applied sciences

MDPI

Article

Impact of Temperature and Humidity on Key Mechanical Properties of Corrugated Board

Damian Mrówczyński [1], Tomasz Gajewski [2], Aram Cornaggia [3] and Tomasz Garbowski [4,*]

[1] Doctoral School, Poznan University of Life Sciences, Wojska Polskiego 28, 60-637 Poznań, Poland; damian.mrowczynski@up.poznan.pl
[2] Institute of Structural Analysis, Poznan University of Technology, Piotrowo 5, 60-965 Poznań, Poland; tomasz.gajewski@put.poznan.pl
[3] Department of Engineering and Applied Sciences, Università degli studi di Bergamo, viale G. Marconi 5, 24044 Dalmine, Italy; aram.cornaggia@unibg.it
[4] Department of Biosystems Engineering, Poznan University of Life Sciences, Wojska Polskiego 50, 60-627 Poznań, Poland
* Correspondence: tomasz.garbowski@up.poznan.pl

Abstract: This research explores how temperature and relative humidity impact the mechanical properties of corrugated cardboard. Samples were treated under a range of controlled climate conditions in a climate chamber to simulate varying environmental exposures. Following this conditioning, we performed a series of mechanical tests: the Edge Crush Test (ECT) to assess compressive strength, four-point Bending Tests (BNTs) in both the Machine (MD) and Cross Directions (CD) to evaluate bending stiffness, Sample Torsion Tests (SSTs) for shear stiffness, and Transverse Shear Tests (TSTs) to measure torsional rigidity. By comparing results across these tests, we aim to determine which mechanical property shows the highest sensitivity to changes in humidity levels. Findings from this study are expected to offer valuable insights into the environmental adaptability of corrugated board, particularly for applications in packaging and storage, where climate variability can affect material performance and durability. Such insights will support the development of more robust and adaptable packaging solutions optimised for specific climate conditions.

Keywords: corrugated board; temperature effects; humidity effects; mechanical properties; edge crush test; bending stiffness test; shear stiffness test; torsional stiffness test

check for updates

Citation: Mrówczyński, D.; Gajewski, T.; Cornaggia, A.; Garbowski, T. Impact of Temperature and Humidity on Key Mechanical Properties of Corrugated Board. *Appl. Sci.* **2024**, *14*, 12012. https://doi.org/10.3390/app142412012

Academic Editor: Ana Martins Amaro

Received: 20 November 2024
Revised: 19 December 2024
Accepted: 20 December 2024
Published: 22 December 2024

1. Introduction

The global market of paper and paperboard packaging, in 2024, was estimated at approximately USD 400 billion and is expected to grow, by 2029, with a compound annual growth rate of almost 5% [1]. Corrugated cardboard is the most popular material for packaging production due to its numerous advantages. Cardboard packaging is lightweight, can be freely formed in terms of dimensions and shape, and can be easily reused or recycled. The increasing emphasis on environmental protection and the development of the e-commerce industry give packaging manufacturers an impetus for continuous development and greater innovation.

Throughout its life cycle, cardboard is subjected to various processes and to the action of many factors that can affect a change in its mechanical properties, as well as packaging made from it. The most important factors influencing the properties of cardboard are relative humidity and temperature. The scientific literature contains studies on the effect of these factors on tensile stiffness [2], moisture content and Young's modulus of cardboard [3] and the strength of packaging [4,5]. Niini et al. determined the strength of trays depending on their folding temperature [6], and Kaeppeler et al. observed the changing structure of cardboard as a result of changing temperature induced by ultrasounds [7]. The change in mechanical properties for different humidity and temperature scenarios was presented by Cornaggia et al. [8]. Furthermore, Su et al. investigated failure mechanisms during cold chain transportation [9], and Niini et al. checked the dimensional stability of press-formed paperboard trays during heating and cooling [10]. Many solutions have also been proposed to increase the water resistance of paperboard, including adding a hydrolysis-resistant polyester-based thermo-plastic polyurethane [11] or spraying with coatings such as polymeric, mineral-filled polymeric and hybrid silica sol–gel products [12].

In addition to humidity and temperature, many factors affect the strength parameters of cardboard and packaging. One of them is cardboard imperfections. Two types of imperfections can be distinguished, namely global and local. Systematic, large-scale deviation from the ideal flat shape of cardboard, modelled as based on the Kirchhoff plate theory, was proposed by Beck and Fischerauer [13]. The topic of local imperfections was dealt with by Nordstrand, who investigated the effect of the size of imperfections on the load-bearing capacity of packaging [14], and later extended the nonlinear buckling analysis of Rhodes and Harvey orthotropic plates by geometric imperfections [15]. Mrówczyński et al. presented numerical analyses of three- and five-layer cardboard, with local imperfections, and their effect on effective stiffnesses [16,17]. In 2022, Cillie and Coetzee conducted an experimental study and numerical analysis of in-plane compression of corrugated paperboard panels considering local and global imperfections [18]. Despite the different origin, other factors influencing the strength parameters of cardboard and packaging are the presence and size of holes or perforations. Archaviboonyobul et al. analysed the effect of hand and ventilation holes on box compressive strength using an artificial neural network [19]. Fadiji et al. also investigated the effect of ventilation holes on the load-bearing capacity of corrugated cardboard packaging, by comparing experimental data with numerical analysis results [20]. In 2011, Giampieri et al. proposed a constitutive model for the mechanical response of the folding of creased paperboard [21], while, in 2009, Beex and Peerlings formulated a mechanical model based on delamination [22]. Garbowski et al. carried out, using homogenisation, numerical analyses of cardboard with creasing or perforation to determine the influence of such factors on the mechanical properties of cardboard materials [23]. In connection with transport conditions, some researchers analysed the influence of various factors, such as stacking load [24], storage time and conditions [25], and hanging of the package on the pallet [26], on the load-bearing capacity of the boxes.

The problem of determining the material parameters of corrugated board is an important and, in some conditions, complicated issue. A reliable laboratory testing turns out to be crucial to obtain values that reflect the actual material behaviour. In 2021, Garbowski et al. determined the effect of creasing on the values of strength parameters of cardboard in bending, shearing, twisting and edge crushing tests [27]. Yoshihara et al. analysed the effect of span length on the bending parameters of cardboard in the three-point bending test [28]. However, due to the action of the shear force in the three-point bending test, for a more effective assessment, it may be necessary to adopt more advanced models [29,30]. Another testing issue studied in the literature was the loss of stability in the edge crush test, which was analysed on the case studies of corrugated board [31,32] and sandwich panels with corrugated core [33]. Additionally, in the bending test, local deformations on supports can be encountered, the influence of which was analysed for different types of corrugated board [34] and sandwich panels [35,36].

From a general standpoint, the main task of corrugated cardboard packaging is to protect transported goods, so it is particularly important to know the actual material parameters of the cardboard from which the boxes are made. For this reason, the main aim of this research is to check the influence of relative humidity and temperature, which can significantly affect the strength of the cardboard. Laboratory tests of bending, shearing, twisting and edge crushing were performed in standard conditions (23 °C and 50% RH) and in several other combinations of temperature and relative humidity. The data obtained can also be used in the design process of packaging, for possible employment in scenarios different from the standard conditions, in view of perspective engineering research and industrial applications.

2. Materials and Methods

The primary objective of this study is to investigate the effect of varying temperature and humidity conditions on the mechanical properties of 3- and 5-ply corrugated cardboard. The selection of specific board types was made after consultation with one of the biggest cardboard manufacturers in Poland based on the most commonly used cardboard sheets. In the first stage, six corrugated cardboard types were selected, including three 3-ply and three 5-ply cases, manufactured from 24 different papers. Detailed information on the corrugated cardboards and papers considered in this study is provided in Table 1.

Table 1. Specifications of corrugated cardboards used in this study.

