3. Baseboard physical properties

Performance properties 111
Laws of nature 112
Flatness and stability 116
Strength and toughness 123
Defined physical properties 125
Tensile strength 125
Compression strength 126
Complex physical properties 128
Tearing resistance 128
Impact burst strength 128
Delamination, interlaminar strength 129
Stiffness 134
Box compression strength 138
Performance properties
Performance properties

The performance properties are related to the physical characteristics of the paperboard. These properties relate to how the paperboard will withstand the surrounding environment. The following performance properties are described in this chapter:

• flatness and dimensional stability
• strength and toughness
• stiffness
• box compression strength.

Measurable properties

The measurable properties are those which are commonly found when describing the technical data for a paperboard grade. The methods described are those most commonly used. They are also used by Iggesund Paperboard.

For further information about specific testing equipment see the manufacturers' product catalogues (e.g. Lorentzen & Wettre).

The measuring methods for the properties listed are described in the following pages:

• tensile strength
• tearing resistance
• interlayer strength, plybond
• bending stiffness
• bending resistance
• bending moment
• density
• dimensional properties - Flatness
• grammage
• grammage (plastic-coated products)
• thickness
• compression strength
• moisture content
• stiffness
• curl and twist.
Laws of nature

Two of the most basic physical properties that define a paperboard are grammage and thickness. These properties tell us how much fibres and coating that is used for one square meter of board, and what thickness that results in. Based on grammage and thickness the density, or the bulk which is the density inverted, can be calculated and is often used to indicate whether a paperboard has a high or a low thickness at a given grammage. E.g. low density = high bulk = high thickness.

Most of the differences in the appearance and performance properties are a result of the types and amounts of pulps used. Within each type of paperboard there are a range of properties depending on the exact fibre composition, furnish, coating application and manufacturing technique. Within certain limits set by nature, each boardmaker can achieve a number of combinations. The main traits of these combinations will be apparent by evaluating thickness, grammage and density.

With a given amount of fibres and amount of coating the grammage is set. Deriving from this the boardmaker tries to optimise stiffness while trying to maintain strength in the sheet. Within the same grammage, optimization of strength by increased amount of chemical pulp will lead to increase in density and loss of thickness. When optimizing stiffness the thickness, or bulk plays an important role together with the strength properties of outer plies in a multi-ply construction. Coating and calendering will affect thickness negatively but promote print- and print finishing result positively. A high amount of coating also limits the amount of fibres within a given grammage, thus decreasing strength or stiffness depending of which types of fibre you spare for the weight compensation.

Strength properties are often described and discussed in relation to density and stiffness performance often discussed in relation to thickness as described in the following chapter.

### Test method and equipment

During production the grammage is measured continuously on-line with an IR device. For calibration and other investigations a gravimetric method is used. The principle is as follows:
1. Cut out a sample with specified area (normally by using a punch, 0.5 dm² or 1 dm²).
2. Carefully rinse all fibres from the plastic film by soaking in diluted NaOH solution.
3. Dry and weigh on a balance (with at least 0.001 g accuracy).
4. Calculate the result in g/m².

### Key characteristics

Grammage is controlled through the flow of pulp to the headboxes (fibre distribution units) on the paperboard machine. Since grammage includes the amount of fibre and moisture in the paperboard, the two together play an important role in the consistency and uniformity of the paperboard characteristics.

By consistency we mean low variation against time of manufacturing, and by uniformity, low variation across the paperboard web.

### Measurable properties

**Measureable properties**

**Grammage (ISO 536)**

The grammage specifies the weight of the paperboard per unit area in g/m².

**Test method and equipment**

Grammage is scanned constantly on-line on the paperboard machine and linked automatically to the process control of moisture and pulp flow. Laboratory tests are routinely done to check the calibration of the on-line equipment. These tests are done by weighing sheets of specified size in a controlled atmosphere.

**Grammage (plastic-coated products)**

The coat weight of the plastic is the weight per unit area and it is normally expressed in g/m².

**Density (ISO 534)**

Density is the expression used to describe the compactness of the paperboard. Density is calculated as the ratio of grammage and thickness in kg/m³. An increasing thickness at constant grammage results in a lowering of density with density being reciprocally proportional to thickness.

**Test methods and equipment**

Density (kg/m³) = \( \frac{\text{grammage (g/m²)}}{\text{thickness (µm)}} \times 1000 \)

Bulk is the inverse of density and is expressed in cm³/g.

**Test methods and equipment**

This property is calculated from measurements of grammage and thickness.
Key characteristics
The main influence on density is the type of fibre used. Mechanical fibres give the potential for lower density than chemical fibre. Multi-ply forming also enables density to be reduced during the forming process. Fibre treatment and mixing of the fibres in the different paperboard layers is used to optimise density.

Surface smoothness conflicts with density (stiffness), as increased calendering to improve smoothness reduces thickness, giving higher density and hence a lower stiffness.

Within the same type of paperboard, at constant density, the thickness increases with increasing grammage. Mechanically processed fibres normally give higher thickness compared to chemically processed fibres for a given grammage. Multi-ply forming benefits high thickness compared to single-ply forming. Increased calendering reduces the thickness but gives a smoother surface.

Basic relationships
Graphics and packaging applications place demands on paperboard that are dependent on combinations of appearance and performance properties. The type and amount of fibre as well as the manufacturing technique permit a large number of possible options. However, there are also constraints governed by natural laws which limit the number of combinations. This section explains some of the most important factors and their interaction, and will clarify some of the basic relationships, in order to assist in better decision making in the challenging world of paperboard selection.

The appearance and performance properties of paperboard can be described in terms such as:
- whiteness, smoothness, and gloss
- chemical character and purity
- elasticity, strength, and density.

Fibre and paperboard properties
Most of these properties are directly or indirectly dependent on the type and characteristics of the basic raw material, i.e. the fibres.
Two main types of fibres are used for all types of paperboard, those produced by mechanically or chemically processing the wood. Due to these very different treatments the properties of the resulting fibres (or pulps as they are known in the industry) are also very different. Some of the basic fibre and paperboard properties are summarised in the illustration below.

All paperboards require a certain combination of whiteness and strength to meet appearance and performance demands.

The most common types of pulps give the combinations shown in the illustration on the previous page.

By mixing mechanical and chemical fibre in a multiply technique, the paperboard maker can optimize the raw material usage and tailor the end use demands to the paperboard properties. A complication is that some of the demands are entirely contradictory. Such an example is to obtain both maximum stiffness and strength with a given fibre composition.

The strength, flexibility, and consolidation behaviour of chemically processed fibres results in well formed, dense, and strong products. Mechanically processed fibres have in these respects the opposite characteristics resulting in open, bulky and weak, but stiff products. As both stiffness and strength are important the boardmaker has to achieve a compromise.

This is done by treating and mixing the fibres and using the multi-ply technique. The illustrations show some physical relationships for single ply sheets.

The multi-ply technique is used to optimise the stiffness and to achieve the desired appearance and surface properties with a minimum use of fibres. With Folding Box Board this is done by putting the high bulk mechanical pulp in the middle layers and the dense, strong, and smooth chemical pulp in the surface layers. By adding a layer of pigment coating a further enhancement of the appearance is achieved. Even if 100 % chemical pulp is used in all plies, the plies are treated differently to make use of the multiply principle.

