IN-PLANE HYGROEXPANSIVITY OF POSTAGE STAMP PAPERS

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Abstract

This paper describes a new method to measure the in-plane hygroexpansivity of paper. The method is used to evaluate the hygroexpansion of stamp papers, with and without adhesive backing. For these materials, the cross-machine direction showed more hygroexpansion than did the machine direction; adhesives increased hygroexpansion, and density and modulus of elasticity were inversely related to hygroexpansion.

Introduction

Hygroexpansivity of paper is defined as the dimensional change of paper in response to moisture content changes. Moisture content changes of paper cause dimensional changes in the machine direction (MD), cross-machine direction (CD), and through the thickness direction of paper, and these changes are related to the nature of cellulosic fibers and the degree of bonding between the fibers (Caulfield, 1988). Accurate measurement of hygroexpansion of paper can lead to a better understanding of the factors affecting hygroexpansion in cellulose structures that may provide new and increased market areas for cellulose products. Uesaka (1991) thoroughly reviewed the literature relating to hygroexpansivity and stressed the importance of incorporating hygroexpansive properties in paper product design.

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Several paper products are affected by their so-called dimensional stability, which is their sensitivity to hygroexpansion. The difference in hygroexpansion between medium and liner paper products can create large moisture-induced stresses in corrugated structures. Poor in-plane dimensional stability may result in improper image registration in multi-image printing. Hygroexpansion also causes curl and pucker of paper products.

Only a few methods have been proposed to determine the in-plane hygroexpansion of paper (Setterholm, 1984). These methods are of two types. In the first type, based on the Neenah-type Expansimeter, a weight is hung from a paper strip. The humidity of the surrounding environment is changed, causing dimensional changes in the paper sample that are measured by the deflection of the hanging weight. This method is the basis for the TAPPI Useful Method 549. However, this method has two disadvantages: (1) the weight may cause creep to occur and obscure the dimension variation caused by moisture content changes, and (2) only the MD or CD may be tested at one time. In the second type, after the sample is exposed to a changed humidity environment, hygroexpansion is determined by the deformation of a grid pattern drawn on the paper sample or by manual measurement of overall sample dimension changes. This second method is labor intensive and subject to operator error (Green, 1985).

Several researchers have used these two types of methods to investigate the dimensional stability of paper products. Callinan and others (1961) measured the dimensional stability of tabulating cards over the range of 0% to 98% relative humidity (RH). They found that several RH cycles were required before the dimensional changes were similar for each cycle. They believed that papermaking-induced residual stresses relaxed with each humidity cycle and that hygroexpansion was related to the papermaking-induced residual stresses in the paper. Other researchers (Prusas, 1963; deRuvo and others, 1976; Green, 1983) have documented increased hygroexpansivity of paper in the CD and have related this increased expansion to lower modulus in that direction.

The knowledge of the in-plane hygroexpansive response of paper can reduce waste of valuable resources and allow for more advanced, faster converting processes. This paper introduces a new method of measuring the in-plane hygroexpansivity of paper and uses this method to evaluate six different postage stamp papers.

Test Method

Tests were conducted on an apparatus developed at the USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin (Considine and Gunderson, 1987). The apparatus consists of a lateral support array, a system for controlling the RH in the small chamber, and two extensometers that

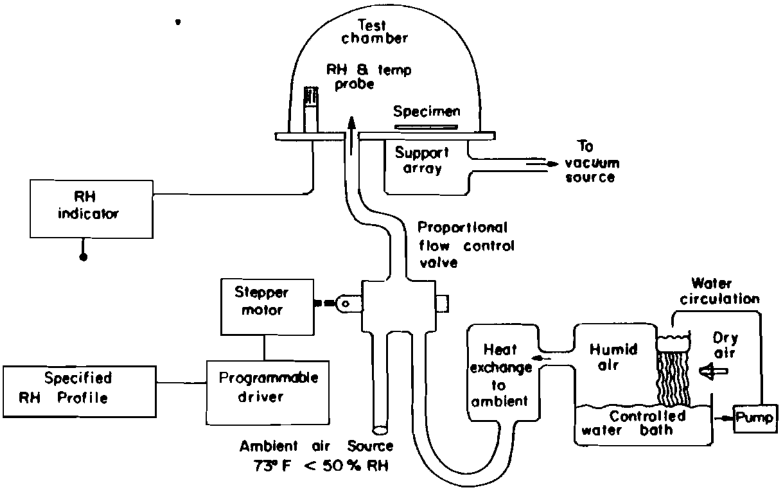

Figure 1. Relative humidity control system. (ML85 5439)

