View metadata, citation and similar papers at core.ac.uk
brought to you by CORE
provided by TU Delft Open Access Journals

2 Paper. History, production, properties and products

A tree is a slow explosion of a seed

Bruno Munari, 'Drawing a tree' [1]

§ 2.1 Introduction

Paper is a material we know from our day-to-day lives because it is used in newspapers, tissues, packaging, etc. Its web-like structure consists of wood fibres and can be visualised by comparing it to the cooking of a portion of spaghetti that is later served onto a plate. [2]

Paper is often associated with traditional materials and production technologies. Brought to life in the second century AD, [3, 4] paper has had a significant role in the history of civilisations, from the Chinese empire through the Guttenberg era up to the current 'digital age'. It has primarily been used as an information carrier and packaging material. However, the architectural applications of paper have been known since the eighth century AD. [5]

Although production technologies and the finish of paper have changed and improved over the years, paper has in fact remained remarkably the same through the centuries. It still has the same composition: cellulose fibres bonded in a wet environment, then pressed and dried. Recently, not only the paper-making industry has undergone change, but other industries, like architecture, electronics, the automotive industry and others, are also receptive to the innovative qualities of paper.

Growing awareness of the scarceness of fossil fuels and natural resources, the need to curb CO_2 emissions and the necessity of reducing the ecological burden caused by the use of materials such as plastics, foam, concrete or steel is encouraging people to find more environmentally friendly solutions, including the circular economy. [6]

Paper and its derivatives can satisfy these needs, although it seems that the golden age of paper is coming to an end. Electronic devices such as smartphones, tablets and e-readers, as well as the growing popularity of electronic media, have taken the place of traditional print media, which has resulted in the paper industry's decline as the producer of information carriers. However, the paper industry can develop in other directions, e.g. smart packaging, the provision of energy and construction materials, where this renewable and cheap material can make a new start, using and being used along with new technologies and innovations. [6]

Sustainable development was first described in the Agenda21 document in 1992 and its appendices, which state that the most important challenges for global policy are *improving people's lives and conserving our natural resources in a world that is growing in population, with ever-increasing demands for food, water, shelter, sanitation, energy, health services and economic security*. [7] Moreover, the European Parliament and the Council of the European Union ordered in Directive 2008/98/EC that by 2020, the weight amount of recycled or re-used construction waste must be increased to a minimum of 70%. [8]

These challenges can be addressed by renewable resources – reusable, recyclable, available and affordable materials, among other things. One of these renewable resources is paper.

§ 2.2 Definitions

Quite often the meanings of paper and paper-based products (including cardboard) are confused. To help us get a better understanding of what is paper and what the differences are between paper and other products of the paper industry, the definitions according to the NEN-ISO 4046 1-5 norm [9] are provided below:

– **Paper** *is a generic term for a range of materials in the form of a coherent sheet or web. In the generic sense, the term of "paper" may be used to describe both paper and board. The primary distinction between paper and board is normally based upon thickness or grammage.*

– **Paperboard** *(also board) is a generic term applied to certain types of paper frequently characterized by their relatively high rigidity*

- **Carton board** *(also folding boxboard) is board intended for manufacture of cartons having good scoring and folding properties*

- **Chipboard** *is a board commonly of low grade, made on a continuous machine from a waste paper*

- **Corrugated fiberboard** *is a board consisting of one or more sheets of fluted paper glued to a flat sheet of board or between several sheets*

- **Solid board** *is a board comprising a single furnish layer (layer of paper or board consisting of one or several plies of the same composition)*

- **Solid fiberboard** *is a board which may be pasted (layered) or unpasted often incorporating a lining of Kraft or other strong furnish intended and suitable for the manufacture of packaging and drums. Solid fiberboard generally has a grammage above 600 g/*m^2.

The above definitions show that paper and board or cardboard are in fact the same type of material, and the difference lies in the thickness or grammage (basis weight).

Christopher Biermann in his immense work entiteled *Handbook of pulping and papermaking* (1996) describes paper as: *pliable material used for writing, packaging, and a variety of specialized purposes. Paper consist of a web of pulp (normally from wood or other vegetable fiber), usually formed from an aqueous slurry on a wire or screen, and held together by hydrogen bonding. Paper may also contain a variety of additives and fillers.* [4]

Several distinctions exist between paper and board or cardboard, depending on the country, industry or traditions. There is no clear division between types of paper-based products. For example, Branko Sekulić (2013) [10] states that paper heavier than 150 g/m^2 is normally called paperboard, and that paper heavier than 500 g/m^2 is called board. On the other hand, the CEPI (Confederation of European Paper Industry) in the *Pulp and Paper Industry Definitions and Concepts* document informs readers that *The paper and paperboard category is an aggregate category. In the production and trade statistics, it represents the sum of graphic papers; sanitary and household papers; packaging materials and other paper and paperboard. It excludes manufactured paper products such as boxes, cartons, books and magazines, etc.* [11] In her PhD dissertation entitled *Cardboard in Architectural Technology and Structural Engineering: A Conceptual Approach to Cardboard Buildings in Architecture* (2009), Onzelm Ayan from ETH Zurich states that paper with a density greater than 200 g/m^3 is generally considered to be cardboard. [12] Almut Pohl in her thesis *Strengthened*

Corrugated Paper Honeycomb for Application in Structural Elements (2009) informs that the grammage of paper used for structural purposes is in the range of 80 g/m² to over 300 g/m². [13] Stefan Jakucewicz (2014) distinguishes paper products according to their grammage and construction, with paper being a single-layered product and cardboard a multi-layered one. Jakucewicz refers to the norm ISO 4046:1978, in which a grammage of 225 g/m² is considered to be the boundary between paper and cardboard. However, ISO 4046:1978 was cancelled and replaced with ISO 4046-3:2002, in which this boundary was removed, and paper was defined as a thin paper product with low grammage and cardboard as a thick product with high grammage. [14] However, some materials with a grammage lower than 225g/m², which are used for the production of boxes or corrugated fibreboard, are called cardboard, while some products with a grammage higher than 225g/m², such as drawing or absorbent paper, are called paper.

The above definitions show that there is not one clear distinction between paper and cardboard. It depends on a country’s national traditions, common names used by the industry, norms and other documents.

To simplify the distinctions between different types of paper products, it can be assumed here that the differences in grammage between paper and cardboard are as follows:

- **Paper** is a material with a grammage lower than or equal to 225 g/m²
- **Cardboard** is a material with a grammage higher than 225 g/m²

In multi-layered materials (i.e., corrugated board) this boundary is equal to 160 g/m²

With this matter it can be assumed that:

Cardboard is a commonly used term that is associated with thick paperboard or corrugated board. However, in the paper industry, the word ‘cardboard’ refers to paper board, solid board and corrugated board. In this dissertation the term ‘cardboard’ will be used for heavy-duty paper, sometimes with additional qualifications, such as corrugated, solid (board), solid fibreboard, chipboard, etc. whose grammage is higher than 225 g/m² for single-layered material and higher than 160 g/m² for multi-layered materials.

Paper based material or paper products is a broad definition of products whose main ingredient is cellulose (mainly wood) fibres.

There are many different grades of paper, board and paper-based products, which will be discussed below, in Section 2.6.9 of this chapter.

§ 2.3 The history of paper production

The 'official' year of the invention of paper is 105 AD. However, paper is likely to have been invented before, and definitely certain species of wasps and hornets had been manufacturing paper and even cardboard ages before man (see Fig. 2.1.). [15] The 'official' birth year of paper is the year in which paper was introduced to Emperor He of the Han Dynasty by the Chief of the Imperial Supply Department, Cai Lun, also know as Ts'ai Lung. [16] Afterwards, paper became a popular medium for writing, slowly replacing silk scarves and bamboo boards as media for messages. As Kiyofusa Narita reports in his book A Life of Ts'ai Lung and Japanese Paper Making (1980), the oldest samples of paper made of flax fibres were found in China by an English explorer, Aurel Stein, in 1907 and have been dated back to the years 65-56 BC. [16] Further evidence that paper existed before 105 AD was the first systematic Chinese dictionary, completed in 69 AD, in which paper had an entry. The legend says that a certain Han Xin, who served at the Court of Emperor Gaozu (247-195 BC), during his youth helped a washerwoman bleach silk floss. Silk floss was cleaned in the water by being beaten on a mat. The broken fibres sneaked through the longer ones and formed a layer on the mat. When such a layer dried, it would become very much like a piece of paper. So the legend followed the logic. [17] On the other hand, there are researchers, among them Jozef Dabrowski (1991), who argue that the product made before Cai Lung was not paper but tapa. [3] Tapa is a material that was used as an information carrier before the invention of paper (see Fig. 2.7). Tapa was obtained by sopping and boiling mulberry tree bark in a lye. Strips of the bark were crushed and beaten with hard tools, then dried. Paper is obtained by a uniform distribution of a slurry containing cellulose fibre on the surface of a screen. A comparison of the structure of paper and tapa will show up differences in the structure of both materials. Tapa consists of strips of material (not pulp), while paper consists of cellulose fibres connected with each other. Despite the differences between both materials, there is no doubt that paper derives from tapa, and the invention of paper-making was closely related to the techniques used to produce tapa.

FIGURE 2.1 Paper nest built on corrugated cardboard

Nevertheless, it is Cai Lun who is recognised by history as the person who gave humankind paper. Cai Lun was asked by the emperor to rearrange the imperial library which consisted of a large number of books made of wooden boards, which were used as a writing material at the time. In order to find handier and lighter material, Cai Lun began experimenting with the bark of mulberry trees, bamboo, grass, hemp, scraps of silk fibres, old fishnets and the bark of *kaji* trees instead of silk floss. The pulped fibres were mixed with some mucilaginous substance in a water solution. Then the material was screened, drained and dried. Although the processes, machinery and technology have changed over the centuries, paper is still made the same way it was then. [16, 17] When paper was invented, its production method was initially kept secret. As a lightweight and relatively cheap material produced out of tree bark, rags and later fishing nets, paper replaced heavy bamboo boards and expensive silk as the preferred material on which to write.

Before paper was introduced and adopted by other parts of the world, other materials were used as information carriers, such as bricks, lead, brass or bronze sheets, pieces of wood (see Fig. 2.3), the inside of tree bark, tree leaves, vellum, parchment, stone tables (see Fig. 2.2) or papyrus (see Fig. 2.4).

FIGURE 2.2 Roseta stone, 196 B.C. – replica

FIGURE 2.3 Wooden slats 27 AD – replica

In China, before the era of paper, rice paper, bamboo boards and the aforementioned tapa were the most popular writing materials. So-called 'rice paper' is actually not paper, nor is it made of rice. The material is produced by carefully cutting the pith of the kung-shu plant. Whereas paper is made of cellulose fibres, rice paper is made of the parenchyma of the plant. It is for this reason that rice paper lacks the strength of conventional paper. [2] . Papyrus, after which paper is named, was the most superior writing surface until the invention of paper. Developed by the Egyptians, papyrus was made of reed leaves that were placed in a row. Then the next row was placed on top of the previous one in the transverse direction. Both layers were pounded together and dried (see Fig. 2.4). During the pounding, the cellulose cells were merged by the formation of numerous hydrogen bonds. Papyrus was widely used as a writing material in Egypt and the Arabic World since 3000 BC. In Central America in the pre-Columbian age, amate was used instead of paper. Amate was produced similarly to tapa (see Fig. 2.5).

FIGURE 2.4 Papyrus

FIGURE 2.5 Amate

FIGURE 2.6 Hemp paper – produced in China, 202 BC-8 AD – replica

FIGURE 2.7 Tapa cloth made in Hawaii

FIGURE 2.8 Parchment sheet with hand-written music, approx, seventeenth century

Prior to the discovery of paper, parchment and vellum (durable, lightweight materials made from the skin of calves, sheep or goats) were the most popular writing materials used in Europe (see Fig. 2.8). Europeans had been using animal hides as a writing material since the second century AD. The name ‘parchment’ is derived from the Persian city of Pergamon, whose sheets of parchment were known to be of very high quality. [4, 15]

§ 2.3.1 Paper in China

One of the main reasons why paper was used in ancient China was to spread the religious ideas of Buddhism, Taoism and Confucianism. Paper was also used in burial ceremonies as a representation of material goods that were buried with the deceased. In addition to religious purposes, paper was also used for the creation of money. Paper money was first used in China back to 812 AD. In the year 868 AD, the first known Chinese printed book was produced: the Diamond Sutra. In 875 AD toilet paper was first reported by travellers, and in 969 AD the existence of paper playing cards was reported. [15, 18]

Early examples of Chinese paper were made out of hemp, jute, flax, ramie, rattan, paper mulberry (kozo), mulberry and bamboo fibres (see Fig. 2.6). The production process took several days. First, different plants were soaked in water, allowing the bark to be stripped and the cellulose fibres to be released and separated from the lignin. Then selected layers of bark were soaked in a solution of water and wood ashes (potash) and beaten with a mallet. This operation allowed paper makers to separate the cellulose fibres from the lignin. The cellulose pulp thus obtained was poured onto a woven mould or sieve which lay in the water. The paper maker then shook the sieve in order to spread the cellulose fibres evenly. Afterwards the mould would be left outside in the sun to dry.

§ 2.3.2 Paper in Japan

Although the Chinese kept the technique used to make paper secret, paper appeared in Korea in the fourth century AD and was introduced to Japan by a Korean Buddhist monk named Donchó in 610 AD. [16] Since then, the Japanese have created their own way to produce paper. Their paper is called *washi* (*wa* means 'Japanese' and *shi* means 'paper'). The main ingredients of Japanese paper are the bark of the *kozo* plant, *gampi* tree and *mitsumata* shrub. However, other fibres, such as bamboo, hemp, rice and wheat, can be used, as well.

The *washi*-paper-making technique involves steaming plant stems, stripping them while still hot, cleaning the bark, cooking it in alkali and gently beating it in order to lengthen the fibres. The fibres are collected from a solution of water and mucilage of *aoi tororo*, a hibiscus genus plant, by waving the screen previously dipped in the solution. The mucilage minimises entanglement of the fibres.

There are two ways to produce traditional Japanese paper. The first method is *tame-zuki*, imported from ancient China. It involves dipping a screen in a solution of paper ingredients just once and then, after removing it from the solution, shaking the frame back and forth, and from left to right, to make sure the fibres face the right direction.

The second technique, called *nagashi-zuki*, involves scooping the fibres from the solution with a bamboo-netted frame screen, shaking it back and forth and sideways to get the desired pattern of fibres facing two ways. This motion is repeated several times in order to obtain a thicker and stronger sheet of paper. The fibres align in the direction of the waving – in other words, at right angles to each other (see Fig 2.9 – 2.13).

FIGURE 2.9 stripping plants for traditional production of *washi* paper in Echizen, Japan

FIGURE 2.10 beaten bark

FIGURE 2.11 waving the screen previously dipped in the solution (*tame – zuki* technique)

FIGURE 2.12 a wet sheet of paper on a bamboo screen

High-quality paper made of hemp and the *kozo* plant was used for the oldest known printed piece of paper, which contains *dharani*, Buddhist charms from about 770 AD, i.e., some 680 years before Johannes Gutenberg invented the printing press. Millions of *dharani* were printed on sheets measuring 6x45cm. They were placed in small (10x13.5cm) pagodas and dedicated to Ten Major Temples, with the aim of bringing about global peace (see Fig. 2.14).

FIGURE 2.13 Placing the Washi paper sheets on the stock

FIGURE 2.14 Small pagodas and Dharani

§ 2.3.3 Paper in the Arabic World

The Arabs learnt the technique of paper-making from the Chinese after conquering the city of Samarkand in 712. Several Chinese paper-making workshops had been established in Samarkand earlier. [14] Some sources (Goedvriend 1988, Scott et al.

