MECHANICAL CHARACTERIZATION OF MULTIFOLD® CARDBOARD ANGLES: EFFECTS OF PAPER AND ADHESIVE TYPES AT TWO DIFFERENT MOISTURE CONTENTS

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ABSTRACT

Cardboard angles are typically used to protect packages during handling, in particular to improve the strength of stacked boxes. With the increased popularity of online retail, the packaging industry is more and more solicited over the current years, motivating the development of a new generation of cardboard angles that reduce their environmental impact, weight and manufacturing cost. To achieve these goals, cardboard angles were produced following a new folding method. The angles have been tested under longitudinal compression and three-point bending loadings after being conditioned to reach two different moisture contents, namely 6% (dry reference) and 10% (wet). Three types of papers (two liners and one medium) and four polyvinyl acetate (PVA) adhesives were studied using this methodology. Results show that, for some raw materials combination, the new folding method can significantly increase the mechanical properties of cardboard angles with similar dimensions. The type of paper used does not appear to have a significant impact on maximum strength while the adhesive type and the moisture content greatly affect this property. Requiring less different raw materials, this new folding method could be a good alternative to the current one.

1 INTRODUCTION

Cardboard angles are used to protect edges of packaging during transport. In certain cases, these products must support loads from pallet stacking and can be in contact with food. Their manufacturing process varies between manufacturers and they are offered in a wide range of sizes. Cardboard angles are usually made from adhesively bonded layers of liner paper. A bonded paper stack is first assembled and folded to obtain an L shape. Due to the nature of their raw materials, cardboard angles are affordable and recyclable. Because of the increase in the e-commerce and the COVID-19 events, the demand for cardboard packaging has increased and it leads to a shortage of paper material in some regions of the world.

Cardboard is a general term and can be applied to corrugated cardboard as well as different grades of paperboard. Cardboard is made from pulp paper which is obtained by a chemical or mechanical process on fibre source material [1]. The chemical processes remove most of the lignin, while mechanical treatments plasticize the lignin without removing it. The first process thus favours better fibre strength properties, whilst the latter offers lower strength but higher production yield. The pulp then goes into a process called beating, or refining, to optimize the fibre's properties before going through a series of rollers, called Fourdrinier machine, to remove excess water and obtain paper sheets. Paper can be repulped to produce recycled paper. Fibres are mostly aligned with the travel direction of the paper during the papermaking process, that explains the anisotropic nature of paper. The travel direction is called machined direction (MD) and the perpendicular direction is called cross-machine direction (CD).

However, papers cannot be recycled indefinitely due to the deterioration of fibres during the process [2]. Papers have higher tensile strength in the MD direction.

It is well known that mechanical properties of paper are greatly affected by moisture content. Some studies [3, 4] show that the tensile properties of paper decrease when the moisture content increases. Similar conclusions were observed for the compressive strength of corrugated cardboard [5]. The decrease in mechanical properties was explained by the inter-fibre delamination due to the moisture that weakens the bonding between fibres and decreases the stiffness of fibres. Humid environment is also responsible for the hygroscopic expansion of paper that induces changes in fibre dimensions. Many factors [6] can influence the extent of this phenomenon on paper, such as wood species, chemical used in pulp making, drying process and fibre orientation. The hygroscopic expansion is usually higher in CD direction than in MD direction and can be observed by a swelling or a curling effect on paper.

When it comes to papermaking, sizing and coating are frequently used to enhance the properties of paper. Sizing solutions are usually used to increase the tensile strength of paper and to reduce liquid penetration. On the other hand, coatings are mostly used to improve the surface quality of paper and board [1].

To combine several papers into a single structure, natural or synthetic adhesives are used. The most common natural adhesive is starch, which is made from vegetables. Their low solids content (20 %-30 %) and high water content require a long drying time. On the other hand, the most frequent synthetic adhesive is a water-based synthetic resin emulsion based on polyvinyl acetate (PVA). These emulsions are usually 50 %-80 % solids, and have shorter drying time than starches [7]. Adding PVA as an additive into the starch adhesive can accelerate the latter's drying speed [8]. The key to obtain an efficient mechanical bonding between the adhesive and the substrate was found to be a good wettability of the adhesive and a good penetration of the adhesive in the substrate [9]. The most important bond strengths are cohesive strength and adhesive strength. The first one is related to the internal bonding strength of a material and the second to the force of attraction between two materials [7]. For paper products, adhesive joint must be at least as strong as the substrate itself to preserve the structure. Thus, a large amount of adhesive usually leads to a cohesive failure into the paper [10].

