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Mechanical properties of paper and their relation to packaging performance

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ABSTRACT

The study investigated the relationship between mechanical paper properties and mechanical performance of corrugated board and boxes, with the aim of linking fundamental paper properties to industrial converting operations and end-use situations. Both virgin-based and recycled-based materials were investigated and compared.

Tensile stiffness and fracture toughness of the papers were measured so as to observe the relationship between paper and packaging properties. Isocyclic creep studies were conducted at packaging level and related to findings in the literature at paper level.

The performance of corrugated board and boxes downstream in the distribution chain were simulated by lab measurements: Die-cutting of board was conducted in a lab die-cutter at 50% RH; bottom deflection was measured under cyclic humidity; bulge, defined as deformation of the side walls of big boxes under compression, was measured under cyclic humidity; drop resistance and tray torsion were measured at 50% RH.

The results showed that fracture toughness could be linked to the die-cutting operation, with board from virgin liner and recycled fluting showing less cracking. Recycled liner with virgin fluting showed the most cracking; approx. 100% more for this composition.

Fracture toughness could also be linked to drop resistance of regular slotted containers. Boxes with virgin liners were found to be superior to those with recycled liners, which yielded five times more cracking than virgin liners.

Tensile stiffness was linked to tray torsion. Trays with recycled liners were found to have approx. 80% of the stiffness of trays with virgin liners.

Bottom deflection of trays subjected to cyclic humidity showed less deflection for virgin-based material. The recycled material showed 35% more deflection.

Bulge measurement under cyclic humidity showed 50% more deformation for recycled liners compared to virgin liners.

The results of the study showed that mechanical properties of papers (tensile stiffness, fracture toughness and isocyclic creep) could be linked to box performance downstream in the supply chain. Differences in paper types, measured as paper properties, could be linked qualitatively to box level.

INTRODUCTION

A prerequisite for competing in today's market when producing corrugated packages is using paper best suited to its purpose. Accordingly, there is an increasing demand for understanding the requirements of the transport chain, as well as the basic mechanics for achieving the desired properties. Using liner and fluting materials efficiently requires material performance to be quantified on the basis of actual, functional properties; ones reflecting the true performance of those materials in the specific end-use situation. There is also a need to clarify the differences between various types of materials.

European market figures show 70% of the material used in corrugated packaging to comprise recycled fibre-based liners and flutings. In the past ten years, the ratio of recycled-based to virgin-based materials has been relatively stable, with a slight increase in recycled fibres from 68% to 72%, according to Fefco annual statistics 2005 [1].

The various materials have different characteristics in terms of traditional mechanical paper properties such as SCT, bursting strength, tensile stiffness and tear strength. These properties are normally specified in a standardised atmosphere of 50% RH (relative humidity) and used for quality control as well as design of corrugated board and boxes. Boxes are often exposed to high humidity and situations where humidity changes over time. For these circumstances, the material needs to be tested in the non-standard atmosphere concerned.

The purpose of this study was to compare a selection of virgin-based and recycled-based materials and link fundamental paper properties to industrial end-use situations.

One of the best-known links between paper properties and packaging end-use is the one between short compression test (SCT) value and

tensile stiffness, with box compression strength (BCT) tested at 50% RH, developed by McKee et al [2]. BCT relates to corrugated board properties according to an equation (1). This equation relates to a regular slotted container (Fefco 0201) of perimeter Z, board properties by bending stiffness in machine direction (D_x) and cross machine direction (D_y). The edgewise compressive strength is given by the edgewise compression test (ECT).

$$BCT = k ECT^{0.5} \left(\sqrt{D_x D_y} \right)^{0.25} Z^{0.5} \quad (1)$$

The link from corrugated board properties, ECT and bending stiffness, to paper properties are described by Seth [3] and Steadman [4] amongst others. ECT is calculated as the sum of the SCT values of the papers, whilst bending stiffness is primarily linked to tensile stiffness and dimensions of the corrugated board (Carlsson, Fellers et al [5]).

Although limited to BCT at 50% RH, the link between paper properties and stacking strength described as BCT has been proved useful and is regularly used in commercial box design.

With the aim of studying stacking strength in humid conditions, the phenomenon known as mechano-sorptive creep is described in the literature by for instance Coffin [6]. Isocyclic creep stiffness is supposed to reflect the behaviour of stacked boxes under cyclic humidity and quantifies the effect of mechano-sorptive creep. Söremark et al [7, 8] and Panek et al [9] demonstrated at paper level that the creep rate was higher for recycled liner than virgin liner. Byrd et al [10] demonstrated the same relationship between recycled and virgin material, but on corrugated board samples. There is a need to quantify these effects for commercial box design, as well as studying the difference between materials at box level.

