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THE RELATIVE MOISTURE SENSITIVITY OF COMPRESSION AS COMPARED TO TENSILE STRENGTH

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ABSTRACT

The moisture sensitivity of compression and tensile strength is compared for a range of packaging papers. It is shown that compression strength falls off more rapidly with increasing moisture content than tensile strength. This is especially true in the range up to 10% moisture content, where there is little effect of tensile strength. Results were obtained using the STFI short span compression test and tensile test carried out in silicone oil. Also included are Concora Medium Tests (CMT) for fluting. Concora Liner Tests (CLT) for liner and Ring Crush Tests (RCT) for compression.

This difference in moisture sensitivity is also very evident for papers which have been given different wet strengthening treatments. For example, after 60 min. of water immersion, such wet strength papers can retain a wet tensile strength which amounts to 30 - 40% of the 50% RH value. The corresponding wet compression strength retention is only 15% to 25%. It is also shown that the tensile stiffness is more moisture sensitive than the tensile strength.

The results are discussed with reference to the glass transition that cellulose and hemicelluloses at 20^{o}C pass through at a given moisture content corresponding to about 10% moisture content for a kraft paper. This transition particularly affects the moduli of the paper, while for tensile strength thermal softening apparently also has some positive effect, by reducing stress concentration.

INTRODUCTION

Compression strength is the most important rupture parameter which is related to the performance of corrugated boxes. Since boxes often are designed also for moist climate, the corresponding moist compression strength and means to improve it are quite important. A recent paper of Gerhards has reviewed moisture and temperature effects on the mechanical properties of wood (1), from which the summary in Table 1 is reproduced. It indicates that compression strength has a much larger moisture sensitivity than tensile strength. Here, a similar comparison is carried out for some standard packaging papers, including those with a wet strength treatment.

For testing paper strength parameters over a large range of moisture content and temperature, a tensile testing cell was developed some years ago to operate in temperature-controlled silicone oil (2). Recently, a similar "in oil" testing cell was built for the STFI short span compresion strength (3) and ring crush test (3). By using oil immersion, the disturbing transient effects that occur when testing in air without complete moisture equilibrium (4) are eliminated. Using those two methods, the moisture and temperature sensitivity of tensile and compression strength have been evaluated and compared.

Property	Relative change in property from 12% MC	
	At 6% MC	At 20% MC
	%	%
Modulus of elasticity parallel-to-the-grain	+9	−13
Modulus of elasticity perpendicular-to-the-grain	+20	−23
Shear modulus	+20	−20
Bending strength	+30	−25
Tensile strength parallel-to-the-grain	+8	−15
Compressive strength parallel-to-the-grain	+35	−35
Shear strength parallel-to-the-grain	+18	−18
Tensile strength perpendicular-to-the-grain	+12	−20
Compressive strength perpendicular-to-the-grain at the proportional limit	+30	−30

Table 1—Approximate middle trend effects of moisture content on mechanical properties of clear wood at about 20°C according to Gerhards (**1**)

EXPERIMENTAL

The procedure for the "in oil" short span compression strength test, described separately (4), follows the short span SCAN-method (5) and the proposals of Fellers (6).

Using the same equipment, "in air" and "in silicone oil" strength values, such as short span compression or tensile strength, do not differ significantly. The tensile energy absorption (TEA) is slightly lower "in oil" (7). For the "in oil" measurements, the strength values are always obtained as a function of the moisture content of the papers. Samples are preconditioned in an atmosphere of a known RH and quickly inserted into silicone oil before being clamped into the test cell, in which the level of pre-thermostated oil then is raised. Samples for moisture content are taken simultaneously.

In this study, detailed results are given for a few papers. For other packaging papers, with and without wet strength treatments, the retention of tensile and compression strength at 90% RH and on water immersion calculated in % of that at 50% RH are compared.

As an example, Fig. 1 shows the "in oil" short span compression measurements for an NSSC corrugating medium paper in the CD (one of the papers in Figures 2 and 3) over a range of temperature and moisture content (8). Each dot represents a mean of 10 samples. To facilitate recalculation of strength values to corresponding RH values, the absorption isotherms at 20°C, are also given for both the papers in Figures 2 and 3. A temperature range up to 45°C can be used for "in oil" measurements without risking the loss of moisture from the paper samples (3).

The tensile properties for these and other corrugating medium papers have been evaluated "in oil" over a range of moisture and temperature and presented earlier (9). Some of the results in Tables 2 and 3 are from earlier publications (10, 11, 12) and a recent evaluation of the moisture resistance of liner and fluting, which is achievable by heat treatment as compared to wet strength agents.

