

Effect of Freeze-Thaw Cycling on the Compression Strength of Folding Cartons made from Different Materials

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ABSTRACT: The quality of frozen food is known to deteriorate in storage due to water migration, in-pack desiccation and frost formation. These same factors can affect folding cartons. The rate of frozen food and folding carton deterioration is further dependent on temperature fluctuations during storage, transportation, loading and unloading. This study was conducted to compare the compression strength of folding cartons made from CNK (Coated Natural Kraft), SBS (Solid Bleached Sulfate), CRP (Coated recycled paperboard) and PCSBS (Poly coated Solid Bleach Sulfate) after subjecting them to multiple freeze-thaw cycles. Compression tests were performed on empty cartons and cartons filled with frozen peas. A two inch headspace was maintained above the peas to prevent them from contributing to carton compression strength. The moisture content of all four carton materials was also determined for all treatments. CNK cartons showed better capacity to withstand compression compared to folding cartons made from SBS, CRP and PCSBS, following freeze thaw cycling.

INTRODUCTION

A large portion of frozen foods are packaged in folding cartons. Approximately 75% of all folding cartons in a supermarket frozen food case are made of SBS (Solid Bleach Sulfate) and less than 10% are made of CNK (Coated Natural Kraft) as reported by a major carton material supplier [1]. There has been a long standing debate about the type of carton material needed to reduce unsaleables caused by carton

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damage. Damaged cartons and containers led to 2.57 billion dollars in losses to the consumer packaging industry for the year 2004 [2]. An independent audit firm found that most of the frozen food carton damage occurred after reaching the supermarket loading dock [2]. Therefore, there is a critical need to develop a carton material that can withstand the rigors of a frozen food distribution system.

The quality of frozen food is known to deteriorate at freezing temperatures due to water migration, in-pack desiccation and frost formation. The rate of frozen food and folding carton deterioration is further dependent on temperature fluctuations in the storage chamber and abrupt increases in temperature during loading and unloading of product during distribution and transportation [2]. Freeze/thaw cycling leads to crystal growth and frost formation on food surfaces and the inner side of packages, such as folding cartons. Therefore surface coating on the exterior wall of the carton is not effective in stopping moisture uptake from the crystals formed inside the pack. Crystal growth and frost formation can be further explained by water migration from the product and in-pack desiccation.

When the temperature in the void volume of a package is lower than in the product, water vapor will transfer from the higher vapor pressure region (within product) to a region of lower vapor pressure, i.e. product surface or inner surface of a package. Moisture is not able to migrate back into the product but accumulates on its surface. This phenomenon is known as water migration. This enables smaller crystals to grow larger by adhering to free water molecules [3] thus accumulating on the product surface and internal surface of the folding carton. Such crystals grow at a faster rate with fluctuating temperatures [4,5].

Similarly, in pack desiccation results in frost formation on the product surface and internal package wall. This mechanism has been explained [6] as follows:

1. "If the outside temperature of a package decreases, then the inside surface of the package will drop below the product surface temperature leading to ice sublimation from product surface causing condensation onto the inside walls of the package".
2. "Similarly, when the outside temperature increases, the process is reversed and water vapor condenses on the product surface".
3. "As the freeze thaw cycling continues, the crystals on the product are more influenced by the package temperature than the product mass. This results in further sublimation of ice from product surface

to the package surface. Eventually this results in frost formation on the package”.

A folding carton used as a frozen food package can be adversely affected by water uptake from the food product inside. The paperboard fibers can swell. This causes deformity in the folding carton structure leading to carton damage. Both water migration and in-pack desiccation are affected by product surface area to volume ratio. A high ratio makes a frozen food package more susceptible to larger crystal formation and greater frost formation on both product surface and package wall. This can cause rapid deterioration in food quality and carton's structural integrity.

