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PAPER TESTING AND STRENGTH CHARACTERISTICS

D. F. Caulfield, Research Chemist
D. E. Gunderson, Research General Engineer
USDA Forest Service, Forest Products Laboratory,
One Gifford Pinchot Dr., Madison, WI 53705-2398
U.S.A.

ABSTRACT

The mechanical and strength properties of paper reflect the intrinsic chemistry, morphology, and structure of the individual fibers as well as the network structure of the paper. These properties also reflect those chemical changes that cause the paper to lose its permanence with time. Strength properties can thereby serve as indicators of the permanence of paper, even when the nature of the chemical changes responsible for the deterioration remains unknown. Careful monitoring of strength properties can also be used for evaluating the effectiveness of treatments for aging. This requires test methods and procedures that have been proven to be reliable. TAPPI test methods for evaluating the properties of tensile strength, bursting strength, tearing resistance, and folding endurance are discussed in terms of the fundamental characteristics of paper on which they depend. Also discussed is the concept of strength-property monitoring in conjunction with accelerated-aging studies. Environmental condition, primarily relative humidity, can have a great effect on measured strength properties. Testing methods are being developed that employ a greater degree of control over environmental conditions and rates of loading. The fundamental mechanical properties of paper revealed by these methods promise a more complete description of the behavior of paper in environments of changing relative humidities.

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INTRODUCTION

The permanence and durability of paper were first distinguished in 1926 (1). Permanence is basically a measure of the chemical stability of paper. Durability, an the other hand, is primarily a function of the performance of paper; it is a measure of the stability of its physical and mechanical properties. A paper that is given rough treatment over a short time should be durable, but little Concern need be given to permanence. A paper that is meant to last for a century must be compounded for chemical stability. Such chemical stability can be enhanced by storing paper at a low temperature; at a constant, low relative humidity; in the dark; and in an atmosphere free of pollutants. But if the paper is also to be used--read, handled, folded, etc.--its mechanical durability is also important. Obviously, permanence and durability are not independent of each other, but rather intimately related. This relationship is so intimate, in fact, that durability or the stability of the strength and mechanical properties of paper has become the most useful indicator of its permanence or chemical stability.

Understanding the mechanical properties of paper in fundamental terms is a difficult task, and it is an area of intense study in many laboratories around the world. The ultimate aim of such studies is to provide a complete understanding of the relationships between the structure and properties of paper and papermaking procedures, so as to be able to tailor-make paper properties to meet any desired end-use requirements. Unfortunately, this goal has not yet been achieved. Instead, an alternate approach is often required; that of assessing the utility of paper to meet a desired need based on its ability to satisfy the requirements of some specified test or tests. Usually such tests are dependent upon particular test instrument designs and carefully defined procedures as to size of samples and other variables. Such tests often measure complex properties of paper that arise from a combination of several of its fundamental characteristics.

We will look at four strength properties of paper and the TAPPI test methods that are typically used to evaluate these properties. These tests evaluate the (1) tensile strength, (2) bursting strength, (3) tearing resistance, and (4) folding endurance of paper. Each of these properties, especially folding endurance, which is a fatigue strength property, has found wide acceptance as a measure of the permanence of paper. We will also discuss how environmental conditions, especially relative humidity, affect test results, and how accelerated aging coupled with strength testing provides a means of estimating permanence. Finally, we will mention recent developments of mechanical testing that incorporate a greater degree of environmental control for more accurately appraising of performance characteristics of paper under actual use conditions.

TESTS OF STRENGTH PROPERTIES

Tensile Strength

Tensile strength can be described by stress-strain graphs and measured by TAPPI tests T-404 and T-494. Stress-strain curves provide a fundamental engineering description of the mechanical behavior of paper when subjected to tensile stress. TAPPI method T-404 measures tensile breaking strength end elongation of paper and paperboard using a pendulum-type tester, and T-494 measures tensile breaking properties of paper and paperboard using constant rate of elongation appartus.

Fundamental behavior of paper in tensile loading. Figure 1 is a generalized illustration of the stress-strain tensile behavior of machine-made paper. The graph represents the behavior of two strips cut from the same sheet of paper in two directions: machine direction (MD--the direction in which the paper moves during manufacture) and cross-machine direction (CD--the direction at right agles to the machine direction). These stress-strain curves provide a fundamental engineering description of the mechanical behavior of paper strips when subjected to tensile stresses that distort or elongate the strips as they are pulled to failure by clamps attached at their ends. The *x* axis is a measure of the tensile strain or elongation of the sample. It is a dimensionless quantity that is defined as the change in length divided by the original Length of the strip. It is most often expressed as a percentage and called percent strain or elongation. The y axis is a measure of the tensile stress, which is defined as the tensile force applied to the sample ends divided by the cross-sectional area of the paper strip. Typical units of stress are pounds per square inch in the English system or Pascals, the preferred SI unit, which represents the force of one Newton (or 10^5 dynes) per square meter.

In the stress-strain plot (starting from the origin), as increasing stress is applied to a strip of paper, the strain or elongation of the strip increases linearly. The initial straight line section of the stress-strain curve, which is characteristic of elastic materials, has a slope that defines the fundamental property known as Young's modulus. Young's modulus is a useful concept in engineering design because it is the material characteristic which, along with the thickness of the material, determines stiffness. Further out on the stress-strain curve, the plot shows an increasing tendency of curvature towards the x axis. This nonlinear behavior of the stress-strain curve for paper indicates the inelastic or viscoelastic character of paper. It is the dual nature of paper, exhibiting both elastic and viscoelastic properties, which makes its behavior so complex.

