



# Influence of different box preparations on creep performance of corrugated fibreboard boxes subject to constant and cycling relative humidity environments

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## Abstract

To understand the effect of load and relative humidity (RH) on box creep in cool storage conditions, standard tests are performed. However, these test conditions are oversimplified compared with actual shipping conditions. Our aim is to develop test conditions that more closely mimic those encountered during refrigerated conditions to investigate their influence on creep performance and box lifetime. We compared three box preparations: (i) empty boxes used as a control, (ii) filled boxes, and (iii) boxes with only two side panels exposed to the atmosphere. A controlled environment test facility was used to subject sets of 24 boxes to 30% of their ultimate failure load under different cyclic and constant relative humidity conditions. Results indicate that filled boxes had substantially reduced performance in terms of secondary creep rate and lifetime. The fill in the box contributed to out-of-plane displacement of the side panels which manifested earlier than in the control, resulting in a higher creep rate. Boxes with only two exposed panels had lower moisture uptake and performed substantially better than the control. These findings demonstrate how creep performance and box lifetime depend on the box conditions including fill and the area of the box that is exposed for moisture transfer. Alternative box preparations which mimic supply chain conditions are worthy of investigation in creep analysis as they will help predict more accurately box performance in the cold supply chain.

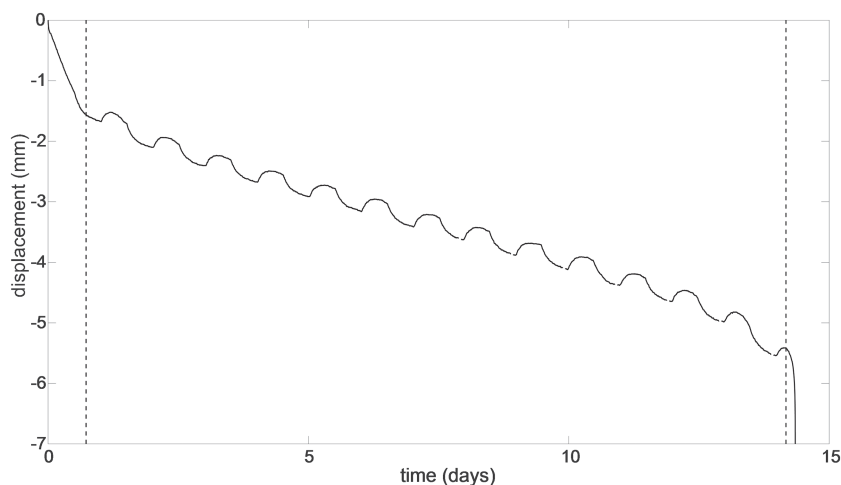
## 1 | INTRODUCTION

Paper and board packaging accounts for 40% of the total packaging market.<sup>1</sup> Corrugated fibreboard boxes are a critical packaging element for local and international trade. Corrugated fibreboard boxes are cost effective and robust with good top-to-bottom compression strength.<sup>2</sup> Boxes fail when an applied load exceeds their compressive strength;

they can also fail due to compressive creep (Figure 1) when a lower magnitude constant load is applied over an extended period. There are three distinct regions of creep deformation, primary, secondary, and tertiary. Primary creep occurs when the load is applied and the top and bottom flaps of the box are compressed and the load is transferred to the perimeter of the box<sup>3</sup> and the rate of box displacement is much greater than in secondary creep. During secondary creep, the

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**FIGURE 1** Box displacement over time for a box subjected to constant compression in cyclic humidity conditions. The vertical dashed lines separate the primary, secondary, and tertiary creep regions, respectively

box panels begin to bulge and the load is transferred to the corners of the box.<sup>3-6</sup> The cyclical nature of the displacement during secondary creep in Figure 1 is a result of hygroexpansion as the paper is the swelling and shrinking as the RH changes.<sup>5</sup> In the tertiary region, box failure is initiated as a result of local buckling near the corners which leads to hinge formation and ultimately catastrophic failure of the box.<sup>3,7,8</sup>

It has been previously reported that the box compression strength is affected by humidity<sup>2,9-11</sup>; likewise, failure rate due to creep is usually faster at higher relative humidities and previous research has reported higher secondary creep rates, shown to be closely related to shorter lifetimes<sup>6,12-16</sup> under cycling RH conditions compared with constant RH.<sup>6,17,18</sup> However, findings by Hussain et al.<sup>3</sup> challenge this notion that box performance is worse when RH is cycling as opposed to constant. They measured creep rates for a single type of box across a range of different cycling times under different constant vertical loads. They found that boxes subject to a 20% BCT or higher at constant 90% RH failed earlier than boxes at these loads exposed to cycling conditions between 50% and 90% RH. This finding was attributed to creep time constants logarithmically shifting to shorter times as a result of the high applied load. Shorter creep time constants mean larger creep rates. High loads and high moisture contents produced large enough creep rates to quickly dissipate stress gradients leading to more creep than cyclic conditions.

