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Can It Still Be Used? Compression Strength Recovery of Corrugated Boxes After Moisture Exposure

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Moisture exposure is a common risk for corrugated fiberboard boxes (CFB) during transport, handling, or storage, especially in humid environments or due to accidental water contact. Boxes that have gotten wet are often seen as unsafe and not strong, so they are thrown away. However, this practice contributes to unnecessary material waste and higher environmental impact. This study aims to examine whether corrugated boxes that have been exposed to water and subsequently dried can retain sufficient compression strength to allow for safe use. In this study, the potential for strength recovery of CFB following water exposure and drying was investigated. The samples were immersed in water for a defined period to simulate realistic exposure scenarios, then dried under controlled conditions. Following this, Box Compression Tests (BCT) were carried out to evaluate the remaining compression strength. The results showed that while compression strength decreases due to water exposure, a significant portion of it can be recovered after drying, depending on the material structure and exposure duration, with reductions ranging from 17 % to 31 %. These findings suggest that moisture-affected boxes may remain suitable for use, which questions the default approach of immediate disposal. By quantifying post-drying strength loss, this research supports data-driven decisions in packaging use, potentially reducing material waste and promoting more sustainable logistics practices.

1. Introduction

Corrugated fiberboard boxes (CFB) are fundamental to global logistics. For instance, Frank (2013) reported that these boxes represent approximately 80 % of all paper-based packaging in the United States. Their widespread use is attributed to advantages such as cost-effectiveness, low weight, and protective capability, as highlighted by Navaranjan et al. (2012). The primary function of these boxes is to withstand compressive loads during stacking, a performance metric quantified by the BCT, which measures the maximum force a box can endure before failure (Dimitrov and Heydenrych, 2009). The BCT is influenced by numerous factors, extending beyond the raw material properties to include both the box's geometry and its interaction with the logistical environment. For instance, structural features such as creasing lines are known to alter the load-bearing capacity of the box panels (Csavajda et al., 2017). The presence of ventilation holes, while often necessary, also introduces structural weaknesses. Fadiji et al. (2016) numerically modeled the effect of vent geometry on the compression strength of corrugated boxes, demonstrating how design parameters influence load-bearing capacity. In a separate study, Fehér et al. (2023) investigated how such openings contribute to creep deformation under loading, further emphasizing the reduction in mechanical performance. External factors related to storage and handling play a crucial role. The stiffness of pallet deckboards directly affects the support provided to the box, influencing its compression strength (Baker et al., 2016), an effect that is amplified in cases of asymmetrical support (Quesenberry et al., 2020). Similarly, pallet overhang, where portions of the box are left unsupported, has been identified as another key factor that diminishes BCT (Kim et al., 2023).

In addition to structural performance, environmental sustainability is increasingly being considered in the design and evaluation of packaging, driven by regulatory pressures and evolving consumer expectations (Lewis et al., 2010). Corrugated fiberboard boxes are widely regarded as a sustainable alternative, primarily because of their biodegradability and recyclability (Garbowski et al., 2021). Life Cycle Assessment (LCA) studies highlight corrugated fiberboard's favorable environmental profile compared to alternative packaging materials. For

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instance, Konstantinidis et al. (2021) demonstrated this advantage in the context of seafood packaging, showing reduced greenhouse gas emissions associated with corrugated board. Similarly, Chowdhury and Kabir (2023) found that paper-based solutions, including corrugated materials, performed well in terms of emissions and end-of-life impact when evaluating package deliveries. These attributes make corrugated packaging a strong candidate for reducing the environmental footprint of supply chains. In this context, exploring the mechanical viability of moisture-exposed boxes contributes directly to reducing avoidable material waste and supporting more responsible use practices.Among all environmental factors, moisture poses the most significant threat to the structural integrity of CFB packaging. Mrówczyński et al. (2024) conducted a comprehensive study using multiple mechanical tests to assess how varying temperature and relative humidity conditions affect strength, stiffness, and torsional performance, identifying the mechanical properties most sensitive to climate variation. Earlier, Allaoui et al. (2009) investigated the influence of relative humidity on tensile strength and highlighted how increased water content and viscoelasticity degrade structural performance. The cellulosic fibers from which the board is made are inherently hygroscopic, meaning they readily absorb water from the environment (Fadiji et al., 2018). This moisture absorption disrupts the inter-fiber hydrogen bonds, reducing the material's stiffness and overall mechanical strength (Sørensen and Hoffmann, 2003). While the negative impact of elevated ambient relative humidity on BCT is well established, the most recent and detailed study by Brown et al. (2024) quantified this effect with precision. They reported that the strength reduction factor ranged from 1.07 to 0.57 as relative humidity increased from 30 % to 90 %, highlighting the significant influence of moisture on structural performance. However, a different and less-studied scenario also presents a practical challenge. In logistical operations, it can occur that empty, flat-folded boxes are exposed to direct liquid water, such as from rain or condensation, before they are filled with product. Zhang et al. (2011) identified direct moisture exposure as a critical hazard factor in dairy logistics, noting that such contact can cause distortion or premature failure of packaging during storage and transportation. Based on industry feedback, the common practice is to discard these boxes due to concerns over their compromised integrity. This approach, while cautious, leads to significant material waste. The central issue is that while a dried box may exhibit aesthetic flaws, its residual functional strength is often unknown, leading to its premature disposal.

