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RESEARCH ARTICLE

Investigating the Mechanical Properties of Paperboard Packaging Material for Handling Fresh Produce Under Different Environmental Conditions: Experimental Analysis and Finite Element Modelling

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ABSTRACT

Paper and paperboard are the most widely used packaging materials in the world. The combination of corrugated medium (fluting) and linerboard can be varied to design a corrugated paperboard package in relation to specific mechanical properties of the paper and paperboard. Tensile tests were performed on five different paper grammages (175 g m-2, 200 g m-2, 225 g m-2, 250 g m-2, and 300 g m-2) in the principal directions of the paperboard (machine direction, cross direction and thickness direction) at standard conditions (23°C and 50% relative humidity) and refrigerated transport conditions (0°C and 90% relative humidity). At the same environmental conditions, edgewise compression tests were performed on the corrugated paperboard. Results showed that the mechanical properties of paper and paperboard were affected by the environmental conditions. At the refrigerated transport conditions, the modulus of elasticity strongly decreased in the range of 20 – 53% compared to standard conditions for all the paper grammages. The modulus of elasticity was observed to be higher in the machine direction (MD) than other directions for all the paper grammages. The buckling behaviour of the experimental edgewise compression test of the corrugated paperboard was compared with numerical results. The finite element model of the corrugated paperboard accurately predicted the experimental value of the incipient buckling load with an error of 0.4% and 5.5% at the standard and refrigerated conditions, respectively.

KEY WORDS: *paper grammage, corrugated paperboard, elasticity modulus, edgewise compression test, relative humidity*

1.0 INTRODUCTION

Paper and paperboard are sheet materials obtained from an interlaced network of cellulose fibres obtained from cellulosic material such as wood, cotton or linen [1, 2]. Paper is an important and one of the most complex engineering materials, especially due to its unique responses to moisture, loads and to temperature [2, 3]. However, paper and paperboard have long been the main packaging material for various products and goods [1, 4, 5]. The reliability of paper and paperboard packaging in the fresh fruit industry is extremely important [6, 7], where packaging plays a continuously increasing role [8-10].

The most important application of paper and paperboard is in corrugated paperboard packages [11, 12]. Corrugated paperboard is inexpensive and lightweight, having a high strength–to–weight and stiffness–to–weight ratios, making the material the best choice for the manufacturing of packages for the transportation of products [13]. Paper and paperboard are orthotropic in nature with different mechanical properties in the three principal directions (Figure 1) [14, 15].

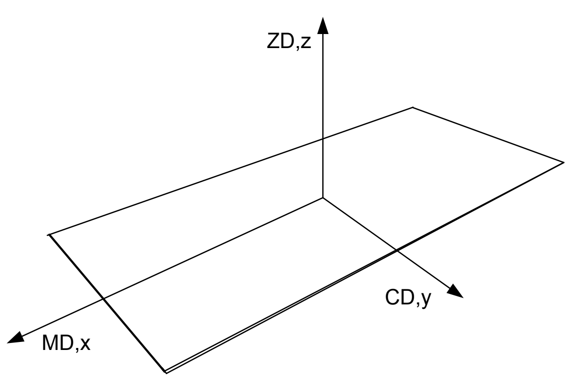


Figure 1: Principal material directions of paperboard (MD is the machine direction, CD is the cross direction and ZD is the thickness direction).

Corrugated paperboard is an orthotropic sandwich structure consisting of the surface plies known as liners, providing bending stiffness, separated by a lightweight bending core (fluting) that provides shear stiffness (Figure 2).

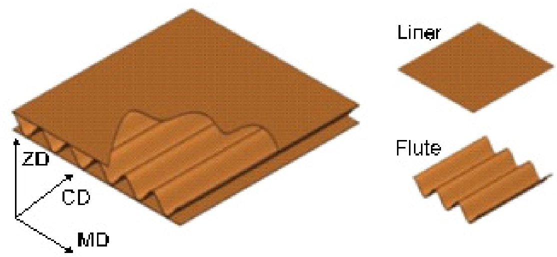


Figure 2. Corrugated paperboard panel geometry (MD is the machine direction, CD is the cross direction and ZD is the thickness direction).

