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THE IMPACT OF WATER SORPTION ON THE COMPRESSION STRENGTH OF PAPER

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ABSTRACT

The effects of preconditioning, moisture content and relative humidity during adsorption and desorption on the compression strength of paper were evaluated for a kraft liner and an NSSC-fluting over a range of moisture content from 1-23%. The method used was the STFI Short Span test.

In general, the results show that compression strength decreases with increasing moisture content. More specifically, if compression strength is evaluated as a function of moisture content, the data points fall on a single curve for both adsorption and desorption. This result is independent of the moisture history of preconditioning of the sample.

If compression strength is evaluated as a function of the relative humidity of the test environment, the moisture history and preconditioning both exert a large influence on the test result. This indicates that samples of unknown moisture history should be preconditioned in much drier atmospheres than previously recommended.

INTRODUCTION

During its life, a corrugated container is exposed to a variety of environments and loading conditions. It is generally considered that among the mechanical properties of the board, bending stiffness and resistance to flat and edgewise crushing are the most important properties governing the stacking and protective properties of boxes (1-3). These properties of the corrugated board can be related to the elastic modulus and compression strength of its individual plies (4-8).

Over the years, the elastic modulus of paper has been thoroughly investigated in different RH and temperature environments (9-13), but compression strength has received increasing attention only during the past decade. A number of methods have been suggested to measure compression strength (14), but only a limited number of investigations have studied the response of paper to different RH-environments (15-18).

This study was undertaken to analyze the effect of changes in moisture content on the compression strength of a linerboard and an NSSC-fluting. It will be shown that the relationship between compression strength and moisture content is completely reversible.

SORPTION AND TESTING STRATEGY

The testing scheme used in this investigation is shown in Fig.1. Production samples of 200 g/m^2 unbleached kraftliner and 150 g/m^2 NSSC-fluting were obtained from a commercial source. Starting from a climate of 20% RH, 23°C, these samples were tested at discrete RH-levels during adsorption and desorption as shown by the rings in the figure. The temperature was maintained at 23°C in all cases.

In addition, two well-defined preconditioning procedures were performed:

1) Samples were exposed to hot air at 105°C for 1hour prior to the starting point at 20% RH in Fig 1.

2) Samples were exposed to steam at approximately 100°C for 1 hour prior to desorption from 95% RH.

Tests were also performed in one very dry climate by embedding the samples in silica gel, and a few very damp climates by placing samples between wet blotters for various times.

The moisture content was determined according to standard procedures (19).

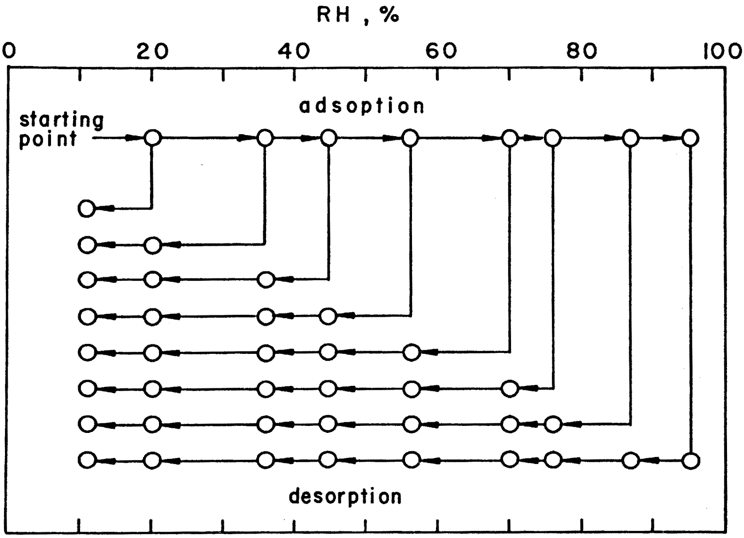


Fig 1—Testing scheme. Starting point is 20% RH

Compression strength was evaluated using the STFI short span test, in which bowing and buckling of the specimen are minimized (20).

RESULTS

Moisture Isotherms

Fig. 2 shows the moisture isotherms for the NSSC-fluting. The solid curves represent adsorption after preconditioning in air at 105°C, and desorption after preconditioning in steam. The well-known hysteresis curves were obtained, with similar isotherms being obtained for the kraftliner. The maximum difference in moisture content obtained by adsorption and desorption at 50% RH is about 2% for fluting and 2.5% for liner.