As stress is further increased, the point of failure is reached, and the paper strip fails or ruptures. The maximum value of the stress that occurs at failure is a measure of the tensile breaking strength of the paper. The maximum value of the strain, or the elongation at rupture, is a measure of the percentage of stretch that the paper can achieve. Typically, for machine-made paper, both Young's modulus and breaking strength measured in the machine direction are 2 to 4 times the values in the cross-machine direction (2). Conversely, the machine-direction value for percentage of stretch may typically range between 0.25 and 0.5 times the percentage of stretch in the cross-machine direction. The differences in the properties of paper in these two directions arise from the tendency of the fibers to align preferentially in the machine direction and from the stretching of the paper web in this direction during manufacture.

Another fundamental measure of the tensile strength properties of paper is represented by the area under the stress-strain curve. This area represents the work expended to cause rupture of the tensile strip of paper; this work is called the tensile energy absorption (TEA) (3). Even though the breaking strength of paper in the machine direction is greater than In the cross-machine direction, it may require more work to break a tensile strip in the cross-machine direction because its greater stretch percentage makes the TEA greater in the cross-machine direction than in the machine direction. In certain instances, TEA can prove to be a significant property relating to durability. Tensile energy absorption is a measure of the ability of paper to absorb energy under variable loading conditions and can be used to gauge the durability of papers chat are subjected to repetitive straining. A stress-strain curve in which the initial slope (Young's modulus) is high, where there is little curvature, and where the value for elongation to break is low, indicates a brittle material. A tough material is one that exhibits more viscoelastic behavior, a pronounced curvature, and a high elongation to break.

TAPPI tensile strength tests. TAPPI tests T-404 and T-494 are useful in evaluating the tensile properties of paper (4). TAPPI T-494 enables the simultaneous evaluation of three properties for the same test specimen: tensile breaking strength. stretch or elongation at break, and TEA (Fig. 2). Method T-404 allows only the evaluation of tensile breaking strength and elongation at break, but the test apparatus is considerably less costly. TAPPI cautions that the two methods, T-404 and T-494, are not strictly comparable because different instruments are used. These tests give similar results for tensile strength and elongation at break only when similar testing conditions apply.

For the purposes of the TAPPI tests. tensile strength is reported with different units than indicated earlier. TAPPI tests define tensile stress as the force per unit width of the test specimen. This differs from the usual engineering definition of stress, which is force per unit cross-section of the test specimen. This difference arose historically because of the difficulty of accurately measuring the thickness of test specimens of paper (5). Similarly, for the purposes of test T-494, TEA is defined in terms of energy per unit area, which differs from the usual engineering definition of energy per unit volume. Because TAPPI defines stress as force per unit width, it is possible to express tensile strength in terms of breaking length by dividing TAPPI tensile strength by grammage (or basis weight). Breaking length is the calculated upper limit of Length of a uniform paper strip that would support its own weight if it were suspended at one end. Breaking length is a convenient measure for comparing the tensile breaking strength of papers of varying grammages. Values of the tensile properties of offset, rag bond, and newsprint of typical grammages are shown in Table 1 (2).

Tensile test results reflect the intimate structure of paper and the properties of its Individual fibers. The dimensions and strength of the individual fibers, their arrangement, and the extent to which they are bonded to each other are all important factors contributing to test results. Papers made with long fibers generally have higher tensile strength properties than paper made of short fibers. However, the extent of interfiber bonding is considered the most important factor contributing to tensile strength properties (6).

Page has provided a useful theory for assessing the relative contributions of individual fiber strength and interfiber bonding to tensile strength properties (7). To separate the effects of fiber strength and bonding, Page's theory requires the measurement of zero span tensile strength. The zero span test is a tensile strength test in which the jaws of the tensile tester are placed as close as possible to each other, that is, with zero separation. The principle behind the zero span test is that the individual fibers span the gap between the jaws, and the tensile breaking strength indicates fiber strength as opposed to bond strength. The method provides can index of the ultimate strength of the longitudinal structure of individual fibers in the test specimen. The ratio between the normal tensile breaking length and the zero span breaking length provides an index of the cohesiveness of fibers in the sheet. Although TAPPI has not yet established a zero span test for papers. TAPPI method T-231, "Zero Span Breaking Length of Pulp," is available (4). Commercial instruments are also available for measuring the zero span tensile strength of paper.

Bursting Strength

Bursting strength is perhaps the most commonly measured strength property of paper. The test apparently originated from the oldtime practice of the papermaker who, in a hands-on quality control evaluation of paper strength, would attempt to push his thumb through the sheet. TAPPI method T-403 is the official test used for measuring the bursting strength of papers with thicknesses up to 0.6 mm (4). It is also commonly known as the Mullen test. Similar TAPPI tests have been adopted for measuring the bursting strength of heavier paperboards and corrugated fiberboard. TAPPI test T403 involves clamping a sheet of paper firmly between two steel plates. These plates are provided with circular openings, and a rubber diaphragm in one plate opening seals off a chamber that can be pressurized by a fluid (Fig. 3a). As the chamber is pressurized, the bulging of the rubber diaphragm is resisted by the overlying clamped paper sheet. Pressure is increased, at a specified rate, until the bulging diaphragm causes rupture of the paper sheet. A pressure gauge on the instrument provides a measure of the bursting pressure needed to rupture the paper. Bursting strength is reported as pressure in pounds per square inch (lb/in^2) or in kilopascals (kPa), the preferred SI unit.