This study, therefore, investigates whether these discarded boxes are truly unusable. The primary objective is to quantify the residual compression strength of CFB packaging after it has undergone a direct water immersion and subsequent drying cycle. By determining how much of the initial BCT value is recovered after drying, this research critically examines the default practice of immediate disposal. The findings aim to provide a scientific basis for more resource-efficient decisions, potentially validating the safe use of moisture-affected boxes and promoting more sustainable logistics practices.

2. Materials and Methods

2.1 Test Specimens and Experimental Groups

Commercially available corrugated fiberboard boxes were utilized in this study. The boxes were grouped into two main categories based on their material specifications and dimensions. The first group comprised boxes constructed from the same fiberboard grade (539 g/m² kraft-wellenstoff-kraft), differing only in external dimensions—18×18×31 cm and 21×21×31 cm—and the manufacturer's joint method (glued or stapled).

The second group consisted of boxes produced from a heavier fiberboard grade (1,096 g/m² kraft-wellenstoff-kraft-wellenstoff-kraft), with dimensions of either 39.5×26.5×31.5 cm or 41.5×28.5×31.5 cm. Similar to the first group, boxes were categorized by the type of joint method used, either glued or stapled.

Each variation included 5 samples, with both water-immersed and dried and non-immersed (control) conditions, resulting in a total of 40 immersed and dried boxes and 40 control boxes, amounting to 80 boxes in total.

Table 1: Properties of the material samples

Marking	Box external dimensions [cm]	Edge Crush Test (ECT) [kN/m]	Grammage [g/m²]	Manufacturer's joint
X3G	18x18x31	7.32	539	Glued
X3S	18x18x31	7.32	539	Stapled
X10G	21x21x31	7.32	539	Glued
X10S	21x21x31	7.32	539	Stapled
X36G	39.5x26.5x31.5	15.48	1,096	Glued
X36S	39.5x26.5x31.5	15.48	1,096	Stapled
X12,8G	41.5x28.5x31.5	15.48	1,096	Glued
X12,8S	41.5x28.5x31.5	15.48	1,096	Stapled

2.2 Water Immersion, Drying Protocol, and Compression Testing Methodology

To simulate direct exposure to water, all boxes were fully immersed for a standardized duration of 30 s. This exposure time was chosen in alignment with the Cobb test (ISO, 2023), a standard recommending 30 s for evaluating water absorption characteristics of paper and board materials. Although full immersion does not follow the surface-specific nature of the Cobb test (ISO 535), the selected 30-second duration was deliberately aligned with its timing standard in order to simulate a severe but standardized moisture exposure scenario. Following immersion, boxes were allowed to drain briefly before undergoing a controlled drying process. The drying protocol consisted initially of storage at 35 °C and 30 % relative humidity (RH) for 48 h according to TAPPI T402 (TAPPI, 2013), subsequently conditioned at 23 °C and 50 % RH for an additional 72 h. Boxes were regarded as adequately dried and ready for testing once tactile dryness was achieved, and their mass had stabilized. Control samples, which were not immersed, underwent identical environmental storage conditions to ensure comparability with immersed samples. Subsequently, the residual BCT of all conditioned specimens was assessed using an Instron 5967 universal testing machine. Testing was conducted strictly following ISO 12048 (ISO, 1994) guidelines. Each specimen was centered on the machine's lower platen and compressed vertically at a consistent rate of 10 ± 3 mm/min until structural failure occurred. Structural failure was defined as the point where the load reached its maximum value, followed by a continuous decrease of at least 10 %, typically accompanied by visible buckling or panel collapse. BCT values were recorded as the peak compressive force (N) sustained by each specimen.