Nearly 57% of supermarket returns are due to packaging damage caused during shipping, handling, receiving and stocking for the reasons mentioned above [2]. This makes it necessary to use a robust folding carton material to reduce unsaleables due to carton damage. A major material supplier produces a 'Coated Natural Kraft' (CNK) carton material topped with a proprietary coating known as 'Custom Kote'. A research study done by an independent audit firm, showed that 'Custom Kote' carton board reduced frozen food unsaleables by 44% [2]. This study was done to determine if this damage reduction was at least partially due to enhanced compression strength compared to uncoated carton stock. This study compared the compression strength of folding cartons made from CNK (Coated Natural Kraft) SBS (Solid bleached sulfate), CRP (Coated recycled paperboard) and PCSBS (Poly coated solid bleach sulfate) after subjecting frozen pea filled cartons to multiple freeze-thaw cycles. The carton stock was procured from two different suppliers to eliminate material source bias in the findings of this study.

MATERIALS AND METHODS

Two sets of die cut carton blanks measuring 9 inch \times 5 inch \times 2-3/4 inch (22.8 cm \times 12.7 cm \times 6.9 cm) made from 4 different folding carton materials were provided by two suppliers. Proprietary coating was applied on the outside of carton. Carton board caliper, basis weight and stiffness were determined in accordance to standard test methods ASTM D 645/D 645M-97 [8], D 646 [9] and D5342-97 [10] respectively.

The folding cartons were sealed using a hot glue gun and a polyethylene base glue stick as the adhesive. Sealed cartons were pre-condi-

tioned according to ASTM D685 [11] prior to testing. Frozen peas were used as the product. They were purchased from a local grocery store and then packed into folding cartons. Frozen peas were packed in the cartons to provide a moisture source during the freeze/thaw cycle. Frozen peas were chosen to provide the maximum surface area to volume ratio, thus maximizing freeze-thaw cycling abuse of the folding cartons.

A top closing coffin freezer held at -18°C (Kelvinator, Cleveland, OH) was used for this study. A Lansmont "Squeezer" compression test system (Lansmont Corporation, CA) was used to determine the compression strength using a fixed platen moving at 0.5 in/min (1.27 cm/min). The software used to interpret peak load was a Squeezer Reader version 2.0.0. (Lansmont Corporation, Monterey, CA).

Cartons were filled with 900 grams of frozen peas with a 2 inch (5.04 cm) headspace (Figure 1). Cartons containing the frozen product were placed in the freezer on their $9\text{ inch} \times 2\text{-}3/4\text{ inch}$ ($22.8\text{ cm} \times 6.9\text{ cm}$) side to maximize freeze-thaw abuse on the four carton faces. Cartons were subjected to a freeze-thaw cycle of 23 hours at -18°C , and then 1 hour at 23°C and 50% RH for five days prior to compression testing. This condition was chosen on the basis of frozen distribution environment [12]. From a preliminary study it was determined that the cartons would be compression tested on the $9\text{ inch} \times 2\text{-}3/4\text{ inch}$ ($22.8\text{ cm} \times 6.9\text{ cm}$) face as it showed the least variation. In addition, the compression strength of empty folding cartons was measured to compare the differ-

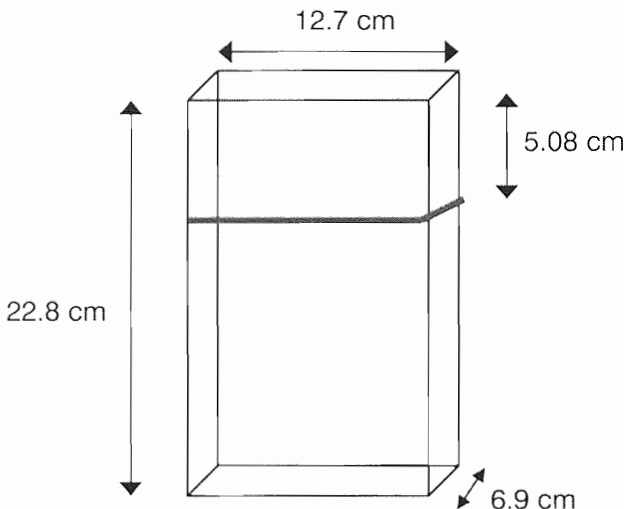


Figure 1. Fill height of frozen peas in the folding carton.

ent carton materials at ambient conditions (23°C, 50%RH) and to folding cartons subjected to freeze-thaw cycling.