1995) indicate that the art of paper-making was acquired by the Arabs forty years later, after the battle of Talas River, in which the Arabs fought the Chinese and won. Some Chinese paper-makers were imprisoned and sent to Samarkand. [17, 18] Afterwards, the secret of paper-making spread quite fast in the Islamic world. The most important role paper played at the time was to distribute verses of the Koran to believers. Paper replaced papyrus, which was heavier and harder to manufacture. The Arabs also improved the pulping process by inventing mechanised pulp-making involving water mills. The ingredients now no longer had to be manually beaten into a pulp. [17]

§ 2.3.4 Paper in Europe

Knowledge of paper-making came to Europe along with the Arab expansion on the Iberian peninsula. The first paper-making workshop was operating in the year 1144 in the city of Xativa, which is recognised as one of the first European paper producer. [6, 14] The Arabs also established paper production centres in the Apennine peninsula, in Amalfi and Fabriano, which resulted in a new European technology of paper production that involved the use of screw-press machines and gelatine sizing. Soon after that, paper production commenced in other countries. A paper mill was operating in Troyes, France, in 1348. By 1390 there was a paper mill on the outskirts of Nuremberg, Germany. Around 1400 the first paper mill was operating in the southern Netherlands. By 1432 Switzerland was producing paper, by 1491 Poland was doing the same, and England followed in 1495. Paper was produced in Russia by the year 1576, and in the USA by 1690. [14, 18]

When paper appeared in Europe in the twelfth century, parchment and vellum were still the most commonly used writing materials. They were valuable and reliable materials used as information carriers. It took paper several centuries to gain the people’s trust. For example, the first printed books in Europe, Gutenberg’s Bible, were printed between 1452 and 1455 on both vellum (45 copies) and paper (135 copies). [15]

The European technique of paper-making differed from the techniques used in China, Japan and the Arab world. Instead of the wind-up screens used in Asia, European paper-makers used moulds with copper or brass wires woven together with gaps in between. Because these wires were fastened to the mould, it was not possible to roll them in order to detach the sheet of paper. In Europe woollen felts were used to transfer the paper from the mould and to create stacks of alternating sheets of paper and felts. Such stacks were pressed in screw-press machines in order to get rid of excess water, then dried by being suspended. European paper-makers, like their

Arab counterparts, used water power. Water mills were used to pulp the raw material, which consisted of linen rags and hemp. In addition to this mechanical pulping, rotting raw material was used during the pulping process. However, this process took approximately fourteen days, so it was time-consuming.

Considerable progress in pulping was made in the province of Zeeland in the northern Netherlands, where wind mills were used for pulping. In the 1660s or early 1670s the Hollander beating machine was invented in the Netherlands. Instead of wooden beats, the Hollander Beater used steel blades that cut the raw material, which resulted in a faster pulping process, which did not require fermentation first. As a result, paper-making became cheaper and faster and the Netherlands soon began exporting paper. [4, 14]

A growing demand for paper and the scarcity of raw materials (until the second half of the eighteenth century, the main ingredient was rags) led to new breakthroughs in paper production. New raw material for paper was researched by people such as French physicist and naturalist René Antonie Ferchault de Réaumur, German clergyman Christian Schäffer and German inventor Friedrich Gottlob Keller.

In 1719 de Réaumur presented to the French Academy of Science a tractate in which he noted that wasps and hornets produced thin and delicate paper from which they built their nests. Wood fibres were the source material for that paper. De Réaumur suggested that if wasps and hornets could produce a paper from wood, humankind should also be able to do so. Schäffer, who experimented with different source materials for paper production, ranging from seeds of poplar trees and tulip leaves to cotton grass and potatoes, also paid attention to wasps' nests. Schäffer concluded in his books (1765-1772) that paper can be made out of any plant, and that the different characteristics of plant structure would result in different paper qualities. [15] In 1840 Keller managed to obtain pulp from mechanically grinded wood. [14] After that, and following a few more improvements, wood became the main source of raw material for paper pulp, resulting in low-cost paper-making on a large scale.

In 1799 Frenchman Louis-Nicolas Robert patented a paper-making machine that produced continuous strips of paper. [4] Robert's machine consisted of a continuous perforated sieve, driven and supported by two rollers. The mechanism was installed over an oval vat. By turning the crank, the sieve was moved at a speed of 5m/min, and the use of vanes allowed the fibre stock to be put on a belt (see Fig. 2.15). Then water was drained through the fibres and the small holes in the belt. Sheets of moist fibres created in this way were passed over a felt-covered roller, then dried. The efficiency of Robert's machine was equal to reaping paper from five vats. Improvements to Robert's machine were funded by Henry and Sealy Fourdrinier and developed by Bryan Donkin, who in 1804 built the first practical paper machine, which was in operation at Two Waters Mill, Hertz, England. Since that time, the Fourdrinier machine has become the basis for many modern paper machines (see Fig. 2.16). [14, 18]

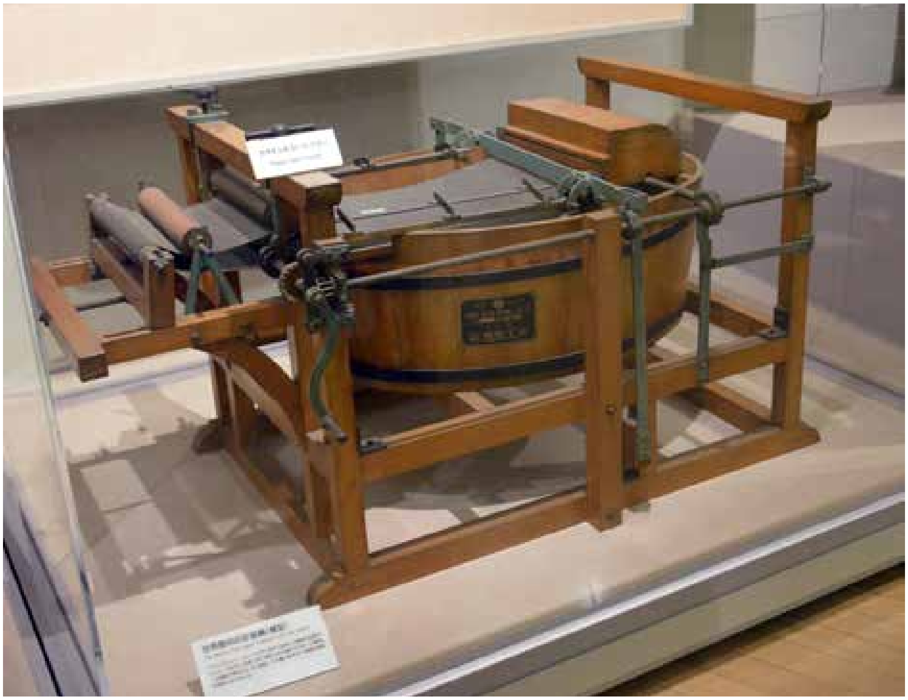

FIGURE 2.15 Model of Louis-Nicolas Robert's paper machine

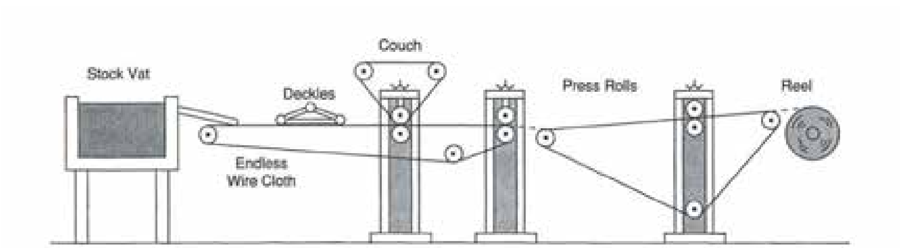

FIGURE 2.16 Diagram of Bryan Donkin's paper machine, 1804

A parallel invention to Robert's machine was a cylinder machine constructed by John Dickinson in 1809. In 1817 Dickinson created a machine with two cylinders, which produced cardboard made of two layers that were combined by wet press. In the same year Dickinson first mentioned a cylinder machine with steam-heated drying cylinders. [4, 14]

In 1881 the American company Thomson & Norris produced the first single-wall corrugated board. [14]

The inventions of the eighteenth and nineteenth centuries concerning raw materials and the production of paper and cardboard resulted in a revolution in the paper industry, which in turn led to mass and cost-effective production of paper products, and further development of the industry. And most importantly, they made paper a widely available material.

Further developments in the twentieth and twenty-first centuries involved chemicals being used in the pulping process and the invention of modern automated machines. In 2010 the German company Voith built the biggest paper machine in the world. It is 600m long and produces paper in rolls that are 11.8m wide at a speed of 1,700m/min, with a maximum efficiency of 4,537 t/24h. Currently there are machines that produce paper rolls with a width of 12.5m at a speed of 2,000m/min, which is four hundred times faster than the first paper machine invented by Louis-Nicolas Robert see Fig. 2.17). [14]

FIGURE 2.17 Modern paper machine, Arctic Paper, Kostrzyn upon Odra, Poland, 2011

Now, in the early twenty-first century, the golden era of paper-making may be about to end. According to statistics provided by CEPI (the Confederation of European Paper Industries), Europe's paper production capacity decreased by 12 percent in the years 2005-2013. Pulp mass production decreased by 10 percent and the production of paper and cardboard by 7%. [19] Due to the advent of modern media such as tablets, computers and other digital file readers, there is less and less need for printing paper. However, the demand for packaging materials is increasing. Paper manufacturers are looking for new business avenues that can offset the reduced demand for traditional paper. One of these new business avenues is the production of new types of paper and cardboard packaging elements such as honeycomb panels, paper tubes, corrugated cardboard and cardboard L- and C-shapes.

§ 2.4 The production of paper

Paper is a material of organic origin, the most popular raw materials from which paper is made are deciduous and coniferous trees. However, paper can also be made out of other plants, such as straw, hemp, cotton, bamboo, cane and other cellulose-containing materials. Moreover, using recycled paper as a source material is more and more popular.

Paper production is divided into two phases. First isthe preparation of paper pulp, second is processing the pulp in paper mills to form paper sheets (see Fig 2.18).

Pulp consists of small, elongated plant cells that form a compact tissue made of the raw material. The pulp used in paper production must be ground into individual fibres. Sheets of paper are produced by using the fibres' ability to form bonds with each other during a process of irrigation, heating and pressing.

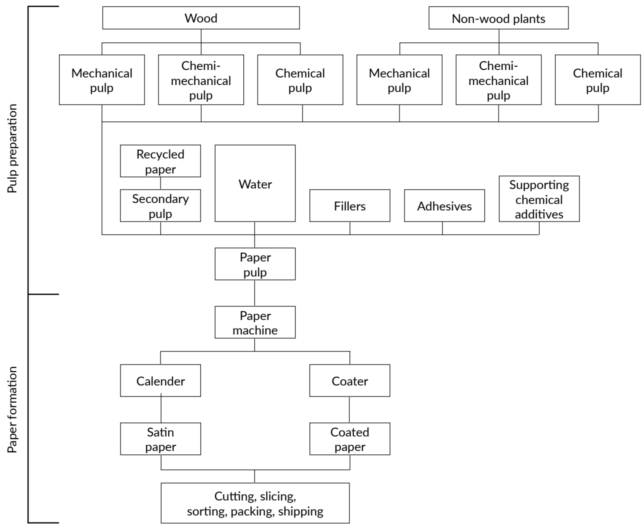

FIGURE 2.18 General scheme of paper production

Figure 2.18 presents the paper production process, including the preparation of the pulp with additives and fillers, and the formation of paper in the paper machine. Calendering is a process during which paper is run through rollers. It derives its smoothness and glossy properties from the application of pressure and heat. Coating is a process that can be applied in the paper machine or elsewhere. Special coatings which are applied to the outer layer of the paper may, for instance, create barrier properties for special paper such as the impregnated or paraffined cardboard used in the building industry.

§ 2.4.1 Raw material for paper production

The main raw materials used for paper production are coniferous wood (spruce, pine, fir, larch, western hemlock and Douglas fir) and deciduous wood (birch, poplar, aspen, beech, alder, acacia, oak, hornbeam and eucalyptus). [14] Recycled paper products, too, are becoming increasingly popular as a source of pulp. In 2014, the recycling rate reached 71% in CEPI countries (Austria, Belgium, Czech Republic, Finland, France, Germany, Hungary, Italy, the Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, the United Kingdom). The recycling rate is the percentage of paper that is used for recycling, compared to production of paper and board. [19] Cellulose fibres can be also obtained from fast-growing trees such as poplar, from straw or from plants with a fibrous structure, such as reed and hemp.

§ 2.4.2 Wood structure

Paper is produced out of cells that form xylem tissue (wood), a part of a tree situated between the pith and the bark. Pith functions as a physiological part of the tree, it stores and transports nutrients through the tree. Xylem arises from vascular cambium.

Bark, being the external protective layer for the tree system, consists of outer bark (which is comprised of dead rhytidome tissue), which serves as a protector from mechanical impacts, pathogens and the atmosphere, and inner bark (which is comprised of living phloem tissue), whose role is to conduct sap or nutrients (see Fig.2.19). Bark is not a desirable ingredient of paper, as it only features about 14-45% cellulose, 15-40% lignin and a high percentage of contaminants, which decrease the quality of paper. [4]

A thin layer of creative cells lies between the bark and xylem tissue. This is vascular cambium, which is responsible for the growth of the tree. Xylem tissue consists of two things: sapwood (which is situated on the outer side of the trunk and transmits saps such as water and soil nutrients up to the leaves) and heartwood (which is situated on the inside of the trunk and gives the tree enough strength to support its crown and keep the tree in place in strong winds).

Wood rays extend vertically through the tree, perpendicular to the growth rings. Wood rays store and move food laterally from the phloem to the living cells of the cambium and sapwood.

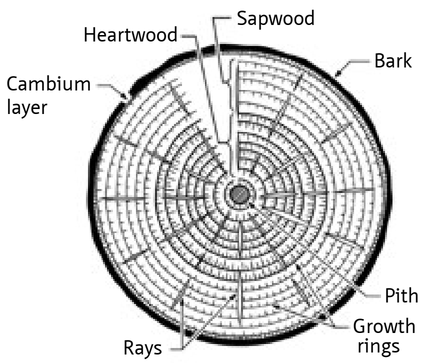

FIGURE 2.19 Transverse section of trunk

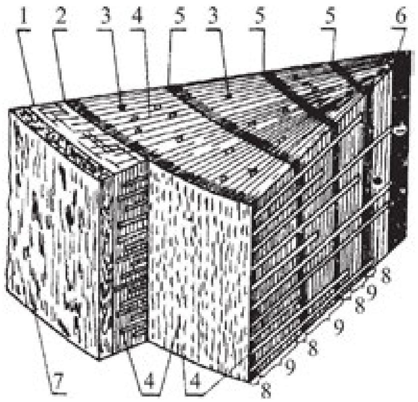

FIGURE 2.20 Diagram of the 4-year-old pine trunk: 1 - phloem, 2 - cambium, 3 - resin canals, 4 - rays, 5 - growth ring, 6 - pith, 7 - bark, 8 - latewood, 9 - earlywood

Wood consists of many cells which are different in size and shapes, depending on their function:

- Tracheids – these occur only in softwood, of which they are a dominant element (over 90%). Tracheids are elongated and slender cells serving as a conductive and mechanical support.
- Libriform fibres – a basic component of hardwood that serves as a reinforcing tissue. They have the shape of long, pointed cells.
- Vessel elements – these occur only in hardwood as a conductive feature; their cells are varied and specific to different species of trees.
- Parenchyma cells – these occur in both hardwood and softwood; they are part of the tissue, forming medullary rays and resin-lining channels. Parenchyma cells are an undesirable component of pulp.

Tracheids and vessels are called tracheary elements.

Both coniferous and deciduous trees are used for paper production. However, their structures differ, which greatly affects the properties of the resulting paper.

Conifers, also known as softwoods, have a simpler anatomy, which consists of 90-95% longitudinal fibre tracheid, 5-10 % ray cells and 0.5-1.0% resin cells.

Hardwoods have more complex structures. The cellular composition of hardwood is 36-70% libriform fibres, 20-55% vessel elements, 6-20 % ray cells and about 2% parenchyma cells. [4]

§ 2.4.3 Wood fibre structure

Wood fibres are elongated wood cells that provide mechanical strength and water transport through openings called pits (see Fig. 2.22). The fibres have hollow centres (lumens) and are heterogeneous in nature.

