

Copyright is owned by the Author of the thesis. Permission is given for a copy to be downloaded by an individual for the purpose of research and private study only. The thesis may not be reproduced elsewhere without the permission of the Author.

**SIGNIFICANT FACTORS AFFECTING HORTICULTURAL
CORRUGATED FIBREBOARD STRENGTH**

**A THESIS PRESENTED IN PARTIAL FULFILMENT OF THE
REQUIREMENTS FOR THE DEGREE OF**

DOCTOR OF PHILOSOPHY

IN

FOOD ENGINEERING

**AT MASSEY UNIVERSITY, PALMERSTON NORTH,
NEW ZEALAND.**

ANDREW LOGIE NEVINS

B.TECH (HONS)

2008

Abstract

The New Zealand kiwifruit and apple industries export the two largest horticultural crops by value and tonnage on long sea routes to distant markets. The long storage and shipping times, low temperature ($\sim 0^{\circ}\text{C}$) and high humidity ($>70\% \text{RH}$) conditions require boxes manufactured from high performance corrugated fibreboard. As the corrugated fibreboard boxes are a significant expense, improvements to reduce the weight and therefore the cost of the corrugated fibreboard, while maintaining their vertical compression strength, would increase the apple and kiwifruit industries profitability

Through analysis of the literature it was established that the greatest contributor to box compression strength was the corrugated fibreboard edgewise compression strength, which is significantly affected by moisture. The strength of corrugated fibreboard decreases with increasing moisture content, which tends to be high in low-temperature high-humidity cool-stores. The literature also indicated that temperature and moisture content of the fluting medium could be optimised to reduce the damage caused during the fluting process.

The objectives of this study included improving box compression strength predictions by measuring the effect of moisture and temperature on the strength of the corrugated fibreboard and measuring the relationship between temperature, humidity and corrugated fibreboard moisture content. The objectives also included developing a mathematical model to optimise the operations preceding the fluting process by predicting the fluting medium moisture content and temperature just prior to the fluting process.

The measurements of corrugated fibreboard properties enabled the widely known McKee's equation to be modified to enable the prediction of box compression strength over a range of moisture contents (7 to 30 %db), the values of which could be estimated using the moisture sorption isotherms developed in this study over the temperature and relative humidity range of 0 to 20°C and 40 to 90 %RH.

A mathematical model was developed to predict how the operation of the corrugator would affect the temperature and moisture content of the fluting medium just prior to the fluting process. The model was tested by running the corrugator at normal and extreme settings based on the model's predictions, and measuring the strength properties of the corrugated fibreboard produced. The measured strength properties indicated that the machine speed and steam shower could have an effect but the too were inconsistent to established firm conclusions.

Acknowledgements

I would like to acknowledge a number of people who have provided assistance which has contributed to the success of this project.

At Massey University I have many to thank. Key support was obtained from Associate Professor John Mawson (Chief Supervisor), and Dr John Bronlund (Co-Supervisor).

I am greatly indebted to John and John for their continual guidance during this project.

I am grateful for the assistance from Dr Owen McCarthy, Dr Jonathan Godfrey, Bryon McKillop, Gary Radford, Sue Nicholson and Peter Jeffery. I thoroughly enjoyed my time as a post graduate student at Massey University and I attribute this largely to the people I worked with in the Institute of Food, Nutrition and Human Health.

I would like to thank AGMART and Carter Holt Harvey Ltd for their financial support.

Within Scion (formally Forest Research Ltd) I would like to thank Ian Chalmers (Co-Supervisor) for his guidance. Ian provided access to laboratories, library and the Paper Test Laboratory staff for their technical assistance.

Within Carter Holt Harvey Ltd I would like to thank Andrew McKenzie (Co-Supervisor) for his guidance, access to the laboratory and library. Onsite at the Levin manufacturing facility, I am grateful to Corey Thompson, Peter Johnston and the Operators of the corrugating machine for their technical advice and assistance.

I would like to thank Dr David Tanner (Co-Supervisor) for working with me during the initial stages to get this project up and running.

On a personal note I would like to thank my wife, Catherine, for her limitless encouragement and support over the duration of this project. Connor, our young son who provided delightful distractions that I will treasure. I would also like to thank my parents, Ann and Peter, and my in-laws Anne and John for their continual support and encouragement.

Table of Contents

List of Figures	ix
List of Tables	xxiii
Nomenclature	xxvii
Chapter 1 Introduction	1.1
Chapter 2 Literature Review – Factors Affecting Corrugated Fibreboard Box Strength	
2.1 Introduction.....	2.1
2.2 Corrugated Fibreboard Components and Strength Tests.....	2.3
2.3 Published Relationships Describing Board and Box Strength.....	2.7
2.3.1 McKee’s Equation.....	2.7
2.3.2 Allerby’s Modified McKee’s Equation.....	2.9
2.3.3 Kawanishi’s Equation.....	2.10
2.3.4 Kellicut’s Equation.....	2.13
2.4 Effect of Linerboard and Medium Properties.....	2.13
2.5 Factors Affecting Corrugated Fibreboard Strength During the Manufacturing Process.....	2.17
2.5.1 Introduction.....	2.17
2.5.2 Corrugated Fibreboard Thickness.....	2.17
2.5.3 Linerboard to Medium Bond.....	2.18
2.5.4 Flute Shape.....	2.19
2.5.5 Flute Formation Process.....	2.22
2.5.6 Temperature.....	2.25
2.5.7 Moisture.....	2.28
2.5.8 Web Tension.....	2.32
2.6 Factors Affecting Corrugated Fibreboard Strength in Horticultural Cool-Stores.....	2.32
2.6.1 Introduction.....	2.32
2.6.2 Temperature.....	2.33
2.6.3 Moisture.....	2.34
2.6.4 Compression Load.....	2.37
2.6.5 Cyclic Humidity Conditions.....	2.40
2.7 Moisture Sorption Isotherms.....	2.41
2.7.1 Isotherm Equations.....	2.41
2.7.1.1 GAB Equation.....	2.41
2.7.1.2 Temperature Compensated Isotherm Equations.....	2.42
2.7.2 Published Isotherms.....	2.44
2.7.2.1 Isotherms Measured at Single Temperatures.....	2.44
2.7.2.2 Isotherm Measured at Multiple Temperatures.....	2.44
2.7.3 Established Isotherm Measurement Methods.....	2.51

2.7.3.1	Methods for About and Below Ambient Temperature	2.51
2.7.3.2	Methods for Elevated Temperatures	2.52
2.8	Summary	2.54

Chapter 3 Moisture Adsorption Isotherms

3.1	Introduction	3.1
3.2	Commercial Horticultural Cool-Store Conditions	3.3
3.2.1	Introduction	3.3
3.2.2	Methodology	3.3
3.2.3	Measured Cool-Store Conditions	3.4
3.3	Development of a Novel Method for Isotherm Measurement	3.9
3.3.1	Introduction	3.9
3.3.2	Laboratory Equipment	3.11
3.3.3	Dew Point Hygrometer Calibration	3.12
3.3.4	Conditioning of Samples	3.13
3.3.5	Equilibrium Relative Humidity and Water Activity Calculation	3.13
3.3.6	Maximum Water Activity	3.17
3.3.7	Sensitivity Analysis	3.18
3.3.8	Effect of Pressure	3.19
3.3.9	Influence of Moisture Transfer Between the Chamber Space and Sample	3.20
3.3.10	Moisture Transfer Between the Sample and Mirror	3.20
3.3.11	Data Processing	3.21
3.3.12	Measurement Limitation	3.24
3.3.13	Heat Transfer Problem	3.24
3.4	Isotherm Measurements	3.26
3.4.1	Variation in Sample Mass	3.26
3.4.2	Isotherm Dataset	3.28
3.4.3	Comparison with Published Isotherms	3.31
3.5	Fitting GAB Equation Coefficients	3.34
3.5.1	Fitting Model Coefficients	3.34
3.5.2	Fitted GAB Isotherm Equations	3.35
3.5.3	Parameter Units	3.45
3.5.4	Comparison Between Samples	3.46
3.5.5	Comparison Against Other Published Isotherms	3.49
3.5.6	Sensitivity Analysis	3.50
3.6	Modelling Moisture Content as a Function of Temperature and Humidity	3.54
3.6.1	Introduction	3.54
3.6.2	Fitted Temperature-Compensated Isotherm Equations	3.55
3.6.3	Comparison Between Samples	3.60
3.6.4	Comparison Between Temperature-Compensated GAB Equations and Single Temperature GAB Equations	3.63
3.6.5	Comparison Against Other Published Isotherms	3.65
3.6.6	Sensitivity Analysis of Temperature-Compensated GAB Equation	3.66
3.6.7	Simplification of the Temperature-Compensated GAB Equation	3.68

3.7	Water Holding Capacity	3.69
3.7.1	Introduction	3.69
3.7.2	Methodology	3.70
3.7.3	Water Holding Capacity Measurements	3.71
3.7.4	Effect of Water Holding Capacity Values on Fitted Isotherm Equations	3.74
3.8	Overall Discussion and Conclusions	3.76

Chapter 4 Effect of Moisture and Temperature on the Strength Properties of Paper Based Packaging