Percent moisture content was determined for the four folding carton materials subjected to the three treatments. The three treatments were empty folding cartons; empty folding cartons subjected to five freeze-thaw cycles and pea filled folding cartons subjected five freeze-thaw cycles. For moisture analysis three carton samples weighing approximately 1.5 g were cut from three different locations from a folding carton. Two of the locations were from the carton faces 22.8 cm × 12.7 cm × 6.9 cm. The third location was on the opposite 22.8 cm × 12.7 cm face. Moisture content of the carton materials was determined according to ASTM D644 [13].

The data was analyzed using statistical software Minitab 13.1 by Minitab Inc, Pennsylvania. Analysis of variance was performed on the collected data for compression strength and percent moisture content. The means were separated using Fisher's LSD and the standard deviation for each treatment was noted.

RESULTS AND DISCUSSION

Carton material properties (basis weight and thickness) were determined prior to conducting the freeze-thaw experiments. It was found that the CNK provided by the first supplier had the highest basis weight (355.5 g/m²) followed by CRP, PCSBS and CSBS (Table 1). The CRP provided by the second supplier had the highest basis weight (382.2 g/m²) followed by CNK, PCSBS and CSBS. The thickness of all carton board material provided by both suppliers was measured to be approxi-

Table 1. Basis Weight and Thickness of Carton Material.

| Carton Material | Supplier 1 | | Supplier 2 | |
|--|----------------------------------|----------------|----------------------------------|----------------|
| | Basis Weight (g/m ²) | Thickness (mm) | Basis Weight (g/m ²) | Thickness (mm) |
| 'Custom Kote' Coated Natural Kraft (CNK) | 355.5 | 0.457 | 356.8 | 0.457 |
| Coated Solid Bleached Sulfate (CSBS) | 324.4 | 0.457 | 330.7 | 0.470 |
| Coated Recycled Paperboard (CRP) | 353.2 | 0.457 | 382.2 | 0.457 |
| Polyethylene coated solid bleach sulfate (PCSBS) | 350.6 | 0.457 | 357.2 | 0.495 |

mately 0.457 ± 0.00254 mm. Hence, the variation in carton material specifications was minimal between the two suppliers.

Under ambient test conditions (23°C, 50%RH) there was a significant difference ($p < 0.05$) in compression strength between the empty folding cartons made from the different carton materials from both suppliers (Figure 2 and 3). However cartons from both suppliers did not show a significant difference in compression strength between CNK and PCSBS empty cartons under ambient conditions. The highest average peak force was observed for cartons made from CNK at 283.3 N (Figure 2) for the first supplier and CRP at 274.3 N (Figure 3) for the second supplier. The lowest average peak force was significantly different from the highest average peak force for cartons made from CRP at 235.8 N (Figure 2) for the first supplier and CSBS at 245 N (Figure 3) for the second supplier. It was also observed that CNK folding carton had the highest bending stiffness in the cross direction compared to cartons made from CSBS, PCSBS and CRP (Table 2). The cartons were compressed top to bottom in the cross direction. Therefore, higher bending stiffness can contribute to a carton's compression strength [14]. So, it could be expected that prior to exposing folding cartons to a freeze-thaw test protocol, CNK cartons may have the highest compression strength at 21°C, 50% RH followed by SBS, PCSBS and CRP folding cartons.