Cardboard	Grammage (g/m^2)	Grammage of Papers (g/m^2)	Thickness (mm)
E flute	508	170–135–170	1.73
B flute	415	125–120–125	2.97
C flute	456	125–130–130	4.02
EE flute	653	125–120–80–120–125	2.77
EB flute	578	125–90–80–90–125	4.19
BC flute	803	170–135–80–135–170	6.72

Next, a range of temperature and humidity combinations was selected to condition the corrugated cardboard samples in a climate chamber. The relative humidity settings for the samples ranged from 30% to 90%, in 10% increments. The temperature settings ranged from 10 °C to 60 °C, in 10 °C increments. A set of samples was also tested under standard laboratory conditions (23 °C and 50% relative humidity) according to relevant standards [37,38]. Each humidity–temperature combination was maintained for 5–8 h (according to ISO 187:2022 [37]) in KK750 climate chamber. The mass change in the samples was periodically checked and at the end of conditioning the hourly mass increase did not exceed 0.25% [37].

In the next stage, samples were prepared for testing on a strength testing machine. All samples were cut using a Computerised Numerical Control (CNC) laser device. The Box Strength Estimation (BSE) machine (Figure 1), part of the Box Strength Estimation System, was used for mechanical testing [39]. Various mechanical tests were conducted including:

- the Bending stiffness Test (BNT) in both the Machine Direction (MD) and the Cross-machine Direction (CD), using a 250 × 50 mm sample [40,41];
- the Edge Crush Test (ECT), using a 100 × 25 mm sample [42–45];
- the Shear Stiffness Test (SST), using a square 85 × 85 mm sample;
- the Torsion Stiffness Test (TST) in both MD and CD, using a rectangular 150 × 30 mm sample.

The bending and torsion tests were carried out in the machine direction, i.e., along the board flute, and in the cross-machine direction, i.e., across the flute. The testing speed in the ECT was equal to 12.5 mm/min, according to the FEFCO Testing Method No. 8 [44], while equal to 0.03 rad/s in the TST and 37.5 mm/min in the BNT and SST.

Figure 2 schematically represents the loading and boundary conditions applied on corrugated board samples for each test setup. Moreover, the pictures shown in Figure 1 depict samples in the measurement sockets of the BSE machine.

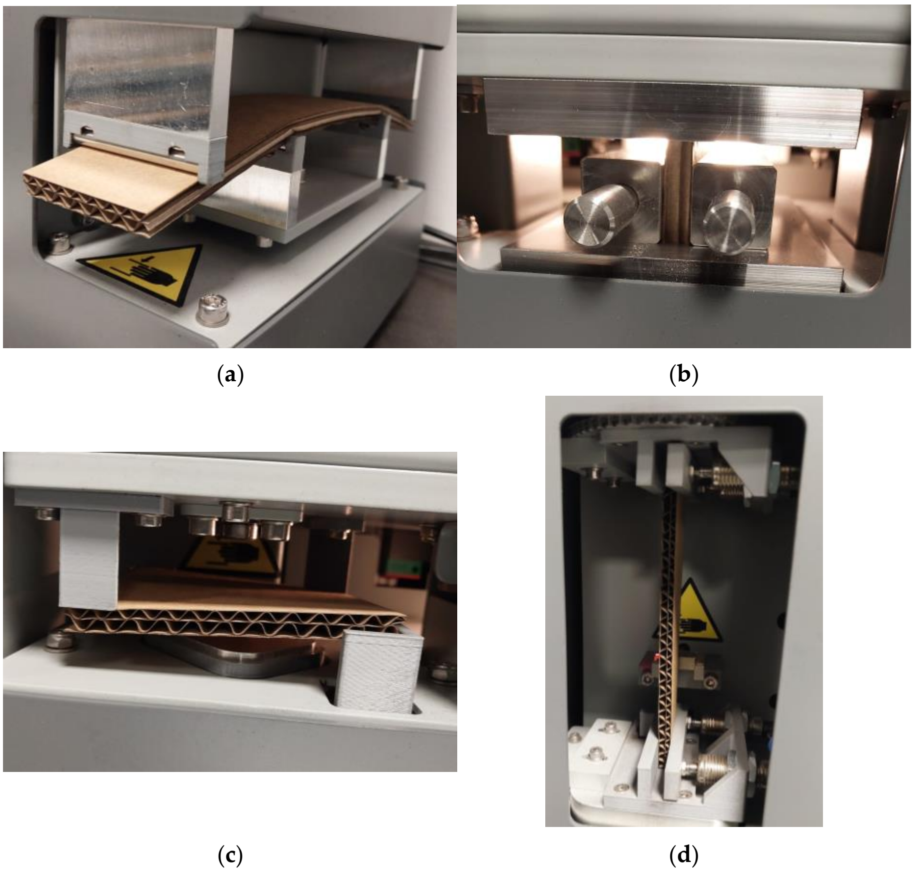

Figure 1. The measurement sockets with cardboard samples: (**a**) the bending stiffness test, (**b**) the edge crush test, (**c**) the shear stiffness test and (**d**) the torsion stiffness test.

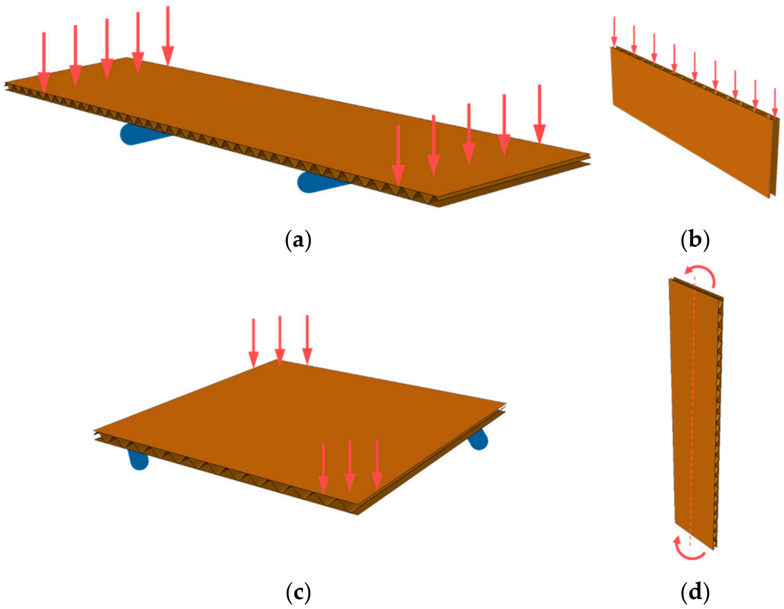

Figure 2. Mechanical tests on cardboards conducted in this study: (**a**) the bending stiffness test, (**b**) the edge crush test, (**c**) the shear stiffness test and (**d**) the torsion stiffness test.

Each test was performed immediately after removing the samples from the climate chamber. In this way, the cardboard properties under 43 different temperature and humidity conditions (6 humidity levels × 7 temperature levels + 1 laboratory standard) for each type of cardboard were captured. Tests on the strength machine were conducted simultaneously for samples in a given direction. For each temperature-humidity combination and type of cardboard, five tests were performed on identical sample sets to obtain statistically representative results. Figure 3 shows a single sample set. A total of 1290 individual tests were conducted—namely, 6 types of cardboard × 5 samples × (7 humidity levels × 6 temperature levels + 1 laboratory standard).