2.3 Data Analysis

To evaluate the impact of water absorption and drying on the boxes, two parameters were calculated: relative moisture absorption and relative BCT reduction. Relative moisture absorption was determined using equation (1):

$$\frac{\mathrm{m}_{wet} - \mathrm{m}_{dry}}{\mathrm{m}_{dry}} \tag{1}$$

where $\mathrm{m}_{\mathrm{wet}}$ is the mass after immersion, but before drying, and $\mathrm{m}_{\mathrm{dry}}$ is the original dry mass of the box. Relative BCT reduction was calculated using equation (2):

$$\frac{\overline{\mathrm{BCT}}_{dry} - \mathrm{BCT}_{wet}}{\overline{\mathrm{BCT}}_{dry}} \tag{2}$$

where $\overline{\mathrm{BCT}}_{dry}$ is the average BCT value measured on non-immersed samples of the same box type, and $\mathrm{BCT}_{\mathrm{wet}}$ represents the BCT value after immersion and drying.

Descriptive statistics (median, interquartile range, relative reduction) were calculated for each box type. Normality was assessed using the Shapiro–Wilk test. Since several groups deviated from normality, non-parametric statistical methods were applied in all subsequent analyses. Differences in BCT reduction across the eight box types were examined using the Kruskal–Wallis test, followed by pairwise comparisons using Dunn’s test with Bonferroni correction. The effect of joining method (glued vs stapled) was further analyzed using Mann–Whitney U-tests, both overall and within low and high ECT subgroups. To explore the relationship between moisture absorption and strength degradation, several regression models were tested. Among these, the power function trendline yielded the highest coefficient of determination and was selected to represent the association between the two variables. All statistical tests were conducted using a significance level of 0.05. The Shapiro–Wilk test evaluates whether data follow a normal distribution, while the Mann–Whitney U and Kruskal–Wallis tests compare group medians without assuming normality, the latter being an extension to more than two groups. In these analyses, U denotes the rank-sum statistic, p the probability under the null hypothesis, and r the effect size, calculated as the standardized Z value divided by the square root of the total sample size.

3. Results and Discussion

3.1 Relative BCT Reduction Across Box Variants

The effect of water immersion and subsequent drying on the box compression strength was examined across 8 corrugated box types with varying dimensions, board strengths, and joining methods. For each sample, relative BCT reduction was calculated as the proportional loss in strength compared to the average dry-state BCT of the corresponding box type. The distribution of these reductions is visualized in a boxplot (Figure 1), showing substantial variation between box types. To evaluate whether these differences were statistically significant, a Kruskal–Wallis test was applied (H = 17.52, p = 0.014). This non-parametric method was selected in light of the non-normal distribution observed in the glued and stapled subgroups, as confirmed by Shapiro–Wilk tests (see Section 3.2). The analysis confirmed that certain designs were more affected by the moisture cycle than others. Pairwise comparisons using Dunn’s test highlighted that certain glued box designs experienced significantly higher BCT reduction than several other types, including both stapled and glued constructions with lower degradation (e.g., X10G and X36G vs. X12.8G).To explore whether the absorbed moisture itself was a driving factor in this strength loss, relative water absorption was plotted against BCT reduction for all boxes (Figure 2). The regression analysis showed no meaningful correlation ($R^2 = 0.0012$), suggesting that the mechanical degradation cannot be explained solely by the amount of moisture absorbed. This implies that other factors, such as grammage, board construction, box geometry, and joining method, contribute to the observed loss in compression strength.

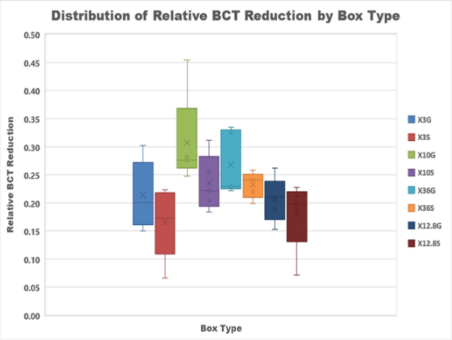

Figure 1: Distribution of relative BCT reduction by box type

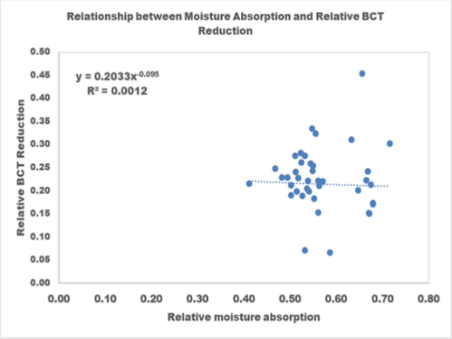

Figure 2: Relationship between relative water absorption and BCT reduction for all box types

3.2 Effect of Joining Method and Material Strength

To evaluate the role of joining method (glued vs. stapled) in moisture-induced compression strength loss, a comparative analysis was performed across all boxes. A boxplot (Figure 3) shows a tendency toward higher degradation in glued boxes.