4.1	Introduction	4.1
4.2	Effect of Moisture on the Strength of Kraft Linerboard and Semi-Chemical Fluting Medium	4.3
4.2.1	Introduction	4.3
4.2.2	Methodology	4.3
4.2.3	Results and Discussion	4.5
4.2.3.1	Sample Moisture Loss	4.5
4.2.3.2	Measurements	4.6
4.2.4	Comparison with Previous Studies	4.13
4.3	Effect of Moisture on Corrugated Fibreboard Strength	4.15
4.3.1	Introduction	4.15
4.3.2	Methodology	4.16
4.3.3	Results and Discussion	4.17
4.3.3.1	Moisture Loss	4.17
4.3.3.2	Measurements	4.18
4.3.4	Board Properties as a Function of Humidity	4.23
4.3.5	Comparison with Previous Studies	4.26
4.3.6	Comparison with Paper Properties	4.27
4.4	Effect of Chilling and Freezing Temperatures on Edgewise Compression Strength	4.29
4.4.1	Introduction	4.29
4.4.2	Methodology	4.29
4.4.3	Results and Discussion	4.32
4.4.4	Comparison with Previous Studies	4.36
4.4.5	Comparison Between the Effects of Moisture and Temperature	4.37
4.5	Conclusions	4.38

Chapter 5 Estimating Horticultural Box Compression Strength

5.1	Introduction	5.1
5.2	Assessment of BCS Equations	5.2
5.3	Estimation of Box Compression Strength	5.5
5.3.1	BCS as a Function of Moisture Content	5.5
5.3.2	BCS as a Function of Relative Humidity	5.7
5.4	Estimation of Edgewise Compression Strength	5.9
5.5	Conclusions	5.10

Chapter 6 Semi-Chemical Fluting Medium Properties at High Temperatures

6.1	Introduction.....	6.1
6.2	Fluting Medium Temperature Profile.....	6.3
6.2.1	Introduction.....	6.3
6.2.2	Methodology.....	6.3
6.2.3	Temperature Profiles.....	6.4
6.3	Effect of Temperatures on Fluting Medium Tensile Properties.....	6.5
6.3.1	Introduction.....	6.5
6.3.2	Methodology.....	6.6
6.3.3	Results.....	6.10
6.4	Conclusion and Discussion.....	6.13

Chapter 7 Development of a Predictive Model of Fluting Medium Temperature and Moisture Content

7.0	Introduction.....	7.1
7.1	Review of Published Models.....	7.2
7.2	Review of the Process to be Modelled.....	7.4
7.3	Assumptions for Model Development.....	7.6
7.4	Overall Mass and Heat Balances.....	7.10
7.5	Thermophysical Properties and Other Model Inputs.....	7.13
7.5.1	Fluting Medium Properties.....	7.14
7.5.1.1	Combined Specific Heat Capacity (C_{com}).....	7.14
7.5.1.2	Porosity (E).....	7.14
7.5.1.3	Fractional Saturation (S).....	7.16
7.5.1.4	Fibre Specific Heat Capacity (C_f).....	7.16
7.5.1.5	Fibre Density (ρ_f).....	7.16
7.5.1.6	Diffusion Coefficient (D_f).....	7.17
7.5.1.7	Differential Heat of Water Vapour Sorption (Q_v).....	7.18
7.5.1.8	Water Vapour Permeability (κ_v).....	7.21
7.5.1.9	Combined Thermal Conductivity (λ_{com}).....	7.23
7.5.1.10	Equilibrium Relative Humidity (ERH).....	7.24
7.5.1.11	Water Vapour Partial Pressure (P_v).....	7.26
7.5.2	Water Thermophysical Properties.....	7.27
7.5.2.1	Liquid Water Thermal Conductivity (λ_w).....	7.27
7.5.2.2	Liquid Water Specific Heat Capacity (C_w).....	7.27
7.5.2.3	Liquid Water Density (ρ_w).....	7.27
7.5.2.4	Water Vapour Thermal Conductivity (λ_v).....	7.27
7.5.2.5	Water Vapour Specific Heat Capacity (C_v).....	7.28
7.5.2.6	Water Vapour Density (ρ_v).....	7.28
7.5.2.7	Water Vapour Enthalpy (H_v).....	7.28
7.5.2.8	Water Vapour Viscosity (μ_v).....	7.29
7.5.3	Heat Transfer Properties.....	7.29

7.5.3.1	Surface Convection Heat Transfer Coefficient to Air (h_c).....	7.29
7.5.3.2	Contact Heat Transfer Coefficient ($h_{contact}$).....	7.30
7.5.4	Mass Transfer Properties.....	7.35
7.5.4.1	Surface Moisture Transfer Coefficient.....	7.35
7.5.5	Summary of Thermophysical Properties and Other Model Inputs.....	7.35
7.6	Numerical Solution.....	7.38
7.6.1	Introduction.....	7.38
7.6.2	Numerical Checking.....	7.39
7.6.3	Model Output Example.....	7.41
7.6.4	Sensitivity Analysis.....	7.47
7.6.5	Comparison with Measured Data.....	7.51
7.6.6	Effect of Q and ERH.....	7.60
7.7	Indirect Model Validation.....	7.61
7.7.1	Introduction.....	7.61
7.7.2	Materials and Methods.....	7.63
7.7.3	Results and Analysis.....	7.65
7.8	Conclusions.....	7.68

Chapter 8 Conclusions and Recommendations

8.1	Rationale and Scope of Study.....	8.1
8.2	Major Findings of This Study.....	8.5
8.3	Recommended Further Work.....	8.11

References	R.1
-------------------------	------------

Appendices

A1 Manufacture of Corrugated Fibreboard

A1.1	Introduction.....	A1.1
A1.2	Wet End.....	A1.1
A1.2.1	First Stage Preheating & Preconditioning.....	A1.2
A1.2.2	Single Facer.....	A1.2
A1.2.3	Bridge.....	A1.2
A1.2.4	Second Stage Preheater.....	A1.3
A1.2.5	Glue Machine.....	A1.3
A1.2.6	Double Backer.....	A1.3
A1.3	Dry End.....	A1.3
A1.3.1	Rotary Shear.....	A1.4
A1.3.2	Slitter-Scorer.....	A1.4
A1.3.3	Stacker.....	A1.4

A2 Apple and Kiwifruit Cool-Store Conditions – Survey (View on CD)

A3	LabVIEW Programme for Measuring Moisture Sorption Isotherms (View on CD)	
A3.1	Introduction.....	A3.1
A3.2	LabVIEW Files.....	A3.1
A4	Moisture Adsorption Data (View on CD)	
A5	Paper Strength Test Results (View on CD)	
A6	Corrugated Fibreboard Strength Test Results (View on CD)	
A7	Conversion of Corrugated Fibreboard	
A7.1	Introduction.....	A7.1
A7.2	Materials and Methods.....	A7.1
A7.3	Results and Discussions.....	A7.2
A7.4	Conclusions.....	A7.7
A8	Development of an Online Moisture Sensor	
A8.1	Introduction.....	A8.1
A8.2	First Prototype.....	A8.2
A8.3	Second Prototype.....	A8.3
A8.4	Discussion.....	A8.5
A9	Development of the Numerical Solution for the Computer Programme MATLAB	
A9.1	Introduction.....	A9.1
A9.2	Mass Balances.....	A9.1
A9.2.1	Internal Nodes.....	A9.1
A9.2.1.1	Mass Flows.....	A9.1
A9.2.1.2	Mass Balance Equation.....	A9.2
A9.2.2	Top Boundary Node.....	A9.3
A9.2.2.1	Surface in Contact with Ambient Air.....	A9.3
A9.2.2.2	Surface in Contact with Preconditioner.....	A9.3
A9.2.2.3	Mass Balance Equation.....	A9.4
A9.2.3	Bottom Boundary Node.....	A9.6
A9.2.3.1	Surface in Contact with Ambient Air.....	A9.6
A9.2.3.2	Surface in Contact with Preconditioner.....	A9.6
A9.2.3.3	Mass Balance Equation.....	A9.7
A9.3	Heat Balances.....	A9.8
A9.3.1	Internal Nodes.....	A9.8
A9.3.1.1	Heat Flows.....	A9.8
A9.3.1.2	Heat Balance Equation.....	A9.9
A9.3.2	Top Boundary Node.....	A9.10
A9.3.2.1	Surface in Contact with Ambient Air.....	A9.10
A9.3.2.2	Surface in Contact with Preconditioner.....	A9.11
A9.3.2.3	Heat Balance Equation.....	A9.12
A9.3.3	Bottom Boundary Node.....	A9.14

A9.3.3.1	Surface in Contact with Ambient Air	A9.14
A9.3.3.2	Surface in Contact with Preconditioner	A9.15
A9.3.3.3	Heat Balance Equation	A9.16

A10 MATLAB ‘m’ files for Fluting Medium Model

A10.1	Introduction	A10.1
A10.2	File 1 – File Name: PaperRun.m	A10.1
A10.3	File 2 – File Name: Paper.m	A10.5
A10.4	File 3 – File Name: C.m	A10.7
A10.5	File 4 – File Name: D.m	A10.7
A10.6	File 5 – File Name: H.m	A10.7
A10.7	File 6 – File Name: K.m	A10.7
A10.8	File 7 – File Name: lam.m	A10.8
A10.9	File 8 – File Name: Psat.m	A10.8
A10.10	File 9 – File Name: Ptotal.m	A10.8
A10.11	File 10 – File Name: pv.m	A10.8
A10.12	File 11 – File Name: Q.m	A10.9
A10.13	File 12 – File Name: RH.m	A10.9
A10.14	File 13 – File Name: S.m	A10.9
A10.15	File 14 – File Name: u.m	A10.10