The link between relative crack length after die-cutting and paper properties were investigated by Cavlin, Edholm et al [11] and Fredlund, Fellers et al [12]. A model was developed to describe the tendency to cracking during die-cutting, eq. (2) by Cavlin, Edholm [11].

$$\frac{l}{l_0} = k \frac{L \cdot FCT^{1.33} \cdot \sigma_t^{*0.66} \cdot b^{1.33}}{2E^* \cdot J^* \cdot w^{1.33} \cdot \epsilon^{0.66}} \quad (2)$$

Where,

l = Crack length

l_0 = Tool length

L = Pitch, length between flutetips (approximate)

σ_t^* = Tensile index

b = Pitch, length between flutetips

E^* = Tensile Stiffness Index

J^* = Fracture Toughness Index

w = Grammage

ϵ = Elongation at break

k = 0.1 empirical constant to fit the data in ref [2]

End-use property to paper relations is scarcely found in literature. This investigation studied the relationship between mechanical paper properties and mechanical performance of corrugated board and boxes with the emphasis on further describing and linking fundamental paper properties to end-use properties. The aim was to create qualitative and quantitative relationships for use when choosing fit-for-purpose materials in practical box design.

MATERIAL AND METHODS

Materials

Corrugated board and boxes were made from seven different commercial papers, see Table I.

Table I. Mechanical properties of the various papers.

Paper	Kraftliner		Testliner		Semi-chemical fluting	Waste-based fluting	
	140KL	186KL	150TL	200TL	140SF	140WF	150WF
Grammage [g/m^2]	142	188	149	196	140	140	148
Bursting strength [kPa]	620	822	333	464	399	325	314
SCT [kN/m]	3.3	4.2	2.6	3.6	3.1	2.5	2.6
Tensile stiffness MD [kN/m]	1355	1646	1189	1364	1486	1043	1181
Tensile stiffness CD [kN/m]	551	702	385	518	501	357	366
Fracture toughness MD [J/m]	2.1	3.0	1.4	2.0	-	-	-
Fracture toughness CD [J/m]	1.9	2.4	0.9	1.5	-	-	-
Thickness [μm]	194	259	238	299	233	221	232

14 different corrugated board compositions were produced from the commercial papers. Boards were produced in single-wall flute (B- and C-flute, 3 mm and 4 mm flute height) and double-wall flute (EB- and BC-flute, 5 mm and 7 mm flute height). Thickness, ECT, bending stiffness and bursting strength were measured for the various board compositions, see Table II.

The various packaging designs used in the study can be seen in Table III.

Virgin and recycled papers were chosen from those commercially available. In the comparison between virgin-based and recycled-based board, the constituent papers were 140 gsm for virgin papers versus 150 gsm for recycled papers. For one board type, BC-flute, 186 gsm kraftliner was compared with 200 gsm recycled liner.

Methods

The paper and corrugated board testing methods used in the investigation are shown in Table IV and Table V.

Table II. Corrugated board compositions in the study.

Board composition	Grammage [g/m ²]	Thickness [mm]	ECT [kN/m]	Bending stiffness [Nm/m]		Burst [kPa]
				MD	CD	
140KL/140SF/140KL, B-flute	487	2.98	6.9	5.4	3.0	1180
140KL/150WF/140KL, B-flute	499	2.97	7.1	5.6	2.9	1214
150TL/140SF/150TL, B-flute	504	3.02	6.7	5.1	2.5	687
150TL/150WF/150TL, B-flute	510	3.02	6.4	5.2	2.3	672
140KL/140SF/140KL, C-flute	497	4.02	6.6	9.4	5.4	1125
140KL/150WF/140KL, C-flute	504	4.01	6.3	9.9	5.4	1162
150TL/140SF/150TL, C-flute	517	4.07	6.7	9.3	4.6	713
150TL/150WF/150TL, C-flute	524	4.07	6.5	9.3	4.5	706
140KL/140SF/140KL/140SF/140KL, EB-flute	835	4.41	13.4	12.6	7.9	1759
140KL/150WF/140KL/150WF/140KL, EB-flute	854	4.42	12.8	12.2	7.4	1669
150TL/140SF/150TL/140SF/150TL, EB-flute	866	4.47	12.4	11.8	6.2	968
150TL/150WF/150TL/150WF/150TL, EB-flute	881	4.44	12.4	11.7	5.9	974
186KL/140WF/200TL/140WF/186KL, BC-flute	Not measured					
200TL/140WF/200TL/140WF/200TL, BC-flute	Not measured					

Table III. Design and dimensions of packaging in the study.

