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THE CREEP RESPONSE OF PAPER

Douglas W. Coffin

Department of Paper and Chemical Engineering, Miami University, Oxford OH 45056

With unchanging load
All action appears to cease
Yet still there is creep

ABSTRACT

This article examines the literature pertaining to the creep behavior of paper. The basic concept of creep, the terminology used to describe creep, and the various ways to present creep are introduced. This is followed by a historical overview of creep in paper. Using this framework, discussions centered on tensile, compressive, and accelerated creep are presented. For years, research efforts have focused on accelerated creep. Because of this diversion, an acknowledged fundamental understanding of paper creep is lacking. Using previous data for tensile creep in constant humidity conditions, a rudimentary model of creep in paper is developed. The model clearly demonstrates that the role of bonding is accounted for simply with an efficiency factor that acts to magnify the stress. In addition to the impact of inter-fiber changes, intra-fiber effects resulting from hardening and wet-straining are demonstrated. It is suggested that compressive creep differs from tensile creep due to material instability. Accelerated creep is taken to be the result of moisture-induced load cycling. The result of this discourse is that to increase understanding, fundamental studies of creep behavior in constant conditions are and will be more fruitful than studies in cyclic humidity.

INTRODUCTION

To the layman, the word *creep* conjures up many images; those that make one's skin crawl and others of people best forgotten. Yet, the word can posses a certain charm such as in this context; *creeping along at a slow and steady pace*. Similarly, creep in paper can be a horror such as when it cuts the lifetime of a box short, and yet the study of creep has a charm unparalleled in paper testing. Compare the slow steady progression towards failure created in a creep test, to the violent and rapid destruction that occurs in a tear test. A tear test is fast and exciting, but it is over before one really appreciates the severity by which the paper was destroyed. Creeping deformation provides ample time for observation and one fully appreciates the complex yet systematic behavior of paper deformation. In the current age of instant everything, we can still rely on the creep test to be slow. (Rumor has it that even creep is now apt to accelerate.)

In materials science, creep is defined as the accrual of deformation over time due to the presence of a constant load. One may associate creep with flow of the material, whether it is viscous or plastic; molecular or structural; recoverable or unrecoverable. In addition, creep may involve redistribution of the load within the material. Creep responds well to its environment, especially changes in that environment. Creep is not selective. Both natural and manmade materials exhibit creep. Under the right conditions, say elevated temperature or moisture, a long lapse in time, or the right load, the creep deformation can be appreciable. Too much creep can lead to poor performance in manufacturing, converting, and end-use. This is the reason why understanding the creep behavior of paper is important.

In the following, the creep behavior of paper is explored. First, the basics of creep behavior including terminology and methods of characterization are presented. A historical overview of the literature is given, to introduce important results and give the reader a flavor of how this area of research developed. A thorough discussion of the tensile creep of paper is presented with emphasis on the role of inter- and intra-fiber influences and how one would account for such affects in modeling. The discussion of compressive creep deals with the specialized methods required for this type of testing and the differences relative to tensile creep. Then a discussion of that infamous accelerated creep phenomenon is provided. The summary brings all of this together and suggests future directions for creep studies.

BASICS OF CREEP

The creep test

In the realm of testing of mechanical properties, tensile creep tests are perhaps the simplest of all tests to set-up. Simple instructions are as follows

- Obtain a strip of paper of length, L_0, a deadweight, W, and a tool to measure the deformation, ΔL.
- Fasten the strip at the top so that it hangs vertically (be sure paper can not slip.)
- At the bottom of the strip, apply the deadweight.
- Reference time from the instant the load is applied.
- Periodically, $t_1, t_2 \ldots t_n$, measure the change in length, $\Delta L_1, \Delta L_2 \ldots \Delta L_n$.
- Evaluate the change in length as a function of time due to the applied load.

Figure 1 illustrates this procedure for the creep test. With the gathered data, calculate the strain as, $\varepsilon = \Delta L_i/L$, and graph the total strain versus time, as illustrated in Figure 2 for a generic creep response.

Typically, this creep behavior is idealized as having an instantaneous response, $\varepsilon(0)$, and a time dependent response $\varepsilon_c(t)$. The total creep strain is the sum of the two components. Typically, the creep strain is a function of load level, temperature (T), and moisture (H), as indicated in Equation (1).

$$\varepsilon(t, \sigma_0, T, H) = \varepsilon(0, \sigma_0, T, H) + \varepsilon_c(t, \sigma_0, T, H),\ t \geq 0 \tag{1}$$

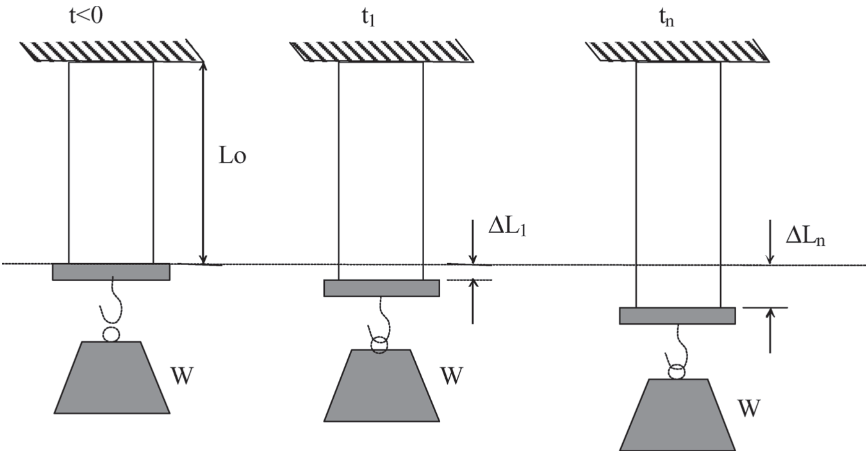


Figure 1 A simple tensile creep test.

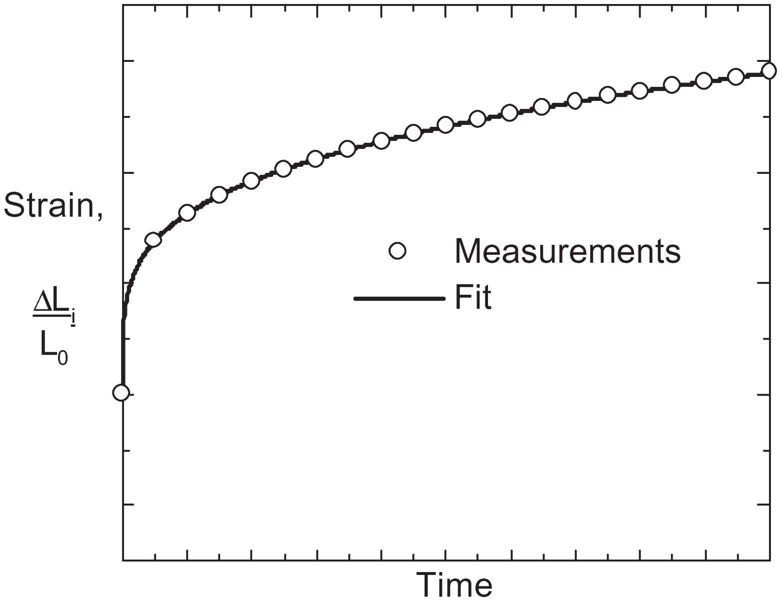


Figure 2 A generic creep response.

where $\varepsilon_c(0,\sigma_0, T,H) = 0$. Although the creep test is simple, the interpretation, analysis, and presentation of creep data have many facets that merit discussion. The following section describes the basics of the theory of creep, so that the reader is equipped with the knowledge and terminology to better appreciate the sections dealing specifically with creep in paper. For more complete information on creep and viscoelastic behavior of polymers references [1–4] should be consulted.

Creep compliance

Creep compliance, $J(t)$, defined as the total strain divided by the load is often used to characterize materials. The load is taken as a stress or load per unit initial cross-sectional area of the sample ($\sigma_0 = W/A$). With the notation introduced in Equation (1), creep compliance is then written as

$$J(t, \sigma_0, T, H) = \frac{\varepsilon(0, \sigma_0, T, H) + \varepsilon_c(t, \sigma_0, T, H)}{\sigma_0}, \; t \geq 0 \qquad (2)$$

The instantaneous response is obtained from the compliance evaluated at time equals zero. The creep compliance curve can be put in dimensionless form as

$$\frac{J(t)}{J(0)} = \frac{\varepsilon(t)}{\sigma_0} = \frac{E\varepsilon(t)}{\sigma_0} \tag{3}$$

where E is a measure of the elastic modulus of the paper and is equal to the inverse of the initial compliance for sufficiently small loads.

The dependence of creep compliance on load merits discussion. For simplification, assume the total creep strain is a function of only load and time, $\varepsilon(\sigma,t)$. Consider a material where the change in creep deformation scales in proportion to changes in load. In this case, a change in load from σ_0 to $k\sigma_0$, where k is a constant has a corresponding increase in total creep strain equal to

$$\varepsilon(k\sigma_0, t) = k\varepsilon(\sigma_0, t). \tag{4}$$

Equation (4) can hold true only when the creep compliance is independent of load. Thus, the creep response of a material that is linearly dependent on load can be written as

$$\varepsilon(\sigma, t) = J(t)\sigma. \tag{5}$$

By developing creep compliance curves from creep tests conducted at different load levels, one can assess the validity of Equation (5) or in words, the load independence of creep compliance and the load-linearity of creep deformation. Say we conduct a series of creep tests at different load levels and obtain the family of creep curves shown in Figure 3(a). If the response is linear with load, the family of creep strain curves will scale with load such to produce the one creep compliance curve shown in Figure 3(b). If the response is not scalable, in other words a nonlinear function of load, the creep compliance curves will not superimpose as shown in Figure 3c. As discussed in the next subsection, even if the material is nonlinear (Figure 3c), it may be possible to shift the curves with respect to time or load so that they superimpose to form one master creep compliance curve.

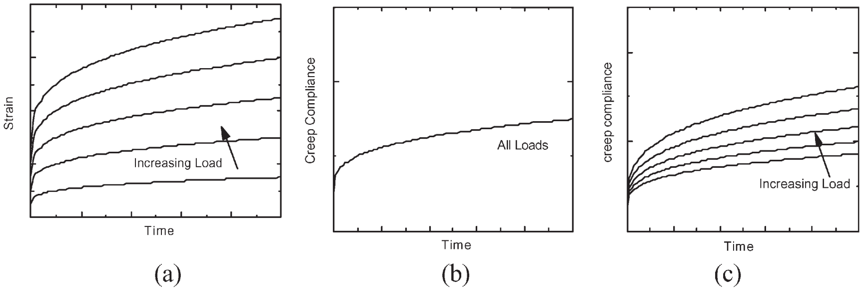


Figure 3 Creep strain and creep compliance. (a) creep curves for different load levels, (b) creep compliance for a linear material, (c) creep compliance for a nonlinear material.

Master creep curves

A useful representation of creep behavior for some nonlinear materials is the master creep compliance curve. For a linear material as was shown in Figure 3(b), there is only one compliance curve for all load levels, but when the response is nonlinear a family of curves exists as was shown in Figure 3(c). For these nonlinear materials, it may be possible to scale or shift the compliance curves in either time or load to produce a master curve. Figure 4 shows the same curves that were shown in Figure 3 (c) but with an appropriate scaling of time so that that all the curves superimpose. The symbols on the curve in Figure 4 represent the beginnings and ends of the individual creep curves. The curve that results from the compilation of the individual curves for various load levels is called the master creep curve.

If the shifts in time and load are systematic such that they can be expressed as a function, a general relationship to predict the creep response at different load levels and time-scales is possible from the expression of a single master creep compliance curve and the appropriate shift functions. Assume that the compliance of the master creep curve can be written as $J_o(t,T,H)$ and the creep curve for any load can be obtained through a shift in time, then the creep compliance can be written as

$$J(t, \sigma, T, H) = J(t + t_s(\sigma), T, H) \; t \geq 0 \tag{6}$$

Likewise if the creep responses at different temperatures and moistures can be formed in to a master creep curve, the creep compliance can be expressed similarly.

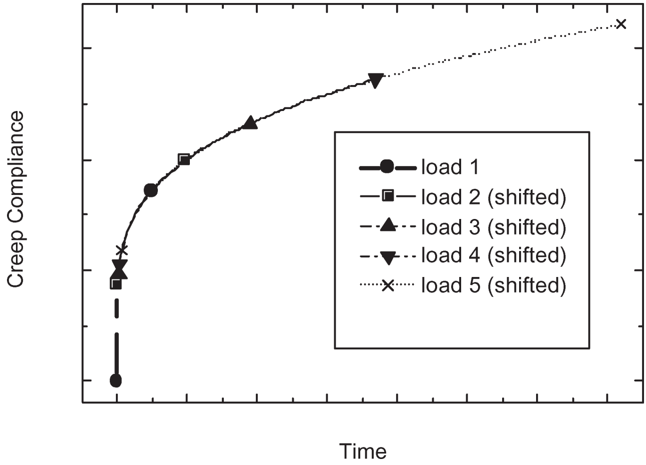


Figure 4 Master creep curve for compliance curves shown in Figure 3c. The symbols show the start and end of the individual creep curves.

Isochronous and isometric creep curves

Isochronous and isometric curves are utilized to represent creep data. Isochronous creep curves are plots of stress versus total creep deformation at a given time. For example, taking a family of creep curves such as presented in Figure 3(a), the creep strain at any given time can be determined for each level of stress. This collection of stress-strain points at a given time, form a curve, and Figure 5 displays these isochronous curves for several values of time. If the creep compliance is a linear function of load, the isochronous curves will be straight lines as shown in Figure 5(a). The slope of any line is equal to the creep stiffness or the inverse of the creep compliance at that time. If the creep compliance is a nonlinear function of load, the isochronous curves will not be straight lines as shown in Figure 5(b). Typical isochronous curves for polymers show linear behavior at small strains and nonlinear response at large strains. Isochronous curves are useful when comparing the creep behavior of different materials.

Another useful representation is the isometric creep curve. The isometric curve plots load versus time for a constant strain. It provides the time required for a given load level to reach a certain strain.

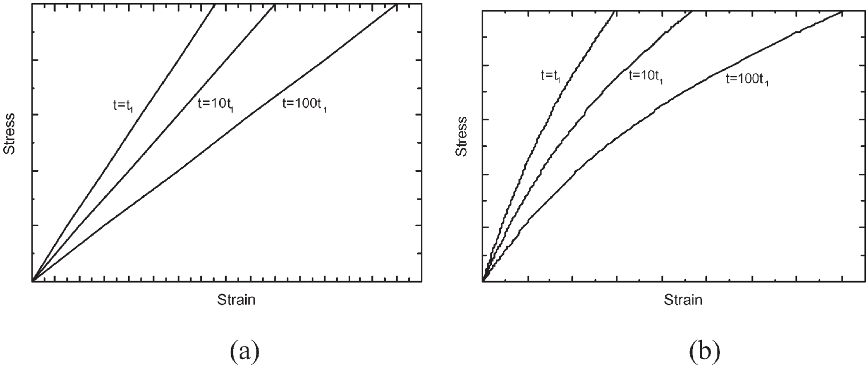


Figure 5 Example of isochronous curves for a linear material (a) and a nonlinear material (b).

Superposition and linearity

A creep compliance that is independent of load is not sufficient for complete material linearity. In addition to load linearity, superposition must hold. Superposition implies that the total deformation at any time for an arbitrary load history can be obtained by summing the creep behavior of each increment of load over the time elapsed from when load increment was added. For example, say that a sample is subjected to a load σ_1 starting from $t = 0$. Then at a given time, t^*, the load is changed to σ_2. Superposition states that the total creep can be determined by adding the creep due to the change in load to the creep caused by the original load. As an equation this criteria is

$$\varepsilon(t) = \varepsilon(\sigma_1, t) + \varepsilon(\sigma_2 - \sigma_1, t - t^*) \; t > t^* \tag{7}$$

The strain can also be written simply as

$$\varepsilon(t) = \varepsilon(\sigma_1, t^*) + \Delta\varepsilon(\sigma_1, \sigma_2, t, t^*) \; t > t^* \tag{8}$$

where $\Delta\varepsilon$ is the additional strain after $t = t^*$ due to the change in load.

Setting Equation (7) equal to Equation (8) gives

$$\Delta\varepsilon(\sigma_1, \sigma_2, t, t^*) = \varepsilon(\sigma_1, t) - \varepsilon(\sigma_1, t^*) + \varepsilon(\sigma_2 - \sigma_1, t - t^*) \; t > t^*, \tag{9}$$

which is the criterion that must be satisfied if superposition holds.

Equations (7–9) are shown graphically in Figure 6. The step increase in

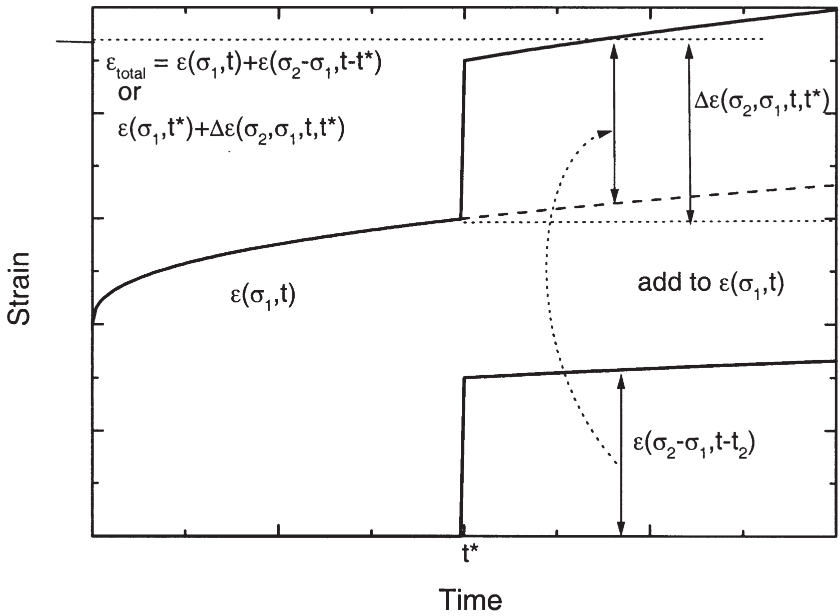


Figure 6 Graphic representation of superposition principle, Equation (7).

load at t = t* causes the strain to follow the solid line. If superposition is valid, the increment in strain can be obtained by a superposition of the strain due to the first load plus the additional strain due to the incremental increase in load starting from t = t* (adding the strain given at the lower right section of Figure 7 to the dashed line.)

Equation (9) provides a requirement for increments of strain that must hold true for superposition to be valid, but it does not require that the creep compliance be independent of load. For example, if upon the removal of load the creep deformation is fully recoverable at the same rate at which it accrued then superposition is valid, even if linear scaling does not apply. One can also have a linear creep response with respect to load level that does not obey superposition. An example of this would be materials that experience aging, for example from a curing process. With curing, even if the load dependence is linear, the creep compliance changes with time independent of the time lapse associated with the application of load rendering superposition invalid.

If the creep compliance is independent of load level and superposition holds, the material is said to be linear. The Boltzmann superposition principle is

(1) The creep is a function of the entire past loading history of the material.
(2) Each loading step makes an independent contribution to the final deformation.

If linear superposition holds, then the strain can be written as the heredity integral given in Equation (10).

$$\varepsilon(t) = \int_{-\infty}^{t} f(t-\tau)\frac{d\sigma}{d\tau}d\tau \tag{10}$$

Equation (10) is a convolution integral and expresses both conditions of superposition and load scaling. Thus, linear viscoelastic material response can be expressed in terms of Equation (10), where the function $f(t)$ is the creep compliance $J(t)$.

If the material behavior is nonlinear, Equation (10) is invalid. There still may be a functional that will describe superposition. For most materials, Equation (10) is valid for low load levels and/or short time intervals, but at higher load levels or longer time lapses, the response cannot be described with Equation (10).

Deformations of creep: Instantaneous, delayed-elastic, and permanent

Assessing the linearity of the creep response is important, but of equal importance is assessing the type of behavior that occurs during creep. For most materials, the deformation response in a creep test can be classified as one of three types: instantaneous, delayed elastic, and permanent creep. The instantaneous response is an idealization that upon the instant of load application, some deformation develops instantaneously. Of course there is some time lapse involved with the deformation and this initial deformation will depend on how much time is involved in the application of the load and measurement of the deformation. But the concept of an instantaneous deformation is suited well for mathematics and interpretation, so we use it. This “instantaneous” creep could have an elastic (recoverable) and inelastic (unrecoverable) component and is the creep compliance at time equals zero. For small load levels, this “instantaneous” response is usually recoverable and referred to as the instantaneous elastic response, and we relate it to a measure of elastic modulus, E, (J(0)=1/E). At large load levels, the initial deformation may include inelastic behavior such as rate independent plastic deformation.

The second type of creep strain is the delayed-elastic response. At the instant of loading, this component of the deformation is zero, but as time passes, deformation begins to accrue and approaches a finite limit. Upon unloading, this deformation is fully recoverable. The third type of creep deformation is non-recoverable creep. This is deformation that accrues over time and upon unloading is permanent. During a creep test, one can not fully differentiate the recoverable and unrecoverable portions of the creep. To assess creep in terms of the recoverable and unrecoverable deformation, one must remove the load and measure the recoverable response.

The three types of creep deformation, instantaneous, delayed-elastic, and permanent are illustrated in Figure 7. An instantaneous elastic deformation develops directly upon loading and is recoverable immediately upon unloading. A delayed-elastic response accrues deformation over time, reaches a limit, and is recoverable over a given time period. A permanent deformation develops over time and fully remains upon unloading.

Mechanical analogies of the three types of deformation are shown in Figure 8. Instantaneous elastic deformation is represented by a spring;

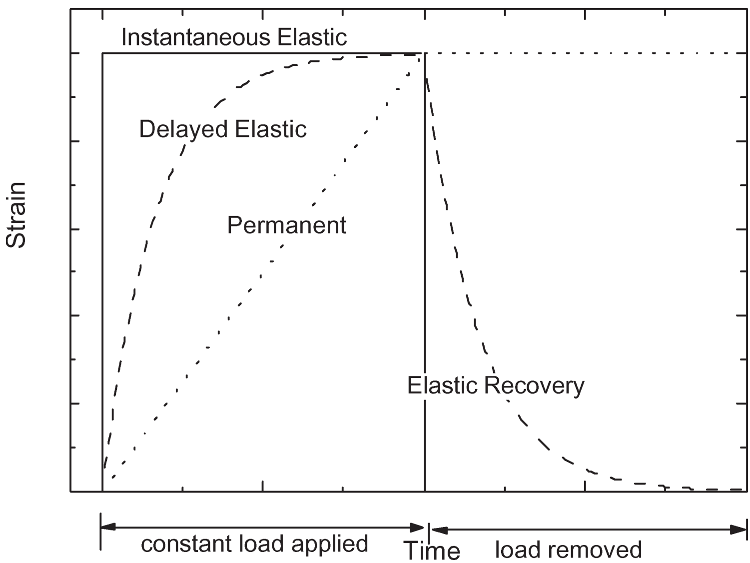


Figure 7 Examples of three types of deformation experienced during creep test shown during loading and unloading.

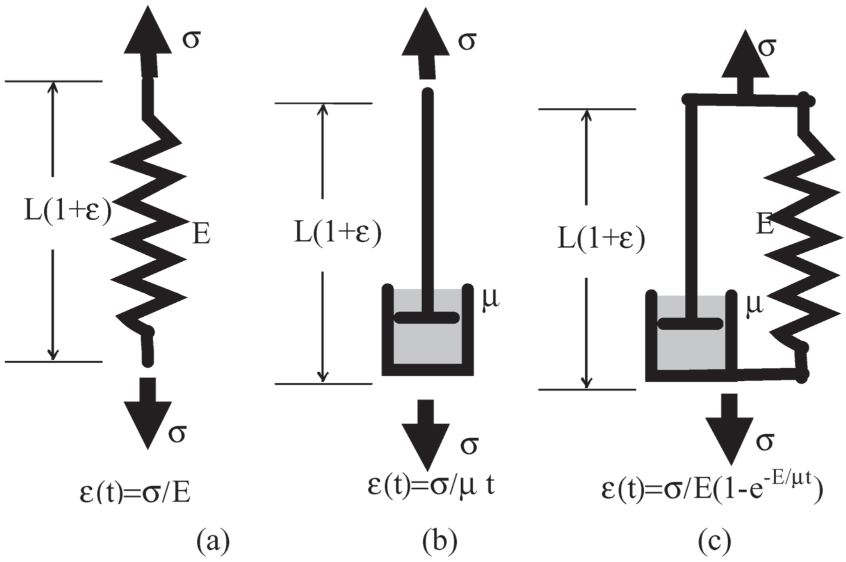


Figure 8 Mechanical analogies for (a) instantaneous elastic, (b) unrecoverable, and (c) delayed-elastic creep behavior.

non-recoverable deformation is represented by a dashpot; and delayed elastic deformation is represented by an elastic spring in parallel with a viscous dashpot. Combinations of these elements are often used to produce models of viscoelastic behavior including creep. Such a model can be made to fit creep data, but it is rare that the same model will also provide an accurate model for other loading histories such as stress-relaxation or a tensile-test.

Deformations of creep: Primary, secondary, and tertiary regimes

Another way to characterize the creep behavior of materials is in terms of time regimes that exhibit characteristic deformations. Figure 9 provides a generic creep diagram broken into three regimes: primary, secondary, and tertiary. The primary creep regime is where the creep rate decelerates with time. The secondary creep rate is characterized by a constant rate of creep, and the tertiary phase is characterized by an acceleration of the creep. This terminology was developed for creep in metals [1, 2] and later applied to polymers with slightly different meanings [4]. Typically for polymers, the rate of creep does not exhibit a secondary creep response with a constant creep

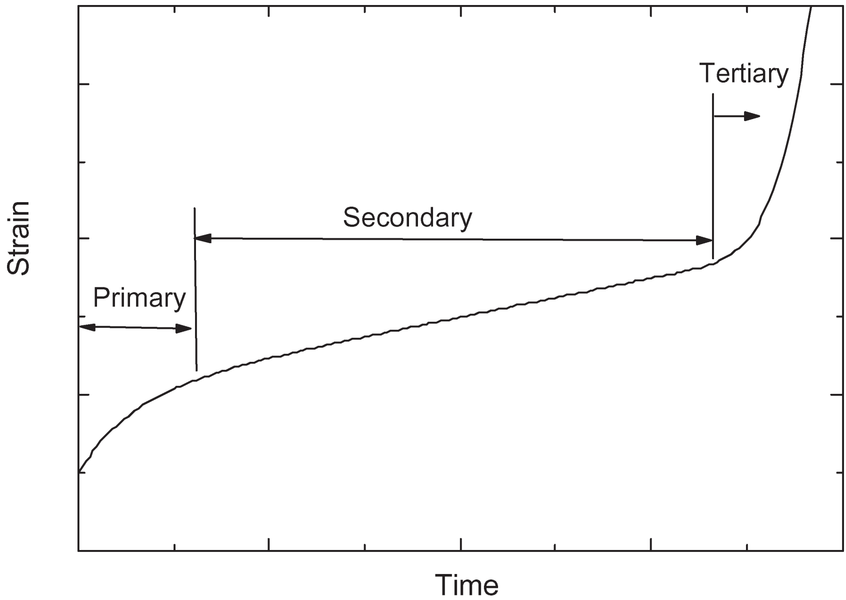


Figure 9 Three regimes of creep response.

rate, but rather the creep rate continues to decrease until the tertiary regime. The connection to the metals definition of primary and secondary creep rates to polymers is not the rate of creep, but the type of deformation. In metals, the primary creep is related to recoverable deformation, and secondary creep is typically unrecoverable. Thus, when we speak of polymers including paper, the primary creep is considered recoverable creep and secondary creep is taken as unrecoverable creep regardless of the functional dependence on time.