List of Figures

Figure 2.1	Initial conceptualisation of manufacturing factors that could affect box performance in commercial horticultural cool-stores.	2.2
Figure 2.2	Initial conceptualisation of cool-store factors that could affect box performance in commercial horticultural cool-stores.	2.2
Figure 2.3	Components of Z-Pack inner corrugated fibreboard.	2.3
Figure 2.4	Dimensions of linerboard, fluting medium and corrugated fibreboard.	2.4
Figure 2.5	Illustration of edgewise compression test	2.4
Figure 2.6	Illustration of (A) three point and (B) four point bending point stiffness tests.	2.5
Figure 2.7	Illustration of flat crush and hardness tests.	2.5
Figure 2.8	Illustration of liner adhesion test.	2.6
Figure 2.9	Illustration of short span compression test for linerboard and fluting medium samples, showing initial gap of 0.7 mm (Markström 1999).	2.6
Figure 2.10	Illustration of linerboard and fluting medium tensile test showing initial gap of 50 mm.	2.7
Figure 2.11	Relationship between composite bending stiffness and the product of edgewise compression strength and thickness squared (McKee et al. 1963, Urbanik 2001 and Allerby et al. 1985).	2.2.9
Figure 2.12	Comparison between tensile and compressive strength of paperboard (Scanned from Cavlin 1988).	2.17
Figure 2.13.	Flute diagram showing nomenclature used by Urbanik (2001) to characterise flute shape (Transferred from Urbanik 2001).	2.20
Figure 2.14.	Contours of constant levels of ECT strength (expressed as % difference from standard profile) and contours of constant levels of flute height to pitch (H/P).	2.21
Figure 2.15.	Contours of constant levels of geometric mean bending stiffness (EI) and ECT strength (expressed as % difference from standard profile).	2.21
Figure 2.16	Short span compression strength of fluting medium in the machine direction (Digitised from Whitsitt and Sprague 1987). 23	23
Figure 2.17	Short span compression strength of roll 1 fluting medium in the cross-machine direction (Digitised from Whitsitt and Sprague 1987).	2.24

Figure 2.18	Effect of single-facer linerboard temperature on edgewise compression strength and linerboard to medium bond strength (Wallace et al. 1995).....	2.26
Figure 2.19	Effect of temperature on machine direction tensile stress-stain relationship and breaking stress of (A) dry machine glazed Kraft paper and (B) dry newsprint (basis weights not stated) (Andersson and Berkyto 1951).....	2.27
Figure 2.20	Effect of temperature at various moisture contents on the specific modulus of elasticity of Kraft sack paper (digitised from Salmen and Back 1980).....	2.28
Figure 2.21	Effect of moisture on the machine direction tensile stress-strain relationship and breaking stress of machine glazed Kraft paper at 20°C (Digitised from Andersson and Berkyto 1951b).....	2.29
Figure 2.22	Modulus of elasticity of softwood 105 g.m ⁻² Kraft sack paper over a range of moisture contents and temperatures (digitised from Salmen and Back 1980).....	2.30
Figure 2.23	Effect of moisture and percentage crystallinity on glass transition temperature (T _g) of cellulose (Digitised from Back and Salmen 1981).....	2.31
Figure 2.24	Effect of moisture on the glass transition temperatures (T _g) of hemicellulose, native lignin and thiolignin (Digitised from Back and Salmen 1981).....	2.31
Figure 2.25	Moisture adsorption isotherm for corrugated fibreboard made from Kraft linerboards and recycled fluting medium (inner corrugated fibreboard sleeve) (Eagleton and Marcondes 1994).....	2.33
Figure 2.26	Effect of moisture on box compression strength as predicted by equations developed by Kellicutt and Landt's (1951) and Kawanishi (1989). RSC – regular slotted carton, WAC – wrap around carton.....	2.35
Figure 2.27	Effect of moisture on edgewise compression strength of corrugated fibreboard (Kawanishi 1989).....	2.36
Figure 2.28	Effect of moisture on maximum tensile stress of three linerboard samples at 23°C (digitised from Benson 1971).....	2.37
Figure 2.29	Duration of load test of corrugated fibreboard boxes conducted in different atmospheres with various dead loads (Digitised from Maltenfort 1988).....	2.38
Figure 2.30	Compression profile for three-high stack of empty boxes loaded to 70% of their maximum compression strength (digitised from Koning and Stern 1977).....	2.39
Figure 2.31	Creep of thermo-mechanical pulp paper (Transferred from Coffin and Habeger 2000).....	2.40

Figure 2.32	Moisture adsorption isotherms (with connecting lines) of paper made from bleached Kraft red alder pulp (Digitised from Foss <i>et al.</i> 2003).....	2.44
Figure 2.33	Adsorption isotherms (with connecting lines added) of Kraft softwood paper (Data from Prahl 1968).....	2.45
Figure 2.34	Desorption isotherms (with connecting lines added) of Kraft softwood paper (Data from Prahl 1968).....	2.46
Figure 2.35	Moisture sorption isotherms of the three telescopic box components for apples (A) Inner corrugated sleeve, (B) Outer corrugated sleeve and (C) Moulded pulp tray (Predictive equation from Eagleton and Marcondes 1994).....	2.47
Figure 2.36	Moisture adsorption isotherm of Kraft softwood pulp. Relative humidity values as calculated by Skogman and Scheie (1969).....	2.48
Figure 2.37	Moisture adsorption isotherm measurements with connecting lines of (A) Wool and (B) Purified Cotton (digitised from Darling and Belding 1946).....	2.50
Figure 3.1	Temperature and relative humidity profile of a commercial apple cool-store in the Hawke's Bay region of New Zealand, from 7th to 29th April 2000.....	3.5
Figure 3.2	Temperature and relative humidity profile of a commercial apple cool-store in the Hawke's Bay region of New Zealand, days 15 to 16 from Figure 3.1. Note: circled points indicate temperature increase during the defrost cycle of the refrigeration system; dots on the temperature and RH profiles represent individual measurements.....	3.6
Figure 3.3	Average daily (A) relative humidity and (B) temperature of six commercial kiwifruit cool-stores in the Bay of Plenty region, New Zealand, from the 10th May to the 13th September 2001.	3.7
Figure 3.4	Temperature and humidity profile of a commercial cool-store (B) in the Bay of Plenty region, New Zealand on day 79 the 29th July 2001. Note: circled points indicate temperature spikes during the defrost cycle of the refrigeration system.....	3.8
Figure 3.5	Layout of chamber, sample and sensors for the low temperature isotherm measurement system. The chamber overall dimensions were 85 × 30 mm.....	3.11
Figure 3.6.	Layout of controlled temperature bath, dew point hygrometer and computer.....	3.12
Figure 3.7	Saturated vapour pressure and corresponding dew and frost point temperatures (List, 1951).....	3.14
Figure 3.8	Maximum water activity as a function of the dry bulb temperature.....	3.18
Figure 3.9	Effect of dew point temperature errors on the ERH at 90 %.....	3.19

Figure 3.10	Effect of dry bulb temperature errors on the ERH at 90 %.....	3.19
Figure 3.11	Example of a dry bulb temperature profile, as measured by the hygrometer during one 100-min hold period.	22
Figure 3.12	Example of a dew point temperature profile, as measured by the hygrometer over 24 hours with 14 hold periods and 9 ABC operations. Note: circles signify ABC operation.....	3.22
Figure 3.13	Example of a dew point and dry bulb temperature profile with an ABC operation and an unstable dew point temperature, both of which were removed.....	3.23
Figure 3.14	Difference between dry bulb and dew point temperature of humid air.....	3.24
Figure 3.15	Temperature profile during one hold period with a target temperature of -20°C	3.25
Figure 3.16	Absolute moisture loss or gain of Kraft linerboard, recycled and semi-chemical fluting medium isotherm samples.....	3.27
Figure 3.17	Moisture gain or loss relative to average moisture content of Kraft linerboard, recycled and semi-chemical fluting medium isotherm samples.....	3.27
Figure 3.18	Moisture adsorption isotherm measurements for (A) 250g.m^{-2} Kraft linerboard, (B) 160g.m^{-2} semi-chemical fluting medium and (C) 160g.m^{-2} recycled fluting medium, all manufactured at the Carter Holt Harvey Ltd. Kinleith pulp and paper mill.....	3.29
Figure 3.19	Moisture adsorption isotherm measurements for 250g.m^{-2} Kraft linerboard, 160g.m^{-2} semi-chemical fluting medium and 160g.m^{-2} recycled fluting medium at the same or similar temperatures.....	3.30
Figure 3.20	Comparison between moisture adsorption data at 20°C from this study and from Ref 1 (25°C - Seborg and Stamm 1931), Ref 2 (25°C - Seborg, et al. 1936), Ref 3* (20°C - Skogman and Scheie 1969), Ref 4 (21.8°C - Prahl 1968), Ref 5 (23°C - Foss et al. 2003), Ref 6** (23.7°C - Bandyopadhyay et al. 2000), Ref 7 Andersson and Berkyto (1951b) and Ref 8*** (20°C - Eagleton and Marcondes, 1994).....	3.31
Figure 3.21	Comparison between moisture adsorption data from this study at (A) 10°C and (B) 0°C and fitted GAB equation lines from Eagleton and Marcondes (1994) at (A) 10°C and (B) 1°C	3.33
Figure 3.22	Comparison between adsorption isotherm measurements from this study at $-20 \pm 0.5^{\circ}\text{C}$ and Ref 3 (-20°C - Skogman and Scheie, 1969).....	3.34

