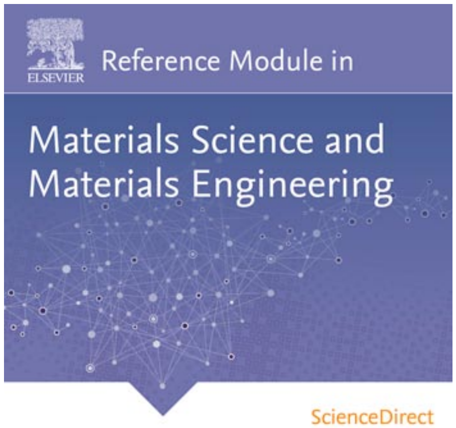

Chalmers I.R., and Abdullahi A.A., Paper Products: Container Board. In: Saleem Hashmi (editor-in-chief), Reference Module in Materials Science and Materials Engineering. Oxford: Elsevier; 2016. pp. 1-7.

ISBN: 978-0-12-803581-8

Paper Products: Container Board ☆

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Introduction

Corrugated board is a paper sandwich construction made by combining three or more paperboard sheets. In its most common form, two paperboard facings (liners) are adhered to each side of an inner paperboard sheet (corrugating medium) which has been formed (fluted) into a sinusoidal shape (**Figure 1**). By virtue of this construction, corrugated board achieves high stiffness and strength with low weight and cost. It is used to make containers, bulk bins, and inner packing and cushioning for packaging commodities. Corrugated containers are used to ship a large percentage of products packaged in the developed world. In the USA this requires about 23 billion boxes annually. The paperboard used in corrugated containers is made from wood fibers, which can be recycled into new containers and other paper products. In addition, flexible packaging material of longest standing, paper applications in the industry have long experienced efforts at substitution. Cellophane, called ‘transparent paper’ in its early days, provided product visibility not available with paper packages (Dunn, 2015).

Statistics have demonstrated that the pulp and paper industry is one of the largest industries in the world, with very high capital investments. The world's total paper production amounted to 403 million tons in 2013. The majority of manufacturing facilities in the paper industry are integrated. Most paper mills begin with wood chipping at the front end, followed by pulping, bleaching, papermaking, and recycling of post-consumer products. Subsequently, this high volume of production lead to municipal solid waste in some part of the world (Bajpai, 2015). An estimated 64 million metric tons of paper and paperboard was generated in the USA municipal solid waste (MSW) in 2011. Landfills remain the primary disposal method for MSW in the USA, although other alternatives (such as recycling, combustion) are available in some parts of the country (Wang *et al.*, 2015). The disposal of paper products in landfills also occurs in other countries that rely heavily on landfills for MSW disposal. Likewise, approximately two million metric tons of paper products were placed for landfills each year in Australia (Ximenes *et al.*, 2008).

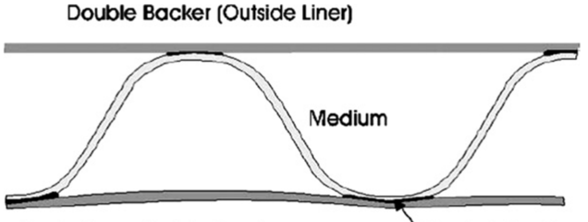

Figure 1 Cross-section of corrugated board showing main components.

☆*Change History*: July 2015. A.A. Abdullahi added abstract, keywords, and the text is expanded with additional review materials. Updated the list of References and provided an update History.

 doi:10.1016/B978-0-12-803581-8.02199-8

During the last few decades, recovered paper and board has become the principal raw material of the paper industry, and 57% of all paper produced worldwide today is based on recovered paper. In addition to the fibrous raw material, recovered paper also contains other substances that are introduced by the paper product itself (printing inks, stickies, and mineral particles) or during its use and subsequent collection (scraps and leftovers, sand, glass, etc.) (Grossmann *et al.*, 2014).

1 Functions and Requirements

The main function of the corrugated container and associated inner packing is to contain and protect the packaged product as it moves through the distribution system. During transportation the container must support compressive loads and protect the contents against impact, vibration, and handling stresses that could break or impair the quality of the product. After being transported, the container must retain enough strength to support high top-to-bottom compressive loads for long periods in warehouse storage. It must continue to provide such protection under adverse conditions of stress, humidity, and temperature. The container is also used to provide product identification and point-of-purchase market appeal. Graphic designs, multicolor printing, and specialty designed configurations are used to enhance selling power.