Because of the symmetry of the test specimen, there is no possibility of assigning machine direction end cross-machine direction values. However, by observing the nature of the rupture pattern on the test specimen, it can be seen that the differences between properties in machine direction compared to cross-machine direction do influence bursting strength. The burst failure usually results in a roughly “H”-shaped tearing pattern in the specimen (Fig. 3b) (3). The orientation of the “H” with the two directions of the machine-made paper indicates that failure initiates in tension along the line at right angles to the machine direction. This occurs in spite of the fact, as shown in Table 1, that tensile strength of paper in the machine direction is greater then that of paper in the cross-machine direction. As the specimen bulges in the bursting test, it is strained equally in both directions. The specimen reaches its strength limit in the machine direction at a lower st~-ain than it does in the cross-machine direction. This indicates that stretch is probably the limiting factor (rather than tensile strength) in determining bursting strength. Tensile breaking strength and bursting strength exhibit good correlation, and those fiber properties and papermaking practices that enhance tensile breaking strength tend to also enhance bursting strength (8). For two papers of equal tensile breaking strength, however, the one with the greater stretch will consequently exhibit the higher bursting strength.

Bursting strengths of three typical papers are shown in Table 2 (2). It is more meaningful to compare bursting strength of papers of differing grammages in terms of burst index. Burst index is obtained by dividing the bursting strength in kPa by the grammage of the paper in g/m^2; burst index values are included in Table 2.

Tearing Resistance

The most commonly used tearing test, T-414, also often called the Elmendorf tear test, measures the internal tearing resistance of paper rather than the edge-tear strength of paper, which is described in T-470 (4). Internal tearing resistance is a measure of the force perpendicular to the plane of the paper necessary to tear a single sheet through a specified distance after the tear has already been started. Edge-tearing strength (T-470) is a measure of the force needed to initiate a tear. The force needed to initiate a tear may be several times the force needed to propagate the tear once it is started. This is commonly known to anyone who has experienced the difficulty of opening a cellophane bag, which, once nicked, tears open easily. Those papers and other film materials that exhibit high tensile stretch or elongation to break also exhibit high edge-tearing strength. High stretch makes it difficult to localize or concentrate stress in a sufficiently small area so that a tear can be initiated.

The Elmendorf method (T-414) measures tearing resistance of paper perpendicular to the plane of the sheet or when paper is torn in the out-of-plane mode (Fig. 4). This is the mode of tearing used for example when deliberately tearing strips of newspapers. The out-of-plane tearing mode is to be distinguished from the in-plane tearing mode. An instance of in-plane tearing is the separation of computer printout sheets along a perforation while both sheets are held on the surface of a desk. In-plane tearing is representative of the tearing failure that can occur during the transport of a paper web through a printing press. The out-of-plane tearing mode, used in the Elmendorf test, resembles the type of tearing that occurs when a nicked sheet in a book is accidentally torn by a reader while turning pages.

During actual testing, several sheets are torn simultaneously in the Elmendorf apparatus, and the work is measured. The work needed to tear a single sheet of a given length is determined by a calibration procedure. When the unit of work is divided by length, the tearing force is obtained.

The work needed to tear paper is only a fraction of the TEA or the work required for rupture in a tensile strength measurement. This is because the tearing action directs a stress concentration at the pex of an advancing tear, and the route that the tear takes will tend to be the course of least resistance. The work done in tearing is made up of two main contributions: (1) the work needed to sever individual fibers and (2) the work needed to pull out unbroken fibers from their surrounding networks. Van den Akker et al. (9) have shown that, in general, less work is needed to sever a fiber than to pull a fiber from the sides of a tear. Becuase short fibers are obviously easier to Pull out than long fibers, papers made of long fibers show much better tearing resistance than those made with short fibers. As interfiber bonding increases in a sheet of paper, a fiber lying in the path of an advancing tear becomes more likely to sever than to pull out. As bonding is improved, stress at the apex of the tear is more concentrated and is less readily shared with the rest of the structure. Consequently, tearing resistance usually shows an inverse correlation with both tensile strength and bursting strength (10). Those papermaking processes that enhance interfiber bonding, such as beating, improve tensile and bursting strength, but tend to decrease tearing resistance.

The tearing resistance of offset paper, rag bond, and newsprint are shown in Table 3 (2). The tearing resistance is reported in either grams-force or millinewtons required to tear a single sheet. Table 3 also lists the tear index, the recommended measure of tear for comparing papers of differing grammages. Tear index is obtained by dividing the tearing resistance measured in units of millinewtons (mN) by the grammage of the paper in units of grams per square meter (g/m^2).