The machine direction (MD) and the cross direction (CD) are the two main directions characterising this material. MD corresponds to the direction of manufacturing of the material while CD corresponds to the transverse direction. However, to refer to the out-of-plane direction, that is the direction through the thickness, a third direction ZD is introduced [16-18]. The analysis of the structural components of the paperboard and investigation of the strength and stiffness properties are very crucial in the design of paperboard packages [13, 19]. Understanding these properties reduces the damage to the product due to lateral crushing and compression loads from stacking. Furthermore, buckling may be avoided by knowledge of these properties and understanding the response of paperboard packages is an important step in designing of packages [13, 17].

Biancolini et al. [19] identified the proper combination of paper for corrugated board as a factor that can affect package design and highlighted the uncertainties involved in the process of design due to the variation in the mechanical properties of paper. In the study by Haslach [2], the complexity of paper was discussed. The author further stated that the structural performance of paper is dependent on time with reference to moisture content, load, and temperature whether constant or variably combined. Several authors have also studied the effect of varied loads and exposure to moisture on the strength of paper and paperboard [3, 20-25]. Navaranjan et al. [20] evaluated the humidity effect on the elastic properties and failure mechanisms of corrugated paperboard. The paper sheets and board samples were tested under compression load. The authors concluded that the failure mechanisms resulted in local buckling of the boards. Despite the complexity of the paper structure, the advent of numerical models such as finite element analysis (FEA) have proven to provide adequate confidence to use it as a design tool [14, 26]. Corrugated paperboard is regarded by several authors as a structure [11, 13, 27], a sandwich [28], or as monolithic material [18]. Irrespective of the approach, knowledge of the mechanical components is vital as the sandwich structure is influenced and governed by the behaviour of the components. A finite element model was developed for different corrugated board configurations in the study by Gilchrist et al. [12]. The authors found reasonable results that correlated well with the experimental assessments. Experimental measurements were reported to be consistent with numerical results in the study by Biancolini et al. [29]. The authors developed two finite element models by using homogenised elements to represent the entire geometry of the corrugated board. Results were also compared with simplified formula and a good correlation was observed. The stiffness properties of corrugated board were evaluated by Biancolini [13], using the finite element method based on a comprehensive micromechanical model to represent a small section of the corrugated board.

The structural performance of corrugated packages is dependent on numerous factors including the quality of the input cellulose fibre, the mechanical properties of the liner and the fluting and the structural properties of the combined board [29-33]. In the parametric study of the post buckling strength of corrugated paperboard sandwich panels, Nordstrand [28] used finite element analysis to calculate the buckling load and the collapse load of the sandwich panel. The author treated the core of the corrugated board as a homogeneous linear elastic layer and Tsai-Wu failure criterion was used for the analysis of the collapse load. In the study, the parametric study was in three phase; first, the impact of the initial imperfections and the transverse shear stiffness on the collapse load; second, how the strength of the panel is influenced by the slenderness and the asymmetry affect; third, how the collapse load is reduced by the eccentric loading. The author concluded how insensitive the collapse load was to small imperfections but could reduce with about 40% with large imperfections. The stress fields generated in the machine direction by a combined board beam was studied by Peterson [52] using finite element model. The author considered linear elastic behaviour in the model and symmetry was used in the procedure. The allowable material strength was compared to the maximum stress values obtained from the model and based on the comparison, the author reported that the corrugating medium under compression is the controlling critical component of the board strength. In the study by Pommier and Poustis [53], finite element model was used to study the bending stiffness of corrugated board structures. The model was designed to simulate the bending stress of the corrugated board. The authors validated the numerical models with experimental models, although concluded that the model was not sufficient in determining the bending flexibility of an equivalent orthotropic sheet. Pommier and Poustis [54] and Fadiji et al. [55] developed a linear elastic finite element model to predict the vertical compression strength of corrugated paperboard package. The experimental results were compared with finite element calculations and the authors reported good agreement. Knowledge about these fundamental attributes can therefore help to improve the package structural performance, by either minimising the amount of material utilised for making corrugated paperboard packages or by allowing for unique and improved designs to enable competition with other materials. The main objective of this study was to investigate the engineering properties of packaging materials used for handling fresh horticultural produce. In this research, the in-plane and the out-of-plane properties of paperboard under different environmental conditions was obtained by conducting tensile tests. Furthermore, the edge compression test of the corrugated paperboard was simulated using finite element analysis and validated with experimental results.