Compressive creep tests are conventionally done on single empty boxes,<sup>3,18</sup> and only recently, some researchers have put plastic balls inside the box to prevent them from inward buckling.<sup>19</sup> In reality, boxes are often palletised and contain product which may impart out-of-plane loading on the box panels thus promoting buckling of panels.<sup>20</sup> This can lower the top-to-bottom compression strength<sup>20</sup> and may accelerate failure due to creep.<sup>21</sup> Furthermore, during transport and storage, boxes are usually packed tightly on a pallet and only have one or two external side panels exposed to the ambient atmosphere. This is in contrast to having all four panels exposed in a traditional creep test. The primary aim of this work was to see whether performing the compressive creep tests with boxes under conditions more aligned with those experienced in the refrigerated supply chain

would yield different conclusions regarding secondary creep rate and box lifetime than creep tests performed on empty boxes.

Cyclic RH creep tests can provide useful information about the performance of boxes for manufacturers.<sup>14,21,22</sup> In practice, the RH rarely exhibits uniform cycles especially in refrigerated conditions.<sup>23-25</sup> As boxed products move through a supply chain, they can experience periods of relatively constant RH interspersed with periods of variable RH. Thus, a secondary aim of this work was to explore how cycle-interval tests consisting of periods of constant RH in between controlled RH cycles would influence the box lifetime and secondary creep rate. This approach could allow manufacturers to simulate in a controlled testing facility the RH profiles experienced by their boxes in a supply chain and potentially economise this testing by focussing on the most harmful conditions experienced by the boxes.

## 2 | MATERIALS AND METHODS

### 2.1 | Materials

For this study, single walled C-flute regular slotted containers were used. The inner and outer liners were 200 and 250 gsm Kraft liner-board made from New Zealand grown radiata pine with a 160 gsm semichem medium. The boxes were manufactured in New Zealand and obtained as flat packs with the manufacturer's flap preglued. They were stored in a controlled environment at 50% RH and 23°C. The outer dimensions of the assembled boxes were 385 × 248 × 295 mm (length × width × height).

### 2.2 | Box compression tests

Box compression tests (BCTs) were conducted to determine the applied load for the creep tests. BCTs were conducted in accordance to Australian and New Zealand standard (AS/NZS 1301.800s:2006). A Wiedemann universal tester was used for this testing. Boxes were compressed at a crosshead speed of 10 mm/min until failure. The

highest load prior to failure was recorded as the BCT load. Ten replicate samples were used for the BCTs, and boxes were conditioned for 48 h at 50% RH and 23°C prior to testing.

## 2.3 | Box preparation

Three preparations of boxes were used in this study: control, filled, and foil boxes. Empty boxes were used as the control. The filled boxes contained  $20 \pm 0.2$  kg of Chelsea® standard granulated white sugar. Sugar was chosen as it has a similar bulk density ( $900 \text{ kg m}^{-3}$ ) to the product normally contained in the boxes and is shelf stable. This left a headspace of  $\approx 80$  mm between the product and the top of the box that ensured that the box would take the applied load and not the contents. Sugar is hygroscopic; to prevent unintended issues with moisture, the sugar was packed in two black plastic (LDPE) rubbish bags which were then sealed with foil tape. The foil boxes had two adjoining external side panels, without the manufacturer's joint, covered in aluminium foil to represent a box on the corner of a pallet. The foil was secured with aluminium tape. All boxes were sealed with standard brown packing tape holding the top and bottom flaps in place. The test facility had 24 presses available and for each trial eight replicates of three different box preparations were set up. Figure 2 shows how the boxes looked with the foil coating applied to two adjacent panels.