Folding Endurance

A folding-endurmce test is used to measure the ability of a paper to maintain its strength after repeated folding. There are two TAPPI test methods (4) used for evaluating this property: T-423, which employs the Schopper tester, and T-511, which employs the MIT tester. The essential differences between these methods arise from the design and function of the test apparatus. In both methods, the test specimen is held under tension and subjected to repeated folding; the number of folds necessary to cause failure is taken as a measure of folding endurance. The Schopper instrument operates at a rate of 120 double folds per minute. A reciprocating motion folds the specimen by looping it snugly around a small cylindrical surface. During the reciprocating motion, the tension applied to the 15-mm-wide test specimen fluctuates between approximately 800 g to 1 kg (7.8 to 9.8 N) in normal operation. The MIT apparatus applies a double fold of 270° (±135°) at a rate of 175 double folds per minute by means of an oscillating jawlike clamp (Fig. 5). The applied tension to the 15-mm-wide specimen is maintained constant during the folding action by means of a spring device. In normal operation, the applied tension in the MIT test is fixed at 1 kg (9 .81 N). However, this tension may be adjusted depending on the strength of the paper being tested. The advantages of the MIT tester over the Schopper tester are that the MIT allows a wider range of paper thicknesses to be used, and the calibration and adjustment of the MIT instrument is less demanding than that of the Schopper. Test results obtained with these methods are not interconvertible because the folding operation is not the same in both cases. The MIT method is viewed as more closely resembling the repeated action of opening and closing a book, and it has been found especially valuable in measuring the deterioration of paper with aging (11).

Folding endurance may be considered a modified tensile strength test because the test specimen is under a tension that eventually causes failure. But the results of the test are affected as much by the flexing ability of the paper as by its tensile strength. Test results reflect the combined elastic and viscoelastic properties of the paper. Lack of folding endurance can result from lack of sufficient fiber length, inadequate fiber bonding, or brittleness. As a rule, rag pulps produce paper high in folding endurance, whereas groundwood papers and heavily filled papers show poorer folding endurance. In the early stages of beating, folding endurance increases as does tensile strength. As beating proceeds, however, folding endurance eventually decreases as interfiber bonding increases the brittleness of the paper.

Folding endurance can be measured in both machine and cross-machine directions (for this test, machine direction signifies the line of fold perpendicular to the machine direction). As a rule, machine direction folding endurance is higher than cross-machine direction folding endurance, which reflects the higher tensile strength usually exhibited by the machine direction. For those papers for which cross-machine direction folding endurance values exceed machine direction values, flexibility or the viscoelastic characteristics of the paper play a more significant role then inherent tensile strength. Table 4 contains the MIT folding endurance values of three typical papers (12). Since, as a general rule, folding endurance increases with basis weight or grammage up to a certain optimum after which it decreases, there is no significance to a concept of "fold index" as there is to tear index and burst index.

One characteristic of folding-endurance tests is that the results vary widely even on presumably identical samples. The source of this high variability stems from the very small area of the sample that is folded. Failure is forced to occur at a specific location rather than at the naturally weakest point in the test strip, as in normal tensile strength measurement. For the folding endurance test method to meet the necessary precision requirements, the TAPPI method now recommends that folding endurance be reported as the logarithm (base 10) of the number of double folds. However, the standard does permit results also to be reported as number of double folds.

ENVIRONMENTAL EFFECTS

TAPPI test methods require strict observance of standard conditioning and environmental conditions during the strength testing of paper. These are covered in TAPPI method T-402. Some properties of paper show a dependence on temperature, and all strength and mechanical properties of paper are strongly influenced by relative humidity. The standard testing environment is 23.0 ± 1.0°C and 50.0 ± 2.0 percent relative humidity. Conditioning the sample for a time in the same environment before testing is required to ensure moisture equilibration of the specimen. Because of the phenomenon of hysteresis, in which the moisture content of a material depends somewhat on its previous history, a preconditioning step is also required. Method T-402 suggests a preconditioning environment between 22 to 40°C and a relative humidity between 10 and 35 percent. Keeping test specimens for a period of time at this lower relative humidity, before equilibrating in the standard test environment. ensures that the effects of their different histories will be minimized.

If it is impossible to maintain the standard humidity conditions, the measured strength properties can exhibit marked differences. Figure 6 demonstrates the typical trends and extents of the differences in ordinary strength properties that one would expect over a range of relative humidities (from 15 to 85 percent) as compared to standard conditions (8). As humidity and the moisture content of the paper increase, the general trends appear to reflect two interacting tendencies: (1) increasing moisture improves individual fiber strength by increasing the viscoelastic character of the fiber, increasing fiber stretch, and allowing a more uniform distribution of stresses to take place, and (2) increasing moisture content competes for bonding sites in the fiber network and interferes with the natural bonding between fibers to weaken the network structure.

Typically, tensile strength measurements tend to show a slight increase with relative humidity up to a level of about 35 percent. As relative humidity further increases (above 35 percent), tensile strength shows a continuous decrease. The initial increase is presumed to arise from a better ability of stresses to be distributed throughout the stressed paper, but above an optimal level the loss of interfiber bonds becomes the predominant effect (8). Bursting strength shows a similar trend, exhibiting a smaller maximum than tensile strength, again around 35 to 40 percent relative humidity. At higher relative humidities, the drop in bursting strength is not as great as the drop in tensile strength. This is probably because improved stretch acts to counter the loss in strength attributed to the loss in interfiber bonding. Bursting strength is a comnlex property influenced by the combination of tensile strength end elongation to break, which moisture affects in different directions. (Moisture acts to lower tensile strength but to increase elongation or stretch.) Thus, of the strength tests, bursting strength is affected least by changes in relative humidity.