As expected, after pea filled folding cartons were subjected to freeze/thaw cycling, the average peak force decreased for all carton materials compared to empty cartons tested at ambient conditions (Figures 2, 3, 4 and 5). This trend was observed in both suppliers. After testing there was a significant difference in the compression strength of cartons made from different carton materials (Figures 4 and 5). For both suppliers the highest average peak force was observed for cartons made from CNK (129.7 N and 139 N), which was significantly higher than the lowest average peak force for cartons made from PCSBS (45.9 N and 64.6 N). Average peak force for CSBS and CRP were not significantly different from each other but were significantly lower than the average peak

Table 2. Bending Stiffness of Different Carton Materials.

| Folding Carton | Machine Direction (TBU) | Cross Direction (TBU) |
|----------------|-------------------------|-----------------------|
| CNK | 170.2 | 98.3 |
| CSBS | 152.9 | 83.4 |
| CRP | 176.8 | 55.1 |
| PCSBS | 165.0 | 83.1 |

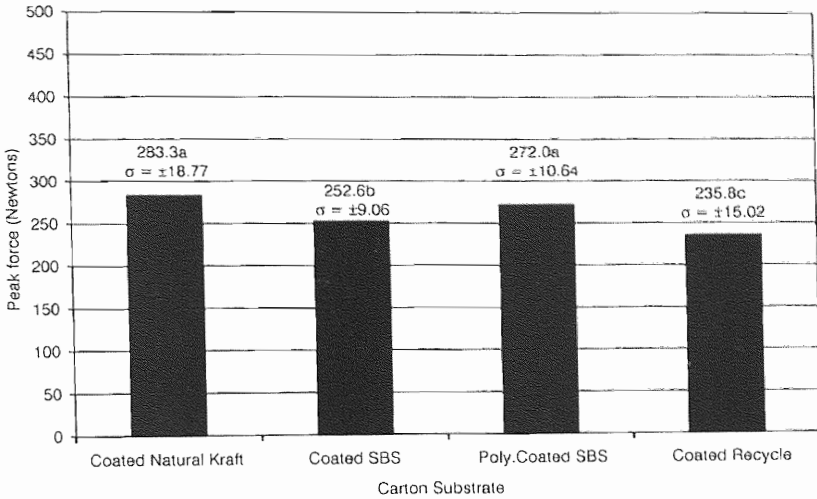


Figure 2. Compression strength of empty cartons at ambient conditions (Supplier 1). Means with different letters are significantly different ($p < 0.05$).

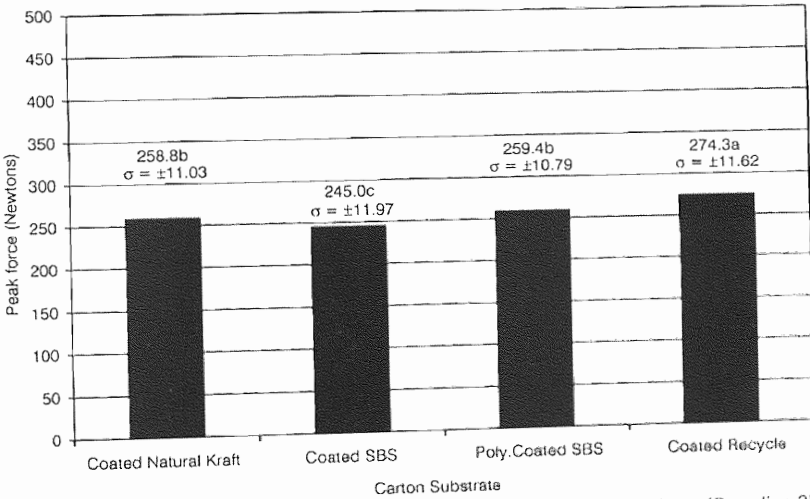


Figure 3. Compression strength of empty Cartons at ambient conditions (Supplier 2). Means with different letters are significantly different ($p < 0.05$).