The objectives of this project are to evaluate a new folding method for cardboard angles and to study the effect of the type of paper, of the adhesive formulation and of the moisture content on the mechanical behaviour. The advantage of this new folding method is that it only needs one type of paper as opposed to the current cardboard angles that use three. This as the benefit of, making it easier for manufacturers to supply raw material, while potentially reducing the environmental impact of manufacturing. Axial compression and three-point bending loading were performed on cardboard angles at 6% and 10% moisture content. Samples were manufactured with a bespoke manual gluing/folding machine. Configurations using one of three different types of papers and four different types of adhesives were considered. A reference group (RG) of specimens consisting of industrially produced cardboard angles manufactured using the current industrial folding method was also tested in the same conditions for benchmarking purpose. This work is part of a larger project where the main goal is to offer cardboard angles which use less raw materials without sacrificing their mechanical properties.

2 MATERIALS

Three types of commercial recycled paperboard, and four PVA adhesives (PVA1, PVA2, PVA3 and PVA4) were used to manufacture cardboard angles following a new folding method. The choice of these materials was based on prior research works. PVA1 adhesive is used on current cardboard angles production. PVA2, PVA3 and PVA4 adhesives were chosen for their short-drying times. Some properties for each paper and adhesives, provided by an internal document at Abzac Canada Inc., are listed in Table 1 and Table 2 respectively.

Liner is usually used for the flat facing in corrugated cardboard. Brown liner is the most common of his type and the cheapest one. The double-side liner used in this research is composed of two layers of paper. The first layer was bleached by a chemical agent during the pulping process, giving it a white colour. The second layer was treated with a black pigmented coating. Double-side liners (DL) are usually more expensive and less available than brown liners (L), but offer better barrier properties. Medium (M) is a type of paper commonly used for the flute in corrugated cardboard and is mostly made from recycled pulp.

Table 1. Characteristics of papers at 7% moisture content used in the manufacturing of cardboard angles using the new folding method.

	Medium (M)	Brown Liner (L)	Double-side Liner (DL)
Weight (g/m^2)	165.9	169.4	211.8
Thickness (µm)	282.6	265.7	258.3
Porosity (sec./100 ml)*	20	25	197

*Porosity was measured by an Emtec PDA.C 02.

Table 2. Characteristics of PVAs used in the manufacturing of cardboard angles using the new folding method.

	PVA1 (1)	PVA2 (2)	PVA3 (3)	PVA4 (4)
pH	4.9	5.1	5.2	4.4
Viscosity (cPs @ 23˚C)	1440	2350	1400	2000
Solid content (%)	19.4	67.8	67.8	56.7

3 METHODOLOGY

3.1 Manufacture of Cardboard Angles

To the best of our knowledge, there is currently no standard for mechanical characterization of cardboard angles that meets our research objectives. Cardboard angles manufactured for this research used two different folding methods, both of which are patented by Abzac Canada Inc. [11]. The paper stack and folded cross-sections corresponding to the two folding methods are shown in Figure 1. The paper sheet counts in each of the folding processes was set in order to attain a target thickness of approximately 4 mm, independent of the folding method.

Reference cardboard angles used the current folding method and were manufactured by a high-speed automated process using a combination of three types of paper. Note that these three types of paper are not all covered in this research for the new folding method. The adhesive PVA1 is applied between each layer of paper in the reference angles. The core of reference cardboard angles is made from three chipboard layers. The core is covered by two recycled liners and then a white liner wraps the whole angle. The chipboard is exclusively made from recycled fibres and is used for its high stiffness.

Cardboard angles manufactured with the new folding method were handcrafted with a gluing/folding device specifically designed for this research. This folding method required five sheets of paper of the same type and one PVA adhesive among those presented in Tables 2 and 3. The optimal dosage and dry times of each adhesive were obtained through a previous study that relied on a peel test. These results were used as a reference for the manufacturing of all cardboard angles using the new folding method. It is noteworthy that the adhesive dosage (as measured by the applied thickness) for the handcrafted samples was higher than for the industrially produced angles used as a reference. This was required in order to increase the drying-time of the adhesive to a length that allowed the hand folding of the paper before the adhesive dried. The fast cure of the adhesive is a desirable property for machine folded angles, but is a hindrance considering the slower hand folding process.