2.0 MATERIALS AND METHODS

2.1 PAPER AND PAPERBOARD MATERIALS

Five different papers with different grammages were used in this study. The required range of paper grammages were obtained from the manufacturer. Four of the paper samples are used as liners while the remaining one is used as fluting material and combined to form a corrugated paperboard. The paper samples were obtained from the same source and preparation. The thickness of paper material is usually not constant because of the fibrous structure of the material and the small imperfections because of the manufacturing process. In order to measure the thickness of the paper material, the ISO 534 [51] standard method for measuring the thickness of paper and board as a single sheet was used. The paper samples were conditioned at temperature 23°C and relative humidity 50% for 4 hours. Ten samples of each paper grammage type were measured. Table 1 shows the means and standard errors of the thicknesses measured for each grammage.

Table 1: Thickness for all the paper materials

Paper Sample	Grammage ($g.m^{-2}$)	Thickness (mm)
Liner	200	0.27±0.0012
	225	0.36±0.0013
	250	0.36±0.0018
	300	0.43±0.0023
Flute	175	0.29±0.0015

2.2 CHARACTERISATION OF PAPER MATERIAL

The elastic modulus of the paper materials (flute and liners) was obtained by performing tensile tests. Since paper is made of oriented wood fibres, the stiffness and strength properties are anisotropic. In most cases, the fibre orientation is approximately symmetric, indicating that the stiffness properties can be assumed to be orthotropic, i.e. three symmetry planes for the elastic properties can be found. Due to the orthotropic nature of the material, the in-plane properties were determined by orienting the paper in the machine direction (MD) and the cross direction (CD). The out of plane (thickness direction, ZD) modulus of elasticity was estimated using Equation 1 [34, 35]:

$$E_{ZD} = \frac{E_{MD}}{200}$$

where E_{ZD} is the modulus of elasticity in the thickness direction and E_{MD} is the modulus of elasticity in the machine direction.

The tensile tests were done according to the standard ISO 1924–2 [36] The Instron Model 4444 Tensile testing machine (Norwood, MA, USA) was used. Rectangular samples of 180 × 15 mm were cut with a guillotine and tested under a constant displacement velocity of 20 ± 5 mm/min. The samples were conditioned for 48 hours in a versatile environmental chamber (model MLR – 352H) at 23ºC and 50% RH and at the refrigerated cold storage condition for fresh produce, 0ºC and 90% RH. Ten replicates of each grammage type were tested.

The shear modulus was evaluated by performing tensile tests on paperboard samples oriented at 45° to the machine direction. The shear modulus (G_{LT}) was approximated using Equation 2 according to Biancolini and Brutti [33]:

$$G_{LT}=\left[\frac{2\nu_{LT}}{E_{MD}} - \frac{1}{E_{MD}} - \frac{1}{E_{CD}} + \frac{4}{E_{45^o}}\right]^{-1}$$

where E_{45^o} is the elasticity modulus in the 45° direction, G_{LT} is the shear modulus, ν_{LT} is Poisson's ratio. Poisson's ratio was approximated and set according to the values used by Biancolini and Brutti [33] for similar materials (0.33 for the flute paper and 0.34 for the liners). The manufacture of corrugated paperboard involves a machinery line process. The corrugator, a high precision machine was used for manufacturing the corrugated paperboard. The central paper called the corrugating medium (fluted shape) was formed using heat, moisture and pressure. The corrugating medium was glued to the two outside paper sheets called the liners to form the corrugated paperboard. Two parts are involved in the manufacturing process of corrugated paperboards: the wet part and the dry part. The fluting is corrugated between two rolls and then glued to the liners in the wet part while heat is applied to dry the corrugated board in the dry part.