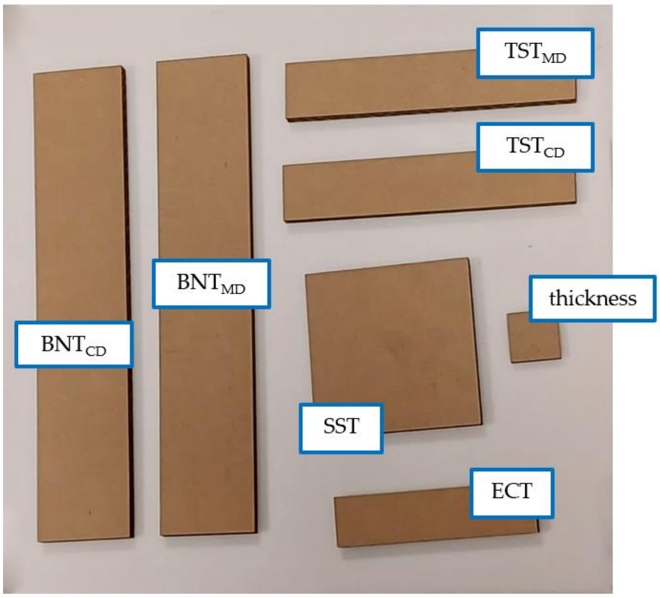

Figure 3. Single set of samples of corrugated boards for all mechanical tests in both the Machine Direction (MD) and the Cross-machine Direction (CD): the Bending stiffness Test (BNT), the Edge Crush Test (ECT), the Shear Stiffness Test (SST), the Torsion Stiffness Test (TST) and thickness.

3. Results

In the experimental campaign conducted in this study, mechanical tests of corrugated cardboard were performed for various types of cardboard, under different temperature and relative humidity conditions. This section systematically presents the test results summarised in tabular form. For each test, a set of experimental curves was obtained, from which representative mechanical values were determined. For the ECT test, the maximum value was identified in accordance with the relevant standard [42,43]. For the other tests, including shear stiffness, torsion stiffness, and bending stiffness, representative values were calculated for each sample.

An example of experimental results in the form of raw curves is shown in Figure 4, illustrating data for B flute cardboard, at a temperature of 20 °C and a relative humidity of 40%. Subsequently, for each sample, under unique temperature and relative humidity conditions for each test, the arithmetic mean was calculated.

The results of all tests are presented in Tables 2–7. The values listed in these tables are normalised, with each representative value divided by the reference value obtained for the respective sample and test under standard laboratory conditions (23 °C and 50% RH). For sake of completeness, the reference values are provided in the table headers. The rows in tables represent results for different temperatures (10 °C, 20 °C, 30 °C, 40 °C, 50 °C, and 60 °C), while columns correspond to varying relative humidity levels (30%, 40%, 50%, 60%, 70%, 80%, and 90% RH). This systematic presentation allows for a clear comparison of the obtained mechanical properties under different environmental conditions, highlighting the influence of temperature and humidity on the performance of corrugated cardboard.

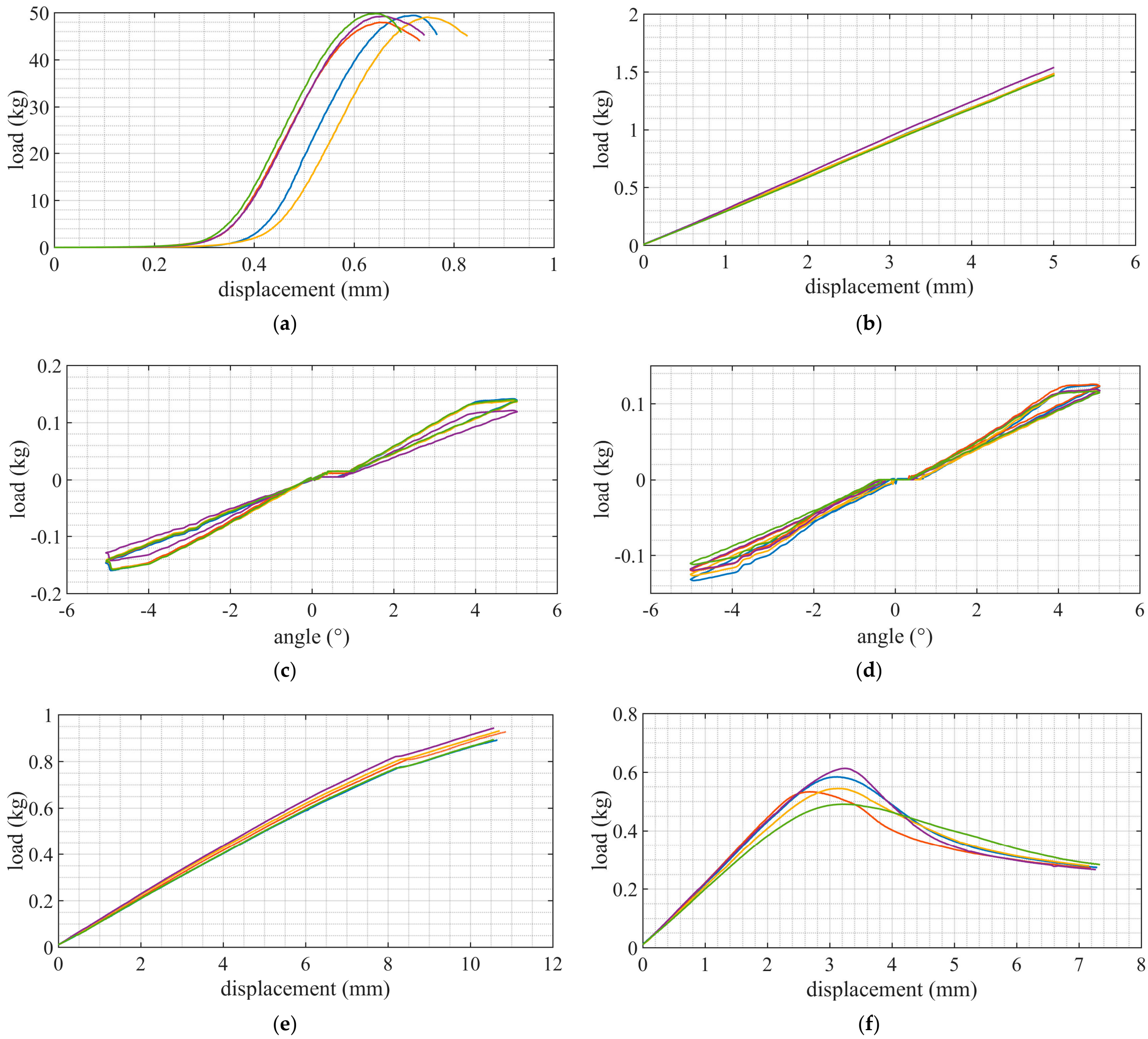

Figure 4. Exemplary experimental results in the form of raw curves illustrating five samples (marked in different colors) data for B flute cardboard at a temperature of 20 °C and a relative humidity of 40% for: (**a**) the edge crush test, (**b**) the shear stiffness test, (**c**) the torsion stiffness test in the cross-machine direction, (**d**) the torsion stiffness test in the machine direction, (**e**) the bending stiffness test in the cross-machine direction and (**f**) the bending stiffness test in the machine direction.

As part of the testing protocol, the grammage and thickness of the cardboard were also measured for each combination of temperature and humidity conditions and for each type of cardboard. However, due to the lesser significance of these results, they have been included in the Appendix A, without additional commentary.

Table 2. Normalised mechanical properties of E flute board measured at varied humidity–temperature conditions.