For papers which have been subjected to a range of preconditioning, tensile parameters (13,14) and more recently short span compression strength (15) have been shown to be primarily a function of moisture content, regardless of how this moisture content is achieved. Thus plots against moisture content (Figures 1-3) for many purposes are more meaningful than plots against relative humidity.

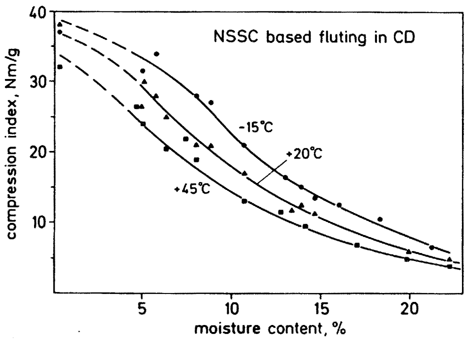
RESULTS

Fig. 2 compares the relative moisture sensitivity of compression and tensile strength of two corrugating medium papers. In this comparison, the 50% RH strength value serves as the basis for calculation of the relative strength values. Fundamental differences are better illustrated in Fig. 3, which uses water free strength values as a basis for comparison. The shape of these curves is less certain, since the data in Figure 1 have been extrapolated to a completely dry state, and there are only a few data points in the low moisture range.

Both Figures illustrate the higher moisture sensitivity of compression strength as compared to tensile strength. This holds true not only above 7% moisture content - i.e. in this case above 50% RH - but also in the low moisture range.

A heat treatment is one way to promote wet strength by auto-crosslinking in the bonding area and within fibers. Therefore using a kraft liner with suitable heat treatment and without, tensile strength and compression strength again were compared, as illustrated in Fig. 4. It appears, that the heat treatment increased the wet and moist tensile more than the wet and moist compression strength. So, the relative difference in moisture sensitivity was somewhat increased by this treatment. The 100% basis in this comparison was set to 30% RH, and the treated liner at this climate has a lower moisture content than the untreated. Therefore the 100% basis for these two papers is different.

To further illustrate the different moisture sensitivity, Table 2 gives the relative retention of short span compression and tensile strength at 90% RH and after



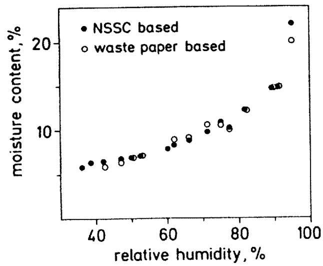
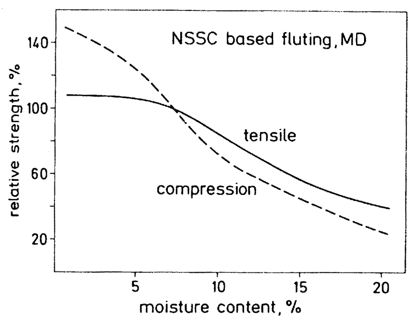


Fig 1—Left: The CD compression index of a 117 g/m² NSSC corrugating medium of density 616 kg/m³, measured in silicone oil over a range of temperature and moisture content. The index is calculated using the grammage at 50% RH throughout.
Right: The absorption isotherms at 20°C for this paper and a 157 g/m² waste based corrugating medium of density 628 kg/m³, when conditioning from 50% RH as a starting climate.



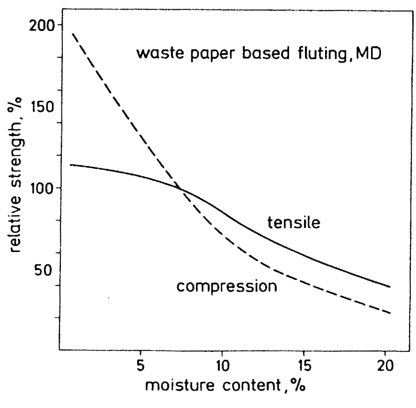
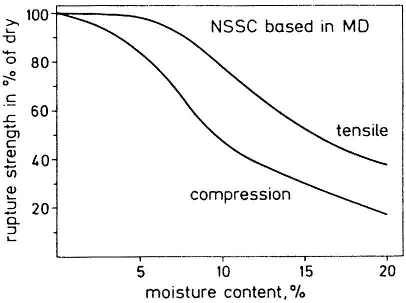


Fig 2—The relative tensile and compression index in the MD at 20°C **vs.** the moisture content for the two corrugating medium papers of fig 1. Strength values are calculated as a percentage of the figure obtained at 50% RH (equivalent to 7.3% moisture content) and each index on the grammage at 50% RH throughout.