ride the paper sample to measure deformation. The support array, developed by Gunderson (1981), holds the sample flat and hastens equilibration to RH changes. A proportional flow control valve mixes dry and saturated air for introduction into the test chamber. A diagram of the support array and humidity control system is shown in Figure 1. A computer is programmed to monitor and control the test. In the experiments performed in this research, the RH was alternately held at 30% and 80% RH for 15 min. at each condition. For each experiment, the cycle sequence was repeated six times. In both the MD and the CD, deformations were monitored frequently during the test. Specimens were 13.8 cm square and conditioned at less than 30% RH for at least 1 week. The temperatures of the preconditioning room and environmental chamber were held at 32°C.

All samples were tested twice to examine repeatability, waiting 1 week between each test. The gummed samples were tested with the gum side next to the rods. The adhesive produced curl at high humidities, but a small vacuum (6.8 kPa) was able to maintain flatness.

Materials

Table 1 lists the stamp papers examined in this experiment. Furnish of each paper was unknown. However, the manufacturer did indicate that LP40H and LP40L had the same furnish and were made on the same machine, with LP40L having a slightly lower grammage and density. Microscopic examination showed that all paper samples were made from predominantly

Table 1. Physical properties of stamp papers[a]

Paper	Grammage (g/m^2)	Density[b] (kg/m^3)	Adhesive thickness (mm)	Fiber length[b] (mm)
Gummed				
LP37	113	—	0.01	—
LP40	106	—	0.01	—
LP54G	130	—	0.02	—
Ungummed				
LP40L	85	840		1.31
LP40H	88	870		1.31
LP54U	96	1,200		1.54

[a] — indicates the adhesive does not allow accurate measurement of these properties.

[b] Measured by Kajaani FS-100 Fiber Length Analyzer, using weight weighted average. Density and fiber length were not measured for the gummed papers. The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

hardwood furnishes. For the gummed papers, substrates and adhesives were as follows: LP40, substrate was LP40H with dry gum adhesive; LP37, substrate was LP40H with a resin dextrin adhesive; LP54G, substrate was LP54U with dextrin adhesive.

Grammage, density, fiber length, and adhesive for the papers examined in this study are given in Table 1. Tension tests were performed on an Instron-type machine that held the specimen horizontally so that an extensometer could ride on the sample to measure deformation. Conditions were maintained at TAPPI standard conditions. The Forest Products Laboratory thickness tester (Setterholm, 1974) was used to measure sample thicknesses.

Table 2 lists measured mechanical properties of the stamp papers. The mechanical properties for LP40L and LP40H were very similar. The LP54U paper had significantly higher tensile strength and modulus of elasticity than did the other ungummed papers but similar strain to failure. All gummed papers had comparable properties. When compared to the properties of its substrate, LP4OH, the resin dextrin adhesive LP37 reduced the MD tensile strength and modulus of elasticity but had little effect on the MD strain to

Table 2. Mechanical properties of stamp papers[a]

Paper	Machine direction			Cross-machine direction		
	Tensile strength (MPa)	Strain to failure (%)	Modulus of elasticity (GPa)	Tensile strength (MPa)	Strain to failure (%)	Modulus of elasticity (GPa)
Gummed						
LP37	47.8 (1.7)	1.92 (0.11)	5.15 (0.14)	26.4 (1.9)	4.71 (0.95)	2.87 (0.13)
LP40	44.0 (1.0)	2.17 (0.15)	4.83 (0.30)	27.8 (1.0)	6.26 (0.42)	2.70 (0.03)
LP54G	46.0 (2.3)	1.59 (0.14)	5.15 (0.17)	33.3 (1.6)	5.27 (0.27)	3.29 (0.27)
Ungummed						
LP40L	53.9 (1.6)	2.04 (0.11)	6.43 (0.27)	27.6 (2.1)	4.96 (0.63)	3.17 (0.21)
LP40H	51.8 (2.8)	2.03 (0.10)	6.30 (0.33)	27.0 (0.7)	4.59 (0.36)	2.87 (0.10)
LP54U	64.2 (5.3)	1.84 (0.19)	7.55 (0.55)	37.7 (1.7)	5.29 (0.25)	4.28 (0.20)

[a] Total sample thickness was used to calculate tensile strength, strain to failure, and modulus of elasticity; that is, for the gummed papers, the adhesive thickness was included. Standard deviations are in parentheses.

failure or on any of the CD properties; the dry gum adhesive LP40 had much the same effect. When compared to the properties of its substrate, LP54U, the dextrin adhesive LP54G reduced the strength and stiffness in both directions but had little effect on either strain to failure.