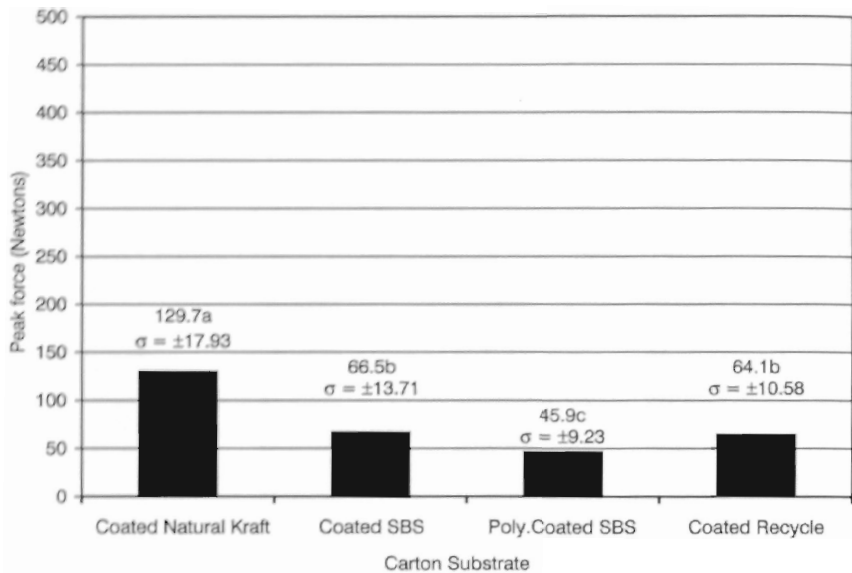


Figure 4. Compression strength of cartons after freeze-thaw cycling (Supplier 1). Means with different letters are significantly different ($p < 0.05$).

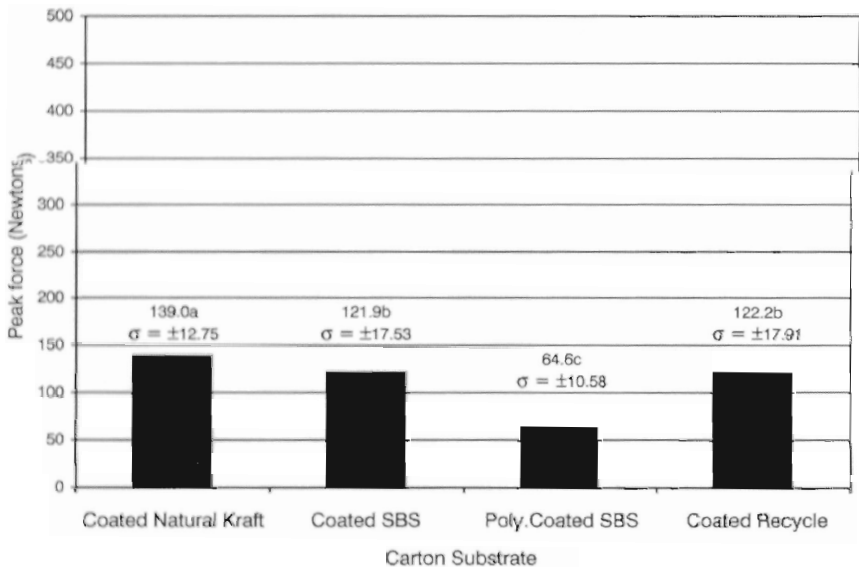


Figure 5. Compression strength of cartons after freeze-thaw cycling (Supplier 2). Means with different letters are significantly different ($p < 0.05$).

force of CNK cartons. CSBS and CRP folding cartons performed better than PCSBS cartons and had significantly higher average peak force than PCSBS cartons (Figures 4 and 5).

It should be noted that comparing the compression strength between cartons made from the same material but procured from different sources did not show a significant difference (Figures 4 and 5). Moreover, the type of carton material had an effect on the compression strength of carton after freeze-thaw abuse. The results show that after exposing pea filled cartons to a freeze-thaw test, CNK cartons had the highest compression strength followed by CSBS, CRP and PCSBS folding cartons (Figures 4 and 5).