Packaging design	Dimensions [mm]		
	Length	Width	Height
RSC*, Fefco 0201 (B-flute, EB-flute)	400	300	300
Pallet size box, Fefco 0201, (BC-flute)	1200	800	800
Tray**, P84/8, (C-flute) "Small tray"	400	300	140
Tray**, P84/8, (EB-flute) "Big tray"	600	400	140

*RSC: Regular slotted container. **Drawings can be sent by the author on request.

Table IV. Paper testing methods used.

Paper property	Method
Grammage	ISO 536:1995
Bursting strength	ISO 2758
Compressive strength, SCT	ISO 9895
Tensile properties	ISO 1924-3
Fracture toughness	SCAN-P77:95
Thickness	ISO 534:1998

Table V. Corrugated board methods used.

Board property	Method
Grammage	ISO 536:1995
Thickness	ISO 3034:1975
ECT	ISO 3037:1994
Bending stiffness	SCAN-P 65:91
Bursting strength	ISO 2758:2001

Die-cutting

Corrugated board was die-cut on a lab die-cutter, see Figure 1 and Cavlin, Edholm [11]. The die-cut form was mounted on a movable plate and the board sample placed on a stationary plate. By means of a link system, the hydraulic cylinder pressed the die-cut form towards the corrugated board at a specified force and speed. The total length of cracks in the liner caused by the rulers were measured (i.e. length of rulers + cracks outside the rulers) and a relative crack length calculated (total crack length over total length of rulers). The tests were performed at a constant climate of 23°C/50% RH.

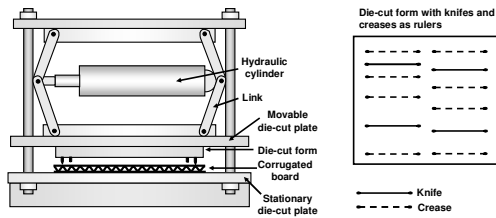


Figure 1. Lab die-cutter and die-cut form.

Drop resistance

Filled boxes were dropped from a Lansmont Drop Tester, Figure 2. The filling material was plastic cylinders (high-density polyethylene) with a diameter and height of 50 mm. The filled boxes, weighing approx. 7.5 kg in total (1/30 of BCT), were dropped five times per box from a specified height. The five orientations for the drops were: flat onto the top, bottom and two sides, and finally onto one corner. The total length of the cracks caused by the five drops was measured. Only cracks larger than 100 mm were counted, which was deemed a simulation of the capability for containing products. A relative crack length (total crack length in relation to the energy subjected to the box) was calculated. These tests were performed at a constant climate of 23°C/50% RH.

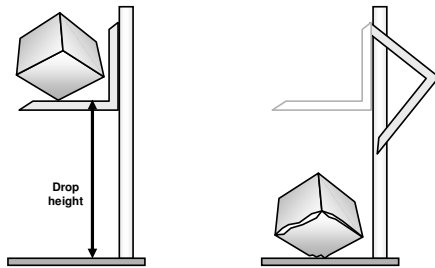


Figure 2. Method for measuring drop resistance.

Torsion stiffness

A tray was placed in a testing device with two diagonal corners on supporting blocks, Figure 3. The two opposing corners were subjected to a downward force, bending the tray diagonally and force and deformation recorded. The force/deformation ratio was calculated in the elastic region and shown as torsion stiffness for the tray. The measurements were performed at a constant climate of 23°C/50% RH.

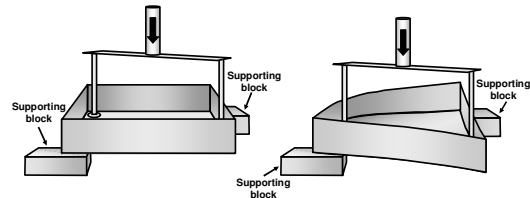


Figure 3. Method for measuring torsion stiffness.