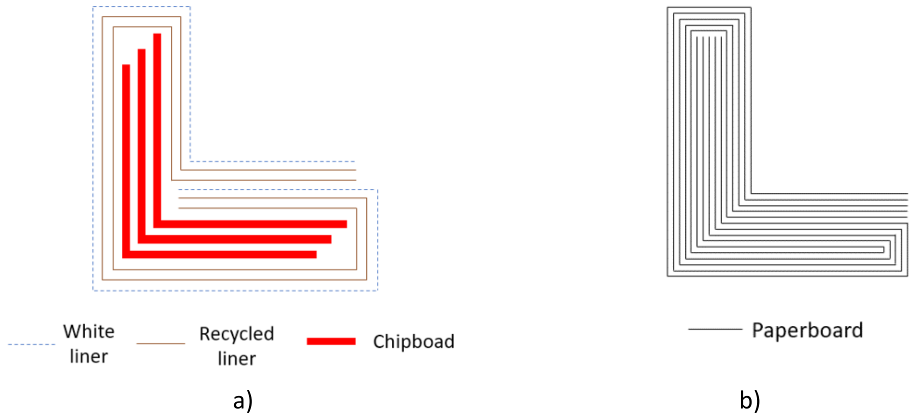


Figure 1. Folding method: a) current and b) new.

3.2 Conditioning

Manufactured cardboard angles are first cut at a length of 305 mm, with a 180 teeth 10 inches electric mitre saw and then placed in a chamber for 48 hours under ambient conditions for initial drying. Relative humidity and ambient temperature are partially controlled by air conditioning and are recorded continuously using an Extech RHT10 sensor. During the conditioning process, the handcrafted cardboard angles are clamped over a 3d-printed drying jig (Figure 2) to ensure a 90° angle between the cardboard angle flanges is maintained.

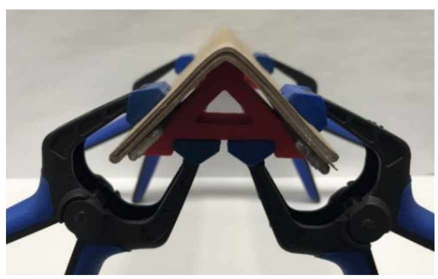


Figure 2. Jigs used during the drying process for the cardboard angles manufactured with the new folding method.

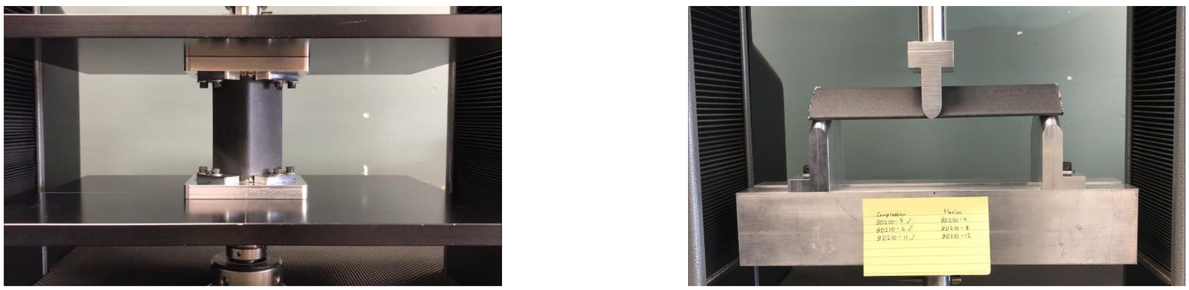
After the initial drying, all cardboard angles are cut again at their final length, before being placed in an industrial convection oven at 40 °C in order to reduce their moisture content to 6 ±0.5 %. The moisture content is described here as the water mass fraction M as given by $M = (m_{wet} - m_{dry})/m_{dry} * 100$, with m_{wet} and m_{dry} the masses of wet and dry specimens. To increase the moisture content to 10 ±0.5 %, cardboard angles are placed in an acrylic box along with a water-filled open container and circulation fans. The moisture content is measured after 24 hours and then measured at intervals of 2 hours with a Delmhorst P 2000 sensor at approximately 25 mm from the edge of the specimen. Measurements are taken until the target moisture content is reached. Once the moisture level is reached, the specimens are removed for testing.

3.3 Experimental Set-up

All specimens of a given test, irrespective of its moisture content, were tested following the same methodology. Quasi-static axial compression and three-point bending tests were done using an Ametek LD10 tabletop servoelectric test frame with a 10 kN load cell. An initial preload of 9 N was imposed, that corresponds to less than 1 %-2 % of the maximum load. The displacement was reset to zero and then the load was applied at a rate of 2 mm/min. The load and the crosshead displacement were measured at a rate of 14 Hz during testing.

