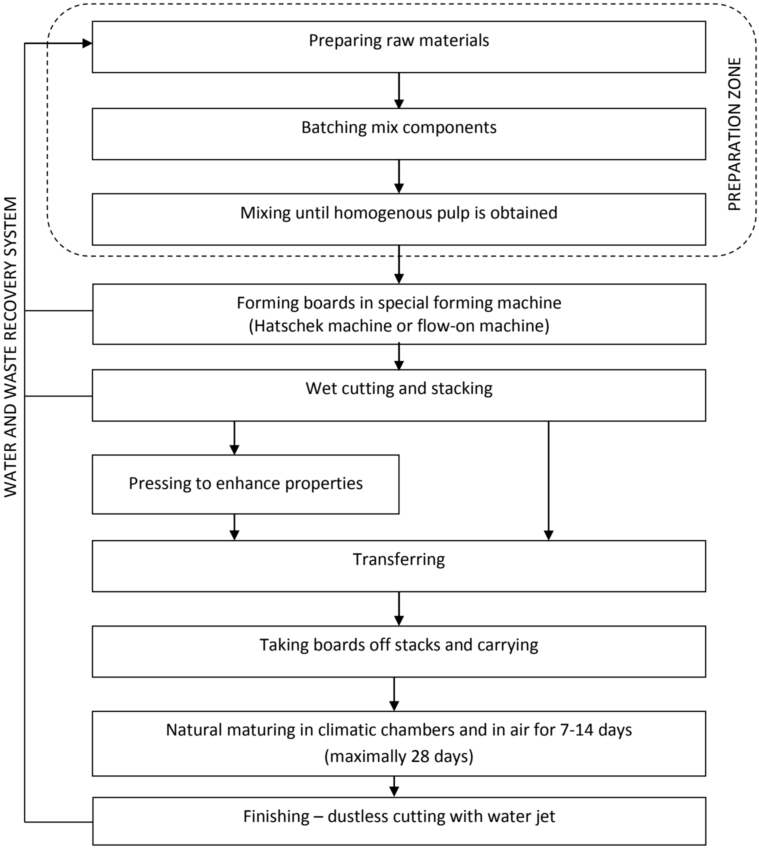

Fig. 1-1. Flowchart of sample fibre cement board production process.

Figure 1-2 shows a sample flowchart of the technological process of fabrication of cellulose fibre cement boards, including seven zones corresponding to the specific production stages [12]. Fig. 1-3 shows a detailed diagram of zones no. 1 and no. 2 in order to outline their complexity. The moisture content of the board varies at each stage and is determined using methods described in the next chapter.

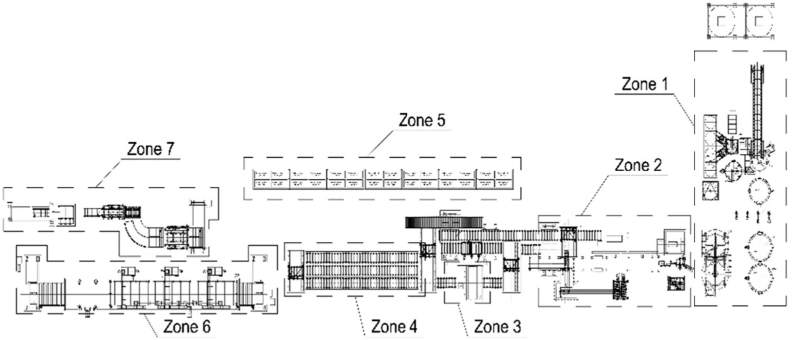

Fig. 1-2. Flowchart of technological process of fabrication of cellulose fibre cement boards.

The fabrication of cellulose FCB starts in the preparation zone (zone 1), where cellulose fibres are mixed with water in a mixer (pulper) until a uniform dispersion is produced. Bulk components (cement with additives) in specific proportions are added to the batched water and mixed until a homogenous plastic compound is obtained. There are two main categories of cellulose fibre cement: low-temperature cured and high-temperature or autoclave cured. Low (air) cured formulations usually contain larger amounts of Portland cement combined with fine-ground fillers such as clays, silica fume, ground limestone, or fly ash. Autoclaved formulations contain less Portland cement and more pozzolanic components and fillers.