Bottom deflection

Two trays were stacked up, Figure 4. A fixed top-to-bottom load of approx. 70 kg was placed on them, representing 10% of the BCT value. The upper box was loaded inside, with a variable load (stone marbles of 10mm diameter) of 0.8-2.4% of BCT (approx. 5-18 kg). The trays were subjected to a cyclic climate (40-85% RH) for three 22-hour cycles. The bottom deflection for the upper tray and deformation of the side wall for both trays was measured over time. The fixed and variable loads were applied in dry conditions, 4½ hours prior to the initial increase in humidity.

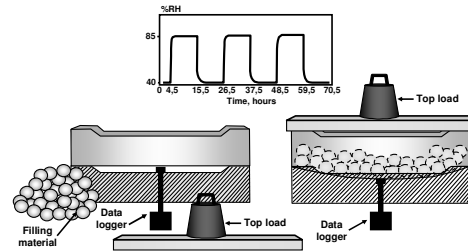


Figure 4. Method of measuring bottom deflection.

Bulge (Deformation of side walls)

Boxes were loaded with a top-to-bottom load and subjected to a cyclic climate (40-90% RH) for three 22-hour cycles. Box bulge was measured over time, see Figure 5. The load was applied in dry conditions, 4½ hours prior to the initial increase in humidity.

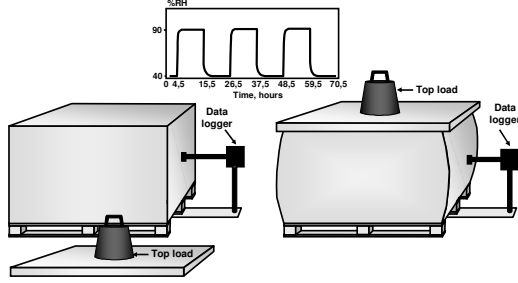


Figure 5. Method of measuring bulge.

RESULTS

The aim of the study was to link industrial end-use situations to fundamental paper properties, i.e. die-cutting (when converting corrugated board), drop resistance, bulge of big boxes, bottom deflection of trays plus torsion stiffness of trays. These end-use properties were linked to fundamental paper properties, as shown in Table VI. This study examined cyclic humidity and static load at box level.

Table VI. Studied link between paper property and end-use property.

Paper property	End use property	Environment
Tensile stiffness	Torsion stiffness of tray	50% RH
Fracture toughness	Die-cutting	50% RH
	Drop resistance	50% RH
Isocyclic creep stiffness	Bottom deflection	Between 40-85% RH
	Bulge of big boxes	Between 40-90% RH

The influence of the liners is shown in Figure 6, which plots the geometrical mean value of the liner fracture toughness and relative crack length after die-cutting.

The difference between recycled-based and virgin-based packaging was evaluated for each end-use property.

Fracture toughness and influence on die-cutting

The relative length of cracks after die-cutting differed between various boards, see Table VII. Board made of recycled liner and virgin fluting showed most cracking. The lowest crack length was seen for board made of virgin liner combined with recycled fluting. The difference in crack length for the two board compositions was approx. 100%.

Table VII. Crack length in the board after die-cutting.

Board composition	Crack length [mm]	Relative crack length [%]	Crack length
140KL/140SF/140KL	42	3.5	1.00
140KL/150WF/140KL	33	2.8	0.78
150TL/140SF/150TL	64	5.3	1.52
150TL/150WF/150TL	56	4.7	1.33

Figure 7 shows that the material could be well described by the model developed by Cavlin, Edholm [11]. The arbitrary empirical constant k in the in the equation (2) from Fredlund, Fellers et al [12] is set to 0.1.

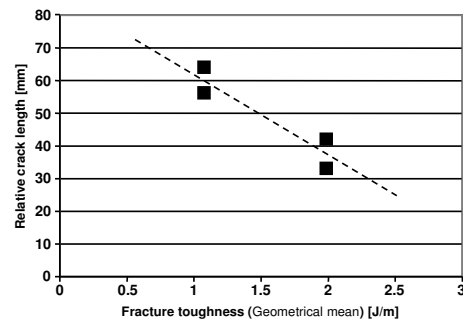


Figure 6. Relative crack length after die-cutting - v- geometrical mean of liner fracture toughness.

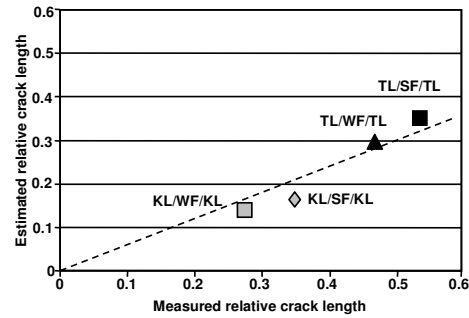


Figure 7. Estimated -v- measured relative crack length.