For a given fibre composition and ply construction the stiffness is strongly dependent on the thickness of the paperboard. In theory stiffness is proportional to the cube of thickness. The strength properties are usually proportional to the weight (grammage).
Paperboard grades and properties

The dominating types of pulp used for paperboard are made from primary wood fibres separated via mechanical and chemical processes, and pulp made from recycled fibres. Due to the quite different characteristics of these pulps, they are utilised in four different types of paperboard:

- bleached chemical pulps – Solid Bleached Board (SBB)
- unbleached chemical pulps - Solid Unbleached Board (SUB)
- mainly mechanical pulps – Folding Box Board (FBB)
- mainly recycled pulps – White Lined Chipboard (WLC).

Most of the differences in the appearance and performance properties are a result of the types and amounts of pulps used. Within each type of paperboard there are a range of properties depending on the exact fibre composition and manufacturing technique. Within certain limits set by nature, each boardmaker can achieve a number of combinations.

In each case, it is important to match the required appearance and performance against the paperboard’s specific characteristics. Based on a large amount of test data for various grades combined with experienced judgement, some typical fibre-dependant differences can be identified. The indicated levels can be moved upwards or downwards, but within limits depending on the type and amount of fibres, ply composition and manufacturing conditions.

Stiffness – strength – appearance

Stiffness and strength are two basic paperboard properties which have a major influence on the mechanical paperboard performance of paperboard. They have a crucial effect on the boards protective properties and also influence carton shape and appearance.

The laws of nature make it impossible to maximize strength and stiffness simultaneously. Every application is a compromise to find the best balance.

Types of fibres

The physical properties of paperboard are determined largely by the types and amounts of fibres used. While these are the key factors influencing most properties, bending stiffness is the property that is most dependent on fibre composition as well as ply construction, specifically, on whether the paperboard consists of one or several plies.

The two main types of fibres used for paperboard are mechanically or chemically processed. Due to the very different treatment of wood in the mechanical and chemical processes, the resulting properties of the two types of fibre differ considerably.

When a paper product is recycled, the repulped fibres still ultimately originate from the same two sources, i.e. mechanical and chemical fibres. During recycling the fibres become contaminated and worn (lose strength). Depending on the application, the maximum number of cycles possible is theoretically in the range of 7–8 but in many cases is only 2–4 depending on the original pulping method, etc. Therefore primary fibres are always needed to maintain the quality of recycled products. Typical values for the different types of fibres are given in the following illustration.
Flatness and stability

Flatness and good dimensional stability are critical paperboard properties. The proper flatness or "shape" of the paperboard sheet, as well as of the die-cut carton blank, is of major importance for good runnability in all processing of paperboard, including packing line efficiency.

For graphical products such as cards, book covers, folders, etc. the flatness as such is important for the presentation of the finished product.

During the converting and packaging processes the paperboard is often exposed to conditions which affect its moisture content. Depending on the type of paperboard, its raw material composition and manufacturing process, the paperboard sheet will experience changes in its shape or dimensions.

In these contexts, shape is a better descriptive term than flatness. In practice, the shape at the point of manufacture differs from absolute flatness in order to compensate for the change in shape which can occur during printing and conversion.

**Measurable properties**

**Moisture content (ISO 287)**

Moisture content is expressed as a percentage of the total paperboard weight. As paperboard is a hygroscopic material, all testing should be done in a controlled climate of 23 °C and 50 % RH. It is also important that exposure during further processing is under controlled temperature and RH conditions.

**Test method and equipment**

The moisture content is measured and controlled continuously on-line on the paperboard machine by scanning equipment which gives a high degree of definition in both the machine direction (MD) and cross direction (CD) of the paperboard web. Laboratory testing is carried out regularly to ensure correct on-line calibration.

**Key characteristics**

Since many paperboard characteristics are influenced by the moisture content, it is important to manufacture to a level which corresponds to the needs of the printing, converting and packaging operations.

Moisture content is controlled during the drying process on the paperboard machine. Independent control of both the print and the reverse side of the paperboard is essential to ensure even drying and curl control. It is also possible to ensure an even moisture profile across the width of the web by on-machine measurement and control.

Cellulose fibres are hygroscopic and will react to changes in humidity by swelling during moisture uptake and shrinking when losing moisture. For the cellulose fibre itself the relative dimensional change is greater in the cross-fibre direction.

On the paperboard machine, the process always gives some preference to fibre orientation in the machine direction (MD) of the paperboard sheet. This means that there are a majority of fibres orientated with the fibre length direction parallel to the machine direction.

The relatively large potential for dimensional change across the fibre, together with the fibre orientation, makes the dimensional change and hence the shape of the sheet more pronounced in the cross-direction (CD).

The fundamental principle for changes in dimensions or shape is shown by the illustration below.

If the two surfaces of the paperboard sheet are equal regarding their relative dimensional moisture change, a change in moisture will only affect the sheet’s dimensions, that is lateral expansion or shrinkage. Such paperboard grades are as close to the ideal symmetric sheet as possible, e.g. equally two-side coated or uncoated paperboard products of symmetric construction regarding composition, construction and treatment.

A paperboard sheet where the surfaces have different relative moisture expansion will bend for a given change in moisture. Examples of such paperboard products are one-side coated products or two-side coated or uncoated...
Paperboard sheet construction and the expected shape change of an asymmetric sheet in different environments.
paperboard with asymmetric composition, construction or treatment of the basic paperboard. In practice almost all paperboard products belong to this type.

**Dimensional changes**
As paperboard is a very hygroscopic material, many of its properties are strongly influenced by the relative humidity in the surrounding air, and hence the moisture content of the paperboard. Accordingly, a consequence of moisture change is a change in the paperboard dimensions.

**Moisture equilibrium**
Paperboard is manufactured to meet a certain shape at a predetermined moisture content. At this moisture content the paperboard will be in equilibrium with a given level of relative humidity (RH) in the surrounding air, that is it will neither gain nor lose moisture at this RH. The equilibrium moisture content will vary depending on the type of paperboard and its fibre composition.

Measurements have shown a negative correlation between the density of the paperboard and the level of equilibrium moisture. The relative humidity (RH) stated in this table applies to the surrounding air.

In printing, die-cutting and other operations it is important to maintain register control and to keep the paperboard blanks flat. Therefore it is important to keep the relative humidity of the surroundings in equilibrium with the specified moisture range of the paperboard.

**Hysteresis**
Hysteresis is a lagging effect in which a memory of the previous state is retained.

There is one range of equilibrium moisture content for increasing relative humidity and a slightly different range for decreasing relative humidity. These ranges vary for various paperboard grades.