The mixture described above is transferred to a board forming machine. The *Hatschek* or *flow-on machine* is used (zone 2) to form boards with a fixed thickness of 4-14 mm. The next (optional) production stage involves the pressing of stacked boards (zone 3). A pressing force suitable for the type of board fabricated (exterior or interior cladding board) is applied. Warm (due to cement hydration heat) cellulose fibre cement boards directly after pressing or forming are transferred to a pre-curing tunnel (zone 4) where they remain for about 14 hours. Next, the boards can be taken off the stack and placed on a pallet. This must be done as quickly as possible since the boards are still quite warm and damp, and so they should not be allowed to cool and dry too much or too quickly.

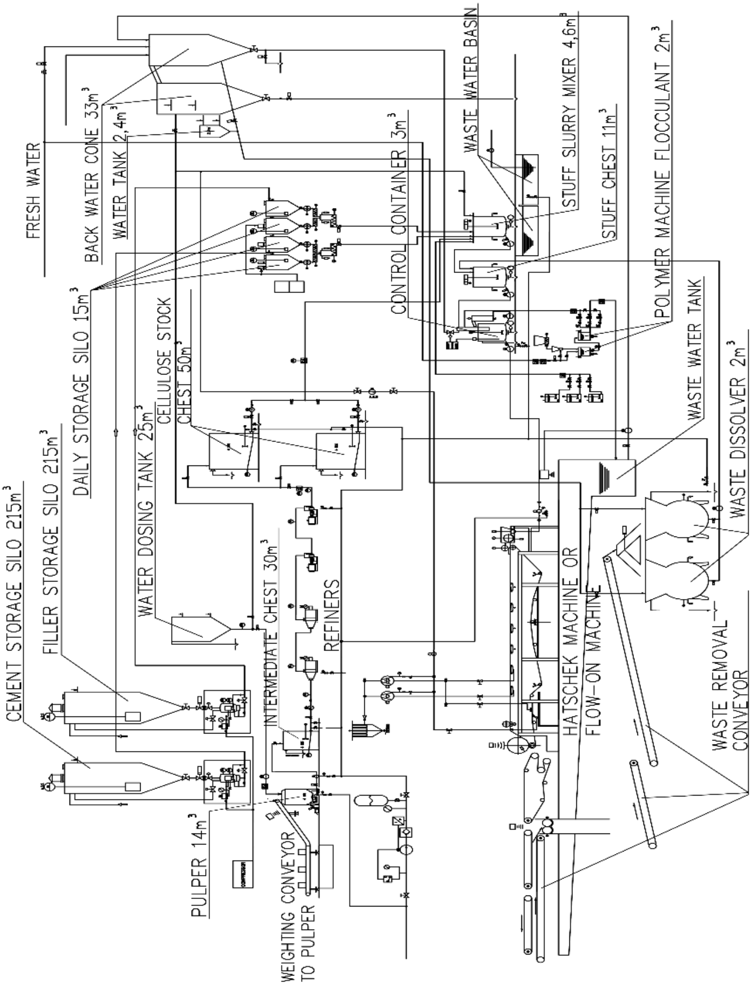

Fig. 1-3. Diagram of zones no. 1 and no. 2.

The boards placed on the pallets are left to mature and are cured in steady thermal-moisture conditions, e.g., in special airtight tarpaulin tents (zone 5) for about 14 days. After that time, the boards obtain the proper bending strength, and some moisture is removed naturally. After the maturation period, the boards are transferred to a final drying oven (zone 6) where they are subjected to three-stage drying at 180°C, 160°C, and

120°C, respectively at stage 1, 2, and 3. Then, the boards are cooled naturally for about 20-30 minutes depending on their thickness. This is a critical stage of the fabrication process. Boards with excessive moisture content are not fit for further treatment, such as impregnation or painting. At the last fabrication stage, the boards are trimmed, and, if necessary, their surface is ground at the edges (zone 7).

Primary raw materials

Table 1-1 shows the typical primary raw materials used in the fabrication of naturally maturing fibre cement boards.

Table 1-1. Typical primary raw materials used in fabrication of fibre cement boards.

Standard ratio	type of raw material	approximate composition
	Cement	~ 60%
	Cellulose (dry)	~ 8%
	PVA	~ 2%
	Kaolin or lime	~ 30%
	Total	~ 100%
	Additives & admixtures	
	Hyperplasticizer	~ 0.1 l/t *)
	Didecyldimethylammonium chloride (DDAC) or bromide (DDAB)	~ 0.1 l/t *)
	Perlite	~ 1 kg/t *)
	Mica	~ 1 kg/t *)
	Microsphere	~ 1 kg/t *)
	Antifoaming agent	~ 0.26 l/t*)
	*) l/t or kg/t = litres or kilograms per ton of finished product	

Properties of PVA fibres

PVA (polyvinyl alcohol) fibres are a major component in the fabrication of naturally maturing cement fibre boards. The basic specifications of PVA fibres, based on the data for Kuralon (manufactured by Kuraray America Inc.) [40], are shown below. Table 1-2 shows the basic specifications of PVA fibres compared to other commercially available fibres.