Fracture toughness and its influence on drop resistance

Table VIII shows the length of cracks on boxes exposed to drop tests. Boxes made of recycled liners gave five times greater crack length than boxes made of virgin liners. The influence of the type of fluting was small compared to that of type of liner.

Table VIII. Crack length of boxes after drop test as well as normalized to virgin material.

Board composition	Crack length [mm/J]	Crack length
140KL/140SF/140KL	1.42	1.00
140KL/150WF/140KL	1.56	1.10
150TL/140SF/150TL	5.86	5.20
150TL/150WF/150TL	5.76	4.90

Figure 8 shows the correlation between fracture toughness, calculated, as the sum of fracture toughness for each liner, and crack length after drop tests.

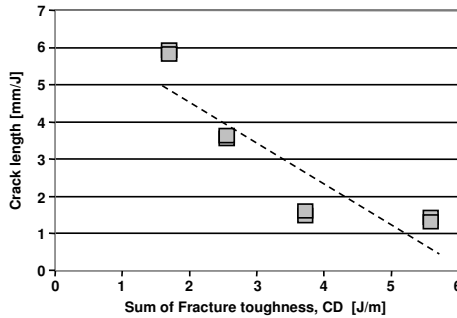


Figure 8. Length of cracks on boxes after drop test -v- sum of fracture toughness for liners in the board used.

Tensile stiffness and influence on tray torsion stiffness

Measurements of tray torsion stiffness at 50% RH showed a difference depending on the type of board used. Table IX shows board made of virgin fibres to be approx. 20% stiffer than board made of recycled liners. No influence from different flutings was apparent.

Table IX. Torsion stiffness in trays composed of different paper types and normalized to virgin material.

Board composition	Tray torsion [N/mm]	Tray torsion
140KL/140SF/140KL (small)	2.76	1.00
140KL/150WF/140KL (small)	2.76	1.00
150TL/140SF/150TL (small)	2.34	0.85
150TL/150WF/150TL (small)	2.28	0.83

Figure 9 shows that the tensile stiffness of the papers correlated with the torsion stiffness when

the design and dimensions of the trays were fixed.

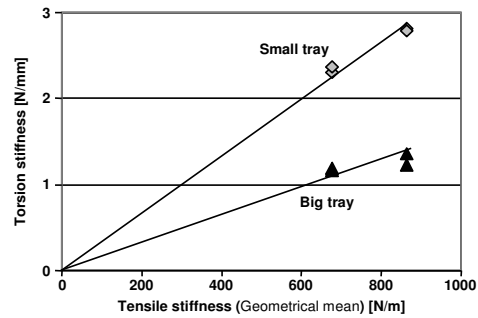


Figure 9. Tensile stiffness -v- torsion stiffness for small (C-flute) and big (EB-flute) trays.

Bottom deflection of trays under cyclic humidity

Deflection prior to the initial increase in humidity was used as the reference point to measure and quantify the effect of cyclic humidity, i.e. initial deflection when loading was excluded. This procedure implies that any difference in bending stiffness (at 40% RH) between materials was not evaluated.

Table X shows the bottom deflection measured after three humidity cycles (40-85% RH) when subjected to the same static load within the upper tray (15 kg). Trays made of recycled board showed approx. 35% more deflection than trays made of virgin board.

Figure 10 shows the bottom deflection after three humidity cycles for various static loads. It can be seen that for the same deformation, e.g. 20 mm, the carrying capacity was more than twice as high for the virgin based board.

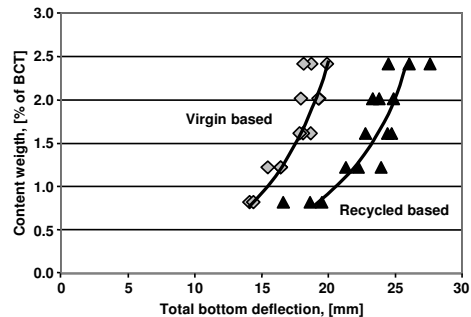


Figure 10. Content weight -v- bottom deflection of virgin and recycled-based trays after three cycles (40% -85% RH).

Table X. Bottom deflection of trays after three humidity cycles 40-85% RH and normalized to virgin material.