<table>
<thead>
<tr>
<th>Moisture content in paperboard at 15% RH</th>
<th>Moisture content in paperboard at 50% RH</th>
<th>Moisture content in paperboard at 90% RH</th>
</tr>
</thead>
<tbody>
<tr>
<td>High density (SBB) %</td>
<td>3.2</td>
<td>-11.5</td>
</tr>
<tr>
<td>Medium density (WLC) %</td>
<td>-6.0</td>
<td>-12.0</td>
</tr>
<tr>
<td>Low density (FBB) %</td>
<td>-3.9</td>
<td>-13.5</td>
</tr>
</tbody>
</table>
Moisture expansion coefficient

The moisture expansion coefficient (β) is defined as the relative dimensional change in percent divided by the corresponding change of moisture content in the paperboard.

\[
\beta_{MC} = \frac{\Delta L}{L \Delta MC} \times 100 \% \]

\( \Delta L \) = Change of length due to moisture expansion
\( \Delta MC \) = Moisture content change in paperboard sample

\( \beta \) is specific for a given type of paperboard and practically constant.

\( \Delta RH \) = Relative humidity change

The moisture expansion coefficient for a typical paperboard is three times as large in the cross direction (CD) as in the machine direction (MD) of the sheet. In the thickness direction it is ten times as large as in the cross direction.

Here once again the hysteresis effect comes into play as the moisture content in the paperboard also depends on whether the paperboard has come to the climate equilibrium from a dry or humid environment.

In a relative humidity of 50 % the equilibrium moisture in the paperboard can be anywhere between the upper and lower part of the hysteresis curve as shown to the right.

The paperboard is manufactured to match a relative humidity during printing and conversion of 50 % RH at +20 °C. It is therefore manufactured to a slightly higher moisture content to allow some drying, which is normal. The paperboard is prevented from drying out too much by a moisture-proof wrapping.

It is very important that the paperboard is handled and stored correctly all the way from printing and converting, through packing and use (see recommendation under General technical information in the Product Catalogue).

### Parameters

<table>
<thead>
<tr>
<th>Calculations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Change in moisture content from 7% to 6.5 %</td>
</tr>
<tr>
<td>Expansion coefficient (CD)</td>
</tr>
<tr>
<td>Dimensional change (%)</td>
</tr>
<tr>
<td>Sheet size (CD)</td>
</tr>
<tr>
<td>Dimensional change (mm)</td>
</tr>
</tbody>
</table>

### Typical β values (SBB)

<table>
<thead>
<tr>
<th>Machine Direction</th>
<th>Cross Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.5 ( \times 10^{-2} )</td>
<td>25 ( \times 10^{-2} )</td>
</tr>
</tbody>
</table>
The paperboard will in practice follow the upper part of the curve during printing and conversion. This implies that from the moisture and moisture expansion (shape) point of view the result is limited to the change from points 1 and 2.

If the paperboard is allowed to dry out to a moisture content below the equilibrium of 50 %, the equilibrium moisture and shape will be unpredictable. This will result in moisture and hence a moisture expansion (shape), depending on where the equilibrium moisture is established on the vertical line between points 2 and 3.

The situation described above is valid for the paperboard during its lifetime in storage and processing throughout packing and use.

By multiplying the moisture expansion coefficient with the actual change in moisture content of the paperboard, the change in dimensions of the sheet is given. It is then easy to calculate the absolute change in mm as shown by the following example.

As the moisture expansion coefficient is specific to the type of paperboard, a different paperboard grade will show a different change in size.

The paperboard choice
In all applications of paperboard – graphical as well as packaging – it is important that the paperboard retains a flat shape. Changes in shape lead to poor runnability in printing, converting and packaging operations. In all graphical applications, e.g. picture postcards, book covers, etc., the shape of the finished product is also of prime importance.

Paperboard is sensitive to changes in humidity. Exposure to variations of humidity will result in a change of paperboard shape or dimensions. Paperboard is manufactured to be flat in a defined environment; exposure to another environment will create a situation where the paperboard shape is unstable. Information concerning the end use environment must be given to the boardmaker. As paperboard is made of cellulose fibres there is practically no way to prevent the paperboard adopting a moisture content which is in equilibrium with the surrounding air. Any change in moisture will affect the diameter of the cellulose fibre and hence the paperboard shape. Depending on the type of fibre and treatment the change in shape can vary from one paperboard grade to another.

Both Folding Box Board and Solid Bleached Board are manufactured from primary fibres, which means that their behaviour in different climate conditions is predictable.

Flatness and dimensional stability characteristics
Flatness and dimensional stability equate with the paperboard’s ability to withstand the effect of humidity changes in the environment.
Assessment of curl and twist

The paperboard's shape is defined by curl and twist. Flatness should be evaluated on a single sheet and not on a pallet, since the shape of a pallet is influenced by the temperature difference between inside and outside.

A curlCD has the axis of curl in the machine direction and a curlMD has the axis in the cross direction. The curl is defined as downcurl when the printing side of the paperboard has a convex shape.

Curl is defined as the inverse of the radius of curvature, \(1/r\) (1/m = m⁻¹). If the sheet is flat, the radius approaches \(\infty\) and accordingly the curl will approach 0.

\[
\text{Curl} = \frac{1}{r} \quad \text{(Units = m⁻¹)}
\]

Another type of curl is reel curl. This type of curl is oriented in the machine direction of the paperboard and is typically caused when the paperboard has been stored for a long period of time in reels tightly wound around a narrow diameter core. This curl can be oriented up or down relative to the printing side depending on whether the printing side has been wound in or out.

When measuring curl and twist, the chords of the nine circles are measured: see L&W curl and twist tester. Two chords C1 and C9 are shown in the illustrations. If these chords have different angles in relation to the horizontal plane the sample has twist.

The change in angle of the chords when moving in the machine direction gives a measurement of twist.

\[
\text{Twist} = 2 \times \frac{\Delta \theta}{\Delta d} \quad \text{(Units = m⁻¹)}
\]

\(\Delta \theta\) = Change of angle in radians
\(\Delta d\) = Movement in positive machine direction (m)

The twist is defined as positive when the chords are turning counter-clockwise when moving in the machine direction and negative when the chords are turning clockwise. The twist angle is the angle in the MD where the sheet has no twist. It can take values between 0 and +/- 45 °.

Key properties

The degree of dimensional, and hence curl, change is influenced mainly by:

- type of fibre and ply construction
- degree of fibre refining and internal sizing
- fibre orientation (anisotropy)
- coating type and composition
- uniformity in moisture profiles.
Measurable properties

Curl and twist

The simplest method of measuring the curl of a paperboard is to cut a square sheet, condition it at 50% RH and 23 °C and match the MD and CD edges to a set of curves of differing radius of curvature. Stability can be checked by measuring shape on a sample after conditioning between pre-determined relative humidities (ascending and descending). The curl and twist tester measures the curl, twist and twist angle of paperboard samples. In addition, an evaluation of how much these properties change in different climates, i.e. the dimensional stability, can also be done.

Five test pieces, taken from positions across the paperboard machine width, are mounted and conditioned to a relative humidity of 35%, 50% or 65%. The curl and twist tester evaluates a cross section through the sheet in parallel with MD (see the illustration above).