As previously stated, the amount of recoverable creep is assessed by conducting a creep recovery test. After the sample has been subjected to a constant load for a given period of time, the load is removed and the change in length of the sample under no load is measured for a period of time greater than the initial creep. At the moment of unloading, the instantaneous elastic deformation will be recovered. Then the delayed elastic creep will recover. The amount of strain recovered over time can be used to determine the delayed elastic response.

Delayed elastic response versus creep recovery strain

An important clarification about creep recovery needs to be made. From a historic point of view following directly from Boltzmann superposition, the *creep recovery strain* at a given time is defined differently than the amount of creep strain that has recovered. Take a given creep test, where the load is applied at $t = 0$ and removed at $t = t_1$. Then at a time $t = t_2$, the amount of elastic recovery is measured. The elastic recovery is defined as the difference, $\varepsilon(t_1)-\varepsilon(t_2)$, but the creep recovery strain is defined as $\varepsilon^*(t_2)-\varepsilon(t_2)$, where $\varepsilon^*(t_2)$ is the creep strain that would have been in the sample had the load remained on the sample until $t=t_2$. This difference is illustrated in Figure 10.

For materials that obey Boltzmann superposition, Equation (10), the creep recovery plotted as a function of recovery time is exactly the same as the initial creep as a function of time. This is regardless of whether the creep is a delayed-elastic deformation or an unrecoverable deformation. It stems from the fact that if superposition holds, then the response after unloading can be

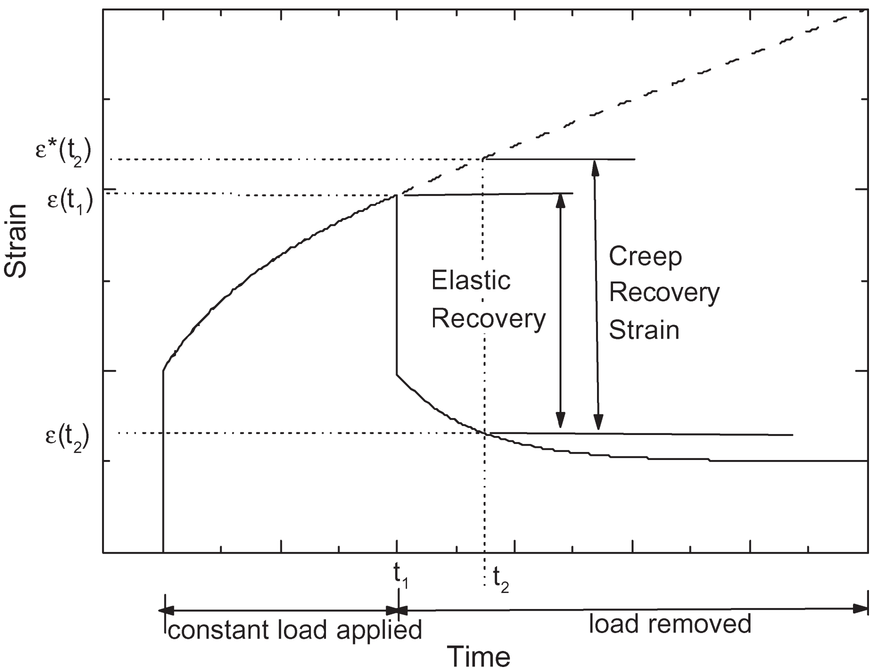


Figure 10 Difference between elastic recovery and traditional definition of creep recovery strain.

obtained by the application of a load of the same magnitude as the creep load but of opposite sign. The superposition of the continued positive creep minus the additional negative creep gives the response for recovery with no load. Therefore, when checking the validity of Boltzmann superposition one needs to plot creep recovery as defined in Figure (8) against the initial creep rather than the actual elastic recovery.

On the other hand, to determine the amount of delayed-elastic creep deformation one simply needs to know the absolute value of the total strain recovered during the recovery period. This distinction is important because in the literature for creep of paper, it appears that delayed-elastic recovery, $\varepsilon(t_1)-\varepsilon(t_2)$, is reported as the creep recovery not the traditional definition of creep recovery strain.

Time-temperature superposition

There is another important principle of creep in polymers that warrants discussion; time-temperature equivalence. In simple terms, time-temperature equivalence implies that the creep behavior at one temperature can be related to the creep response at another temperature by a change in time-scale only. Typically, when creep compliance as a function of time is plotted on a double-logarithmic scale the curves can be shifted horizontally along log-(time) until they superimpose. By keeping track of the shift factor as a function of temperature, a master creep curve can be formed to provide creep response for various loads, temperatures and times. If time-temperature equivalence is valid for the material, one can conduct creep tests at elevated temperatures to predict the response at long times for low load levels.

Lifetime

When a material creeps, a limiting strain may be reached, such as a pure delayed-elastic response, but more often the creep will continue until failure occurs. The time lapse from the time when the load is applied until the time the sample fails is called lifetime, as demonstrated in Figure 11. Lifetime is a key factor used to evaluate the performance of materials and products expected to sustain loads for long periods of time. Lifetime is often correlated to load level and creep rates. The most obvious criteria for lifetime would be a maximum creep strain. If tertiary creep is included in the model, the point where the rate of creep approaches infinity may be taken to signal failure.

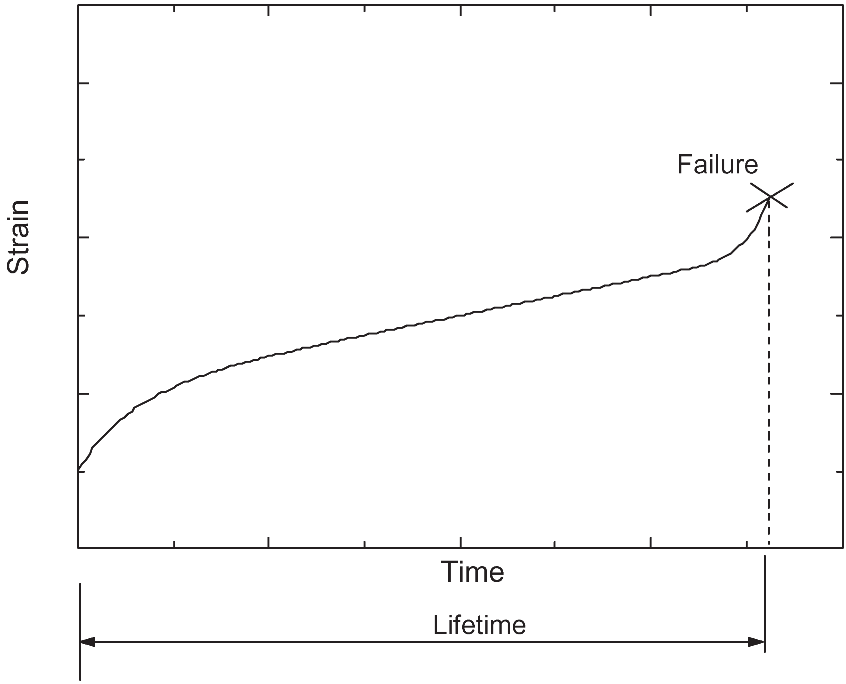


Figure 11 Illustration of the term lifetime with regards to creep.

THE HISTORICAL VIEW OF RESEARCH ON CREEP IN PAPER

A fitting start

For paper-based materials, the main issue for which creep is a significant factor is the performance of corrugated boxes. Although creep plays a role in many problems, it is fitting that the oldest creep literature [5] that was located for this review pertains to corrugated boxes. In 1935, A. P. Kivlin, an Assistant Chief Engineer of the Freight Container Bureau, discussed failures in corrugated fiber containers [5] and devoted a few paragraphs to creep. Kivlin noted:

> *Fibreboard containers have another inherent and characteristic weakness, which is not common with other types of containers. This weakness causes a container to fail under a comparatively light load as compared with the maximum test load to which it might have been subjected without failure.*

He goes on to say that this weakness may explain why the lower containers in a stack collapse for no apparent reason. Kivlin further states:

> . . . *after a time under the steady application of this dead load, they* (the containers) *collapsed*.

This is creep! It should be noted that the early work on creep in boxes refers to creep as fatigue, which has nothing to do with the traditional material science meaning of fatigue. By 1949, investigations of the creep testing of corrugated boxes had begun [6]. Figure 12 shows a photograph of an early creep test on a stack of boxes with quite an amusing collection of items for deadweight, which maintained symmetry. From this humble beginning over 50 years ago, there has arisen quite an interest in the creep of paper, board, and boxes. Some of the highlights are covered in the following overview.

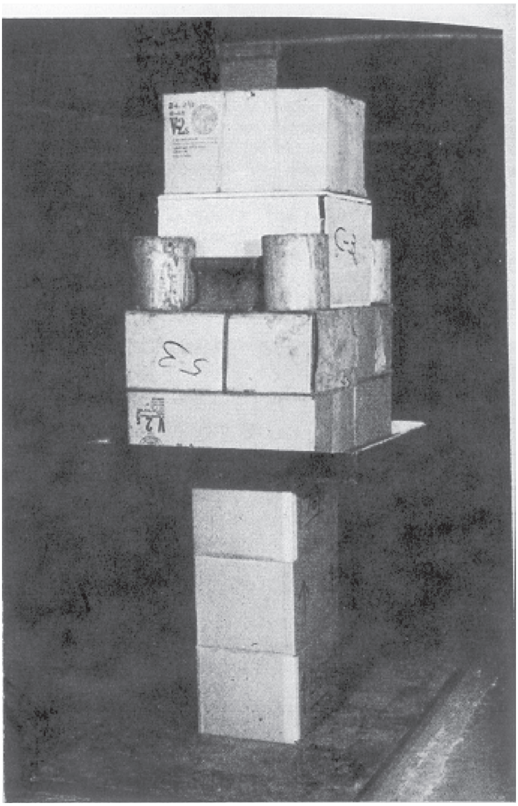


Figure 12 Early creep test of stacked corrugated containers. [6]

Creep testing of boxes continued steadily for the next several decades [7–11]. Much of this work dealt with studying box lifetime; defined as the time at which the box fails due to creeping. All these early tests studied lifetime under constant humidity conditions. The earliest work attempted to develop predictions of lifetime based on load level [7–9], the latter work [10, 11] focused on the rate of creep in the secondary creep regime, which for boxes, is approximately constant for a significant period of time. The latter approach was found to be a much better predictor.

Early creep studies

Interestingly, many of the initial studies of creep were not aimed at understanding box lifetime, but at unlocking the mysteries of the time-dependent behavior of paper. At about the same time that creep studies in boxes were initiated, interest in understanding the viscoelastic properties of paper had arisen [12–14]. This early work dealt mainly with the viscoelastic behavior of paper as observed from tensile tests, but creep was discussed. The first in-depth study of the creep behavior of paper was presented by Brezinski in 1956 [15]. Brezinski's work and several follow-up doctoral studies conducted at the Institute of Paper Chemistry [16–18] are likely the best collection of work on the basic tensile creep of paper that can be found in the literature. It should be re-emphasized that the purpose of this body of work had nothing to do with boxes, but was aimed at gaining a fundamental understanding of the viscoelastic behavior of paper. This body of work is heavily relied on for the critical evaluation of tensile creep in the following section.

Brezinski [15] completed an extensive study the tensile creep response of handsheets produced from a commercial softwood alpha pulp. He used two levels of beating and wet-pressed to various levels to produce a range of different density sheets. He also performed creep tests at a multiple of load levels and in a range of relative humidity environments. In addition, to basic first creep tests, he measured creep recovery and creep in conditioned (previously crept) samples.

The basic creep behavior he observed was the same for all conditions. Brezinski [15] established that the creep deformation of paper exhibited all three distinct behaviors: initial-elastic, delayed-elastic, and unrecoverable deformation. He also found that the initial creep deformation could be fit with a power-law equation, but for high load levels and long times, the creep deformation was linear with the logarithm of time. The equations Brezinski [15] used to fit his creep data were

$$\varepsilon = Bt^{a} + C \tag{11}$$

for short times and low loads, and

$$\varepsilon = K\log(t) + D \tag{12}$$

for long times and high loads. The terms *B, a, K, C, and D* were constants used to fit the data. He referred to the portion of the curve between these two regimes as a transition zone.

Although the creep compliance was found to be a nonlinear function of load, a shift along the logarithmic time scale, as shown in Figure 13 could be used to form a master creep curve [15]. Even better was the fact that, the required time shift on a logarithmic scale was a linear function of load. For creep recovery, it appeared that the recoverable or primary creep was in the regime expressed by the power-law creep and the unrecoverable or secondary creep was associated with the log-linear creep.

Brezinski [15] explored the recoverable component of creep by subjecting the paper to three cycles of 24-hour creep followed by 24 hours of no-load recovery. Then a fourth cycle of creep at the same or lower load level was performed. For low load levels, the creep response was completely recoverable, but at higher loads there was still unrecoverable creep. From this finding, Brezinski [15] concluded that the superposition principle was in

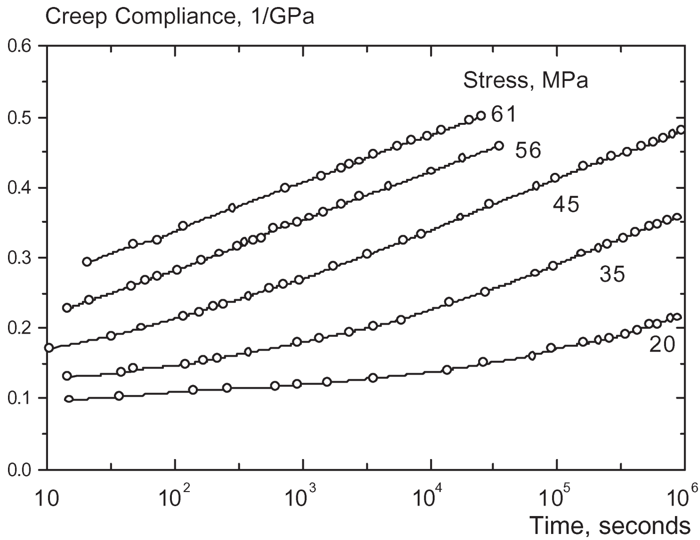


Figure 13 Creep compliance for various load levels data [15].

general not applicable to paper. Brezinski [15] did feel that superposition may be valid for low load levels where irrecoverable creep has not occurred because the creep curve and recovered creep curve superimposed with each other.

Brezinski [15] also presented 24-hour isochronous creep curves for the various handsheets. The effect of increased beating and wet-pressing was a shift in the creep compliance such that higher load levels were required to obtain the same deformation. Wet-pressing alone did not appear to alter the amount of recoverable creep, but increased refining did appear to have a slight increase in the amount of recoverable creep. From these results, it appears that the effect of changes in bonding can be accounted for by a shift in apparent load level, but fiber changes result in a new shape of the creep compliance curve.

As one would expect, Brezinski found that by increasing the moisture content, the creep compliance increased. His 24-hour isochronous curves show that increasing the moisture causes a large shift to lower loads at any given strain. Brezinski uncovered much more interesting interactions with moisture changes. First Brezinski found that the creep properties versus moisture exhibited a break somewhere between 50–60% RH (7.4–8.5% moisture). A plot of creep deformation versus relative humidity, Figure 14, shows the break point.

Brezinzki tested unconditioned sheets that remained at low moisture after drying and conditioned sheets that had been exposed to 97.8% relative humidity for 48 hours before conducting creep tests at various moisture contents. He found that for tests conducted in sheets at lower moisture contents (something less than 8%) specimens never exposed to high moisture crept less than those that had been pre-conditioned with exposure to high moisture. This observation suggests that exposing samples to high moisture removes previous hardening in the paper. Of most interest is that prior to conditioning he could not form a master creep curve, but after conditioning the curves corresponding to different moisture contents could be shifted with a logarithmic time shift to form a master creep curve. For these pre-conditioned sheets, the slope of the logarithmic creep appeared to be independent of moisture content.

Figure 14 shows the total creep as a function of relative humidity and a creep strain that is termed the delayed creep. The delayed creep is the creep that accrued between 10 seconds and 24 hours. The graph shows that the unconditioned samples were hardened as compared to the preconditioned samples, but at relative humidity above the break point, the delayed-creep was actually greater than the conditioned sample. This increase in the delayed creep was credited to a release of dried-in strains. At higher moisture con-

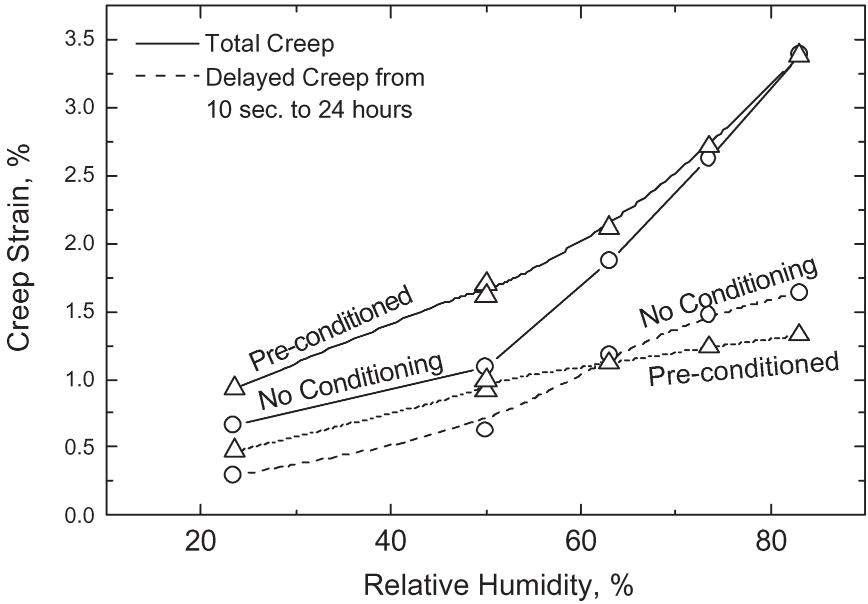


Figure 14 The influence of relative humidity and pre-conditioning on creep of paper [15].

tents, more of the strain was released, adding to the total creep. The hardening effects were removed.

Finally, Brezinski [15] looked at recovery that occurred when a previously crept sample was exposed to high moisture content. Samples were first pre-conditioned to remove the dried-in strains and the breaks in the creep curves. Then a specimen was crept at 50% RH for 24 hours and allowed to recover strain for 7 days. Then the sheet was exposed to 97.8% RH for 24 hours with no load. The total strain after each step is shown below.

	Initial Creep	→	After Recovery	→	After High Moisture
Total Strain:	1.13%		0.51%		0.05%

All but 0.05% of the strain was recovered. The process was repeated three more times with almost compete recovery. Brezinski [15] states that most of the recoverable strain was strain that occurred before the onset of logarithmic creep. A part of the logarithmic creep was recoverable, but the bulk of this creep was not recoverable.

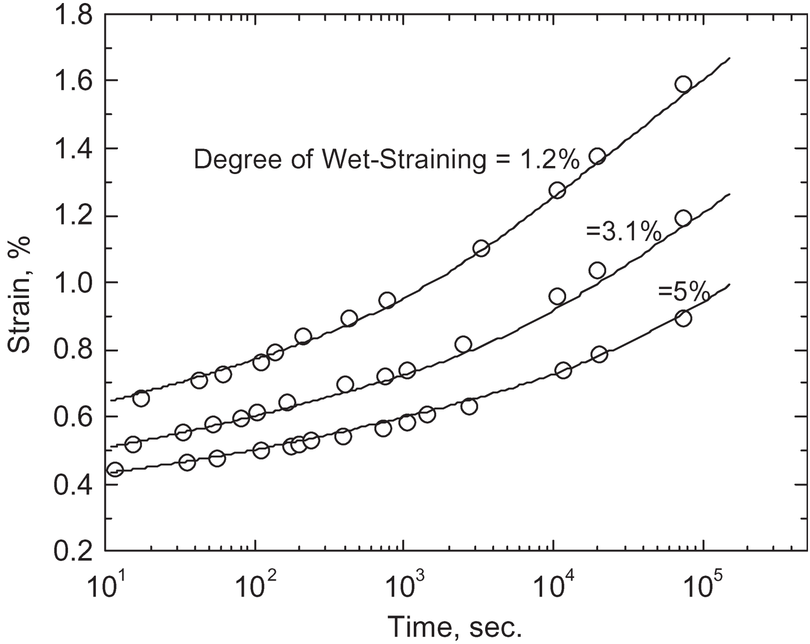


Figure 15 Influence of wet-straining on the tensile creep response of paper [16].

Shortly after the work of Brezinski [15], Shultz [16], Sanborn [17], and Parker [18] published additional work on the creep of paper. Shultz [16] investigated the effect of the degree of wet straining on the creep response of paper. Typical of the stiffening effect of wet-straining on mechanical properties, he found that increased degree of wet-straining decreased the creep compliance to as shown in Figure 15.

At some level of wet-straining, the creep compliance reached a minimum. For wet-straining beyond this level, the creep compliance again increased. For the data shown in Figure 15, the minimum creep compliance occurred at the 5% wet-straining value.

Figure 16 shows the 24-hour total creep strain, the tensile strength, and the stretch as a function of degree of wet straining for another of the pulps tested by Schultz [16]. The degree of wet-straining where the creep was a minimum corresponded to the degree of wet-straining where the tensile strength reached a maximum. Tensile strength shown in Figure 16 is equal to the mass specific stress in units of length multiplied by the density of cellulose.

One of the more interesting findings of Shultz [16] was that for many of his

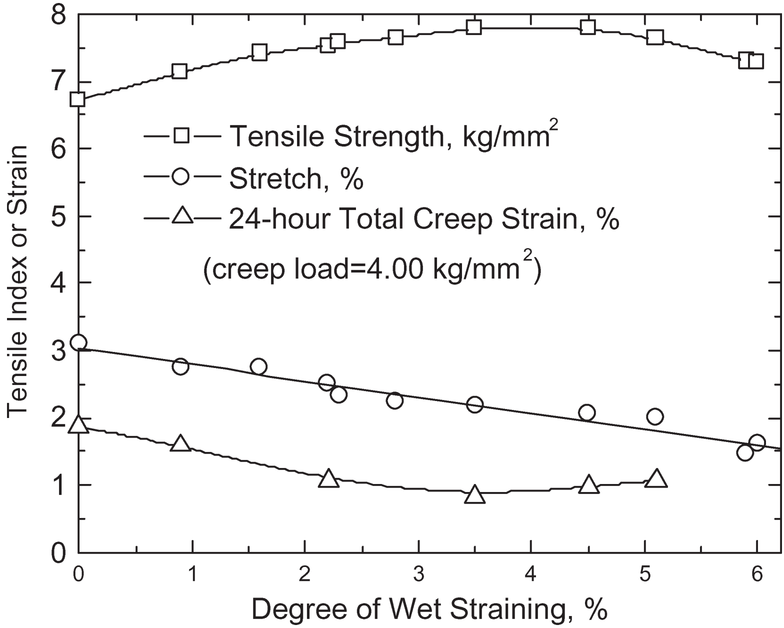


Figure 16 Effect of wet-staining on Total creep strain [16].

pulps, there was a direct relationship between the amount of creep recovery and the total first creep regardless of the amount of wet-straining or load level. In addition, the effect of refining on this relationship was minimal. Shultz concluded that wet-straining the sheet and drying that imposed strain into the sheet, only changes how stress is distributed through the network. After drying the sheet under strain, the sheet carries load more efficiently, so much so that even though the degree of bonding decreased with wet-straining the load carrying capacity of the sheet increased. In addition to altering the efficiency of the network it is likely that the fiber properties themselves are altered by wet-straining. Shultz [16] did not investigate the effect of moisture or preconditioning, which given the observations from Figure 13 would have been interesting.

In order to differentiate inter-fiber versus intra-fiber mechanisms for creep, Sanborn [17] studied changes in the structure of paper due to creep. He found good correlations between the amount of irreversible creep and increases in light scattering, and increases in air permeability. Therefore, he concluded that creep induces loss of inter-fiber bonding. He also studied the energy loss during creep and recovery and concluded that appreciable portions of the dissipated energy likely come from within the fiber.

Parker [18] also tried to determine if creep was dominated by inter- or intra-fiber mechanisms. He produced handsheets at different wet pressing levels for pulps treated with different concentrations of aqueous ethylamine. The ethylamine changed the fibers as observed by decreases in the crystallinity index and the zero-span tensile strength, but also induced changes in the structure and probably the degree of bonding. An interesting finding of Parker's is that he could not form master creep curves for paper made from pulps that had undergone drops in crystallinity. These same pulps had more recoverable creep for a given amount of total creep. Thus, Parker concluded that at least some of the creep behavior is attributable to intra-fiber effects.

Hill [19] conducted creep tests on single fibers in tension. The basic creep results for single fibers are similar to that of paper. Although he could not determine a mathematical model for the initial creep response, the high load/long time creep was linear with the logarithm of time. In addition, there was recoverable and unrecoverable creep.

From these initial creep studies [15–19] a good foundation of the creep response of paper emerged. Clearly both intrinsic material properties and structure influence the creep response. It appears that the basic creep response is a result of the materials and structure of the fibers (intra-fiber effects) where as bonding and network structure (inter-fiber effects) tend to shift the basic creep curves to other time scales or load levels. The following bullets summarize these early findings for tensile creep.

- A characteristic of primary and secondary tensile creep in paper is decreasing creep rates with time.
  - Primary creep rate decreases inversely to time raised to a power less than one ($\propto 1 / t^{1-a}$).
  - Secondary creep rate decreases with the inverse of time ($\propto 1 / t$).
- Creep compliance of paper is a nonlinear function of load.
  - Change in load effect is equivalent to a logarithmic shift in time.
- A master creep compliance curve can be formed.
- Previous straining of paper produces mechanical hardening
  - If wet-straining exceeds a critical value creep compliance increases.
  - Previous creeping induces hardening
- Increased moisture increases creep compliance.
  - The effect of moisture on secondary creep is a logarithmic time-shift.
- Hardening effects can be reduced or eliminated by exposure to high moisture.

- The inherent creep response of paper appears to be primarily that of intra-fiber creep.
- Inter-fiber bonding will influence the creep response in a manner equivalent to that of a shift in load or time.

A change of atmosphere for creep research

After these early researchers laid an excellent foundation for the creep behavior of paper [15–19], a Ph.D. student at NC State carried out an investigation that literally created a completely new atmosphere for the study of creep in paper. In the early seventies, Byrd [20] studied the influence of cyclic humidity on creep. This work marks a turning point. Byrd's results triggered a realization for the packaging industry that they had not been studying the worst case scenario to evaluate box lifetime. It brought about new interest in compressive creep testing, and it brought on much speculation on mechanisms for the influence of moisture on creep.