Moisture analysis of the carton stock was performed to determine the effect of water migration and in-pack desiccation on the compression strength of cartons. The standard deviation across all treatments and carton materials was low. There was a considerable difference in moisture content between empty carton stock at 23°C, 50% RH and frozen pea filled folding carton stock subjected to freeze/thaw test (Figures 6 and 7). Frozen pea filled carton stock had higher moisture content than empty cartons. The multiple freeze-thaw empty (MFT Empty) carton stock did not have considerably higher moisture content than 'Empty' carton stock. Therefore, water migration into carton stock was due primarily to the product inside the carton and not from the carton's surroundings during the thawing phase of the FT cycle. This is evident from the percent moisture content of the empty carton stock exposed to FT cycles (Figures 6 and 7). This increase in moisture content most likely occurred due to water migration from frozen peas during the multiple freeze-thaw (MFT) cycling. Also, there was a significant difference in moisture content between cartons made from different carton materials. CNK carton stock had the lowest moisture content for treatment 'MFT Peas' (Figures 6 and 7). PCSBS carton stock (frozen pea filled carton) was observed to have the highest moisture content (Figures 6 and 7) after FT cycling. It should be noted that the moisture content of peas used for supplier 1 and supplier 2 were different, so there is a difference in the moisture uptake for the same material between the two suppliers (Figures 6 and 7). Keeping in view the above observations, this suggests that 'CNK' is a more robust material that can withstand temperature fluctuations during distribution.

There appears to be an inverse relationship between material moisture content and carton compression strength. With increasing moisture content there is a decrease in compression strength of cartons made

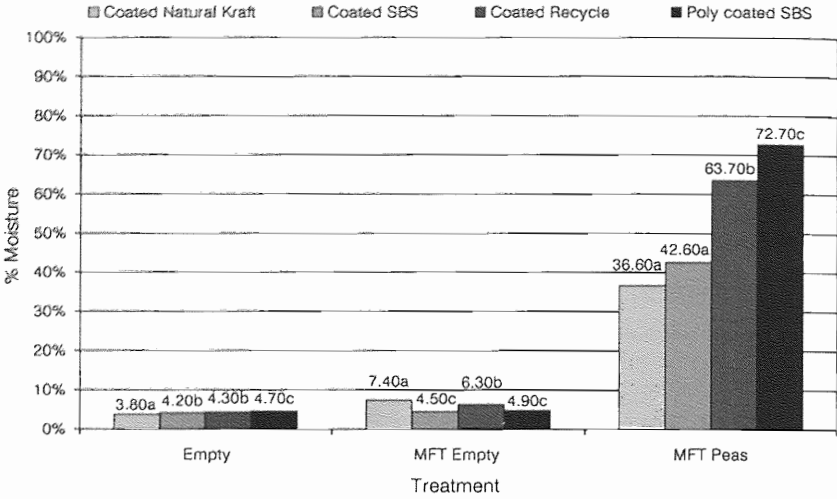


Figure 6. Moisture content (dry basis) of folding carton materials (Supplier 1). Means with different letters are significantly different ($p < 0.05$).

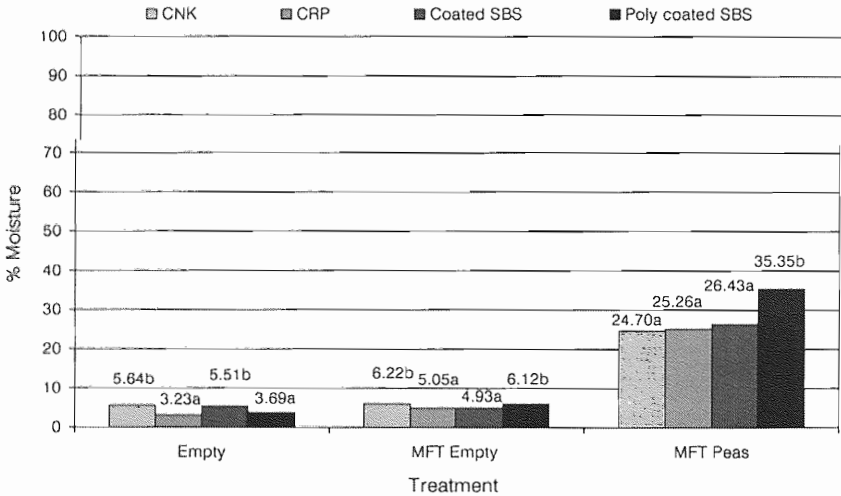


Figure 7. Moisture content (dry basis) of folding carton materials (Supplier 2). Means with different letters are significantly different ($p < 0.05$).