The tensile properties of the papers indicate that the strength and modulus of the adhesives were significantly less than the MD strength and modulus of the papers but were similar to the CD strength and modulus of the papers.

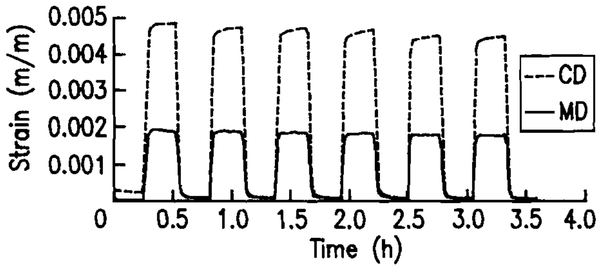

Figure 2. Typical hygroexpansive strain measurement. Note the rapid dimensional stability and repeatability of the measurement.

Results and Discussion

Figure 2 shows the results of a typical hygroexpansivity test for LP40. As expected, the hygroexpansive strains in the CD were much larger than in the MD. Also, dimensional stability was reached rapidly because of the lateral restraint system that draws the prescribed RH air through and around the specimen. Because each sample quickly reached dimensional stability, the median strain for each hold period (strain at 7.5 min into the hold period) was used as the equilibrium strain.

Figure 3 shows the effects of repeated cycles on the hygroexpansive strain changes for gummed and ungummed specimens. The hold periods are even numbers for adsorption strain changes and odd for desorption strain changes. For example, hold period 2 indicates that the sample was held at 80% RH. The hygroexpansive strain change for each period was calculated by taking the absolute value of the difference between the median strain from the previous hold period and the median strain for current hold period. Therefore, hygroexpansive strain change was not calculated for hold period 1.

Figure 3 shows that the effect of repeated cycling was small. Therefore, hygroexpansive strain changes for each hold period were averaged to determine an effective hygroexpansive strain change for the test. These tendencies agree with the results of Wink (1961), who found that repeated RH cycles eventually induced a constant hygroexpansive strain change. For the papers examined, the RH cycle from 30% to 80% was insufficient to release a discernible amount of papermaking-induced residual stress. An RH cycle with an upper limit of 90% would allow more relaxation of internal stresses and produce more shrinkage.

To evaluate repeatability, each sample was tested twice, with a 1-week conditioning period between each test. For the materials tested, each specimen had nearly identical hygroexpansivities for the first and second test. Because

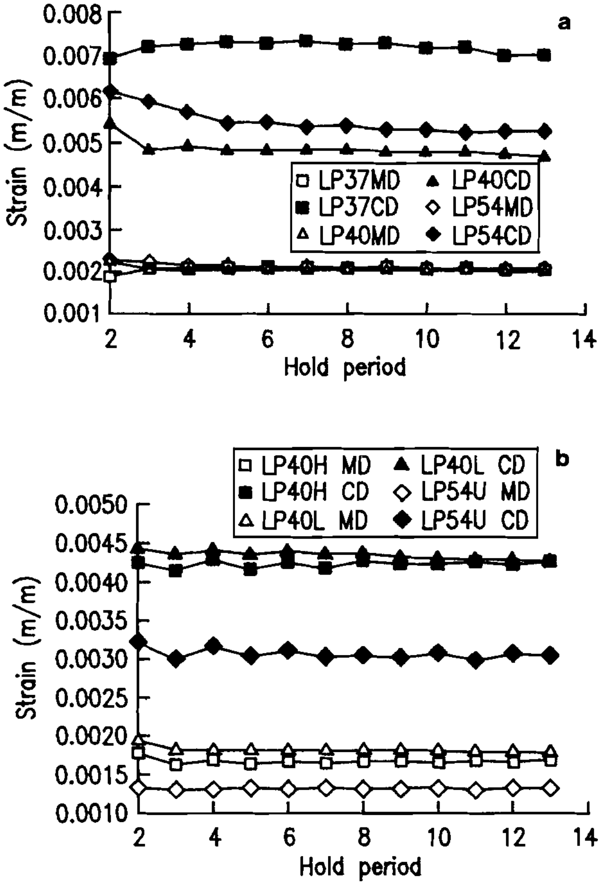

Figure 3. Hygroexpansive strain for each hold period for the (a) gummed and (b) ungummed specimens. As expected, CD has much larger hygroexpansive strain than MD.