ECT (%) [* 6.36 kN/m]

T (°C) \ RH (%)	30	40	50	60	70	80	90
10	115%	109%	93%	81%	77%	58%	34%
20	118%	106%	98%	99%	85%	64%	36%
30	123%	111%	108%	98%	92%	77%	49%
40	125%	123%	109%	109%	103%	92%	78%
50	131%	134%	131%	125%	110%	96%	82%
60	137%	140%	131%	129%	119%	108%	85%

SST (%) [* 0.92 Nm]

T (°C) \ RH (%)	30	40	50	60	70	80	90
10	111%	112%	100%	90%	75%	51%	28%
20	112%	112%	101%	103%	85%	60%	28%
30	115%	110%	109%	105%	89%	73%	46%
40	117%	112%	112%	103%	99%	84%	71%
50	127%	108%	114%	112%	104%	90%	74%
60	125%	114%	113%	112%	108%	103%	84%

TST_{CD} (%) [* 0.38 Nm]

T (°C) \ RH (%)	30	40	50	60	70	80	90
10	105%	103%	95%	97%	89%	71%	47%
20	105%	105%	97%	100%	92%	74%	45%
30	111%	108%	103%	100%	87%	76%	50%
40	108%	103%	103%	95%	89%	79%	70%
50	103%	103%	103%	97%	92%	84%	70%
60	108%	103%	103%	100%	95%	87%	79%

TST_{MD} (%) [* 0.38 Nm]

T (°C) \ RH (%)	30	40	50	60	70	80	90
10	105%	105%	103%	97%	92%	74%	53%
20	113%	105%	105%	103%	95%	74%	47%
30	111%	108%	105%	100%	89%	79%	53%
40	111%	105%	105%	100%	95%	84%	71%
50	111%	108%	105%	100%	97%	87%	79%
60	108%	105%	105%	103%	100%	92%	79%

BNT_{CD} (%) [* 0.60 Nm]

T (°C) \ RH (%)	30	40	50	60	70	80	90
10	95%	107%	92%	90%	78%	62%	33%
20	102%	100%	103%	97%	85%	68%	32%
30	110%	105%	98%	97%	83%	67%	42%
40	105%	100%	107%	90%	85%	78%	65%
50	108%	103%	103%	95%	83%	82%	72%
60	105%	103%	103%	97%	90%	87%	73%

BNT_{MD} (%) [* 1.87 Nm]

T (°C) \ RH (%)	30	40	50	60	70	80	90
10	103%	102%	101%	93%	88%	74%	49%
20	106%	103%	103%	101%	93%	78%	50%
30	114%	109%	105%	102%	91%	80%	56%
40	109%	108%	102%	98%	91%	89%	76%
50	114%	111%	106%	104%	98%	93%	81%
60	113%	109%	107%	107%	100%	93%	82%

* Value measured in standard laboratory conditions.

Table 3. Normalised mechanical properties of B flute board measured at varied humidity–temperature conditions.

ECT (%) [* 4.51 kN/m]

T (°C) \ RH (%)	30	40	50	60	70	80	90
10	108%	111%	97%	90%	80%	63%	41%
20	119%	107%	95%	103%	93%	76%	45%
30	124%	118%	114%	104%	95%	88%	73%
40	118%	123%	111%	106%	113%	106%	97%
50	137%	134%	125%	118%	112%	120%	108%
60	137%	119%	133%	124%	120%	123%	113%

SST (%) [* 1.06 Nm]

T (°C) \ RH (%)	30	40	50	60	70	80	90
10	105%	106%	97%	97%	84%	69%	43%
20	109%	106%	102%	99%	92%	75%	43%
30	108%	107%	104%	96%	92%	83%	72%
40	112%	105%	103%	102%	99%	95%	77%
50	113%	110%	113%	106%	107%	103%	100%
60	114%	109%	111%	109%	108%	107%	101%

Table 3. *Cont.*

***TST_{CD}* (%) [* 0.75 Nm]**

T (°C) \ RH (%)	30	40	50	60	70	80	90
10	101%	111%	92%	93%	87%	69%	47%
20	108%	111%	108%	96%	96%	77%	56%
30	115%	103%	97%	103%	93%	87%	73%
40	112%	103%	99%	101%	96%	92%	87%
50	104%	111%	99%	105%	97%	101%	93%
60	105%	111%	107%	101%	100%	96%	97%

***TST_{MD}* (%) [* 0.65 Nm]**

T (°C) \ RH (%)	30	40	50	60	70	80	90
10	103%	108%	102%	95%	92%	77%	58%
20	112%	106%	103%	100%	95%	82%	58%
30	112%	102%	100%	103%	94%	85%	77%
40	111%	109%	105%	100%	103%	97%	94%
50	106%	102%	100%	103%	100%	98%	98%
60	108%	105%	102%	102%	100%	100%	88%

***BNT_{CD}* (%) [* 1.54 Nm]**

T (°C) \ RH (%)	30	40	50	60	70	80	90
10	106%	105%	98%	98%	88%	75%	54%
20	113%	110%	108%	105%	95%	78%	55%
30	115%	106%	102%	100%	94%	81%	65%
40	113%	105%	105%	99%	102%	93%	81%
50	114%	110%	108%	108%	106%	102%	92%
60	114%	110%	110%	110%	105%	101%	90%

***BNT_{MD}* (%) [* 3.39 Nm]**

T (°C) \ RH (%)	30	40	50	60	70	80	90
10	101%	109%	94%	97%	93%	84%	63%
20	108%	103%	102%	105%	95%	84%	67%
30	105%	104%	101%	101%	96%	89%	77%
40	109%	104%	103%	101%	104%	97%	89%
50	103%	113%	104%	105%	107%	99%	88%
60	104%	109%	104%	101%	99%	101%	83%

* Value measured in standard laboratory conditions.

Table 4. Normalised mechanical properties of C flute board measured at varied humidity–temperature conditions.

ECT (%) [* 5.75 kN/m]

T (°C) \ RH (%)	30	40	50	60	70	80	90
10	100%	98%	81%	78%	67%	48%	23%
20	112%	105%	94%	91%	79%	60%	34%
30	118%	110%	105%	97%	91%	78%	75%
40	122%	113%	111%	103%	107%	100%	91%
50	130%	129%	126%	123%	116%	111%	113%
60	135%	131%	128%	125%	120%	119%	113%

SST (%) [* 1.78 Nm]

T (°C) \ RH (%)	30	40	50	60	70	80	90
10	99%	104%	93%	92%	76%	60%	28%
20	104%	104%	102%	99%	87%	70%	40%
30	110%	107%	102%	97%	88%	77%	70%
40	113%	103%	104%	101%	100%	97%	92%
50	112%	112%	111%	106%	103%	103%	102%
60	112%	111%	107%	108%	107%	99%	99%

***TST_{CD}* (%) [* 1.37 Nm]**

T (°C) \ RH (%)	30	40	50	60	70	80	90
10	92%	99%	85%	82%	65%	62%	33%
20	104%	97%	95%	92%	82%	63%	34%
30	105%	101%	92%	87%	89%	71%	66%
40	103%	102%	94%	93%	92%	85%	87%
50	109%	98%	100%	95%	91%	92%	95%
60	101%	104%	103%	94%	96%	92%	94%

***TST_{MD}* (%) [* 0.80 Nm]**

T (°C) \ RH (%)	30	40	50	60	70	80	90
10	90%	99%	91%	89%	80%	69%	48%
20	108%	103%	98%	96%	88%	78%	55%
30	104%	103%	98%	93%	86%	83%	75%
40	103%	100%	100%	98%	94%	85%	85%
50	101%	98%	95%	95%	94%	91%	94%
60	101%	94%	95%	93%	91%	90%	90%

Table 4. *Cont.*

T (°C) \ RH (%)	BNT_{CD} (%) [* 3.43 Nm] 30	40	50	60	70	80	90	BNT_{MD} (%) [* 4.65 Nm] 30	40	50	60	70	80	90
10	99%	104%	91%	88%	80%	63%	30%	110%	104%	104%	102%	89%	84%	48%
20	108%	107%	105%	98%	86%	69%	37%	112%	101%	117%	109%	98%	89%	58%
30	114%	106%	102%	99%	88%	76%	67%	112%	107%	106%	107%	98%	96%	85%
40	113%	108%	103%	97%	101%	92%	86%	105%	107%	99%	104%	110%	105%	98%
50	114%	115%	114%	108%	106%	103%	99%	98%	112%	105%	106%	110%	106%	93%
60	116%	112%	112%	110%	109%	107%	99%	105%	104%	106%	107%	107%	100%	97%

* Value measured in standard laboratory conditions.