Byrd discovered that paper experienced more creep deformation in an environment of cyclic moisture compared to creep at constant high moisture. This was counterintuitive and it captured the attention of many researchers. The same phenomenon had already been studied in other materials and reported as early as 1942 for concrete [21] and 1960 for wood [22], but a good understanding of the cause of this phenomenon was lacking. The increased creep rates during cyclic humidity along with several other related and seemingly bizarre couplings between moisture and mechanical response were labeled the mechanosorptive effects. Accelerated creep or mechanosorptive creep were the names given to this cyclic moisture-induced increase in creep rates.

Byrd showed that accelerated creep occurred both in tension for handsheets [20] and edgewise compression for corrugated board [23] as shown in Figure 17. Shortly after Byrd's publication, De Ruvo *et al.* [24] reported studies showing that the time of failure during creep, or lifetime was shorter for cyclic humidity conditions than constant humidity conditions.

After Byrd's *discovery* of accelerated creep in paper, which of course should have been determined much earlier given the reported observation of other materials [21, 24], research emphasis on the mechanosorptive effects steadily grew. Bryd continued to conduct studies of accelerated creep for both corrugated board, and paperboard. In 1978, he and Koning [25] presented results comparing constant and cyclic humidity creep rates for corrugated board made from liners produced from various pulp types. They reported that creep rates for board with liners made from virgin pulp were lower than the rates for board made from liners using a "recycled" pulp. By recycled they

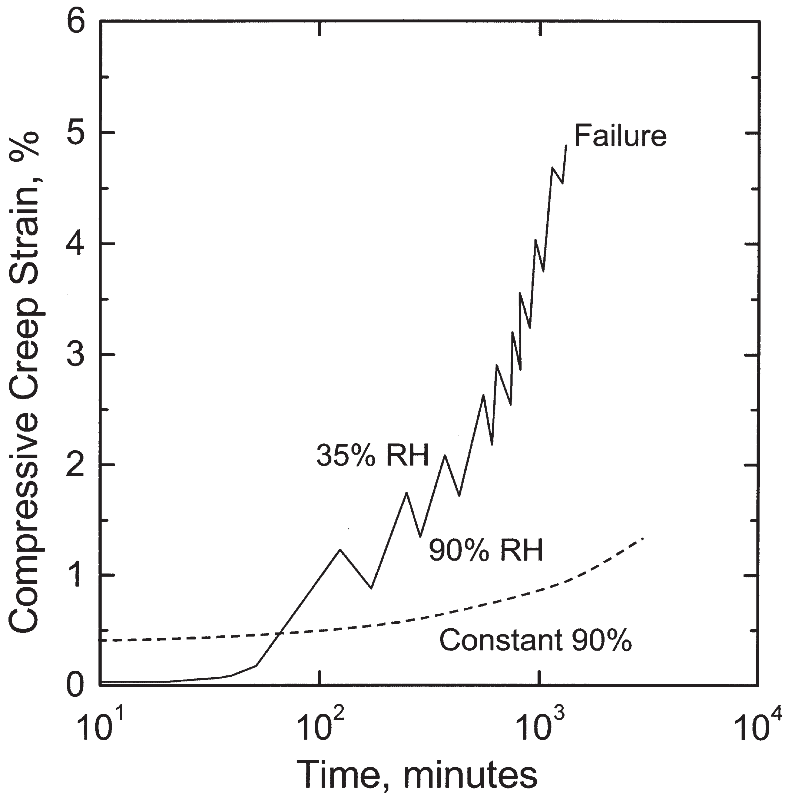


Figure 17 Byrd's [23] results of accelerated creep in corrugated board in compression.

meant that the virgin liners were re-pulped and made into handsheets three times. Since this time there has been some debate as to whether recycled pulps exhibit more or less creep than virgin pulps.

Byrd and Koning [25] also conducted tests with three and 24-hour moisture cycles on ECT creep test of corrugated board. They reported that 3-hour cycles had lower creep rates, than 24-hour cycles. In 1984, Byrd [26] presented compressive creep results for the components of the corrugated board.

During the next several years, many researchers were investigating accelerated creep and mechanosorptive effects. There was a bit of a delay before results hit the literature with full force. During this intermediate time, there were several works dealing with creep that are worth mentioning.

The lull after the discovery

In order to quantify the effect of cationic starch on filled papers, Lindström *et al.* [27] measured creep lifetime as a function of load and then determined a stress concentration factor that accounted for the loss of lifetime with filler content and improved lifetime with starch addition. It is noteworthy, that Lindström *et al* [27] attribute increased creep compliance to stress concentrations in conjunction with activation energy.

Byrd [28] conducted a study of accelerated creep in lap joined paperboard specimens and found that creep rates when a water-sensitive adhesive (PVA) were three times those of just the paperboard or when a water-resistant adhesive (Cellulose Nitrate) was used. Thus, he felt that adhesive may play an important role in the creep of corrugated board.

Pecht *et al.* [29] presented a constitutive equation for creep that captured both the power-law and log-linear portions of the creep behavior. The equation also accounted for time-load superposition and thus was capable of producing a master creep curve. The basic equation for creep compliance was

$$\frac{\varepsilon(t)}{\sigma_0} = \frac{1}{E} + k \log[1 + g(t)f(\sigma_0)] \tag{11}$$

where

$$g(t)f(\sigma_0) = \left(\frac{t10^{A(\sigma_0 - \sigma_R)}}{t_0}\right)^n \tag{12}$$

where σ_R is the reference stress that forms the basis of the master creep curve; k, t_0, and n are material properties, A is a shift factor, $g_{(t)}$ is time-shift function assumed to have the form of a power law $(t/t_0)^n$, and $f(\sigma_0)$ is a generic stress shift function with the specific form, Equation (12), to account for the linear relationship between load and a logarithmic time shift.

Equation (11) with the specific function defined in Equation (12) yields both the power-law creep at low loads and short times and log-linear creep at high loads and large times. Pecht and Johnson [30] extended the model to include the influence of moisture on creep compliance but only considered cases of constant humidity.

The hay-day of accelerated creep

In the 1990s research focusing on accelerated creep flourished. Starting in 1992, five international symposia [31–35] were held with a focus on moisture effects on paper and paperboard. The mechanosorptive behavior of paper was a major theme of these meetings. The first meeting [31] held in 1992 at the Forest Products Laboratory in Madison, WI, USA dealt entirely with packaging and accelerated creep. At this conference, Selway and Kirkpatrick [36] presented their views of mechanisms for accelerated creep in terms of a model for plastic ratcheting. They provided a statement about creep ratcheting caused by transient stresses and nonlinear dependence of creep rate on load.

Söremark and Fellers [37, 38] introduced the idea of dislocations and stress-induced hygroexpansion. They also discuss stress-redistribution during moisture changes. Calvin [39] discussed a rapid method for predicting lifetime based on results of constant load rate tests.

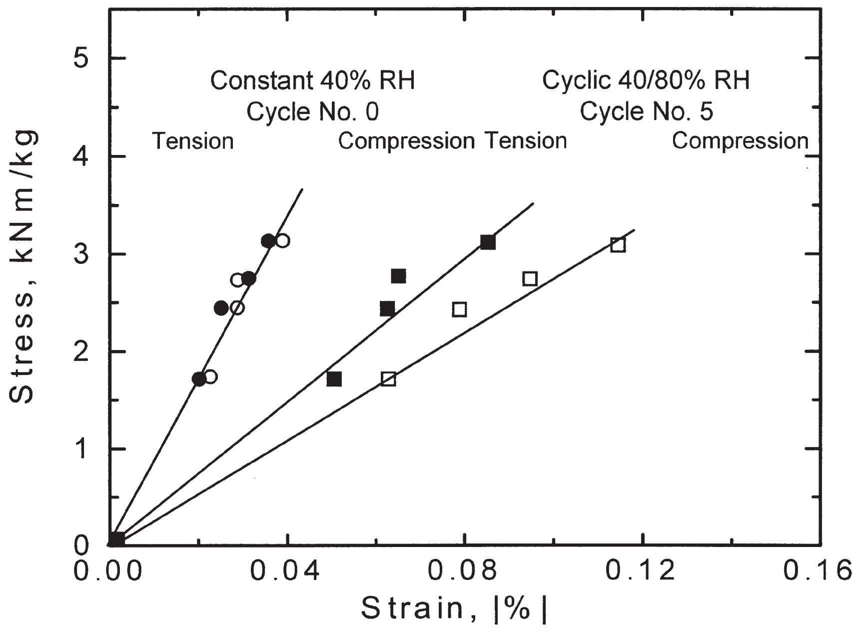


Figure 18 Differences in tensile and compressive creep isochronous curves for constant and cyclic humidity [40].

The year after this first "creep conference" the 10th Fundamental Research Symposium held at Oxford, UK contained three papers that dealt with accelerated creep [40–42]. At that conference, Söremark *et al.* [40] presented their work on creep in bending of corrugated board to discuss the effect of drying and fiber orientation. Besides testing single wall corrugated board, they made special board where they substituted one of the liners with steel ribbons. By looking at the bending creep of this composite sample, they were able to isolate the creep of the paperboard liner in either tension or compression.

Söremark *et al.* [40] also advocated the use of isochronous creep curves for characterizing creep behavior for both constant and cyclic moisture conditions. In general, they found that for short times, the creep behavior was the same in tension and compression and fairly linear in the response to load in constant humidity. In cyclic humidity, the compressive creep had lower creep stiffness than tensile creep. Figure 18 displays isochronous curves demonstrating this. Figure 19 demonstrates that MD creep is lower than CD creep in

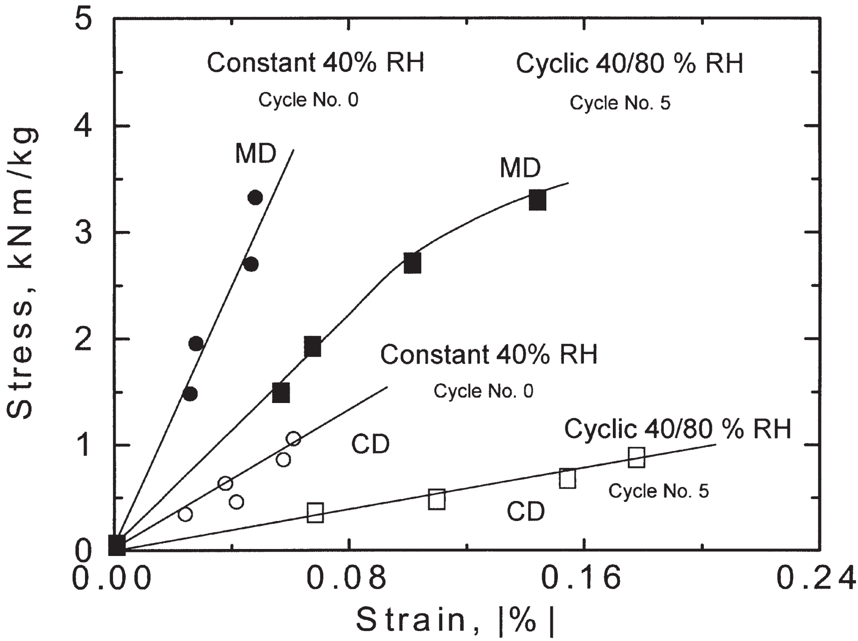


Figure 19 Effect of MD/CD orientation on isochronous curves for constant and cyclic moisture on creep [40].

both constant and cyclic moisture conditions. They also found that sheets dried under restraint exhibit less creep than freely dried sheets for both constant and cyclic humidity conditions.

Another paper presented on creep at the 10th FRC, authored by Padanyi [41], dealt with a new observation on the creep behavior of paper. Padanyi pretreated his sheets in either a high or low humidity environment until moisture equilibrium was achieved, and then placed the samples in a 50% RH environment. After moisture equilibrium was achieved, aging time was allowed to pass before the creep test was begun. He found that the creep compliance decreased as aging time increased. He likened this to physical aging observed in polymers which have been brought from a temperature above glass transition to a temperature below glass transition. Even after the temperature has equilibrated, the sample is not in thermodynamic equilibrium and the material exhibits increased creep rate. As the material ages, the creep rate decreases. He suggested that this may have ramifications to accelerated creep. The explanation given by Padanyi [41] is not satisfying because as shown in Figure 20 (b) even exposures to low relative humidity caused some de-aging and aging effects. This effect is probably related to that observed by Brezinski [15] of change in creep compliance after exposure to high moisture and the recovery of strain upon moisture cycling.

The last paper with significance for creep in the same transactions was that of Haraldsson *et al.* [42]. They presented a new device for conducting creep tests of paperboard in either tension or compression. One of the main focuses of research on creep had been to develop methods to conduct creep in edgewise compression while suppressing any lateral buckling. Their results show that at low load levels the tensile and compressive creep response is the same, but at high load levels there is more creep in compression. In addition, they found that in compression the strain at failure was the same for creep tests at different load levels and equal to the strain of failure from a compressive constant strain rate test. This is important because it suggests that the strain at failure can be used as a criterion for lifetime. Haraldsson *et al.* [42] utilized isometric curves to show lifetime as a function of load-level.

The second creep conference was held in 1994 at STFi in Stockholm, Sweden. This is the meeting where Sedlachek and Ellis [43] reported that there is no accelerated creep in single fibers tested in axial tension. Haraldsson *et al.* [44] presented further results on their model for the lifetime of boxes in constant humidity based on the observation that the strain at break is constant, and using isometric curves, curves of stress versus time for constant creep strain, to predict the time of failure at low load levels from high load level tests. They also advocated the use of isochronous creep curves to evaluate performance. Forsberg [45] continued the previous work of Calvin [39]

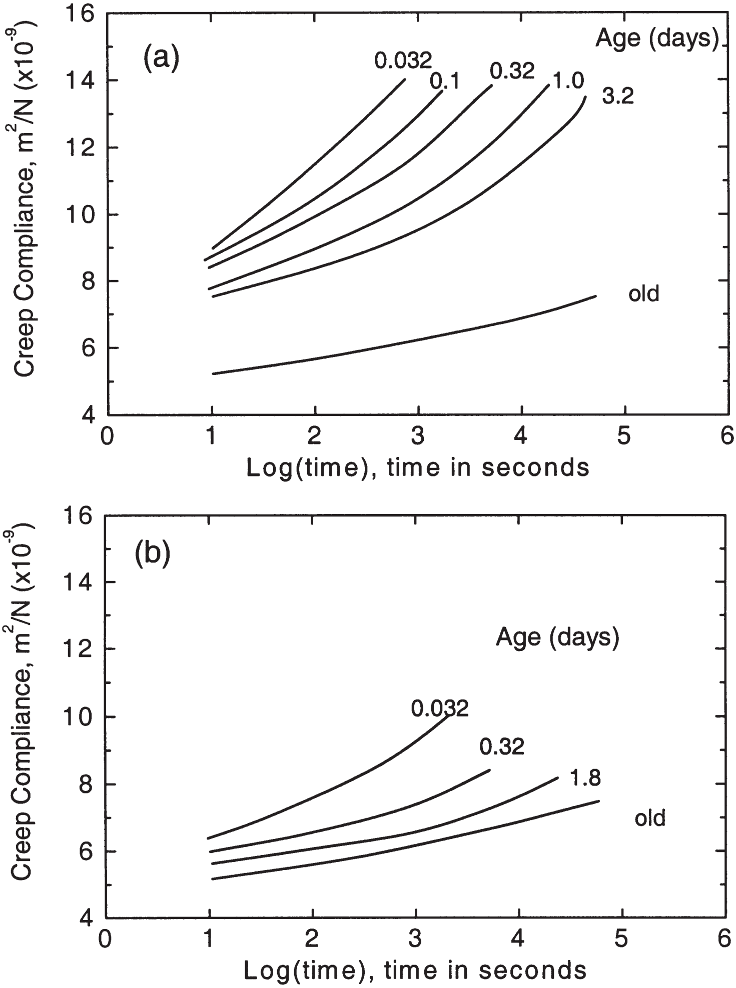


Figure 20 Physical aging of paper for both de-aging at high moisture (a) and de-aging at low moisture (b) [41].

and her results show that the large variability in results make it hard to predict lifetime based on short term results. Bronkhorst and Riedmann [46] introduced the simple equation given on Equation (13) that the lifetime of a box was inversely proportional to the secondary creep rate.

$$\text{Lifetime} = \frac{\text{A}}{\text{secondary creep rate}} \tag{13}$$

In 1997, the third meeting was held at PAPRO in Rotorua, New Zealand. Coffin and Boese [47] confirmed that single pulp fibers in tension do not exhibit accelerated creep and ascribed this to the fast sorption time of individual fibers. They also put forth a mechanistic explanation of accelerated creep based on stress concentrations and nonlinear creep behavior that supported the single fiber observations. Jackson [48] also showed that rayon fibers did not exhibit accelerated creep. Haraldsson *et al.* [49] extended the use of isochronous curves for cyclic humidity testing of boxes in compression. It is interesting to note that at this conference only about half of the papers dealt directly with creep, as compared to 100 percent for the first conference.

The fourth creep conference was held in Grenoble, France in 1999. Chalmers [50] presented creep results using a vacuum compression tester and found that both load and creep rate could be used to predict lifetime. He found that the hygroexpansion could be separated from the creep in compressive creep tests, when the sample was exposed to cyclic humidity before the application of creep load. The hygroexpansion was lower under compression than under no load. Coffin and Habeger [51, 52] presented a detailed model of accelerated creep that could explain all observed phenomena. Jackson *et al.* [53] presented a ring crush creep test. Haraldsson and Fellers [54] presented results that showed that increased density and straighter fibers increased creep stiffness. Micro-compressions in virgin fibers reduced stiffness, but had little effect with recycled fibers. Vullierme *et al.* [55] introduced a new device for measuring compressive creep in variable humidity environments by forming the paper into a rolled cylinder. As one can see this was an exciting conference for those interested in accelerated creep and the feeling at this conference was that 30 years of research were starting to pay off.

In 1999, Patel [56] presented a nonlinear model for creep of paper and corrugated board. He conducted creep and recovery tests on corrugated boxes. He found that the Schapery model, a nonlinear viscoelastic superposition functional, was capable of fitting creep and recovery data, and applied it with the finite-element method to model board in conditions of constant humidity.

Many of the papers written on accelerated creep put forth explanations for the causes of accelerated creep [37, 41, 55–60]. One can refer to [61] for a discussion of the proposed mechanisms. Everything from thermodynamic explanations, to glass transitions, to fiber bond slipping was suggested. Elements of certain explanations were appealing, but for the most part these explanations could not fully explain all the observations that had been made. The approach that Habeger and Coffin [47, 51, 52] had been developing on the mechanics of accelerated creep was published in 2000 [62]. They put forth a physical explanation for accelerated creep and showed through the use of a simple model that accelerated creep was a natural consequence of two interconnected events that occur during creep in cyclic humidity. This mechanism could also explain other mechanosorptive effects [63]. Some of the basic ideas put forth in their explanation can be gleaned from previous literature. The first observation in that the total deformation under the action of a cyclic load is greater than the creep due to the application of the mean load. The second is that changes in moisture content give rise to stress gradients (not a uniform distribution of the dead load). During creep in cyclic humidity the stress at any given point will be cycling. The overloaded regions contribute more to creep than that which is suppressed by the under-loaded regions. The net effect is an acceleration of creep during and for some time after a change in moisture. A model based on this explanation yielded accelerated creep, Padanyi's physical aging [62], and transients in the dynamic mechanical properties [63].

The last of the creep conferences was held in Marysville, Australia in 2001. Unfortunately, the proceedings have not been published, but several of the papers from that meeting were forwarded to the author for this review. Chalmers *et al.* [64] presented a study of creep of corrugated board in bending under conditions of cyclic humidity. They had success using the Pecht model [29] to fit the creep curves through the local minima of the creep data. The model worked well for predicting the creep at different load levels. Van Weert and Donkelaar [65] presented a finite-element model for both the moisture transport and creep in cyclic moisture. They utilized a nonlinear diffusion model for moisture transport and a nonlinear creep equation. The model predicted accelerated creep via the mechanism outlined in [62]. Both these modeling approaches have their advantages. The advantage of the approach taken in [64] is that it is simple and can be used to rank different papers. The advantage of the work presented in [65] is that it is fundamental and the accelerated creep is a natural consequence of the material properties, creep load, and cyclic moisture changes.

After this conference the mystery and intrigue that had been associated with accelerated creep was greatly diminished. A reasonable explanation for accelerated creep had been demonstrated to explain all observations. Interest in the subject subsided. There has been no outcry for another conference, and the lack of publication of the last proceedings seems to be indicative of the end of a chapter on creep in paper. The newest chapter is even more interesting and still challenging. The need to improve box lifetime still exists.

Understanding why accelerated creep occurs does not solve the practical problems. We still do not have sufficient knowledge to overcome accelerated creep. If we accept the simple explanation for accelerated creep, we have essentially broken the mechanosorptive effects back into separate mechanical moisture effects that can be studied independently and then re-coupled for the case of cyclic moisture.

Recently, Alfthan *et al.* [66] furthered the understanding of accelerated creep by developing a network model based on the earlier proposed mechanism [62]. They showed that the magnitude of the stresses created by anisotropic swelling of crossing fibers was sufficient to cause accelerated creep in paper. This development creates the opportunity to obtain understanding of how the network structure influences accelerated creep.

Olsson and Salmén [67] investigated creep in paper by evaluating changes in the dynamic modulus and mid to near IR spectra during creep in both constant and cyclic humidity. They found that the dynamic modulus increased with creep strain in both environmental conditions. This trend along with the results of the IR measurements suggests that the cellulose structure is re-aligned during creep. The IR results did not show any molecular differences in samples creep in either constant or cyclic relative humidity.

Urbanik [68] presented a new approach to model the creep behavior of paper that combines results of previous work and accounts for primary, secondary, and tertiary creep in compression. He first described the rates of creep for each component in terms of functions and then integrated to get creep strain. Although the equations Urbanik used are complicated, the approach is simple and work of this type may lead to equations that can be used to evaluate accelerated creep in boxes.

In 2002, Zhang *et al.* [69] confirmed many of the observations of Brezinski such as the ability to form master creep curves and the effects of wet pressing and beating. They advocate using the normalized creep compliance (creep compliance multiplied by elastic modulus), which they call the creep number to evaluate creep behavior. They evaluated the creep response of sheet made from three pulp types, one was high in hemicellulose, one was a sulphate (alpha) cellulose, and the third was a high yield kraft pulp. The creep response of these three pulps differed. Specimens made from the pulp with high lignin content crept the least, but it is not clear that this is due to the lignin or different forms of the cellulose in the pulps. Since this sheet has a tensile index that is almost twice that of the alpha pulp. Several methods of drying were used to make the sheets that included standard handsheet drying, cylinder drying, a hot-air impingement drying, and combinations of cylinder and impingement drying. Drying with high temperatures appeared to reduce the creep response of the lignin containing pulp as well as the pulp containing high hemicellulose. The authors concluded that there were no systematic changes to the creep responses based on drying conditions.

At the 2003 paper physics conference, Lehti *et al.* [70] presented results on the effect of moisture on creep. They verified the results of Brezinski [15] that the effect of moisture could be treated with logarithmic time shift that was a linear function of moisture content. They also showed that the CD creep was greater than the MD creep, but that the time-shift was only slightly larger. Their creep curves were fit using a power-law.

At the same conference, Westerlind *et al.* [71] presented an extensive study of the effect of strength additives on the mechanical properties of paper. This included CD compressive creep data for tests on cylinders carried out in a cyclic humidity environment. The results showed that the compressive logarithmic creep rate in CD was inversely proportional to the product of the CD specific longitudinal stiffness, C_{CD}, and the CD specific transverse shear stiffness, $C_{ZD\text{-}CD}$, as measured by ultrasonic methods. Using the data supplied in their tables, the inverse proportional relationship as shown in Figure 21 was obtained. (Note, Westerlind *et al.* [71] state that the relationship to related to the square root of the geometric mean stiffness, but the re-analysis as

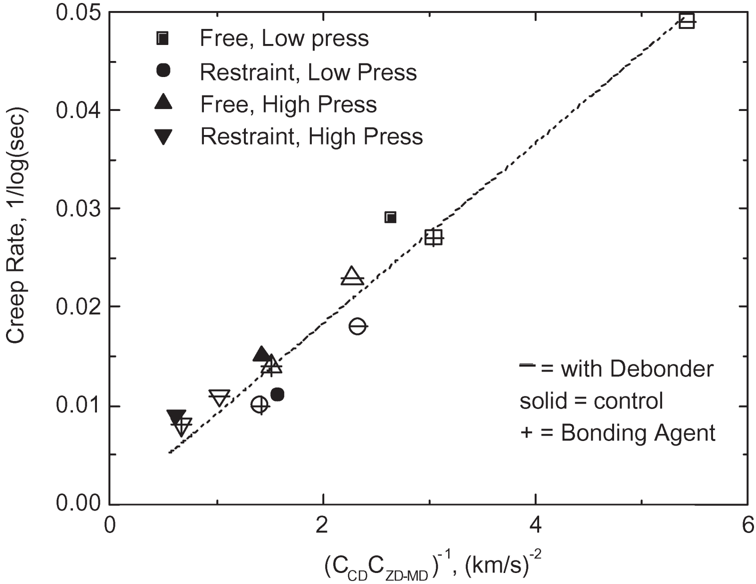


Figure 21 The logarithmic compressive creep rate versus inverse ultrasonic stiffness parameter [71].

presented here shows that it should have been stated as the square of the geometric mean stiffness.) This geometric stiffness term was chosen by Westerlind *et al.* [71] because the analysis and experimental results of Habeger and Whitsitt [72] showed that the short-span compressive strength of paper was directly proportional to this term and related to the shear instability of the layered structure. The creep rate should be related to this stiffness term inversely and the square relationship implies that that the creep rate is more sensitive to changes in this term than strength.

Since accelerated creep is just creep accentuated by a transient stress concentration, a better understanding of the inherent creep behavior of paper would be useful. This is work that was put on hold for 30 years. Prior to the discovery of accelerated creep, there were great gains in understanding the creep of paper. After that time until just recently, the gains were all made on developing experimental methods, clarifying observations, and stating general trends, but there was little progress in understanding the creep behavior of paper. Since 2000, there again have been new gains made [66, 69–71, 74]. The research direction has once again changed back towards an understanding of creep. For example, at the 2004 Progress in Paper Physics Meeting, DeMaio and Patterson [73] presented preliminary results of tensile creep testing under constant humidity on samples where he varied the degree of bonding through wet-pressing in a regime where the modulus was constant. These results showed that the same master creep curve was obtained for sheets with different amounts of bonding and the increased bonding only tended to increase the strain at which tertiary creep initiated. This is the type of work that is needed to further our understanding.

Panek *et al.* [74] recently addressed the practical methods of evaluation for creep in both constant and cyclic humidity. As they point out, there have been many different techniques used to evaluate creep. Some researchers used total deformation while others consider only the creep strain. Both master and isochronous curves are used. Lifetime, creep rates, ratios of creep rates, creep compliance and creep stiffness have all been used to characterize creep.