Adsorption for samples which had been brought to 20% RH from an undefined climate follows the dotted line starting from point A. Point B is the turning point at 95% RH, from which desorption follows the other dotted line.

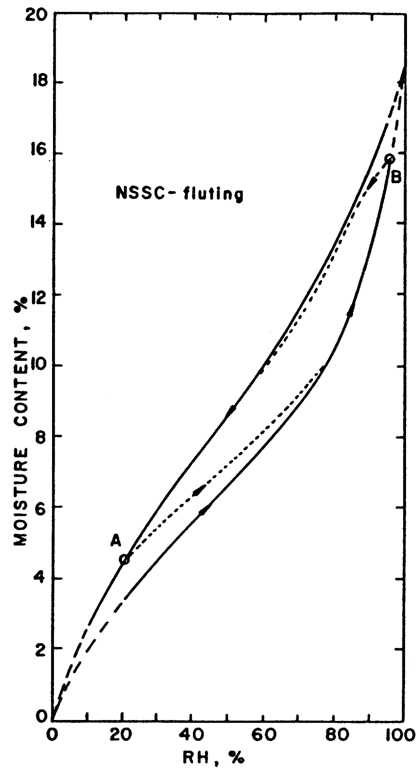
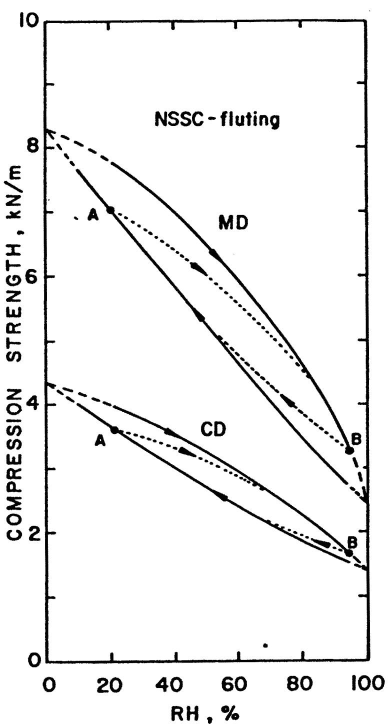


Fig 2—Moisture isotherms at 23°C for NSSC-fluting

Clearly, the dotted isotherms follow a significantly different course, from which it can be concluded that preconditioning is of great importance when comparing the moisture content of samples with an unknown history.

Compression Strength Versus RH

The compression strength decreases with increasing RH, as shown in Fig. 3. The two test samples exhibit hysteresis behaviour which has a similar form to the moisture sorption curve in Fig. 2. Solid lines and points A and B refer to the same conditions as in Fig. 2. The maximum difference in compression strength obtained by adsorption and desorption at 50% RH is about 15%.



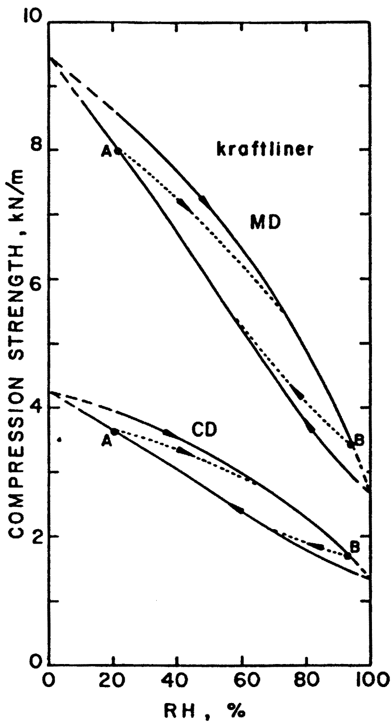
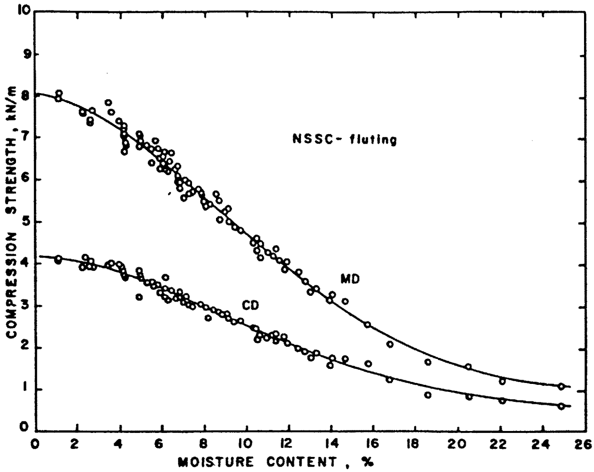


Fig 3—Compression strength versus RH for NSSC-fluting and kraftliner

Note that the sheet moisture content is higher during desorption than during absorption when compared at equal RH. Consequently, the compression strength at a given RH is lower during desorption than during adsorption.