Table 5. Normalised mechanical properties of EE flute board measured at varied humidity–temperature conditions.

T (°C) \ RH (%)	ECT (%) [* 8.68 kN/m] 30	40	50	60	70	80	90	SST (%) [* 1.24 Nm] 30	40	50	60	70	80	90
10	101%	98%	83%	82%	72%	57%	34%	98%	102%	94%	94%	85%	75%	49%
20	107%	105%	93%	93%	85%	72%	47%	104%	107%	103%	101%	93%	81%	55%
30	116%	111%	104%	98%	91%	86%	86%	109%	103%	98%	99%	91%	85%	81%
40	119%	109%	109%	109%	109%	104%	81%	108%	109%	100%	97%	98%	95%	84%
50	133%	128%	134%	129%	121%	122%	116%	115%	113%	114%	110%	107%	102%	99%
60	134%	142%	136%	129%	123%	121%	110%	116%	114%	109%	106%	107%	104%	102%

T (°C) \ RH (%)	TST_{CD} (%) [* 0.90 Nm] 30	40	50	60	70	80	90	TST_{MD} (%) [* 0.81 Nm] 30	40	50	60	70	80	90
10	98%	102%	94%	93%	90%	80%	54%	91%	101%	99%	101%	95%	86%	59%
20	99%	106%	97%	98%	90%	82%	56%	104%	105%	104%	102%	98%	88%	63%
30	100%	99%	94%	98%	91%	84%	78%	106%	104%	101%	101%	94%	89%	81%
40	100%	96%	98%	92%	93%	90%	78%	106%	101%	99%	96%	96%	95%	81%
50	101%	97%	102%	101%	94%	91%	90%	109%	107%	106%	102%	99%	96%	100%
60	102%	108%	97%	92%	96%	93%	91%	109%	109%	107%	106%	101%	99%	101%

T (°C) \ RH (%)	BNT_{CD} (%) [* 1.55 Nm] 30	40	50	60	70	80	90	BNT_{MD} (%) [* 3.34 Nm] 30	40	50	60	70	80	90
10	99%	105%	95%	99%	92%	83%	58%	96%	99%	97%	98%	91%	84%	63%
20	108%	106%	106%	102%	97%	86%	60%	103%	104%	102%	101%	93%	87%	64%
30	103%	106%	100%	99%	93%	86%	76%	107%	101%	99%	97%	91%	88%	78%
40	106%	103%	98%	98%	97%	94%	79%	107%	103%	97%	97%	94%	91%	80%
50	110%	109%	111%	106%	105%	99%	97%	111%	108%	110%	106%	105%	98%	97%
60	111%	108%	101%	105%	102%	101%	93%	111%	112%	103%	104%	105%	102%	98%

* Value measured in standard laboratory conditions.

Table 6. Normalised mechanical properties of EB flute board measured at varied humidity–temperature conditions.

ECT (%) [* 7.52 kN/m]								**SST (%) [* 2.17 Nm]**							
T (°C) \ RH (%)	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**T (°C) \ RH (%)**	**30**	**40**	**50**	**60**	**70**	**80**	**90**
10	101%	97%	86%	85%	67%	48%	22%	**10**	100%	100%	89%	95%	82%	64%	27%
20	115%	107%	99%	90%	81%	63%	35%	**20**	109%	104%	101%	99%	92%	76%	45%
30	116%	111%	110%	101%	93%	86%	77%	**30**	111%	106%	102%	99%	96%	87%	77%
40	123%	118%	113%	108%	104%	98%	93%	**40**	111%	107%	101%	100%	99%	94%	90%
50	128%	129%	129%	126%	117%	111%	113%	**50**	117%	112%	113%	111%	108%	102%	103%
60	130%	131%	130%	125%	121%	118%	117%	**60**	116%	114%	108%	112%	111%	107%	103%
TST_{CD} (%) [* 1.49 Nm]								**TST_{MD} (%) [* 1.02 Nm]**							
T (°C) \ RH (%)	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**T (°C) \ RH (%)**	**30**	**40**	**50**	**60**	**70**	**80**	**90**
10	90%	95%	82%	86%	79%	64%	34%	**10**	98%	100%	92%	100%	83%	73%	42%
20	108%	108%	98%	93%	86%	74%	42%	**20**	119%	105%	96%	93%	88%	76%	56%
30	108%	109%	106%	97%	88%	75%	69%	**30**	115%	105%	108%	102%	98%	86%	76%
40	107%	107%	103%	93%	87%	89%	82%	**40**	120%	103%	107%	100%	98%	93%	92%
50	113%	107%	108%	109%	97%	93%	101%	**50**	111%	110%	110%	110%	106%	101%	111%
60	109%	109%	107%	105%	105%	103%	96%	**60**	125%	120%	103%	104%	110%	104%	109%
BNT_{CD} (%) [* 3.53 Nm]								**BNT_{MD} (%) [* 6.57 Nm]**							
T (°C) \ RH (%)	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**T (°C) \ RH (%)**	**30**	**40**	**50**	**60**	**70**	**80**	**90**
10	98%	101%	90%	91%	81%	65%	29%	**10**	102%	102%	96%	97%	86%	76%	41%
20	108%	107%	105%	98%	88%	73%	43%	**20**	102%	104%	102%	101%	94%	80%	58%
30	109%	104%	103%	101%	90%	78%	74%	**30**	104%	97%	97%	97%	97%	89%	77%
40	110%	106%	100%	96%	97%	90%	83%	**40**	103%	98%	98%	96%	95%	91%	83%
50	114%	110%	112%	108%	105%	98%	97%	**50**	99%	95%	96%	98%	99%	94%	91%
60	116%	112%	109%	107%	108%	101%	98%	**60**	100%	95%	93%	91%	87%	94%	85%

* Value measured in standard laboratory conditions.

Table 7. Normalised mechanical properties of BC flute board measured at varied humidity–temperature conditions.

ECT (%) [* 9.58 kN/m]								**SST (%) [* 4.70 Nm]**							
T (°C) \ RH (%)	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**T (°C) \ RH (%)**	**30**	**40**	**50**	**60**	**70**	**80**	**90**
10	106%	99%	88%	89%	71%	60%	34%	**10**	103%	100%	92%	89%	81%	65%	41%
20	116%	103%	98%	99%	92%	73%	46%	**20**	102%	105%	103%	95%	92%	77%	59%
30	109%	107%	106%	99%	94%	86%	81%	**30**	113%	104%	105%	98%	96%	88%	84%
40	115%	114%	108%	105%	109%	102%	98%	**40**	113%	108%	109%	105%	97%	95%	96%
50	124%	122%	125%	122%	116%	112%	117%	**50**	113%	111%	116%	111%	107%	108%	105%
60	125%	127%	126%	118%	115%	117%	118%	**60**	114%	113%	115%	112%	115%	116%	108%

Table 7. *Cont.*

TST_{CD} (%) [* 3.57 Nm]							
T (°C) \ RH (%)	30	40	50	60	70	80	90
10	97%	103%	93%	96%	82%	69%	44%
20	111%	108%	103%	97%	92%	76%	57%
30	112%	112%	106%	98%	94%	86%	78%
40	111%	111%	110%	104%	91%	90%	84%
50	107%	108%	107%	104%	98%	95%	88%
60	108%	101%	106%	99%	106%	95%	94%