In the USA, general specifications for corrugated shipping containers are set out in Rule 41 of the Official Freight classification of the railroads and Item 222 of the National Motor Freight classification. Under these conditions, corrugated board is manufactured in several grades to give a graduated range of properties. Each grade is specified in terms of maximum total package weight, maximum box size, minimum combined weight of the facings (liners), and minimum bursting strength of the corrugated board used to make the box. Bursting strength is a measure of the strength of the board to resist rupture when pressure is applied in a prescribed way to one side of the board. The rules also specify the minimum basis weight and thickness of the corrugated medium. Many additional containers are made outside Rule 41 and Item 222 specifications to satisfy specific needs.

2 Types of Board

To satisfy the many uses of corrugated board, four main types are manufactured, as shown in **Figure 2**. Single-wall (double-faced) board, consisting of two facings adhered to one fluted medium, is suitable for most packaging demands and constitutes 85–90% of the market. Double- and triple-wall corrugated boards have two and three fluted layers with liners interspersed as shown. These are used for more severe applications. Some corrugated boards may consist of glued sheets of any of the previous constructions, for example, two double-walled sheets glued together to form a quadruple wall. This style is used for horticultural bulk bins and heavy manufactured goods such as stoves. Single-faced board is used in very small quantities for cushioning, inner packing, and for small, fragile items such as light bulbs. **Table 1** lists the flute dimensions used. Most corrugated board is produced with C flutes. Historically, flute sizes A, B, and E were used to give additional flexibility in meeting the specific requirements of a given application, and flutes F, G, and N have since been added that compete with cartonboard.

A major advance in flute profiles has been the development of the Xitex double-flute profile by Amcor in Australia. This profile uses a precision corrugating section to produce two flutes glued tip to tip, as shown in **Figure 3**. This profile effectively eliminates the use of a middle liner in a double-wall board to produce a corrugated board with improved compression performance per unit weight and with 200 flutes m^{-1}, improved printability.

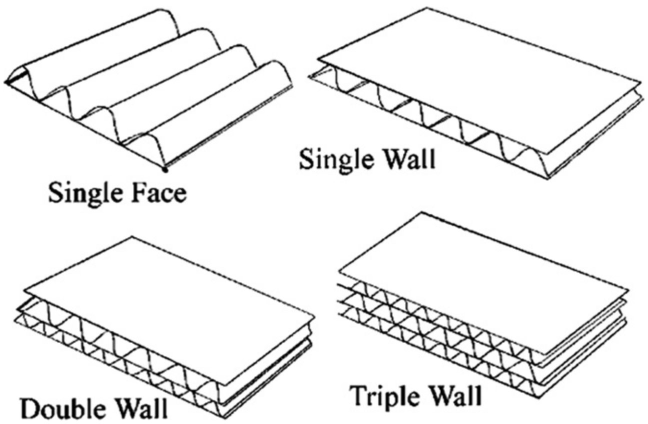

Figure 2 Types of corrugated board.

Table 1 Flute configurations in corrugated board

Flute	*Average flute height (mm)*	*Average number of flutes per meter*	*Medium take-up factor*
A	4.70	110	1.54
C	3.61	129	1.45
B	2.46	154	1.33
E	1.14	295	1.26
F	0.75	417	–
G	0.55	555	–
N	0.40	555	–

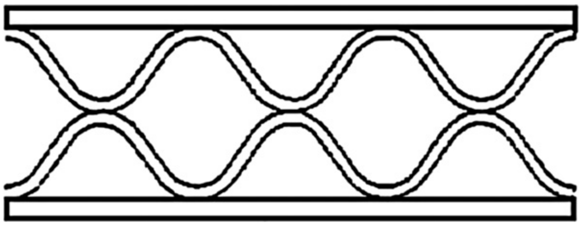

Figure 3 Xitex board.

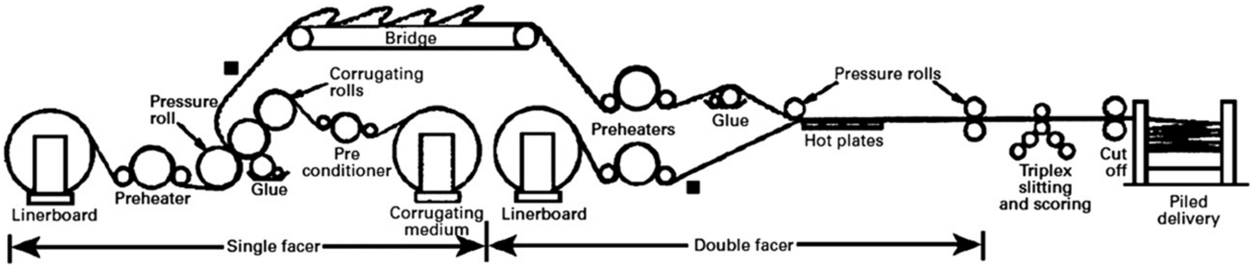

Figure 4 Schematic of a corrugator.