Main advantages of Kuralon fibres:

- non-toxic,
- long-term presence on the market,
- established manufacturing process,
- high quality.

Table 1-2. Specifications of PVA fibres compared to other commercially available fibres [40].

Parameter	type of fibre						
	Kuralon	PET	Nylon	PAN	PP	Aramid	Carbon
tenacity (cN/dtex)	11-14	6-8	5	2-4	6-8	22	13-23
Young’s modulus	250-300	80-145	40-80	30-70	30-110	400-700	1190-2370
alkali resistance	·	X	X	X	·	X	·
adhesion to cement	·	X	X	X	X	X	◀
weather resistance	·	·	◀	·	X	·	·

· = good, ◀ = normal, X = bad

Figure 1-4 shows micrographs of the cross-sections of fibre cement boards reinforced with different fibres.

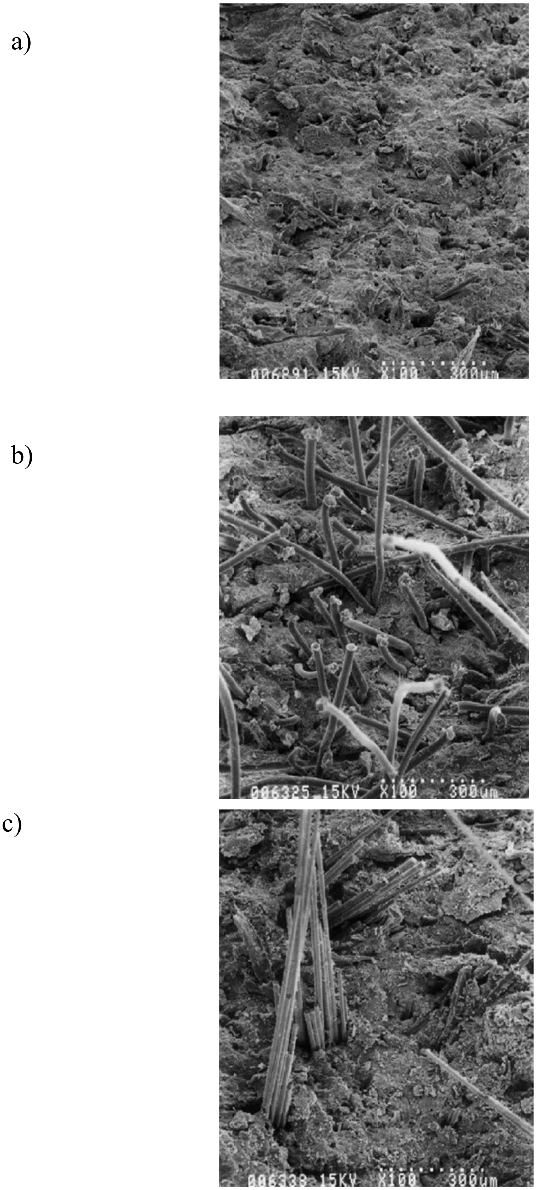

Fig. 1-4. Micrographs of cross-sections of fibre cement boards reinforced with different fibres [40]: a) Kuralon fibres; b) polypropylene fibres; c) ARG fibres.

Figure 1-5 shows the relationship between fibre tenacity and bending strength of fibre cement boards reinforced with different fibres [40].