## 2.4 | Creep tests

Cyclic RH creep tests often use a range of at least 40% RH, with cycling between 50% and 90% of RH being commonly used.<sup>6,15,26</sup> In these trials, low and high RH levels of 70 and 90% at a temperature of 4.5°C were chosen. The rationale for this approach is that refrigerated storage and transport is particularly common for horticultural and agricultural exports. RH in refrigerated conditions is typically between 70% to 90% and the typical temperature range is 0–8°C and product dependent<sup>27,28</sup>; the boxes used in this study are made for refrigerated product. The WHITE (Weight Humidity Intervals Temperatures Experiments) room test facility at the Scion Te Papa Tipu Innovation Park

was used for this work. Four different compressive creep conditions were performed for this study as detailed in Table 1. Boxes were subjected to 30% of the BCT for in all trials to represent highly loaded boxes, for example, those on the lowest layer of a pallet.

The box conditioning protocol used by Hussain et al.<sup>3</sup> was employed for this study. Prior to preparing the boxes, they were conditioned for 48 h at 23°C and 50% RH as they would be for BCT. Once the boxes had been prepared, they were placed in a press in the test room. All boxes were initially subjected to two 24-h humidity cycles, consisting of 12 h at 70% RH and then 12 h at 90% RH with no load applied. Each press was equipped with a load cell and linear variable differential transformer (LVDT) which enabled the applied load and displacement to be measured, while the relative humidity and temperature in the test room was measured and recorded using multiple sensors. All data were recorded at 5-min intervals. Table 1 outlines the RH conditions for the four trials. Trials (A) and (C) were stopped at the end of a 12-h 90% RH cycle, and trial (B) was stopped at the end of a 5-day constant 90% period. This was to ensure the moisture content of the boxes would be at their maximum for the respective trials. All trials were run for between 21 and 25 days.

## 2.5 | Box lifetime and secondary creep rate

The R code developed by Hussain et al.<sup>3</sup> was used to determine secondary creep rate and box lifetime. Briefly, a method was developed to detect the peaks in the box displacement versus time data. For boxes which did not fail, a linear regression was fitted through the peaks of the data between 20% and 80% of the experimental time

**TABLE 1** Creep testing conditions

Trial	RH conditions
A	Cycling; 24 h cycles (12 h at 70% RH, 12 h at 90% RH)
B	Cycle/interval; 5 times 24 h cycles (12 h at 70% RH, 12 h at 90% RH), 5 days constant RH at 90%
C	Constant RH at 90%
D	Constant RH at 70%

**FIGURE 2** Assembled box with two normal panels (A) and aluminium foil covering two adjacent panels (B), the top flaps of the box were sealed with tape after the aluminium foil was applied



period. Secondary creep rate is given by the absolute value of this gradient divided by the height of the boxes (295 mm). Figure 3 illustrates peak detection method used to calculate the secondary creep rate. For boxes which failed, a numerical differentiation method was used to see when the steepest gradient occurred and thus give the time at which a box failed. The secondary creep rate for boxes which failed used the same peak detection method; however, 10% to 90% of the time period was used in order to get a suitable secondary creep rate value as the time period to failure was often much shorter than boxes which did not fail.

## 2.6 | Moisture content

At the end of the trials, the moisture content of the boxes was measured. The trials concluded with the 90% RH cycle apart from the constant 70% RH trial. The four side panels from each box were cut out and weighed immediately after the test; they were then dried at 105°C for 72 h to obtain the dry weight. The % moisture content of the board at the end of the trial was given by (wet weight-dry weight)/wet weight.

## 3 | RESULTS AND DISCUSSION

### 3.1 | Box compression tests

The mean BCT value measured was 4.41 kN (450 kg force) with a standard deviation of 0.186 kN (18.9 kg force); 30% of the BCT value was chosen for the creep tests as it gives a load of 1.32 kN (135 kg force), which is close to the gross maximum load that these boxes would experience when palletised in the supply chain. The boxes used in this study are typically palletised with an interlock pattern six high, which is an equivalent total load of 1.23 kN (125 kg force plus

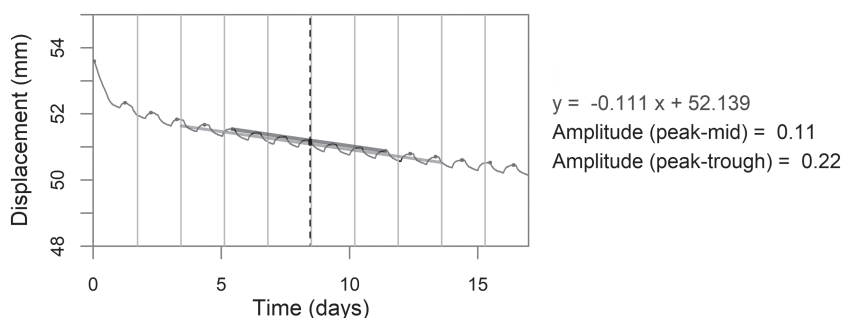
packaging weight) on the boxes on the bottom layer of a pallet. It is important to acknowledge that the load distribution on a box in creep and compression tests is simplified compared with a real-world scenario. The stacking configuration, box misalignment, and the pallet itself all influence the load distribution.<sup>29–31</sup>