Samples with a length of 102 mm were used for axial compression tests. The effect of the specimen's length on the failure under axial compression was previously studied and it appears that at 102 mm and below, most of the parasitic failure modes, like global buckling, are avoided. Samples were mounted in a 6061-T6 aluminum support device at both ends to prevents failures due to end crushing or slipping. Figure 3.a shows the compression test set-up.

Samples with a length of 254 mm were used for three-point bending tests. The support span was set at 234 mm. The loading nose and supports, both made from 6061-T6 aluminum, had a cylindrical contact surface of 10 mm radius. The supports which follow the angle 90º wedge shape of the cross-section of a cardboard angle. Figure 3.b shows the set-up for three-point bending tests.



a) b)

Figure 3. Experimental set-up for a) axial compression and b) three-point bending.

3.4 Design of Experiments

Table 3 shows the design of experiments and the number of specimen repeats per sampling condition. In total, 10 samples were tested, each of which a specific construction and contained at least three specimens per test condition. Specimens for nine of 10 samples were manufactured following the new folding method. Due to the fast drying speed of PVA2, PVA3 and PVA4, and the low manufacturing process for the new folding method, it was not possible to make cardboard angles combining medium and any of the adhesives cited previously without damaging the paperboard. For this reason, cardboard angles made from medium were only made with PVA1 adhesive.

Table 3. Design of experiments and a number of repeats per testing condition.

Folding method	Paperboard	Adhesive	Label	Axial compression		Three-point bending	
				Dry	Wet	Dry	Wet
New	Medium	PVA1	M1	3	3	3	3
	Liner	PVA1	L1	3	3	3	3
		PVA2	L2	3	3	3	3
		PVA3	L3	3	3	3	3
		PVA4	L4	3	3	3	3
	Double-side liner	PVA1	DL1	3	3	3	3
		PVA2	DL2	3	3	3	3
		PVA3	DL3	3	3	3	3
		PVA4	DL4	3	3	3	3
Current	White liner, recycled liner, chipboard	PVA1	RG	9	9	9	9

4 RESULT AND DISCUSSION

The mean and standard deviations of the maximum stress for axial compression and three-point-bending are shown in figure 4.a and 4.b respectively. Each figure provides results for the 6 % and 10 % moisture contents and for all constructions tested. To calculate the maximum stress, the assumption that the deformation is uniform until the maximum stress is reached was made.