Figure 3.23	Moisture adsorption isotherms of 160 g.m ⁻² semi-chemical fluting medium manufactured by Carter Holt Harvey Ltd. Kinleith Mill, New Zealand. Note: these GAB equations were fitted individually to the data sets corresponding to the one of the five target temperatures.	3.38
Figure 3.24	Moisture adsorption isotherms of 250 g.m ⁻² Kraft linerboard manufactured by Carter Holt Harvey Ltd. Kinleith Mill, New Zealand with fitted GAB equation lines. Note: these GAB equations were fitted individually to the data sets corresponding to the one of the five target temperatures.	3.39
Figure 3.25	Moisture adsorption isotherms of 160 g.m ⁻² recycled fluting medium manufactured by Carter Holt Harvey Ltd. Kinleith Mill, New Zealand. Note: these GAB equations were fitted individually to the data sets corresponding to the one of the five target temperatures.	3.40
Figure 3.26	Fitted GAB moisture adsorption lines of 250 g.m ⁻² Kraft linerboard 160 g.m ⁻² semi-chemical fluting medium and 160 g.m ⁻² recycled fluting medium manufactured by Carter Holt Harvey Ltd Kinleith Mill, New Zealand.	3.42
Figure 3.27	Plot of slope of the ln(RH) vs 1/T for Kraft linerboard based on fitted GAB equations (Table 3.4).....	3.44
Figure 3.28	Heat of sorption for Kraft linerboard based on slope of linear equations fitted to data in Figure 3.27.	3.44
Figure 3.29	Comparison between fitted GAB equation lines of 250 g.m ⁻² Kraft linerboard, 160 g.m ⁻² semi-chemical fluting medium and 160 g.m ⁻² recycled fluting medium.	3.47
Figure 3.30	Absolute differences between fitted GAB equation lines of 250 g.m ⁻² Kraft linerboard, 160 g.m ⁻² semi-chemical fluting medium and 160 g.m ⁻² recycled fluting medium. Note for (A) -17°C for Kraft and -20°C for Semi-chemical and Recycled samples, (B) -10°C, (C) 0°C, (D) 10°C, (E) 20°C and K – Kraft, SC – semi-chemical, R – recycled and MC moisture Content.	3.48
Figure 3.31	Comparison between equilibrium moisture content predictions from fitted GAB adsorption isotherms (A 20°C and B 0°C) and by Prahl, (1968) (A 21.8°C), and Eagleton and Marcondes, (1994)* (A 20°C and B 1°C) adsorption equations.	3.50
Figure 3.32	Fitted Kraft linerboard GAB adsorption equations using average, initial and final moisture contents.	3.53
Figure 3.33	Difference between fitted Kraft GAB adsorption equations using average sample moisture content and (solid lines) initial moisture contents and (dashed lines) final moisture contents.	3.54

Figure 3.34	Kraft linerboard isotherm data and fitted equations (A) temperature-compensated GAB equation (2.24 and 2.27 to 2.29), (B) Chen's (1998) equation (2.30 and 2.31) and (C) Chen's (1998) equation (2.30 and 2.32).	3.57
Figure 3.35	Semi-chemical fluting medium isotherm data and fitted equations (A) temperature-compensated GAB equation (2.24 and 2.27 to 2.29), (B) Chen's (1998) equation (2.30 and 2.31) and (C) Chen's (1998) equation (2.30 and 2.32).	3.58
Figure 3.36	Recycled fluting medium isotherm data and fitted equations (A) temperature-compensated GAB equation (2.24 and 2.27 to 2.29), (B) Chen's (1998) equation (2.30 and 2.31) and (C) Chen's (1998) equation (2.30 and 2.32).	3.59
Figure 3.37	Comparison between sample moisture contents as predicted by equations (2.24) and (2.27) to (2.29) and the coefficients in Table 3.10. Note: solid and dashed lines represent comparison between predictions at 0 and 20°C respectively. The average moisture content for normalised plot calculated from the predicted moisture content at the selected ERH value of the two samples being compared.	3.62
Figure 3.38	Comparison between predicted moisture content using fitted temperature-compensated GAB equations and GAB equations fitted to data sets from the five target temperatures. Note: A Kraft linerboard, B semi-chemical fluting medium and C recycled fluting medium.	3.64
Figure 3.39	Comparison between equilibrium moisture content predictions from fitted temperature-compensated GAB equation (equations 2.24 and 2.27 to 2.29 and Table 3.10) and predictions from Prah, (1968) (A 21.8°C), and Eagleton and Marcondes, (1994)* (A 20°C and B 1°C) adsorption equations.	3.66
Figure 3.40	Effect of number of time a sample was spun in a 1.0 m radius at approximately 1 Hz on the moisture content of Kraft linerboard, semi-chemical and recycled fluting medium samples.	3.71
Figure 3.41	Water holding capacity of individual samples. Note: diamonds correspond to moisture content after 1 set of ten cycles; squares correspond to moisture content after 2 sets of ten cycles.	3.72
Figure 3.42	Effect of number of time a sample was spun in a 1.0 m radius at approximately 1 Hz on the moisture content of Kraft linerboard, semi-chemical and recycled fluting medium samples with extrapolated values.	3.73
Figure 3.43	Kraft linerboard isotherm data with water holding capacity values and fitted temperature-compensated GAB equation (2.24 and 2.27 to 2.29).	3.74

Figure 3.44	Kraft linerboard isotherm data with water holding capacity values and fitted equations (A) Chen's (1998) equation (2.30 and 2.31) and (B) Chen's (1998) equation (2.30 and 2.32).....	3.75
Figure 4.1	Absolute (A) and relative (B) moisture loss during strength testing from the Kraft linerboard and semi-chemical fluting medium samples that were selected to be oven dried to determine their moisture contents. The average sample moisture content was used as the basis for the relative moisture loss calculation.....	4.6
Figure 4.2	Short span compression strength of 250 g.m ⁻² Kraft linerboard and 160 g.m ⁻² semi-chemical fluting medium over a range of moisture contents, at 23°C with fitted exponential equation (Table 4.2). Note: each data points represents the average of the 4 measurements from a single sample.....	4.7
Figure 4.3	Calculated specific (per unit basis weight) short span compression strength for 250 g.m ⁻² Kraft linerboard and 160 g.m ⁻² semi-chemical fluting medium at 23°C. Short span compression strength was estimated using equations in Table 4.2.....	4.8
Figure 4.4.	Tensile strength of 250 g.m ⁻² Kraft linerboard and 160 g.m ⁻² semi-chemical fluting medium over a range of moisture contents, at 23°C. Equations for fitted linear lines given in Table 4.3. Data points represent average of the 2 measurements per sample.....	4.9
Figure 4.5	Calculated specific (per unit basis weight) tensile strength for 250 g.m ⁻² Kraft linerboard and 160 g.m ⁻² semi-chemical fluting medium. Tensile strength was estimated using the equations in Table 4.3.....	4.9
Figure 4.6	Normalised short span compression strength of 250 g.m ⁻² Kraft linerboard and 160 g.m ⁻² semi-chemical fluting medium over a range of moisture contents, at 23°C. Values normalised at 7 % (db) moisture using equations from Table 4.2.....	4.10
Figure 4.7.	Normalised tensile strength of 250 g.m ⁻² Kraft linerboard and 160 g.m ⁻² semi-chemical fluting medium over a range of moisture contents, at 23°C. Values normalised at 7 % (db) moisture using equations from Table 4.3.....	4.11
Figure 4.8	Tensile stiffness of 250 g.m ⁻² Kraft linerboard and 160 g.m ⁻² semi-chemical fluting medium over a range of moisture contents, at 23°C with fitted linear equations (Table 4.4).....	4.12
Figure 4.9	Normalised tensile stiffness of 250 g.m ⁻² Kraft linerboard and 160 g.m ⁻² semi-chemical fluting medium over a range of moisture contents, at 23°C. Values normalised at 7 % (db) moisture using equations from.....	4.13