3 Board Manufacture

A corrugator has four main sections (**Figure 4**): single-facer, storage bridge, double-backer, and cutoff–takeoff section. In the single-facer the medium is formed to the flute contour and bonded to one facing (liner) to make single-faced board. The single-faced board web is conveyed onto a storage bridge, from which it is pulled into the double-backer section, where the second facing is bonded to the fluted medium. The finished double-faced (single-wall) board web is then slit and scored and cut to length to form sheets which are stacked in the cutoff–takeoff section. Double- and triple-wall board is made on corrugators equipped with multiple single-facers, bridges, and double-backer adhesive sections. Production speeds may be up to 300 m min^{-1}.

The corrugating process has two main elements: forming or fluting of the corrugating medium and bonding of the medium to the liners. In forming, the medium is drawn under tension into the nip between the corrugating rolls. As the medium is bent to the flute shape, it is subjected to high tensile, compressive, and shear stresses at the center of the nip (**Figure 5**). High transverse compressive stresses are applied to help 'set' the fluted shape. After passing through the forming process the medium must retain sufficient strength to fulfill its role in the corrugated structure. This is achieved through proper choice of medium properties, proper design of the flute contour, and, in conventional practice, by using heat and steam to soften the medium during fluting. The medium properties important to high-speed forming and strength retention are the kinetic friction in the plane of the sheet and the out-of-plane shear stiffness properties.

Bonding of the medium to the liners is commonly achieved with an aqueous starch adhesive (with borax and caustic) employed at a solids content of ~20%. Most of the adhesive is raw, uncooked starch kept in suspension by a small amount of cooked starch. To form a bond the raw starch component is gelatinized *in situ* and the excess water is driven off by the heat applied to the components in the single- and double-facer sections. In the single-facer, bonding is characterized by short duration, high-pressure combining. By contrast, double-face bonding involves longer duration, low-pressure combining. These contrasting

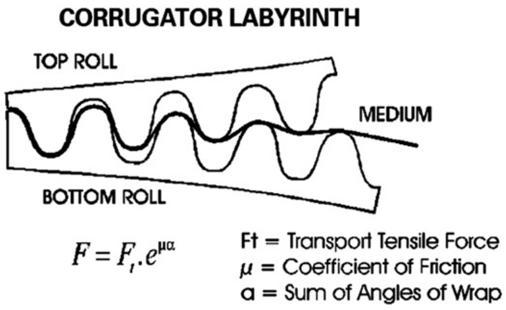

Figure 5 Forces on medium during corrugating.

combining conditions require different adhesive properties and proper balance of such medium and linerboard gluability properties as contact angle, receptivity, smoothness, and porosity to obtain strong, uniform bonding at high speeds.

To increase the rate of manufacture of corrugated board and to allow use of more economical starch formulations, many modern corrugated plants use the Jet Set process which speeds up the relatively slow gelatinization step (Griffiths *et al.*, 1969). This process involves full-width application of steam to the medium side of the single-facer to pregelatinize the starch immediately before its bonding to the second liner ply. Two Jet Set units are required, one at each single-facer ply, to pregelatinize the starch in making double-wall board, while three units are desirable for producing triple-wall board.

In the finishing operation, sheets of corrugated board from the corrugator are made into containers or other structured forms by operations involving scoring (creasing), folding, cutting and slotting, gluing, and printing. High tensile strengths are required for successful folding. Good surface properties for printing are a necessity.

4 Properties

4.1 Corrugated Board

In addition to satisfying Rule 41 or Item 222, the board must also provide high box compressive strength and resistance to damage for product protection and retention of strength. The adverse effects of long-term loading (creep) and high humidity are usually accommodated by safety factors in box design.