TST_{MD} (%) [* 1.87 Nm]							
T (°C) \ RH (%)	30	40	50	60	70	80	90
10	94%	103%	100%	101%	93%	82%	53%
20	111%	108%	104%	107%	100%	85%	63%
30	104%	105%	101%	101%	98%	93%	84%
40	111%	108%	107%	105%	99%	103%	93%
50	113%	109%	106%	98%	101%	98%	102%
60	107%	100%	106%	107%	104%	106%	99%

BNT_{CD} (%) [* 13.43 Nm]							
T (°C) \ RH (%)	30	40	50	60	70	80	90
10	104%	105%	93%	99%	89%	77%	53%
20	105%	106%	106%	101%	98%	83%	60%
30	108%	105%	101%	100%	96%	85%	79%
40	105%	103%	101%	96%	95%	92%	85%
50	105%	105%	105%	101%	101%	97%	98%
60	107%	106%	106%	105%	103%	98%	94%

BNT_{MD} (%) [* 17.78 Nm]							
T (°C) \ RH (%)	30	40	50	60	70	80	90
10	109%	108%	92%	94%	86%	82%	63%
20	103%	104%	97%	96%	95%	89%	65%
30	103%	104%	86%	92%	100%	97%	92%
40	99%	102%	99%	99%	101%	104%	90%
50	101%	98%	99%	100%	96%	103%	100%
60	106%	100%	108%	99%	99%	97%	96%

* Value measured in standard laboratory conditions.

4. Discussion

The results presented in Tables 2–7, which examine the influence of temperature and humidity variations on the mechanical properties of 3- and 5-layer corrugated boards, emphasize the significant impact of environmental conditions on the load-bearing capacity of cardboard. Changes in these environmental parameters also affect the structural integrity and load-bearing capacity of corrugated board packaging. The data illustrate the degree of reduction or enhancement in mechanical properties depending on variations in temperature and relative humidity.

A clear trend can be observed: higher temperatures combined with lower relative humidity lead to improved mechanical performance. Conversely, lower temperatures and higher relative humidity result in weaker mechanical properties. This pattern is consistent across all tested characteristics of the cardboard, irrespective of direction (CD or MD), type of corrugated board, or the number of layers. These findings underline the universal relevance of temperature and humidity as critical factors influencing cardboard performance. When isolating the effect of relative humidity, it becomes evident that as humidity increases, the mechanical properties of the cardboard deteriorate. Similarly, when considering the impact of temperature, lower temperatures are associated with worse performance across all mechanical properties. On the other hand, higher temperatures and low relative humidity seem to enhance the mechanical performance, possibly due to the paper material becoming much stiffer. On the contrary, intuitively, when paper is wet, it tends to weaken.

Among the tested properties, ECT strength appears to be the most sensitive to changes in temperature and humidity. The maximum ECT values from Tables 2–7 reached 140%, 137%, 135%, 142%, 131%, and 127% in regard to reference values for flutes E, B, C, EE, EB, and BC, respectively. Conversely, the minimum ECT values were 34%, 41%, 23%, 34%, 22%, and 34% for the same flute types. Other stiffness-related parameters also exhibited significant sensitivity, however to a slightly lesser extent; maximum values ranged between 110% and 120%, while minimum values were between 40% and 50%.

Interestingly, results obtained under standard laboratory conditions (23 °C and 50% RH) align closely with values along a diagonal pattern within the matrix of temperature and humidity variations. This diagonal ranges approximately from 10 °C at 30% RH to 60 °C at 90% RH.

To aid in interpreting the data in Tables 2–7, the cells are color-coded using a gradient scale. Lower values are represented in red, while higher values are shown in green. This visualisation reveals specific trends, including localised anomalies. For example, in Table 5 for bending stiffness in CD, representing EE flute at 50 °C and 50% RH, the results show less predictable behaviour, with localised deviations from the general trends. This suggests that certain combinations of temperature and humidity may introduce complex interactions affecting the mechanical properties.

There are studies in the literature that address similar issues. Nienke et al. presented graphs of the tensile stiffness of bleached kraft paper for relative humidity from 10% to 90% [2]. The results clearly show that with increasing relative humidity, the tensile strength of the paper decreases in both the machine and cross directions. Wang checked the effect of temperature and relative humidity on the elastic modulus of the corrugating medium in the cross direction [3]. The experiment showed that an increase in temperature strengthens the elastic modulus, while an increase in RH weakens it. Fadiji et al. presented the behaviour of the packaging strength under different environmental conditions [4]. Higher relative humidity and lower temperature resulted in lower strength of the box by up to 60%. All of those observations of other researchers are consistent with the results obtained from the conducted experiment here presented and underline the importance of detailed analysis when designing corrugated boards, especially for applications exposed to varying environmental conditions. Moreover, such systematic studies on the topic, according to the authors' best knowledge, have not been conducted so far, making this a valuable foundation for a deeper understanding of how temperature and humidity affect mechanical properties of cardboards. Furthermore, it can serve as a significant source of data for validating numerical models and holds significant practical importance for practitioners, such as cardboard manufacturers and box designers.

5. Conclusions

This study aims to examine how varying temperature and humidity impact the mechanical properties of 3- and 5-ply corrugated cardboard. Six types of cardboard were conditioned in a climate chamber across a range of relative humidity (30% to 90%) and temperature (10 °C to 60 °C) settings, as well as across a standard laboratory condition. Mechanical properties, including bending, edge crush, shear, and torsion stiffness, were tested using a strength testing machine. Overall, almost 1300 tests were conducted to capture the cardboard properties under distinct environmental conditions for each cardboard type.

Both factors, temperature and relative humidity, significantly impact the mechanical properties of cardboard, regardless of its thickness or the number of layers. This study confirmed that the higher the temperature and the lower the relative humidity are, the higher the mechanical performance (for all tests considered), whereas the lower the temperature and the higher the relative humidity, the worse the mechanical properties.

The test results were presented in a normalised way, in reference to the values obtained under standard conditions. Across defined temperature and relative humidity ranges, the greatest variability was observed in ECT measurements, with values ranging from 20% up to 140% of the reference value. Shear stiffness values ranged from 30% to 120% of the reference, while torsional stiffness ranged from 35% to 110% in cross direction and 40% to 125% in the machine direction. Bending stiffness exhibited relatively smaller increases, but similarly significant decreases, with values between 30% and110% for CD and 40–110% for MD.

Author Contributions: Conceptualization, D.M., T.G. (Tomasz Gajewski) and T.G. (Tomasz Garbowski); methodology, D.M.; validation, D.M. and A.C.; formal analysis, D.M. and A.C.; investigation, D.M.; writing—original draft preparation, D.M. and T.G. (Tomasz Gajewski); writing—review and

editing, D.M., A.C. and T.G. (Tomasz Garbowski); visualization, D.M. and T.G. (Tomasz Gajewski); supervision, T.G. (Tomasz Gajewski) and T.G. (Tomasz Garbowski); project administration, T.G. (Tomasz Gajewski); funding acquisition, T.G. (Tomasz Garbowski). All authors have read and agreed to the published version of the manuscript.

Funding: The research was funded within the grant of The National Centre for Research and Development under the number POIR.01.01.01-00-0002/21.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: The authors would like to thank Werner Kenkel Sp. z o.o. for providing the samples used in this study. Additionally, the authors extend their gratitude to FEMat Sp. z o.o. for supplying the laboratory facilities, testing equipment, and software required to conduct this research.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

Appendix A

In addition to the results presented in Section 3, the appendix reports on the grammage and thickness of the cardboard which were also measured for each combination of temperature and humidity conditions and for each type of cardboard, see Table A1.

Table A1. The mean values of grammage and thickness of the cardboards measured for each combination of temperature and humidity conditions and for each type of cardboard.