Compression Strength Versus Moisture Content

Fig. 4 shows the MD and CD compression strength versus moisture content for the two test samples.



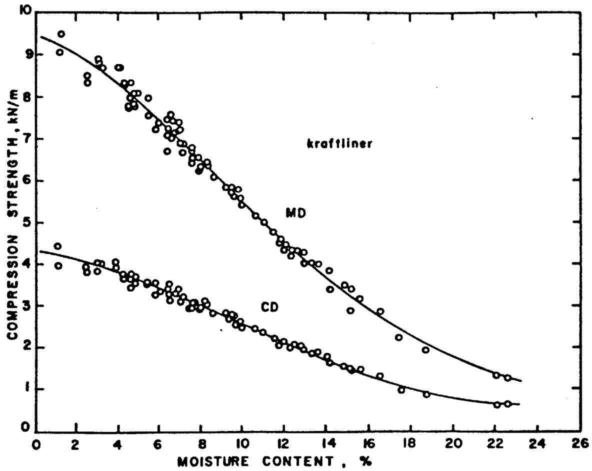


Fig 4—Compression strength versus moisture content for NSSC-fluting and kraftliner

The significant result is that all data for a given paper tested in a given direction fall on one single curve which has been fitted by a 4th degree polynomial. There is no discrepancy between values obtained by adsorption or desorption.

Within the moisture content range of 5-13%, all the curves may be approximated by straight lines passing through their inflection points. Using 8% moisture content as a reference, the relative change in compression strength is approximately 8% for each percentage point change in moisture content.

In a separate investigation, these slopes were evaluated for a number of liners and flutings, manufactured from both waste paper and virgin furnishes. The compression strength moisture sensitivity varied between 6-12% per % moisture content, which suggests that this parameter may be an important property of paper in relation to its end-use.

The sensitivity of the compression strength of paper to sheet moisture content is about the same order of magnitude as the sensitivity of the elastic modulus. The compression strength is more sensitive than tensile strength, where a maximum slope of about 6% per % moisture content has been reported over the same range of moisture content (9,11,17,18).

DISCUSSION

The most significant result from this investigation is that the compression strength of paper is governed by its moisture content, regardless of its moisture history. This has also been shown for tensile strength and elastic modulus (9-13).

If papers of unknown moisture history are compared at equal RH, the paper is stronger if the RH is attained by adsorption rather than by desorption. In order to avoid this discrepancy, it is recommended to precondition the samples in such a way that the moisture history is neutralized. The SCAN standard (21) stated that the preconditioning climate for high precision measurements shall be 25-35% RH and 40°C for 24 hours. However, the results obtained in this investigation indicate that this preconditioning climate may not be dry enough to eliminate the effects of moisture history.

At a theoretical level, the failure of paperboard in compression may be seen as the result of an unstable state of loading and yielding (14,16,22). The two crucial questions are: where is the compression failure initiated, and what constitutes the basic yield phenomenon?

It has been argued that both microfibrils and the matrix material contribute to the compression strength of the individual fibers, and consequently to the compression strength of the paper sheet (16-22).

At the level of the cell wall ultrastructure, the microfibril, which is a slender structural element, and the surrounding matrix of hemicellulose and lignin are a favourable environment for the growth of instabilities or yielding. Furthermore, disordered zones along the microfibril may be envisaged as weak spots in compression loading. The matrix may thus play two roles; it may act as a load-bearing component in the fiber, and it may support the slender microfibrils against buckling.

The effect of moisture content on the compression strength of paper follows from these structural considerations. During drying, the paper undergoes transitional changes which are similar to the rubber-glass transition found in amorphous polymers. During one transitional stage, the microfibrils are "frozen" in a state of stress which is governed by the restraint imposed upon the sheet during drying. This change has been found to occur over a range of 40-70% solids content (12,23,24). A further decrease in moisture content increases the stability of the microfibrils, with a consequent increase in the compression strength of the sheet.