Tearing resistance generally shows a continuous increase with increasing relative humidity over the range of relative humidities (15 to 85 percent). For every percent increase in relative humidity, there is an approximate 1 percent increase in tearing resistance. The increased stretch and viscoelastic character caused by the increased moisture content helps delocalize and distribute the stress at the tearing point, and promotes fiber pullout rather than fiber breakage as the dominant mode of failure (10). At very high humidities (above 85 percent) or when paper is wetted, tearing resistance also decreases because of the ultimate disruption of the interfiber network bonds caused by the water. The loss in the tearing resistance of paper on wetting, however, is not as great as the loss in tensile strength that occurs under the same conditions.

Folding endurance is the strength property of paper that is most affected by relative humidity. Folding endurance tends to show an increase of between 1 and 5 percent for every 1 percent increase in relative humidity over the range of 15 to 85 percent relative humidity. This increase reflects the increase in flexibility and vlscoelascic character caused by the increasing moisture content. At very high humidities, the tensile load that is applied to the fold specimen becomes the limiting factor, and fold-endurance measurement, too, shows a dropoff near saturation. Because folding endurance is the strength property that exhibits both the greatest variability in measurement and the greatest sensitivity to moisture content, careful humidity control and proper conditioning of specimens are essential for reliable folding-endurance testing (13).

Sorption of moisture with changes in relative humidity also causes a significant dimensional change in paper, in both in-plane and thickness directions. These changes are attributed to shrinking and swelling of the individual fibers and to release of strains built into the paper during the initial drying process. The extent of dimensional change is variable, but a gross in-plane change of 1 percent is not uncommon in the change from 25 to 90 percent relative humidity. Perhaps more significant is the fact that the dimensional change can vary significantly over the sheet, leading to sheet curl and patterns of local buckling termed cockle. New instrumentation is being developed to evaluate dimensional stability and curl (14).

ACCELERATED AGING

Two indirect indicators of the chemical changes responsible for lack of permanence are the discoloration of paper end the loss of strength properties that occur with time. The reasons for the loss in strength with aging are not completely understood, but they are presumed to be directly related to the chemical and/or structural changes that occur at the molecular level. Because of this presumption, researchers have felt justified in applying concepts of chemical kinetics in quantifying the effects of aging (11). In the chemical kinetics approach, the loss in strength property with time is used to characterize the rate of deterioration of the material. Obviously, the best way of measuring stability of strength properties is by natural aging. But realtime studies are an impractical and costly method for assessing the long-term use potential of paper. Techniques of chemical kinetics, on the other hand, provide a means of effectively accelerating the natural aging process. According to the Arrhenius kinetic theory, the rate of an ordinary chemical reaction will be accelerated by approximately a factor of two if the temperature at which the reaction is run is raised by 10°C.

Since it is usually not possible to describe a normal aging environment, TAPPI has proposed two provisional methods that simulate two different aging environments (4). Method T-453 describes a method for evaluating the effect of dry heat on the properties of paper, and T-544, a method for evaluating the effect of moist heat on the properties of paper and board. Knowledge of the environment in which the paper would likely be stored aids in selecting the most appropriate type of accelerated-aging environment. It is known that moisture greatly accelerates the aging of paper, but the rate at which this increase occurs varies greatly depending on the type of paper. Therefore, dry-heat aging of paper is less sensitive and probably does not rank papers in order of stability as accurately as moist-heat aging. However, dry-heat aging is considerably easier to accomplish. The older dry-heat method utilizes only a forced ventilation oven that is maintained at 105°C. Test specimens in the oven need only be shielded from direct radiation from the heating elements. The moist-heat method utilizes laboratory apparatus devised by Graminski for maintaining an environment of 90°C end a relative humidity of 25 percent. Because of the demanding humidity control (±1 percent), temperature must be maintained at an accuracy better than 0.5°C (preferably 0.1°C). With both methods, papers are maintained in the specified environment for varying lengths of time; 24, 48, 72 end 144 hours. Each specimen, after appropriate conditioning to the standard test environment, is tested by the TAPPI test method of interest. Test methods employed to evaluate the effects of aging typically may include brightness (T-452), pH (T-509), copper number (T-430), and sodium hydroxide volubility (T-212), in addition to any of the strength tests mentioned previously. The tested property indicates a progressive deterioration with time. Since it is impossible to describe a normal environment, TAPPI cautions against relating results from accelerated aging to actual aging. However, the results of several investigations have indicated that accelerated dry-heat aging at 105°C for 72 hours corresponds approximately to "normal" aging of 25 years (15).

A plot of the data as a function of time allows one to calculate the slope or the rate at which the property deteriorates. Figure 7 shows typical shapes of curves encountered during the aging of paper (13). Only rarely is truly straight-line behavior observed. Concave curves occur more often then convex curves. It is common practice to linearize the curve by using logarithmic plots, or by fitting the data to the best straight-line relationship. From the straight-line plots, it is possible to evaluate half-lives that are useful in comparing and ranking the relative stability of different papers end in establishing the effectiveness of chemical treatments to improve permanence.

Some organizations officially recognize the importance of heat aging in helping to determine the suitability of papers for long-term applications. The National Association of State Textbook Administrators, for example, requires that all papers shall meet strength specifications after accelerated aging of 24 hours in a dry oven at 100°C (16).