2.3 CORRUGATED PAPERBOARD STRENGTH TEST

2.4 EDGEWISE COMPRESSION TEST

Edgewise Compression Test (ECT), otherwise known as the Edge Crush Test., evaluates the in-plane compressive strength of corrugated paperboard. The ECT measures the ability of a vertically placed sample of corrugated paperboard to sustain a top-to-bottom load. The Edge Crush Test was performed using the FEFCO No. 8 Standard for rectangular corrugated paperboard samples that were cut to 100 mm long and 25 mm wide using the Edge Crush Tester (Messmer 937 model). The corrugated paperboard used for the test was a single wall of type "C" flute (Figure 3). The corrugated paperboard was held tightly in the test fixture (two metal guide blocks). The blocks align the board samples vertically so that the applied force is parallel to the cross direction (CD). The clamping force on the bottom and top of the board held it to be perpendicular to the test force so there is no chance of tipping that causes lower results.

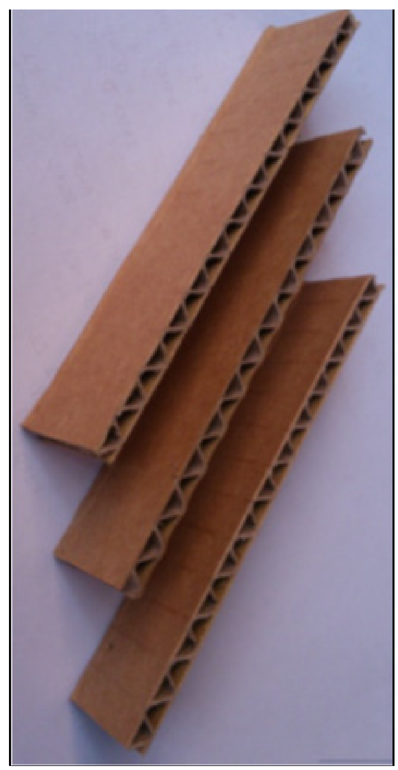


Figure 3: Corrugated paperboard samples

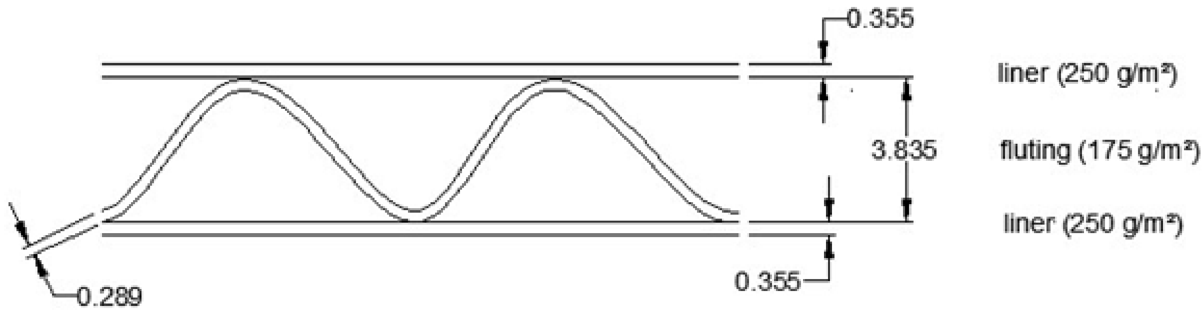


Figure 4: Dimensions in mm of the corrugated paperboard used for the finite element model of the edge compression test

Figure 5: Approximate sine wave shape of the corrugated paperboard fluting used in the finite element model of the edge compression test

The corrugated paperboard used is made from Kraft paper with a paper grammage of 250 g m^{-2} for both inner and outer liners and a paper grammage of 175 gm^{-2} for the flute (corrugated medium). The corrugated paperboard was inserted between two compression platens with no waxed edges or mechanical support beyond the initial vertical alignment at a constant speed of 12.5 ± 0.25 mm/min until instability occurred. The maximum force that the sample could resist before failure was recorded. To obtain the value for the ECT, the maximum force was normalised by the length of the sample as described by McKee et al. [37].

2.5 SIMULATION OF THE ECT OF CORRUGATED PAPERBOARD

To accurately model the corrugated paperboard, the numerical simulation must be able to represent the physical model. The dimensions of the corrugated paperboard used in the finite element model are shown in Figure 4. The fluting was approximated by modelling its shape as a sine wave (Figure 5).