the hygroexpansive strain changes appeared to be independent of cycle and test order for the materials tested, the hygroexpansive strain changes for the papers were determined by averaging the hygroexpansive strain changes of all the samples for each paper, regardless of cycle and test. Table 3 shows the measured hygroexpansive strain changes for each material tested in both the MD and CD.

Table 3. Hygroexpansive strains for the materials tested

	Strain ($\times 10^{-6}$ m/m)	
Paper	Machine direction	Cross-machine direction
Gummed		
LP37	2,075 (131)	7,200 (319)
LP40	2,065 (245)	4,891 (401)
LP54G	1,830 (134)	5,781 (294)
Ungummed		
LP40L	1,792 (89)	4,325 (131)
LP40H	1,662 (72)	4,178 (240)
LP54U	1,314 (76)	3,068 (190)

[a] Standard deviations are in parentheses.

Table 4. Hygroexpansive coefficients for each paper

	Coefficient of hygroexpansion ($\times 10^{-6}$/% RH)	
Paper	Machine direction	Cross-machine direction
Gummed		
LP37	41.5	144.0
LP40	41.3	97.8
LP54G	36.6	115.6
Ungummed		
LP40L	35.8	86.5
LP40H	33.2	83.6
LP54U	26.3	61.4

Figure 4 shows the hygroexpansive strain changes for each of the gummed papers. As expected, the CD hygroexpansive strain changes were greater than the MD hygroexpansive strain changes. The MD hygroexpansive strain changes for the ungummed papers were very similar.

Figure 4 also shows the hygroexpansive strain changes for the ungummed samples. Note that LP40L has slightly higher hygroexpansive strain change in both CD and MD than in LP40H, and that LP40H has higher hygroexpansive strain change in both CD and MD than in LP54U. Figure 5 shows in-plane hygroexpansion strain change compared with density. Clearly, CD is

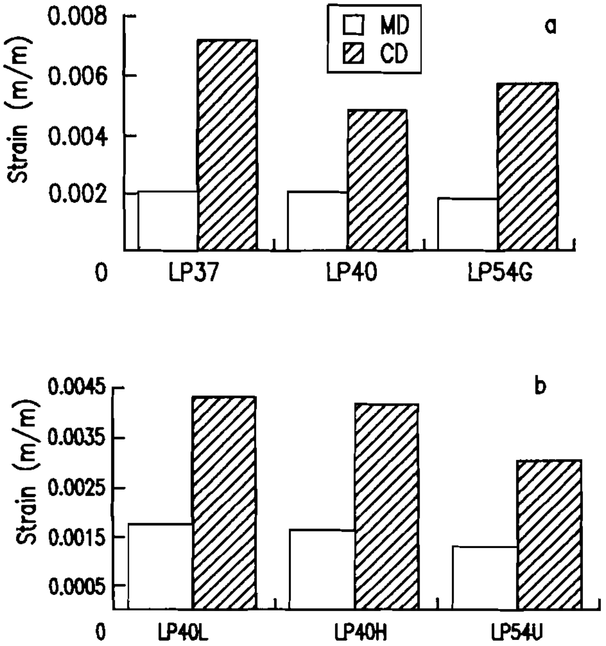

Figure 4. Comparison of hygroexpansive strain of (a) gummed and (b) ungummed papers.

more affected by density than MD, but both have larger hygroexpansive strain changes at lower densities and are well represented by linear models.

Salmen and others (1985) found that for freely dried sheets, hygroexpansivity increases with increasing density, and for paper dried under restraint, hygroexpansivity decreases slightly in the MD and is unaffected in the CD. However, most commercial paper machines cannot provide the necessary restraint to show this result. Our results agree with those of Lorey and Libby (1954) and de Ruvo and others (1976) who found that hygroexpansion decreases with increasing density. However, note that the opposite is true for volumetric hygroexpansion (Stamm, 1964). Therefore, measurement of paper density prior to converting (printing) processes would provide an estimate of hygroexpansion.

