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PAPER AS A BUILDING MATERIAL – MECHANICAL PROPERTIES OF PAPER-BASED PRODUCTS

Anna KAROLAK*, Paweł NIEWIADOMSKI*

* Wydział Budownictwa Lądowego i Wodnego
Politechnika Wrocławska
ul. Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Polska

E-mail: pawel.niewiadomski@pwr.edu.pl

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ABSTRACT

Today, a lot of attention is paid to the idea of sustainable development, which is related, among others, to the application of innovative or unusual materials in architecture and construction. One idea might be to use economical, ecological, and environmentally friendly materials of natural origin, such as paper.
According to the literature [1-4], paper, cardboard, and other paper-based products are described as inhomogeneous, hygroscopic, anisotropic materials characterized by non-linear, visco-elastic-plastic behaviour. Their mechanical properties are strongly dependent on the orientation of the fibers and the type of fiber binder that determine the structure and density of the material. Moreover, there are many other factors that can influence the mechanical behaviour of paper-based products, such as moisture content, humidity and temperature, time of loading, etc. Importantly, when defining the mechanical properties of paper and paper-based products, the identification of the directions related to the production process needs to be done. The directions are machine direction (MD), cross-machine direction (CD), and thickness direction (ZD). They are presented in Fig. 1.

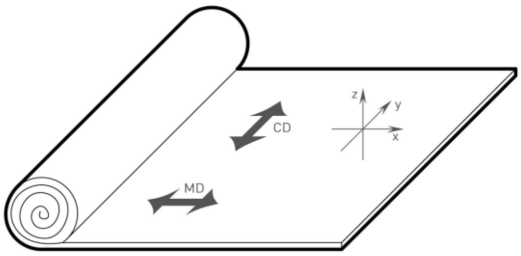

Fig. 1. Directions of paper: machine direction (MD), cross-machine direction (CD)

In their works [5-7], some researchers presented selected values of elastic stiffness parameters for different types of paper-based products, obtained in tensile tests within the range of load significantly below the failure load. They are presented in Tab. 1. Unfortunately, accurate data on the type of material, such as its dimensions, density, etc., which may have a significant impact on the values of the parameters presented, is not always given.

Tab. 1. Values of elastic stiffness parameters in tensile loading according to [4]

Parameter/ Material	Paperboard	Carton	Corrugated cardboard (linerboard)	Coated paper, middle of web	Coated paper, web edge
Density [kg/m^3]	640	780	691	1140	1140
E_x – MD [MPa]	5420	7440	7460	7690	7660
E_y – CD [MPa]	1900	3470	3010	3050	2570
E_z – ZD [MPa]	17	40	29		140
G_{xy} [MPa]	1230	2040	1800	1910	1820
G_{xz} [MPa]	8.8	137	129		
G_{yz} [MPa]	8.0	99	104		
v_{xy}	0.38	0.15	0.12	0.33	0.27
v_{xz}	-2.20	0.08	0.011		
v_{yx}	0.14			0.07	0.10
v_{yz}	0.54	0.021	0.021		
v_{zx}	0.05				-0.04
v_{zy}	0.05				0.03

In his studies [8], Fellers, claimed that paper presents better parameters in tension than in compression. The stress-strain curves of paper in tension and in compression for machine direction and cross-machine direction are presented in Fig. 2.

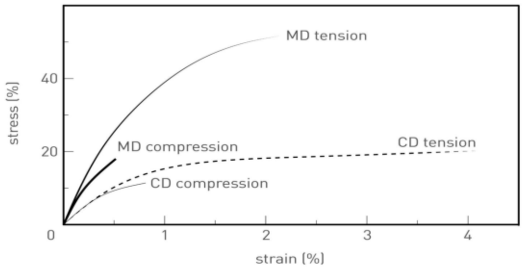

Fig. 2. Static behaviour of paperboard according [8]

Due to the production process, paper and paper-based products present better parameters in machine-direction than in cross-machine direction. In their works [9-10], Schönwälder and Rots, presented the relations between the mechanical properties of paperboard. They are shown in Tab. 2.

Tab. 2. General relations of the mechanical properties of paperboard from [9-10]

Parameter/ direction	Machine direction	Cross-machine direction
E [GPa]	2 – 20	1/4 – 2/3 E_{MD}
σ_t [MPa]	15 – 45	1/3 – 1/2 $\sigma_{t, MD}$
σ_c [MPa]	1/3 $\sigma_{t, MD}$	1/2 $\sigma_{c, MD}$
ε_t [%]	1.5 – 2.5	3.0 – 4.0
v	0.4	0.1
G [GPa]	1/3 $(E_{MD}E_{CD})^{1/2}$	

There are some specific values of selected mechanical parameters of different types of paper-based products presented in the literature. Unfortunately, the detailed data about the dimensions of the products are not given, although it the parameters are strictly related to the products dimensions.