The corrugated paperboard was modelled using the detailed geometry of the liners and the flutings. The finite element analysis was performed with the commercial code SimXpert/Nastran (MSC Software Corporation, California, USA). In order to accurately model the geometry in a finite element model, some basic assumptions were made. The behaviour of paperboard material is orthotropic and the material properties obtained from the tensile test for the liners and the flute were used as input parameters in the finite element models. The material was approximated as linear elastic. Linear quadratic elements were used for the ECT models

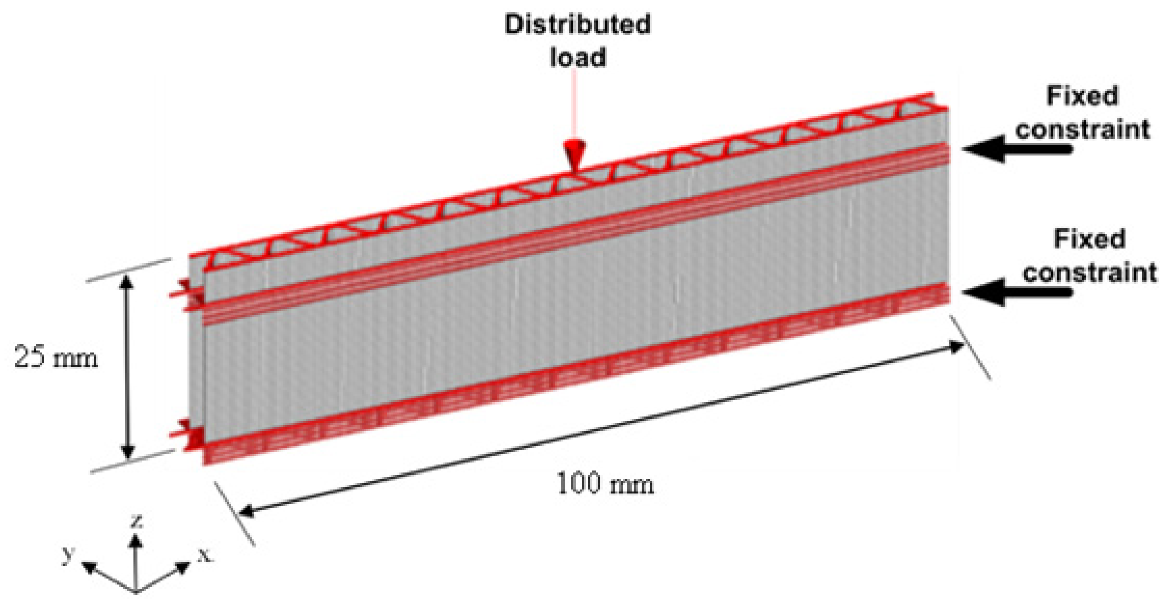


Figure 6: The finite element model setup for the edge compression test showing the boundary conditions.

and they were oriented properly so as to capture the actual pattern of the paperboard of liners and the flutings. The model of the ECT was according to the standard FEFCO No. 8 with a rectangular (100 mm x 25 mm) shaped corrugated paperboard. The aim was to model the boundary condition (Figure 6) as closely as possible to the experimental setup.

A fixed constraint (x, y and z) was applied to the bottom of the model and at the outside edges close to the top where the model is clamped. A uniformly distributed load of 1 N was applied at the top of the model across all nodes. A linear buckling analysis was performed on the ECT model in order to determine the most likely buckling shape and estimate the critical buckling load. The material properties of the paperboard combination are shown in Table 2.

3.0 STATISTICAL ANALYSIS

The statistical tests were performed using Statistica (v. 11.0, Statsoft, USA). The experimental data were treated with one-way analysis of variance (ANOVA) at 95% confidence level and with the differences at $p<0.05$ considered statistically significant. Graphical representations were made using GraphicPad Prism 6 software (GraphicPad Software, Inc. San Diego, USA).