Board composition	Bottom deflection [mm]	Bottom deflection
140KL/140SF/140KL/140SF/140KL	19.0	1.00
140KL/150WF/140KL/150WF/140KL	22.4	1.17
150TL/140SF/150TL/140SF/150TL	22.8	1.20
150TL/150WF/150TL/150WF/150TL	25.7	1.36

The measurements showed the major part of the deflection to be due to the bending of the bottom. The deformation (compression) of the side walls was only 11-14% of the sum of panel compression and bottom bending.

Bulge of side walls of big boxes under cyclic humidity

Figure 11 shows the load-deformation curve of big boxes exposed to three humidity cycles. As is apparent from the difference between the two board materials, the board with virgin outer liners showed higher resistance to cyclic humidity. At equal deformation, assuming the maximum permitted deformation to be, say, 40 mm, the load applied was approx. 50% higher for virgin-based material compared to recycled-based material. Assuming the static load to be given, say, 14% of BCT, Figure 11 shows that the recycled board will deform 50% more than board with virgin outer liners.

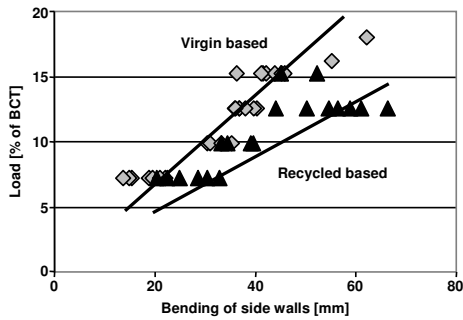


Figure 11. Load-deformation curve of big boxes, after three cycles (40%-90% RH).

Note that the curves in Figure 11 show the effect on side-wall deformation by cyclic humidity. The initial bending from the applied load was not measured, i.e. the deformation prior to the initial increase in humidity was used as a reference point. This procedure implies that any difference in bending stiffness (in 40% RH) between materials was not evaluated.

DISCUSSION

Functional paper properties can be qualitatively linked to important end-use properties. This study, and those in the literature, show that the link between mechanical paper properties and mechanical board and packaging properties can be described for the various tests as:

1. A short compression test (SCT) is strongly linked to stacking resistance at constant climate
2. Tensile stiffness is linked to stacking strength as well as torsion stiffness in constant climate
3. Fracture toughness is linked to die-cutting in the converting process as well as drop-resistance

4. Isocyclic creep stiffness is linked to stacking resistance, bottom deflection and bending of side walls under cyclic humidity

Using the above properties, papers can be characterised and their tolerance to requirements downstream in the supply chain evaluated. The fundamental paper properties also provide the opportunity to describe and compare existing paper types in the market. The trade-off between required paper (packaging) properties can be optimised through such analysis.

Furthermore, identified paper properties can serve as focus points in the development of new materials for the corrugated business, when mechanical characteristics are taken into consideration.

From the results, it can be seen that the quantitative performance difference between virgin and recycled materials differ depending on the property in question.

The largest differences seen in this study were for drop resistance where recycled board gave five times more cracking. Under cyclic humidity the difference was measured as deformation, with approx. 50% for bulge and 35% for bottom deflection, with virgin materials showing higher resistance.

The smallest difference in performance was for torsion stiffness. For this, the virgin material was approx. 20% stiffer.

For die-cutting, the lowest crack length was for mixed paper types, i.e. virgin liner plus recycled fluting. This combination gave only half the crack length of recycled liner combined with virgin fluting.

It should be noted that the weight of the virgin and recycled papers under comparison was not exactly the same, as they were chosen from commercially available papers. This meant the weights of the recycled papers were 7% higher.

The findings of this study may be used in the design of corrugated packaging. The study demonstrates which paper properties to concentrate on for various distribution requirements as well as indicating the difference between materials. The results can be used to further improve fibre utilisation in the corrugated industry.

CONCLUSION

The link between mechanical paper properties and mechanical board and packaging properties can be described as:

1. Short compression test (SCT) is strongly linked to stacking resistance in constant climate.
2. Tensile stiffness is linked to stacking strength as well as torsion stiffness in constant climate.
3. Fracture toughness is linked to die-cutting in the converting process as well as drop resistance.
4. Isocyclic creep stiffness is linked to stacking resistance, bottom deflection and bending of side walls under cyclic humidity.

The quantitative performance difference between virgin and recycled materials differed depending on the property in question. Virgin-based materials showed higher mechanical properties in all end-use properties studied.

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