### 3.2 | Moisture content

The moisture content of the board at the end of the creep tests is given in Table 2. Across the four different conditions used, the average moisture content was highest for the filled boxes followed by the control, the nonfoil side from the foil covered box and the foil covered panels. Aluminium foil provides a complete barrier to moisture and restricts the direct vapour access to the covered panels, so the moisture content will be lowest for the covered panels.

It takes a long time for the board to reach equilibrium moisture content as can be seen from the difference between the constant 90% RH condition and the two cycling trials where the boxes were only held at 90% RH for 12 h and 5 days, respectively. From the sorption and desorption isotherms for corrugated fibreboard presented in the literature,<sup>3,32,33</sup> the equilibrium moisture content for sorption at 90% RH and desorption at 70% RH are similar. We hypothesise that even during the cycling RH in trial A the mean moisture content of the panels has a narrower range than the equilibrium moisture content at 70% and 90% RH, respectively.

In all trials, the highest moisture content was measured for the filled boxes (Table 2). This indicates that the actual moisture content of boxes in the supply chain could be higher than what is measured from empty boxes in compressive creep tests. However, this difference may not be significant enough to influence box behaviour. Having product inside the box might result in the inner liner having a higher moisture content. In an empty box, moisture from the inner liner desorbs into the air space and is adsorbed by the top and bottom



**FIGURE 3** Example of box displacement data over time for a box from trial A. The black dots indicate peaks and the solid grey lines are linear regressions through the peaks and a rolling mean respectively, taken within the second and eighth data quantiles represented by the outermost dotted vertical lines

Trial	Control	Filled boxes	Foil sided bare	Foil sided covered
A	13.4 (0.25) <sup>b</sup>	14.0 (0.34) <sup>a</sup>	13.3 (0.32) <sup>b</sup>	12.2 (0.27) <sup>c</sup>
B	14.2 (0.28) <sup>a,b</sup>	14.5 (0.22) <sup>a</sup>	14.1 (0.36) <sup>b</sup>	13.1 (0.31) <sup>c</sup>
C	14.9 (0.25) <sup>a</sup>	15.0 (0.40) <sup>a</sup>	14.7 (0.59) <sup>a</sup>	14.7 (0.55) <sup>a</sup>
D	11.0 (0.21) <sup>a,b</sup>	11.1 (0.13) <sup>a</sup>	11.0 (0.20) <sup>a,b</sup>	10.8 (0.14) <sup>b</sup>

Note: For each trial, means followed by a common letter are not significantly different by the HSD test at 5% level of significance.

**TABLE 2** Moisture content (% wet basis) of the board at the completion of the trials, mean with standard deviation in brackets

flaps. If there is a product occupying most of the internal space, the rate of mass transfer from the inner liner to the air space and box flaps will be reduced. This will result in the inner liner of the panels having a higher moisture content as there is less moisture transfer to the air space and box flaps than in an empty box.

As can be seen Table 2, some preparations affect the moisture content under some test conditions. The moisture content and its variation in fibreboard during cycling for different box preparations is something which has not previously been investigated. The response of moisture content in relation to changes in RH is further complicated by the adsorption and desorption phenomena which is also worth pursuing in future studies. Given the correlation between box performance and moisture content such information could help understand vulnerability of boxes to creep.

### 3.3 | Box failure and lifetime

Boxes were examined at the end of the trials to assess the failure they experienced. Failure was observed in all trials and preparations except for constant RH 70% and the foil covered boxes with the 12-h cycling time where there were no failures; 100% failure was observed for the control and filled boxes in trial B. The type of failure exhibited by the control and filled boxes was as previously described<sup>26,34</sup> where buckling occurs in the corners which results in hinge formation leading to out-of-plane displacement on the larger side panels (Figure 4A,B). An interesting observation was that boxes with the foil coating behaved differently to the control and filled boxes where the panels with foil buckled inwards. Having foil on the outer liner likely results in the inner liner gaining moisture at a

faster rate. The overall strength and response to loading of these panels could be altered by this imbalance in moisture content between the inner and outer liners and result in the panels bowing inwards.