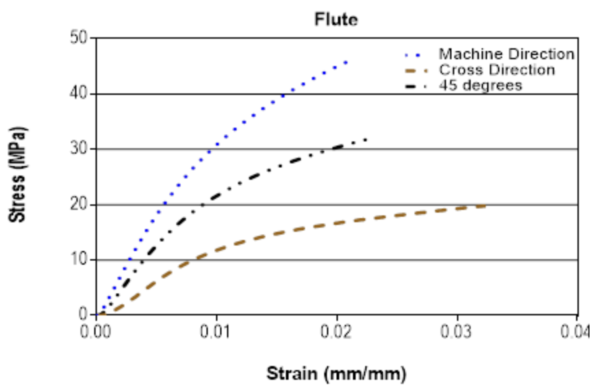
Table 2: Mechanical properties of paperboard material used for finite element analysis (FEA)

Properties	Standard Condition (23°C and 50% RH)		Refrigerated Condition (0°C and 90% RH)	
	Liner	Flute	Liner	Flute
Elasticity modulus (MD) (MPa)	2194	2160	1198	1491
Elasticity modulus (CD) (MPa)	359	456	220	306
Poisson's ratio	0.34	0.33	0.34	0.33
Shear modulus (MPa)	565	1890	338	301

4.0 RESULTS AND DISCUSSION

4.1 EFFECT OF PAPER GRAMMAGE AND ENVIRONMENTAL CONDITION ON PAPER PROPERTIES

Typical characteristic stress–strain curves for both the liner and the flute paper is shown in Figure 7.



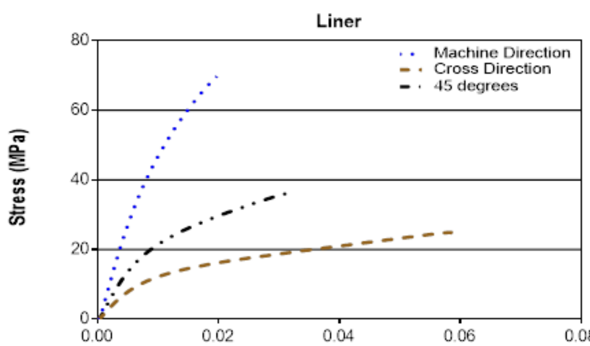


Figure 7: Typical stress-strain curves obtained from testing flutes and liners

The stress–strain curves were used for the characterization of paper behaviour under tension.

The linear part of the curve, which precedes the non–linear part, is in general dependent on the cellulose fibre, the moisture content and the hydrogen bonds [38]. The apparent and natural difference between the machine direction and the other directions was reported in the study by Salminen [39], to be due to the straining behaviour of the MD, which is less plastic and ductile. In addition, due to the orientation and the distribution of the fibres during the forming of the paper sheets in the machine direction, the paper has the ability to resist a higher stress and is usually stiffest in the machine direction [30, 40]. The elasticity moduli of the different paper grammage at two different environmental conditions are shown in Table 3. The machine direction showed the highest elasticity modulus for paper grammage of 200 g m^{-2} at the standard condition for the liners while the lowest under the same condition was observed for flute paper grammage of 175 g m^{-2} with a reduction of about 41%. The same trend was observed in the machine direction at the refrigerated condition with about 42% reduction. However, the paper grammage of 250 g m^{-2} showed the lowest elasticity modulus in the machine direction. This may be attributed to the fact that during production, linerboards and heavier basic weights or paper grammages are made at slower speed because of drying and drainage limitations and thus are comparatively less strongly oriented [56]. For all the paper grammages in the principal directions under both the standard and the refrigerated conditions, the decrease in the elasticity modulus from the highest to the lowest was in the range of 27 – 54%.

In the study by Vishtal and Retulainen [41], it was reported that the presence of moisture in paper materials softens the material and changes the behaviour of the stress-strain curve of paper fibres by reducing the elastic modulus and tensile strength. It was observed in this present study that on changing the conditions from standard to refrigerated, for the principal directions, the elasticity moduli decreased in the range of about 20 – 53% for all the paper grammages (Table 3). Allaoui et al. [38] observed similar results and reported that the elastic modulus of paperboard decreased with about 50% in the cross direction and about 30% in the machine direction, when the relative humidity