E Flute Cardboard															
	Grammage (g/m²)								**Thickness (mm)**						
T (°C) \ RH (%)	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**T (°C) \ RH (%)**	**30**	**40**	**50**	**60**	**70**	**80**	**90**
10	504	507	509	512	520	531	555	**10**	1.72	1.72	1.73	1.73	1.74	1.75	1.76
20	500	503	507	510	519	527	551	**20**	1.71	1.73	1.72	1.73	1.74	1.74	1.76
30	499	504	506	509	516	522	544	**30**	1.71	1.72	1.71	1.73	1.73	1.74	1.75
40	495	498	507	505	510	514	523	**40**	1.72	1.72	1.72	1.73	1.73	1.73	1.74
50	490	493	495	501	503	510	518	**50**	1.71	1.71	1.71	1.71	1.73	1.72	1.73
60	488	489	493	493	500	506	514	**60**	1.70	1.71	1.72	1.71	1.71	1.71	1.73
B flute cardboard															
	grammage (g/m²)								**thickness (mm)**						
T (°C) \ RH (%)	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**T (°C) \ RH (%)**	**30**	**40**	**50**	**60**	**70**	**80**	**90**
10	411	411	417	418	420	426	439	**10**	2.96	2.95	2.96	2.97	2.97	2.98	2.95
20	409	410	414	415	419	425	440	**20**	2.97	2.94	2.96	2.97	2.97	2.98	2.98
30	407	411	411	412	415	420	426	**30**	2.96	2.96	2.97	2.96	2.96	2.97	2.97
40	402	408	409	408	410	414	416	**40**	2.95	2.96	2.96	2.96	2.97	2.96	2.97
50	399	400	401	402	408	409	411	**50**	2.96	2.96	2.94	2.94	2.96	2.96	2.96
60	395	396	399	401	403	404	409	**60**	2.94	2.95	2.95	2.95	2.96	2.96	2.96

Table A1. *Cont.*

C flute cardboard

T (°C) \ RH (%)	grammage (g/m²) 30	40	50	60	70	80	90	thickness (mm) 30	40	50	60	70	80	90
10	453	451	458	459	464	474	498	4.02	4.02	4.03	4.05	4.04	4.03	4.02
20	450	452	456	457	461	469	490	4.02	4.03	4.04	4.02	4.04	4.04	4.01
30	449	450	452	456	457	461	466	4.01	4.02	4.00	4.02	4.03	4.03	4.02
40	442	446	447	450	451	452	456	4.01	4.00	4.01	4.01	4.04	4.02	4.01
50	437	439	436	442	443	445	447	4.02	4.01	4.00	4.02	4.02	4.01	4.01
60	435	432	437	439	440	443	445	4.00	4.00	4.00	4.00	4.01	4.00	3.98

EE flue cardboard

T (°C) \ RH (%)	grammage (g/m²) 30	40	50	60	70	80	90	thickness (mm) 30	40	50	60	70	80	90
10	651	648	656	658	664	672	693	2.78	2.78	2.80	2.78	2.80	2.83	2.82
20	642	648	653	654	661	667	687	2.78	2.78	2.79	2.79	2.79	2.80	2.83
30	639	644	647	652	655	660	665	2.77	2.77	2.78	2.77	2.80	2.78	2.80
40	635	639	641	645	643	648	659	2.75	2.77	2.78	2.78	2.77	2.78	2.78
50	627	627	628	630	636	636	641	2.74	2.75	2.77	2.81	2.79	2.79	2.79
60	624	621	625	628	627	633	633	2.76	2.76	2.77	2.78	2.78	2.75	2.76

EB flute cardboard

T (°C) \ RH (%)	grammage (g/m²) 30	40	50	60	70	80	90	thickness (mm) 30	40	50	60	70	80	90
10	579	577	582	583	588	602	635	4.15	4.17	4.19	4.19	4.22	4.25	4.20
20	570	572	579	580	586	594	619	4.19	4.22	4.21	4.21	4.21	4.23	4.21
30	564	572	573	578	580	586	593	4.18	4.19	4.17	4.22	4.20	4.22	4.19
40	562	566	570	573	575	578	580	4.20	4.17	4.21	4.20	4.20	4.21	4.17
50	556	561	558	561	565	569	567	4.16	4.13	4.16	4.19	4.21	4.21	4.20
60	553	552	558	560	559	562	563	4.14	4.17	4.14	4.17	4.21	4.18	4.17

BC flute cardboard

T (°C) \ RH (%)	grammage (g/m²) 30	40	50	60	70	80	90	thickness (mm) 30	40	50	60	70	80	90
10	801	797	809	809	815	833	861	6.74	6.72	6.75	6.74	6.74	6.74	6.74
20	789	794	800	806	811	823	852	6.73	6.70	6.73	6.73	6.74	6.71	6.74
30	787	788	795	799	806	811	817	6.71	6.71	6.68	6.77	6.76	6.77	6.76
40	780	786	789	792	795	798	807	6.71	6.67	6.69	6.72	6.68	6.74	6.71
50	773	774	777	781	784	787	787	6.63	6.66	6.71	6.71	6.70	6.69	6.68
60	769	768	774	776	774	779	778	6.70	6.68	6.67	6.67	6.69	6.71	6.72