Folding endurance is the most sensitive test indicator of the deterioration of paper on aging. Changes in folding endurance of paper show up long before there is a change in the tensile strength, bursting strength, or tearing resistance. Both TAPPI method for heat aging of paper suggest that folding endurance is the preferred test method. Until recently, the Library of Congress relied solely on the folding-endurance test after heat aging for demonstrating the improved life of treated paper (17). In addition to folding endurance, the Library now also recognizes the zero span tensile strength test for evaluating the effects of aging. It has been found that this test is especially useful for evaluating degraded book papers, which would not survive even a single fold, but which might still have useful life if restorative treatments could be effective (17). Zero span breaking length is considerably more sensitive as a measure of the effects of aging than is normal tensile breaking length. This suggests that fiber weakening or the creation of weak points along the fiber plays a significant role in heat aging of paper (11).

FUTURE NEEDS

We have reached the point where the performance of paper at standard conditions is fairly well understood, We have also been able to utilize artificial aging environments that simulate some of the changes in physical characteristics of paper that occur naturally with time. But until now we have not been able to measure mechanical and strength properties that are relevant in the world of changing environments, including cyclic humidity. It has long been known that the mechanical properties of paper are different at different humidities, but dramatic changes can also occur under fluctuating or nonsteady conditions. If paper is stressed slowly over a number of cyclic humidity changes, for example, the strain to failure will exceed the strain to failure that would occur under high, but constant, relative humidity conditions. This dramatic acceleration of the distortion of paper induced by long-term stresses in cyclic relative humidities is a prime example of how nonsteady environments influence the mechanical behavior of paper (11). This mechanical effect overlays the chemical changes that are believed to be accelerated by storage in changing humidity environments. With behavior like this, it seems likely that standard, constant-condition tests do not provide an adequate picture of behavior in the world of changing environments. Current research at Forest Products Laboratory seeks to observe and explain the mechanical behavior of paper in transient end cyclic humidity environments (18). For this purpose, instrumentation has been designed and constructed (Fig. 8) that allows for the characterization of the fundamental mechanical properties of paper under conditions of constant or cyclic relative humidity end constant or cyclic stress. Stresses may be applied either in tension or in compression, and strain as well as Young's modulus may be measured continuously or intermittently as a function of time during changes in environment or stress application. Because the dimensions of paper also change with humidity along with mechanical properties, corrections must be made to obtain true strain measurements.

The combined effects of stresses and changing environmental conditions are especially revelant to the performance of paper in packaging materials, where relatively short-term failures are noticeable in cyclic humidity conditions. But these effects may also play a role in the long-term performance of library materials. Paper continually undergoes stresses because of its anisotropic properties and because of changes in temperature and humidity. These induced stresses. although small, may play a role in accelerating the loss of mechanical properties when paper is stored for decades under conditions of cyclic humidity and temperature changes. The instrumentation and methods under development should help quantify these effects and provide a fuller explanation of the connections between the mechanical durability and permanence of paper.

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Table 1. Tensile properties of paper.

Type of paper	Tensile strength (kN/m)		Breaking length (km)		Stretch (percent)		TEA[1] (kJ/m^2)	
	MD[2]	CD[3]	MD	CD	MD	CD	MD	CD
Offset ($107\ g/m^2$)	5.55	3.21	5.30	3.06	2.5	4.1	14.9	15.8
Rag bond ($75\ g/m^2$)	3.60	2.55	4.90	3.47	1.8	4.7	6.29	13.2
Newsprint ($50\ g/m^2$)	1.79	0.90	3.65	1.84	1.1	1.4	1.78	1.29

[1] Tensile energy absorption.

[2] Machine direction

[3] Cross-machine direction.

Table 2. Bursting strength of paper.

Type of paper	Bursting strength (lb/in^2)	Bursting strength (kPa)	Burst index ($kPa \cdot m^2/g$)
Offset ($107\ g/m^2$)	33	288	2.13
Rag bond ($75\ g/m^2$)	25	172	2.29
Newsprint ($50\ g/m^2$)	4.5	31	0.62

Table 3. Tearing resistance of paper.

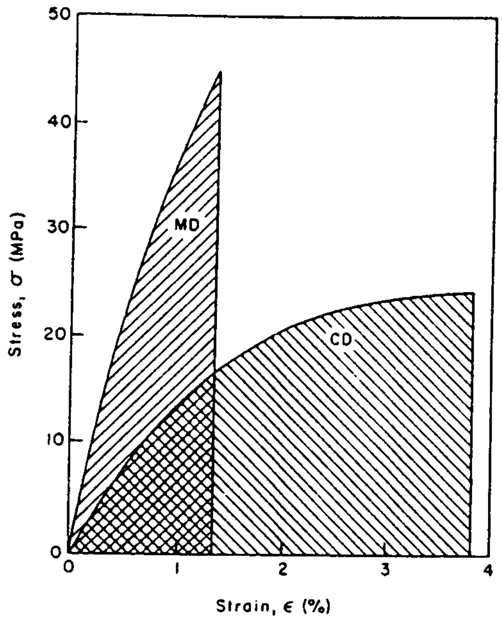
Type of paper	Tearing resistance (g) MD[1]	Tearing resistance (g) CD[2]	Tearing resistance (mN) MD	Tearing resistance (mN) CD	Tear index ($mN \cdot m^2/g$) MD	Tear index ($mN \cdot m^2/g$) CD
Offset (107 g/m^2)	68	85	667	833	6.23	7.79
Rag bond (75 g/m^2)	65	65	637	637	8.50	8.50
Newsprint (50 g/m^2)	12	23	118	226	2.35	4.70

[1] Machine direction.