The most distinctive elements that constitute the xylem cells are the long tracheary elements that transport water. Two types of tracheary elements can be distinguished: tracheids (in softwood) and vessels (in hardwood) (see Fig. 2.21).

In softwood tracheid cells constitute 90-95% of the wood. In hardwood vessels and libriform fibres constitute approximately 65-70% of the volume of the xylem.

FIGURE 2.21 Hierarchical structure from the tree to the cellulose molecule

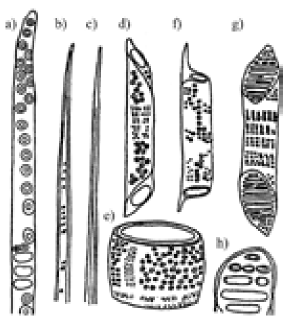

FIGURE 2.22 soft and hardwood cells: **a)** pine vessel, **b)** libriform fibers of apple-tree, **c)** libriform fibers of oak **d), e)** vessel element of oak, **f)** vessel element of apple-tree, **g)** vessel element of alder, **h)** front wall of vessel

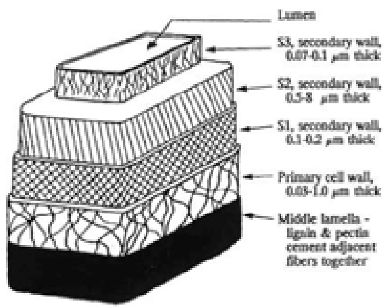

FIGURE 2.23 A mature softwood fiber

The quality of paper depends on the length and slenderness of the fibres used, as well as their resilience. The longer, slimmer and more flexible the fibres, the stronger the paper made out of them. In order to describe the slenderness of fibres, a ratio of length to width is used. The stiffness of the fibres is described by a stiffness index, which is the ratio of twice the thickness of the cell wall to the diameter of the lumen cells.

THE TYPE AND SPECIES OF TREE	DIMENSION OF THE CELLS			SLENDERNESS RATIO	STIFFNESS INDEX
	length (mm)	Width (µm)	Thickness of the wall (µm)		
Softwood (coniferous)					
pine	3,3	37	4,5	90	0,3
spruce	3,2	32	4	100	0,3
fir	3,1	36	4	90	0,3
Hardwood (deciduous)					
birch-tree	1,1	22	4,5	50	0,7
poplar	1,2	24	4	50	0,5
beech	1,0	20	5,5	50	1,2
oak	0,8	18	6	45	2,0

TABLE 2.1 Dimensions of wood fibers

As Table 2.1 shows, the cells of coniferous trees are longer, more slender and more flexible (less stiff) than the cells of deciduous trees. Therefore, they are more likely to create a strong bond during the paper-making process, which makes them more suited to the production of strong paper for packaging purposes, while the cells of deciduous trees are more suited to the creation of printing paper.

The shape of a single wood fibre causes anisotropy (see Fig. 2.22). Each cell is much stronger in its longitudinal direction than in its transverse one. Additionally, the composition of cells built out of smaller fibrils makes them much stiffer in their longitudinal direction.

Wood fibre walls have a layered structure. Each of these layers is characterised by a specific arrangement of fibrils. [24] There is a clear distinction between the primary and secondary walls (see Figs. 2.23 – 2.25). The secondary wall is divided into three different layers: the outer secondary layer (S1), the middle secondary layer (S2) and the inner secondary layer (S3).

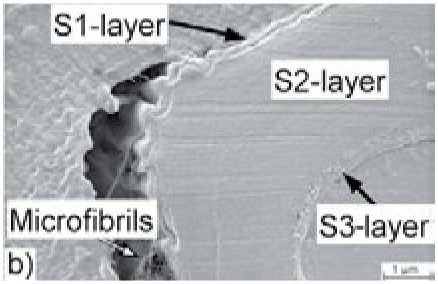

FIGURE 2.24 Transverse section through the cell walls of wood fiber

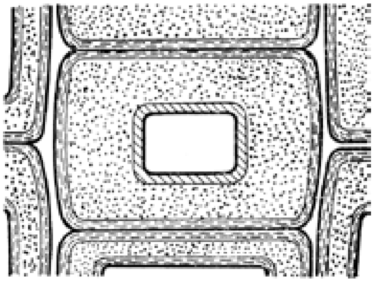

FIGURE 2.25 Structure of wood pulp fiber – microtomed cross section

The S2 layer of the secondary wall of the wood fibre is the thickest layer and dominates the overall properties of the fibre. The S2 layer has a chiral or helical structure made of micro-fibrils. The cellulose micro-fibrils are oriented at 10-30 degrees from the main longitudinal axis of the fibre. As a result, the fibre has great tensile strength in this direction. [2]

The elastic modulus is controlled by the amount of cellulose in the fibres as well as the micro-fibril angle. The higher the amount of cellulose and the lower the MFA (micro-fibril angle), the higher the elastic modulus.

The walls of plant fibres are composed of cellulose, hemi-cellulose, lignin, extractives (pectin) and minerals. The layers are complex biocomposites made of cellulose fibril aggregates embedded in a matrix of hemi-cellulose and lignin. The composition of the walls of fibres can vary depending on the species and type of wood – i.e., whether it is softwood or hardwood (see Table 2.2).

TYPE OF WOOD	CELLULOSE	HEMICELLULOSE	LIGNIN	EXTRACTIVES	MINERALS
	%				
Softwood	42	27	28	1 – 5	0,5 – 1
Hardwood	44	33	20 – 22	2 – 4	0,5 – 1

TABLE 2.2 Chemical composition of hard- and softwood

§ 2.4.4 Physical properties of wood

The most important physical properties of wood as a source material for paper production are density (the ratio of weight to volume) and moisture (the percentage of water in tested material). The moisture content of wood processed in paper mills is about 30%. [23] Another important characteristic property of wood is its absorbability, which is its susceptibility to absorption of aqueous solutions.

Hardwood is denser than softwood, and thus provides more pulp from the same volume of raw material. Hardwood also has higher absorbability, which positively affects the pulp-producing process.

§ 2.4.5 Chemical composition of wood

Wood is composed mainly of organic substances. The most important substances for the paper industry are cellulose, hemicellulose and lignin. Cellulose is the most valuable component of the wood used in paper manufacturing. Together with hemi-cellulose it forms the backbone of the cell membranes of wood. Depending on what pulping process is used, different amounts of hemi-cellulose and lignins may be present between the cellulose micro-fibrils.

An important difference between the structure of hardwood and the structure of softwood is its chemical composition. Softwood has a higher lignin content than hardwood. Cellulose content in both conifers and deciduous trees is approximately 40 percent.

§ 2.4.6 Cellulose

Cellulose is the main structural fibre of the plant kingdom. In the words of Klemm et al. (2005), *cellulose is the most common organic polymer and is considered as an almost inexhaustible source of raw material for the increasing demand for environmentally friendly and biocompatible products*. [25] The global production and decomposition of cellulose is ~1.5×10^{12} tonnes per year, which is comparable to the planetary reserves of the main fossil and mineral sources. [26]

Cellulose is the most valuable material and main component of the plants used for paper production. The extraction of cellulose in its fibrous character is the basic process of pulp production.

Cellulose is a natural multi-molecular compound, belonging to the polysaccharide group. The macromolecule has a chain structure in which the so-called glucose residues are linked by β-glycosides bonds. Together with hemi-cellulose it builds the skeleton of the cells. Cellulose is a colourless, insoluble fibrous substance with a density of 1.58 g/cm^3. [14] A single cellulose fibre has an elastic modulus of about 130 GP, and its tensile strength is close to 1 GPa. [10]

The subsequent (from smallest to biggest) cellulosic components of cellulose are:

- the cellulose molecule with the dimensions of 0.853 nm width, 0.395 nm thick, 2μ length (see Fig. 2.26),
- the elementary fibril,
- the microfibril (see Fig. 2.27),
- the macrofibril and the cellulose fibers (see Fig.2.28).

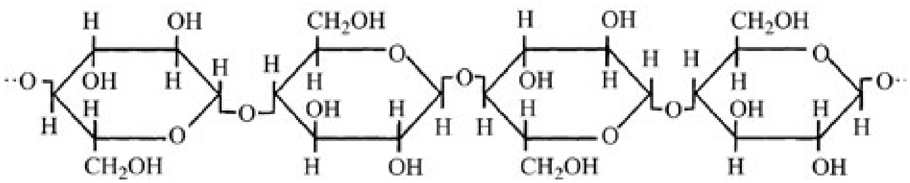

FIGURE 2.26 Cellulose molecule

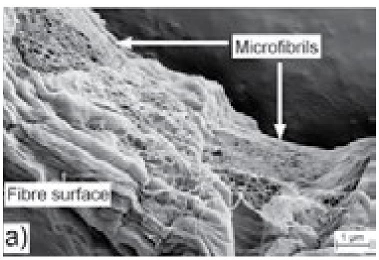

FIGURE 2.27 Cellulose fiber and microfibrils

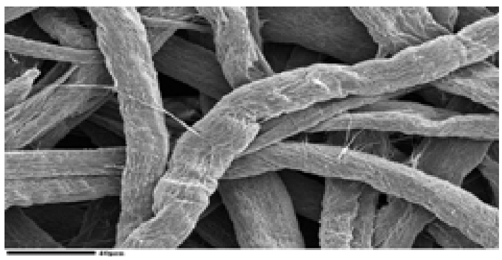

FIGURE 2.28 Cellulose fiber

The elementary fibrils are universal structural units of natural cellulose, as the same biological structure was encountered in cotton, ramie, jute and wood fibres. The bundling of elementary fibrils into micro-fibrils is caused by purely physically conditioned coalescence as a mechanism of reducing the free energy of the surface. [24] Aggregations of 200- 400 micro-fibrils create macro-fibrils.

Cellulose is produced when D-glucose polycondensates. The by-product this reaction is water. The synthetisation of the multi-molecular compound is called polymerisation and the product is a multi-particulate compound polycondensation homopolymer: polysaccharide.

Cellulose is a long linear homopolymer composed of 3,000-14,000 β-D glucopyranose ($C_6H_{12}O_6 - H_2O$) units linked by (1→4) glycosidic bonds. [10, 14]

The number of glucopyranose units describes the length of the cellulose chain. This is called the *degree of polymerisation* (DP).

The DP for cellulose molecule in wood is approximately 3,000-6,000. There are crystalline areas in cellulose molecules, which cause the cellulose to be insoluble in water.

The polymerisation structure of cellulose can be changed by chemical agents (hydrolysis, oxidation), physical conditions (temperature, light, mechanical grinding) and biochemical factors (enzymes produced by fungi and bacteria). During the pulping, the DP number of cellulose fibres decreases to 700-3,000.

Bonds are easily formed between the macromolecules of cellulose hydrogen. Such bonds bind together macromolecules, which results in the formation of filamentous fibrils. Intertwined fibrils build a skeleton of cells. Hydrogen bonds are also formed between the cellulose fibres. This phenomenon is crucial in the process of paper-making. Due to the organised structure of cellulose chains and the type of bonds between fibrils, cellulose is resistant to many chemical agents, but at the same time it is sensitive to hydrolytic degradation (decomposition under the influence of water) in an acidic medium.

§ 2.4.7 Hemicellulose

Hemi-cellulose is a polymer of different types of saccharides, not just of glucose residues, like cellulose. Its degree of polymerisation (DP) is much lower (less than 300), which results in weaker and degradable bonds. In the process of creating pulp, most of hemi-cellulose is degraded, while the remaining molecules have a positive impact on the process of creating paper. They are the natural glue that facilitates the bonding of fibres. Hemi-cellulose has a much lower elastic modulus than cellulose. As a result, the elastic modulus of paper pulp fibre can be lower than the elastic modulus of cellulose. [2]

§ 2.4.8 Lignin

Lignin is a natural organic multi-particulate compound with the spatial structure of polymer. Lignin can be found both between wood cells and within cell walls. It possesses mechanical properties that make the cell rigid and provide it with a stable structure. Lignin is an undesirable ingredient in the process of paper-making. Its presence causes hardening and the deterioration of the mechanical properties of paper. Lignin is removed in the pulping process.

§ 2.4.9 Other components of wood

Extractives (resin, waxes, fats, essential oils, dyes, etc.) account for 5% of wood by weight. These substances may affect the properties of wood pulp. They affect resistance to micro-organisms, but they have a corrosive effect on the production apparatus. Minerals are present in minimal quantities.

§ 2.5 Paper-production process

Paper production consists of several stages. Raw material in the form of wood is first prepared to be cut into smaller pieces and decorticated. Then wood chips are sent to a digester, where they are defibrated. The next stage is to screen for and reject particles bigger than desirable. This process is followed by pulp washing, bleaching and refining. Finally the pulp is transported to the paper machine, which produces paper in the form of a sheet. The final product can be refined by superficial additives in order to ensure that it maintains its desired properties, such as water resistance, incombustibility, etc. The steps making up the process are described below in order to provide a better understanding of the process of paper-making (see Fig. 2.29).

1. Preparing the wood – sawmill
   a. Slasher deck
   b. Barker

2. Storage – wood in the form of logs or chips is stored in warehouses or outdoors, in the open air. This can result in the decay of the wood due to atmospheric conditions, fungi, bacteria and insects. Coniferous wood is more resistant to decay than deciduous wood.

3. Chipping in the wood-chipper. The next step in the preparation of pulp is chipping. Wood logs are cut into small chips about 10-30mm long, 10-20mm wide and 2-8mm thick. The chipped wood is then treated with pulping chemicals. Chips that are oversized are removed and sent to the chipper again. Chips are assessed for their size. For the Kraft cooking process, chip thickness is of primary concern.

4. Digester – this is a pressure vessel in which wooden chips are cooked in order to soften and pulp them. Chemical, mechanical and chemi-mechanical pulping processes are carried out in the digester.

5. Pulp screening – this is the process in which pulp is separated from knots, dirt and other debris. Rejected particles are removed by screens and are sent to the digester again or removed.

6. Pulp washing – this is a process in which pulp is washed in water to remove chemicals and lignin. Certain chemicals, like black water, are recovered, filtrated and used again in the pulping process.

7. Pulp bleaching – bleaching involves treating wood pulp with chemical agents in order to brighten it. Pulp is chemically bleached by lignin removal. The removal of lignin

results in better inter-fibre bonding, but at the same time, the strong chemicals used for bleaching can weaken cellulose fibres by decreasing the length of their molecules. Mechanical pulp can also be bleached, by chemically altering the lignin molecules that absorb light. [4] Lignin removal is accompanied by a significant loss of pulp yields and also has a negative effect on the strength of the individual fibres. However, the strength of inter-fibre bonding increases after bleaching.

8 Pulp refining – this is a mechanical treatment given to pulp fibres in order to bring out their optimal properties. Refining increases the strength of inter-fibre bonds by increasing the fibre surface area. It also improves the formation of sheets on paper machines. The refining process increases the flexibility of the fibres and results in the creation of denser paper. Pulp refining involves fibre brushing (roughening the surface of the fibres in order to improve inter-fibre bonds), fibre cutting, water drainage, fibrillation (mechanical dishevelling of the fibres, e.g. by breaking the primary fibre walls). The Hollander Beater mentioned earlier is also a pulp-refining machine.

9 Paper machine – this is a device for continuously forming, dewatering, pressing and drying a web of paper fibres. Previously prepared stock consists of chemical, chemi-mechanical, mechanical or recycled pulp and a mixture of all these things is sent to the paper machine. The quality of the paper is determined by the quality of the prepared pulp. The pulp is pumped into the headbox of the paper machine and is mixed with water and some other chemical additives. Such an aqueous slurry consists of 99% liquids and 1% fibres when producing printing paper, and of 99.7% liquids and 0.3% fibres when producing strong packaging paper. The greater the percentage of liquids in the slurry, the better and more equal the spread of the fibres, and thus the mechanical properties of the end product. Next the slurry is spread from the headbox through the slice on the wire. This process, which is called the forming, is the most important part of paper-making, and at the same time the most difficult one. The formation process takes place in a former on the flat wire, also known as a Fourdrinier (with a maximum speed of 800m/min), cylindrical sieve (with a maximum speed of 400 m/min) or twin wire machine. The cylindrical sieve, although it is slower, is suitable for the production of multi-layered cardboard, decorative paper, banknotes, securities and other long-fibre papers. [14] After the forming, the paper web is drained, pressed and dried.