At this cross section, the curvature of the sheet is assumed to follow a circle with radius r. The curvature at this cross section is expressed as the inverse of the radius r (r is expressed in metres). Each sample is assessed by nine scans, giving 81 measuring points. Sample size is 10 x 10 cm. How closely the scans correlate to a perfect circle is given by a correlation factor, where 1 means full correlation and 0 no correlation with a circle.
Strength and toughness

Strength and toughness are composite terms used to describe one or several of the paperboard’s physical (mechanical) properties. They play an important role, directly or indirectly, in a large number of paperboard applications and users’ situations. Strength and toughness are important characteristics for the paperboard’s ability when it comes to:

- **promotion**
  Sophisticated surface design, such as embossing, or complicated box construction, creative shape and functional shape.

- **protection**
  Physical protection and resistance to stacking, handling and stresses from the environment.

- **production**
  Conversion and treatment of paperboard such as embossing, cutting, creasing, and folding. Important for packaging and conversion efficiency.

The physical properties of paperboard can be split into two groups:

- **well-defined physical properties**
- **complex (less well-defined) physical properties.**

Examples of well-defined properties are those where generally accepted definitions and methods (from physics) are applied to paperboard. An example is tensile strength. Complex, or less well-defined, properties are those where one or several properties are combined into a functional characteristic or where methods are used that try to simulate a user’s situation. Box compression strength and tearing resistance are examples of this category.
The paperboard choice

In packaging applications, protection is the primary paperboard function. Therefore the paperboard's ability to withstand a range of applied stresses is an important consideration in the choice of paperboard. This need is achieved by the strength and toughness properties of the paperboard.

A first step in choosing a paperboard is to identify the applied stresses to which the paperboard will be exposed in printing, conversion, packaging, distribution, and consumer use. Any exposure to extremes of temperature or humidity in the environment results in changes to the moisture content of the paperboard. If high moisture contents occur there will be a significant loss in strength. The weight of the product, its shape, whether it has sharp edges, whether it is a solid, granular, a powder or a liquid, are all features which influence the paperboard requirement.

Strength and toughness are complex properties, which are defined by characteristics such as elasticity, elongation, stiffness, tensile strength, box compression strength, etc. Some properties are well defined and easy to measure, such as tensile strength. Others are more difficult, such as box compression strength. The contribution of the structural design to complex properties such as box compression strength is best examined by box compression tests, travel tests or other realistic handling testing.

Converters often have requirements on the strength of paperboard, in order to perform certain operations, such as printing and cutting, without stoppages and production delays. Sometimes the demands from the conversion operations on the strength properties are contradictory. A low tearing resistance might be needed when a pull tab is to be used for opening but a higher value would be better if the package is to be opened and closed a number of times. Because paperboard is a visco-elastic material, permanent deformation occurs during creasing and embossing but that must be avoided during printing. Delamination strength must be balanced to allow the paperboard to delaminate when creased but to stay intact during other operations and use.

The different types of fibres have an effect on the strength properties, the longer the fibres the higher the strength. Solid Bleached Board (pure bleached chemical pulp) has good strength properties and Folding Box Board (mechanical pulp with bleached chemical pulp in the surface plies) has high stiffness. The printing, conversion and end-use application determines the relative importance of the various strength properties. For any given type of paperboard strength properties vary with grammage and thickness.
Defined physical properties

Well-defined physical properties are:
- elasticity
- tensile strength
- elongation
- compression strength.

Elasticity
Paperboard has an elastic behaviour up to a given limit – the elastic limit. This means that the force applied to the paperboard is proportional to the deformation caused by the applied force. If the force is removed the paperboard regains its original dimensions. This is summed up by Hooke's law:

\[
\text{stress} = \frac{\text{modulus of elasticity} \times \text{strain}}{\text{applied force}} \quad \frac{\text{material constant}}{\text{dimensional change}}
\]

Paperboard deformed beyond the elastic limit has a plastic behaviour. This means that the applied force is no longer proportional to the deformation. When the force is removed the paperboard does not regain its original dimensions – it has become elongated. The value of the elastic limit is typically 0.2–0.5 % relative elongation.

After exceeding the elastic limit a permanent change of dimensions occurs. In practice this is a common reason for misregister during web printing.

The modulus of elasticity, $E$ also known as Young’s modulus, is proportional to the initial slope of the curve.

\[
E = \frac{\Delta F}{\Delta e} \quad (\text{Units} = \text{N/m}^2)
\]

$E$ = Modulus of elasticity
$\Delta F$ = Tensile force increment
$\Delta e$ = Elongation increment

Tensile strength and elongation
Tensile strength is the force per unit width which is required to rupture a strip of paperboard. The value is usually determined in a tensile testing machine where the paperboard test strip is gradually pulled to failure. The maximum force and elongation are recorded.

\[
\text{Tensile strength} = \frac{F_{\text{max}}}{\text{Width}} \quad (\text{Units} = \text{kN/m})
\]

The elongation is calculated as the relative increase in length.

\[
\text{Elongation} = \varepsilon = \frac{\Delta L}{L} \times 100 \quad (\text{Units} = \%) \]

The maximum elongation, i.e. at break, $\varepsilon_{\text{max}}$ is also called strain to failure.

Measurable properties
Tensile strength (ISO 1924-2)
Tensile strength is evaluated by measuring the force required to break a 15 mm wide paperboard strip. The force is divided by the sample width and the result is expressed in kN/m.

\[
\text{Tensile strength} = \frac{F}{w} \quad \text{F} = \text{maximum force} \quad \text{w} = \text{initial sample width}
\]

Test methods and equipment
All Iggesund Paperboard’s products are tested using a tensile tester. Besides tensile strength, the instrument also measures the elongation at break, the tensile energy absorption, and the tensile stiffness (elastic modulus).
**Compression strength**

Because paperboard is a porous material consisting of a large number of fibres in a complex structure, its physical behaviour is different under tension than under compression after passing the elastic limit. Under tension the fibre network is gradually strained, aligning more and more fibres to carry the increasing load until the test strip and the fibres completely break (are separated from each other).

Under compression, the fibre network, which can be seen as consisting of a large number of supporting columns, collapses in the microscale by compression failure in the fibres themselves and by fibre buckling and bending.

After compression failure the fibre strength is basically unchanged, which means that the tensile strength is maintained with the material holding together. The different mechanism of compression also means that the compression strength is always 2–3 times lower than the tensile strength. This is unique for paper and paperboard and is the fundamental explanation as to why paperboard has the ability to be creased and folded.
Compression strength is defined as the maximum force per unit width a strip of paperboard can withstand under compression (also known as edge or short span compression strength).

\[
\text{Compression strength} = \frac{F_{\text{max}}}{\text{Width}} \quad \text{(Units = kN/m)}
\]

Maximum compression, or strain at failure, is given by \( \varepsilon_{\text{max}} \) in \%. 

Paperboard is a strong material in relation to its weight and thickness. Most paperboard grades for graphical and packaging applications have a thickness below 1 mm. To prevent the thin paperboard strip from bending (elastic buckling) the free length must be small in relation to the thickness. Otherwise it is not possible to record the maximum force the material can withstand. The only way to do this is to reduce the free length of the test strip to 0.7 mm. This allows us to determine the intrinsic compression strength.
Complex physical properties

Complex (less well-defined) physical properties are:
- stiffness
- box compression strength
- tearing resistance
- impact or burst strength
- delamination or interlaminar strength
- surface strength.
Stiffness and box compression strength are described in separate sections.