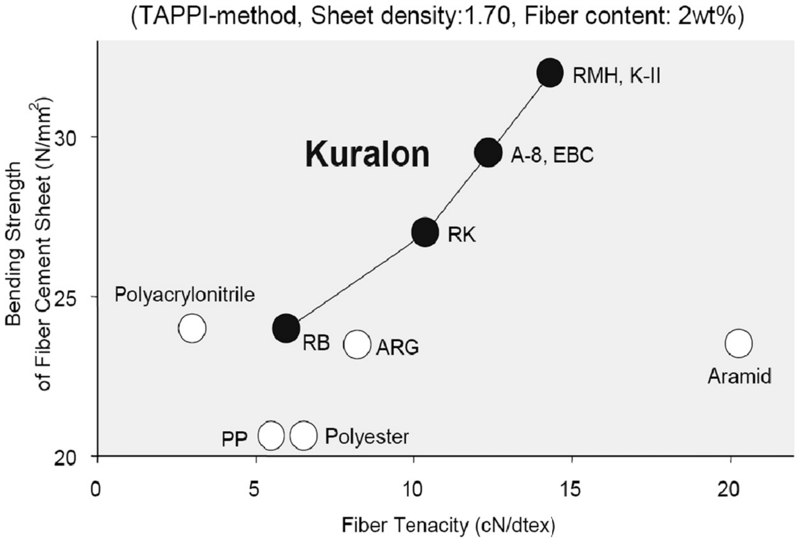

Fig. 1-5. Relationship between fibre tenacity and bending strength of fibre cement boards [40].

Raw material preparation and mixing zone

The preparation zone of a fibre cement boards fabrication usually includes the following:

- 2 cement and additive (e.g., limestone powder) silos, each with a capacity of about 100-200 m^3,
- a water tank with a capacity of 20-30 m^3,
- 4 daily stock silos with a capacity of 15-20 m^3,
- a belt conveyor for transferring cellulose and waste paper to the pulper,
- a pulper with a capacity of 12-16 m^3,
- an intermediate cellulose tank (a buffer pulp tank) with a capacity of 20-40 m^3,
- up to 4 refiners (depending on their type),
- 2 cellulose tanks (refined pulp storage tanks) with a capacity of 40-

  60 m^3,
- a mixer (for mixing all the components) with a capacity of 5-7 m^3,
- an intermediate filler tank (a buffer tank for the mixed liquid pulp) with a capacity of 10-15 m^3,
- a density calibrating tank with a capacity of 2-4 m^3,
- chemical agents tank (a flocculant batching device).

The production of boards starts at the two silos located outside the production building (Fig. 1-6), from which the raw materials are transported by a belt conveyor (situated under the silo (Fig. 1-7)) and then by a pneumatic conveying system to the daily stock silo in the production building (Fig. 1-8).

Fig. 1-6. Raw material silos, with a capacity of 200 m^3 each, outside the shop floor.

Fig. 1-7. Pressure vessel and belt conveyor under silo.

Fig 1-8. Sample daily stock silos, with a capacity of 15 m^3 each.

The first production stage involves preparing the cellulose, which is the source for the fibres that reinforce the composite fibre cement boards in the cellulose preparation zone. The cellulose (and waste paper, if required) is fed in weighed-out portions (bales) into the pulper via the belt conveyor (Fig. 1-9) with integrated scales.

Fig. 1-9. Sample belt conveyor with scales (weighing cellulose and waste paper) feeding weighed-out portions into the pulper.

Next, the main water is supplied from the tank (Fig. 1-10) to the pulper in order to macerate and pre-defibre the cellulose. The cellulose is pulped in the pulper (Fig. 1-11). Water is used throughout the entire pulping process.

Fig. 1-10. Sample water tank with a capacity of 25 m^3.

The cellulose content in the pulp is 4% (wt.). A biocide is batched into the pulper to protect the cellulose fibres against biodegradation. Also, depending on the type of fabricated boards, a hydrophobizing agent can be added at the same time.

Fig. 1-11. Sample pulper with a capacity of 14 m^3.

Since, as mentioned earlier, some cellulose can be reclaimed from the waste paper, the cellulose fibres should undergo a special impregnation process. This can be done in accordance with, e.g., US Patent No. US 7.244.388 B2 “Method of producing stable cellulose fibres with improved biological stability and products made of them,” patent date 17 July 2007.

The cellulose fibres obtained using this method feature higher biological resistance and stability. Even though the previously used methods of treating cellulose with biologically toxic compounds would result in a higher resistance of the cellulose to decomposition, they were not completely satisfactory, since the fibres had to be cleaned before use and the energy demand of the cleaning process was very high, while the loss of fibre length was quite significant. Studies show that the treatment of cellulose fibres with didecyldimethylammonium chloride (DDAC) or bromide (DDAB), carried out as per the method disclosed in the patent yields the best results. Thanks to these substances and some copper content, the product is characterized by a very good biological stability, but not at the expense of a significant increase in energy demand through the cleaning process or fibre length loss. The treated fibres provide excellent reinforcement of the fibre cement board products and guarantee high resistance to degradation.