10 Paper conversion – the last process in a paper-making machine, in which paper is coated, calendared or treated with additives designed to give it certain special features. The process of paper-coating can be compared to the plastering of a wall before painting. The holes in the wall (porous in the cellulose fibre network) are filled with a paste that is sheared onto the surface of the paper. [2]

11 Rolls or sheets of paper are now shipped to the customer.

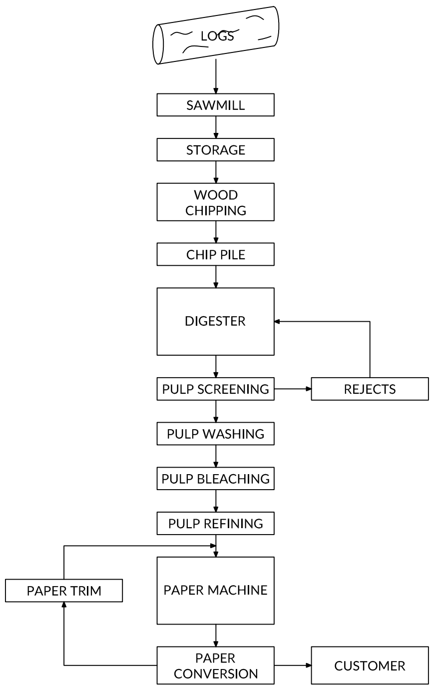

FIGURE 2.29 Paper production scheme

§ 2.5.1 Pulp production methods

Pulp is obtained by means of mechanical, chemi-mechanical, semi-chemical and chemical processes. Pulp consists of cellulose fibres, hemi-cellulose fibres and lignin, derived from vegetable materials (wood, stalks, straw, hemp) or from recycled paper products. During the pulping process the outermost layers of the wood fibres, which hold together the wood, are partly or completely removed. As a result, the fibres disintegrate in the pulping process. [2]

Pulp is also the source material for products other than paper, such as fibreboard and MDF (medium-density fibreboard), as well as a component of certain plastics and composites. The raw materials that are suitable for paper production are cellulose and hemi-cellulose. Lignin, on the other hand, is an undesirable part of the pulp, since it makes paper stiff and brittle. The following methods can be used to remove lignin from the pulp or reduce its impact on the properties of paper:

- **The mechanical method** involves refining, crushing and separating the wood fibres in order to obtain wood pulp. Thermal treatments are also provided during the refining process to soften the lignin. The pulp thus obtained is called thermo-mechanical pulp (TMP). The product resulting from the mechanical treatment of groundwood is used in the manufacture of paper and fibreboard. The mechanical method is the most efficient way to produce pulp (95-97% yield). Pulp resulting from a mechanical process contains lignin. In order to get rid of this lignin, a chemical process of discolouring lignin polymers is used (so-called whitening). This process is reversible over time, which results in the yellowing of printed matters produced from mechanical pulp. Due to its lignin content, pulp produced by the mechanical method is only suitable for newsprint (non-archival paper); it is not appropriate for the manufacture of durable packaging paper, so it is not suitable for use as an architectural material, either. Currently mechanical pulp accounts for 20 percent of all virgin fibre material. [11, 28]

- **The chemo-mechanical method** or chemo-thermo-mechanical pulp (TCMP) consists of two stages. First a chemical solution is added to wood chips or logs in order to soften the wood. Then the logs are pulped by means of a stone. The original lignin structure and content are preserved, but the extractives and some small amount of hemi-cellulose are lost. The pre-treatments used in the chemo-mechanical method are hot sulphite or cold soda. This method can be applied to hardwood to ensure high-quality pulp. The yield of the chemo-mechanical method is 85-95 percent. This pulp has properties that make it well suited to the manufacture of tissue paper.

- **The semi-chemical process** is a high-yield chemical process with yields of 60-80 percent. It involves two steps. The first step is to add a chemical treatment to the wood, followed by mechanical refining. In this method both lignin and hemi-cellulose are partly removed. The first step of the semi-chemical method is similar to other chemical methods, although it involves lower temperatures, shorter cooking time and less chemicals. The semi-chemical method is used to create corrugated cardboard with flutings.

- **The chemical method** (which involves sulphate, sulphite and soda) consists in dissolving and removing most of the lignin from the fibrous mass structure. This process results in a cellulosic pulp. Using sulphite results in a medium-strength pulp with soft, flexible fibres, and in yields between 40-52 percent with minimal lignin content in the pulp.

- **The sulphate method** is called **Kraft**, a name derived from the German word Kraft, which means 'strength' or 'power'. This method yields the strongest paper with the smallest amount of lignin, about 3-5 percent. [4] For this reason, the sulphate method is the most appropriate for strong packaging paper which can be applied in architecture.

§ 2.5.2 Kraft pulping method

Kraft pulping is a fully chemical method that involves sodium hydroxide (NaOH) and sodium sulphide (Na_2S). Wood chips are cooked in a digester at a temperature of 160-180°C and a pressure of about 800 kPa for half an hour to three hours. During the cooking process, lignin is softened and the cellulose fibres are dissolved. Kraft pulp has a low lignin content, approximately 15% hemi-cellulose and 85% cellulose. [10]

All kinds of wood can be pulped with the Kraft method, and the presence of bark does not constitute a problem. The Kraft method has an efficient energy and chemical recovery cycle. The downsides of the Kraft method are the relatively low yield and the very smelly emissions caused by the sulphate used during the pulping process.

The yield of the Kraft method depends on whether the end product is white (bleached) or brown paper. For brown paper the yield is about 65-70%, and 43-45% after the bleaching. [4] Kraft is the most expensive method, but also produces the strongest end product.

Currently, the most popular method for producing paper pulp is the sulphate (Kraft) method. Approximately 80% of global pulp production involves the use of the sulphate method. The remaining 20% is produced by means of the mechanical and semi-chemical methods. [14] This is due to the strength properties of the mass obtained by these methods (compared to the sulphate method), the fact that any type of wood can be used, and the development of production systems that minimise the discharge into the drain.

Before being formed into paper, pulp may be subjected to chemical processes and whitening treatments, and it is the additives that cause the release of the cellulose.

The Kraft pulping method is the preferred method to produce strong paper that may be used as an element of architectural structures. Due to the single-fibre properties, the best paper for architectural use is softwood Kraft paper.

§ 2.5.3 The properties of pulp

The properties of pulp are described in the following terms:

- The degree of digestion, which is the process of delignification defining lignin content by weight after the chemical digestion process. The lower the lignin content, the more flexible and durable the end product. The pulp's degree of digestion is determined by its kappa number, which is determined by performing an analysis of the ratio of delignification agent (e.g. potassium permanganate) to the amount of pulp. There are three types of pulp: hard with a high lignin content, normal and soft with a low or non-existent lignin content, and bleached pulp, which is completely free of lignin.
- Pulp viscosity, which is an average cellulose chain length described by number of polymerisation DP. Higher viscosity indicates stronger pulp and paper.
- Grindability, characterised by the pulp's susceptibility to mechanical grinding.
- Moisture content, which is determined by drying some pulp in an oven and compering its weight to that of undried specimen.
- Strength properties, which are the most important properties from an architectural point of view. The strength properties of tested specimens are divided into tensile strength (indices: self-tearing and extensibility), puncturing (burst ratio), tear (tearing resistance index), bending (index number of double bends) and hardness, rigidity, torsional rigidity and resistance to breaking.
- Fibre length – the standard fibre length measured in the pulp
- Colour of the pulp – whiteness indicator
- Pulp purity – the basis for the categorisation of pulp, used to determine the extent to which the pulp is polluted by other molecules, e.g. bark, coal, carbon, etc.
- Special features of the pulp required for the production of paper for special uses, e.g. blotting paper (absorption), electric paper, writing paper (high opacity), etc.

§ 2.5.4 Paper making process

The paper-making process consists of four stages, which in general can be described as:

1. Forming and draining
2. Pressing
3. Drying
4. Callendaring

A slurry consisting of 99%-99.7% water and chemical additives and 0.3-1% pulp fibre is poured onto a travelling mesh or rotating cylinder which is used for heavyweight boards. [4, 28] The greater the amount poured onto the machine, the thicker the paper. The fibres are aligned mostly in the direction of travel and interlace in order to improve the formation of the sheets of paper. During this process, cellulose fibres create hydrogen bonds between each other. The same principle is used for both machine- and hand-made paper.

The next step is removing the remaining water from the fibre web formed in the previous step. This is done by means of vacuum boxes and pressing sections (after which the paper will have a 65% moisture content) and later by drying parts of the paper machine by means of steam. At the end of this process, the moisture content of the paper is equal to 3-6% (see Fig. 3.30).

Paper products can also be converted into special types of paper, or alternatively, their properties, such as smoothness and gloss, can be improved by coating, calendering, etc. This is done when the paper has a moisture content of 3-6%. If a special type of paper is to be manufactured, the next step of the finishing or conversion process starts here. However, for regular paper this is the final step, and so the paper is wound on a roll in the desired dimensions, sorted or packed and shipped to customers.

During the paper-making process, after draining the pulp, the planar fibre network is held together by surface tension forces, which gives paper its viscoelastic character. Afterwards, the paper web is pressed by rollers and heated by hot cylinders to remove the remaining water. In this process the water menisci between the fibres shrink and pull the fibres against one another so that hydrogen bonds are created at the molecular contact between the adjacent fibres. These bonds between the fibres are the factor determining all the mechanical properties of paper. In wet conditions the helix of the fibre wall is swollen, more in the transverse direction than in the axial direction. When paper is dried, the anisotropic shrinkage leads to internal stresses in the fibre network. This is caused by the axial stiffness of the fibres, which resist transverse shrinkage. Paper that dries under tension has a larger elastic modulus than paper that was free while drying. The tension maintained in the paper machine in the machine direction (MD) prevents shrinkage during drying. Like the orientation of the fibres, this causes paper to have better mechanical properties in machine direction (MD) than in cross-machine direction (CD). [2]

Chemical and energy recovery make up an essential part of paper process. Half of the raw material provided by the wood is utilised as chemical pulp fibre, while the other half is utilised as fuel for electricity and heat generation. The chemical pulping process generates more energy than it uses. Extra energy produced by paper mills can be sold and transmited to the electricity grid. [28]

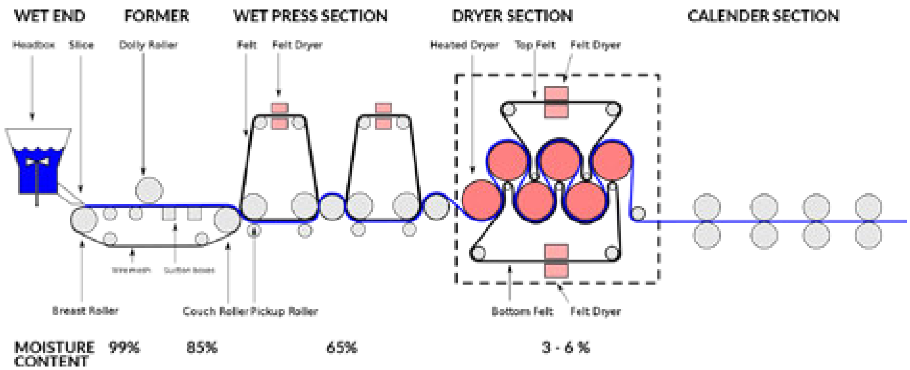

FIGURE 2.30 Diagram of Fourdrinier (flat sieve) paper machine

§ 2.6 The properties of paper

The basic properties of paper are characterised by weight and density, moisture content, physical characteristics, strength properties, optical properties and other criteria.

This section will discuss those properties of paper that have a significant impact on the extent to which paper can be used as an architectural and structural material. This means that optical properties, such as brightness, transparency, colour, smoothness, glossy finish, etc. will not be discussed here, as they are irrelevant to architects.

§ 2.6.1 The chemical and physical structure of paper

As paper is made out of cellulose fibres, it is possible to distinguish its properties on a micro- and macro-structure level.

The micro-structure of paper is based on fibrils. Fibrils are the smallest parts forming paper. Fibrils are composed of cellulose chains with a maximum length of 5µm. [22] Bundles of extended-chain molecules are arranged into monodisperse fibrils which form fibril aggregates. Bigger fibril aggregates form lamellae or cell walls. Thanks to their highly crystalline fibrous structure and strong network of hydrogen bonds, cellulose fibrils are insoluble in water and have great mechanical strength.

The mechanical properties of paper can vary, even between sheets of paper made out of the same pulp. The mechanical properties of fibres and bonds are influenced by the paper-making process. Fibres in sheets of paper are oriented randomly, so each production series may differ. The more bonds are created between cellulose fibres, the stronger the paper. The points at which the fibres overlap create bonds between fibres. The mechanical properties of paper are governed by fibres and the bonds between them.

§ 2.6.2 The structural characteristics of paper

Paper's web-like structure, consisting of wooden fibres, can be visualised by comparing it to cooked spaghetti that is served on a plate (see Fig.2.31). This plate of spaghetti resembles paper after it has been drained and allowed to dry. However, the significant difference between the simplified example of spaghetti and paper lies in the helical internal structure of wood fibres. [2] During the paper-making process, after draining the pulp, the planar fibre network is held together by surface tension forces, which give paper its viscoelastic character. The length of a single fibre ranges from 1 to 3mm (which is approximately ten times more than the thickness of a typical sheet of paper), and the width and thickness of a single fibre range from 10 to 50 µm. [10] There are ten to forty inter-fibre bonds per fibre in a sheet of paper. The structure of paper is very close to a fully random, uncorrelated planar fibre network. [2] The number of fibres per unit area is described in terms of basis weight or grammage [g/m^2].

The thickness of paper is always specified by the grade of the paper. The thickness of paper can vary depending on the moisture content of the material. Common printing and writing paper is about 0.1mm thick. Cardboard can be 0.3 up to 4mm thick.

Typical apparent density values range from 0.5 to 0.75 g/cm^3. Since cellulose density is 1.5 g/m^3, this means that 50 percent or more of most types of paper is empty space. This space is occupied by air. Apparent density is one of the most important factors affecting the mechanical, physical and electrical properties of paper.

The porosity of paper (whose level is determined by its density) has a significant impact on the other properties of paper. Porosity is the ratio of pore volume to the total volume of a sheet of paper. It is akin to air permeability, which is the property of paper that allows air to flow through a sheet of paper under changing pressure conditions. Air permeability is a structure-related property of paper and is inversely related to its strength properties. It also affects paper's resistance to water and other liquid reagents. [18]

Paper is a non-uniform material, with respect to the direction of the fibres in a sheet of paper. When paper is formed, cellulose fibres are arranged mainly in two directions. Machine direction (MD), which accounts for about 70-80% of the fibres and cross-machine direction (CD), which makes up approximately 20% of fibres. Furthermore, some fibres may be arranged perpendicular to the direction of the sheet of paper, which is called the Z-direction (ZD) (see Fig.2.32). [30]

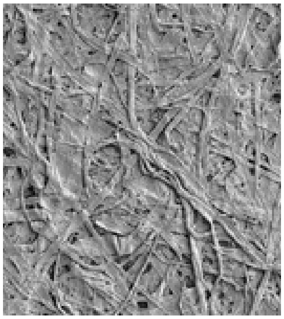

FIGURE 2.31 Magnified wood pulp paper

FIGURE 2.32 Magnified edge of a paper

§ 2.6.3 The mechanical properties of paper

The mechanical properties of paper are determined by the properties of the fibres used in paper-making, the bonding between the fibres and their geometrical disposition. The smallest particle of paper, which is the wood cellulose fibre, has an elastic modulus of around E = 35 GPa, and its ultimate strength is σ = 120 MPa. It is much smaller than pure cellulose molecule fibres, due to the cellulose micro-fibril angle (MFA), which varies by 10-30° from the main longitudinal axis of the fibre. These values are not equal to the values of paper as other factors influence the final mechanical properties of paper. [10] The mechanical properties of fibres depend on the geometry and chemical composition of said fibres. The chemical properties of fibres depend on the raw material (fresh or recycled, hardwood or softwood) and pulping method used (e.g. chemical, mechanical, chemo-mechanical, etc.). As stated before, the Kraft chemical method results in the strongest pulp, i.e. the pulp that is richest in cellulose. In the web-like structure that is paper, single-fibre parameters such as form and surface influence the quality of the bonds between the fibres. These bonds are also affected by the quantity of fibres, fillers and additives. Lastly, the mechanical properties of paper are also determined by the production process (forming, pressing, drying, calendering, etc.). [31] In other words, the properties of paper depend on different factors affecting the material at both the fibre level and the network level.