Figure 4.10	Normalised tensile strength of Benson's (1971) three unbleached Kraft paper samples. Values normalised at 7 % (db) moisture using equations from Table 4.5. Note: solid lines - machine direction, dashed lines - cross-machine direction	4.14
Figure 4.11	Normalised specific modulus of elasticity of Kraft sack paper from Salmen and Back, (1980). Note: values were normalised using the measurement with approximately 7 % (db) moisture.	4.15
Figure 4.12	Moisture loss during testing of corrugated fibreboard samples (BS(CD)-bending stiffness cross-machine direction, BS(MD)-bending stiffness machine direction, LA-liner adhesion, ECT-edgewise compression test, FCT-flat crush test). Note: negative moisture loss represents a moisture gain during testing.	4.17
Figure 4.13	Relationship between corrugated fibreboard edgewise compression strength and moisture content at 23°C fitted with an exponential curve.	4.18
Figure 4.14	Relationship between corrugated fibreboard flat crush test and moisture content at 23°C fitted with an exponential curve.	4.19
Figure 4.15	Relationship between corrugated fibreboard hardness and moisture content at 23°C fitted with an exponential curve.	4.19
Figure 4.16	Relationship between corrugated fibreboard liner adhesion and moisture content at 23°C fitted with an exponential curve.	4.20
Figure 4.17	Relationship between corrugated fibreboard bending stiffness (cross-machine direction) and moisture content at 23°C fitted with a linear model.	4.20
Figure 4.18	Relationship between corrugated fibreboard bending stiffness (machine direction) and moisture content at 23°C fitted with a linear model and the fitted linear model for the cross-machine direction.	4.21
Figure 4.19	Examples of force-displacement curves of edgewise compression strength measurements.	4.22
Figure 4.20	Force-displacement curves for edgewise compression test strength measurements.	4.23
Figure 4.21	Corrugated fibreboard properties as a function of equilibrium relative humidity at 20°C. A edgewise compression strength, B hardness, liner adhesion and flat crush test, C bending stiffness (MD and CD).	4.25

Figure 4.22	Comparison between the normalised edgewise compression strength as predicted by the equation in Table 4.7 and by Kawanishi (1989). Strength at 7 %(db) used to calculate normalised values. Kawanishi - wb and Kawanishi - db lines calculated assuming Kawanishi's model uses moisture content in % wet basis (wb) and % dry basis (db), respectively. Note: dashed lines are extrapolation of Kawanishi's model.....	4.27
Figure 4.23	Relationship between normalised corrugated fibreboard test results and moisture content modelled from their respective exponential or linear equations (refer to Table 4.7 for abbreviations used in graph key). The normalised values were calculated using the equations in Table 4.7, with the strength at 7 %db used as the basis of the calculation.....	4.28
Figure 4.24	Relationship between normalised short span compression strength of Kraft and semi-chemical paper and corrugated fibreboard edgewise compression test (ECT) results and moisture content based on their respective equations (MD – Machine Direction, CD – Cross-machine Direction). The normalised values for were calculated using the equations from Tables 4.2 and 4.7, with the strength at 7 %db used as the basis of the calculation.....	4.29
Figure 4.25	One of the two acetal slabs with bagged sample, sitting in the groove which provides edge support, between two aluminium strips.....	4.31
Figure 4.26	Edgewise compression test results of corrugated fibreboard (C-flute 250g.m ⁻² Kraft linerboard - 160 g.m ⁻² semi-chemical fluting medium - 250 g.m ⁻² Kraft linerboard) with corresponding moisture contents for samples tested at 20°C and fitted curve for samples tested at 23°C from section 4.2. The intersection of the two sets of crossed lines represents the average moisture content and edgewise compression strength for treatments 1 and 2.....	4.33
Figure 4.27	Edgewise compression test results of corrugated fibreboard (C-flute 250g.m ⁻² Kraft linerboard - 160 g.m ⁻² semi-chemical fluting medium - 250 g.m ⁻² Kraft linerboard) with corresponding moisture contents for samples tested at temperatures between -25 and 21°C and measurements at 23°C from section 4.2.....	4.35
Figure 4.28	Influence of water on the glass transition temperature of cellulose for different degrees of crystallinity (digitised from Back and Salmen, 1981). Dashed line indicates completely swollen cellulose The red rectangle indicates temperature and moisture content range of treatments 1, 3, 4, 5 and the samples from section 4.2.....	4.36

Figure 5.1	Comparison between estimated and measured box compression strength, Scion data set - using McKee's et al. (1963) box compression strength equation (2.2).....	5.3
Figure 5.2	Comparison between BCS predictions from McKee's et al. (1963) two equations (2.1 and 2.2) and Allerby's et al. (1985) equation (2.4) using McKee's et al. (1963) data set of corrugated fibreboard and BCS measurements. Scion data set shown as well. The drawn line represents $x = y$	5.4
Figure 5.3	Comparison between BCS predictions from McKee's et al. (1963) two equations (2.1 and 2.2) and Allerby's et al. (1985) equation (2.4) using Allerby's et al. (1985) data set of corrugated fibreboard and BCS measurements. Scion data set shown as well. The drawn line represents $x = y$	5.5
Figure 5.4	Comparison between actual (solid lines) and normalised (dashed lines) predicted box compression strength (BCS) and edgewise compression test strength (ECT). Note: strength at 7 % (db) moisture used as basis to calculate normalised values and normalised values for equation (5.2) were identical to the normalised ECT values.	5.7
Figure 5.5	Relationship between predicted box compression strength and equilibrium relative humidity at different temperatures as predicted by equations (2.24), (2.27) to (2.29), (5.2) and Table (3.9). Note: (1) 0.0045 m and 1.8 m used as the corrugated fibreboard calliper and box perimeter, respectively, (2) thick section on 0°C line indicates cool-store conditions.	5.8
Figure 5.6	Comparison of measured edgewise compression strength (Figure 4.13), cross-machine-direction short span compression strength (SSCS, Table 4.2) of Kraft linerboard and semi-chemical fluting medium. Note: the estimated accumulative intrinsic edgewise compression strength (AIECS) calculated using equation (2.8) and the adjusted accumulative intrinsic estimated edgewise compression strength (Adj-AIECS) calculated using equation (2.10).....	5.10
Figure 6.1	Profile of 160 g.m ⁻² semi-chemical fluting medium bottom surface temperature and corresponding speed during commercial production of corrugated fibreboard.....	6.4
Figure 6.2	Profile of 120 g.m ⁻² semi-chemical fluting medium bottom surface temperature and corresponding speed during commercial production of corrugated fibreboard.....	6.5
Figure 6.3	Preparation of samples for high temperature tensile testing strength testing of fluting medium samples (160g.m ⁻² semi-chemical pulp).....	6.7
Figure 6.4	Tensile strength testing of fluting medium sample in a laminate bag with concertina fold.....	6.8

Figure 6.5	Examples of force-displacement curves from tensile testing.....	6.10
Figure 6.6	Machine direction tensile strength of 160 g.m ⁻² semi-chemical fluting medium. Note: data for 23°C was taken from section 4.2.....	6.12
Figure 6.7	Machine direction tensile stiffness of 160 g.m ⁻² semi-chemical fluting medium. Tensile stiffness calculated at displacement of 0.5 mm after sample achieved tensile strength measurement of 0.5 kN.m ⁻¹ and over a range of + 0.025 mm.....	6.13
Figure 6.8	Maximum relative humidity at atmospheric pressure.....	6.15
Figure 7.1	Corrugator process prior to the single-facer on the fluting medium side, with labels A to H for sections with different boundary conditions.....	7.4
Figure 7.2	Modes of mass transfer over the four different pairs of boundary conditions – direction of arrows based on mass balance convections.....	7.5
Figure 7.3	Modes of heat transfer (other than heat transfer via mass transfer) over the four different pairs of boundary conditions– direction of arrows based on heat balance convections.....	7.6
Figure 7.4	Estimated porosity of 160 g.m ⁻² semi-chemical fluting medium based on the linear relationship of porosity and density of Reardon’s (1994) five different paper types and Foss’s et al. (2003) paper sample.....	7.15
Figure 7.5	Examples of the linear relationship between Ln(RH/100) and the inverse of temperature in Kelvin at a number of moisture contents for Prah’s (1968) desorption isotherm data.....	7.19
Figure 7.6	Linear relationship between Ln(RH/100) and the inverse of temperature in Kelvin at a number of moisture contents for Prah’s (1968) desorption and Houtz and McLean’s (1939) linen rag paper adsorption isotherm data.....	7.20
Figure 7.7	Comparison between heat of sorption values calculated from Prah’s (1968) desorption isotherm and Houtz and McLean’s (1939) isotherm (calculated from slops of data sets in Figure 7.6).....	7.21
Figure 7.8	ERH values predicted using Reardon (1994) isotherm equation fitted to Prah’s (1968) Kraft softwood pulp desorption isotherm data (equation 7.25). Note: above 80°C the predictions are outside the bounds of the original data set.....	7.26
Figure 7.9	Vector diagram for contact force between fluting medium and preconditioner roll.....	7.32
Figure 7.10	Effect of basis weight and contact pressure on contact heat transfer coefficient for dry paper - based on equation (7.43).....	7.33