Historically, the burst and basis weight requirements of Rule 41 or Item 222 was satisfied by choosing liners of proper weight and burst values, the latter because corrugated board burst values are a function of the burst values of the liners, the medium contributing very little. The effect of the revision to the rules in the early 1990s was to provide an alternative criterion that placed more emphasis on the edgewise compressive strength (ECT) of the liners and medium. The medium must simply be of proper weight and caliper. The altered rules allow the use of new lightweight, high-performance grades that have superior ring crush or short-span compression (SCT) values that reduce cost, improve stacking, and save fiber.

Theoretical and experimental results show that container compressive strength is primarily dependent on the ECT of the board in the direction of box load, the flexural stiffness of the board in both directions, and the box geometry. The ECT of corrugated board is essentially the combined compressive strengths of the components; board caliper (flute size) has only a minor effect. Greater strengths are thus obtained by using heavier liners or medium, or selecting a multiwall construction.

Flexural stiffness of corrugated board, the other important factor in box compressive strength, varies with the direction of test (machine direction (MD) or cross direction (CD)), flute size, and the elastic stiffness (modulus % thickness) of the components. The MD stiffness can be two or three times greater than the CD value, primarily because of the inherent directionality of linerboard. For given components, corrugated board flexural stiffness varies as the square of the caliper. So, for example, A-flute boards are much stiffer than B-flute boards (and hence give greater ECT). **Table 2** lists engineering properties of single-wall corrugated boards made in a range of constructions. The data of **Table 2** are taken from a number of sources and are believed to encompass normally encountered ranges of strength.

Product cushioning and resistance to damage of the corrugated structure are determined primarily by response to compressive loads applied perpendicular to the board plane. Flat crush strength is the measure of this property. It is primarily dependent on the MD compressive properties of the fluted medium and varies inversely with flute height. A typical flat crush value for C-flute board made from a 127 gm^{-2} medium is 295–330 kPa. Values for A- and B-flute boards would be below and above C-flute values, respectively.

The tensile properties of corrugated board are not often measured, owing to experimental difficulties. Empirical measures of tearing resistance or puncture are sometimes used to relate to container rough handling performance.

In the late 1980s it was found that cyclic humidity service environments had a serious effect on the stacking performance of corrugated boxes (Leake, 1988). This mechano-sorptive effect is much more severe than for storage in high humidity alone and to

Table 2 Mechanical properties of single-wall corrugated board

Flute	*Liners (gm^{-2})*	*Medium (gm^{-2})*	*Total board grammage (gm^{-2})*	*Minimum burst (kPa)*	*Thickness (mm)*	*CD ECT (kNm^{-1})*	*Flexural MD (kNm^{-1})*	*Stiffness CD (kNm^{-1})*
A	185	127	566	1200	4.7–5.0	–	26–39	11–15
A	205	127	606	1380	4.8–5.2	7.0–8.8	27–49	15–17
A	337	127	870	1900	5.1–5.5	8.8–10.5	52–70	18–30
A	439	127	1074	2410	5.2–6.0	10.5–13.1	–	–
C	127	127	438	860	3.6–3.9	4.9–5.8	14–23	6–8
C	185	127	554	1200	3.7–4.2	7.0–8.8	18–26	7–10
C	205	127	594	1380	3.8–4.2	7.0–9.6	20–30	8–14
C	337	127	858	1900	4.3–4.7	9.6–13.1	28–40	15–20
C	439	127	1062	2410	4.4–4.8	12.3–15.8	–	–
B	205	127	579	1380	3.0–3.2	7.0–8.8	12–15	4–6
B	337	127	843	1900	3.3–3.6	10.5–13.1	18–25	9–12
B	439	127	1047	2410	3.4–3.8	–	–	–

Table 3 Linerboard and corrugating medium properties at 50% RH and 23 °C

Property	*Orientation*	*Test ranges*	
		Linerboard	*Medium*
Nominal basis weight (gm^{-1})	–	205	127
Thickness (mm)	–	0.30–0.35	0.23–0.30
Bursting strength (kPa)	–	690–830	–
Edgewise compressive strength (kNm^{-1})	MD	2.7–3.5	–
	CD	1.9–2.6	0.9–1.4
Tensile strength (kNm^{-1})	MD	14–17	4.5–9.5
	CD	5–6.5	2.0–3.3
Stretch (%)	MD	1.3–2.0	1.0–1.7
	CD	3.0–4.4	1.3–4.2
Tensile (elastic) stiffness (kNm^{-1})	MD	1500–1700	660–1100
	CD	500–1000	235–390
Tearing strength (N)	MD	2400–3500	–
	CD	2900–4000	–
Concora flat crush (N)	–	–	245–290
Water drop (s 100 ml^{-1})	–	–	15–600 +
Porosity (Bendtsen) ($mlmin^{-1}$)	–	–	300–1400
Transverse shear stiffness(kNm^{-1})	MD	–	~25–30
Kinetic friction coefficient vs. steel	MD	–	0.29–0.62

allow for this phenomenon an allowance needs to be built into the box performance specifications over and above those anticipated for high-humidity environments.