Use of isochronous curves is preferred by Panek *et al.* [74] for creep evaluations. In the case of cyclic moisture testing, they use number of cycles instead of time and call the curves isocyclic stress-strain curves. Their empirical equation for the isochronous curves that can be used for both tension and compression is

$$\sigma = \left[a_1 \tanh\left(\frac{a_2}{a_1}\varepsilon\right) + a_3\varepsilon \tanh\left(\frac{a_2}{a_3}(100\varepsilon)^2\right)\right]\left(\frac{t}{t_1}\right)^{-p} \tag{14}$$

where a_1, a_2, a_3 are fitting parameters, and t_1 is a reference time of 1 sec. The first term in the equation represents the small strain response and the second term in the equation represents the large strain response. The form of Equation (14) implies that the isochronous curves for different times are only scaled or that the parameters must be functions of time. Panek *et al.* [74] present six different parameters taken from the isochronous and isocyclic curves that can be used to characterize material parameters. This work presents many good ideas for one trying to characterize and compare the creep response of different materials.

There is still much we do not know about creep. The current trend towards investigating the fundamental creep response of paper will help in our efforts to improve product performance. The work being developed on methods of characterization will help in sorting out the creep response of different materials. Yet there remain insights into the creep behavior of paper found in the existing literature that have not been thoroughly exploited.

In the following sections, we will explore some of this information. In the section entitled "Tensile Creep," we will take the view of an engineer and determine how to express the effect of various parameters on tensile creep albeit with a very elementary equation. The results of this work were eye-opening for the author and hopefully the beauty the systematic nature of the tensile creep response of paper will be conveyed to the reader. After a thorough discussion of tensile creep, we focus on how compressive creep differs from tensile creep. Finally, we emphasize the mechanical explanation of accelerated creep, how the evidence in the literature supports this simple view, and stress that the whole mechanosorptive phenomena has received too much attention at the expense of basic understanding of creep under constant conditions.

TENSILE CREEP

For our discussion of tensile creep, we will use a simple empirical equation that captures the essence of the tensile creep. This equation comes with its own warning, and is only introduced so that we can evaluate the effects of various parameters such as load, degree of wet-pressing and wet-straining on the creep behavior. In addition, it was the equation used to produce the lines shown in the graphs of this section. For the present discussion, this numerical creep response is used to complement the experimental results so that we can extrapolate the experimental findings and explore the general behavior of the tensile creep of paper. The extrapolations taken here do not go far beyond what we can surmise from the literature, but it does provides a framework to

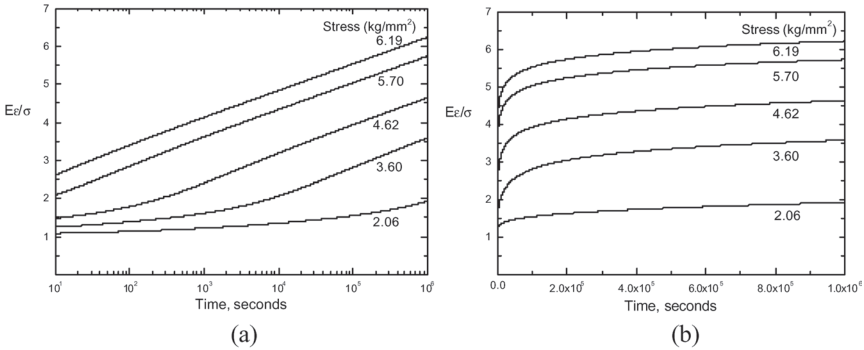


Figure 22 Representation of Brezinski's creep data [12] as the product of initial modulus and creep compliance (a) time is a logarithmic scale, (b) time is a linear scale.

unify the trends and findings of individual results from the literature and make general statements that can be confirmed or refuted with future experimental results.

As previously mentioned, Brezinski [15] conducted one of the earliest studies of creep in paper, and it is probably the most complete study of tensile creep under conditions of constant humidity. Therefore, we start with this data to provide the root input for our numerical model. Figure 22 shows the numerical representation of Brezinski's creep data [15], which is comparable to Figure 13, but shown as the creep compliance normalized with the elastic modulus. In this section, the units of stress are taken as an apparent stress equal to the mass specific stress multiplied by the density of cellulose.

Figure 22 (b) shows the creep data plotted on a linear scale to accentuate that the creep rate continues to decrease with time. When a dead load, is applied suddenly, the deformation increases dramatically, then the creep rate continues to decrease towards zero, but before it reaches failure the creep rate once again will begin to increase signaling tertiary creep. Brezinski [15] never observed a tertiary creep response in his testing, which suggests that for his tests any creep-rate increase, signaling the onset of failure, occurred at very short time intervals and was not measured. Tertiary creep in tension is typically very short in duration. Throughout the literature, there is very little evidence of tertiary creep in tension. Creep curves obtained from A. DeMaio at IPST-GIT, are illustrated in Figure 23. Creep versus time curves are given for two samples. Both samples were subjected to a tensile load equivalent to 75% of the tensile strength of the paper and conducted at constant 50% relative humidity. Both samples show tertiary creep. The tertiary creep begins

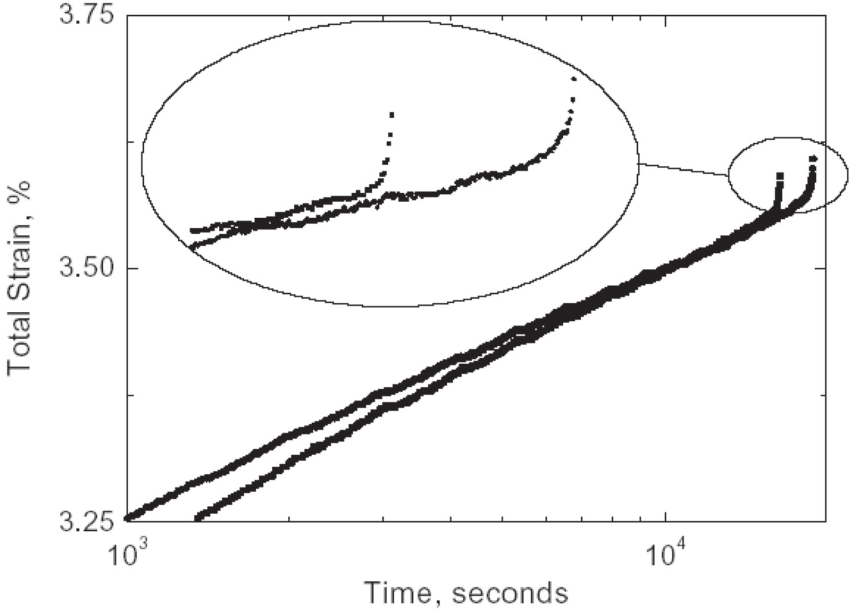


Figure 23 Example of tertiary creep in paper. Data provided by A. DeMaio (2005).

about ten minutes before failure a small time relative to a lifetime of about five hours. The tertiary strain was only 0.0005 greater than the total strain of about 0.0355. Since the amount of tertiary strain is small and the relative lapse in the logarithm of time is short, we will exclude tertiary creep in this section.

Empirical tensile creep equation

The equation used for creep is entirely empirical and was developed for use in this review. The Pecht [29] equation, Equation (11) was not used because it does not separate primary from secondary creep. Panek's [74] equation, Equation (14) was not utilized because the inversion to get a creep equation in not straightforward. Urbanik's [68] equations are written for compression and therefore also were not used. A nonlinear heredity integral possibly could have been utilized but the point of this entire exercise would have been lost in the expression of the functional.

First, assume that the initial deformation is an instantaneous linear-elastic deformation, $\varepsilon_{i\text{–}e}$, given as

$$\varepsilon_{i\text{-e}} = \frac{1}{E}\sigma \tag{15}$$

where E is the elastic modulus, and σ is the applied dead load written as stress. The modulus can be taken as that measured from a standard tensile test. Therefore, this term captures all the viscoelastic response of the material that occurs at times shorter than the initial measurements.

The expression for the primary or delayed-elastic creep is based on the observations of Brezinski [15] that the initial creep exhibits an allometric or power-law response, but that there is a limit to the amount of primary creep. Therefore, the primary creep is written as a delayed elastic response, $\varepsilon_{d\text{-e}}$, expressed as

$$\varepsilon_{d\text{-e}} = \frac{\sigma}{E_2}(1 - e^{-at^{\alpha}}) \tag{16}$$

where E_2 is an elastic modulus of the delayed response, a is a time scaling factor representing flow, and α is the exponent of the power-law behavior observed for small times. Equation (16) can be thought of as a generalization of a diffusion controlled creep process, where $\alpha = 1/2$ would hold [3]. The creep given in equation (16) is taken to be fully recoverable upon unloading. For short times, equation (16) reduced to

$$\varepsilon_{d\text{-e}} = \frac{\sigma}{E_2}(at^{\alpha}),\ at^{\alpha} << 1 \tag{17}$$

The secondary creep is also based on the observations of Brezinski [16] that long-term creep is linear with the logarithm of time, and expressed as

$$\varepsilon_s = \sigma(\tilde{B}\ln(bt + 1) \tag{18}$$

where $\tilde{B}$ is a creep flow parameter and b time-scaling factor. For long times, Equation (18) is approximately

$$\varepsilon_s = \sigma\tilde{B}[\ln(t) + \ln(b)],\ bt >> 1. \tag{19}$$

The total strain is taken as a summation of the three strain components, Equations (15), (16) and (18). In addition, a modulus term is factored out of E_2 and $\tilde{B}$, and the total creep strain is given as

$$\varepsilon = \frac{\sigma}{E}[1 + A(1 - e^{-at^{\alpha}}) + B\ln(bt + 1)] \tag{20}$$

or in terms of creep compliance

$$J = \frac{\varepsilon}{\sigma} = \frac{1}{E}[1 + A(1 - e^{-at^{\alpha}}) + B\ln(bt + 1)]. \tag{21}$$

In Equations (21) and (22), $A = \frac{E}{E_2}$, and $B = E\tilde{B}$. Given Brezinski's [15] observation that the log-rate of secondary creep appears to be independent of moisture content, it is probably not reasonable to pull the modulus out of B', but it is done anyway for convenience.

Brezinski [15] found that the dependence of creep compliance on load was proportional to a shift in the logarithm of time. To satisfy this requirement, the parameters *a* and *b* must be functions of load. The relationship between the time shift and load is written as

$$\ln(t_s = \beta(\sigma - \sigma_{ref}) \tag{22}$$

where β is the slope of the line and σ_{ref} is a reference load to which all the other creep curves are shifted. In order for the curves to shift with the logarithm of time from some time t_1 to some time t_2,

$$t_2 = t_1 t_s = t_1 e^{\beta(\sigma - \sigma_{ref})} = t_1 e^{-\beta\sigma_{ref}} e^{\beta\sigma} \tag{23}$$

must hold true. To form a master creep curve, the shift must hold for all times, and thus the functions of a and b are written as

$$a = a_0 e^{\alpha\beta\sigma} \text{ and } b = b_0 e^{\beta\sigma} \tag{24}$$

where the reference state is incorporated into the terms a_0 and b_0. Thus, our creep compliance equation that satisfies time-load equivalence can be written as

$$J(t,\sigma) = \frac{\varepsilon}{\sigma} = \frac{1}{E}[1 + A(1 - e^{-a_0 e^{\alpha\beta\sigma} t^{\alpha}}) + B\ln(b_0 e^{\beta\sigma}\, t + 1)] \tag{25}$$

Warning: *Equation (25) is for educational purposes only. It is neither fundamental to paper behavior nor applicable to any other deformation processes other than creep.*

Equation (25) represents the numerical representation for the creep behavior of paper. It has seven parameters, E, A, B, a_0, b_0, α, and β. This seems like a lot of parameters but they are needed to adequately describe (1) elastic response, (2) primary creep with (3) variable activation and (4) allometric behavior, (5) secondary creep, with (6) variable activation, and (7) load non-linearity. Once we fit this model to creep data, we can easily explore the tensile creep behavior of paper. For example, we generate isochronous curves, investigate the amount of total strain versus recoverable strain, and evaluate the influence of the papermaking process or sheet structure on the six parameters of the creep Equation (25), and with one more assumption explore lifetime.

The parameters used for the fit of Equation (25) to Brezinski's data as shown in Figure 22 are

$$E = 1000\ \text{kg/mm}^2,\ A = 1.05,\ B = 0.7/\ln(10),\ a_0 = 10^{-2}/\text{s}^{0.23},\ b_0 = 10^{-9}/\text{s},$$
$$\alpha = .23,\ \text{and}\ \beta = 1.42\ln(10)\text{m}^2/\text{kg}. \tag{26}$$

Four of the seven values, E, B, α, and β were reported directly by Brezinski [15], except the B and β are adjusted to go from base 10 to natural logarithms. The value of B was taken from the limiting recoverable creep compliance given in Figure 6 of reference [15]. The final two terms a_0, and b_0 were then chosen to give the appropriate time of activation to fit the master creep curve.

Now, armed with our creep equation we can begin to explore the tensile creep behavior of paper. Figure 24 shows the isochronous creep curves corresponding to creep response previously shown in Figure 22. The initial creep stiffness for each curve is equal to J(t,0). The creep stiffness drops as load increases. At high loads the slope of the curves are approximately equal and continue to drop. If tertiary creep were included, then at some level of strain the slope would decrease faster.

The shape of the curves shown in Figure 24 is analogous to stress-strain curves for strain-hardening materials, which have no well-defined yield point. These curves are similar to that expressed by Panek's [74] isochronous Equation (14), but there are several differences. The effect of time for the curves given in Figure 24 is not just a scaling factor as suggested by Equation (14). The inability to scale the curves in Figure 24 is due to the fact Equation (25) can not have the time dependence factored out separately. The distinction here would have consequences for modeling and the validity of the implications of Equation (14) should be evaluated. The expectation based on the results of Seth and Page [75] that stress-strain curves evaluated for different strain-dates do not superimpose, would be that isochronous curves for different times would not superimpose. The second difference is minor, but the

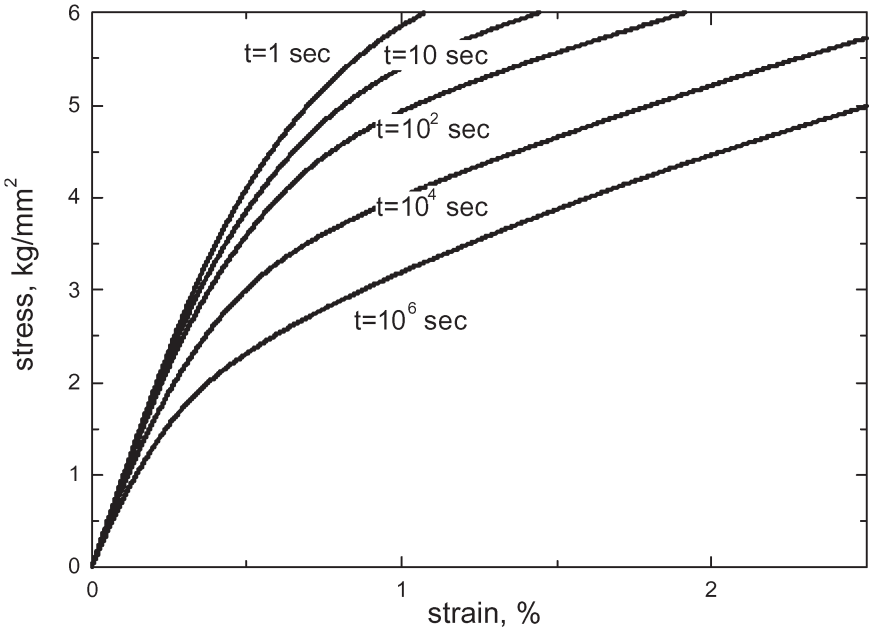


Figure 24 Isochronous creep curves based on results of Brezinski [15].

slopes of the curves in Figure 24 continue to decay, whereas Equation (14) yields a limiting constant slope.

Recoverable deformation versus total deformation

The primary creep regime is characterized by recoverable creep deformation. At small times and low load levels much of the creep is recoverable. Brezinski [15] found that after 24 hours of creep the recoverable creep plotted against total creep produced a curve that reached a limit as shown in Figure 25. In this figure, the recoverable creep and total creep are shown in dimensionless form. Brezinski [15] noted that the log-linear creep was observed to begin when the primary creep began to level off and provides some justification for the simple separation taken for the empirical equation.

Isochronous curves can also be used to show the difference between recoverable and total deformation. Figure 26 shows the isochronous curve from Figure 24 corresponding to $t = 10^6$ seconds. The curve also shows an isochronous curve for just the recoverable deformation, which includes the initial

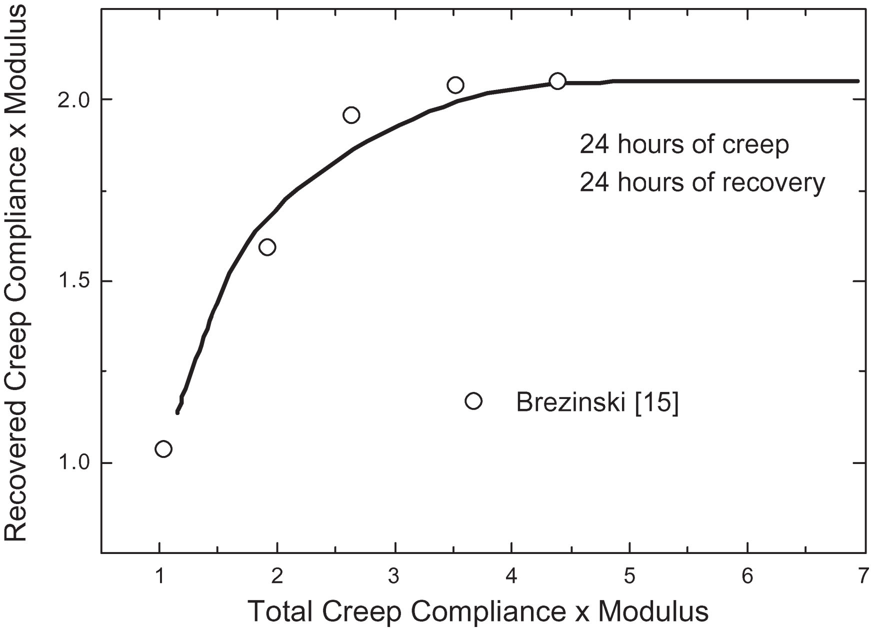


Figure 25 Recovered creep compliance versus total creep compliance. (Dimensionless parameters are the product of creep compliance and modulus).

elastic deformation and the primary creep. Now, the previous analogy of the isochronous curve to the stress-strain curve of a strain-hardening material with a transitional yield is even more appealing. The "yielding" in the isochronous curves are the transition from primary to secondary creep, and the strain-hardening is the secondary creep. Consider the shifting of the primary creep to intersect the total creep curve as shown by the dashed line in Figure 25 for a load of 4 kg/m^2. The intercept with the strain axis gives the separation between the recoverable and permanent strain. One would expect the isochronous curve for the creep-hardened sample to follow the dashed line and then the solid line. This would agree with the observations of Brezinski [16] that the strain hardening effects were only observed for loads lower than first creep load.

A method of approximating the effect of creep hardening now can be developed. If we ignore any changes in properties that may occur due to the hardening such as a slight increase in modulus, the main effect should be a logarithmic time shift of only the secondary creep. The time shift is obtained from Equation (19) assuming that the time needed for secondary creep to re-

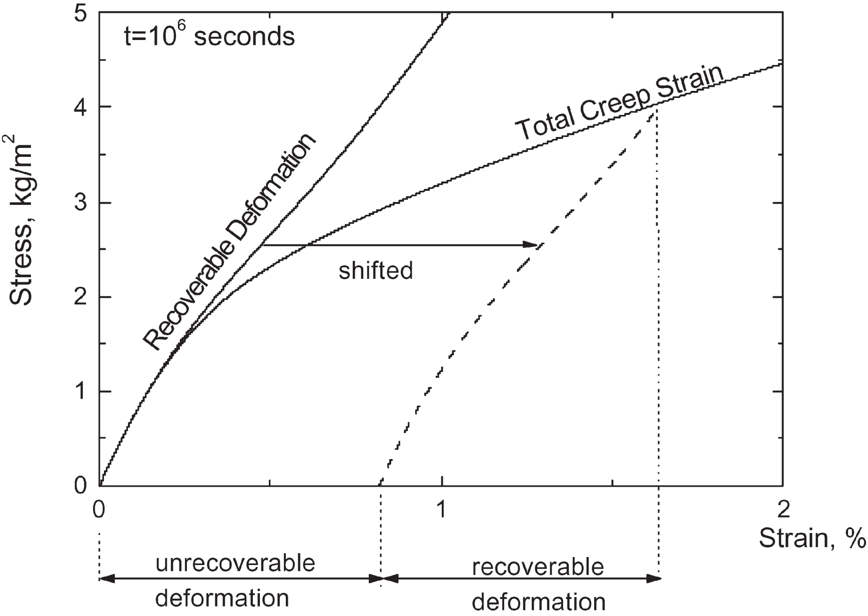


Figure 26 Demonstration of concept for creep-hardened isochronous curves.

activate in the hardened sample would be increased by the time that was initially required to create the plastic strain at any given load level. In this case, the time shift is written as

$$\log(t_s) = \frac{E\varepsilon_p}{\sigma B} \tag{26}$$

where, ε_p, is the amount of permanent creep experienced during creep-hardening step.

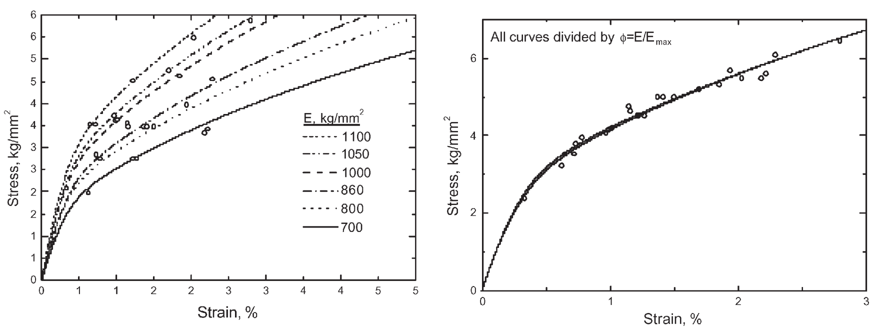
$$J(t, \sigma, \varepsilon_p) = \frac{\varepsilon}{\sigma} = \frac{1}{E}\left[1 + A(1 - e^{-a_0 e^{\alpha\beta\sigma} t^{a}}) + B \ln(b_0 e^{\beta\sigma - \frac{E\varepsilon_p}{\sigma B}} t + 1)\right] \tag{27}$$

Equation (27) will produce work-hardened creep curves. The actual behavior of hardening is more complex than described in Equation (27) and shown in Figure (26), but the essence of hardening is captured. Based on the discussion of results by Brezinski [15], the time shift factor may also change with hardening. Further testing of creep-hardening is required to fully understand the effects.

Wet-pressing

Brezinski's isochronous curves for sheets wet-pressed to different levels are shown in Figure 27 (a) along with the empirical fits. Seth and Page [75] showed that the stress-strain curves of paper scaled with an efficiency factor if only bonding is changed. If we scale each of these curves by an efficiency factor of $\phi = E/E_{ref}$, the isochronous curves collapse to form one curve as shown in Figure 27 (b). The term E_{ref}, refers to the value of the modulus used in the original fit as given in Equation (26). The parameter β could be adjusted to correspond with the case of maximum modulus, $E_{ref} = E_{max}$, so that the efficiency factor $\phi = E/E_{max}$ has a maximum value of one $\phi=E/E_{ref}$. This scaling of the isochronous curves implies that the effect of wet-pressing or degree of bonding on the creep curves can be accounted for with an efficiency factor that describes how well the network carries the load. It also implies that the changes in bonding only change the amount of load carrying material in the sheet and thus should be accounted for by only scaling the load by the ratio of elastic modulus, ϕ. This factor ϕ could be interpreted as a stress concentration factor, such that the real stress is the average stress divided by the factor ϕ.

The empirical creep compliance described by Equation (27) can easily be modified to account for changes in sheet efficiency arising from bonding



(a) (b)

Figure 27 Isochronous curves for different degrees of wet-pressing as observed by different elastic modluii: (a) isochronous curves, (b) scaled isochronous curves. Open circles are taken from [15]. Lines represent fit of Equation (29).

simply by multiplying the stress by the factor ϕ. Thus, Equation (27) becomes

$$J(t,\sigma,\varepsilon_p,\phi)=\frac{\varepsilon}{\sigma}=\frac{1}{E}\left[1+A\left(1-e^{-a_0 e^{\frac{\alpha\beta\sigma}{\phi}}t^a}\right)+B\ln\left(b_0 e^{\frac{\beta\sigma}{\phi}\frac{E\varepsilon_p}{\sigma\mathrm{B}}}t+1\right)\right] \tag{28}$$

or we can write the modulus in terms of the reference modulus and obtain

$$J(t,\sigma,\varepsilon_p,\phi)=\frac{\varepsilon}{\sigma}=\frac{1}{\phi E_0}\left[1+A\left(1-e^{-a_0 e^{\frac{\alpha\beta\sigma}{\phi}}t^a}\right)+B\ln\left(b_0 e^{\frac{\beta\sigma}{\phi}\frac{E\varepsilon_p}{\sigma\mathrm{B}}}t+1\right)\right]. \tag{29}$$

The lines shown in Figure 27(a) were evaluated using Equation (29) with the modulii reported by Brezinski [15] and given in the Figure 27(a). The other parameters remained unchanged as given in Equation (22). The agreement is adequate, and we have captured the essential effect of changing bonding on the pre-tertiary tensile creep response of paper. Although the last statement requires many qualifiers it is quite a striking statement. In fact, it is worth restating for emphasis. The effect of decreased bonding in the sheet is accounted for simply by a magnification of the stress by the inverse of the efficiency factor.

The implication of this result is that sheets that are less efficient in carrying load will be more creep compliant because the creep curves will be shifted to shorter times. In addition, the increase in creep rates will be inversely proportional to the change in elastic modulus. If the product of creep compliance and modulus are plotted, the resulting curves for sheets with different efficiency factors will only be shifted in time. The magnitude of the time shift will be inversely proportional to the efficiency factor. Figure 28 shows creep curves for different efficiency factors using Equation (29) with the parameters given in Equation (22).