This inward deflection would not occur under supply chain conditions as the product in the box would provide support and prevent this from happening. This is shown in Figure 4C,D which shows the uncovered and foil covered panels of the same box which failed in trial (B).

The mean box lifetime for the filled boxes was around half that of the control boxes in trials (B) and (C). The boxes with foil coated panels had the longest lifetime and lowest creep rate across all trials. The mean and median box lifetimes were similar with the largest difference being 2.4 days for the control boxes in trial B.

If the number of box failures is low the box lifetime is not a useful metric. However, the box failure rate provides a good indication of relative box performance across different preparations and test conditions. The failure rate of boxes which experienced 12-h cycling was lower than those at constant 90% RH (Table 3), this finding is in line with Hussain et al.<sup>3</sup> but in contrast to several previous studies It is noteworthy that no foil boxes under cycling conditions failed while a significant number of foil boxes failed when exposed to constant 90% RH and the cycle/interval conditions. These results support the notion that exposure to constant high RH% can be worse for box performance than cycling conditions with a load greater than 20% BCT. Furthermore, this shows that if one wants to mimic the conditions a box will experience in the supply chain, periods of constant high RH should not be omitted and may increase creep rate more so than continuous cycling. Further research in this area will undoubtedly be of some benefit to the packaging industry.



**FIGURE 4** Manifestations of box failure as a result of creep deformation observed in this study: (A) and (B) show all panels of a control box in which it can be seen that creases and hinges form at the corners of the box which leads to buckling and global failure; (C) and (D) show the panels of a foil box, where similar creases and hinge formation is observed while the foil coated panels moved inward, this was observed for all foil boxes which failed

**TABLE 3** Box lifetime results for each trial in this study

Trial	Preparation	Median life time (days)	Mean life time (days)	CV (%)	Number of boxes	Number of failures	Failure rate
A	Control	11.4	11.4	14	14	2	14%
	Filled	12.7	12.3	26	16	12	75%
	Foil	n/a	n/a	n/a	16	0	0%
B	Control	12.4	12.4	45	6	6	100%
	Filled	5.5	5.6	6	8	8	100%
	Foil	16.0	15.9	32	6	5	83%
C	Control	7.2	9.6	70	8	4	50%
	Filled	3.4	5.4	101	8	7	88%
	Foil	11.1	10.4	36	7	5	71%
D	Control	n/a	n/a	n/a	8	0	0%
	Filled	n/a	n/a	n/a	8	0	0%
	Foil	n/a	n/a	n/a	7	0	0%

**TABLE 4** Mean secondary creep rate for all trials with boxes at 30% BCT

Trial	Condition	Creep rate per day	CV (%)	Log creep rate
A	Control	2.82E-04 <sup>a</sup>	74%	-8.17
	Filled	8.90E-04 <sup>b</sup>	36%	-7.02
	Foil	1.31E-04 <sup>a</sup>	24%	-8.94
B	Control	8.12E-04 <sup>a</sup>	24%	-7.12
	Filled	1.57E-03 <sup>b</sup>	20%	-6.45
	Foil	5.23E-04 <sup>a</sup>	52%	-7.56
C	Control	9.36E-04 <sup>a</sup>	88%	-6.97
	Filled	2.88E-03 <sup>b</sup>	56%	-5.85
	Foil	7.05E-04 <sup>a</sup>	61%	-7.26
D	Control	1.78E-05 <sup>b</sup>	25%	-10.9
	Filled	2.92E-05 <sup>a</sup>	32%	-10.4
	Foil	2.28E-05 <sup>a,b</sup>	22%	-10.7

Note: For each trial, the secondary creep rate for each box preparation was compared with a post hoc Tukey HSD test. Means that do not share a letter are significantly different.