[2] Cross-machine direction.

Table 4. MIT (0.5 kg) Folding endurance of paper.

Type of paper	Folding endurance: Number of double folds MD	Number of double folds CD	Log_{10} of double folds MD	Log_{10} of double folds CD
Offset Paper	660	495	2.8	2.7
Rag bond	4,280	2,860	3.6	3.5
Newsprint	74	7	1.9	0.9



ML88 5588

Figure 1. Stress-strain behavior of paper in two directions: MD (machine direction) and CD (cross-machine direction). The area under the curve is a measure of the work needed to rupture and is called the tensile energy absorption (TEA).

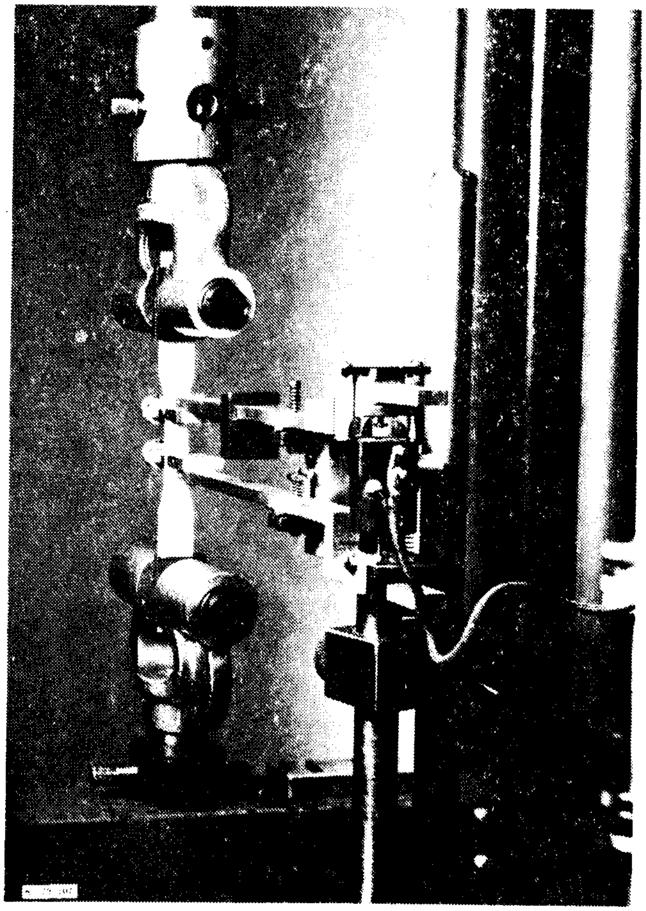


Figure 2. Test strip mounted in tensile testing apparatus, equipped with load cell and direct reading strain gage (ref. 19). (M 129107)

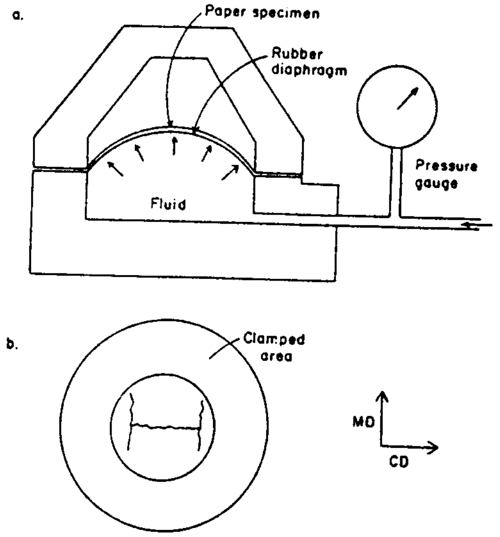


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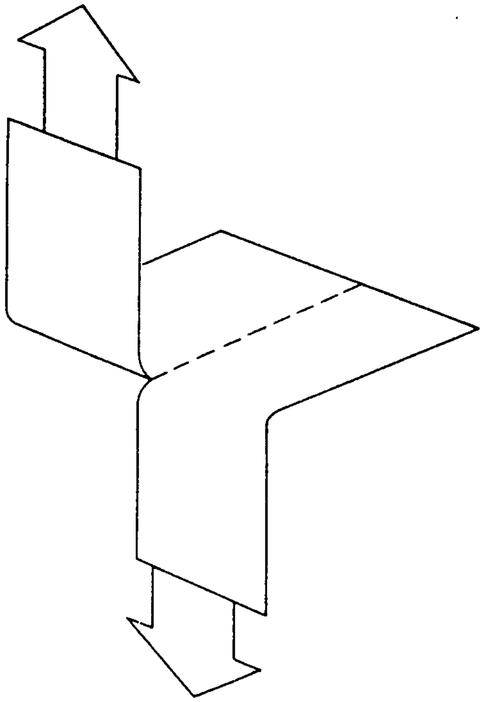
Figure 3. (a) Schematic of bursting test apparatus. (b) Appearance of a typical bursting test specimen after failure; failure initiates along the rip at right angles to the machine direction. MD, machine direction, CD, cross-machine direction.