Figure 7.11	Effect of moisture content, basis weight and contact pressure on contact heat transfer coefficient, based on equation (7.47). Note: solid lines 1 kPa, dashed lines 26 kPa contact pressure).....	7.34
Figure 7.12	Division of the fluting medium into layers.....	7.38
Figure 7.13	Relationship between J value (number of nodes -1) and the weighted average temperature and moisture content just prior to the single-facer. Relative and absolute tolerance set to 10 ⁻³ and 10 ⁻⁶ respectively.....	7.40
Figure 7.14	Relationship between relative tolerance and mass average temperature and moisture content. The J value and absolute tolerance were set to 40 and 10 ⁻⁶ respectively.....	7.40
Figure 7.15	Relationship between absolute tolerance and mass average temperature and moisture content. The J value and relative tolerance were set to 40 and 10 ⁻³ respectively.....	7.41
Figure 7.16	Predicted moisture content and temperature profiles for 160 g.m ⁻² semi-chemical fluting medium between the roll-stand and single-facer with the steam shower on.....	7.43
Figure 7.17	Predicted temperature and moisture content profiles for 160 g.m ⁻² semi-chemical fluting medium through the thickness of the web at the beginning and end of the seven sections as shown in Figure 7.1 with the steam shower on. Note: nodes 1 and 41 are at the bottom and top of the fluting medium web respectively.....	7.45
Figure 7.18	Predicted temperature and moisture content profiles for 160 g.m ⁻² semi-chemical fluting medium between the roll-stand and single-facer with the steam shower off.....	7.46
Figure 7.19	Predicted moisture content and temperature profiles for 160 g.m ⁻² semi-chemical fluting medium through the thickness of the web at the beginning and end of the seven sections as shown in Figure 7.1 with the steam shower off. Note: nodes 1 and 41 are at the bottom and top of the fluting medium web respectively, and profile for position G not shown.....	7.47
Figure 7.20	160 g.m ⁻² semi-chemical fluting medium paper emissivity and corresponding temperature error. Note. all 12 replicate measurements shown in plot.....	7.52
Figure 7.21	Relationship between machine speed and fluting medium bottom surface temperature 0.3 m before steam shower. Note: for 120 g.m ⁻² predictions model was run with fluting medium thickness of 0.118 m and basis weight of 112 g _{dry fibre} .m ⁻² otherwise average values from section 7.5.5 used as model inputs except for single-board speed.....	7.53
Figure 7.22	Effect of changing the contact heat transfer coefficient ($h_{contact}$), on the fluting medium bottom surface temperature at the location of the IR temperature sensor. Note: average	

	values for model inputs were used from section 7.5.5 except for machine speed and $h_{contact}$	7.55
Figure 7.23	Comparison between predicted and measured fluting medium bottom surface temperature 0.3 m before steam shower. Note: for data points $h_{contact} = 290 \text{ W.K}^{-1}\text{m}^{-2}$ and $h_{contact} = 500 \text{ W.K}^{-1}\text{m}^{-2}$ average values for model inputs were used from section 7.5.5 except for machine speed (MS = 100, 140 and 180 m.min^{-1}), surface moisture transfer coefficient ($h_m = 0.0 \text{ ms}^{-1}$) and contact heat transfer coefficient ($h_{contact} = 290, 500$ and $1000 \text{ W.K}^{-1}\text{m}^{-2}$).....	7.57
Figure 7.24	Comparison between predicted and measured fluting medium bottom surface temperature 0.3 m before steam shower. Note average values for model inputs were used from section 7.5.5 except for where stated otherwise with $h_{cont} =$ surface mass transfer coefficient ($500 \text{ W.K}^{-1}\text{m}^{-2}$).....	7.58
Figure 7.25	Comparison between predicted and measured fluting medium bottom surface temperature 0.3 m before steam shower. Note average values for model inputs were used from section 7.5.5 except for where stated otherwise with $h_{cont} =$ surface mass transfer coefficient ($1000 \text{ W.K}^{-1}\text{m}^{-2}$).....	7.59
Figure 7.26	Comparison between diffusion driving force at the fluting medium surface from ERH values calculated using equation (7.25) capped at 80°C and from ERH values calculated using equation (7.25) extrapolating above 80°C . Note: values for extrapolated ERH converge at 180°C as extrapolated equation (7.25) maxes out (ERH > 100 %) at very high temperatures. Ambient air conditions of 20°C and 60 %RH were used to calculate the diffusion driving force.....	7.61
Figure 7.27	Edgewise compression strength values of C-flute corrugated fibreboard (145 g.m^{-2} Kraft linerboard - 120 g.m^{-2} recycled fluting medium - 145 g.m^{-2} Kraft linerboard) manufactured at a range of single-facer speeds, with the steam shower on or off. Conditions of manufacture given in Table 7.18.....	7.65
Figure 7.28	Flat crush strength values of C-flute corrugated fibreboard (145 g.m^{-2} Kraft linerboard - 120 g.m^{-2} recycled fluting medium - 145 g.m^{-2} Kraft linerboard) manufactured at a range of single-facer speeds, with the steam shower on or off. Conditions of manufacture given in Table 7.18.....	7.65
Figure 7.29	Board performance index values of C-flute corrugated fibreboard (145 g.m^{-2} Kraft linerboard - 120 g.m^{-2} recycled fluting medium - 145 g.m^{-2} Kraft linerboard) manufactured at a range of single-facer speeds, with the steam shower on or off.....	7.66

List of Tables

Table 2.1	Values used for the sensitivity analysis of Kawanishi's (1989) equation.....	2.12
Table 2.2	Test method coefficients (equation (2.8), Markström 1999).....	2.15
Table 2.3	Influence of crushing on edgewise compression test (Kroeschell 1992).....	2.18
Table 3.1	Characteristics of the refrigeration system on/off and defrost cycles for 6 different commercial kiwifruit cool-stores.....	3.9
Table 3.2	Dew point hygrometer calibration.....	3.13
Table 3.3	Distribution of measurements relative to the dry bulb temperatures.....	3.26
Table 3.4	Coefficients for fitted GAB equations, correlation coefficients (R^2) and number of measurements. Note: water holding capacity moisture contents not included in data sets.....	3.36
Table 3.5	GAB equation coefficients fitted to paper based packaging by Eagleton and Marcondes (1994)*.....	3.41
Table 3.6	Kraft linerboard heat of sorption data.....	3.43
Table 3.7	Humidity range for prediction of sample moisture contents.....	3.45
Table 3.8	Relative increase in the sum of squares following an increase or decrease of a single GAB equation coefficients using the Kraft linerboard, semi-chemical and recycled fluting medium 20°C data sets.....	3.51
Table 3.9	Coefficients for fitted GAB equations and correlation coefficients (R^2) for equations fitted against initial and final moisture contents.....	3.52
Table 3.10	Coefficients for fitted temperature-compensated GAB adsorption isotherm equation (2.24 and 2.27 to 2.29) with correlation coefficients.....	3.55
Table 3.11	Coefficients for Chen's (1998) temperature-compensated isotherm equation (2.30 and 2.31) with correlation coefficients.....	3.55
Table 3.12	Coefficients for Chen's (1998) temperature-compensated isotherm equation (2.30 and 2.32) with correlation coefficients.....	3.56
Table 3.13	Humidity range for prediction of sample moisture contents.....	3.60
Table 3.14	Relative change to the sum of squares following a change to one of the Kraft temperature-compensated GAB equation coefficients relative to the default sum of squares.....	3.67

Table 3.15	Relative change to the sum of squares following a change to one of the semi-chemical temperature-compensated GAB equation coefficients relative to the default sum of squares.....	3.67
Table 3.16	Relative change to the sum of squares following a change to one of the recycled temperature-compensated GAB equation coefficients relative to the default sum of squares.....	3.67
Table 3.17	Relative change in the sum of squared residuals following the removal of the temperature dependency terms for one or more of the GAB equation coefficients.....	3.68
Table 3.18	Coefficients of simplified temperature-compensated GAB equations. Correlation coefficients of full temperature-compensated GAB equations shown in parenthesis.....	3.69
Table 4.1	Relative humidity above saturated salt solutions at 23°C (Greenspan, 1977).....	4.3
Table 4.2	Fitted exponential equations relating the short span compression strength and moisture content of Kraft and semi-chemical paper at 23°C. Correlation coefficient (R^2) included.....	4.8
Table 4.3	Best fit linear equations for the tensile strength and moisture content of Kraft and Semi-chemical paper at 23°C.....	4.9
Table 4.4	Coefficients for the fitted linear equations to estimate the sample tensile stiffness from its moisture content. Correlation coefficients (R^2) included.....	4.12
Table 4.5	Coefficients for the linear equations fitted to Benson's (1971) maximum tensile stress measurements.....	4.14
Table 4.6	Corrugated fibreboard tests with sample dimensions.....	4.16
Table 4.7	Exponential and linear equations fitted to corrugated fibreboard properties measurements at 23°C.....	4.22
Table 4.8	Edgewise compression tests on samples at nominal temperatures of 23 to -21°C and 8 and 21 %(db) moisture.....	4.33
Table 4.9	Comparison between average treatment moisture content values and edgewise compression test strength values using t-test for difference between means using equation (4.5) and t critical values from Freund (1988).....	4.34
Table 6.1	Equilibration time for samples.....	6.8
Table 6.2	Average tensile strength, tensile stiffness and moisture content values for the 20°C bagged and non-bagged 160 g.m ⁻² semi-chemical fluting medium samples and a comparison between the values using t-test for difference between means using equation (4.5).....	6.11