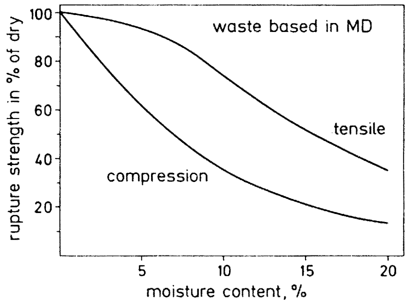


Fig 3—The tensile and compression index in the MD at 20°C **vs.** the moisture content for the two corrugating medium papers shown in figs 1 and 2. Here, the moisture-free strength value is set as 100%.

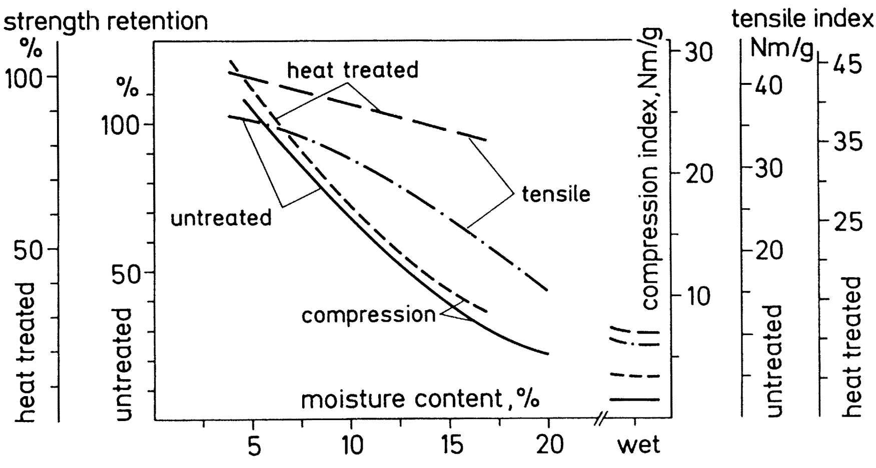


Fig 4—The tensile and compression index at 20°C of a 225 g/m² **vs.** the moisture content for a liner with and without 3.2 seconds of heat treatment at 350°C of density 631 and 614 kg/m³ respectively at 50% RH. Scales to the right give absolute strength values. Scales to the left are relative, with the 100% value set at the equilibrium moisture obtained at 30% RH. This corresponds to 5.6% moisture content for the untreated paper, and 4.5% moisture content for the heat treated paper. Strength index based on grammage at 50% RH throughout.

60 minutes of water immersion in % of the value at 50% RH. The 90% RH value was achieved by conditioning from the dry side. The retention of tensile stiffness index, also called specific modulus, is given in these tables, where evaluated. In Table 3 the relative strength retention is illustrated by RCT, CLT and CMT test results. These tests were used earlier to evaluate compression strength and failure occurs in a somewhat different way than in the STFI short span test. The strength index in these Tables is always based on grammages at 50% RH. Thereby the strength and tensile stiffness index is unaffected by the thickness swelling of the paper, when absorbing moisture.

Property	kraftliner MD/CD			sack paper MD/CD		corrugating medium MD/CD			
						NSSC			waste
	225 g/m²		200 g/m²	110 g/m²		127 g/m²		117 g/m²	157 g/m²
					0.8 %				
	untreated	heat-treated 1)	heat-treated 2)	untreated	urea resin 3)	untreated	heat-treated 2)	untreated	untreated
compression index									
Nm/g at 50 % RH	35/23	39/27	33/20	31/21	28/21	46/22	50/24	37/25	31/20
% retention at 90 % RH	/48	/53				/50	/55	47/50	42/41
% retention on wetting	8/9	15/16	10/10	8/8	11/12	8/7	10/11	5/5	6/7
tensile index									
Nm/g at 50 % RH	84/33	95/42	90/37	74/37	80/53	94/28	94/30	68/31	51/28
% retention at 90 % RH	65/57	78/86	68/74		71/	57/65	64/67	58/	60/
% retention on wetting	8/9	34/36	26/30	16/18	31/31	5/6	20/21	8/9	9/11
specific modulus									
Nm/g at 50 % RH	7.9/4.0	8.4/4.2	8.2/3.8	6.1/3.4	5.6/3.2	9.7/3.3	9.5/3.2	8.7/4.1	7.1/4.1
% retention at 90 % RH	86/62	76/68	57/39		54/	59/51	59/52	67/	59/
% retention on wetting	10/4	23/10	14/8	20/9	13/6	5/2	13/7	6/5	8/7

1) and 2) equilibrium moisture reduced by heat treatment but "strength index"-calculated on original basis weight at 50 % RH. Heat treatment: 1) 3.2 s at 350°C 2) 36 s at 260°C

3) retained amount

Table 2—Tensile and short span compression strength retention when moist or wet.