Key characteristics
The strength properties are increased by increasing grammage. Moreover, the potential for high tensile strength is governed by the type of fibre and the production method, e.g. chemically processed, long fibres from species such as pine and spruce give the best results. Methods of fibre treatment, e.g. refining, are also important. The ratio of strength in MD/CD is dependent on the forming process at the wet end of the paperboard machine.

Impact, burst strength
Several more or less complicated methods exist to evaluate the physical resistance of paperboard to impact or penetration loads. The most commonly used method is the burst test, which is a modified paper test method.

Burst or puncture test methods are complicated because many physical parameters are involved. Parameters such as tensile strength and elongation, bending stiffness, and tear are involved depending on the geometric conditions for the test used. This makes it very difficult to draw more specific conclusions. However, in this case a higher value does mean a strong and tough material that is tolerant of various types of stresses and strains.

Tearing resistance
Tearing resistance is a property based on a method which attempts to simulate the tearing of paper (tearing perpendicular to the plane of the sheet).

After an initial cut, tearing is performed according to well-defined testing conditions. Despite this the physical meaning of the value (the tearing energy) is less obvious.

In general, high tearing resistance depends on the general strength level (tensile strength and elongation) and the amount of long, well-bonded fibres (more and longer fibres give a better result).

Measurable properties
Tearing resistance (ISO 1974)
Tearing resistance is the force required to tear the paperboard from an initial cut.

Test method and equipment
A tear tester of the Elmendorf type is used for this test. The test is made in both the machine direction (MD) and cross direction (CD) and is expressed in mN.

The method is fairly good for paper but less useful for paperboard. Due to the way the test is performed, values for thick paper and paperboard are influenced by stiffness due to bending during tearing. Another factor is that the tearing of, for instance, multi-ply paperboard sheets sometimes changes the mode of failure from tearing into
delamination, or a combination of the two. Due to these circumstances tearing resistance has a limited practical value considering its complexity and built-in errors. However, the value does indicate if the paperboard is brittle or tough.

Methods have been identified that, under controlled conditions, are able to measure in-plane propagation resistance. This is a scientific value which means there are also methods to quantify tear and delamination behaviour according to material physics.

**Key characteristics**

Good tearing resistance is needed in almost every packaging or graphical application, e.g. tearing strips for opening of a package, hanging displays for a blister package, book covers, brochures, etc.

**Delamination, interlaminar strength**

Delamination strength or interlaminar strength is usually defined by a number of methods designed to measure the force or energy required to separate or delaminate the interior structure of paperboard – i.e. the bonding within or between the plies, not the interface between the fibres and coating or within the coating itself.

For many graphical and packaging applications a certain level of interlaminar strength should be maintained. This should be high enough to make edges, corners and flaps resist handling damage but low enough to allow for good delamination during creasing and folding. The fact that paperboard is a relatively thin but strong material with a complex porous fibre structure makes it extremely difficult to develop accurate and reliable test methods.

Methods have been developed to measure delamination by using pulling (z-strength), peeling or combinations of the two. The complex loading conditions, very often using tape between the paperboard and the testing unit, create a number of restrictions and potential errors in these measuring methods.

Due to their complexity the established methods do not explain interlaminar strength. A method based on z-directional toughness has been developed by Innventia (formerly STFI-Packforsk). This method eliminates previous difficulties and measures a well-defined physical quantity.
Complex physical properties

Key characteristics
Chemically processed fibres from wood containing long fibres, like pine and spruce, together with optimised fibre treatment (refining), give the best potential for high interlayer strength.

In packaging applications a frequent failure, which is due to low strength, is the failure of the tearing strip where only the top layer tears off.

Measurable properties
Interlayer strength, plybond (TAPPI 569)
As a multi-ply paperboard is built from several layers of fibres, it is important that these layers are well bonded together. Interlayer strength is the expression used to quantify this property and may be measured using a variety of techniques.

Test method and equipment
The method used for all Iggesund Paperboard products is plybond using a Scott Bond type tester. In this test the energy needed to delaminate a sample by applying a perpendicular force to the paperboard surface is quantified. The test result is expressed in J/m² and the principle of the method is shown in this illustration.
Mechanical behaviour

The typical differences in mechanical behaviour can be explained by observing the loading and elongation behaviour (stress-strain behaviour). Recording the force and elongation during tensile testing allows us to obtain the curves shown in the illustration.

Products containing 100% chemical pulp are approximately three times stronger than those with 100% mechanical pulp, and the elongation value is some 50% higher. The main reason is that chemically processed pulp gives long, well-bonded fibres resulting in strong and dense products. The initial slope of the two curves corresponds to the differences in the modulus of elasticity.

Paperboard consists of a fibrous network, and due to the manufacturing process more fibres are aligned parallel to the running direction of the paperboard machine. Therefore the physical properties of paperboard are directionally dependent. This means that parallel to the running direction, (the machine direction), the products are typically stronger than in the cross machine direction. Usually these directions are abbreviated MD (machine direction) and CD (cross direction). This means that paperboard is stiffer and stronger in the MD and consequently weaker in the CD. On the other hand, the elongation is less in the MD and greater in the CD. These directional-dependent differences have a large influence in many user applications, not only for physical protection but also for printing requirements such as register control, curl and flatness, creasing, and folding.

The differences in the two directions should be as low as possible and are usually referred to as the MD/CD ratio for stiffness. An established way of averaging the differences in the various directions of the paperboard is to calculate the geometric mean value \( \text{SGM} = \sqrt{\text{SMD} \times \text{SCD}} \). In this way it is possible to facilitate comparison of the levels of different materials regardless of the MD/CD ratio. The typical differences in the tensile elongation curves are shown below.

Specific material properties

Paperboard is a fibrous porous network consisting of cellulose fibre material and air. Consequently the loadbearing elements, the fibres, only partly fill the volume or the cross section of a paperboard strip.

The apparent stress, \( \sigma \), when a load, \( F \), per unit width (\( b \), width of test piece) is acting on the total cross-sectional area \( A \), is given by:

\[
\sigma = \frac{F \times b}{A}
\]

The stress \( \sigma_F \) related to the cross-sectional area \( A_F \) of the fibres is:

\[
\sigma_F = \frac{F \times b}{A_F}
\]

It can be shown that

\[
\frac{\sigma_F}{\rho_F} = \frac{\sigma}{\rho} = \sigma^*
\]

where \( \rho_F \) and \( \rho \) are the fibre and sheet density respectively. Thus the specific stress acting on a sheet is equal to the specific stress acting on the fibres.

In this context the asterisk (*) denotes a normalisation with regard to density.

Paper and paperboard may in many cases be treated as a homogeneous engineering material in spite of their fibrous, porous structure. However, since paperboard in its end use is in most cases judged by its properties per unit width, the properties: tensile failure stress (\( \sigma_t \)), compression failure stress (\( \sigma_c \)), and elastic modulus (\( E \)), which are expressed in terms of force per unit cross-sectional

![Elasticity, strength and elongation](image1.png)

![Differences in tensile elongation](image2.png)
area, are less suitable quantities for the characterisation of different products. Furthermore, these properties are sensitive to changes in sheet thickness (produced by e.g., calendering) even though the changes in thickness may not be accompanied by any real change in extensional properties. This difficulty may be overcome by expressing the sheet properties by the expressions: \((\sigma_t \times t)\), \((\sigma_c \times t)\), and \((E \times t)\), i.e. by multiplying the tensile failure stress, compression failure stress, and elastic modulus, respectively, by the thickness \((t)\) to give properties having the dimensions of force per unit width.