Table 6.3	Tensile properties of 160 g.m ⁻² semi-chemical fluting medium over range of temperature and two moisture contents with 95% confidence intervals in parentheses.....	6.11
Table 7.1	Boundary conditions for each section of the process.....	6.7.5
Table 7.2	Time dependent heat and mass transfer coefficients and conditions.....	6.13
Table 7.3	Measured paper properties (Reardon, 1994).....	6.14
Table 7.4	Porosity for various papers (Karlsson and Stenstrom 2005).....	6.15
Table 7.5	Paper fibre specific heat capacity for various papers (Reardon \$1994).....	6.16
Table 7.6	Cellulose density (Reardon 1994).....	6.17
Table 7.7	Linear equation slope and correlation coefficient values (R ²) from plot of Ln(RH/100) vs 1/T with corresponding Heat of sorption values.....	6.19
Table 7.8	Thermal conductivity for various papers (Reardon 1994).....	6.24
Table 7.9	Thermal conductivity for various papers (Seyed-Yagoobi et al. 1992).....	6.24
Table 7.10	Environmental and initial conditions and machine settings.....	6.36
Table 7.11	Exact properties / constants.....	6.36
Table 7.12	Author defined properties.....	6.36
Table 7.13	Properties defined by equations.....	6.37
Table 7.14	Machine dimensions.....	6.37
Table 7.15	Properties defined by exact functions.....	6.37
Table 7.16	Sensitivity analysis of fluting medium temperature and moisture content model.....	6.49
Table 7.17	Effect of change in operating conditions from normal speed with steam shower off - hypotheses.....	6.63
Table 7.18	Speeds and steam shower status of blank samples.....	6.64
Table 7.19	Corrugated fibreboard tests with sample dimensions.....	6.64
Table 7.20	Comparison between average sample board performance index, ECT and FCT values using t-test for difference between means using equation (4.5). t critical values range between 2.021 and 2.048* (Freund 1988) and t values in bold signify significant differences between samples.....	6.67
Table 7.21	Effect of change in operating conditions from normal speed with steam shower off – observations from t-tests in (Table 7.20).....	6.68

Nomenclature

A	=	flute constant (dimensions not stated)
$A_{FM/P}$	=	contact area between fluting medium and preconditioner roll (m^2)
$AIECS$	=	accumulative intrinsic edgewise compression strength ($N.m^{-1}$)
$AIECS_{Adj}$	=	adjusted accumulative intrinsic edgewise compression strength ($N.m^{-1}$)
a_w	=	sample water activity (dimensionless)
a_{w1}	=	water activity of sample at T_1 in Kelvin (dimensionless)
a_{w2}	=	water activity of sample at T_2 in Kelvin (dimensionless)
a_{w3}	=	water activity at TP_3 (dimensionless)
a_{w4}	=	water activity at TP_4 (dimensionless)
B	=	box constant (dimensions not stated)
BCS	=	box compression strength (N)
BCS_{KL}	=	box compression strength (dimensions not stated)
BP	=	box perimeter (m)
BP_K	=	box perimeter (cm)
BP_{KL}	=	box perimeter (dimensions not stated)
BS	=	bending stiffness of corrugated fibreboard (Nm)
BS_{CD}	=	corrugated fibreboard cross machine direction (CD) bending stiffness (N.m)
BS_{HS}	=	ending stiffness of homogeneous strip (Nm)
BS_{MD}	=	corrugated fibreboard machine direction (MD) bending stiffness (N.m)
BS_W	=	bending stiffness (dimensions not stated)
BT	=	box type factor (dimensions not stated)
BW	=	basis weight ($g.m^{-2}$)
b_w	=	fluting medium basis weight ($kg_{dryfibre}.m^{-2}$)
$b_{w.B}$	=	total basis weight of corrugated fibreboard ($g.m^{-2}$)
$b_{w.L}$	=	total basis weight of linerboards ($g.m^{-2}$)
$b_{w.M}$	=	basis weight of fluting medium (dimensions not stated)
C	=	corrugated fibreboard thickness (or calliper) (m)
C'	=	fitted constant to express temperature dependence of C (dimensionless)
c_a	=	air specific heat ($1005 J.kg^{-1}K^{-1}$)
C_B	=	board thickness (dimensions not stated)
CC	=	average corrugation count (dimensions not stated)
C_{com}	=	combined (fibre, liquid water and water vapour) specific heat capacity ($J.kg^{-1}K^{-1}$)
C_f	=	specific heat capacity of paper fibre ($J.kg^{-1}K^{-1}$)
CFB	=	corrugated fibreboard (subscript)
C_G	=	Guggenheim constant (dimensionless)
C_{HS}	=	thickness of homogeneous strip (m)
C_K	=	corrugated fibreboard thickness (mm)
C_L	=	linerboard thickness (dimensions not stated)
CS_{CD-DBL}	=	compression strength of the double-backer linerboard in the cross-machine direction ($N.m^{-1}$)

CS_{CD-M}	=	compression strength of the fluting medium in the cross-machine direction ($N.m^{-1}$)
CS_{CD-SFL}	=	compression strength of the single-facer linerboard in the cross-machine direction ($N.m^{-1}$)
C_v	=	specific heat capacity of water vapour ($J.kg^{-1}K^{-1}$)
C_w	=	specific heat capacity of liquid water ($J.kg^{-1}K^{-1}$)
D_f	=	diffusion coefficient of water vapour in the fluting medium ($m^2.s^{-1}$)
$D_{water-air}$	=	diffusivity of water in air ($m^2.s^{-1}$)
$D1$	=	roll-stand to preconditioner distance (m)
$D2$	=	over first preconditioner roll distance (m)
$D3$	=	between preconditioner rolls distance (m)
$D4$	=	over second preconditioner roll distance (m)
$D5$	=	between preconditioner and Steam-shower distance (m)
$D6$	=	steam-shower distance (m)
$D7$	=	between steam-shower and single-facer distance (m)
E	=	sheet porosity (dimensionless)
E_{CD}	=	fluting medium Young's modulus in the cross machine direction (dimensions not stated)
ECT	=	corrugated fibreboard edgewise compression test strength ($N.m^{-1}$)
ECT_1	=	edgewise compression test value of A and AB flute corrugated fibreboard ($kgf.cm^{-1}$)
ECT_2	=	edgewise compression test value of B flute corrugated fibreboard ($kgf.cm^{-1}$)
ECT_A	=	edgewise compression strength of A-flute corrugated fibreboard ($kgf.cm^{-1}$)
ECT_{AB}	=	edgewise compression strength of AB-flute corrugated fibreboard ($kgf.cm^{-1}$)
ECT_{est1}	=	estimated edgewise compression test strength based on linerboard and fluting medium properties and equation 2.7 (N)
ECT_{est2}	=	estimated edgewise compression test strength based on linerboard and fluting medium properties and equation 2.9 (N)
E_{HS}	=	elastic modulus of homogeneous strip ($N.m^{-2}$)
EI	=	geometric mean bending stiffness (N.m)
E_L	=	elastic modulus of linerboards (dimensions not stated)
E_{MD}	=	fluting medium Young's modulus in the machine direction (dimensions not stated)
ERH	=	sample equilibrium relative humidity
f_c	=	skin friction coefficient (dimensionless)
FC_1	=	fitted constants (dimensions not stated)
FC_2	=	fitted constants (dimensions not stated)
FC_3	=	fitted constant (dimensions not stated)
FC_4	=	fitted constants, value not stated (dimensions not stated)
FC_5	=	fitted constants, value not stated (dimensions not stated)
FC_6	=	fitted constants, value not stated (dimensions not stated)
FC_7	=	fitted constants, value not stated (dimensions not stated)
FC_8	=	fitted constant (dimensions not stated)
FC_9	=	fitted constant (dimensions not stated)

FC_{10}	=	fitted constant (dimensions not stated)
FC_{11}	=	fitted constant (dimensions not stated)
FC_{12}	=	fitted constants (dimensions not stated)
FC_{13}	=	fitted constant (dimensions not stated)
FC_{14}	=	fitted constant (dimensionless)
FC_{15}	=	fitted constant – value unknown (dimensions not stated)
FC_{16}	=	fitted constant – value unknown (dimensions not stated)
FC_{17}	=	fitted constant (dimensionless)
FC_{18}	=	fitted constant (dimensionless)
FC_{19}	=	fitted constant (dimensionless)
F_{CF}	=	contact force between fluting medium and preconditioner roll (N)
FCT	=	corrugated fibreboard flat crush (kPa)
FM	=	fluting medium (subscript)
H	=	corrugated fibreboard hardness (N)
h_c	=	convection heat transfer coefficient ($W.m^{-2}K^{-1}$)
h_{cB}	=	bottom boundary heat transfer coefficient ($J.K^{-1}m^{-2}$)
$h_{contact}$	=	surface contact heat transfer coefficient ($W.m^{-2}K^{-1}$)
h_{cs}	=	convection coefficient for curved surfaces ($W.m^{-2}K^{-1}$)
h_{cT}	=	top boundary heat transfer coefficient ($J.K^{-1}m^{-2}$)
h_m	=	surface mass transfer coefficient ($m.s^{-1}$)
h_{mB}	=	bottom boundary mass transfer coefficient ($kg.m^{-2}$)
h_{mT}	=	top boundary mass transfer coefficient ($kg.m^{-2}$)
h_{oc}	=	over all heat transfer coefficient ($W.m^{-2}K^{-1}$)
h_{ps}	=	convection coefficient for planar surfaces ($W.m^{-2}K^{-1}$)
h_R	=	surface heat transfer coefficient to air ($W.m^{-2}K^{-1}$)
H_v	=	water vapour enthalpy ($J.kg^{-1}$)
i	=	i^{th} measurement
K'	=	fitted constant to express temperature dependence of K (dimensionless)
K	=	linerboard factor (dimensions not stated)
k	=	test method coefficient (dimensions not stated)
K_G	=	factor correcting properties of the multi-layer molecules with respect to the bulk liquid (dimensionless)
LA	=	corrugated fibreboard liner adhesion (N)
$LB1$	=	single-facer linerboard (subscript)
$LB2$	=	double-backer linerboard (subscript)
M	=	moisture content ratio of fluting medium ($kg_{water}.kg_{fibre}^{-1}$)
M_1	=	reference moisture content ratio ($kg_{water}.kg_{solids}^{-1}$)
M_2	=	new moisture content ratio ($kg_{water}.kg_{solids}^{-1}$)
MC	=	moisture content (% db)
MC_{SW}	=	sidewall moisture content (% , basis not given)
MC_{UKB}	=	moisture content (% , basis unknown)
M_i	=	initial moisture content ratio of the fluting medium i.e. moisture content of the fluting medium on the roll-stand ($kg_{water}.kg_{fibre}^{-1}$)
M_o'	=	fitted constant to express temperature dependence of M_o ($kg_{water} kg_{dry fibre}^{-1}$)
M_o	=	mono-layer moisture content ratio ($kg_{water} kg_{dry fibre}^{-1}$)