Table 3: Elasticity modulus of the paper grammages at two storage conditions

Paper grammage ($g.m^{-2}$)	Elasticity modulus (MPa)							
	Machine direction (MD)		Cross direction (CD)		Thickness direction (ZD)		45 degrees	
	Standard condition*	Refrigerated condition**	Standard condition*	Refrigerated condition**	Standard condition*	Refrigerated condition**	Standard condition*	Refrigerated condition**
175	2155.57 ± 31.92^{e}	1491.34 ± 27.49^{g}	456.13 ± 16.93^{op}	306.22 ± 4.37st	10.78 ± 0.16^{v}	7.46 ± 0.14^{v}	1385.69 ± 18.40^{h}	587.31 ± 8.63^{n}
200	3670.47 ± 69.75^{a}	2592.38 ± 36.73^{d}	331.64 ± 3.15^{sr}	262.29 ± 1.91^{ut}	18.35 ± 0.35^{v}	12.96 ± 0.18^{v}	950.43 ± 13.73^{k}	689.88 ± 8.50^{m}
225	3044.75 ± 43.43^{b}	1445.48 ± 26.31^{g}	430.67 ± 6.49^{qp}	273.61 ± 2.66^{ut}	15.22 ± 0.22^{v}	7.23 ± 0.13^{v}	1122.23 ± 22.39^{j}	498.33 ± 6.61^{o}
250	2193.48 ± 37.15^{e}	1198.62 ± 16.75^{i}	358.78 ± 7.32^{sr}	220.38 ± 2.00^{ut}	10.97 ± 0.19^{v}	5.99 ± 0.08^{v}	850.54 ± 13.38^{l}	514.11 ± 3.65^{o}
300	2858.05 ± 24.22^{c}	1597.30 ± 24.90^{f}	378.64 ± 6.20^{qp}	231.64 ± 2.44^{ut}	14.29 ± 0.12^{v}	7.99 ± 0.12^{v}	869.63 ± 14.18^{l}	522.89 ± 8.04^{o}

Note:
*Standard condition (23°C and 50% RH)
**Refrigerated condition (0°C and 90% RH)

was increased from 50 to 90%. The equilibrium moisture content of paper is closely linked to the relative humidity of the surrounding environment [30]. When the RH of paper material alternates, the paper fibre absorbs moisture from or releases moisture to the environment. Furthermore, when paper material absorbs moisture, the water content increases significantly and the bond of the cellulose fibre of the paper material breaks, greatly affecting the mechanical properties [30, 38, 42, 43]. There was a significant difference in the elastic moduli at all directions between the standard and refrigerated conditions for all the paper grammages except for the thickness direction (Table 3). This may be due to the preferential orientation of fibres in the plane of the paper [40]. For the MD, the highest percentage difference of 71.23% was observed between the standard and refrigerated conditions at paper grammage of 225 g m^{-2}. Similarly, for the thickness direction ZD, the highest percentage difference of 71.18% was observed at paper grammage of 225 g m^{-2}. However, for the CD, the highest percentage difference of 48.17% was observed at paper grammage of 300 g m^{-2}. For all the directions, the lowest percentage difference was observed between the standard and refrigerated conditions at paper grammage of 200 g m^{-2}.

Paper fibre experiences shear stresses when the tensile loads do not line up to the orientation of the in–plane fibre of the paper [40]. The shear modulus was higher at the standard condition than at the refrigerated condition (Figure 8). Paper grammage 175 g m^{-2} had the highest shear modulus at the standard condition. This paper grammage is suitable for the fluting in a corrugated paperboard as the purpose of the fluting is to carry shear stresses and to keep the facings (liners) of the board apart.

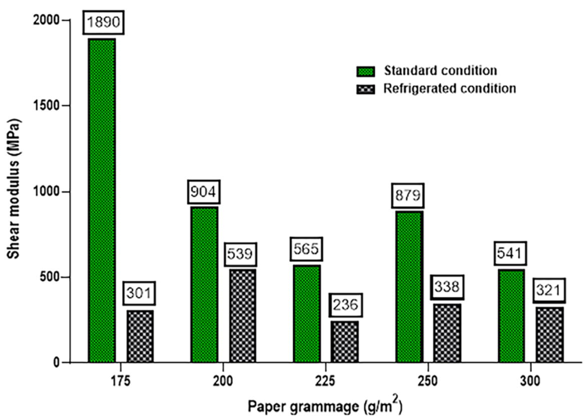


Figure 8: Shear modulus of different paper grammages stored at different enviornmental conditions (standard conditions; 230C and 50% RH and refrigerated conditions; 00C and 90% RH)

Knowledge of the mechanical properties of paper is very important because the strength properties of paper can aid in the design of paperboard packages [30, 41]. Furthermore, mechanical properties of paper, especially at varied environmental conditions [30, 44], can be used as input parameters in numerical models such as the finite element method of paperboard packages [45]. This can help to predict the mechanical behaviour of corrugated paperboard packages such as buckling, transverse shear, stability, collapse, elasticity and ultimate failure [17, 27, 46-48].