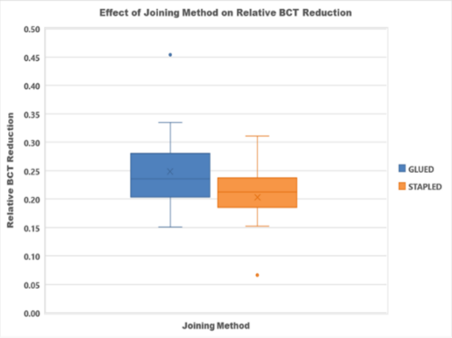

Figure 3: Effect of joining method on relative BCT reduction

The assumption of normality was evaluated using the Shapiro–Wilk test, which indicated that the stapled group deviated from normal distribution ($p = 0.032$), while the glued group did not ($p = 0.114$). Based on these results, a non-parametric Mann–Whitney U test was used, revealing a marginally significant difference between the two groups (U = 129, p = 0.056 two-tailed; p = 0,028 one-tailed). The moderate effect size (r = 0.30) suggests that the joining method may meaningfully influence strength retention after moisture exposure.

To determine whether this effect depends on the mechanical quality of the board, boxes were grouped into two categories based on their ECT values: low (7.32) and high (15.48). In the low-ECT group, the Mann–Whitney test approached significance (p = 0.083 one-tailed; r = 0.31), while in the high-ECT group, no significant difference was observed (p = 0.22 one-tailed; r = 0.18).An interaction plot (Figure 4) was constructed to visualize the relationship between board strength and joining method. The non-parallel lines suggest a potential interaction, as glued variants experienced markedly greater strength loss in low-ECT boxes. In contrast, the difference between joining methods was less substantial in high-ECT designs. This finding indicates that the influence of joining configuration is more pronounced in structurally weaker materials.

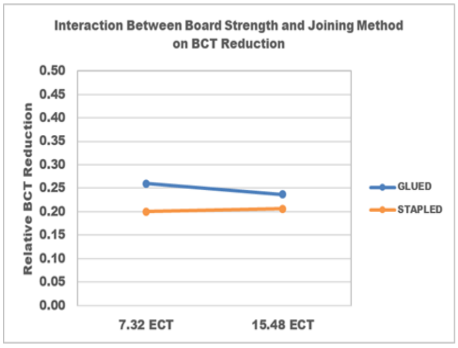

Figure 4: Interaction effect of board strength and joining method on BCT reduction

3.3 Relating Strength Loss After Immersion and Drying to Relative Humidity-Based Benchmarks

The average relative BCT reductions were measured across the eight tested box types, ranging from 0.17 (X3S) to 0.31 (X10G), indicating substantial variability in moisture-related strength loss. When interpreted in the context of previously reported humidity and strength relationships, such as those described by Brown et al. (2024), these values correspond to degradation levels typically associated with relative humidity conditions between 70 % and 90 %. For example, the 30 % reduction in compression strength recorded for X10G corresponds to a strength reduction factor of 0.70, which has been linked to RH levels around 80 % to 90 %.

4. Conclusion

This study investigated how moisture absorption followed by drying affects the BCT of corrugated fiberboard boxes of various constructions. While all tested boxes exhibited a measurable loss in strength after water exposure, the extent of this reduction varied significantly across designs.

Non-parametric statistical analysis confirmed that construction type plays a critical role in post-exposure performance. Glued variants generally showed greater strength degradation than stapled ones, particularly in boxes made from lower-grade board. However, the relationship between relative moisture absorption and BCT loss was found to be negligible ($R^2 = 0.0012$), suggesting that degradation is not driven by absorbed water alone, but also by structural design and joining method.

An interaction between material strength and joint type was also identified. For boxes made from lower ECT board, glued versions experienced substantially greater strength loss compared to stapled ones. In contrast, in higher ECT board designs, the difference between joining methods was less pronounced.

From a sustainability perspective, these findings are significant. They indicate that certain corrugated box types, particularly stapled high ECT variants, may retain sufficient mechanical performance even after moisture exposure and drying. This suggests a potential for extending the service life of such boxes in less demanding applications, contributing to more resource-efficient packaging practices. Rather than discarding all previously wetted boxes, performance-aware sorting could enable the continued use of those that remain functionally adequate, reducing unnecessary material waste. From an operational perspective, establishing performance-based acceptance criteria for moisture-exposed boxes may support more sustainable decision-making, especially in contexts where perfect structural integrity is not essential.

While non-parametric methods were applied to address the limited sample size, the relatively small number of replicates per configuration (n = 5) remains a constraint, and future studies should include broader replication to confirm these findings. Furthermore, as this study focused on controlled mechanical testing after immersion and drying, the real-world reuse potential of affected boxes under operational conditions remains to be validated and warrants further investigation.

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