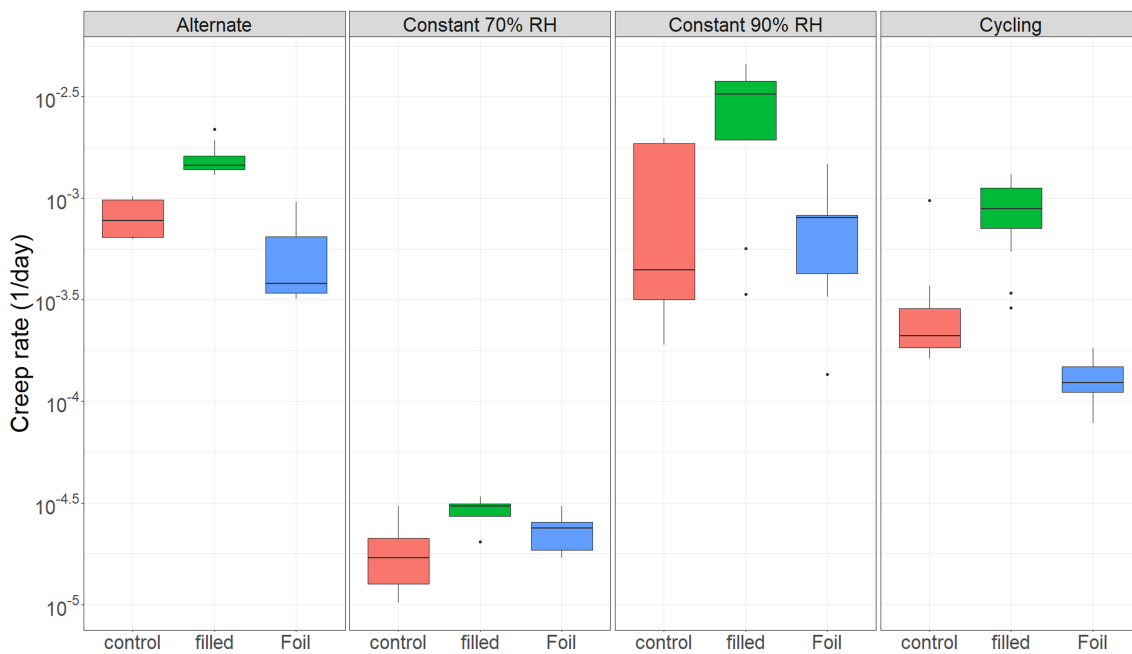
### 3.4 | Secondary creep rate

The mean creep rate for each trial is shown in Table 4, and the creep rate data are presented in a box and whisker plot in Figure 5. A post hoc Tukey HSD test was performed to determine if there were significant differences in the mean creep rate of the box preparations within each trial and to compare the effect the RH conditions had on each box preparation (Table 5). The coefficient of variation (CV) for creep rate is higher than found in most previous studies<sup>3,26,32</sup>; however, it is worth noting that CV was positively correlated with %BCT in the study by Hussain et al.<sup>3</sup> and the load used in this study is at the upper end of this range. The control in trials A and C have a notably higher CV of 74% and 88% and the failure rate of boxes in these tests was 14 and 50%, respectively. This tends to skew the variation in creep rate as the boxes which fail, especially if they fail early on, usually have a considerably higher creep rate. For trials A, B, and C, the creep

rate of the filled boxes is significantly different from the control and foil boxes, while there is no difference between the control and foil box preparations. These results show that the internal pressure from the box fill can have a significant negative impact on box performance and creep rate under certain conditions. At constant 70% RH, the box fill had less of an influence on creep rate, there was a significant difference between the filled and control boxes but not the filled and foil boxes. The reason why the filled boxes performed worse at higher humidities could be due to the mechanical properties of paper decreasing with increasing moisture content. A likely mechanism is that at higher moisture contents the stiffness of the panels decrease to a point where the internal pressure from the box fill can increase the rate of panel bulging relative to the control and in turn increase the creep rate. These results give merit to having different box preparations in creep tests as box performance is significantly affected when presented in a way that is more representative of supply chain conditions.

There is no significant difference in the creep rates of the foil and control boxes within the same trial. In constant RH conditions, the foil does not prevent the box panels from reaching the same moisture content as the uncoated panels so the creep rate will be similar. However, under cycling conditions, the foil has a significant effect on the moisture content of those panels as the 12 h cycle time is not long enough for them to reach equilibrium. While the difference in creep rate is not statistically significant, Figure 5 shows that the maximum creep rate observed for the foil boxes is lower than the median for the control. Extrapolation box performance from creep tests on normal boxes could result in creep rate and box lifetime being under-predicted as box performance is influenced by uneven distribution of moisture content. When boxes are palletised, boxes on the side of the pallet have only one panel exposed to the ambient conditions and boxes within the pallet can have all surfaces in contact with other boxes and no ambient exposure.