Out-of-plane (Elmendorf) tearing mode

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Figure 4. Out-of-plane tearing mode used in the Elmendorf tearing resistance test.

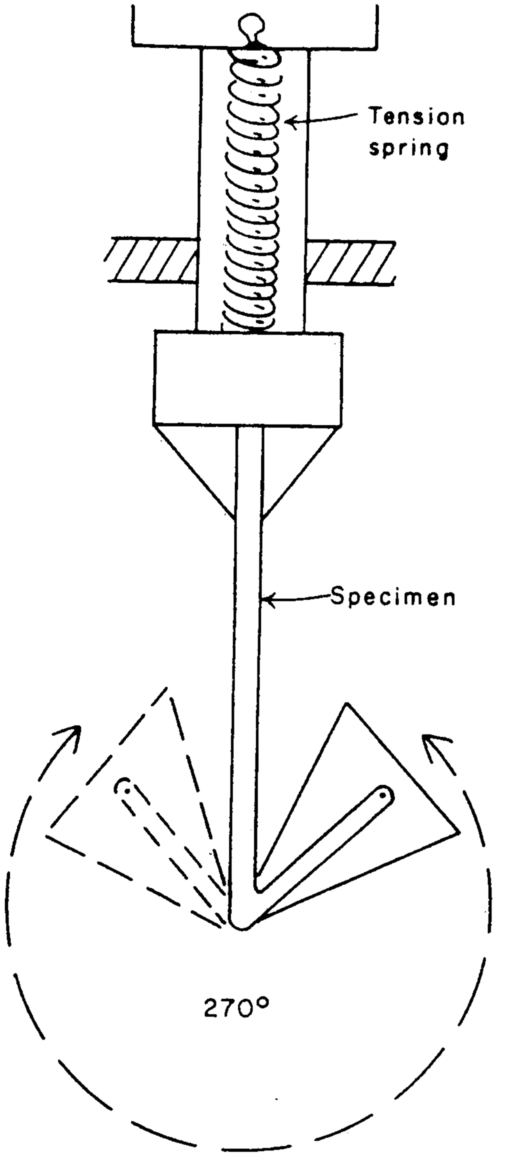

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Figure 5. Schematic of the MIT folding endurance apparatus.

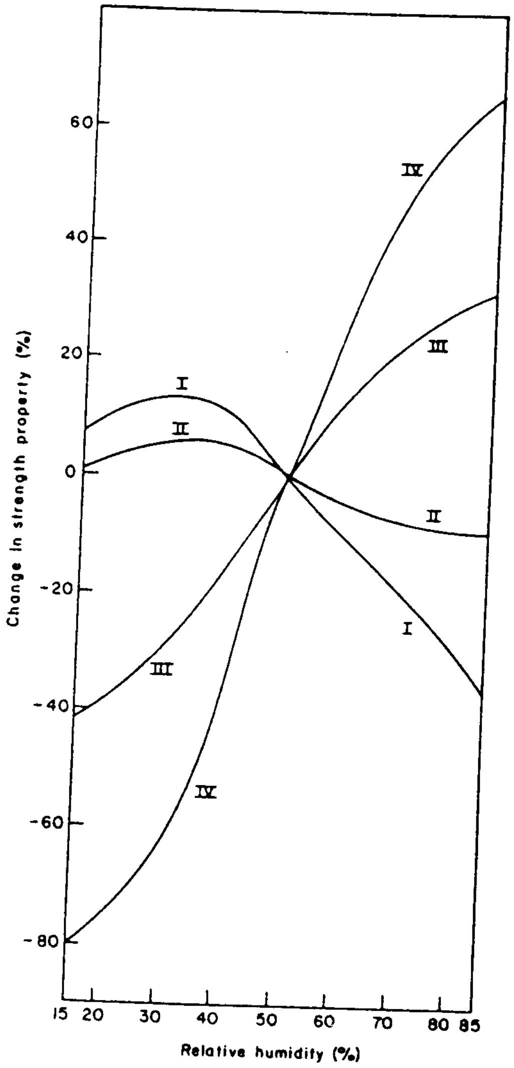

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Figure 6. Generalized effect of relative humidity on strength properties of paper; I is tensile strength, II bursting strength, III tearing resistance, and IV folding endurance.

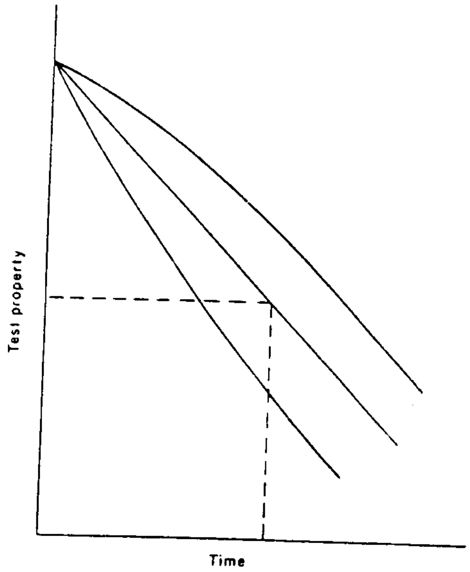

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Figure 7. Types of curves found for strength property behavior as a function of aging time.

Figure 8. Instrument for mechanical stress-strain testing of paper in which the environment may be cycled between high and low relative humidities. (M87 0318-7)