What this also means is that every piece of paper can vary from another, as paper is a web of randomly oriented fibres. Such differences can be even more significant if the various types of paper are not produced from the same raw material, by means of the same method and in the same paper machine.

In general, paper and cardboard are inhomogeneous, anisotropic, non-linear, visco-elastic-plastic and hygroscopic materials. [31]

During the production processes in the paper machine, about 70-80% of the fibres are oriented in the direction of the machine (‘machine direction’ or ‘MD’), while 20% are oriented perpendicularly (‘cross direction’ or ‘CD’), and 10% are oriented in the direction of the thickness of paper. [32] It is this configuration of the fibres that gives paper its anisotropic characteristics, because MD fibres are stronger than CD fibres. The MC/CD ratio depends on the nature of the fibres and the production process, so it is not possible to set this value as a constant.

Paper is stronger in tension than in compression, as can be seen from the graph presented by Schonwalder. [31] The graph also shows that the tested specimens behaved differently in MD and CD (see Fig. 2.31). Paperboard tested in CD was less stiff, weaker and quicker to deform. As Schonwalder noted, the tested specimen showed a relatively brittle failure, which means that there was no significant plastic deformation before breaking. The very ends of the compression curves show post-peak behaviour, which means that paper loaded with maximum force can still carry some forces, which is important information from a structural safety point of view.

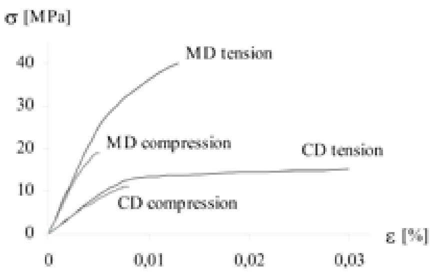

FIGURE 2.33 Typical stress-strain curves of solid board for tension and compression in MD and CD

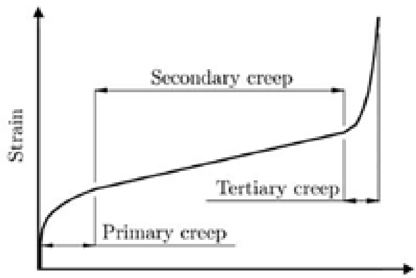

FIGURE 2.34 General shape of the creep curve of paper

The elastic modulus of paper and board ranges between 2 and 20 GPa, and typical value is 5 GPa. The differences in the elastic modulus can be seen in MD, which is 1.5 to 4 times higher than the elastic modulus in CD. The modulus is the same for compression and tension in the respective fibre directions.

The tensile strength is 15-45 MPa, but there are types of paper with a tensile strength of up to 80 MPa. Tensile strength in CD is 0.3-0.5 of the tensile strength in MD.

The compression strength of paper is smaller than its tensile strength. Its compression strength is 0.3 to 0.5 of its tensile strength. Its compression strength in CD is approximately half of its compression strength in MD.

The breaking strain under tension is 1.5-2.5% in MD and 3-4% in CD. The breaking strain under compression is 0.25 of the tensile breaking strength in MD and 0.2 in CD. [31]

The stiffness of paper is two to four times greater in MD than in CD. The bending stiffness depends on the thickness of the paper and its elastic modulus. Failure in bending is caused by fibre buckling at the compression side of the paper sheet. [13]

According to Schonwalder, Poisson's ratio (v), which describes the ratio of lateral strain to axially applied strain under a longitudinal load, is usually vMD = 0.4 and vCD = 0.1

for paper. However, Szewczyk states that Possion's ratio is one of the most difficult to determine for paper, and he assumes that it ranges from 0 to 1. [33]

The share modulus G was estimated by Schonwalder to be one-third of the geometric mean of Young's modulus in MD and CD, $G \approx 1/3(E_{MD}\, E_{CD})^{1/2}$.

In order to compare the mechanical properties of paper with traditional building material their properties are listed in Table 2.3. Steel, concrete and glass are strong and stiff materials, but on the other hand they are heavy. Paper has a weight density comparable to wood. Wood similarly to paper is anisotropic material. Wood is stronger in grain direction while paper in machine direction. The table shows that cardboard fits into the range of building materials however it has very low stiffness. The data presented in table were gathered by Julia Schonwalder. The table includes the outcomes of tests performed by Schonwalder on a solidboard with the grammage 1050m/m².

ISOTROPIC	Modulus of elasticy [GPa]		Ultimate stress compression [MPa]		Ultimate stress tension [MPa]		Weight density [kN/m³]	Em-bodied energy [MJ/kg]	Recycling
Concrete C20/25	29		20		2.2		24	1.9	downcycling
Steel Fe E235	210		360		360		78.5	25	recycling
Glass (EN 572-1) Float glass	70-75		700-900		30-90		24	13.7	recycling
Polyethylene	0.6-0.9		20-30		20-45		9.5	80.9	recycling
ANISOTROPIC	‖	⊦	‖	⊦	‖	⊦			
softwood	8.5-11	0.6-0.9	35-45	3-9	30-80	3-4	4.5-6	4.7	recycling
Paper	2-20	0.5-10	5-10	2-5	15-45	5-20	6-9	5-20	recycling
Solidboard	3.5	1.6	8.0	5.6	27.1	13.5	6.9	9.4	recycling

‖ *wood in grain direction, paper – machine direction*
⊦ *wood in perpendicular to grain direction, paper – cross-machine direction*

TABLE 2.3 Comparison of the properties of paper and traditional building materials

§ 2.6.4 Viscoelastic properties

When subjected to long-term loading, paper is considered an orthotropic, non-linear viscoelastic material. Creep is an increase of strain whose stress level remains constant over time. Thee creep rate (φcr) varies, depending on the nature of the paper, forces, relative humidity and other factors. Three stages of creep can be observed in paper. First the strain in the material will increase rapidly. Then a linear increase in strain will become noticeable over time. Finally, a very rapid increase in strain and subsequent failure will occur (see Fig. 2.32). At a low level of stress the material may not enter the third stage of creep. [13] Fifty percent of the total strain is tertiary creep, which means that if material is kept at a lower stress level, it will never reach the stage of tertiary creep, and the creep strain will be significantly reduced. [10] If the stress level is never higher than 50% of the maximum load, paper will not experience tertiary creep. [34]

The creep rate of paper increases with increasing humidity. In paper that has fallen prey to creep, the cellulosic micro-fibrils slide past each other as rigid bodies. This sliding requires that all the bonds of such micro-fibrils break. This process is accelerated by moisture and variations in moisture levels. When paper ages, seasonal changes in humidity, changing temperatures and forces will cause a change in the mechanical properties from which the paper will recover slowly.

The above information shows that it is not easy to standardise paper and that each pile of paper may be quite different from the one next to it, depending on the source material, production method and other factors.

§ 2.6.5 The influence of moisture on the properties of paper

Paper is vulnerable to water, moisture and air humidity. The hydrogen bonds that are formed between cellulose fibres during the production process can weaken when the moisture content of the material rises. Additionally, the matrix between the cellulosic crystals softens when the moisture content increases. Paper is a hygroscopic material, which means that it can absorb moisture from the atmosphere. If paper gets wet, it deforms and finally turns into pulp again. The moisture content of paper depends on relative humidity and temperature. The highest level of moisture is absorbed in humid and cold conditions.

The optimal moisture content of paper is 5-7%, which is the typical moisture content in standard conditions for paper-product testing, at 21°C and 50% relative humidity (RH). If this moisture level is exceeded, strength is reduced by 10% for every one-percent increase in moisture content. [35] Furthermore, the dimensional stability of paper changes depending on the moisture content. For example, in paper tubes, a one-percent change in the moisture content of the material will cause the length of the tubes to change by 0.12%, and their outside diameter by 0.09%. [36]

When the engineers of BuroHappold conducted their preparatory studies for the paper building to be erected at a primary school in Westborough, UK (see Section 4.3.8) , they found that the moisture threshold for the best mechanical properties of paper tubes is 7%. If this threshold is exceeded, the strength of the paper tubes decreases by 10% for every one-percent increase in moisture content. The sustainable moisture content of a tube is approximately 7-10% in a room with a humidity level of 30-70%, which is typical for UK interiors. [37]

According to research conducted at Lodz University of Technology's Institute of Papermaking and Polygraphy , paper has a moisture content of 6% when subjected to a relative humidity of approximately 50%. When subjected to a relative humidity of 90%, the moisture content of paper increases to 14%. [23]

Julia Schonwalder and Jan Rots of Delft University of Technology (TU Delft) report that paper has a moisture content of 5% at a temperature of 23°C and a relative humidity of 50%. If paper is subjected to a relative humidity of 90%, its moisture content rises to 14%, and at the same time its strength decreases by 50%. [38]

Tests on paper tubes used for Shigeru Ban's Paper Dome project, conducted by Prof. Minoru Tezuka at Chiba Polytechnic College's Department of Housing Environment in 1997, demonstrated that the strength of paper tubes decreases gradually up to a moisture content of 7%, then decreases radically with a moisture content between 7 and 13%, and shows a linear decrease when the moisture content exceeds 13%. At the same time, the paper's strength will decrease by almost 50% at 7% (approx. 110 kg/cm^2) and at 13% (less than 60 kg/cm^2). [39]

The aforementioned studies show that the optimum moisture content of paper is a moisture content of 7%. If the 7% threshold is exceeded, the strength of paper will significantly decline. In a relative humidity of 50%, the moisture content of paper that have not been impregnated is 5-6%. In a relative humidity of 90%, the moisture content of paper that have not been impregnated rises to 13-14%, and their strength is reduced by half.

As LC Bank and TD Gerhardt report, paper with a higher moisture content is likely to experience higher creep rates, but paper also exhibits accelerated creep when it is subjected to changes in the humidity level. [36] Changing humidity levels cause higher creep rates than even the highest (but constant) level of humidity.

The hydro-expansive strain or shrinkage is equal to zero when the moisture content is constant. After first two years the structures gain the moisture balance and there is no more shrinkage. Hydro-expansive strain is a linear and reversible function of moisture content (MC). Hydro-expansion is the hydro-expansive strain divided by the corresponding change of the moisture content. Hydro-expansion is typically three to five times larger in CD than in MD. [31]

The greatest risk for a structure made of paper is the moisture content of its material being affected by direct contact with water, e.g. rain or high humidity. Paper, being a fibrous material composed of cellulose fibres affected by water, undergoes hydrolysis when moist, which causes the fibres to dissolve in water. During the paper-making process, hydrogen bonds are formed between the fibres; these bonds are essential to the creation of paper. However, the bonding process can also be reversed under the influence of water and moisture. Thanks to the organisational structure of the fibres and the type of bonding between the cellulose fibrils, cellulose is resistant to many chemical agents, but it does have a sensitivity to hydrolytic degradation (decomposition under the influence of water) in an acidic medium. [23]

§ 2.6.6 The impact of fire on paper

A thin sheet of paper can burn easily. The ignition temperature of paper is 230°C. However, tests conducted on thicker cardboard show that the flammability of a paper tube is similar to the flammability of timber. The burning rate of paper depends on the density of the material. For dense cardboard it can be assumed that the burning rate is similar to that of wood (0.7 mm/min). [13]

Thicker paper is harder to ignite. A series of tests examining the flammability of the material was conducted on the occasion of the Local Zone project in the Millennium Dome in London. [10] By covering the tubes with the intumescent coating it was possible to obtain a class-0 flame spread over the surface (flammability) . The tests were carried out by Warrington Fire Laboratories, which awarded the appropriate certificate. The test results were sufficient to help the Local Zone project satisfy the applicable building codes Tests were carried out on uncoated and coated tubes. The edges of the tubes were subjected to fire at a temperature of 1,000°C, which resulted in a protective charred layer just like happens to wood. After being exposed to flames for sixty minutes, the 150mm tube was charred. The application of intumescent paint on the ends of the tube did not change the behaviour of the material.

§ 2.6.7 The impact of micro-organisms on paper

Like wood, paper can be destroyed by fungi and other micro-organisms. High humidity and high temperatures encourage bacterial growth. Impregnation or chemicals added to a paper structure can minimise the growth of micro-organisms and deter rodents. [13]

§ 2.6.8 Impregnation methods

A traditional method of impregnation involves the use of egg protein, but more tests need to be carried out on this solution.

Covering paper tubes with a layer of waterproof liner has been known to make tubes stronger and less prone to varying levels of strength in the external environment. Another option is to cover tubes with a layer of PVC, but this solution is not environmentally friendly.

Shigeru Ban in his patent documentation includes information on the possibilities of using paraffin to impregnate paper. However, in his projects he generally uses polyurethane liquid, in which the paper tubes are dipped. He also suggested using polyethylene to impregnate paper. [40]

Taco van Iersel of TU Delft's Faculty of Architecture proposed using PE foil to cover the paper components of buildings. [32]

Paper tubes can be impregnated during the production process. For example, the innermost and outermost layers of the tubes can be coated with polyethylene. Alternatively, the coated layer can be placed inside the paper tube, in such a way that the inner- and outermost layers will remain pure paper, but with a coated layer in between. This can improve the natural appearance of the tube, when used indoors, or allow contractors to put extra layers on the inner and outer surface, e.g. by dipping them in the repellent.

BuroHappold proposed covering paper tubes with polyethylene film, or alternatively, producing sandwich paper tubes in which the innermost and outermost layers are made of aluminium. [41]

BuroHappold also mentioned various types of paint and varnish. These are used in the production of paper canoes in the USA and Australia.

Bank and Gerhardt suggest the use of polyurethane-based or other impervious polymer coatings. [37]

In principle, there are two approaches to paper waterproofing. The first is the application of protective layers on the surface, and the second is internal impregnation of fibres.

§ 2.6.9 Paper grades

Paper products are classified as paper and paperboard. Paper products are distinguished according to the fibres used in their production, the production and pulping methods and the weight of the paper.

There are several grades of paper, whose categorisation depends on properties such as weight, usage, conversion, raw material or pulping method. Different countries use different weights to determine grades of paper.

The following weight-based grades of paper are recognised:

- **Tissue**: Low weight <40 g/m^2
- **Paper**: Medium weight 40 - 120 g/m^2
- **Paperboard**: Medium High weight, 120-200 g/m^2
- **Board**: High weight >200 g/m^2

According to the norm ISO 4046 1-5 of 1978, products with a weight lower than 225 g/m^2 are called paper, and products with a weight over 225 g/m^2 are recognised as cardboard. For multi-layered products the threshold is 160 g/m^2.