Since these expressions are dependent on the basis weight of the sheet, the measurement may finally be normalised by dividing by the basis weight \((w)\). Expressions for the specific tensile failure stress, specific compression failure stress, and specific elastic modulus are then obtained, which are equivalent to dividing the tensile failure stress, compression failure stress and elastic modulus by the density. These specific material properties are thus identical with the strength indices commonly used in the paperboard industry, as shown in the table below.

### Key properties

Basic features that have an impact on strength and toughness:
- type of pulp
- grammage
- moisture content
- amount of pulp
- thickness
- bulk or density.

### Test methods

There are numerous ways of measuring strength and toughness. The elastic modulus is calculated using stress and strain data from tensile testing. The strain to failure, or elongation, is recorded when the sample fails during the tensile strength measurement.

Hooke’s law may be modified to apply to specific properties:

\[
\sigma^* = E^* \times \varepsilon
\]

where

- \(\sigma^* = \frac{\sigma}{\rho}\) = specific stress
- \(\varepsilon = \text{strain}\)
- \(E^* = \frac{E}{\rho}\) = specific E-modulus

In a material that contains air it is useful to use specific properties, which means that the strength is related to the mass of the material.

### Specific properties

#### Specific tensile failure stress

\[
\sigma_t^* = \frac{F_{tw}}{w} = \sigma_t^*
\]

- **Properties used in the paperboard industry**: Tensile index

#### Specific compression failure stress

\[
\sigma_c^* = \frac{F_{cw}}{w} = \frac{\sigma_c}{\sigma_t^*}
\]

- **Properties used in the paperboard industry**: Compression index

#### Specific E-modulus

\[
E^* = \frac{E \times t}{w} = \frac{S_t}{w} = \frac{E^*}{w} = \frac{E^*}{S_t}
\]

- **Properties used in the paperboard industry**: Tensile stiffness index

---

The force per unit width, \(F\), acting on the test sample of paperboard is borne by the cross-sectional area occupied by the fibres.
**Law of mixtures**
Defined properties such as modulus of elasticity, tensile and compression strength follow the laws of mixtures. This means that the final strength of the product is determined by the amount and strength of the ingoing components.

**Typical values for different types of fibres**
The following illustrations give some typical ranges of properties for major types of fibres used for paperboard. The illustrations indicate the levels and ranges typically found and also indicate the strong effect of density on the physical properties.

---

**Tensile stiffness vs. sheet density for boards made from different raw materials. Density is varied by varying the wet-pressing.**

---

**Tensile index vs. sheet density for boards from different fibre sources. The density is varied by varying the wet-pressing.**

---

**The compression index vs. density for boards made from different raw materials. The density is varied by varying the wet-pressing.**

---

**Tensile strain vs. sheet density for boards made from different fibre sources. The results are obtained for boards dried under restraint. The density is varied by varying the wet-pressing.**
Stiffness

After grammage and thickness, stiffness is the next most important property that a paperboard specifier usually considers when choosing paperboard. Stiffness is particularly important when determining the correct grade of paperboard for packaging applications.

It is stiffness that enables paperboard to be used for a wide range of packaging and graphical applications. Without stiffness paperboard would not be able to perform its primary function of providing the packaged contents with physical protection.

Stiffness itself also relates to other strength properties such as compression strength, toughness, creasability, foldability, etc. It is, however, in itself a very individual property which is easily measured, although less easily understood in terms of its interaction with other parameters.

To the converter or end user, stiffness is a critical parameter which impacts heavily on conversion and packaging line efficiency. Maximum stiffness has to be achieved at the lowest possible grammage and thereby cost, whilst maintaining a consistent and uniform level. Beyond the packaging line, stiffness continues to play an important role in the distribution chain right through to the retailer and then the consumer.

To the paperboard maker, stiffness is one of the major considerations during manufacture and production conditions are carefully controlled to ensure maintenance of the specified values. Much effort has been expended in designing the product to ensure that the chosen fibre composition and structure offer the most cost-effective route to achieve the desired, and most consistent, performance.

Stiffness characteristics
Stiffness is defined as the paperboard’s resistance to bending caused by a given applied force.

Stiffness can also be defined as a measure of the force which must be applied to deflect a defined piece of material through a defined distance or angle. This definition is applied to the most generally accepted methods of stiffness measurement.

High values of stiffness can be achieved with high thickness and a high modulus of elasticity concentrated in the outer layers of a multi-ply sheet. High tensile stiffness in the surface plies is of great importance for enduring the stress applied during bending. The elastic properties are greatly influenced by the type of fibre used. Long fibres from chemical pulp make it possible to have good bonding and hence a high elastic modulus, and are most efficiently utilised in the outer plies of the paperboard. The type of fibre also influences thickness, for example mechanical fibre creates higher bulk when used in the centre plies. This approach to increasing stiffness can be compared to the I-beam principle, which offers a higher rigidity per unit weight when compared with a solid cross section. The various layers of fibres have to be well bonded together for optimum utilisation of the fibre characteristics.

Different paperboard ply constructions
When choosing between different paperboard products, an important consideration is to analyse what happens when a sheet of multi-layered paperboard is bent. The layers on the convex side are extended and those on the concave side compressed. There is also an intermediate surface called the neutral plane where no change in length occurs. It is the resistance of the surface layers to this extension and compression that affects the overall stiffness of the product.
compression, as measured by their modulus of elasticity, which significantly influences the stiffness of the sheet.

A high modulus of elasticity is achieved by the use of pure, bleached, chemically separated cellulose pulp produced from wood species such as spruce and pine. The pulp contains relatively long fibres and achieves excellent fibre to fibre bonding during consolidation on the paperboard machine.

**Elasticity**

Elasticity is the physical property that enables a material, in this instance paperboard, to regain its original shape when the applied stress is removed. The elastic limit is the maximum stress which can be applied before the material is permanently deformed. These concepts apply to the strength of all solid materials, including paperboard.

They are summed up in Hooke’s law which states that for small deformations up to the elastic limit, involving both compression and extension, the stress is proportional to the resulting strain:

\[
\text{Stress} = E \times \text{Strain} \\
\text{Applied force} \quad \text{Dimensional change}
\]

where \( E \), the constant of proportionality, is called the elastic modulus or Young's modulus, expressed in N/m² or Pa.

Every material, such as steel, glass, plastic and paperboard has a defined modulus of elasticity depending on composition.

Stiffness itself, as defined above, is the resistance to bending caused by an externally applied force. This is related to the modulus of elasticity and thickness by the expression

\[
\text{Stiffness} = S = \text{Constant} \times E \times t^3
\]

The cubic relationship is valid for homogeneous materials provided the elastic limit is not exceeded. For Solid Bleached Board and Folding Box Board the index is in fact slightly lower than 3, at about 2.5–2.6. Hence stiffness depends very much on thickness. For example, if the thickness of a given grade of paperboard is doubled the stiffness increases by about 5.5 times.