The prepared pulp is transferred from the pulper via a system of pipes and pumps to the buffer pulp tank (Fig. 1-12). Next, the pulp is transferred from the tank to the refiners, where it is refined. Depending on the type of refiner, up to four refiners (Fig.1-13) can be used in the fabrication plant.

Fig. 1-12. Sample buffer pulp tank with a capacity of 30 m^3.

Fig. 1-13. View of four refiners.

The refined pulp is conveyed to one of the two storage tanks, with a capacity of, e.g., 50 m^3 each. Depending on the process requirements, pulp with fibres reclaimed from waste paper, impregnated with a hydrophobizing agent, can be stored in one tank, while pulp with non-impregnated cellulose fibres can be stored in the other tank. Fig. 1-14 shows sample pulp storage tanks.

The pulp is transferred from the storage tanks to a mixer with a capacity of 4.6 m^3, where it is mixed with other raw materials, i.e., cement, additives (e.g., limestone powder), and chemical agents, thus giving the liquid cellulose-cement mix the required rheological (consistency) properties. All of the components (except for the pulp) are batched from the daily stock silo and auxiliary plants.

The liquid mix is transferred to an 11 m^3 buffer tank (Fig. 1-16). The liquid mix is transferred from the tank via a system of pipes to the second zone, where the boards are formed in the Hatschek machine, as described below.

Fig. 1-14. Refined pulp storage tanks with capacity of 50 m^3.

Fig. 1-15. Mixer with a capacity of 4.6 m^3.

Fig. 1-16. Liquid mix buffer tank with a capacity of 11 m^3.

Detailed operation of Hatschek machine and fibre film formation

Fig. 1-17 shows a diagram of a Hatschek machine. The main section includes one (or more) vat(s) with a cylindrical sieve rotating in contact with a diluted water-based fibre slurry capable of forming a filtering film and mineral materials, including Portland cement. The sieve is driven by a continuous felt wrapped around the top of a rotating cylinder by a couch roller. The filtering film moves on the felt to a forming roller. The felt continuously travels between a drive roller and a tail roller.

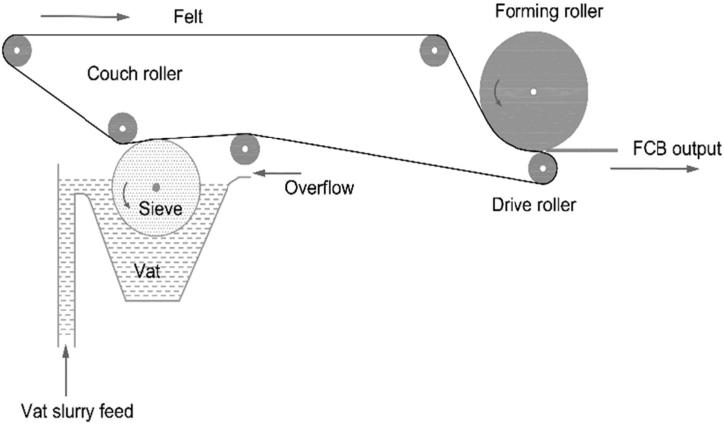

Fig. 1-17. Hatschek machine diagram.

The sheets are formed in the Hatschek machine in accordance with the following procedure [13]. When the clean sieve is pulled under the slurry in the vat, water from the slurry runs through the sieve to deposit a soft porous film of fibres and cement on the surface of the sieve. The sieve moves the film onto the felt. The excess water is removed when the sieve is pressed to the felt. The felt transfers the film onto the forming roller. When the required number of films is wrapped around the forming roller to form a sheet of a required thickness, the stack of films is removed from the roller and laid out flat to form a board. The draining of successive films in contact with each other under pressure is sufficient to bind the films together and form a continuous solid material.

Typical sieve mesh sizes are approx. 0.4 mm, whereas the non-fibrous particles are significantly smaller (approx. 50 µm in diameter). Therefore, these particles can freely pass through the sieve out of the formed layer, whereas the fibres are retained on the sieve. Thus, entrapment of the non-fibrous materials within the film on the surface of the sieve depends on the structure of the fibre layers formed.

The efficiency with which the filter layer retains the non-fibrous material depends on the fineness of the cellulose kraft pulp. This is achieved by a special processing, i.e., by crushing the fibres to reduce their diameter without affecting their length. High quality kraft pulp can form a network of fine fibres capable of trapping at least the larger non-fibrous particles. This forms an initial filter layer on the surface of the sieve and