In their work [10], Schönwälder and Rots, also presented the specific values of selected mechanical parameters of paper/ cardboard tubes and honeycomb panels/ sheets. The compressive and tensile strengths of the tubes were about 8 MPa, and the long-term compressive and tensile strengths were about 1-2 MPa, which is several times lower. And the value of the modulus of elasticity of the paper tubes was about 1-1.5 GPa. In turn, for honeycomb panels with a thickness of 20 mm, the value of bending strength was about 7 MPa and the value of the modulus of elasticity was about 1 GPa.

Paper tubes with thick walls were also described i.a. by Correa, in [11] and by Block in [12]. They presented the values of the modulus of elasticity, allowable compression and bending stresses under short-term and long-term loads. The modulus of elasticity under short-term load was about 1-1.5 GPa and under long-term load – about 1 GPa. The allowable stresses under-short term load were, respectively, for compression stress – about 4.4 MPa and for bending stress – about 6.6 MPa. The values of these parameters were twice lower for long-term load.

In [13] Bank and Gerhardt presented mechanical parameters of paper tubes established by static testing: axial compression and bending. The tubes had different dimensions: diameters from 75 to 220 mm and wall thickness from 10 to 30 mm. And the levels of moisture content were different, from 7% up to 10%. The studies showed that the compressive strength was about 5-10 MPa, the modulus of elasticity in compression was about 1-2 GPa, the bending strength was about 8-16 MPa, and the modulus of elasticity in bending was 1.5-2 GPa. The same authors presented more results of the modulus of elasticity in bending of paper tubes from dynamic modal testing in [14-15]. The measured values of the modulus of elasticity in bending for tubes with different diameters and wall thickness ranged from 1.7 to 4.2 GPa.

In turn, Pohl et al. [16] presented the results of mechanical parameters from compression and shearing tests for corrugated paper honeycomb. The authors established that the material exhibited linear load-displacement behaviour up to at least 50% of the failure load. The results of the tests were as follows: out-of-plane compressive strength – 1.4 MPa, out-of-plane compressive modulus – 0.2 GPa, shear strength in weak and strong direction, respectively, 0.4-0.8 MPa and shear modulus in the weak and the strong direction, respectively, 0.04-0.09 GPa. The parameters were compared with the corresponding parameters of hexagonal paper honeycomb, described i.a. in [17] and it turned out that the corrugated paper honeycomb had similar strength and shear moduli as the typical hexagonal paper honeycomb with density 20-50 kg/m^3, while the out-of-plane compressive strength of corrugated paper honeycomb was higher.

Corrugated paper honeycomb core sandwich composites were analysed by Ayan in [18]. The component with a core thickness of 52 mm and steel facing of 1,5 mm achieved in the axial compression test a destructive force of 66 kN.

Also, Heyden et al. in [19] presented the results of the compression, tension, and shearing tests of corrugated cardboard as a core material for sandwich panels. The results showed that the material parameters were significantly dependent on the humidity level and the load direction. The material turned out to have similar or higher strength and stiffness compared to commonly used core materials, such as mineral wool or polyurethane foam. The authors concluded that the use of corrugated cardboard as an alternative core material for sandwich panels may be appropriate, but more tests of the material, especially for its long-time behaviour, are required.

All things considered, it can be stated that paper and paper-based materials appear to be promising construction materials with respect to their mechanical properties. Nevertheless, it should be remembered that using paper and paper-based products as a building material requires the analysis of other parameters, such as paper durability, resistance to environmental conditions, biological and chemical corrosion, and fire resistance. Paper and paperboard turn out to be materials comparable to the commonly used construction materials. There are also many advantages of paper and paperboard, such as density and weight, recyclability, ease of obtaining and processing, etc. As a summary, Tab. 3 presents the values of the mechanical parameters of paper and paperboard in comparison with other commonly used building materials.

Tab. 3. Mechanical parameters of common building materials and paper, paperboard

Material/ Parameter	**Compressive strength [MPa]**	**Tensile strength [MPa]**	**Modulus of elasticity [GPa]**	**Max. strain [%]**	**Density [kg/m^3]**
Concrete (PN-EN 1992-1-1, PN-EN 1991-1-1)	12-90	1.6-5	27-44	0.18-0.28	2400
Steel (PN-EN 1993-1-1)	360-570	360-570	210	17-26	7850
Wood parallel to the grain (PN-EN 338)	18-26	11-24	9-14	-	380-500

Wood perpendicular to the grain (PN-EN 338)	5-6	0.3-0.4	0.3-0.5	-	380-500
Paper and paperboard machine direction [10]	5-10	15-45	2-20	1.5-2.5	600-800
Paper and paperboard cross-machine direction [10]	2-5	5-20	0.5-10	3-4	600-800

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