Table 4 gives the calculated hygroexpansion coefficients (values in Table 3 divided by 50) for each material. The coefficients for the ungummed papers are near the range described by Larocque (1936), which are 20 to 40 ($\times 10^{-6}$/% RH) for MD and 77 to 237 ($\times 10^{-6}$/% RH) for CD.

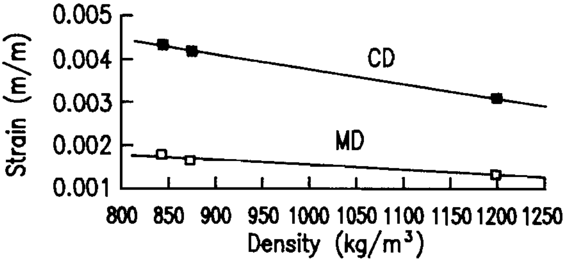

Figure 5. Relationship between density and hygroexpansive strain. Densification improves dimensional stability.

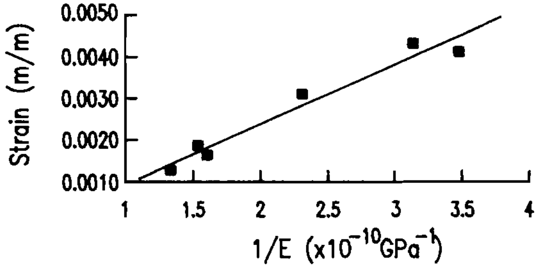

Figure 6. Relationship between modulus of elasticity and hygroexpansive strain.

Schulgasser (1987) developed a relationship showing that, in the elastic region, the hygroexpansion in a given direction is proportional to the inverse of modulus of elasticity in that direction. Figure 6 illustrates the validity of this relationship for the ungummed stamp papers examined in this study. A corresponding figure for gummed stamp papers is not shown, because the adhesives were different for each paper. To develop a relationship for the gummed papers, further investigation of several papers with the same adhesive is required.

Figure 7 shows the hygroexpansive strain changes caused by the adhesive alone. The hygroexpansive strain changes of the ungummed samples were subtracted from the hygroexpansive strain changes of the gummed samples. The resin dextrin adhesive LP37 produced almost four times as much additional strain than did the dry gum adhesive LP40 in the CD. The dextrin adhesive LP54G also produced much more strain in the CD than in the MD. For each paper, the MD experienced only a small amount of additional

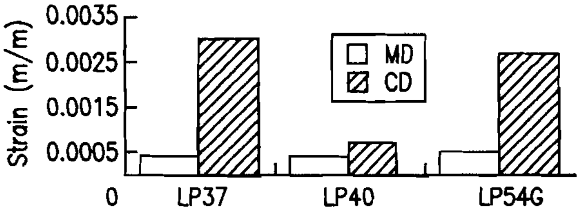

Figure 7. Effect of adhesive on hygroexpansive strain. Adhesive produces more hygroexpansive strain in the CD than in the MD.

hygroexpansivity caused by the adhesive. Observation prior to testing showed that the unrestrained samples would curl, unless restrained, at high humidities as a result of unbalanced sheet construction, that is, differing coefficients of hygroexpansion between the paper and adhesive. It is likely that the CD experienced a larger effect from adhesive than did the MD, because CD is less stiff and unable to resist the expansional forces caused by the adhesive.

Conclusions

Several conclusions follow from this work. The presented method developed for measuring the hygroexpansive strains in paper produces accurate, repeatable results and excellent measurement resolution. In addition, it avoids the limitations of previous methods.

Hygroexpansion was observed to be about twice as large in the CD than in the MD.

The humidity cycles, 30% to 80% RH, did not cause an observed release of papermaking-induced residual stresses.

The in-plane hygroexpansivity for ungummed stamp papers was inversely related to density and modulus of elasticity, confirming Schulgasser's (1987) theory.

Each adhesive produced additional hygroexpansive strain in both directions, but the additional hygroexpansion was much larger in the CD than in the MD. Therefore, adhesives should be chosen carefully in hygroexpansive-sensitive applications.

Acknowledgments

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