4.2 Linerboard

Linerboard is the paperboard used for the facings in corrugated board. Most domestic linerboard is made from long-fiber softwood species chemically pulped by the kraft process and not bleached. However, linerboards are available having a bleached or mottled white surface or a colored surface to meet decorative packaging and display requirements. Kraft linerboard is made on fourdrinier paper machines, often in a two-ply construction. Common liner grade weights include 127, 161, 186, 205, 229, 337, and 439 gm^{-2}. Table 3 lists, for a common grade weight of linerboard, various mechanical properties important to converting and container performance. The ranges shown are representative but not all-inclusive.

Bursting strength, the liner specification stemming directly from Rule 41 or Item 222, is dependent on basis weight, fiber furnish, fiber–fiber bonding, and many pulping and papermaking factors. The use of long-fiber softwood pulp for liner is predicated, in part, on satisfying the burst requirement. Long fibers also give good tear resistance, but this is reduced by the refining necessary to achieve bursting strength. Hence, these properties are somewhat in conflict, but bursting strength has a decided edge in importance.

Tensile and compressive strengths and elastic stiffness are all very important to converting and corrugated board properties. All are sensitive in various degrees to basis weight, fiber furnish, fiber–fiber bonding (density), fiber orientation, pulp yield, dry strain, strength additives, and other factors. Thus, linerboard manufacture requires adjustment of these to produce the proper blend of property values for end use.

There are several methods for measuring edgewise compressive strength of paperboard, including the ring crush test (see test values in **Table 3**). This method uses a cylindrical test specimen to minimize buckling. Despite this, the test specimens often fail by buckling or crushing along the loaded edges, resulting in test values lower than the intrinsic compressive strength of linerboard and medium. The intrinsic compression value is better quantified by a newer test called the short-span compression test (SCT) where the compression resistance of a 15 mm wide sample is measured over a 0.7 mm (or thereabout) long span which eliminates buckling. The ring crush test is still popular because it more closely simulates the span encountered between flutes in corrugated board.

4.3 Corrugating Medium

Corrugating medium is the paperboard component used to form the corrugated or fluted member in corrugated board. It is usually made from semichemical hardwood pulps (short fibers) or recycled fiber (mostly from used containers). Most domestic medium is made on fourdrinier paper machines at a nominal grade weight of 127 gm^{-2} and a thickness of 0.23 mm or more. Heavier weights are made, up to $\sim$205 gm^{-2}, to meet special packaging needs.

In addition to basic weight and thickness, the most common mill quality tests are Concora flat crush and some indication of water receptivity as a measure of bondability. Concora flat crush is a standard test of the Technical Association of the Pulp and Paper Industry (TAPPI) which relates to combined board flat crush. Concora flat crush values usually range from $\sim$245 to 290 N on nominal 127 gm^{-2} media.

Desired corrugating medium properties depend on both the process and end-use requirements. The satisfactory forming of medium requires a high MD tensile strength, Young's modulus, or stiffness, low MD transverse shear modulus, and a low friction coefficient toward *hot* steel or chromed surfaces. In the corrugating operation the medium must have suitable surface properties to promote bonding to the linerboard facings. These include receptivity to aqueous adhesive, smoothness, and porosity.

For end-use requirements, the medium must contribute high edgewise compressive strength in both directions. In the machine direction, high compressive strength promotes high resistance to stresses of flat crush type for the corrugated board. In the cross direction, high edgewise compressive strength contributes importantly to container compressive strength. **Table 3** summarizes the mechanical and other properties of the most common commercial grades of corrugating medium.

5 Specialty Treatments

Corrugated board is often coated and/or impregnated with chemicals such as wax to provide extra protection under the humid or wet conditions encountered in packaging poultry, fresh fruits, and vegetables. Other treatments provide protection, for example, against insect infestation, product corrosion, or grease transfer. Antiskid coatings may be applied to prevent slippage of stacked boxes.

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