According to another categorisation, paper products under 150 g/m^2 are called paper, products between 150 and 500 g/m^2 are called paperboard, and products over 500 g/m^2 are called board. [10]

Almut Pohl (2009) recognises paper with a grammage between 80 and 300 g/m^2 as being appropriate for use of architecture. [13]

The following types of paper exist: [4]

- **Tissue** – lightweight paper of 15-60 g/m². Tissue paper is mostly made from chemically bleached softwood but also contains some hardwood pulp. It can also be produced from de-inked recycled fibres.
- **Groundwood paper**, which can be sub-divided into uncoated and coated groundwood paper. Groundwood paper is made of mechanical pulp to which some chemical pulp has been added for strength purposes. Uncoated groundwood paper is mainly used for newsprint and printing paper. Coated groundwood paper is used for magazines and offset printing.
- **Wood-free paper**, which, like the previous category, can be sub-divided into uncoated and coated paper. Uncoated wood-free paper is made of softwood subjected to Kraft or sulphite treatment, with the addition of some mechanical pulp and recycled fibres. This type of paper is used for envelopes, photocopy paper. Coated wood-free paper is used for the production of smooth and glossy printing paper for magazines, books, etc.
- **Kraft wrapping paper** or bags, made of bleached or unbleached softwood paper subjected to a Kraft treatment.
- **Cast-coated paper** – very glossy paper used for wrapping materials, carbon paper, wax-base paper and special types of paper.
- **Special paper** made for special purposes, which may include packaging, manufacturing or printing, or electrically conductive paper, cigarette paper or greaseproof paper.
- **Kraft paperboards** – paperboard is paper heavier than 134 g/m². Kraft paperboard comes in two varieties: unbleached and bleached. Unbleached paperboard is mainly used for packaging, i.e. for milk cartons, cups and plates. Unbleached paperboard is used to create linerboard and corrugating medium. The production of paperboard may well involve recycled fibres.
- **Chipboard and recycled paperboard**. Chipboard is a thick paper of low density. It is often used for low-strength fibre boxes. The source material is recycled newsprint or inexpensive pulp. It is used to produce gypsum linear, tubes and clay-coated folding boxboard.

Paper can be also graded according to its usage:

- **Newsprint paper** – characterised by a short lifespan, low costs and a high percentage of mechanical pulp. Newsprint paper tends to be between 40 and 64 g/m².
- **Bond paper** – used for high-quality printing or writing paper.
- **Fine paper** – high-quality and smooth paper used for both writing and printing.
- **Tissue** – soft and absorbent paper. Can be sub-divided into three categories: sanitary tissues, wrapping tissue and tracing tissue.
- **Glassine and greaseproof paper** made from refined chemical pulp, which results in very dense translucent paper.

- **Linerboard** – unbleached softwood paper subjected to the Kraft treatment. It is used for the outermost plates of corrugated board, which are combined with corrugating medium, with the machine direction perpendicular to the fluting in order to strengthen the corrugated board in both directions.
- **Corrugating medium** – made from unbleached semi-chemical pulp. Must have a high degree of stiffness and be crush-resistant.
- **Construction board** – a thick board used in the building industry, e.g. as an insulation board.
- **Moulded pulp products** such as egg cartons, flower pots, etc.

In a document dated December 2014 entitled 'Pulp and Paper Industry: Definitions and Concepts', CEPI (the Confederation of European Paper Industries) distinguished the following grades of paper: [11]

- **Graphic paper**
- **Packaging paper**
- **Sanitary paper**
- **Other types of paper and board**

§ 2.7 Paper products in architecture

Essentially, there are five products that are mass-produced by the paper industry which can be used as structural elements in architecture:

- **Paperboard**
- **Paper tubes**
- **Corrugated cardboard**
- **Honeycomb panels**
- **L- and U-shapes**

§ 2.7.1 Paperboard

Paperboard is a generic term applied to certain types of paper characterised by relatively high rigidity. The first paperboard was produced in England in the early nineteenth century for packaging purposes. In the second half of the nineteenth century, folding boxes were invented, as were mechanical die cutting and creasing of blanks.

The following types of paperboard can be distinguished: carton board (board manufactured for the production of cartons with good folding and scoring properties), chipboard (board made of low-grade waste paper), solid board (board consisting of one or several layers of the same material) (see Fig. 2.35) or solid fibreboard (with a grammage exceeding 600g/m², which can be finished with a lining of Kraft paper or another strong type of paper). Paperboard has high density. The material can either have a homogeneous structure or it can be produced from several plies. Paperboard can be finished with a liner made of special paper, e.g. waterproof paper. The thickness of paperboard can range from 0.25mm to 4mm. Its grammage ranges from 224 g/m^2 to 1,650 g/m^2. Solid board is characterised by high strength and stiffness. [44] The structural behaviour of paperboard is affected by its number of layers, the direction of the fibres (MD or CD) and the type of adhesive used.

Tests conducted by Julia Schonwalder at TU Delft showed that, depending on the composition of the material and the type of adhesive used, paperboard has a tensile strength between 9.7 and 29.8 MPa in MD and between 5.9 and 15.5 MPa in CD. The bending stress ranged from 3.7 MPa for a 20-layered solid board beam laminated with polyvinyl acetate that was bent horizontally to 32.1 for an 8-layered solid board beam laminated with wood glue that was bent vertically (see Fig. 2.36). [45]

FIGURE 2.35 Paperboard

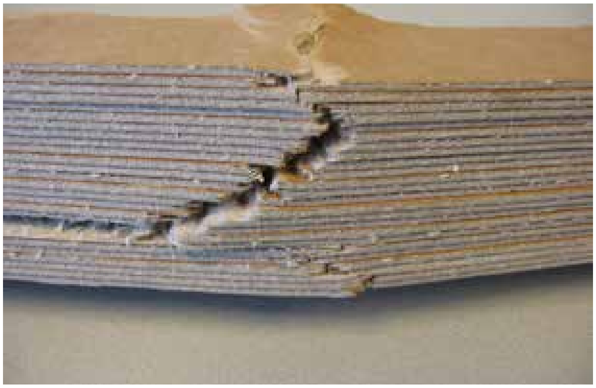

FIGURE 2.36 24 layer solidboard tested for bending

§ 2.7.2 Paper tubes

Paper tubes, also known as paper cores, are the most popular products of the paper industry used in architecture (see Fig. 2.37). This is because of the great popularity of Shigeru Ban's architectural projects. Tubes are mainly used by the paper industry and other industries for transportation and storage purposes. Paper towels, toilet paper, wrapping plastics, metal foil and many other products we come across in our daily lives are wound on small paper tubes, whose diameter ranges from 10 to 25mm, and the thickness of whose walls ranges from 0.5 to 1.5mm. Bigger tubes are used for rolls of printing paper, plastic film and textiles. The diameter of these tubes will be between 70 and 200mm, and their walls will be 10 to 25mm thick. [36] In the building industry, bigger paper tubes are used mainly as a disposable formwork for concrete columns. Such formwork tubes, also called Sonotubes as they were invented and patented by Sonoco Products Company in 1945, have diameters ranging from 50 to 1,600mm and may be up to 18m long. Another Sonoco products that can be used in architectural applications is a voided slab, in which paper tubes are placed horizontally before being cast in concrete.

There are two ways to produce paper tubes: parallel winding and spiral winding (see Fig. 2.38). Parallel winding consists in winding a sheet of paper with a fixed width around a core. Subsequent layers of paper are glued together. The length of the tube is determined by the width of the sheet of paper. Spiral winding consists in winding a sheet of paper around a core at a fixed angle. This production method is called endless and the length of the tubes is determined by where the tubes are cut during the production process. Tubes that are created using the parallel winding method are more durable and their axis concurs with one of the main orthotropic directions of paper (MD or CD), which also makes it easier to describe their mechanical properties. Most paper tubes created using the spiral winding method have a winding angle between 10 and 30 degrees, depending on the inner diameter (ID) of the tube. A larger winding angle improves the fatigue strength of the tube, as the plies of the paper are positioned closer to the paper production direction (MD or CD). [40]

FIGURE 2.37 Paper tubes

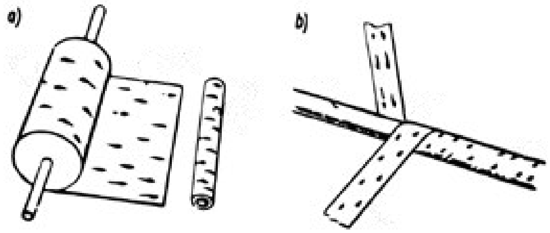

FIGURE 2.38 Two methods of paper tubes production a) parallel winding, b) spiral winding

The type of paper used for the production of tubes has thickness which generally ranges from 0.3mm to 1.2mm. [36]

Factors such as the quality of adhesive-bonded joints without air blisters between layers of paper have a significant impact on the mechanical properties of paper tubes. The properties of spiral winding tubes are determined by the angle at which the paper is wound and the presence or absence of breaks or overlapping layers of paper. Each subsequent layer should half overlap with the previous one. Using modern technology, spiral paper tubes can be produced with a speed as high as 160 m/min, but the speed depends on the winding angle. The number of laminated plies of paper may vary from 2 to 40. [36]

The most popular adhesive used by paper tube manufacturers is starch or PVA. However, certain types of tubes, such as the ones used as formwork, are laminated with cross-linked polyvinyl adhesive to make them more moisture-resistant. Another popular adhesive is liquid glass, but this type of lamination requires extra drying time, as well as the right conditions

When used as a part of a structure in architecture, paper tubes often undergo tensile forces parallel to the tube's longitudinal axis and bending forces.

Tests measuring the compression strength of paper tubes are conducted using different methods.

In a flat crushing method tubes are installed between two parallel plates and are subjected to a load which is applied in a direction perpendicular to the longitudinal axis of the tube. Another test often conducted by the paper industry is the radial crush.

When subjected to axial compression, a tube may be pressed, locally buckled or globally buckled, depending on the diameter of the tube (see Fig.2.37).

Despite the viscoelastic character of fibre material like paper, it is possible to forgo taking into account the viscous characteristics and treat paper as an elastic material. This kind of simplification can be used during a short-term load tests involving forces that are far from destructive.

Another simplification used during paper tube testing is the assumption that paper tubes are homogeneous material without differentiating between the layers of paper and laminate. In such cases, Young's module might differ for axial and bending forces because of the orthotropic properties of paper. It is important to note that Young's module can be changed by layers made of different material (e.g. waterproof material applied to the inner- and outermost layers of a tube for impregnation purposes). [46]

When conducting laboratory tests, it is assumed that the paper tubes are made of elastic material. It is also assumed that sabsequent layers of paper are glued to the surface without any air bubbles and gaps and that the lamination is strong enough to withstand the whole strength test, which is to say that the delamination process will not start before the paper tubes are subjected to maximum forces. Moreover, it should be assumed that the climatic conditions in which the properties of paper were established are similar to the conditions under which the tests are conducted.

The paper tubes are tested in standard RH (relative humidity) and temperatures. The moisture content has a considerable impact the mechanical properties of paper. Significant strength reduction can be observed with increased moisture content above 7-8%, which is the typical moisture content in standard testing conditions at 21°C and 50% RH, and with sustained axial loading (creep rupture).

As Bank et al. report (2016), the flat and radial crush strength of paper tubes are both reduced by about 50 percent when the moisture content of the tubes increases from 5.5% to 13%. [39] Furthermore, the dimensional stability of the tubes changes depending on the moisture content. For every one-percent change in a tube’s moisture content, the length of the tube will change by 0.12% and its outside diameter will change by 0.09%.

As the properties of paper tubes can vary depending on the material used (i.e., the grade of paper) or on the winding angle and the diameter, both of which affect the mechanical properties of the tubes, it is common to test specimens before they are incorporated into a structure.

It is advisable to use 10-50% of the axial strength capacity when the tubes are under sustained long-term loads.

Connections – it is assumed that the total load on paper tubes is shared between screws in a connection.

Paper tubes are the most effective when they are used as a beams and columns in a small-scale framing system or small house-like structures.

The bending strength of paper tubes is approximately 40-70% higher than their compressive strength. The bending capacity of a tube can be enhanced by means of a thin layer of pultruded fibre-reinforced polymer.

Both parallel- and spiral-wound paper tubes were tested in the laboratory of Lodz University of Technology's Institute of Papermaking and Polygraphy. In the early stages of loading, both types of tubes behaved like elastic material. The deformation graph is almost linear initially. Next, the deformation increases even if the load decreases. This is related to the viscoelastic and plastic properties of paper. If slim tubes are used global buckling can occur as well. During the tests, spiral-wound specimens were destroyed parallel to the direction of winding, whereas parallel-wound tubes were destroyed perpendicular to the axis of forces (see Fig.2.38). [4]

FIGURE 2.39 Paper tubes test on axial compression at TU Delft, noticable buckling

FIGURE 2.40 Paper tubes test on axial compression at TU Delft, wrinkles caused by axial compression

During the research for paper building of Westborough Primary School (see also section 4.3.8), BuroHappold determined that Yuong's module should be assumed to be 1 GPa and maximum compression force should be assumed to be 8.0-8.8 MPa.

It was also stated that paper is sensitive to atmospheric moisture and that a waterproof barrier is needed to prevent moisture from compromising the strength of the material. Furthermore, it was established that creep of paper tubes starts at 10% of the maximum compression level. Bending tests conducted at the University of Bath showed that paper tubes deform easily but with just a small amount of permanent deformation.

Compression tests conducted by BuroHappold showed limited endurance at 8.75 MPa. Tensile force tests showed that tensile and compression strength are similar, and that it is important to protect the connections at the ends of the tubes.

In order to minimise creep, a creep factor of 5 was established by BuroHappold and it was also established that the maximum long-term load should not exceed 1.6 MPa. BuroHappold also found out that paper tubes with a large diameter are weaker than paper tubes with a small diameter because their paper is wound at a greater angle relative to the tube axis. [40]

It is also important to take into account the angle at which the paper is wound to the core during the production of paper tubes. [42]

The book Shigeru Ban by Matilda McQuaid contains a great deal of information about stress tests conducted during the construction process of some of the Shigeru Ban's projects. [39] It includes information on the following buildings, whose structures were made of paper tubes:

1. Library of a Poet (tests carried out between August 1990 and August 1991)
2. Paper House (tests carried out between 14 October and 20 November 1991)
3. Paper Dome (tests carried out in July 1997)
4. Japan Pavilion at Expo 2000 in Hannover (tests carried out in November 1991).

In order to measure creep of the material, paper tube specimens with a length of 400mm were installed between two steel plates, which were fastened at 1000 kg (which was less than one-third of the maximum compression strength). The changes to the length of the tubes were measured for one year at one-week intervals. Temperatures and humidity levels were also measured at one-week intervals. The test results showed that the length of paper tubes is likely to undergo changes in wetter periods. The greatest change to the length of the tubes that was measured in the tests was 1.5-1.8mm (0.375% -0.45%) in a relative humidity of 80%. The tests showed that time played no role in the changing lengths of the tubes. This indicates that paper tubes are resistant to creep, if they are kept in hygroscopic equilibrium. Shigeru Ban confirmed this, telling the author of this dissertation that the dimensions of paper tubes may change in the first year of their being used, but that they stabilise after a while.

PROJECT	PAPER TUBE DIMENSION	MOISTURE CONTENT (%)	COMPRESSION STRENGTH (MPa)	AXIAL YOUNG'S MODULUS (GPa)	BENDING STRENGTH (MPa)	BENDING YOUNG MODULUS (GPa)
Library of Poet	outer Ø 100, inner Ø 75 mm	-	10,12	1.82	-	-
Paper House	outer Ø 280, inner Ø 250 mm, length 600 mm	8,8	11,17	2.36	16,82	2,17
Paper Dome	outer Ø 291, inner Ø 250 mm, length 600 mm	10,0	9,74	2.07	14,9	2,11
Japan Pavilion	outer Ø 120, inner Ø 76 mm, length 240 mm	8,7	9,53	1,57	14,5	1,46

TABLE 2.4 Properties of paper tubes used in Shigeru Ban projects

Recommendations by BuroHapold on the mechanical properties paper tubes:

Maximum compression, tension and bending strength: 0.8 MPa adapted by a factor 0.1 for creep in relation to 8.1. The load at the attachment should not exceed 1.4 MPa. Maximum strength of adhesive for peeling: 0.3 MPa. Young's modulus 1-1.5 GPa. Monitoring of the material throughout its lifetime. [40,43]

During the realisation of the Paper House designed by Shigeru Ban, tests were carried out on five paper tubes, each with a length of 400mm. The tubes were tested using the three-point bearing method. When a tube was subjected to the maximum load, deformation was 124mm in the middle of the tube. The bending test resulted in the formation of diagonal wrinkles corresponding to the direction in which the paper is wound around the tube. They only appeared under compression (in the upper part of the tube).