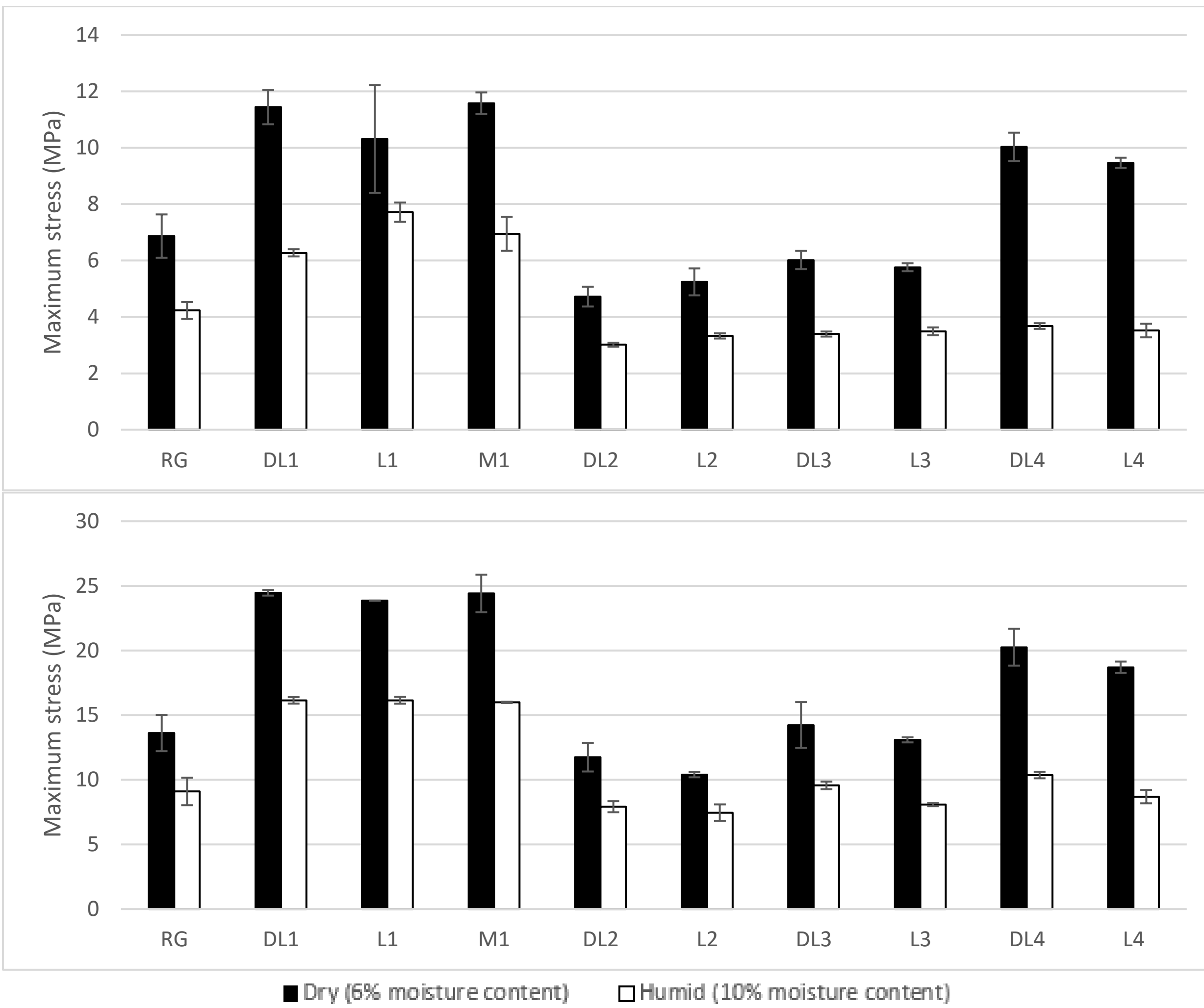


Figure 4. Maximum stress means all groups of samples at 6% and 10% moisture content: a) compressive stress and b) flexural stress.

4.1 Effect of the Type of Paper

The specimen groups for the new folding method, each with a different type of paper, were compared based on the type of adhesive and the moisture content. The comparison did not include the reference group as it used three different types of paper per specimen. The results show that, for cardboard angles manufactured with the new folding method, the type of paper does not have a significant impact on maximum stress neither for the axial compression nor for the three-point bending loading conditions.

As a result, samples DL1, L1 and M1 share a similar maximum compressive and flexural stresses, both at 6 % and at 10 % moisture contents. Regarding the mechanical test and the moisture content, the same conclusion applied to the pair of sample groups DL2/L2, DL3/L3 and DL4/L4.

4.2 Effect of the Type of PVA Adhesive

The four types of PVA adhesive in various specimen groups were compared according to their type of paper and their moisture content. With a moisture content of 6 %, the PVA1 adhesive clearly shows a better performance in terms of maximum stress in both mechanical tests compared to the other adhesives at the same moisture level. PVA2 and PVA3 show similar performance, while PVA4 is slightly under PVA1's performance. These results suggest that an inverse correlation exists between the percentage of solid content in the adhesive and maximum stress. Figure 5 shows the mean maximum stress for L and DL as a function of solid content fraction for both mechanical tests and moisture content. A low solid content in the adhesive thus apparently increases the maximum stress, with PVA1, PVA4, PVA2 and PVA3 respectively having 19.4 %, 56.7 %, 67.8 % and 67.8 % of solid content.

With a moisture content of 10 %, PVA2, PVA3 and PVA4 adhesives give similar results regarding maximum stresses, while PVA1 adhesive still offers the best performance. However, the effect of solid content in adhesive was not studied and further research is needed to accurately understand its impact on paper products strength.