References

1. Mordor Intelligence. Global Paper And Paperboard Packaging Market Size & Share Analysis—Growth Trends & Forecasts (2024–2029). Available online: https://www.mordorintelligence.com/industry-reports/global-paper-and-paperboard-packaging-market (accessed on 19 October 2024).
2. Nienke, T.; Kwade, A.; Eggerath, D. Influence of moisture, temperature and bleaching on the mechanical properties of coated fiber-based substrates. *Coatings* **2022**, *12*, 1287–1299. [CrossRef]
3. Wang, D. Elastic Modulus Prediction of Corrugating Medium under Different Temperature and Relative Humidity. *IOP Conf. Ser. Mater. Sci. Eng.* **2018**, *439*, 042043. [CrossRef]
4. Fadiji, T.; Berry, T.M.; Coetzee, C.J.; Opara, U.L. Mechanical design and performance testing of corrugated paperboard packaging for the postharvest handling of horticultural produce. *Biosyst. Eng.* **2018**, *171*, 220–244. [CrossRef]
5. Berry, T.M.; Ambaw, A.; Defraeye, T.; Coetzee, C.; Opara, U.L. Moisture adsorption in palletised corrugated fibreboard cartons under shipping conditions: A CFD modelling approach. *Food Bioprod. Process.* **2019**, *114*, 43–59. [CrossRef]
6. Niini, A.; Tanninen, P.; Laukala, T.; Varis, J.; Leminen, V. A folding method to increase the rigidity of paperboard tray packages. *BioResources* **2022**, *17*, 1427–1441. [CrossRef]
7. Kaeppeler, U.; Hünniger, J.; Hofmann, A.; Berlich, A.; Engisch, L. Thermal influence on the mechanical properties of cardboard during an ultrasonic-assisted embossing process. *BioResources* **2020**, *15*, 5110–5121. [CrossRef]
8. Cornaggia, A.; Gajewski, T.; Knitter-Piątkowska, A.; Garbowski, T. Influence of Humidity and Temperature on Mechanical Properties of Corrugated Board—Numerical Investigation. *BioResources* **2023**, *18*, 7490–7509. [CrossRef]
9. Su, H.; Huang, C.; Li, C.; Zhao, Y.; Zheng, D.; Duan, Q. Failure mechanism of the corrugated medium under simulated cold chain logistics. *ACS Omega* **2023**, *8*, 23673–23682. [CrossRef]
10. Niini, A.; Tanninen, P.; Varis, J.; Leminen, V. Effects of press-forming parameters on the dimensional stability of paperboard trays. *BioResources* **2021**, *16*, 4876–4890. [CrossRef]
11. Cataldi, P.; Profaizer, M.; Bayer, I.S. Preventing water-induced mechanical deterioration of cardboard by a sequential polymer treatment. *Ind. Eng. Chem. Res.* **2019**, *58*, 6456–6465. [CrossRef]
12. Marinelli, A.; Diamanti, M.V.; Lucotti, A.; Pedeferri, M.P.; Del Curto, B. Evaluation of coatings to improve the durability and water-barrier properties of corrugated cardboard. *Coatings* **2022**, *12*, 10–24. [CrossRef]
13. Beck, M.; Fischerauer, G. Modeling Warp in Corrugated Cardboard Based on Homogenization Techniques for In-Process Measurement Applications. *Appl. Sci.* **2022**, *12*, 1684. [CrossRef]
14. Nordstrand, T.M. Parametric study of the post-buckling strength of structural core sandwich panels. *Compos. Struct.* **1995**, *30*, 441–451. [CrossRef]
15. Nordstrand, T. Analysis and testing of corrugated board panels into the post-buckling regime. *Compos. Struct.* **2004**, *63*, 189–199. [CrossRef]
16. Mrówczyński, D.; Knitter-Piątkowska, A.; Garbowski, T. Numerical Homogenization of Single-Walled Corrugated Board with Imperfections. *Appl. Sci.* **2022**, *12*, 9632. [CrossRef]
17. Mrówczyński, D.; Garbowski, T. Influence of Imperfections on the Effective Stiffness of Multilayer Corrugated Board. *Materials* **2023**, *16*, 1295. [CrossRef]
18. Cillie, J.; Coetzee, C. Experimental and Numerical Investigation of the In-Plane Compression of Corrugated Paperboard Panels. *Math. Comput. Appl.* **2022**, *27*, 108. [CrossRef]
19. Archaviboonyobul, T.; Chaveesuk, R.; Singh, J.; Jinkarn, T. An analysis of the influence of hand hole and ventilation hole design on compressive strength of corrugated fiberboard boxes by an artificial neural network model. *Packag. Technol. Sci.* **2020**, *33*, 171–181. [CrossRef]
20. Fadiji, T.; Coetzee, C.J.; Opara, U.L. Compression strength of ventilated corrugated paperboard packages: Numerical modelling, experimental validation and effects of vent geometric design. *Biosyst. Eng.* **2016**, *151*, 231–247. [CrossRef]
21. Giampieri, A.; Perego, U.; Borsari, R. A constitutive model for the mechanical response of the folding of creased paperboard. *Int. J. Solids Struct.* **2011**, *48*, 2275–2287. [CrossRef]
22. Beex, L.A.A.; Peerlings, R.H.J. An experimental and computational study of laminated paperboard creasing and folding. *Int. J. Solids Struct.* **2009**, *46*, 4192–4207. [CrossRef]
23. Garbowski, T.; Knitter-Piątkowska, A.; Mrówczyński, D. Numerical Homogenization of Multi-Layered Corrugated Cardboard with Creasing or Perforation. *Materials* **2021**, *14*, 3786. [CrossRef] [PubMed]
24. Gallo, J.; Cortés, F.; Alberdi, E.; Goti, A. Mechanical behavior modeling of containers and octabins made of corrugated cardboard subjected to vertical stacking loads. *Materials* **2021**, *14*, 2392. [CrossRef] [PubMed]
25. Zhang, Y.-L.; Chen, J.; Wu, Y.; Sun, J. Analysis of hazard factors of the use of corrugated carton in packaging low-temperature yogurt during logistics. *Procedia Environ. Sci.* **2011**, *10*, 968–973. [CrossRef]
26. Kim, S.; Horvath, L.; Molina, E.; Frank, B.; Johnson, S.; Johnson, A. Predicting the effect of pallet overhang on the box compression strength. *Packag. Technol. Sci.* **2023**, *36*, 927–939. [CrossRef]
27. Garbowski, T.; Gajewski, T.; Mrówczyński, D.; Jędrzejczak, R. Crushing of Single-Walled Corrugated Board during Converting: Experimental and Numerical Study. *Energies* **2021**, *14*, 3203. [CrossRef]
28. Yoshihara, H.; Yoshinobu, M.; Maruta, M. Bending stiffness and moment capacity of cardboard obtained from three-point and elastica bending tests. *Nord. Pulp Pap. Res. J.* **2022**, *38*, 73–85. [CrossRef]

29. Buannic, N.; Cartraud, P.; Quesnel, T. Homogenization of corrugated core sandwich panels. *Compos. Struct.* **2003**, *59*, 299–312. [CrossRef]
30. Garbowski, T.; Gajewski, T. Determination of transverse shear stiffness of sandwich panels with a corrugated core by numerical homogenization. *Materials* **2021**, *14*, 1976. [CrossRef]
31. Nordstrand, T. On buckling loads for edge-loaded orthotropic plates including transverse shear. *Compos. Struct.* **2004**, *65*, 1–6. [CrossRef]
32. Popil, R.E. Overview of recent studies at IPST on corrugated board edge compression strength: Testing methods and effects of interflute buckling. *BioResources* **2012**, *7*, 2553–2581. [CrossRef]
33. Åslund, P.E.; Hägglund, R.; Carlsson, L.A.; Isaksson, P. Modeling of global and local buckling of corrugated board panels loaded in edge-to-edge compression. *J. Sandw. Struct. Mater.* **2014**, *16*, 272–292. [CrossRef]
34. Mrówczyński, D.; Pozorska, J.; Garbowski, T.; Pozorski, Z. Bending stiffness of unsymmetrical multilayered corrugated board: Influence of boundary conditions. *BioResources* **2023**, *18*, 7611–7628. [CrossRef]
35. Błaszczuk, J.; Pozorski, Z. The analysis of the influence of core compression effect on the determination of the shear modulus of sandwich panel core. *Sci. Res. Inst. Math. Comput.* **2012**, *11*, 5–13. [CrossRef]
36. Pozorska, J.; Pozorski, Z. The comparison of numerical models of a sandwich panel in the context of the core deformations at the supports. *AIP Conf. Proc.* **2018**, *1922*, 050007.
37. *ISO 187:2022*; Paper, Board And Pulps—Standard Atmosphere for Conditioning and Testing and Procedure for Monitoring the Atmosphere and Conditioning of Samples. International Standard; ISO: Geneva, Switzerland, 2022.
38. *TAPPI T402 sp-21*; Standard Conditioning and Testing Atmospheres for Paper, Board, Pulp Handsheets, and Related Products, Test Method TAPPI/ANSI T 402 sp-21. TAPPI: Atlanta, GA, USA, 2021.
39. FEMat Systems: BSE System. Available online: http://fematsystems.pl/bse-system_en/ (accessed on 19 October 2024).
40. *ISO 5628:2019*; Paper and Board—Determination of Bending Stiffness—General Principles for Two-Point, Three-Point and Four-Point Methods. International Standard. ISO: Geneva, Switzerland, 2019.
41. *TAPPI T836 om-20*; Bending Stiffness, Four Point Method, Test Method TAPPI/ANSI T 836 om-20. TAPPI: Atlanta, GA, USA, 2020.
42. *ISO 3037:2022*; Corrugated Fibreboard—Determination of Edgewise Crush Resistance (Non-Waxed Edge Method). International Standard. ISO: Geneva, Switzerland, 2022.
43. *ISO 13821:2020*; Corrugated Fibreboard—Determination of Edgewise Crush Resistance—Waxed Edge Method. ISO: Geneva, Switzerland, 2020.
44. *FEFCO Testing Method No. 8, Edgewise Crush Resistance of Corrugated Fiberboard*; European Federation of Corrugated Board Manufacturers: Brussels, Belgium, 1997.
45. *TAPPI T839 om-24*; Edgewise Compressive Strength of Corrugated Fiberboard Using the Clamp Method (Short Column Test), Test Method TAPPI T 839 om-24. TAPPI: Atlanta, GA, USA, 2024.