Wet-straining

Shultz [16] studied the effect of wet-straining, and some results were previously shown in Figure 15 and 16. To understand the effect of wet-straining on the creep response, the data was scaled to see if they could be shifted to a master creep curve. By forming the product of creep compliance and elastic modulus, the resulting curves could be shifted to form a master curve as shown in Figure 29. This implies that wet-straining can be described by both the change in modulus and a logarithmic time shift. For the results of Shultz

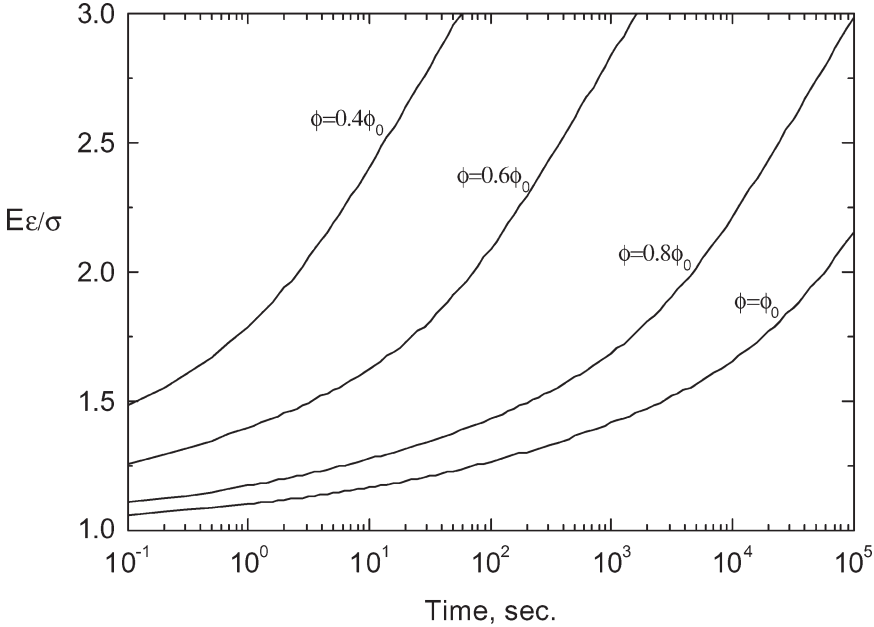


Figure 28 Creep curves for different network efficiency factors.

[16] the time shift was linearly related to the degree of wet-straining. Thus, one can extrapolate back to zero wet-straining and obtain a shift factor that is proportional to the degree of wet-straining. This fit and extrapolation are shown in Figure 30. For Shultz's results the change in elastic modulus with degree of wet-straining could be approximated with a line and the resulting equation was

$$E = 36DWS + 625\ kg/m^2 \tag{30}$$

where DWS is the degree of wet-straining in percent.

Now the creep curve for zero wet-straining can be determined and is shown in Figure 31.

The effect of wet-straining is easily added to our empirical equation as follows. Equation (29) was fit to the curve given in Figure 30 and the parameters were obtained as

$$\begin{aligned}&A = 1.4,\ B = 0.9/\ln(10),\ a_0 = 10^{-2}/s^{0.26},\ b_0 = 10^{-9}/s,\ \alpha = .26,\\&\text{and } \beta = 2.42\ln(10)\mathrm{m^2/kg},\ \varepsilon_p = 0.\end{aligned} \tag{31}$$

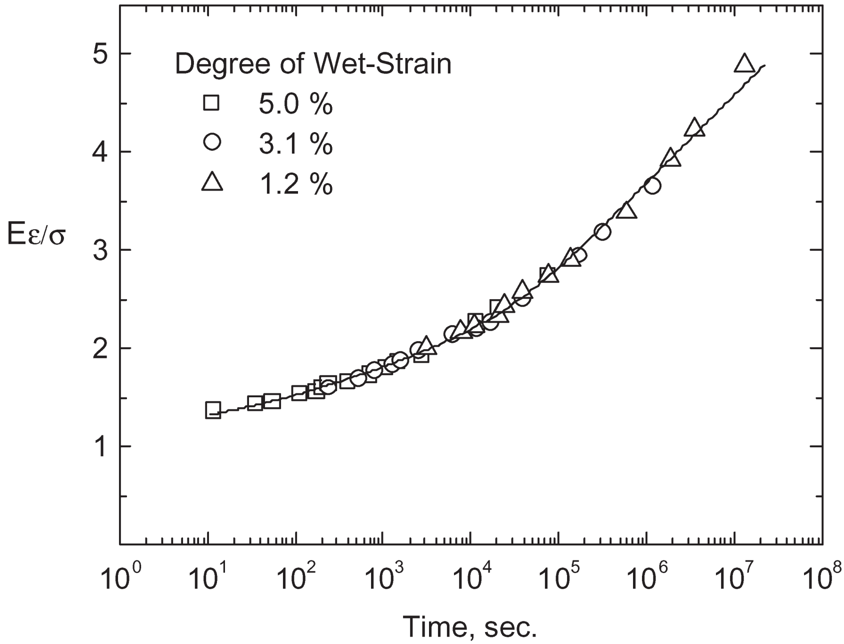


Figure 29 Shifting of creep curves for different degrees of wet-straining for data from Shultz [17] and load level =2.6 kg/mm^2.

The values of elastic modulus were given by Shultz [16] for the three levels of wet-straining of 1.2, 3.1, and 5.0% as $E = 663$ kg/mm^2, 750 kg/mm^2, *and* 800 kg/mm^2 respectively, the extrapolated value at DWS = 0 was 625 kg/mm^2. Because there is only data at one load level, the value of a_0 and b_0 could not be determined independently from β so the values of a_0 and b_0 were taken from the previous fit of Brezinski's data.

Equation (29) can be expanded to account for wet-straining by allowing the modulus to be a function of wet-straining and having a logarithmic time shift for the DWS. This shift could easily be written in terms of a change in stress, $\Delta\sigma_{DWS}$, which is a function or the degree of wet-straining.

$$J\,(t, \sigma, \varepsilon_p, \phi, DWS) = \frac{1}{E(DWS)}\left[\,1 + A\left(1 - e^{a_0 e^{\frac{a\beta(\sigma - \Delta\sigma_{DWS})}{\phi}} t^{a}}\right) + B\ln\left(b_0 e^{\frac{\beta(\sigma - \Delta\sigma_{DWS})}{\phi}}\, e^{-\frac{E\varepsilon_p}{\sigma B}}\, t + 1\right)\right] \tag{32}$$

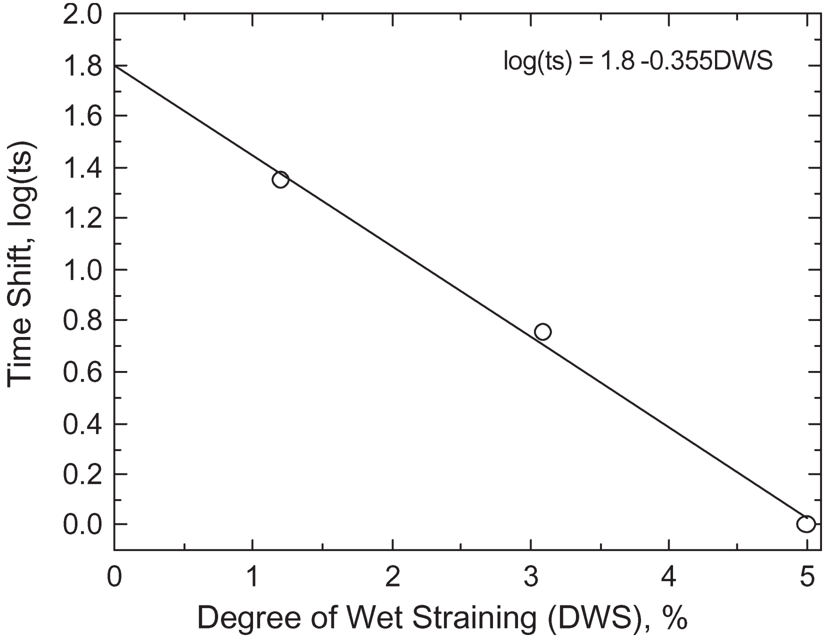


Figure 30 Logarithmic time shift as a function of degree of wet-straining with extrapolation back to restraint dried condition (DWS = 0%) and a reference state of 5% DWS.

For the data of Shultz [17], $\Delta\sigma_{DWS}$ 14.68DWS kg/m^2. It is conjectured that the term $\Delta\sigma_{DWS}$ may be related to the increase in drying stress accompanied with increased degree of wet-straining.

Based on Equation (29) with the above fitting parameters, isochronous creep curves for different degrees of wet-straining were determined and are given in Figure 32. The dashed line represents a scaling of the wet-strained sheet by the ratio of initial elastic moduli. Wet-straining does not produce isochronous curves that are scalable. This is in contrast to the effect of wet-pressing. This implies that wet-straining changes the properties of the fibers and changes the general shape of the isochronous creep curves. This result is not unexpected since the same thing holds for the stress-stain curve of paper [75].

The importance here is the reason that the isochronous curves do not superimpose. The effect of wet-straining on initial elastic modulus is different than the effect on the time shift and thus, the shape of the resulting isochron-

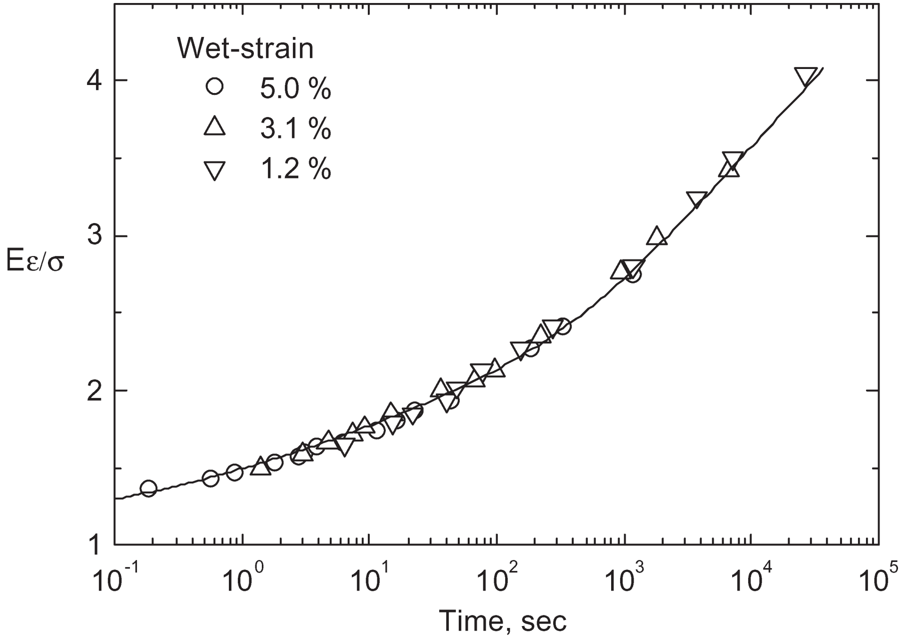


Figure 31 Master curve for product of creep compliance and modulus for fully restraint-dried sheet extrapolated from data of Shultz [17] and load level = 2.6 kg/mm^2.

ous curves is fundamentally different. This is in contrast to the effect of wet-pressing where the time shift factor was the ratio of modulii. This is indicative of the role of inter- and intra-fiber effects on the tensile creep response of paper. It is also note-worthy that by scaling the creep compliance with the elastic modulus a master creep curve was formed and thus the effect of wet-straining can be predicted.

The discussion given above is fine as long as the moisture is held at a constant value where no release of the hardening occurs. As was shown in Figure 14, increased moisture removes the hardening effects. This can be understood much better if we look at Brezinski's data, shown in Figure 14, as a function of moisture content rather than relative humidity. Luckily, Brezinski [15] reported the corresponding moisture contents for both his unconditioned and preconditioned samples. Figure 33 shows the plots.

Because of the hysteresis in the moisture–relative humidity relationship, the points shift from Figure 14. Whereas Figure 14 was not very enlightening,

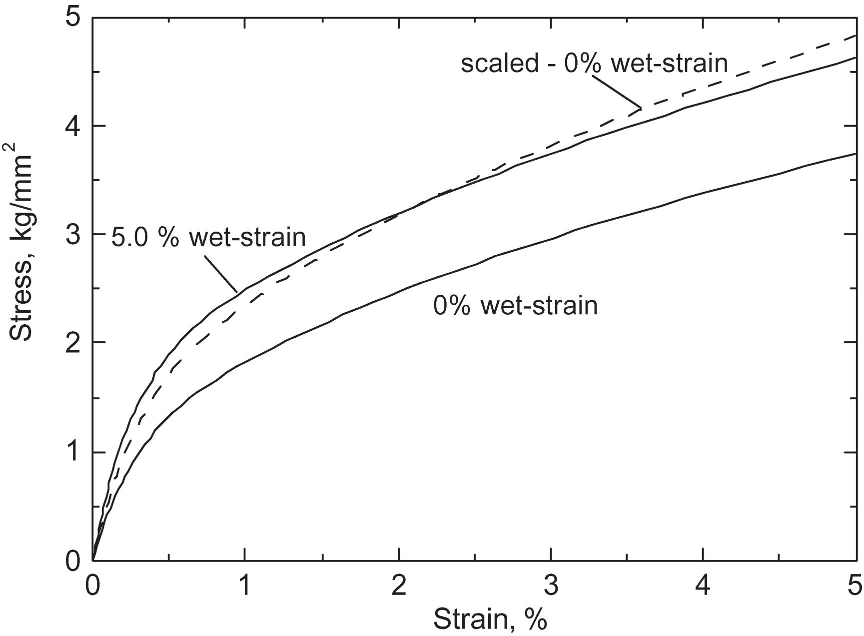


Figure 32 Isochronous creep curves for two different degrees of wet-straining.

Figure 32 reveals the release of dried-in strains during creep. The preconditioned samples appear to produce smooth curves of creep versus moisture content with no break in them. The unconditioned samples have the break. At low moisture, it appears that the previous hardening has only shifted the curve to higher moistures. At high moisture content, it appears that the curve is shifted to lower moistures. In the middle range of moisture, the break is adding another strain. The interpretation of this behavior is, of course, that the "creep" strain causing the break is a release of previous restraint dried into the sheet. Higher moisture contents lead to release of more restraint. This causes the creep curve of the unconditioned sample to go from one being hardened to one of effectively being softened. Both the total creep and the delayed creep exhibit the same behavior. Figure 34 shows the difference between the total creep and the delayed creep, merely it is the creep at 10 seconds. This too shows the same effect. In addition, it appears that the release of restraint on the short time creep continues at higher moistures.

The release of the dried-in-strains occurred over the entire 24-hour creep test, such that it increased the slope of the creep versus logarithm of time for

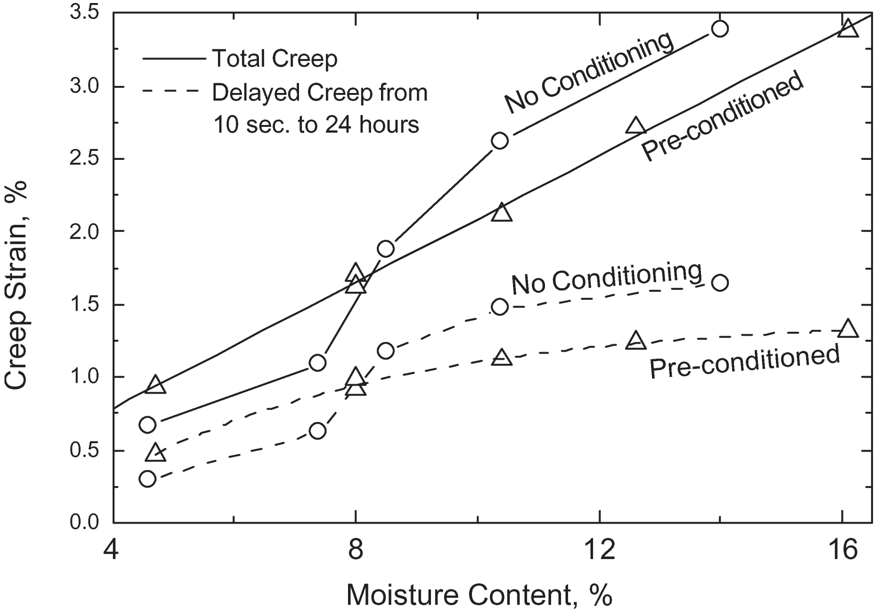


Figure 33 Total creep and delayed creep as a function of moisture content for both unconditioned and preconditioned sheets (Data from [15]).

the secondary creep. This is illustrated in Figure 35. Brezinski [16] found that for the test at 23.5% relative moisture for the sheet preconditioned with high moisture, log-linear creep was not observed over the 24-hour test period. At some time frame, it is presumed that log-linear creep would occur, so the graph is extrapolated back just to accentuate the effect that of dried-in strains on hardening at lower moistures and softening at higher moistures.

Fiber orientation

The results in the literature, such as previously shown in Figure 18, show that MD creep stiffness is greater than CD creep stiffness (CD creeps faster). In machinemade papers this difference is due to both drying restraint and fiber orientation. To assess the affect of fiber orientation separately from drying restraint we can look at results for two sets of sheets, one of which was previously reported [76]. The first set consisted of oriented handsheets (Figure 36(a)), and the second set of sheets [76] were made on a pilot machine

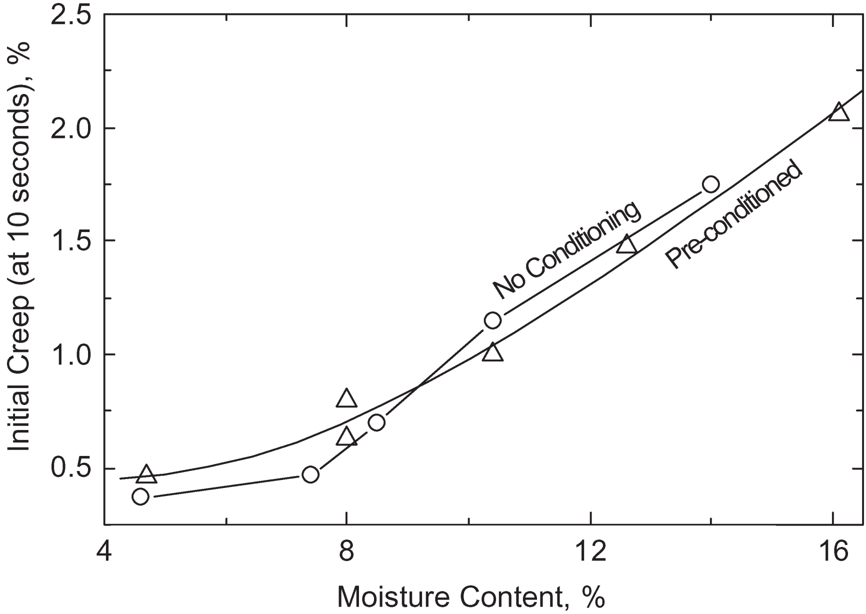


Figure 34 Creep at 10 seconds as a function of moisture for unconditioned and preconditioned samples.

Table 1 Properties of two pulps used for fiber orientation study.

	Pulp 1	Pulp 2
MD/CD ratio of Modulii	1.5 and 2.7	1.1 and 1.5
Grammage, g/m^2	96	105
Density, g/m^3	0.48	0.8
Creep load, N/mm	0.59	0.96

but the wet sheets were cut into sheets and dried under full restraint (Figure 36(b)). Some of the properties of the sheet are given in Table 1.

Both sets of sheets were produced from unbleached kraft pulp. For each pulp, there were two different orientations, and the geometric mean elastic modulus was constant for a given pulp. For all the data CD, creep was greater than MD creep. For the highly oriented sheet, the creep is significantly higher. For the pilot machine sheets, which both have low orientation; the geometric

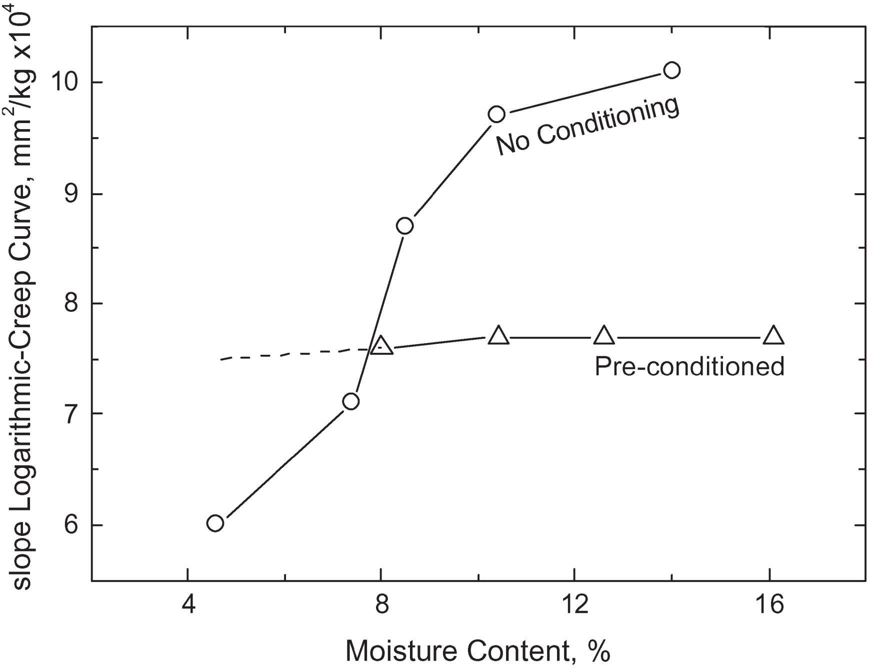


Figure 35 Effect of release of dried-in strains during the creep test on secondary creep rate (strain/log(time)).

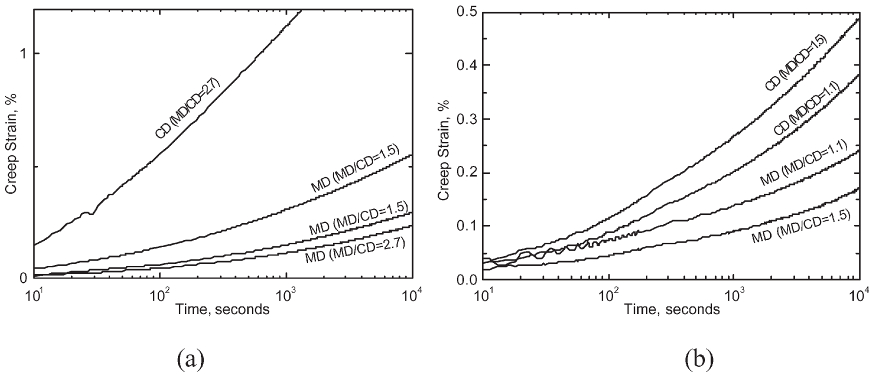


Figure 36 Effect of fiber orientation on creep for (a) pulp 1 and (b) pulp 2.

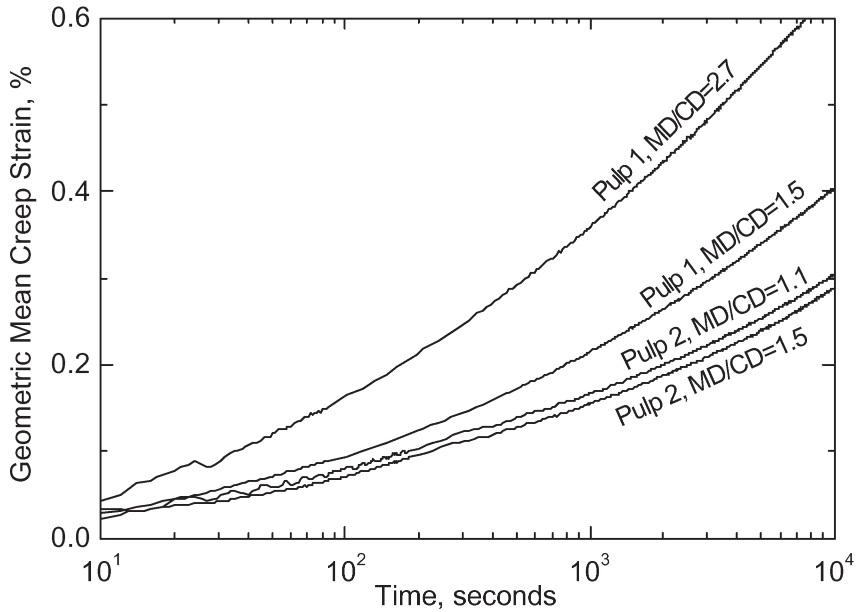


Figure 37 Geometric mean creep response for pulps 1 and 2 at different orientation levels.

mean creep is fairly constant, Figure 37, with pulp two, the geometric mean creep for the highly oriented sheet is much larger than that of the sheet with lower orientation ratio. The effect of orientation can not be accounted for with simply a time shift. It is possible to scale the creep results to get creep curves that are of similar magnitude to each other, scaling the CD curves by the inverse of the MD-CD ratio of elastic modulii squared brings it close to the MD curve. To understand the role of fiber orientation on the creep response requires additional testing.

Example using normalized creep compliance

The use of the normalized creep compliance, the product of elastic modulus and creep compliance, would be useful for interpreting differences in creep behavior. This is the point emphasized by Zhang et al. [69]. We have already observed that bonding changes only create logarithmic time shift of the normalized creep compliance. Insight into the creep differences in sheets made from either virgin or once-dried fibers can also be attained by comparing

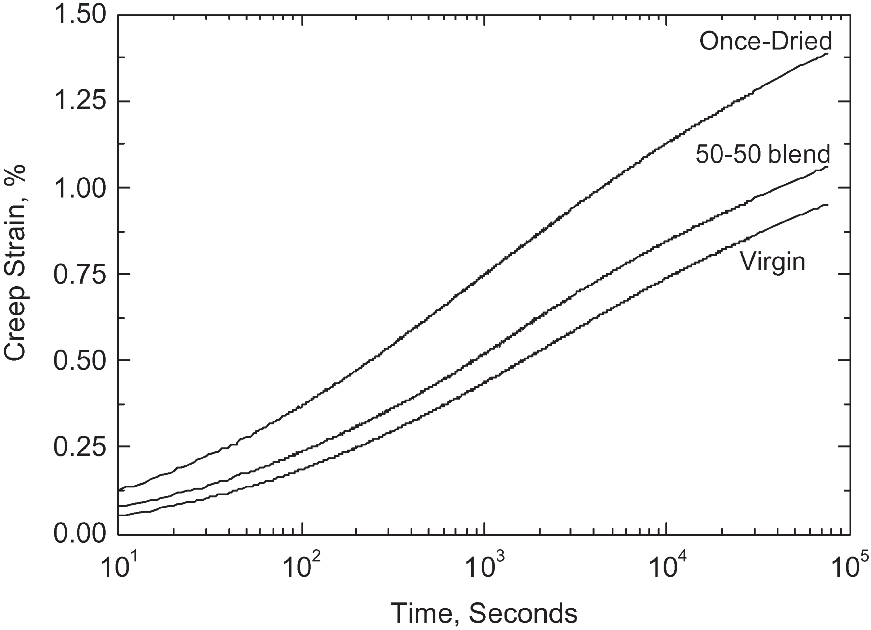


Figure 38 Comparison of tensile creep in sheets made from virgin, once-dried, and a 50–50 blend of fibers [77].

normalized creep compliance. The creep data from a previous study [77] was utilized for this example. In that study, a source of virgin unbleached softwood fibers were made into handsheets and dried under restraint. Some of the handsheets were then re-pulped and re-made into new restraint dried handsheets. Additional sheets were made of a 50–50 blend of the two fiber sources.