Average strength for bending was 15.79 MPa, which is 1.42 of compression strength. Young's modulus was 2.18 GPa, which is equal to 92% of Young's modulus of compression. The average moisture content of the tubes was 8.9%. [41]

§ 2.7.3 Corrugated cardboard

Corrugated cardboard, also known as corrugated board or corrugated fibreboard, is the most popular material used in the packaging industry. Its production in Europe reached 43.4 million m2 in 2016, up 1.7% from 2015. [47]

Corrugated cardboard was invented and patented by two Englishmen, Edward Healey and Edward Allen, in 1856. The material was used as neat fluted paper used to line men's tall hats. In 1871 Albert L. Jones used corrugated cardboard for wrapping fragile items such as bottles. [48] A few years later, corrugated board with one side glued and both sides glued to a liner were patented in the United States. Corrugated cardboard was used as a material for packaging boxes since the early 1900s.

Corrugated cardboard is a sandwich composition of two flat layers of paper with a layer of corrugated medium (also known as fluting) in between (see Figs. 2.41 and 2.42). The layers are then laminated together. The thickness of the fluting can range from 0.8 mm to 4.8mm, and its grammage will be between 80 and 180 g/m2, while the liners have a grammage ranging from 115 to 350 g/m2. [49] The most popular types of paper used in the production of liners are Kraftliner (made of Kraft paper) and testliner (made of recycled paper). The corrugated medium (fluting) is made of recycled paper, which is also known as Wellenstoff paper, or of virgin paper, made using the semi-chemical pulping method.

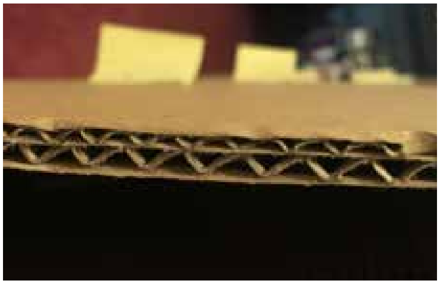

FIGURE 2.41 Double wall corrugated cardboard

FIGURE 2.42 Stack of corrugated cardbord plates

Corrugated cardboard is mainly produced for the packaging industry. The production of corrugated cardboard consists of three stages (see Fig. 2.43). First, the flutes are corrugated. Corrugation is obtained by pressing a sheet of paper at high temperatures, softening it by means of steam and forming by means of grooved metal rolls. The corrugation is created perpendicular to the Machine Direction of the paper. Next the outer liners are affixed with glue to one or both sides. Lastly, the laminated corrugated board is cut into the desired shape. The most popular adhesive in the production of corrugated board is starch, which, being a natural polymer, can be easily recycled. Special synthetic adhesives are used for water-resistant corrugated cardboard. The maximum size of corrugated cardboard is 2.40-3.25 metres wide and up to 5.0-6.20 metres long. [12]

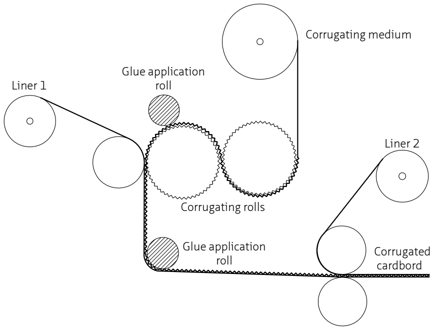

FIGURE 2.43 Corrugated cardboard production scheme

There are different types of corrugated cardboard, e.g. single-wall board (with a single corrugated medium and one or two liners), double-wall board (with two corrugated mediums and three linerboards) and triple-wall board (in which three corrugated mediums are alternated with four linerboards) (see Fig. 2.44). The most commonly produced type of corrugated cardboard is single-layered.

There are several types of corrugation. The smallest, type G, is less than 0.55mm high. The largest, type K, is over 5.0mm high. Corrugation height and pitch are the distances between two flute tips in the vertical and horizontal directions. The ratio of the length of uncorrugated material to the length of corrugated cardboard is called the take-up factor (see Table 2.5 and Fig. 2.45).

TYPE	HEIGHT [MM]	PITCH [MM]	TAKE-UP FACTOR
K	≥ 5.0	≥ 5.0	
A	4.0-4.9	8.0-9.5	≈ 1.5
C	3.1-3.9	6.8-7.9	≈ 1.45
B	2.2-3.0	5.5-6.5	≈ 1.4
D	1.9-2.1	3.8-4.8	≈ 1.5
E	1.0-1.8	3.0-3.5	≈ 1.25
F	0.6-0.9	1.9-2.6	≈ 1.25
G	≤ 0.55	≤ 1.8	≈ 1.25

TABLE 2.5 Types of corrugated cardboard

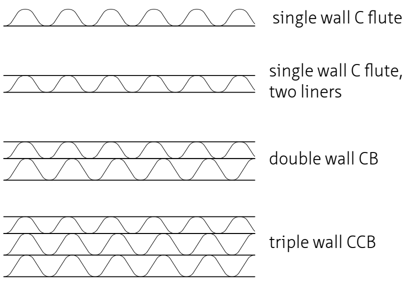

FIGURE 2.44 Types of corrugated cardboard

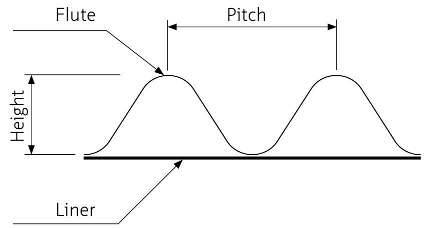

FIGURE 2.45 Dimensions of corrugation

The mechanical properties of corrugated cardboard depend on the material used for its production, as well as the type of corrugation.

The edgewise compression strength of corrugated cardboard is parallel to the axis of a corrugation and it is related to the type of paper used as well as to the geometry of the corrugation. The edgewise compression strength ranges from about 3 kN/m for single-wall board to more than 20 kN/m for double- or triple-wall corrugated boards. [13]

The bending stiffness is higher in the axis perpendicular to the axis of the corrugation and it comes from corrugated layers, while the stiffness in bending parallel to the axis of the corrugation comes from the liner layers. Increasing the corrugation size increases the bending stiffness due to the sandwich effect. The bending stiffness of corrugated board bent in the Machine Direction ranges from 3 Nm to 80 Nm. CD stiffness (i.e., the direction parallel to the corrugation) is about 50-70% of MD stiffness.

The in-plane shear resistance is higher in cross-machine direction than in machine direction. In the MD a lower ratio of the corrugation height to the corrugation pitch results in higher in-plane shear forces. Shear moduli for corrugated cardboard range between 1.8 MPa and 11.6 MPa in the MD, and between 11.2 MPa and 31.5 MPa in the CD.

Corrugated cardboard's high thermal performance is due to its structure, i.e. the liners, the layer of corrugation and the air kept between the layers. Its thermal resistance depends on the thermal conductivity of its components and the size of the corrugation. Larger cavities (higher waves) show higher thermal insulation properties. The thermal conductivity of corrugated cardboard at room temperature ranges from 0.29 W/mK for small corrugations to 0.045 W/mK for bigger corrugations (e.g. Type A, B or C).

§ 2.7.4 Honeycomb panels

Honeycomb panels are low-density, cellular sandwich panels (see Fig. 2.46). They are made up of three layers: two facings and one core layer, which have a honeycomb-like structure (see Fig. 2.47). The panels can be made from paper or other materials such as fibreboard, plywood, aluminium , resins, or other metals and polymers. Honeycomb panels were introduced to the industry in the early 1900s. Since that time their application has become widespread in different industries, including construction and furniture production. [50] During World War II, research on this high-strength and light-weight material was accelerated by the aviation industry.

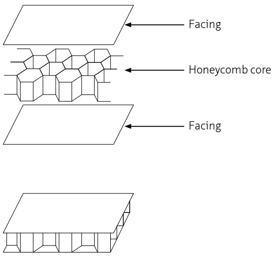

FIGURE 2.46 Honeycomb panel sandwich structure

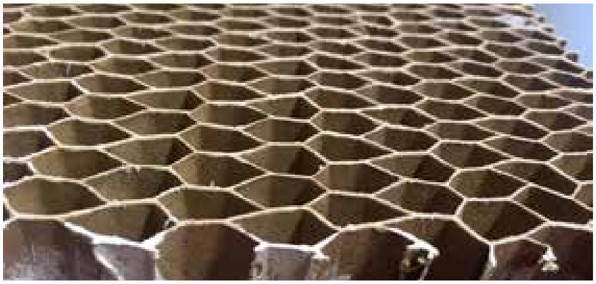

FIGURE 2.47 Honeycomb panel core

Honeycomb panels are often used in furniture, mainly as a filler of tabletops and shelves. They are also a material commonly used as door fillers. In the packaging industry, honeycomb panels, being bio-degradable materials, have come to replace foam products used as inner packaging. They are also used in the automotive industry, as sandwich panels composed of cardboard honeycomb core and finishing layers made of glass fibres or natural fibres.

Cardboard honeycomb panels are produced in two steps. First the honeycomb core is prepared. Then it is laminated to the facings.

In a traditional production process, the honeycomb core is produced by the lamination of sheets of paper by means of glue lines printed on flat sheets (see Fig. 2.48). Then the sheets are stacked on top of each other. After the glue has cured, the block of paper sheets is sliced. Lastly, the slices are pulled apart, thus expanding into a hexagonal honeycomb core. The residual stress in paper honeycombs is relaxed after expansion by heat. [51]

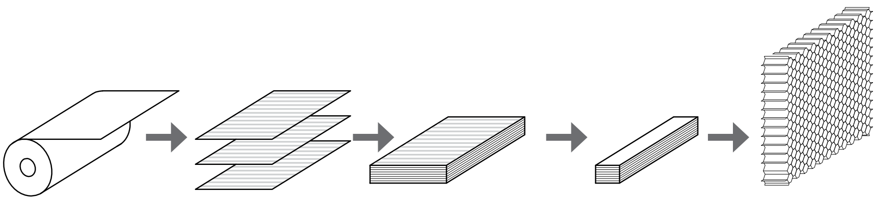

FIGURE 2.48 Honeycomb core traditional production method

The second method, also called the corrugated honeycomb core production process, uses corrugated cardboard sheets, which are first glued to each other, then sliced and expanded (see Fig. 2.49) The second process results in smaller cells, depending on the type of flute used, and is cheaper.

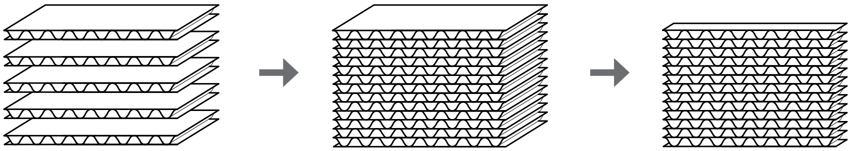

FIGURE 2.49 Honeycomb core production from corrugated cardboard

The size of the honeycomb panels produced as outlined above depends on the dimensions of the liner paper, which are typically 1,200mm. The length depends on the length of the machine, and typically reaches 24,000 mm. The height of the panels varies from 8 to 100mm.

The most popular type of paper for used for the production of panels is Kraft or recycled paper with a grammage between 140 g/m² and 300 g/m².

Honeycomb panels are characterised by high compression strength in the Z-direction, i.e. perpendicular to the surface, which may be as high as 100 kN/m². [44]

§ 2.7.5 U- and L- shapes

Cardboard U- and L-profiles consist of several layers of paper pressed into shape, laminated and covered with a finishing layer, which can be coloured, high gloss or printed (see Fig. 2.51). Layers of paper, which can be as heavy as 450 g/m² and 0.7mm thick, are laminated with water-based liquid adhesive. The flanges (A and B) can be between 35 and 100mm and can have a thickness (T) of 2 to 10mm (see Fig. 2.50). Profiles are produced in lengths (L) ranging from 50 millimetres to 10 metres. Profiles are used primarily for transportation purposes, as a means to protect the edges of goods being transported, e.g. books or furniture. [52]

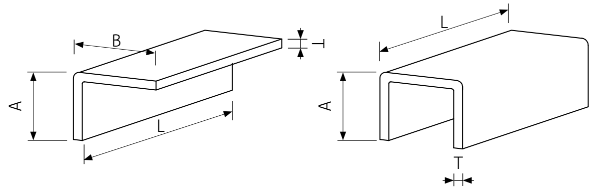

FIGURE 2.50 L- and U- shapes dimensions

FIGURE 2.51 Cardboard beam made from two laminated U-shapes

Tests conducted at TU Delft showed that the compression strength of profiles made out of recycled cardboard was as high as 8.53 MPa. Their Young's modulus was 1.28 GPa (also see the Appendix).

§ 2.7.6 Other paper-based products

Currently there are many other paper-based products which can be used in design and architecture.

Nanopaper consists of cellulose fibrils that have been reduced to nanometre size. In its production process wood cells are dissolved and refined. This smaller particles display better adhesive properties and create more homogenous paper with cavities, which increase the product's resilience. This extremely tear-resistant material is produced without any additives, so the fundamentals are the same as in normal paper.

Vulcanised paper is produced by bathing sheets of paper in zinc chloride, which turns the surface of the paper rubbery and sticky. Then the paper sheets are pressed together and the zinc chloride is rinsed away. Vulcanised paper is water-resistant, very strong and durable and does not contain any additives such as glues, binding agents or resins. This type of paper was traditionally used for the production of armour for Japanese sword fighters. It can be used as a light-weight structural element.

Transparent construction panels are made out of cellulose acetate. Transparent cellulose made of pure cellulose is produced by dissolving pulp in soda and carbon disulphide.

‘Monifex’ are the honeycomb-shaped, light-weight and air-permeable panels produced by Isoflex. [53]

Kraftplex is a panel containing pure cellulose. Its material and shaping properties are similar to those of metals and plastics. Kraftplex is made of softwood fibres by a German company called Well, which only uses water pressure and heat during the production process, without any chemical additives, bleach or adhesives. [54]

Pressed cellulose panels are produced out of paper sheets, which are pressed together under high temperatures and great pressure. During this process the cellulose coalesces into a rigid substance. [54]

Ceramic paper is a product developed by PTS, a German research organisation that works for the paper industry. During the production process, standard paper is enriched by means of aluminium, silicon powder and latex. The paper can be shaped and folded like typical paper. However, it is then processed at a temperature of 1,600°C, after which the paper ingredients are burned away, which results in a concentrated and solid object. This product is characterised by a good resilience to pressure, chemicals and high temperatures. [55]

Fire-resistant paper (produced by a German company called Additherm Group) is manufactured by adding seed crystals to the pulp. During the drying process a chemical bond is created between the crystal matrix and the cellulose fibre matrix. Several types of products can be manufactured by using this technology, such as laminated cardboard, paper foam and paper-insulating boards. The AddiTherm Stop Steel Coating is a cellulose-based product that is used as a fire-prevention coating for steel beams. [52]

In association with Shigeru Ban, company UPM-Kymmene, a company working with the foresting industry, developed a new paper-based material for the construction of an exhibition pavilion for a furniture-making company called Artek. The material consists of waste paper which is chaffed and extruded into L-shaped profiles. The product only contains recycled adhesive labels without any plastic or adhesives. UPM-Kymmene now produces UPM ProFi Deck outdoor flooring boards, based on this product.

The ‘Paper brick’ is an invention by WooJai Lee, a Korean-Kiwi designer based in Eindhoven, the Netherlands. ‘Paper bricks’ are made of recycled newspapers, which are pulped, mixed with glue and shaped into bricks. In the words of the designer, ‘Sturdy as real bricks, they combine a pleasing marbled look with the warmth and soft tactility of paper. When you touch the ‘Paper bricks’, you can feel the soft textile-like texture’ (see Figs. 2.52 and 2.53). [56]

FIGURE 2.52 'Paper brick'furniture

FIGURE 2.53 Structure of the 'Paper brick'

§ 2.7.7 The paper industry and its future

It seems that the golden era of paper-making may be about to end. According to statistics provided by CEPI (the Confederation of European Paper Industries), Europe's paper production capacity decreased by 12 percent in the years 2005-2013. The production of pulp mass decreased by 10 percent, while the production of paper and cardboard fell by 7%. The production of printing paper has especially decreased. Modern information media, such as the Internet and e-books, have recently contributed to a considerable decrease in newspapers' circulation and newsprint production. At present, entrepreneurs of the paper industry are not investing in the development of machines producing newsprint and other types of printing paper. Rather they are focusing on reducing the amount of printing paper they produce. In addition, they seek to strengthen the paper-making sector by producing packaging paper and packaging materials, paper-based filling materials used in transport, and particularly mass-produced boxes made of corrugated board. They also produce more niche products such as shaft cores, or highly advanced paper products with a honeycomb structure, which are perfect structures observed in nature, distinguished for their high efficiency and minimal use of material, and therefore material-efficient and very light.