The findings here demonstrate that the creep rate and box lifetime are highly dependent on how the box is prepared. Notably the boxes with product performed considerably worse, having a shorter



**FIGURE 5** Secondary creep rate from all trials, box length depicts the interquartile range and the median is the horizontal line in the box, whiskers represent the maximum and minimum ranges of the data, except the outliers (black circles) which exceed 1.5 times the interquartile range

**TABLE 5** Comparison of secondary creep rate for box preparation as function of trial conditions

Box preparation	Trial condition	Secondary creep rate (day <sup>-1</sup> )
Control	Constant 90% RH	9.36E-04 <sup>a</sup>
	Alternate	8.12E-04 <sup>a</sup>
	Cycling	2.29E-04 <sup>b</sup>
	Constant 70% RH	1.80E-05 <sup>b</sup>
Filled boxes	Constant 90% RH	3.69E-03 <sup>a</sup>
	Alternate	1.57E-03 <sup>b</sup>
	Cycling	9.72E-04 <sup>c</sup>
	Constant 70% RH	3.10E-05 <sup>d</sup>
Foil boxes	Constant 90% RH	8.00E-04 <sup>a</sup>
	Alternate	5.23E-04 <sup>a</sup>
	Cycling	1.31E-04 <sup>b</sup>
	Constant 70% RH	2.30E-05 <sup>b</sup>

Note: Outliers identified using the interquartile range (IQR) criterion have been removed. Means that do not share a letter are significantly different.

lifetime and higher creep rate than the other two preparations. Factors such as the internal pressure from the product<sup>20</sup> and the distribution of moisture content of the box panels can significantly affect box performance. Including these enables the box performance to be quantified in conditions which are more representative of supply

chain conditions where boxes contain product and do not have uniform exposure to the ambient conditions. It is acknowledged that dynamic loading and vibration are two other phenomena which further impair box performance and are important in real world scenarios,<sup>24</sup> the stiffness of pallet deckboards also influence box compression strength.<sup>31</sup> However, these aspects have not been considered here due to cost and complexity and because the primary aim of this work was to isolate humidity effects on box performance.

#### 4 | CONCLUSIONS

The secondary creep rate and lifetime of boxes containing product was significantly shorter than the control and foil-covered boxes. This was attributed to the internal pressure imparted on the panels by the product; this can result in out-of-plane displacement of the side panels manifesting much earlier leading to a higher creep rate and shorter lifetime. Conversely, boxes which had two panels covered with foil had lower moisture uptake and performed better than the control in cycling conditions. The resultant lower moisture content of the coated and uncoated panels of this box preparation means the box remains stronger for longer. Furthermore, the foil acts as a barrier so the panels are not subjected to as larger changes in moisture content so the MC% will remain closer to the mean value.

These results show that future studies should consider mimicking the actual surface available for moisture transport as it has a significant influence on the box lifetime. The lifetime of the filled boxes in the cycle-RH interval tests was shorter than those which experienced only cycling conditions, but those exposed to constant 90% RH had the shortest lifetime. The results presented here further support the findings

of Hussain et al.<sup>8</sup> that conditions of constant high humidity can result in poorer box performance than cycling when the load is greater than 20% BCT and therefore that this factor plays an important role in box failure.

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## DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request. Open access publishing facilitated by Massey University, as part of the Wiley - Massey University agreement via the Council of Australian University Librarians.