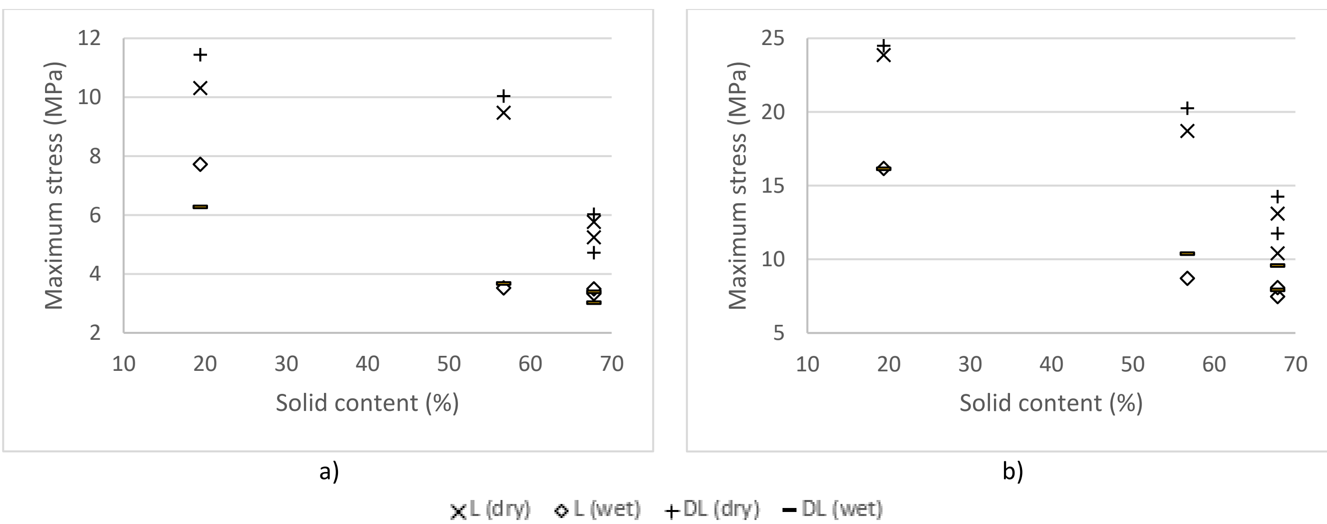


Figure 5. Maximum stress as a function of solid content: a) axial compression and b) three-point bending.

4.3 Effect of the Moisture Content

Each group of cardboard angles was tested at 6 % and 10 % moisture content. The increase of moisture content significantly decreases the maximum stress in both axial compression and three-point bending loadings. On average, when the moisture content increases form 6 % to 10 %, specimen groups manufactured respectively with PVA1, PVA2, PVA3 and PVA4, show a decrease in their maximum stress in axial compression of approximately 40 % for the first three and 65 % for the last. For the three-point bending loading, the same observation is made with a decrease of 3 5%, 30 %, 35 % and 50 % respectively. As a result, PVA4 adhesive appears more sensitive to moisture content level than other adhesives. It is also noteworthy that, when the moisture content increases, the standard deviation of maximum stresses tends to decrease despite an increase of about 3 %-6 % of the angles flange thickness.

4.4 Effect of the Folding Method

Considering the fact that the type of paper studied doesn't have a significant impact on maximum stresses and that the reference group was manufactured with the PVA1 adhesive, the comparison of the two folding methods can be made between groups of cardboard angles that share the same adhesive. The maximum compressive and flexural stresses for the sample RG is lower than DL1, L1 and M1 at both moisture content.

However, each of the two folding method has a very different manufacturing process. Among others, the adhesive dosage in the automated process is dictated by economic imperatives (targeting the minimum amount of adhesive) and the processing speed is such that the drying speed of adhesive is not an issue. On the contrary, the handcrafted process requires a higher dosage because of its much longer process duration and one of the factors allowing more work time is an increase in adhesive dosage. Despite these facts, results can give us an insight for the potential of the new folding method and it shows that it is possible to manufacture new cardboard angles that are at least as good as the ones currently on the market, while using only one type of paper.

5 CONCLUSION

Cardboard angles were manufactured following a new folding method and by using three different types of paper and four different PVA adhesives. Specimens were manufactured, conditioned and then tested in quasistatic axial compression and three-point bending. The effects of the type of paper, of the type of adhesive and of the moisture content on the strength of cardboard angles were studied.

Results show that the type of paper doesn't have a significant impact on maximum stress at failure. On the contrary, the type of adhesive and the moisture content have an important influence, with lower solid content adhesive providing the higher strength and moisture dramatically reducing the cardboard angle strength.

It was demonstrated that the new folding method using a single paper type could provide equal or better mechanical strength for the angle. This result is promising because it means that the problem of raw material supply can be mitigated by opting for an alternative type of paper without excessively affecting the mechanical properties of cardboard angles. Moreover, the use of a single type of paper can reduce the environmental impact of the manufacturing process. On the other hand, further studies are needed to find out if there is a weight advantage to using only one type of paper as such an advantage can have an impact on transportation cost and on the related greenhouse gas emissions

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7 CONFLICT OF INTEREST

All authors state that there is no conflict of interest of any kind.

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