We can support the paper industry by looking for new ways of using not only paper, but all sorts of renewable, inexhaustible plant material, which can be used to produce the aforementioned elements by means of paper-making methods. Paper- and cellulose-based materials and products have great potential for use in architectonic design, in the broadest sense of these words. Paper elements can be successfully used in furniture, industrial design and small architectonic forms, as well as in architecture.

Contemporary trends in architecture are centred around environmentally friendly solutions that make use of renewable and eco-friendly materials and have a low built-in energy factor (kJ/kg) – in other words, materials whose production and processing are simple and energy-saving.

Great significance is attached to the whole life cycle of a building, which consists of three stages: construction, use and demolition.

What is essential is that a building material should only have the slightest possible impact on the natural environment after its demolition.

§ 2.8 Conclusions

Paper is a material of organic origin. The most commonly used raw materials from which paper is made are deciduous and coniferous trees. However, paper can also be made of other plants, such as straw, hemp, cotton, bamboo, cane and other cellulose-containing materials. Moreover, recycled paper is increasingly used as a source material for new paper.

Paper was invented in 105 AD by the Chief of the Chinese Imperial Supply Department, Cai Lun, also known as Ts'ai Lung. Afterwards, paper became a popular medium for writing, slowly replacing silk scarves and bamboo boards as media used for messages. Paper was also commonly used as a material for objects for everyday use. Although the Chinese kept the technique used to make paper secret, paper appeared in Korea in the sixth century AD and was introduced to Japan in the seventh century AD. In the eighth century, the art of paper-making spread to the Arab world. The Arabs introduced paper-making techniques to Europe in the twelfth century.

In the centuries that followed, many countries developed paper-producing techniques, but the most significant development took place in Europe between the seventeenth and nineteenth centuries. During those centuries new production techniques were developed, the most notable of which was the first machine to produce paper strips continuously, invented by Louis-Nicolas Robert in 1799. The other major breakthrough in the production of paper was the research conducted on the raw material for paper. The growing demand for paper and the scarcity of raw materials (until the second half of the eighteenth century, mostly rags) resulted in new breakthroughs in the production of paper. New raw material for paper was researched by French physicist and naturalist René Antonie Ferchault de Réaumur, German clergyman Christian Schäffer and German inventor Friedrich Gottlob Keller. After 1840, when Keller managed to gain a pulp from mechanically ground wood, wood (with some added improvements) became the main source of raw material for paper pulp, which resulted in a low-cost but large-scale production of paper [4, 14, 15].

Although production technologies and the finish of paper have changed and improved over the years, paper has in fact remained remarkably the same over the centuries. It still has the same composition: cellulose fibres bonded in a wet environment, then pressed and dried. Recently, not only the paper-making industry has undergone change, but other industries, such as architecture, electronics and the automotive industry, have also proved receptive to the innovative qualities of paper.

Paper-making is divided into two phases. The first stage is the preparation of paper pulp, while the second one is the processing of the pulp in paper mills, so as to form sheets of paper.

Pulp consists of small, elongated plant cells that form a compact tissue made of raw material. The pulp used in paper production must be ground into individual fibres. Sheets of paper are produced by using the fibres' ability to form bonds with each other during a process of irrigation, heating and pressing.

Paper is created by a uniform distribution of a slurry containing cellulose fibres across the surface of a screen. The Kraft pulping method is the preferred method to produce strong paper that may be used as an element of architectural structures. Due to its single-fibre properties, the best paper for architectural use is softwood Kraft paper.

Cellulose is the most valuable material and main component of the plants used for the production of paper. Pulp is produced by the extraction of cellulose, whose fibrous character forms the basis of paper.

Cellulose is a natural multi-molecular compound, belonging to the polysaccharide group. The macromolecule has a chain structure in which so-called glucose residues are linked by β-glycoside bonds. Together with hemi-cellulose, cellulose forms the skeleton of cells.

The basic properties of paper are characterised by weight and density, moisture content, physical characteristics, strength properties, optical properties and other criteria.

The properties of paper that have a significant impact on the extent to which paper can be used as an architectural and structural material are apparent density, mechanical properties and vulnerability to water, fire, microorganisms and animals.

The mechanical properties of paper are determined by the properties of the fibres used in paper-making, the bonding between the fibres and their geometrical disposition. The mechanical properties of fibres depend on the geometry and chemical composition of said fibres. The chemical properties of fibres depend on the raw material and pulping method used. The Kraft chemical method results in the strongest pulp, i.e. the pulp that is richest in cellulose. In the web-like structure that is paper, single-fibre parameters such as form and surface influence the quality of the bonds between the fibres. These bonds are also affected by the quantity of fibres, fillers and additives. Lastly, the mechanical properties of paper are also determined by the production process (forming, pressing, drying, calendering, etc.). In other words, the properties of paper depend on different factors affecting the material at both the fibre level and the network level.

This also means is that every piece of paper can vary from another, as paper is a web of randomly oriented fibres. Such differences can be even more significant if the various types of paper are not produced from the same raw material, by means of the same method or by the same paper machine.

Currently there are many different products made of paper or its derivatives that are used in the building industry. They include products such as laminates, wallpaper, paper tubes used as a stay-in-place formwork, honeycomb boards (which are used as door fillers), etc.

There are five main products, which are mass-produced by the paper industry, which can be used as structural elements in architecture:

- Paperboard
- Paper tubes
- Corrugated cardboard
- Honeycomb panels
- L- and U-shapes

Plate products like corrugated board or honeycomb panels work well as wall or roof elements, whereas paper tubes can be used most efficiently when employed as slender, load-bearing structures. However, plates can also be used as structural elements of a building when they are incorporated with other members. Corrugated cardboard can be used as a load-bearing material. However, when a greater span is required, use of more slender and stiffer elements is recommended. Plate products, when used as wall or as roof elements, can be incorporated into sandwich panels. An external layer of a protective material such as polyethylene, aluminium, impregnated solid boards, fibreboards or plastic foil is an optional solution. Plates can also be altered by means of insulating material, such as polyurethane foam.

Due to the properties of paper products (e.g. creep when an element is subjected to constant loading), it is generally better to use short elements rather than long ones.

Each of the aforementioned products has its own characteristics and properties. Paperboard can be applied as structural elements, such as connections between load-bearing elements or as a finishing, protective layer of a building envelope. Paper tubes and L- and U-shapes made of full board are the best products for use as pillars and beams or linear elements. Corrugated cardboard is at its strongest when used parallel to the direction of the corrugation. It can be used as a bulding element with forces applied parallel to its surface and following the direction of the flute. Honeycomb panels can be used as building elements with the forces applied perpendicular to the surface.

Developing and using functional and sustainable paper requires creativity and open-minded approach from researcher, industry and marketing.

References:

1 Munari, B., Drawing a Tree. 2004: Edizioni Corraini.

2 Alava, M. and K. Niskanen, The physics of paper. Rep Prog Phys. Vol. 69. 2006. 669-723.

3 Dąbrowski, J., et al., Rękodzieło papiernicze. 1991: Wyd. nakł. Wydawnictwa Czasopism i Książek Technicznych "SIGMA" NOT, Spółka z o.o.

4 Biermann, C.J., Handbook of pulping and papermaking. 1996, Academic Press: San Diego :.

5 van der Reyden, D., Technology and treatment of a folding screen: comparison of oriental and western techniques. Studies in Conservation, 1988. 33(1): p. 64-68.

6 Beurden, H.v., Paper Breakthroughs, European answer to societal challange, ed. H. Communicatie. 2015, Amsterdam: !mpressed.

7 Sustainable development knowledge platform. [cited 2017 25.01.2017]; Available from: https://sustainabledevelopment.un.org/resourcelibrary.

8 DIRECTIVE 2008/98/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 19 November 2008 on waste and repealing certain Directives. 2008.

9 Standarization, I.O.f., NEN-ISO 4046 1-5 Paper, board, pulps and related terms - Vocabluary 2016.

10 Sekulić, B., Structural cardboard: feasibility study of cardboard as a long-term structural material in architecture, in Universitat Politècnica de Catalunya. Departament d'Estructures a l'Arquitectura. 2013, Universitat Politècnica de Catalunya.

11 Pulp and Paper Industry Definitions and Concepts A.C. Eric Kilby, Editor. 2014, Confederation of European Paper Industries.

12 Ayan, O.z., Cardboard in architectural technology and structural engineering a conceptual approach to cardboard buildings in architecture. 2009, ZürichETH.

13 Pohl, A., Strengthened Corrugated Paper Honeycomb for Application in Structural Elements. 2009: vdf-Hochschulverlag AG an der ETH Zürich.

14 Jakucewicz, S., Wstęp do papiernictwa 2014, Warsaw: Oficyna Wydawnicza Politechniki Warszawskiej.

15 Oliver Helfrich, A.P., The book of Paper. The Books of ... 2010: Post Editions, Rotterdam, the Netherlands.

16 Narita, K., A life of Ts'ai Lung and Japanese paper-making. 1980: The Paper Museum Tokyo.

17 Goedvriend, G.J.M., Papermaking past and present. Endeavour, 1988. 12(1): p. 38-43.

18 Scott, W.E., J.C. Abbott, and S. Trosset, Properties of paper : an introduction. 2nd ed., rev. ed. 1995, Atlanta, GA :: TAPPI Press.

19 Key Statistics 2014 EUROPEAN PULP AND PAPER INDUSTRY, CEPI, Editor.: Brussels.

20 Paperonline. 2017 [cited 2017 14.02.2017]; Available from: http://www.paperonline.org/.

21 Clifford, B. The Woodturner's Workshop. 2016 [cited 2015 10.10.2015]; Available from: http://www.turning-tools.co.uk.

22 Halonen, H., Structural Changes During Cellulose Composite Processing. 2012: Chemical Science and Engineering, KTH Royal Institute of Technology.

23 Wandelt, P., Technolologia celulozy i papieru. Technologia mas włóknistych. Vol. 1. 1996, Warszawa: Wydawnictwa Szkolne i Pedagogiczne. 281.

24 Chinga-Carrasco, G., Cellulose fibres, nanofibrils and microfibrils: The morphological sequence of MFC components from a plant physiology and fibre technology point of view. Nanoscale Research Letters, 2011. 6(1): p. 417.

25 Klemm, D., et al., Cellulose: Fascinating Biopolymer and Sustainable Raw Material. Angewandte Chemie International Edition, 2005. 44(22): p. 3358-3393.

26 Heinze, T., Cellulose: Structure and Properties, in Cellulose Chemistry and Properties: Fibers, Nanocelluloses and Advanced Materials, O.J. Rojas, Editor. 2016, Springer International Publishing: Cham. p. 1-52.

27 Biorefinery Site. Fiber Images 1. [cited 2017 01.02.2017]; Available from: http://biorefinery.utk.edu/ragauskas_fiber_images.html.

28 Bajpai, P., Bleach Plant Effluents from the Pulp and Paper Industry. SpringerBriefs in Applied Sciences and Technology. 2013: Springer International Publishing.

29 Egmason. Diagram of a Fourdrinier machine, created in Inkscape. 2010; Available from: https://en.wikipedia.org/wiki/Paper_machine.

30 Elise van Dooren, T.v.I., Cardboard Architecture. 2006, Arnhem, the Netherlands: Kenniscentrum Papier en Karton. 72.

31 The Science of a Paper Cut. 2016 [cited 2017 2017.05.17]; Available from: https://sites.psu.edu/siow-fa16/2016/09/14/the-science-of-a-paper-cut/.

32 The project paper a new light on paper. 2009 [cited 2017 07.07.2017]; Available from: http://paperproject.org/semgallery/semgallery2a.html.

33 Julia Schonwalder, J.G.R., F.A. Veer. Determination and Modelling of the Mechanical Behaviour of Cardboard as a Building Material. in 5th International PhD Symposium in Civil Engineering. 2004. Delft, the Netherlands: A.A. BALKEMA Publishers.

34 Elise van Dooren, T.v.I., Cardboard Architecture. 2006, the Netherlands: Kenniscentrum Papier en Karton.

35 Szewczyk, W., Determination of Poisson's Ratio

36 in the Plane of the Paper. FIBRES & TEXTILES in Eastern Europe, 2008. 16(4 (69)): p. 4.

37 Schonwalder, J. and J.G. Rots, Cardboard: An innovative construction material. Sustainable Construction Materials and Technologies, 2007: p. 731-740.

38 Schonwalder, J., G.P.A.G. van Zijl, and J.G. Rots, A Computational Model for Cardboard Creep Fracture, in Fracture of Nano and Engineering Materials and Structures: Proceedings of the 16th European Conference of Fracture, Alexandroupolis, Greece, July 3–7, 2006, E.E. Gdoutos, Editor. 2006, Springer Netherlands: Dordrecht. p. 475-476.

39 Correa, C., Designing with Paper Tubes. Structural Engineering International, 2004. 14(4): p. 277-281.

40 Bank, L.C. and T.D. Gerhardt, Paperboard tubes in structural and construction engineering. 2016: p. 453-480.

41 Andrew Cripps, H.G., Constructing a prototype cardboard building. Design Guide., B. Happold, Editor. 2001.

42 McQuaid, M., Shigeru Ban. 2003, London: Phaidon. 240 p.

43 Ban, S., Building structure. 2000, Google Patents.

44 Andrew Cripps, H.G., Constructing a prototype cardboard building. Final report, B.H. Ltd., Editor. 2001.

45 J. Schonwalder, J.G.R. Cardboard: An innovative construction material. in Conference on Sustainable Construction Materials and Technologies. 2007. Coventry, United Kingdom.

46 C. van Kranenburg, J.S., F.A. Veer, J. Zuidema, M. Wnuk. Investigation on multilayer paper boards as a structural material. in Third International Conference on Structural Engineering, Mechanics and Computation. 2007. Cape Town: IOS Press.

47 Wlodzimierz, S., Mechanical Properties of papaer cores. Part I. Testing methods. Polish Paper Review, 2011(2): p. 91-94.

48 2016 [cited 2017 17.09.2017]; Available from: http://www.fefco.org/about-fefco/what-fefco.

49 Minke, G., Alternatives Bauen : Untersuchungen und Erfahrungen mit alternativen Baustoffen und Selbstbauweisen. 1980, Kassel :: Forschungslabor Für Experimentelles Bauen, Gesamthochschule Kassel.

50 Morad, A.-K., A. Faggal, and Y. S El-Metwally, Efficiency of Corrugated Cardboard as a Building Material. 2012.

51 Chen, Z. and N. Yan, Investigation of elastic moduli of Kraft paper honeycomb core sandwich panels. Composites Part B: Engineering, 2012. 43(5): p. 2107-2114.

52 Pflug, J., I. Verpoest, and D. Vandepitte, FOLDED HONEYCOMB CARDBOARD AND CORE MATERIAL FOR STRUCTURAL APPLICATIONS. 1999.

53 Schmidt, P. and N. Stattmann, Unfolded: Paper in Design, Art, Architecture and Industry. 2009: Birkhäuser.

54 2014 [cited 2017 13.08.2017]; Available from: http://www.isoflex.se/.

55 kraftplex. 2017 [cited 2017 13.08.2017]; Available from: http://www.kraftplex.com/en/.

56 2017 [cited 2017 13.08.2017]; Available from: https://www.ptspaper.com/.

57 Lee, W. studio woojai. 2016 [cited 2017 08.11.2017]; Available from: www.woojai.com.