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## REFERENCES

- Market Statistics and Future Trends in Global Packaging. 2008, World Packaging Organisation. [WWW.worldpackaging.org](http://WWW.worldpackaging.org)
- Frank B. Corrugated box compression—a literature survey. *Packaging Technology and Science*. 2014;27(2):105-128. doi:10.1002/pts.2019.
- Hussain S, Coffin DW, Todoroki C. Investigating creep in corrugated packaging. *Packaging Technology and Science*. 2017;30(12):757-770. doi:10.1002/pts.2323.
- Köstner V, Ressel JB, Sadlowsky B, Böröcz P. Measuring the creep behaviour of corrugated board by cascade and individual test rig. *Journal of Applied Packaging Research*. 2018;10(1):4. doi:10.14513/actatechjaur.v10.n2.445.
- Urbanik TJ. Hygroexpansion-creep model for corrugated fiberboard. *Wood and Fiber Science*. 1995;27(2):134-140.
- Urbanik TJ, Lee SK. Swept sine humidity schedule for testing cycle period effects on creep. *Wood and Fiber Science*. 2007;27(1):68-78.
- Coffin DW, Niskanen K, Gustafsson P, Berglund L, Hagglund R. *Mechanics of Paper Products*. 2011, De Gruyter, doi:10.1515/9783110254631
- Zhao LL. *Evaluation of the Performance of Corrugated Shipping Containers: Virgin Versus Recycled Boards*. Victoria University of Technology; 1993.
- Allaoui S, Aboura Z, Benzeggagh M. Effects of the environmental conditions on the mechanical behaviour of the corrugated cardboard. *Composites Science and Technology*. 2009;69(1):104-110. doi:10.1016/j.compscitech.2007.10.058.
- Marcondes J. Corrugated fibreboard in modified atmospheres: moisture sorption/desorption and shock cushioning. *Packaging Technology and Science*. 1996;9(2):87-98. doi:10.1002/pts.277009204.
- Navaranjan N, Dickson A, Paltakari J, Ilmonen K. Humidity effect on compressive deformation and failure of recycled and virgin layered corrugated paperboard structures. *Compos Part B Eng*. 2013;45(1):965-971. doi:10.1016/j.compositesb.2012.05.037.
- Bronkhorst C. Towards a more mechanistic understanding of corrugated container creep deformation behaviour. *Journal of Pulp and Paper Science*. 1997;23(4):J174-J181.
- Koning Jr J, Stern R. Long-term creep in corrugated fiberboard containers. Tappi [Technical Association of the Pulp and Paper Industry], 1977.
- Leake C. Measuring corrugated box performance. *Tappi Journal*. 1988;71(10):71-75.
- Leake C, Wojcik R. Humidity cycling rates: how they influence container life spans: Corrugated containers. *Tappi Journal*. 1993;76(10):26-30.
- Urbanik T. A more mechanistic model of the compression strain-load response of paper. *Journal of Pulp and Paper Science*. 2002;28(6):211-216.
- Habeger Jr CC, Coffin D. The role of stress concentrations in acceleration creep and sorption-induced physical aging. 1999.
- Van Hung D, Nakano Y, Tanaka F, Hamanaka D, Uchino T. Preserving the strength of corrugated cardboard under high humidity condition using nano-sized mists. *Composites Science and Technology*. 2010;70(14):2123-2127. doi:10.1016/j.compscitech.2010.08.011.
- Sherman NNL. Investigation into the effect product can have on box failure during creep tests. 2012.
- Peleman D, Singh J, Saha K, Roy S. Evaluation of a bulge reduction technology for corrugated fiberboard containers under static compression. *Journal of Applied Packaging Research*. 2020;12(1):6.
- Coffin DW. The creep response of paper. in 13th Fundamental Research Symposium, Cambridge. 2005.
- Morgan DG. A mechanistic creep model and test procedure. *Appita: Technology, Innovation, Manufacturing, Environment*. 2004;57(4):299 doi:10.1016/B978-012226570-9/50076-4.
- Nevis AL. *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*. Massey University; 2008.
- Eagleton DG. *Creep Properties of Corrugated Fibreboard Containers for Produce in Simulated Road Transport Environment*. Victoria University of Technology; 1995.
- Ruiz-Garcia L, Barreiro P, Robla JI, Lunadei L. Testing ZigBee nodes for monitoring refrigerated vegetable transportation under real conditions. *Sensors*. 2010;10(5):4968-4982. doi:10.3390/s100504968.
- Kutt H, Mithel B. Studies on compressive strength of corrugated containers. *Tappi*. 1968;51(4):A79.
- Gray-Stuart E. Unpublished data—Pallet transfer trial of dairy products in refrigerated shipping container. 2018.
- Lukasse L and Leentfaar G. Humidity control and fresh air exchange in reefer containers: lowest feasible relative humidity, temperature and energy consumption. 2020.
- Singh SP. Instability of stacked pallet loads due to misalignment. *Journal of Testing and Evaluation*. 1999;27(5):349-354. doi:10.1520/JTE12236J.
- Baker MW. Effect of pallet deckboard stiffness and unit load factors on corrugated box compression strength. *Virginia Tech*. 2016;29(4-5):263-274. doi:10.1002/pts.2201.
- Quesenberry C, Horvath L, Bouldin J, White MS. The effect of pallet top deck stiffness on the compression strength of asymmetrically supported corrugated boxes. *Packaging Technology and Science*. 2020;33(12):547-558. doi:10.1002/pts.2533.
- Byrd V, Koning Jr J. Corrugated fiberboards: edgewise compression creep in cyclic relative humidity environments [Southern pine pulps]. Tappi [Technical Association of the Pulp and Paper Industry], 1978.
- Popil RE, Hojjatie B. Effects of component properties and orientation on corrugated container endurance. *Packaging Technology and Science*. 2010;23(4):189-202. doi:10.1002/pts.889.
- Niskanen K. *Mechanics of Paper Products*. Walter de Gruyter; 2011.

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