Property	liner 225 g/m² MD/CD un-treated	liner 225 g/m² MD/CD heat-treated[1)]	sack 120 g/m² MD/CD 6 % Escorez 1102 B	sack 110 g/m² MD/CD 0.8 % urea resin[4)]	NSSC 127 g/m² MD/CD un-treated	NSSC 127 g/m² MD/CD heat-treated[2)]
tensile index						
Nm/g at 50 % RH	84/33	95/42	83/43	80/53	94/28	94/30
% retention at 90 % RH	65/57	78/86	72/73	71/	57/65	64/67
% retention on wetting	8/9	34/36	11/10	31/31	5/6	20/21
specific modulus						
Nm/g at 50 % RH	7.9/4.0	8.4/4.2	8.0/4.2	5.6/3.2	9.7/3.3	9.5/3.2
% retention at 90 % RH	86/62	76/68	54/44	54/	59/51	59/52
% retention on wetting	10/4	23/10	10/8	13/6	5/2	13/7
RCT						
kN/m at 50 % RH			1.1/1.3	0.94/0.79	2.1/1.3	2.5/1.7
% retention at 90 % RH			60/56	64/62	43/50	43/44
% retention on wetting			12/14	17/[illegible]	8/6	12/11
CLT CMT[3)]						
N at 50 % RH	500/300	500/360			300/	340/
% retention at 90 % RH	60/62	63/67			44/	45/
% retention on wetting	9/10	24/22			8/	15/

1) 3.2 s at 350°C 2) 36 s at 260°C 3) CLT for liner, CMT for corrugating medium

4) retained amount

Table 3—Relative compression strength retention of moist and wet papers as evaluated by RCT, CLT and CMT.

Again, the higher moisture sensitivity of compression as compared to tensile strength is evident. In both Tables the difference in wet strength retention after total water immersion of these packaging papers is most pronounced when various wet strengthening treatments have been used. In these cases, tensile stiffness is also more sensitive to moisture than tensile strength. As mentioned above wet strength treatments - especially heat treatment - reduce both the equilibrium moisture content of a paper at a given relative humidity and the thickness swelling.

DISCUSSION

The moisture sensitivity of paper (14, 16), building boards (17) and wood (18) has been explained by the water acting as a softener on the various wood polymers. At a given moisture content, the glass transition of these polymers is passed as the temperature is raised. Similarly, at a given temperature, the glass transition is passed when raising the moisture content in the paper from a low to a high value. In practice, depending on the frequency, the glass transition of the remaining lignin component is not passed at temperatures below 70°C. Only the glass transitions of amorphous cellulose and hemicellulose polymers then are passed below 70°C, and these two transitions are not easy to separate in paper.

Passing from the glassy to the rubber-elastic phase, considerably reduces the moduli of the polymer. As a secondary phenomenon it reduces the interpolymer cohesion, which reduces intrinsic strength. It might be proposed that the increased mobility within the polymer softener system also reduces local stress concentration at points where dislocations and asperities occur within the bonding area and within the fibers. Therefore, the relative effect of softening due to a glass transition is less on tensile strength than on moduli and on the tensile stiffness, i.e. the specific modulus in plane. For example, for rayon sheets and many types of single fibers, tensile strength actually increases with increasing moisture content, from zero to e.g. 8% moisture, due to the equalizing action of water on stress distribution, while the specific modulus falls off due to action of the softener (19).

For paper products, this effect can be demonstrated explicitly by plotting the ratio of tensile index to specific modulus against moisture content, as in Fig. 5. Details in this Figure are not yet understood. Also on thermal softening in the water free state, this ratio of tensile rupture index to specific modulus is found to increase significantly at the glass transition temperature. For a dry hardboard based on TMP it was found to increase as much as from 0.5 to 0.9% over the glass transition range from 160 to 250°C, while from dry to 15% moisture content it increased only from 0.5 to 0.7% more continuously. For the corrugator medium papers in Figures 1 to 3, the effects of moisture and temperature on this ratio of tensile to modulus was less pronounced, probably due to their high lignin content.