M_w	=	molar mass of water ($\text{kg}\cdot\text{mol}^{-1}$)
n	=	number of measurements (count)
n_1	=	sample size for sample 1 (count)
n_2	=	sample size for sample 2 (count)
P_c	=	contact pressure (kPa)
$P_{FM/P}$	=	contact pressure between the fluting medium and the preconditioner roll (Pa)
$P_{ice, \theta}$	=	vapour pressure of pure ice at $\theta^\circ\text{C}$ (Pa)
P_{iceT}	=	vapour pressure of pure ice at T Kelvin (mbar)
$P_{ice, \text{ sample db } \theta}$	=	vapour pressure of pure ice at the sample dry bulb temperature (Pa)
$P_{ice, \text{ sample dp } \theta}$	=	vapour pressure of pure ice at the hygrometer dew point temperature output (Pa)
Pr	=	Prandtl's number (dimensionless)
PR	=	printed ratio (dimensionless)
$P_{\text{ sample } , \theta}$	=	partial water vapour pressure exerted by the sample at $\theta^\circ\text{C}$ (Pa)
$P_{\text{ sat } , \theta}$	=	saturated water vapour pressure at $\theta^\circ\text{C}$ (Pa)
$P_{\text{ sat } , \text{ sample db } \theta}$	=	saturated water vapour pressure at the sample dry bulb temperature (Pa)
$P_{\text{ sat } , \text{ sample dp } \theta}$	=	saturated water vapour pressure at the hygrometer dew point temperature output (Pa)
$P_{\text{ sat } T}$	=	saturated water vapour pressure T Kelvin (mbar)
P_v	=	water vapour partial pressure (Pa)
Q	=	differential heat of water vapour sorption ($\text{J}\cdot\text{kg}^{-1}$)
Q_R	=	differential heat of sorption as calculated by Reardon ($\text{J}\cdot\text{kg}^{-1}$)
Q_s	=	heat of sorption ($\text{J}\cdot\text{mol}^{-1}$)
R	=	gas constant ($8.314 \text{ J}\cdot\text{K}^{-1}\cdot\text{mol}^{-1}$)
r	=	radius of curvature of the fluting rolls (dimensions not stated)
R^2	=	correlation coefficient (%)
RCT_L	=	overall ring crush test strength of the linerboards (dimensions not stated)
R_{DB}	=	gas constant ($\text{cal}\cdot\text{R}^{-1}\cdot\text{mol}^{-1}$)
RH	=	air relative humidity (%)
$R_{\text{ max}}$	=	maximum pore radius (m)
R_0	=	gas constant ($82.05 \text{ cm}^3\cdot\text{atm}\cdot\text{gmol}^{-1}\cdot\text{K}^{-1}$)
RR	=	retention ratio – ratio of compressive strengths of fluted to non-fluted medium (dimensionless)
S	=	degree of fractional saturation (dimensionless)
S^2_1	=	variance for sample 1 (dimensions vary)
S^2_2	=	variance for sample 2 (dimensions vary)
SC	=	fluting medium sheet thickness (m)
SCR	=	secondary region compression rate ($\text{in}\cdot\text{in}^{-1}\cdot\text{hr}^{-1}$)
$SSCS$	=	short span compression strength ($\text{kN}\cdot\text{m}^{-1}$)
$SSCS_{\text{ CD-DBL}}$	=	short span compression strength of the double-backer linerboard in the cross-machine direction ($\text{N}\cdot\text{m}^{-1}$)
$SSCS_{\text{ CD-M}}$	=	short span compression strength of the fluting medium in the cross-machine direction ($\text{N}\cdot\text{m}^{-1}$)
$SSCS_{\text{ CD-SFL}}$	=	short span compression strength of the single-facer linerboard in the cross-machine direction ($\text{N}\cdot\text{m}^{-1}$)

SSE	=	error sum of squares (dimensions vary)
T	=	temperature (K)
T_1	=	temperature of sample 1 (K)
T_2	=	temperature of sample 1 (K)
t	=	time (s)
TF	=	take-up factor ($m_{fluting\ medium}m_{board}^{-1}$)
T_i	=	initial temperature of the fluting medium i.e. temperature of the fluting medium on the roll-stand ($^{\circ}C$)
TP_1	=	total pressure of condition 1 (atm)
TP_2	=	total pressure of condition 2 (atm)
TS_L	=	tensile stiffness of the liner ($N.m^{-1}$)
TS_{gth}	=	tensile strength ($kN.m^{-1}$)
t_{stat}	=	t statistic for two-sample t test (dimensionless)
TtF	=	time to failure (hours)
V_1	=	tensile force vector ($N.m^{-1}$)
v_a	=	air velocity ($m.s^{-1}$)
v_e	=	air velocity at boundary layer edge ($m.s^{-1}$)
V_L	=	molar volume of water ($18\ m^3.gmol^{-1}$)
$VP_{air\theta}$	=	water vapour pressure of the air at temperature θ (Pa)
VP_R	=	vapour pressure ratio ($Pa\ Pa^{-1}$)
$VP_{sat\theta}$	=	saturated vapour pressure at temperature θ (Pa)
W_{FM}	=	width of fluting medium – cross-machine direction (m)
x	=	proportion of conduction heat transfer via parallel analogy
\bar{x}_1	=	average of sample 1 (dimensions vary)
\bar{x}_2	=	average of sample 2 (dimensions vary)
\hat{y}	=	estimated dependent variable value (dimensions vary)
y	=	measured dependent variable value (dimensions vary)
z	=	dimension in the fluting medium thickness direction (m)
ΔH_{adsorp}	=	heat of adsorption of water vapour onto adsorbent ($cal.mol^{-1}$)
ΔH_C	=	difference in enthalpy between bulk liquid and multilayer, fitted variable ($J.mol^{-1}$)
ΔH_{cond}	=	heat of condensation of water ($cal.mol^{-1}$)
ΔH_K	=	difference in enthalpy between monolayer and multilayer, fitted ($J.mol^{-1}$)
ΔH_M	=	fitted constant to express temperature dependence of M_o ($J.mol^{-1}$)
δ	=	0.0 for difference between two means (dimensions vary)
δ	=	diffusibility factor (dimensions not stated)
θ	=	fluting medium temperature ($^{\circ}C$)
θ_{AB}	=	temperature of ambient air or preconditioner in contact with bottom surface ($^{\circ}C$)
θ_{AT}	=	temperature of ambient air or preconditioner in contact with top surface ($^{\circ}C$)
θ_{CA}	=	contact angle between fluting medium and preconditioner roll ($^{\circ}$)
κ_{AB}	=	permeability of ambient air at bottom surface (m^2)
κ_{AT}	=	permeability of ambient air at top surface (m^2)
κ_r	=	relative permeability (m^2)

K_S	=	saturated intrinsic permeability (m^2)
K_V	=	fluting medium water vapour permeability (m^2)
λ_1	=	thermal conductivity for components in series ($W.m^{-1}K^{-1}$)
λ_2	=	thermal conductivity for components in parallel ($W.m^{-1}K^{-1}$)
λ_{com}	=	combined thermal conductivity of fibre, liquid water and water vapour ($W.m^{-1}K^{-1}$)
λ_{eff}	=	effective conduction coefficient ($W.m^{-1}K^{-1}$)
λ_f	=	paper fibre thermal conductivity ($W.m^{-1}K^{-1}$)
λ_v	=	water vapour thermal conductivity ($W.m^{-1}K^{-1}$)
λ_w	=	liquid water thermal conductivity ($W.m^{-1}K^{-1}$)
μ_v	=	water vapour viscosity ($kg.m^{-1}s^{-1}$)
π	=	pi (dimensionless)
ρ_a	=	air density ($kg.m^{-3}$)
ρ_f	=	density of paper fibre ($kg.m^{-3}$)
ρ_M	=	density of fluting medium (dimensions not stated)
ρ_v	=	density of water vapour ($kg.m^{-3}$)
ρ_w	=	density of liquid water ($kg.m^{-3}$)
ϕ_P	=	diameter of pressure roll (m)
ρ_v	=	water vapour density ($kg_{water vapour}.m^{-3}$)
ρ_{vA}	=	water vapour density of ambient air ($kg_{water}.m^{-3}$)
ρ_{vAB}	=	water vapour density of ambient air in contact with bottom surface ($kg_{water}.m^{-3}$)
τ	=	tortuosity factor (dimensions not stated)
$\phi(MC)$	=	water content dependent function (dimensions not stated)