Significant Factors Affecting Horticultural Corrugated Fibreboard Strength

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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 (~0°C) and high humidity (>70 %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 valves 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.

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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)
$CS_{CD\text{-}DBL}$	=	compression strength of the double-backer linerboard in the cross-machine direction ($N.m^{-1}$)

$CS_{CD\text{-}M}$	=	compression strength of the fluting medium in the cross-machine direction ($N.m^{-1}$)
$CS_{CD\text{-}SFL}$	=	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 ($m^2.s^{-1}$)
$D_{water\text{-}air}$	=	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
fc	=	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 ($kg.mol^{-1}$)
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 θ°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)
$P_{sample,\theta}$	=	partial water vapour pressure exerted by the sample at θ°C (Pa)
$P_{sat,\theta}$	=	saturated water vapour pressure at θ°C (Pa)
$P_{sat,\text{ sample db }\theta}$	=	saturated water vapour pressure at the sample dry bulb temperature (Pa)
$P_{sat,\text{ sample dp }\theta}$	=	saturated water vapour pressure at the hygrometer dew point temperature output (Pa)
P_{satT}	=	saturated water vapour pressure T Kelvin (mbar)
P_v	=	water vapour partial pressure (Pa)
Q	=	differential heat of water vapour sorption ($J.kg^{-1}$)
Q_R	=	differential heat of sorption as calculated by Reardon ($J.kg^{-1}$)
Q_s	=	heat of sorption ($J.mol^{-1}$)
R	=	gas constant (8.314 $J.K^{-1}mol^{-1}$)
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 ($cal.R^{-1}.mol^{-1}$)
RH	=	air relative humidity (%)
R_{max}	=	maximum pore radius (m)
R_O	=	gas constant (82.05 $cm^3.atm.gmol^{-1}K^{-1}$)
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 ($in.in^{-1}hr^{-1}$)
$SSCS$	=	short span compression strength ($kN.m^{-1}$)
$SSCS_{CD\text{-}DBL}$	=	short span compression strength of the double-backer linerboard in the cross-machine direction ($N.m^{-1}$)
$SSCS_{CD\text{-}M}$	=	short span compression strength of the fluting medium in the cross-machine direction ($N.m^{-1}$)
$SSCS_{CD\text{-}SFL}$	=	short span compression strength of the single-facer linerboard in the cross-machine direction ($N.m^{-1}$)

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 (°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
$x\text{bar}_1$	=	average of sample 1 (dimensions vary)
$x\text{bar}_2$	=	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 (°C)
θ_{AB}	=	temperature of ambient air or preconditioner in contact with bottom surface (°C)
θ_{AT}	=	temperature of ambient air or preconditioner in contact with top surface (°C)
θ_{CA}	=	contact angle between fluting medium and preconditioner roll (°)
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)

κ_S	=	saturated intrinsic permeability (m^2)
κ_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 ($kg_{watervapour}.m^{-3}$)
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)