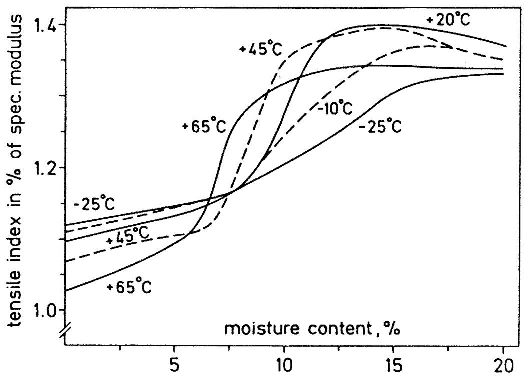


Fig 5—The ratio of tensile index to specific modulus in % **vs.** the moisture content for an 112 g/m² sack kraft paper of density 600 kg/m³ at several temperatures. Measurements were carried out in silicone oil (**16**).

The failure mechanism on compression loading is discussed elsewhere in this conference (15). Earlier, it has been stated that compression strength depends less on the actual degree of fiber to fiber bonding and more on paper and fiber modulus than does tensile strength (20, 21). Other experimental data point out a more direct correlation, indpendent of furnish or paper anisotropy, between the edgewise compression strength and the product of the in plane normal stiffness (in plane modulus) and the out of plane (inter-laminar) shear stiffness, the compression strength being approximately proportional to the square root of this product (22). The larger moisture sensitivity of compression strength as compared to tensile strength, both in wood and in paper could become an integrated part of understanding compression failure. It has also been shown that - although the absolute value of the specific modulus of paper is significantly varied by drying restraints - its relative moisture senstivity is not changed thereby (23).

Data collected for wood by Gerhards, similar to Table 1, with less significance also indicate a large temperature sensitivity of compression than tensile strength (1). With a few data for the fluting of Figures 1-3 such an effect did not show up.

ACKNOWLEDGEMENTS

I am indebted to Gunilla Richardson, Anne-Mari Olsson and Signar Danielsson for excellent assistance with experimental data.

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Transcription of Discussion

The Relative Moisture Sensitivity of Compression as Compared to Tensile Strength
by E.L. Back

V.L. Byrd Mead Corp., Chillicothe, USA

Have you measured any values of rupture energy in compression, as well as in tension and how does that vary with moisture content?

Prof E.L. Back We have measured the tensile energy absorption. It usually has a maximum just a little above the glass transition temperature of about 9 or 10% moisture content depending on both temperature and the type of furnish. In compression we have no such measurements since they would be very difficult to pursue.

Page PPRIC, Pointe Claire, Canada

Dr. Seth and I have just completed a paper entitled "The mechanism of compressive strength" which will be presented at next year's TAPPI Paper Physics Seminar. I think it is relevant to your paper.

We showed at the last Symposium, Cambridge 1981, that the stress-strain curve of paper in tensile came from the fibres. The yield point and plastic flow in paper is caused by the yield of the matrix as the microcompressed regions of fibres are extended. However, this flow reduces the amplitude of the microcompressions tending to reduce the shear stress in the matrix.

We propose that a similar mechanism is responsible for the failure of paper in compression.

The matrix in a microcompressed region of a fibre in a sheet under compression will yield at the same stress that it will yield under tension. However, when it yields under compression, the amplitude of the microcompressions is increased so that further flow occurs. The sheet, therefore, fails in compression at the same stress that it yields in tension.

We have checked, that for fibres containing no built-in stresses, the strength in compression is equal to the yield stress in tension.

This has relevance to your work because it emphasises the importance of the matrix, which is sensitive to moisture.

Dr. D. Caulfield USDA Forest Prod. Lab., Madison, USA

Dr. Page has mentioned that you expect the elastic modulus to be the same, both in compression and tension. We have a compression modulus tester at the Forest Products Lab. that can be run in tension as well as in compression and we always get a straight line running right through the origin.

J. Fromond Dow Chemical, Rheinmuenster, W. Germany

How would the ratio of compression and tension be effected if you use a wet strength agent? For example urea or melamine formaldehyde?

Back There is some small amount of data in the tables in the paper. Typically in the wet state the ratio of compressive on to tensile strength is about 50% of that ratio at 50% RH, i.e. in the dry range.