4.2 EFFECT OF ENVIRONMENTAL CONDITION ON CORRUGATED PAPERBOARD ECT

The ECT value can be used as an indicator of the quality of corrugated paperboard [30, 37]. Furthermore, the ECT value is usually used to evaluate the compression strength of the corrugated paperboard in the direction of the medium and its resistance to crushing [5, 30]. The experimental and the numerical ECT results of the investigated corrugated paperboard are shown in Table 4.

Table 4: Edgewise compression resistance

Environmental condition	Environmental (kN. m^{-1})	Numerical (kN. m^{-1})
Standard	7.94	7.91
Refrigerated	4.91	4.64

It was observed that the simulation of the ECT accurately predicted the experimental ECT values and the differences between the experimental results and the simulation results were 0.4% and 5.5% for the standard and the refrigerated conditions, respectively. The influence of the environmental factors between the standard condition and the refrigerated condition was observed as the strength of the corrugated paperboard reduced by 38% experimentally and was as high as 41% with the FEA results. A similar study has shown that the edge compression strength of a corrugated paperboard reduced by 19% when the relative humidity was gradually increased from 30 to 90% [42]. Figures 9a and 9b show the failure mechanism of the FEA model for the ECT simulation and the actual failure mechanism, respectively.

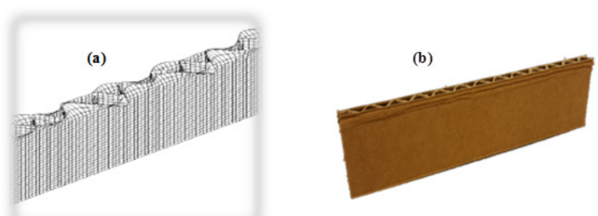


Figure 9: (a) Finite element model result showing failure mechanism of the ECT simulation; (b) actual failure mechanism

The ECT value can be used by packaging industries to predict and estimate the strength of a corrugated paperboard package from the package geometry and the paperboard properties using the well-known McKee formula [37]. The requirement for the strength of corrugated paperboard packages are greatly influenced by changes in environmental conditions such as temperature and relative humidity [49, 50]. Therefore, package designers must accommodate these factors in designing corrugated paperboard packages to withstand frequent changes that may occur throughout the life cycle of the package and for long-term storage.

5.0 CONCLUSIONS

The current study investigated the tensile properties of five different paper grammages and edgewise compression test (ECT) of corrugated paperboard at standard condition (230 and 50% RH) and refrigerated condition (00C and 90% RH). The ECT was also investigated by finite element analysis to evaluate the structural performance of the corrugated paperboard. The experimental tensile tests showed a variation in properties in the principal directions of the paperboard, indicating the orthotropic nature of the paper material. The machine direction had the highest elasticity modulus because the paper fibres are oriented in the machine direction during forming of the paper sheets. The elasticity modulus for all the directions was observed to be sensitive to the environmental conditions with a reduction as high as 53% at the refrigerated conditions compared to the value obtained at the standard conditions. The ECT value also reduced with about 41% at the refrigerated conditions. The developed FEA model accurately predicted the incipient buckling load of the corrugated paperboard. The accuracy of the model was validated by comparing the experimental ECT values. An excellent agreement was observed between experimental ECT results and the numerical results. The experimental results and the simulation results differed by 0.4 and 5.5% for the standard and the refrigerated conditions respectively. The tensile properties might be useful for the selection of the best combination of papers for liners and fluting to obtain maximum strength of the corrugated paperboard and can also be used as input material properties for the FEA model. The numerical tool can be utilised in package design to optimise corrugated paperboard packages thereby improving the overall packaging strength and lowering cost.

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