Figure 38 provides the tensile creep curves for the samples all tested at the same load level. Note the creep in the sheets with once-dried fibers is greater than the sheets made with the virgin fibers. The 50–50 blend is in between these two sheets. These creep curves were then scaled to the ratio of elastic modulus to that of the virgin sheet ($\phi = 0.77$ for once-dried and 0.966 for 50–50 blend). The result is given in Figure 39. These scaled sheets appear to differ only by a logarithmic shift in time. A shift of $\log(t) = 0.5$ for the once-dried sheets, and $\log(t) = 0.3$ for the 50–50 blend were required. The shifted curves are shown in Figure 40. The time shifts do not correspond with just a scaling

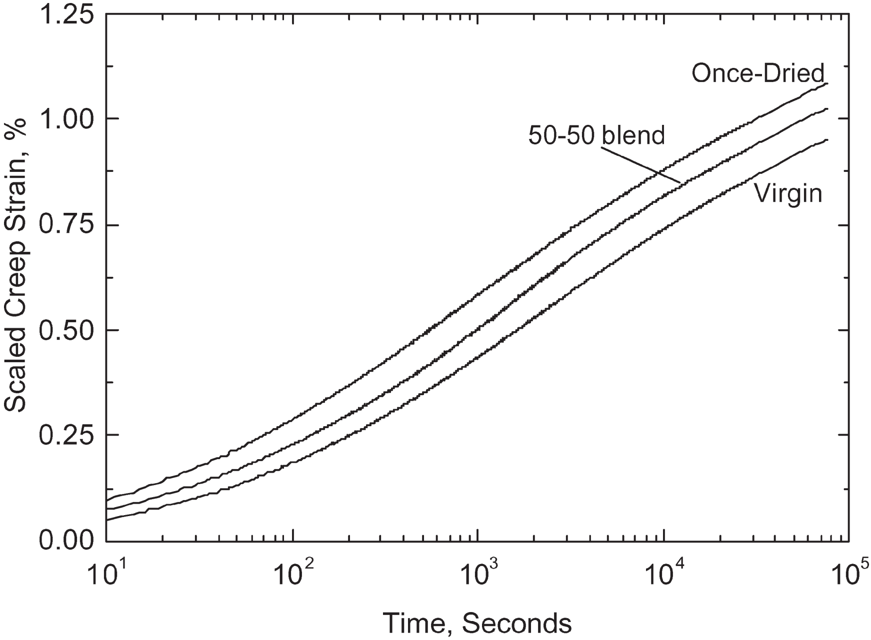


Figure 39 Creep curves scaled by ratio of elastic modulus.

of the load factor by $1/\phi$. Therefore, the differences in the effects of using once-dried fibers is likely to be caused by more than just changes in bonding efficiency. One could speculate that lack of bonding in the once-dried fibers causes an increase in creep rate, but that some of this is offset by some type of hardening so that the time shift is not as large as would be expected just based on bonding differences. However, with the limited data, no firm conclusions can be made. The point is that using the normalized creep compliance may give better interpretation of data.

Lifetime

If we use the observation that failure occurs at the same total strain regardless of load level [42], lifetime can be predicted using Equation (29). For tension we take the maximum strain to be the stretch. Putting the stretch in as the creep strain in Equation (29) yields a relationship for lifetime as a function of load level. This relationship is investigated in the following using the previous fits of data from references [15] and [16].

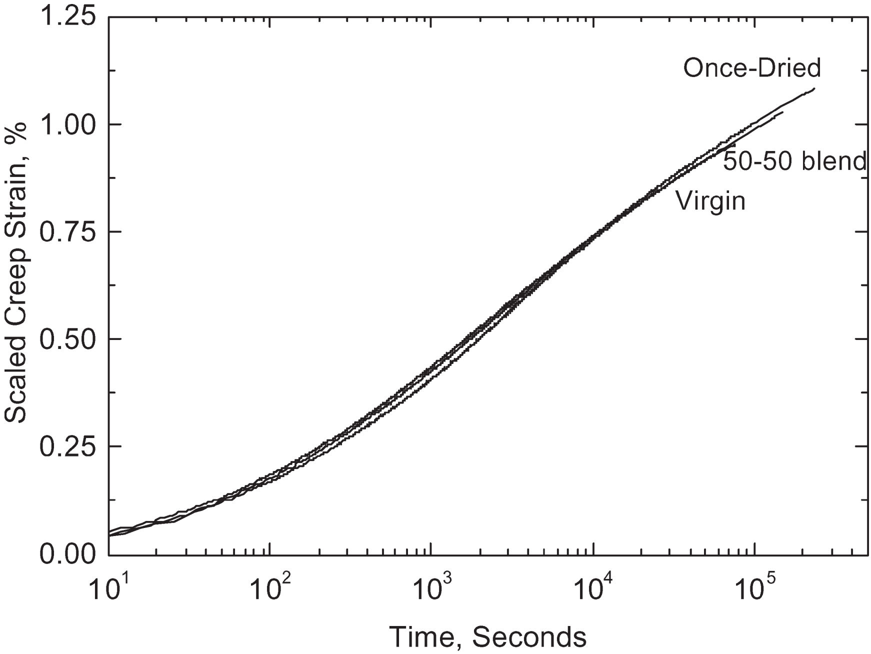


Figure 40 Shifting of scaled creep curves from Figure 39.

Creep hardening as accounted for in Equation (29) has essentially no effect on lifetime. Hardening lowers the stretch and to first order the stretch would decrease by the previous amount of permanent strain created in the hardening process. A sample with no hardening and one that is hardened would reach their respective failure strains at approximately the same time. Figure 40 show creep curves for samples with no hardening as the solid lines, for several load levels using Equation (29) with the fitting parameters given in Equation (26). The dashed lines in Figure 41 represent creep curves for samples creep-hardened by 0.5% permanent strain. Note, Brezinski [15] shows the failure strain to be approximately 3% for this paper and thus for the hardened sample the failure strain would be reduced to 2.5%. For the highest load level shown in Figure 41, the curves reach their respective maximum strains at the same time. Creep hardening could improve lifetime if the hardening lowers the logarithmic slopes of the creep curves or decreases the rate of primary creep accumulation.

Changes in the efficiency factor have a major impact on lifetime. Figure 42

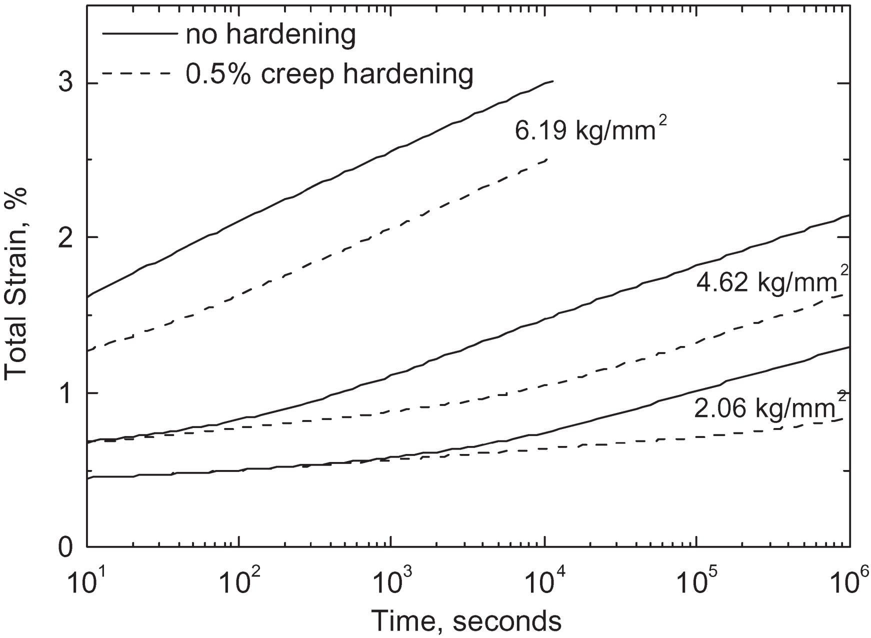


Figure 41 Creep curves showing effect of hardening on lifetime.

provides isometric curves for lifetime versus load level for two efficiency factors. For a given stretch, the isometric curves scale with load. For example, in Figure 42 the curve corresponding to $\phi = 0.7$ and $\varepsilon_{max} = 3\%$ is obtained from the curve of $\phi = 1$ and $\varepsilon_{max} = 3\%$ by simply scaling the load by 0.7. But if the efficiency factor decreases, so does the stretch, and this loss of stretch would further decrease lifetime, as illustrated in Figure 40 by the curve corresponding with say $\varepsilon_{max} = 2.25\%$. For a given load, the drop in lifetime can be several orders of magnitudes! The loss in stretch could be determined from the stress-strain curve of the fully efficient sheet. For a sheet with efficiency less than one, the stretch equals the strain from the fully efficient curve determined at a stress level equal to the tensile strength of the sheet with lower efficiency divided by its efficiency factor. It is of interest to note that the load required to reach a lifetime of 1 second was equal to the tensile index of the sheet for the case of $\phi = 1$ shown in Figure 41. This is the only strength value that can be gleaned from [15].

The influence of wet-straining on lifetime can be determined using the fit of Shultz's [16] data. For the creep curves shown in Figure 29, Shultz

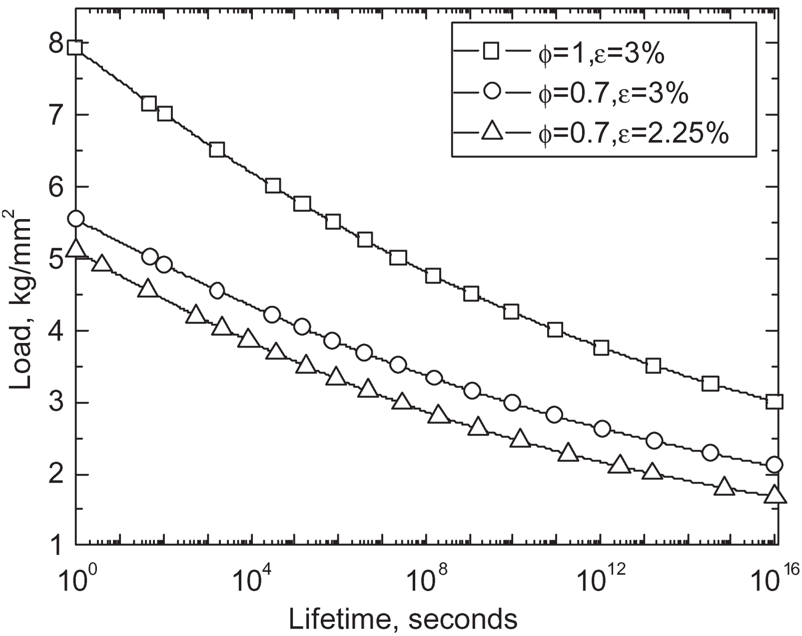


Figure 42 Influence of efficiency factor on lifetime. Data generated using Equation (29) with parameters given in Equation (22).

reported the strain and break and the tensile strength. This data along with the parameters given in Equation (31) were used to produce the isometric curves given in Figure 43. Equation (31) was used to produce the isometric curves. The curves given in Figure 43 show that there is not a systematic trend for the effect of wet-straining on lifetime. There is a shift to longer lifetimes for wet-straining from 1.2% to 3.1%, but that gain is lost for wet-straining to 5%. The tensile strength was a maximum at a wet-straining level of 5.1%. This result needs to be further investigated. If the lifetimes had been predicted using a linear fit of stretch as a function of degree of wet-straining, very little differences in lifetime would have been predicted for the three cases shown in Figure 43. The variability in stretch for Shultz's [16] data is fairly large and this accounts for the differences in lifetime at a given load.

From the data shown above, it is clear that the efficiency factor will have the largest impact on lifetime. This is because as the efficiency factor increases both the stretch and the creep stiffness increase to produce a longer lifetime. With hardening from either previous creep or wet-straining, the creep stiffness increases, but the stretch decreases and lifetime are not affected much. Therefore, changes in bonding should be a dominate factor in lifetime.

COMPRESSIVE CREEP

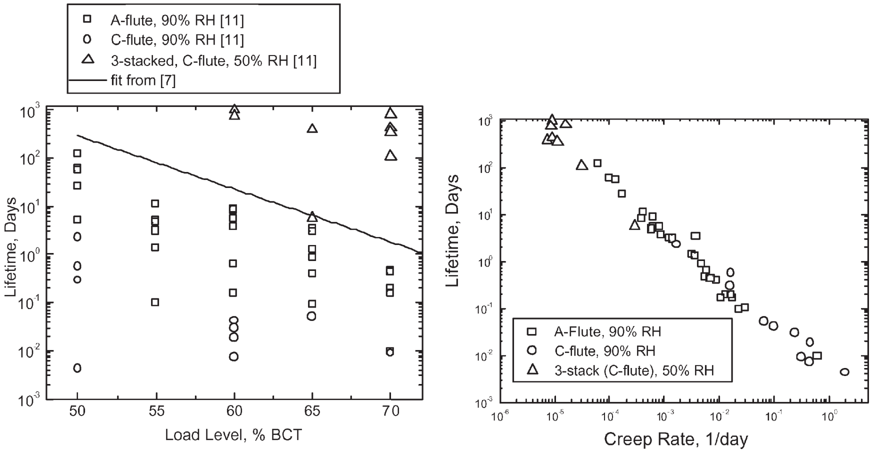
The simplicity associated with the tensile creep test is replaced with complexity when testing paperboard in compression. The challenge for creep testing in compression is to adequately deal with buckling. Many interesting and varied apparatuses have been developed to carry out compressive creep studies that inhibit, control or embrace the buckling of the paper. Compressive creep is of interest for packaging, especially in corrugated boxes. Creep of boxes, corrugated board, or the paperboard itself is studied in an attempt to determine how to improve performance.

Box lifetime

The first compressive creep tests were on corrugated boxes [6,7]. As Figure 12 demonstrated, box testing requires no special testing equipment. For box testing, buckling or bowing of the side panels is allowed because it mimics field performance. The structure of the box provides the resistance to buckling allowing the creep test to be carried out without special equipment. The box creep test is actually a simpler test than the tensile creep test. If a tensile test is a stallion, than the box test is a Clydesdale as it has been the workhorse for industry.

Kellicutt and Landt's [7] results for compressive creep of boxes in constant humidity show the three distinct regions of primary, secondary, and tertiary creep. The secondary creep was approximately linear with time. Contrast this constant creep rate to the strong decay of rate found for tensile tests. Bulging of the box side panels was observed during secondary creep. Tertiary creep was in clear evidence in compression. Kellicutt and Landt [7] found that load level had a profound effect on the lifetime of boxes. At load levels below about 75% of the box compressive strength, the logarithm of lifetime was a linear function of load. The relationship between load and lifetime was associated with high variability.

Koning and Stern [11] found that the secondary creep-rate was a much better predictor of lifetime. Their empirical relationship was that lifetime was proportional to the secondary creep rate to a power, –1.038. This relationship was valid for single containers, stacks of three boxes, empty or filled boxes, boxes constructed of A- or C- flute, two adhesives, various load levels, and two environmental conditions. That is an impressive array of conditions for



(a) (b)

Figure 43 Box lifetime versus load level (a) and secondary creep rate (b) for data from Koning and Stern [11].

which the relationship held, and Koning and Stern felt that the relationship was fairly general. Figure 43(a) shows data from their analysis along with the fit from [7] for lifetime as a function of load level. Figure 43(b) shows the same data plotted as a function of secondary creep rate.

One of the reasons for the improved fit when using creep-rate is simply because both the creep-rate and lifetime are measured quantities from the test. The load is prescribed, but the variability from sample to sample will affect both creep rate and lifetime. The other reason is that the relationship between creep rate and lifetime appears to be rather insensitive to moisture conditions and box type. This implies that there is a certain deformation at which the box will fail regardless of conditions.

Leake [78] found that lifetime was proportional to the secondary creep rate raised to a power, –0.957. For cyclic humidity, he found a similar relationship, but the power was –1.121. A follow-up study by Leake and Wojcik [79] found similar results again with the power of –1.206. In addition, they conducted edgewise-compressive creep tests on samples of combined board and found lifetime proportional to the secondary creep rate raised to the power –1.175. Another interesting result of this study [79] was that the combined board tests gave longer lifetimes at the same secondary creep rate, implying that the failure strain is larger in the ECT creep test than the BCT creep test.

Bronkhorst [80] reviewed the previous data and completed additional studies of box and board lifetimes. He noted that when looking at the studies relating lifetime to secondary creep rate, all the empirical relationships could be approximated as

$$T = d\dot{\varepsilon}_{sc}^{-1} \tag{33}$$

where

d = the total amount of secondary creep developed during the box's lifetime

$\dot{\varepsilon}_{sc}$ = the secondary creep rate.

The appeal of this equation is that it has a physical interpretation. If the secondary creep rate is constant, then the term d given in Equation (33) represents the magnitude of the secondary strain at the point of failure. This was referred to as the ductility by Bronkhorst [80]. The data supports this

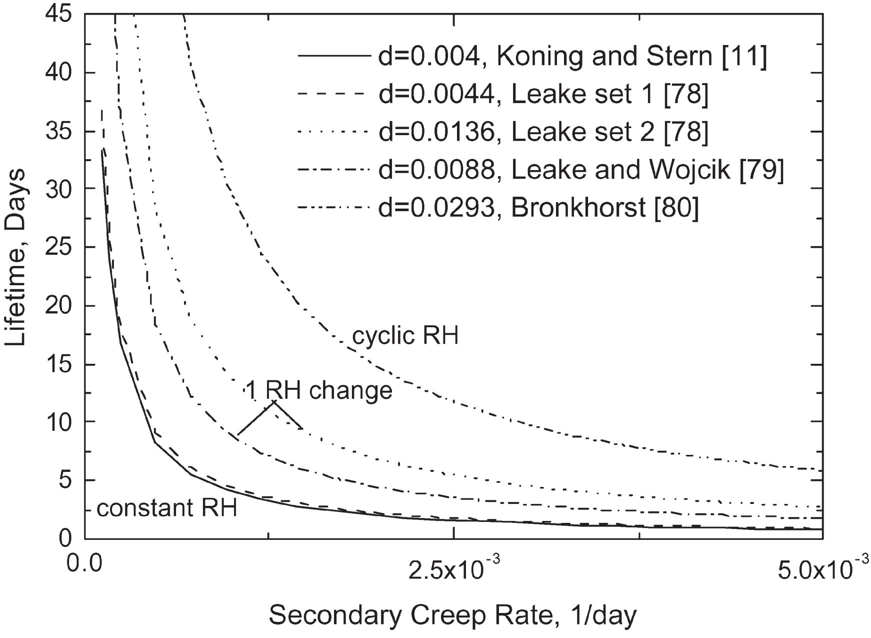


Figure 44 Creep rate versus lifetime curves using fits of Equation (33) to results in the literature (based on results in [80]).

equation since failure occurred at the same ductility, *d*, independent of load level. From the results in the literature, it appears that boxes in cyclic humidity have higher secondary creep strains at failure than boxes in constant humidity. This is demonstrated in Figure 44. It could also be that *d* is a function of test methods employed since every investigator obtained different ductility factors.

In addition, Haraldsson *et al.* [42] found that associating failure with a constant maximum deflection or strain could be used to predict lifetime in paperboard. Chalmers [50] found that the compressive creep of paperboard samples followed a power-law function, but that the exponent decreased with time. His tests were conducted on a tester with vacuum to hold the specimen flat. He results show that for a sample with a relatively short lifetime, the secondary creep response was fairly linear with time. He found good correlation for the lifetime being inversely proportional to the secondary creep rate.

Differences between tensile and compressive creep

For compressive creep, it appears that the predicting the secondary creep rate is the key factor to predicting lifetime. A secondary factor is the ductility. In order to make use of this knowledge a better understanding of compressive creep is required.

The compressive and tensile creep responses of paper are different. Figure 18 provided an example of differences between isochronous curves for tension and compression. Another good example from reference [42] is shown in Figure 45. The creep stiffness is lower in compression at least for long times and large load durations. At short times, and low load levels, the tensile and compressive creep responses are essentially the same. This can be observed by the fact that isochronous curves for tension and compression will coincide at the lowest load levels.

This behavior was confirmed by Vorakunpinij [81] who observed that for low load levels tensile and compressive creep behavior was the same, but as load level increased compressive creep rates decayed less than tensile creep rates and the two responses deviated from one another. The fact that the tensile and compressive creep behavior essentially coincide at low loads and short times, suggests that the initial creep is a material property response not a structural response.

A reasonable explanation for the difference between tensile and compressive creep is that in compression the materials becomes unstable and at some load level or time limit elements within the sheet and fiber will buckle and directly increase the creep deformation relative to if no buckling occurred. This buckling could be on elements at all scale level including molecular or

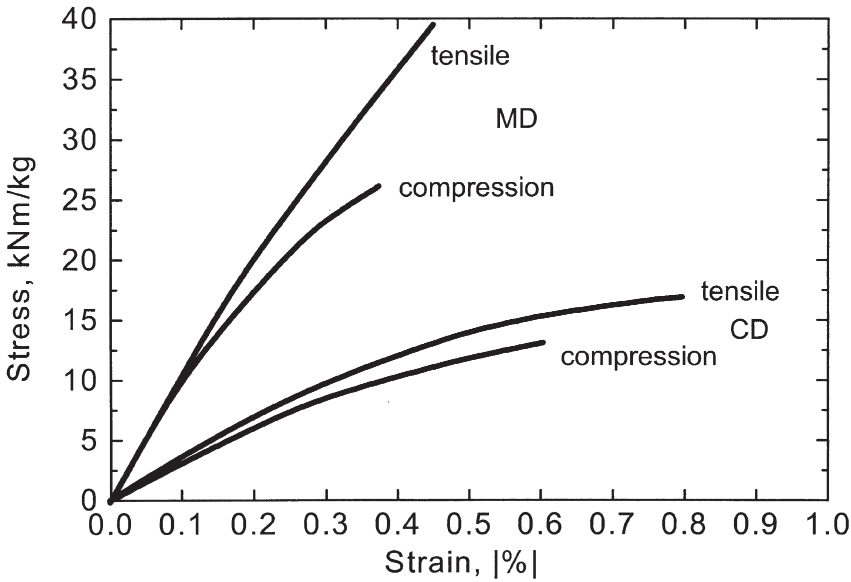


Figure 45 Isochronous curves for tension and compression for both MD and CD creep [42].

the entire sheet. Once buckling occurs, deformation will accrue at a faster rate.

If buckling of the fibrous elements causes increased compressive creep rates, then increased sheet density should postpone the buckling. As a result, tensile and compressive creep curves should coincide for a longer period of time. This was observed by Vorakunpinij [81]. As discussed previously, increased density reduces creep because of improved load carrying efficiency of the sheet, but in addition to the overall decreased creep rate, the difference in creep rate between compression and tension are reduced. Figure 46 shows master creep curves for two different handsheets both having a grammage of 185 g/m^2, but one sheet a has a density of 472 kg/m^3 and one sheet has a density of 882 g/m^2. Clearly, the creep compliance for tension and compression coincide for a longer period of time in the high density sheets. The curves shown in the figures, are power-law fits to the master creep curves as determined by Vorakunpinij [81].

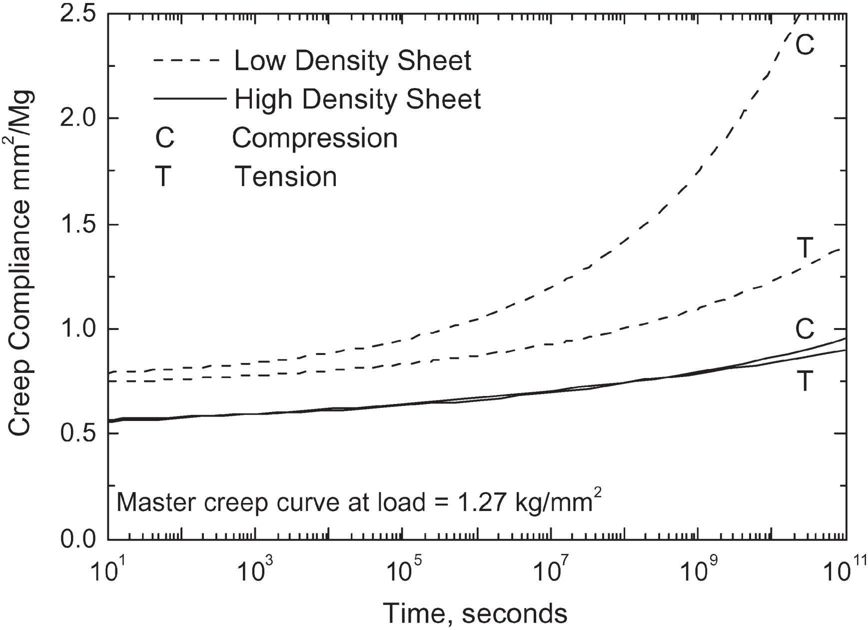


Figure 46 Comparison of master creeps for tension and compression for low and high density sheets [81].

For the curves shown in Figure 46, the difference in density was achieved by wet-pressing. Therefore, if the master creep curves for the low density sheet are scaled by the efficiency factor, ϕ, and then shifted in the logarithm of time by $1/\phi$, the tensile curve should coincide with the creep curves for the high density sheet. A value of $\phi = 0.8$ was determined from the ratio of the slopes of the log-time shift versus load level curves used to form the master creep curves. Figure 47 shows the comparison of master creep curves after the scaling and shifting. The tensile curve for the low density sheet now superimposes with the curves for the high density sheets. The master curve for the high density sheet does not superimpose. This is presumably due to compression instabilities of elements within the sheet.

The findings of Westerlind *et al.* [71] suggest that the product of in-plane modulus and transverse shear modulus, which would account for improved resistance of the sheet to buckling, could be a predictor of compressive creep rates. It would be of interest to determine of one could predict compressive creep from tensile creep by accounting for the instability using other measurable parameters.

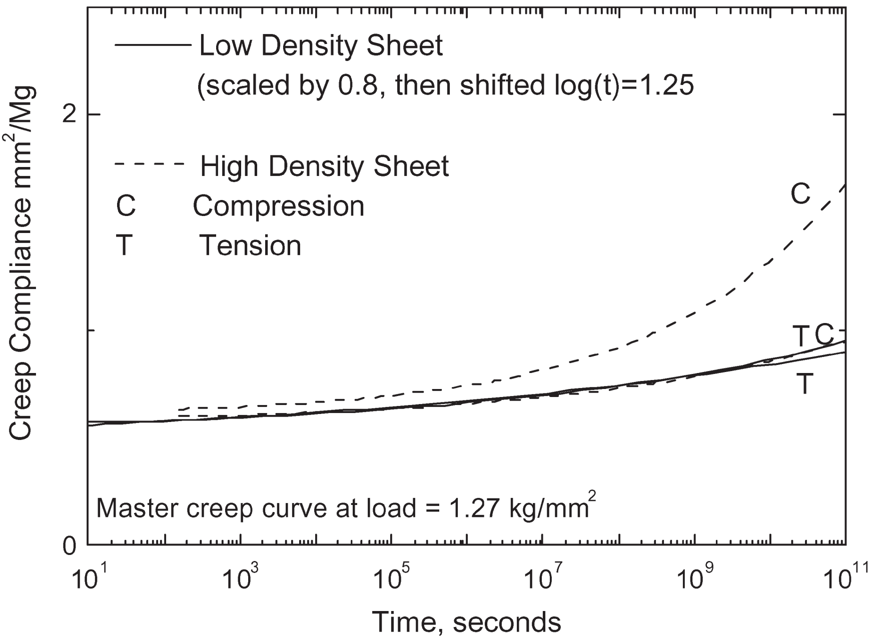


Figure 47 Comparison Low and high density master creep curves scaled and shifted to account for efficiency factor.