The moisture content of the paperboard has a strong influence on the elastic modulus and hence on stiffness. A rule of thumb is that stiffness decreases about 10 % per 1 % increase in moisture content.

**Assessment of stiffness**

The property of stiffness relates to the way a material reacts to an externally applied force or strain. When stress is applied it produces a strain or dimensional change. This may be an extension or compression depending on the type of stress.

A large number of different procedures have been developed for the assessment of stiffness in paper products. Of these, some are more suitable for lower stiffness products (<150 g/m²), e.g. the resonance method, and others for higher stiffness (corrugated or fluted material), e.g. the four point beam method.

For paperboard, however, there are four methods which are probably the most widely recognised:

- bending stiffness ISO 5628 (mNm) (L&W 5 °) (DIN 53 121)
- bending resistance ISO 2493 (mN) (L&W 15 °)
- bending moment ISO 2493 (mNm) (Taber 15 °)
- bending stiffness ISO 5629 (mNm) (L&W Resonance) (DIN 53 123).

Folding Box Board products are tested using the Taber method and measurements of bending moment are converted by a simple calculation into bending resistance.

Solid Bleached Board products are converted to Taber from bending resistance in the opposite way.

Since paperboard is an anisotropic material, measurements are made on strips cut in the machine direction (MD) and cross direction (CD) of the paperboard web. The stiffness ratio (MD/CD) gives an assessment of paperboard anisotropy.

---

**Stiffness**

- The relationship between stiffness and moisture level
- Paperboard is an elastic material
Stiffness

Definition of bending resistance and bending stiffness

Bending resistance is the force required to bend a rectangular paperboard sample through an angle of 15 °. Bending stiffness is calculated from the force registered at an angular deflection of 5 °.

For the majority of paperboards a bending angle of 15 ° greatly exceeds the elastic limit. An angle of 5 °, however, usually remains within the elastic limit, and is accepted as a standard value. Set-up accuracy is very important since a degree of error of only 0.5 ° will result in a measurement error of some 10 %.

Bending stiffness, bending resistance, and bending moment are measured using the two-point method. In this method, one end of the sample is fastened in a clamp as shown below and the sample is loaded with force, F, at a distance, l, from the clamp. The sample then bends through a distance, δ.

**Measurable properties**

**Bending stiffness (ISO 5628)**

Test method and equipment, PTE

Bending stiffness is commonly measured using a Messmer-Büchler stiffness tester. A 38 mm wide strip is clamped in the instrument and bent through an angle of 5 °. The free end of the paperboard makes contact with a load cell and the force registered is proportional to the paperboard stiffness. The clamp is then turned through a further 10 ° and the force at 15 ° is registered as the bending resistance 15 ° in mN.

\[
\text{Bending stiffness } = \frac{60 \times F}{\pi \times \text{deg} \times b} \times \text{Bending force (5 °)}
\]

(Units = mNm)

l = sample length (m) = 0.050
π = 3.14
deg = bending angle (°) = 5
b = sample width (m) = 0.038

therefore:

Bending stiffness = 0.2514 × Bending force (5 °)

(L&W 5 °)

**Explanation of terms**

Because paperboard is an anisotropic material, which means that the properties have a direction caused by the alignment of fibres in the machine direction (MD), it is necessary to make measurements of stiffness both in this direction and in the cross direction (CD). This directional effect will always result in higher stiffness values in MD than in CD.

Stiffness ratio is an expression of the relation between MD and CD levels of stiffness. The higher the ratio, the higher the MD stiffness relative to the CD.

\[
\text{Stiffness ratio } = \frac{S_{MD}}{S_{CD}}
\]

In order to express stiffness as a single value, it is possible to take both MD and CD values and calculate the geometric mean stiffness (GM) value, which is:

\[
S_{GM} = \sqrt{S_{MD} \times S_{CD}}
\]

GM stiffness is rarely used when specifying stiffness requirements but is useful when comparing products for absolute levels of stiffness and is particularly important when the carton design does not favour either direction. As a general rule, larger carton designs place greater demands on MD stiffness and small carton designs require greater attention to CD stiffness.

**Measurable properties**

Bending resistance and Bending moment (ISO 2493)

Note that it is not possible to convert from bending stiffness to bending moment or bending resistance with any degree of accuracy.

Bending resistance (L&W 15 °) mN = bending moment (Taber 15 °) mNm × 20.70

**Definition of bending moment**

Bending moment is the product of bending resistance and the sample length to which a force has been applied to bend the sample through an angle of 15 °.

Test method and equipment, Taber

Measurement of bending moment is done using a Taber stiffness tester. A 38 mm wide strip is clamped at one end and a force applied to the other to induce a 15 ° bend. The bending moment is read directly from the scale and corrected for the range weight used. The mean value of readings taken in opposing directions is recorded and expressed in mNm.

Bending moment (Taber 15 °) mNm = bending resistance (L&W 15 °) mN × 0.0483

Note: If Taber is expressed in gcm (gramme · centimetre) then: Taber in mNm = Taber in gcm × 0.0981
The paperboard choice

Stiffness is probably one of the most commonly specified paperboard parameters and in this respect the converter or end user is given a significant amount of information.

Initially, however, the choice of stiffness is not so easy to relate to end use requirements. In the majority of cases this is done by experience. There are many complex theories available to assist the specifier with his choice but unfortunately most are beyond a simple explanation and can be affected by even minor changes in packaging or process design.

When specifying for a new end use or product, several factors must be taken into account. First are the weight and size of the product to be packaged, or, if it is not a packaging application, the strain that is to be applied to the material. Once this is understood the design can be finalised to take account of these factors. With cartons it is only possible to consider the stiffness after the shape and dimensions have been decided. At this stage it is important to emphasise that not all paperboards of the same grammage or thickness have the same stiffness, and a careful judgement must also take the desired print result and appearance into account.

Solid Bleached Board (SBB) offers excellent stiffness and strength characteristics per unit grammage of material. In contrast, because of their high bulk characteristics, Folding Box Board (FBB) products are able to offer very high levels of stiffness in relation to grammage.

As primary fibre products, both SBB and FBB, offer excellent consistency and reproducibility. They have distinct advantages when compared to high density recycled materials which cannot offer the advantage of 100% primary fibre contents, or high bulk characteristics, and thus give a low return on stiffness per unit grammage.

Key properties

Stiffness is itself a prime paperboard strength property that is relatively simply measured. Basic paperboard features that impact on stiffness are:

- grammage
- thickness
- bulk or density
- multi-ply and single-ply.

Other related properties that are closely linked to stiffness:

- tear strength
- tensile strength
- moisture content.

Moisture content can impact considerably on stiffness with high moisture levels significantly reducing stiffness. Conversely, a drier product will have improved stiffness. Other dependent properties include:

- gluability (spring back force)
- creasability.

Stiffness also has a major effect on the carton’s resistance to bulging.
Box compression strength

During transport and storage cartons are usually stacked and subjected to compression loading. The development towards more efficient packing means that the cartons must contribute more protection because the secondary packaging is often removed completely or partly replaced with other materials such as plastic shrink wrapping.