from different carton materials. It has been observed that moisture uptake is mainly from the peas inside the carton. Therefore the surface coating on the outer face does not play a major role against moisture absorption. This trend was observed for all carton types from both suppliers (Figure 8). There is a distinct difference between the carton materials, where frozen pea filled CNK cartons had the highest percent retained compression strength and the lowest moisture content following freeze/thaw cycling (Figure 8). Since, CNK has unbleached pine fibers with higher levels of natural, residual internal sizing, it will absorb less moisture compared to the other carton materials. The carton material had obstructed moisture ingress of condensed water droplets on the carton surface during FT cycling. Frozen pea filled PCSBS cartons had the lowest average peak force with the highest moisture content after FT cycling (Figures 4 and 5). Since the moisture uptake was observed to be from the inside of the carton, this explained adhesion failure in the PCSBS folding cartons between the polyethylene layer (inside layer of carton) and the SBS paperboard substrate (outside layer of carton). This resulted in the carton's poor performance during compression strength testing. It appears that irrespective of the carton material supplier, folding cartons made from CNK hold their structural integrity better in a frozen distribution network.

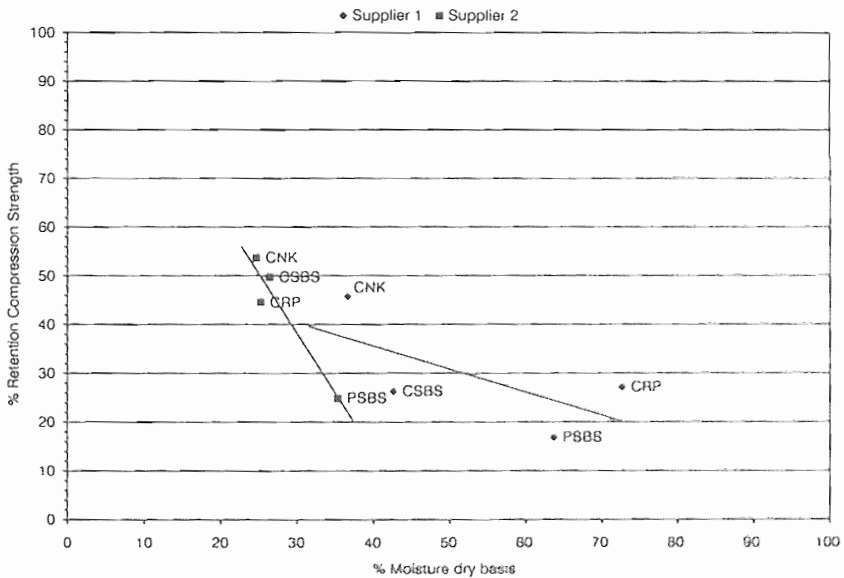


Figure 8. Effect of freeze-thaw cycling on compression strength of folding.

CONCLUSIONS

The higher bending stiffness of CNK (Table 2) can be attributed to longer fiber length compared to the other carton materials thus positively affecting carton compression strength. It was also observed that frozen pea filled CNK cartons subjected to freeze-thaw cycling had significantly higher capacity to withstand compression compared to folding cartons made from SBS, CRP and PCSBS (Figures 4 and 5). Multiple freeze-thaw cycling (Figure 8) of folding cartons resulted in increased moisture uptake and decreased compression strength. Since, frozen pea filled CNK cartons absorbed the least moisture from the inner surface of the carton during the multiple freeze-thaw cycling (Figure 8), they had the highest compression strength. Surface coating does not affect compression strength because moisture uptake is due to in pack desiccation as a result crystal formation on the inner surface of the carton. Coated Natural Kraft comprise of unbleached pine fibers providing stronger bonding sites compared to other carton materials thus retaining better dry value strength. This explains higher compression values for CNK cartons compared to SBS, CRP and PCSBS cartons, after multiple freeze-thaw cycling. It can be concluded that Coated Natural Kraft will provide more carton compression strength for packaging frozen food compared to folding cartons made from SBS, PCSBS and CRP.

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