Test methods for compression

Even though we can not suppress the internal buckling in the sheet, we must suppress the global buckling if we are to obtain the inherent compressive creep response of the paper. This is the same problem encountered in edgewise compression strength tests, and Fellers and Donner [82] provide a good overview of the issues and testing methods for compression testing.

For edgewise compressive loading of a corrugated board sample, global buckling of the sample is avoided by choosing an appropriate slenderness ratio. Researchers [23, 25, 83, and 84] have typically used the dimensions of a standard Edgewise Compressive Strength (ECT) test of the corrugated board such as specified by *TAPPI Standard Test Methods 811 or 841*. Gunderson and Laufenberg [83] noted that the liners exhibit a local buckling of the free span between the flute-tips during ECT creep. Figure 48 shows an example of the inter-flute buckling that occurs during ECT creep tests. This buckling is inherent to the creep of liners in corrugated board, but when one is interested in the inherent creep of the paperboard itself, this buckling must be avoided.

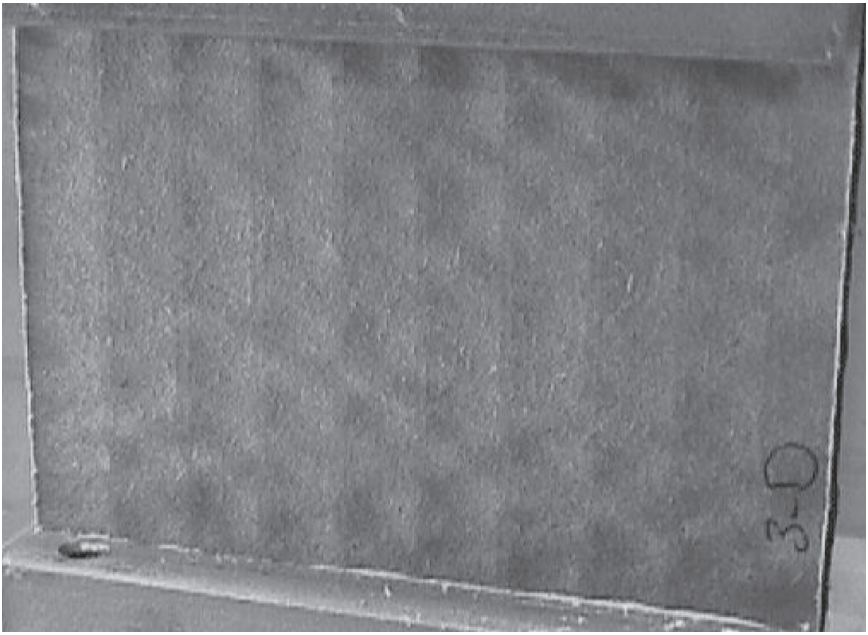


Figure 48 Inter-flute buckling resulting from creep of edgewise compressive loading of corrugated board [84].

One method of restricting the lateral buckling of the paper is to form the sheet into a cylinder and then load it in axial compression. The curvature of the cylinder increases buckling resistance of the paperboard. This approach has been utilized by several researchers for creep testing [55 and 71]. The idea stems from methods utilized for compressive strength testing [85]. Compression testing of cylinders has some drawbacks. For example, the cylindrical geometry leads to a multi-component stress state that would affect the test results and limits the minimum size of the cylinder or the maximum size of caliper. Moisture diffusion would likely be different from the inside and outside of the cylinder. This could be beneficial since in a box moisture diffusion typically occurs from one side. The apparatus developed by Vullierme *et al.* [55] and named the VARIPRESS, uses a cylinder formed by rolling the paper multiple times. The cylinder is placed in guiding cylinders, but is free on the inside surface. Gaps are used to allow compression of the cylinder. A schematic of this instrument is shown in Figure 49.

Gunderson [86] developed a method using a light vacuum to hold the

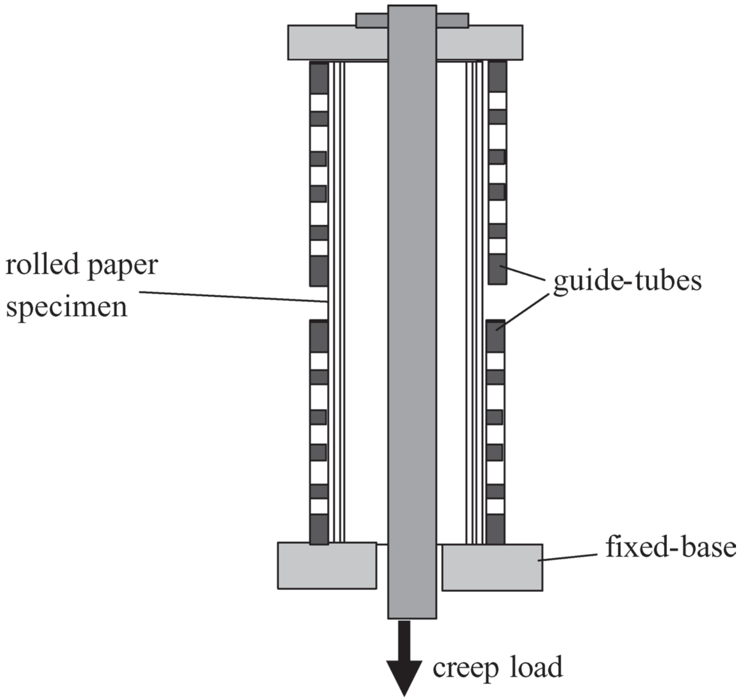


Figure 49 Simplified schematic of VARIPRESS creep tester for rolled paper cylinders adapted from [55].

sample against lateral support blades, and thus increase the buckling resistance of a specimen. This design used support leaves with 0.25 mm thickness and 25.4 mm width that was 114 mm length, spaced at intervals of 0.7 mm. Later the support leaves were replaced with a system of bronze rods, 3.2 mm square by 152.4 mm length [87]. A schematic of the modified system is shown in Figure 50. For this system, the vacuum pressure that hold the sheet to the rods, also pulls air through the sheet and creates faster sorption times. In addition, the pressure differences from one side of the sheet to the other create a moisture gradient though the thickness of the sheet that would persist throughout the test.

Haraldsson et al. [42, 88] developed a creep tester with columns that support the paper to prevent buckling. Spaces between the columns allow for moisture to move in and out of the sheet. Panek *et al.* [74] refined the apparatus so that the columns were longer and had thin sections at the ends that acted like hinges. The ends of the columns move with the paper and the

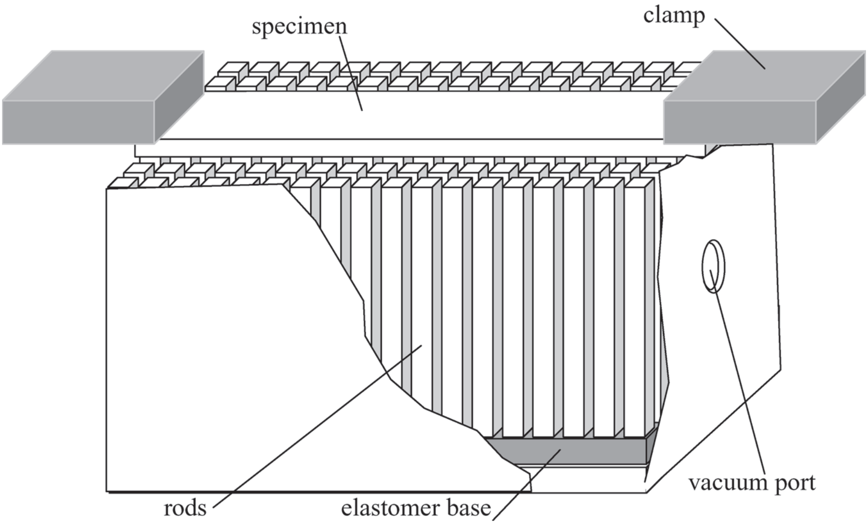


Figure 50 Vacuum restraint tester showing support rods [87].

hinges accommodate the creep movement with little interference. Deformation is measured by tracking the movement of two of the columns spaced 43 mm apart. A simplified schematic of this apparatus is shown in Figure 51.

Vorakunpinij *et al.* [89] developed a flat support apparatus based loosely on previous testers for compressive strength [90]. The sample is completely supported by two plates that slide relative to each other. The specimen is fixed to one plate at each end. Lateral pressure is measured to account for any friction. To eliminate the effect of shear near the ends, the deformation is measured directly from the middle section of the paper. This apparatus, as shown in Figure 52, was used for tensile and compressive creep testing in constant humidity environments.

Even the ring crush test has been adapted for creep testing [53 and 91] with results having similar trends to those of other compressive creep testing. The long-term secondary creep rate in ring-crush was found to be linear with time and may be attributed to buckling of the sample. Short term creep was fit with a power-law equation. Good correlation was found between lifetime and minimum secondary creep rate similar to previous studies using a power-law equation. The exponent was close to 1. The relationships were slightly different for different environmental conditions. Using the interpretation implied by Equation (33), Jackson's [53] results show that the ductility increases when testing in constant 50% RH to constant 90% RH to cyclic RH.

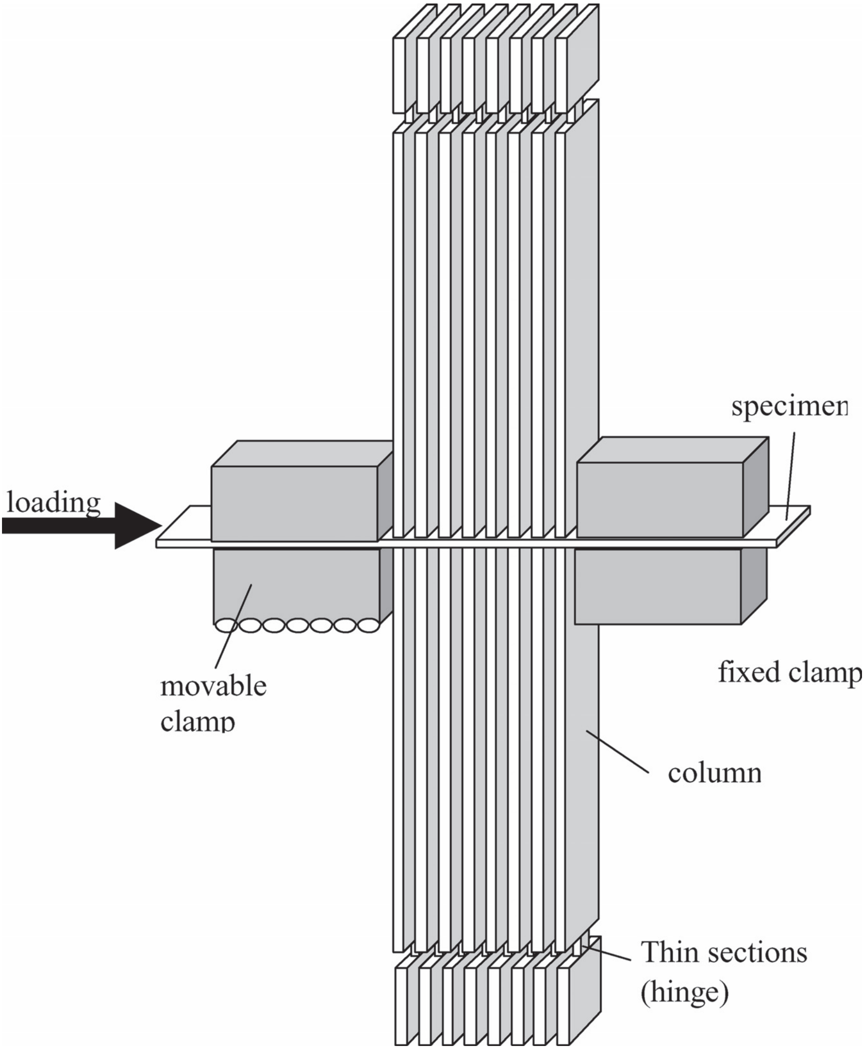


Figure 51 Finger supported Tester [51].

There is no one best method for testing the edgewise compressive creep behavior of paper. All methods have their advantages and disadvantages. The general trends appear to be similar. The more the buckling is suppressed the more likely that the creep follows a power-law dependence on time. With sufficient buckling, the secondary creep rate becomes fairly linear with time.

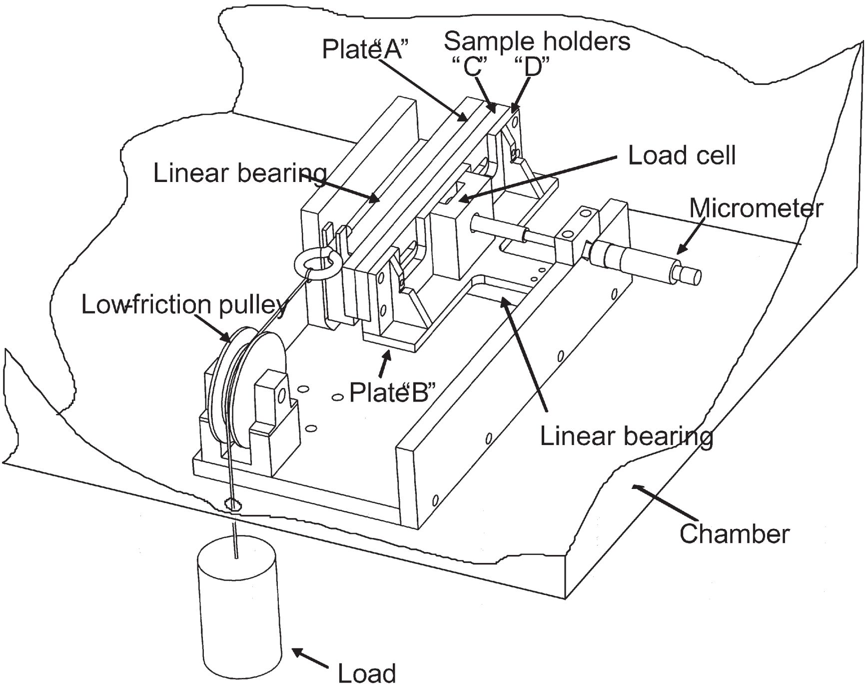


Figure 52 Flat plate creep tester [89].

A good approximation is that the lifetime is inversely proportional to the minimum secondary creep rate. The proportionality factor is a ductility term related to the amount of secondary creep that the sample can accrue without failure. The ductility increases with moisture content and appears to be larger for cyclic humidity conditions.

ACCELERATED CREEP

Under conditions where the moisture cycles between high and low levels creep tends to accrue at a faster rate than even if the conditions had been held at constant high moisture. On the surface this is counter intuitive. Water typically plasticizes the polymers found in paper [92], increased moisture produces a drop in elastic modulus and an increased in creep compliance. If this softening were the only consideration, high moisture content should be

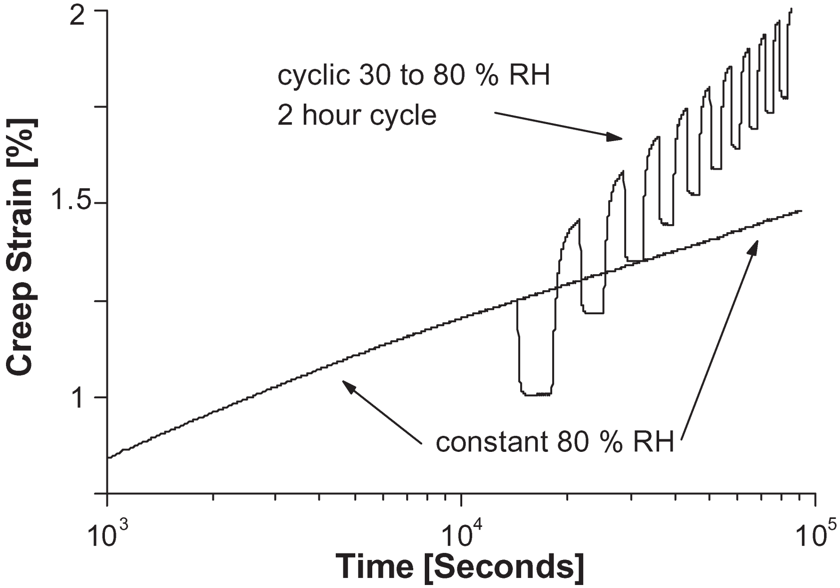


Figure 53 Accelerated Creep in Paper [51].

the worst case scenario for creep behavior. Alas, for many materials including paper this simple logic does not hold. Instead, cyclic moisture leads to what has been termed accelerated or mechanosorptive creep. This puzzling behavior has captured the attention of many researchers, and as the literature review documents accelerated creep has dominated the field of creep in paper for the past 30 years.

Figure 53 presents a graph of two creep curves for paper. The monotonically increasing curve corresponds to creep at constant 80% relative humidity (RH). The curve that exhibits the cyclic strain response is the creep of a sample that was first held at constant 80% for a period of time, and then cycled from 30% to 80% relative humidity. This demonstrates the dramatic increase in the rate of creep that occurs when moisture cycling commences. This is accelerated creep. The saw tooth behavior shown in the graph is due to the hygroexpansion and the change in elastic modulus of the specimen. The peaks and valleys correspond to periods of high and low moisture, respectively.

For the sample shown in Figure 53, the first time the sample experiences a decrease in moisture, the strain becomes flat. During last few excursions to low moisture the strain continues to decrease during the entire period of low moisture. The strain in the low moisture regimes is the combined result of the shrinkage due to the decrease in moisture and the creep due to the applied load. During the first excursion, these two components offset each other, but as the material hardens the rate of creep decreases and the shrinkage is observed for the entire period of low moisture. In addition, the shrinkage and swelling strains are larger during the first cycles than during the latter cycles.

When the moisture is cycled, there are at least three components of strain: the creep strain, the change in elastic strain, and the hygroexpansion. In addition, there could be a release of previous hardening. A simple superposition of the strain components from separate hygroexpansion and creep tests will not give the combined results. The missing strain is not only from the extra creep, but there are also changes in hygroexpansion [93] and elastic modulus that will occur [92]. None the less, it seems reasonable that the hygroexpansion and the change in elastic strain could be removed from the total strain. In addition, one could subtract the constant moisture creep cyclic moisture response. By removing these strains from the total response, the extra strain due to cycling moisture can be evaluated.

An approximation of this strain subtraction is done in Figure 54. The solid line is the difference in the total strains for the two creep curves shown in Figure 53. The reversible strains from cycle to cycle are not known. Therefore a pseudo reversible strain was constructed from the data of the last cycle going from 30–80–30 cycle of RH. The shape was taken directly from the response and the magnitude was taken from the shrinkage portion. The same swelling-shrinkage was assumed for all cycles. The dashed line in Figure 54 shows the result of subtracting this approximation of the reversible strain from the difference in total strains. The remaining strain is the extra accumulated strain. Additional swelling and shrinkage strains in the early cycles are also present. The result shows that most of the extra creep occurs during the change from low to high RH. For this sheet, the overall strain was greater than 1% when cycling commenced. It is likely that the creep rate for the paper at 30% RH and at this strain level is quite small even if high stress concentrations are present.

The fact that the cyclic RH creep curve exceeds the creep curve of constant 80% RH in Figure 53 is actually noteworthy. Even if one appreciates that material nonlinearity in conjunction with stress concentrations can lead to excess creep, the minimum expectation should be that the creep rate only be above that of the average of the low and high creep. Since many observations reported in the literature are that creep in cyclic humidity exceeds that in high humidity, the responsible actions must be potent.

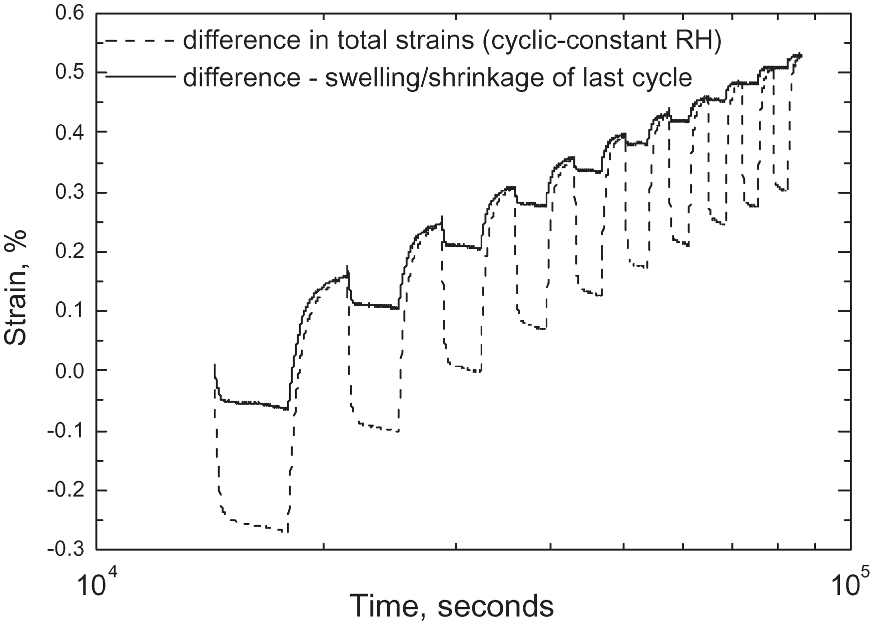


Figure 54 Difference in total creep strain for cyclic and constant humidity (dashed) and approximate extra creep strain (solid).

Mechanisms

Haslach [61] provided a thorough review of mechanosorptive creep covering literature up to circa 1997. He emphasized the experimental findings and the conjecture on the causes of accelerated creep. Because accelerated creep is such an amazing phenomenon, there were many explanations for him to cover. The following presents just a few of the major factors that have been proffered to cause accelerated creep. The view taken is biased towards the mechanical explanation of accelerated creep, but it is held that this bias is justified.

Early on for wood, it was thought that moisture diffusion drove accelerated creep, but the experimental results of Armstrong [94] showed this to be wrong. To get around this, Bažant [57] argued that it was moisture in the micropores disrupting bonds, but not affecting diffusion. Ranta Maunus [58] took the approach that accelerated creep was directly related to the change in moisture and not linked directly to material compliance. These explanations are not satisfying.

Other researchers have assigned responsibility to the structure. Söremark and Fellers [37–38] suggested a model of moisture induced stress-redistribution causing extra dislocations in the fiber network. Haslach [60] favors an explanation based on network structure and anisotropic swelling of the fibers. There are even results that upon cursory review support these fiber network explanations. Cyclic moisture tests on single fibers conducted by Sedlachek [43] showed no accelerated creep rates. Only during the first excursion from 50 to 90% RH in tests started at 50% RH was there an increase in creep. This was likely attributed to a release of dried-in strains. Coffin and Bose [47] verified that single pulp fibers exhibit no accelerated creep. Byrd observed increases in light scattering and therefore bond-breaking during creep and during the moisture changes [20]. Salmén and Fellers [95] observed accelerated creep in paper, but no accelerated creep in bundles of Nylon 6,6 fibers. This was attributed to fact that Nylon 6,6 does not have anisotropic swelling. As appealing as those three pieces of experimental evidence are each has a rational explanation.

Coffin and Boese [47] point out that the sorption of water in these single pulp fibers is very fast. There is very little time when moisture gradients are present in the fibers and therefore, there is very little action to drive accelerated creep. This is the same reason that the tests of Salmén and Fellers [95] showed no accelerated creep. In fact, synthetic fibers have been shown to exhibit accelerated creep even Nylon 6,6 [96]. When the diameter of the fiber is sufficiently large and the moisture cycle is sufficiently fast accelerated creep will occur in homogenous and isotropic materials [62 and 96]. These thicker fibers undergo large swelling gradients for a significant portion of the cycle time and have ample time to give an accelerated creep response [96].

That leaves us with a bond breaking explanation. The problem with measurements of the changes in light scattering with creep is that the measurements by themselves can not show cause and effect. Which came first, bond breaking or creep deformation? The only thing these measurements show is that creep and loss of bonded area occurred together. The evidence would point to the fact that simply a loss of bonded area will not necessarily lead to more creep. Decreased bonding occurs during wet-straining and previous creep deformation. Both of these actions lead to less creep not more. This is because of intra-fiber changes and improved network efficiency. The role bonding plays in creep is to act as a stress concentration factor, which in essence speeds up the creep process. This is very important especially on lifetime, but it does not control the basic creep response it only magnifies it. With a significant loss of bonding during creep, there probably is an increase in creep rate, which is tertiary creep.

For tensile creep in constant humidity, the creep compliance will not change with increased bonding once the efficiency factor has reached a value of one. The only change will be the increase in failure strain. There is no reason to expect the accelerated creep response to be different. Increased bonding above a minimum level should not reduce accelerated creep, even though a loss of bonded area will occur during the creep.

An explanation of the mechanosorptive effects put forward by Padanyi [41] was that cycling to high moisture causes components of the material to rise above the glass transition temperature. This event triggers the sample to undergo de-aging. When the sample returns to low moisture content there is excess free volume and the sheet is not in thermodynamic equilibrium. During this time the sheet is more compliant, and experiences more creep. The paper slowly ages and returns to its former state. This is a somewhat appealing argument, but Padanyi showed that similar aging occurred after an excursion to low moisture and any appeal to glass transition is invalid. Proponents of this argument state that the rapid change in dimensions creates the excess free volume needed for increased compliance. This is more of an interpretation of the action in terms of free volume rather than a rational explanation. Perhaps it is better to state that this apparent increase in free volume is a result of stress concentrations.

The mechanical explanation given by Habeger and Coffin [62] and utilized in [65] and [66] is capable of explaining all observed mechanosorptive effects without any hand waving or appeals to special phenomena. It is well established that Boltzmann superposition does not apply to paper; in other words, the material is not linear. In addition, it is clear that the heterogeneity of paper and the creation of any moisture gradients within the paper produce nonuniform swelling. This nonuniform swelling produces stress gradients. Because of material nonlinearity, the highly loaded regions will contribute more to creep than is conserved in the unloaded regions. The net result is the seemingly abnormal response of the paper known as accelerated creep. It also results in Padanyi's aging [41], and even the transients in dynamic mechanical properties [97, 63]. The fact is that these mechanosorptive effects should be the expected behavior of the materials. They are a completely normal response of the material when subjected to multiple changes of load, moisture, time, and/or temperature.

Figure 55 shows a schematic of a sample subjected to a load F. Because of material heterogeneity or nonuniform swelling/shrinkage, the stress will not be uniformly distributed as shown in Figure 55(b). We know only the applied load, F, and not knowing any more assume that the average stress is acting on the material as shown in Figure 55(c). If the material response is nonlinear, then different distributions of stress will give different responses even though

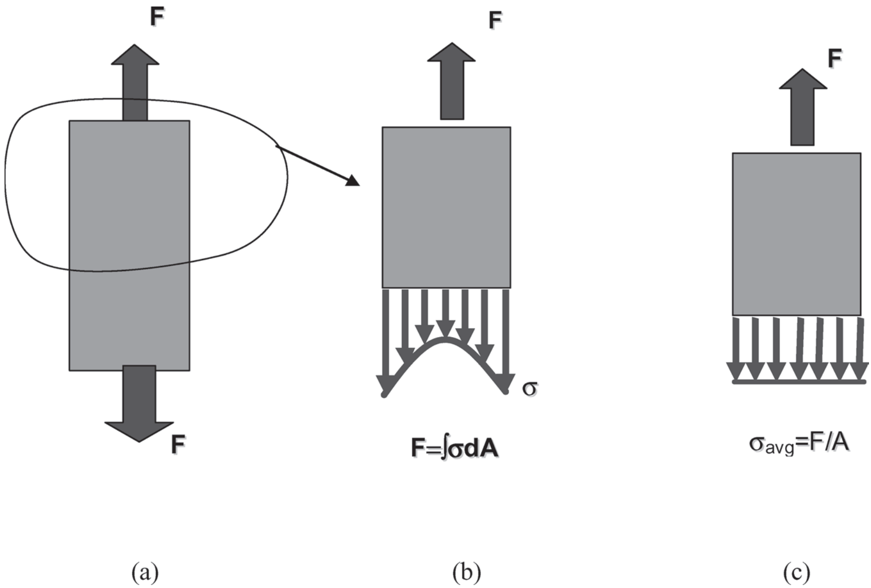


Figure 55 Concept of nonuniform stress distribution in a specimen.

the average stress remains constant. This is what happens when moisture is cycled during a creep test.