The box compression strength requirement (physical protection) depends on a number of factors:
- the structural design of the carton, i.e. size and dimensions, supporting elements in the carton design, flap design, and loading direction
- whether the contents support the package or not
- types of secondary (transport) packaging
- transport, storage methods and conditions (palletisation, stacking, climatic conditions)
- material properties such as stiffness and compression strength of the paperboard.

The selection of structural designs and paperboard grades is based to a large degree on experience. To prevent damage, margins of safety are often applied when selecting the paperboard. However, this often leads to over-specifying due to a lack of factual information. Today’s awareness of the importance of packaging and the need to save resources makes it even more important to develop material-efficient but functional solutions.

Key characteristics
Compression strength shows a similar relationship to density or chemical pulp content as does tensile strength. The higher the density and the amount of chemical pulp the higher the compression strength.

Structural designs and paperboard properties have to be matched to provide the required degree of performance from the packaging machine all the way through to the consumer. The carton must withstand various types of external loading and handling, protect the contents and reach the consumer without damage. The mode and duration of loading and climatic conditions are all important.

Measurable properties
Compression strength (short span compression test) Compression strength is defined as the maximum compression force per unit of width that a paperboard sample can withstand in a compression test without buckling or bending. The result is expressed in kN/m. When paperboard packages are stacked, the maximum load will of course occur in the bottom layer, and the risk of collapse there can be estimated. The important property of the material in this respect is the compression strength.

Test method and equipment
A 15 mm wide paperboard strip is fixed between two clamps. The free length between the two clamps is 0.7 mm to prevent elastic bending. The sample is compressed until the paperboard strip collapses, and the maximum force is registered.

<table>
<thead>
<tr>
<th>Loading and handling</th>
<th>Loading and handling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Types of loads:</td>
<td>Point loads</td>
</tr>
<tr>
<td></td>
<td>Evenly distributed loads</td>
</tr>
<tr>
<td></td>
<td>Shock loads – impact, temperature/moisture</td>
</tr>
<tr>
<td>Effects on the carton:</td>
<td>Bulging</td>
</tr>
<tr>
<td></td>
<td>Distorted or destroyed shape</td>
</tr>
<tr>
<td></td>
<td>Damaged corners</td>
</tr>
<tr>
<td></td>
<td>Destroyed or lost contents</td>
</tr>
</tbody>
</table>
The paperboard choice

Box compression strength is a complex property. Since it is mainly determined by the box design, testing under realistic conditions gives the most useful data for the choice of paperboard. Stiffness and compression strength (short span) measurements can be used to estimate the box compression strength. Due to differences between the test situation and the real world, we apply a safety margin.

Box compression strength characteristics

When discussing the physical protection provided by cartons a number of terms are used, of which some but not all are defined. The following definitions are used here:

Box compression strength, \( F_B \): The maximum load bearing capacity of a carton (with given design and size). Units = N.

Compression strength (short span), \( F_C \): The paperboard’s (intrinsic) maximum load bearing capacity per unit width. Units = kN/m.

Stiffness, \( S \): Resistance to bending. Units = N/m.

The following equation describes the relationship:

\[
F_B = K \times F_C^a \times S^b
\]

(K, a, and b are constants)

By replottting loads and the corresponding times to failure, lifetime expectancy curves are obtained (illustration C). The practical box compression load is typically several times less than the values from conventional static testing (illustration A). Therefore safety margins from 2–5 are often applied by scaling up the load.

Reasonably simple, accurate and reliable methods for measuring and predicting the lifetime of boxes have not been developed. All the contributing factors such as material type, box dimensions, loading and climatic conditions are well known but not yet accurate enough to be used for predictive carton life expectancy.

Among the test methods used, the ones in the illustration on the following page are well documented and relate the compression strength of the carton to the properties of the paperboard.

During transport and storage the box will carry dynamic loads for a specific time period. The loading conditions can be simplified into two types. Loading with a constant deformation rate (Illustration A) or a constant load over a longer time period (Illustration B).

Ordinary box compression tests are done at a constant deformation rate.

Lifetime tests are done by recording the time to compression failure at various constant loads, creep testing according to the upper curve.
Assessment of box compression strength

By combining test results using the above methods with theories from physics it has been shown that the compression strength of the paperboard panel is described by the following expression:

\[ F_p = c \times \sqrt{\frac{F_c \sqrt{S_{MD} \times S_{CD}}}{S_{MD} \times S_{CD}}} \]

- \( F_p \) = Panel compression strength
- \( F_c \) = Compression strength (short span) in the direction of loading
- \( S_{MD} \) = Stiffness MD
- \( S_{CD} \) = Stiffness CD
- \( c \) = Constant
- \( \sqrt{S_{MD} \times S_{CD}} \) = Geometric mean stiffness

By simplifying geometrical parameters and panel size it has been found that for a range of carton panel sizes the constant \( c \) has a value of approximately 2\( \pi \) equal to 6.28. The minimum size of the panel is approximately 60 \( \times \) 90 mm (width \( \times \) height). If the panel is smaller, bulging is gradually diminished and the above relationship is no longer accurate.

The compression strength of a paperboard panel \( F_p \) is then:

\[ F_p \approx 2\pi \times \sqrt{F_c \sqrt{S_{MD} \times S_{CD}}} \]
\[ \approx 6.28 \times \sqrt{F_c \sqrt{S_{MD} \times S_{CD}}} \]

and consequently for a complete box consisting of four panels 4 \( \times \) \( F_p \):

\[ F_b = 4F_p \approx 8\pi \times \sqrt{F_c \sqrt{S_{MD} \times S_{CD}}} \]

The box compression strength is controlled by the paperboard stiffness and the compression strength. The illustration below gives the relationship between measured panel compression strength and the predicted value based on measurements of short span compression strength and stiffness of the paperboard, using the above equation. As can be seen, the agreement is very good.

Based on these simplifications it is possible to quantify how the measured properties of the paperboard, i.e. compression strength (short span) and stiffness, contribute to the panel and box compression strength. It is, however, important to realise that the size of the carton and the flap design have a large influence on the practical results.
The relative importance of carton size is shown in the illustration below. For very small cartons, bulging of the panels is small or non-existent, which means that only the paperboard’s compression strength is of importance (stiffness plays a minor role). In contrast, cartons with very large panels are much more dependent on stiffness than compression strength.

When comparing different materials it is also important to remember that it is not possible to find materials with maximum stiffness and compression strength at the same time.

**Key properties**

The box compression strength of a carton is governed by the paperboard’s compression strength (short span) and stiffness. Fundamental research and experimental data have shown that within certain limits it is possible to predict box compression performance based on the paperboard’s compression strength and stiffness. This means that for the paperboard these values can be used to compare different grades. However, it is important to point out that knowledge and facts are still lacking for a real prediction of the long term behaviour of boxes during compression loading that takes place during storage and transport.

Load distribution along the perimeter of a carton subjected to compression loading. The load is concentrated in narrow zones along the corners.

Panel compression strength calculated from the equation $\sqrt{FC/SMD \times SCD}$ N.

Panel compression strength, measured vs. calculated.