After this stage, the matrix rigidity becomes a controlling factor for the compression strength. During another transitional stage, which occurs in the solids content range of 70-90%, the matrix is "frozen" (12). As drying proceeds, the matrix rigidity increases and leads to further increases in the compression strength.

In the dried state, the sorption of moisture in the RH region will cause a reversible softening of the matrix material, which in turn affects the compression strength in a reversible manner.

The fact that compression strength is more sensitive to moisture content variation than tensile strength follows from considerations of the mode in which the fibers are loaded. In the tensile loading mode, the disordered zones along the microfibril may extend and allow the fiber to carry further loading, thus reducing the relative contribution of the matrix material. It follows that the tensile strength of the sheet will be less affected by variations in moisture content in the RH range (16,22).

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Transcription of Discussion

The Impact of Water Sorption on the Compression Strength of Paper

by C. Fellers and A. Brange

Professor R. Attala IPC, Appleton, USA

I have listened to these two different points of view presented to explain the effects of moisture. I would like to suggest a composite of both. We know that the manufacture of paper involves a substantial amount of mechanical transformation, we also know that it causes some disaggregation among both the cellulosic component and the hemicelluloses. Also, we know that the re-absorption of moisture can bring about re-crystallisation. For example, we have fabricated amorphous celluloses, which are extremely sensitive to moisture as regards the degree of crystallinity. Therefore, I can see no reason why both mechanisms could not be contributing to the phenomena one is observing.

Baum I would like to put forward the model Habeger and Wittsitt proposed because it seems to include elements of this discussion. They claim that there are basically two things which control the compressive strength of materials. One would be the stiffness of the material in the direction of loading and the second would be the connectiveness of the elements, or if you prefer, the out-of-plane shear modulus. It seems to me that what we have been discussing this morning can be described by the use of this simple model. If you have fibres that are weak and you start to load them axially in a well bonded sheet, it is their stiffness which is important. Failure of the fibres loaded in axial compression due to dislocations in the cell wall, as proposed by Page, would lead to compressive failure. In the case of changing moisture content, the degree of connectiveness between fibres would be the predominant factor. Therefore, you would expect that compressive strength is far more sensitive to moisture content than is tensile strength, because increasing moisture would lead to a decrease in bonding and a lower out-of-plane shear modulus.

Dr. C. Fellers What you have said may be very useful on a practical level, for instance, if you want to measure these properties on line on the paper machine to control compression strength. The compression failure mechanism is, in my view, not an elastic phenomenon. What I am seeking is an explanation on a more fundamental level. In my Thesis on compression strength, I point out that the compressive failure is not an elastic but rather a yield phenomenon. For example, if you look at permanent strain as function of applied strain, it is much higher in compression than in tension all the way up the stress-strain curve, which demonstrates that local yielding in the fibres in fact triggers the final failure of the whole sheet. This is also seen from SEM photos of fibres which have been subjected to compression loading prior to gross failure of the sheet. You then see local kinks, i.e. yielding, at the fibre walls.

Caulfield Both you and Dr. Salmén seem to favour an explanation based on hemicellulose. I would like to point out that exactly the same phenomena occur for cotton where there is no hemicellulose. Secondly, I would like to caution that some people might get the idea that hysteresis can be avoided by just plotting isotherms versus moisture content instead of relative humidity. Thermodynamics does not work that way.

Atalla Could I just make a point regarding Dr. Caulfield's comments. Cotton when subjected to mechanical deformation behaves in its aggregation characteristics in a manner not unlike that of hemicellulose. So cotton is, in this sense, not behaving in a manner contrary to what was described this morning for wood pulp fibres.

Prof. G.G. Allan University of Washington, Seattle, USA

I understand that STFI has done a great deal of work on improving the compressive strength of boxes by the inclusion of phenolic resins. Can the results you have reported today be connected with that work?

Fellers Suppose we have this strong and stiff cellulose microfibrill including both crystalline and disordered regions. In order to get wet strength in compression then you need something to stiffen up the disordered regions. You would require a low molecular weight resin to achieve that, whereas a high molecular weight resin would not do the job. In fact, putting in a phenolic resin marginally increases the tensile strength, while the compressive strength reaches the level of tensile strength or higher, even in moist climates. This was published by de Ruvo. Unfortunately, the sheet becomes extremely brittle.