If the material can flow, the stresses will try to redistribute to a uniform state. In cyclic moisture conditions, we continually disrupt the stress distribution. Consider each point as being subjected to a cyclic stress. Because of material nonlinearity, the sample will experience more creep during these times of stress gradients.

The mechanism for accelerated creep can be stated as follows:

> *Accelerated creep can occur in materials where (1) the creep behavior is a nonlinear such that cycling the load gives more creep than the average load and (2) stress distributions are created due to material heterogeneity and/or moisture gradients.*

There is precedence in the literature for this mechanism. For example Pickett [21] in addressing accelerated creep in concrete suggested

> *. . . an increase in creep accompanying non-uniform shrinkage or swelling is a natural consequence of the fact that sustained-stress-vs.-strain curve for concrete is not linear.*

Selway and Kirkpatrick [36] suggested a similar mechanism

> *Changes in moisture can cause rapid transient increases in stress and the creep rate is a highly nonlinear function of stress there can be significant increases in the creep rate.*

Neither of these statements point out the cyclic load criteria. Kevlar fibers are an example of a material that requires the distinction of cyclic load in the statement. Kevlar fibers exhibit accelerated creep [98] but are rather load insensitive. Kevlar fibers do exhibit more creep upon cyclic loading than from the constant mean load [96].

Haslach [61] states

> *Another hypothesis is that the changing moisture content during cyclical relative humidity sets up a stress gradient within individual fibers that accelerates the strain.*

He dismisses this hypothesis because it is difficult to test. Also, the stress gradients can easily be between fibers not just within a fiber. Dillard [59] lists the possibility of this mechanism as follows:

> *Stress and Hygroscopic swelling – a possibly important category which might include altered residual stress states, nonlinear viscoelastic effects, and even damage, all of which could result from the swelling and swelling gradients which result as the diffusion process occurs.*

Dillard [59] chose to follow an explanation based on free volume instead. Söremark and Fellers [37] tied redistribution of stresses into their proposed dislocation explanation.

In the statement of the mechanism for accelerated creep, it is essential that the nonlinearity criteria be stated in terms of cyclic load causing more creep than constant average load. It is possible for a material to have nonlinear scaling and still produce no accelerated creep.

Observations

There are some instructive examples of accelerated creep that support this mechanical view of accelerated creep over other explanations. Figure 56 shows an example of accelerated creep in cellophane. This demonstrates that in general accelerated creep is more than a special phenomenon relegated to anisotropic fibrous materials. It is not just material heterogeneity that will cause accelerated creep. In this case, the diffusion of water into the cellophane causes moisture gradients that lead to stress concentrations and subsequently accelerated creep.

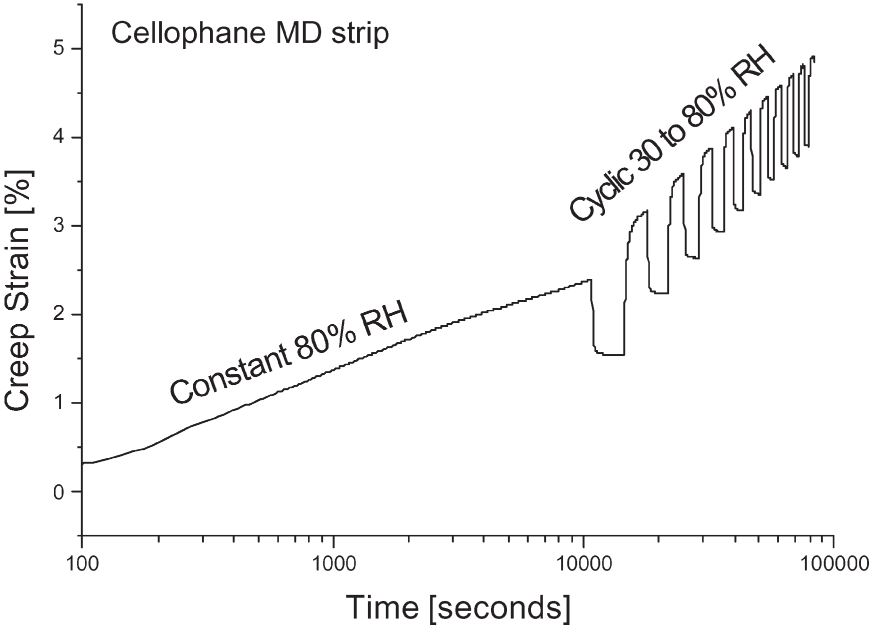


Figure 56 Accelerated creep in cellophane [51].

Figure 57 illustrates that accelerated creep also occurs when cycling to low humidity conditions. This dispels any notion that the sample must go above glass transition for accelerated creep to occur. In fact, the severity of the change in creep from the constant 50% to the cyclic portion is severe. Compare to that shown in Figure 53. The acceleration of creep was so strong that during the first desorption the shrinkage was overcome by extra creep and even this point ends up above the constant 50% creep curve. The reason for this dramatic display of accelerated creep is that at low moistures the stress concentrations can not relax. At the lower moisture, the stiffness of the material is high it creates such extreme stress concentrations that the material creeps rapidly. In subsequent excursions, the material has hardened and the excess creep is small compared to the change in swelling/shrinkage, but still there is creep even in the low RH conditions. Note that the overall strain level here is low so the creep rates are relatively high. Whereas the creep from low to high humidity had most of the extra creep only in the excursions to high moisture, the curve shown in Figure 57 demonstrates that there is extra creep during the drop in moisture. After studying Figure 54, one may have doubts about the mechanism because extra creep at the lower moisture would be

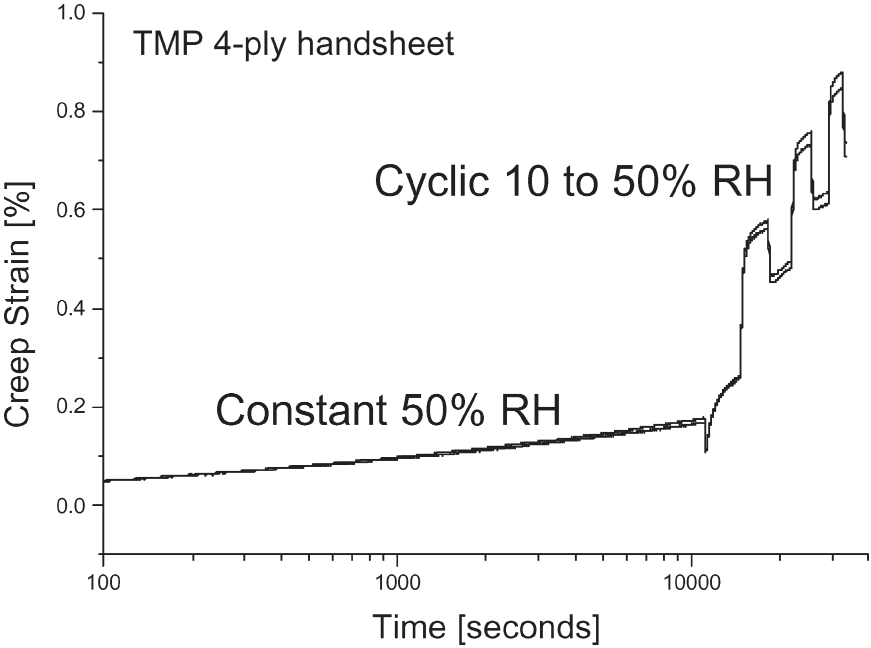


Figure 57 Creep in cyclic humidity from mid to low moisture content for two samples [51].

expected. In fact, there probably was since we subtracted the creep at 80% RH, where the creep rate would be higher than at 30% RH. For the curve shown in Figure 57, the acceleration of creep is accentuated leaving no doubt that even the moisture changes induce excess creeping at low moistures.

The rate of accelerated creep should vary with the period of the moisture cycle. If cycle times are long, the stress gradients will dissipate and the creep rate will diminish. If the cycle time is too short, there will not enough time for creep to occur and for very short cycle times the sheet will even obtain moisture equilibrium. There would be an optimum time where the stress gradients would be re-created with each cycle and the change in moisture would occur at a frequency so that the stress concentrations would not be diminished. This optimum cycle time would be a function of the characteristic times of moisture sorption and relaxation times. Figure 58 provides an example of how the rate of creep changes as the cycle time changes.

As a last example, consider Padanyi's physical aging tests. Figure 59 provides verification of his result that exposure to low moisture "de-ages" the

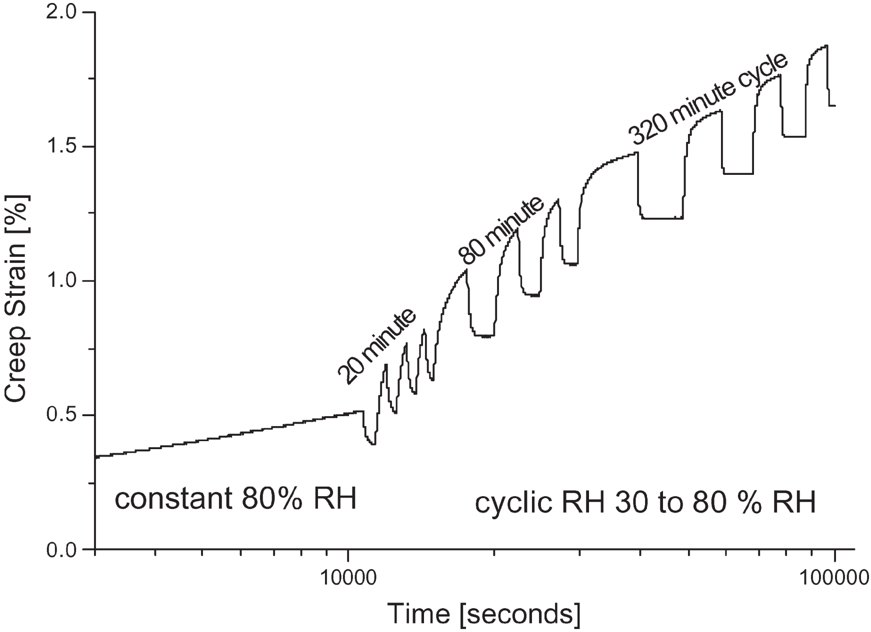


Figure 58 Change in rate of creep with changes in cycle time. [51]

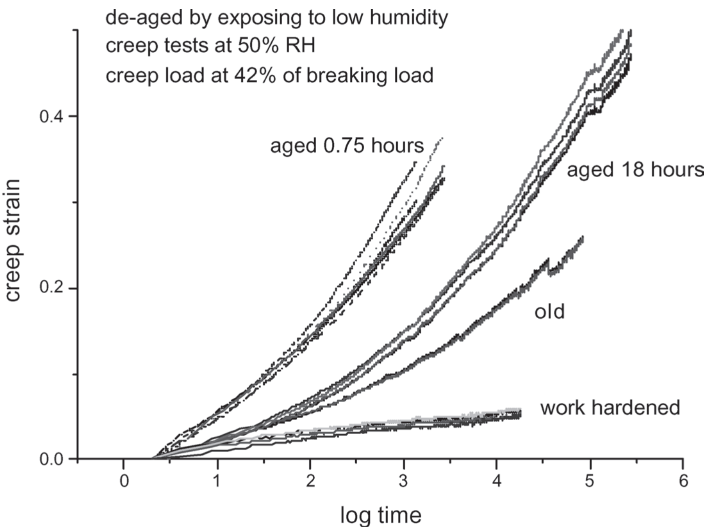


Figure 59 De-aging tests conducted by exposure to low relative humidity, 10% [62].

material as observed by the increased creep compliance [62]. The paper was handsheets made from a TMP pulp. The curve labeled "old" is the creep curve for a sample that was stored at 50% RH for a long time. Samples were exposed to 10% humidity for 1 hour and then re-conditioned at 50% for 45 minutes. Creep tests were conduced and the sample exhibited increased compliance. The samples were again de-aged and then after either 45 minutes or 18 hours creep tests were once again started. Longer aging times result in lower creep compliance. The work hardened curves correspond to samples that have been de-aged twice and then subjected to 18 hours of creep. Another creep test with our de-aging results in work-hardening. A very reasonable explanation for this phenomenon is that during the moisture cycle under no load, large stress-gradients are created and do not relax quickly. The added stress concentration has the effect of increasing the effective compliance. As time passes with no load application the stresses concentrations will dissipate and the material will age. Without de-aging, the samples will show very little creep. In these tests, there may have been some permanent hardening of the samples de-aged twice at 45 minutes but it is small.

The examples of accelerated creep behavior discussed above demonstrate that the basics of the accelerated creep phenomenon can be understood on a mechanistic level. The tests conducted at lower humidity offer strong evidence that accelerated creep is the natural consequence of cyclic stress gradients applied to nonlinear materials.

If one were to accept this explanation for accelerated creep, or in the least accept it as a natural way to account for accelerated creep, the entire issue of mechanosorptive effects decouples into understanding the two phenomena separately. The first issue that needs to be addressed is how the material generates more creep upon cyclic loading versus constant mean load. The second and separate issue is how moisture changes create stress gradients. Gains in understanding each phenomenon can be made separately, and then accelerated creep will be one of the consequences of coupling the results back together again. In this paper, we did not discuss the second issue of moisture sorption and swelling but focused on the creep response of the paper.

Assessing material nonlinearity

By decoupling the accelerated creep problem into two problems, (1) moisture diffusion and swelling and (2) material nonlinearity, undertaking studies of creep at constant humidity are validated. For tension, we have been able to put together many of the pieces. Since compression creep testing for paper did not begin until after the era of accelerated creep, we have very little knowledge of the fundamental compressive creep response of paper. We know that is different from tension, but we can not systematically account for the differences.

Focusing on tension, we have already discussed that the load dependence of creep is basically accounted for as a logarithmic time shift of creep compliance curves. As the shift parameter β increases, the nonlinearity of load cycling increases, and since a large part of this load dependent creep is permanent, accelerated creep would be expected to increase. Therefore, to reduce accelerated creep one must find ways to reduce this factor. Increasing the efficiency factor ϕ will also achieve the same effect. This is accomplished by increasing the bonding in the sheet. This is probably of major importance to lifetime. The other parameters that control creep play a secondary role in causing extra creep due to load cycling. Of course as far as lifetime is concerned, anything that reduces overall creep while not having a detrimental effect on stretch will improve performance on both cyclic and constant moisture conditions.

The trouble with creep tests in cyclic humidity

It is very difficult to gain insights into accelerated creep beyond, just ranking which materials have more or less creep than others. The reason for this is that there are two many things going on at one time. The mechanical response of paper depends on load level, moisture content, temperature, and time scales. In a creep test under constant conditions, we keep everything constant except time. Of course, internally load is being redistributed but that is accounted for in the creep compliance. By holding all but one variable constant during the test, we can determine the effects of load, moisture, temperature, and history on the creep compliance. In this manner, a systematic characterization of creep behavior is attained.

When conducting a cyclic humidity test, all the parameters are changing. One sample may show more accelerated creep because of increased intrinsic load nonlinearity. Another may exhibit increased differential swelling. Another may have differences in bonding, and yet another may have differences in dried-in strains. When the moisture is cycled, each of these factors will influence the creep response to an unknown amount. Rarely will strong correlations be found between sheet properties that will have broad application to all conditions. To pinpoint the cause behind one paper having more accelerated creep than another more information about the creep behavior than just that from cyclic tests is likely required.

To illustrate that more involved study is required to understand cyclic humidity creep consider these two case studies. Leake [77] showed that seemingly equivalent boxes based on ECT strength and lifetime in constant humidity creep did not exhibit the same lifetimes in a cyclic humidity environment. Thus, cyclic humidity triggered a material response that was not active in the other test conditions. The difference in these two boxes was the basis weight of the medium. Again, in reference [78] two boxes and boards tested were seemingly equivalent in terms of ECT and BCT, but the secondary creep rates for the cyclic humidity creep tests were dramatically different. In this second case, the difference between the two boxes was the adhesive. Boxes made from the high-amylose adhesive had twice the lifetime as boxes made with a cornstarch adhesive. Constant RH tests are not enough. By assessing the properties of the two boxes at multiple load levels and characterizing the diffusion and hygroexpansion of the box, one could probably explain why the two boxes behaved differently.

Furthermore, there is no one moisture-temperature history that will be the worst case scenario for all papers. The choice of testing conditions is arbitrary and conclusions made from one set of tests probably not hold under another set of conditions. In the field, the environment is truly transient with changes in temperature and relative humidity that are not regular. Except for practical applications, testing with a complex environmental history probably reaps little insight.

SUMMARY

Ponder the following statement. Everything we know about the basic behavior of creep in paper has come from tests completed in conditions of constant humidity. In fact most of the knowledge came from the early work in the field. We know that the creep process for paper is a self-retarding or hardening process at least until a critical state is reached where *damage* has occurred such that tertiary creep imitates and failure is eminent. We know that the creep deformation has a recoverable component. We know that a component of the deformation at least at the time scales of practical evaluation is unrecoverable. We know that hardening effects can be removed with exposure to high moisture in the unloaded state.

Results in the literature suggest that the creep behavior is predictable. The effect of load on creep compliance is a shift of the compliance curves along the logarithmic time scale (scalar magnification of time.) The effect of moisture on secondary creep also acts to scale time. Increased moisture can also lead to a release of dried-ins-strains and produce an apparent increase in creep compliance. Network efficiency as accounted for by degree of bonding simply acts to magnify the stress and hence scales the creep compliance and shifts the curves in log-time. By using the creep compliance normalized by the elastic modulus, the effect of network efficiency becomes only a time-shift. In fact, many of the effects of many fiber and network changes can be accounted for by scaling the creep compliance and magnifying the time in a systematic manner. Use of dimensionless quantities will likely reconcile many of the differences observed for different paper materials.

The initial compressive creep response is inherently the same as that in tension, but because the material becomes more stable in tension and less stable in compression, the creep response deviates and paper creeps faster in compression.

The major contribution from cyclic humidity testing is the observation that it produces more creep than high moisture. In addition, we know that comparative creep tests conducted at constant humidity will often not yield the same ranking as a comparison in cyclic humidity. The general conclusion from this observation is that creep tests in constant humidity are not useful. This is not a good conclusion.

Since a cyclic moisture creep test is the coupling of moisture changes with creep, with at least two factors influencing the response, it would be too much to expect one creep test conducted at constant humidity to capture the behavior. Knowing that the accelerated creep is a result of load cycling, one is going to have to assess this behavior. The assessment of how changes in load affect the creep response, even in constant humidity, will help expose the reason one paper performs worse than another. For example, take the case of Kevlar fibers that exhibit accelerated creep, but not nonlinear scaling of load (doubling load more than double creep response.) To understand this one, needs to determine why cyclic load causes more creep deformation as compared to constant mean load. This should be a much easier problem to tackle than trying to adequately describe the cyclic moisture case. There is sound logic in the argument that more focus be given to assessing the effects of load and other parameters under conditions of constant moisture.

Of course, there is still the need to carry out cyclic humidity tests. Cyclic testing is essential for ranking materials in a search for those that will provide improved lifetime. In addition, cyclic testing provides the critical test for our hypotheses and models. Once we change the way we look at the problem, we may also develop methods to predict the effective response of an accelerated creep test with load magnification factors, or strain scaling factors.

To illustrate the type of understanding that can be obtained from constant humidity testing, a rudimentary model of tensile creep was developed as part of this review. For tensile creep in constant cyclic humidity, the role of bonding and hardening were clarified and the analysis revealed that our understanding the creep response should be a direct extension of our understanding of the stress strain curve of paper as outlined in reference [75].

Clearly, the basic response to load is governed by the materials and bonding acts merely to magnify the stress. Because the creep rate and lifetime are such a strong function of load level, degree of bonding is probably a major factor in determining which materials show more and less creep. Changing the fiber properties through hardening reduces creep rates, but this is offset by a decrease in rupture strain.

Creep in compression appears to be the same as tension, but magnified by compressive instabilities. If the susceptibility of the material to buckling is assessed, it may be possible to predict the compressive creep from the tensile creep response. Very little is known about the compressive creep response of paper. Therefore, it is difficult for us to predict how a given paper will behave when subjected to compression.

Lifetime predictions are troublesome because and variability in parameters is magnified at long times. Therefore, predicting lifetime from say applied load level without minimizing or accounting for material variability will yield discouraging results. Using another measured quantity like secondary creep rate eliminates much of that variability, but it does no help with the prediction. We still must predict the secondary creep rate for a given material.

There is much we still do not understand about creep. After carrying out this review and contemplating what information was missing, the following research suggestions are offered.

1. Pre-rupture Tensile Creep

- Characterize the effect of raw materials on master creep curves at different moisture contents.
- Determine the loss of hardening that takes place when samples are preconditioned with high moisture by characterizing the creep of sheets made to different degrees of wet-straining or shrinkage.
- Determine a relationship between MD/CD fiber orientation changes and MD/CD creep behavior uncoupled from effects of restraint.
- Verify that bonding can be treated simply by accounting for the efficiency factor as ratio of elastic modulii.
- Verify that the effect of moisture on secondary creep rates is only a logarithmic time shift for a sample with no dried-in strains. Characterize effect of moisture on primary creep.
- Through study of creep and creep recovery better characterize the relationship between primary and secondary creep.
- Determine the connection between creep-hardening from restraint during drying to drying stresses.
- Determine how much of the "secondary creep" is recoverable over longer

time spans or that can be recovered in an accelerated mode with moisture cycling.

2. Compressive Creep

- Complete studies on the characterization of compressive creep in terms of nonlinearity as a function of load, primary versus secondary creep, and role of material and process parameters.
- Determine the role of structural instability on compressive creep.
- Determine effect of process parameters on rupture strain in compression.

3. Creep Failure

- Determine criteria for creep failure. Is it controlled by total strain, secondary strain, or even an energy criterion?
- Connect equation relating creep lifetime to secondary creep-rate directly to materials and structural properties.
- Determine effect of moisture history on failure criterion.

The critical review of tensile creep presented in this review article, actually brought forth refined and clarified understanding of creep. These insights should help in experimental work, modeling, and practical application. These findings are summarized as follows.

For Tensile creep:

1. The role of bonding can be accounted for with a sheet efficiency factor based on the ratio of actual elastic modulus to fully developed elastic modulus. The effect is two-fold. The creep compliance is inversely proportional to the efficiency factor, and the logarithmic time shift for different load levels is inversely proportional to the efficiency factor.
2. The effect of wet-straining can be accounted for by scaling the creep compliance with the ratio of elastic modulii and a logarithmic time-shift for the onset of secondary creep.
3. The release of the dried-in strains (internal stresses if you prefer) can be observed from a plot of creep strain versus moisture. At low moistures where the strain is locked-in to the sheet the creep is hardened. At high moisture contents above that where the dried-in strain is released the material shows no hardening effects.
4. The isochronous creep curves can be used to show the effect of creep-hardening analogous to strain-hardening in a tensile test. The primary creep is analogous to elastic deformation and the secondary creep is analogous to plastic deformation.

5. The geometric mean MD-CD creep does not remain constant but increases as the MD/CD ratio increases.

For compressive creep, it was shown that using the efficiency factor as done for tensile creep can account for some of the differences in creep of sheets with different levels of bonding, but that compressive instabilities are also affected by bonding.

Both master creep curves and isochronous creep curves are useful for characterization of creep. If all the time-shifting functions are known the master creep curve contains all the information necessary to characterize the creep of a paper. Only if the isochronous curves scale with time will one curve provide all the information. It appears that scaling is not strictly valid and thus a set of isochronous curves give only a partial picture of the creep response. Still the analogy of an isochronous curve to a stress-strain curve from a tensile test destines it to be used for practical studies. Two points about these curves should be emphasized.

1. The use of the normalized creep compliance, the product of creep compliance and elastic modulus, provides a fundamental quantity that may allow for more general master creep curves to be formed. Such as was done here for wet-pressing, wet-straining, and virgin versus once-dried sheet.
2. Isochronous creep curves provide an excellent method for comparing the creep response of different materials, and demonstrating the effect of changes in process parameters.

Author's note

After completing this review, and pulling together many of the thought and ideas of others, I realized we have much better fundamental understanding of creep than previously believed. I hope this work is enlightening to others and adequately demonstrates that the creep response of paper can be understood on a fundamental level. Furthermore, this understanding is not so very different than our understanding of any other mechanical response of paper. Finally, I hope this paper encourages others to carry out fundamental studies on the creep of paper.

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Transcription of Discussion

THE CREEP RESPONSE OF PAPER

Douglas W. Coffin

Department of Paper and Chemical Engineering, Miami University, Oxford OH 45056

Errata received from the author to be included in the proceedings

The reference to Figure 43 on page 711 should be the figure as shown below, say Figure 43a:

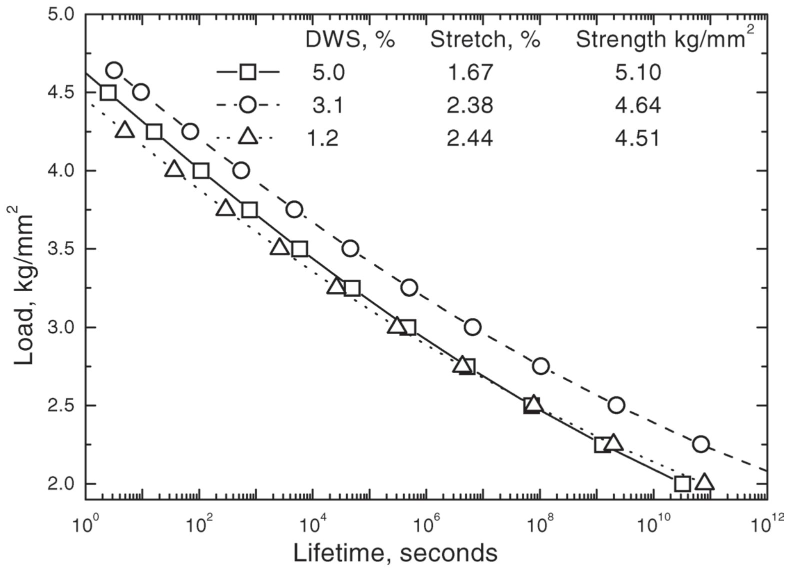

Figure 43a Effect of Wet-straining on Lifetime

Figure 47 on page 718 should be as follows:

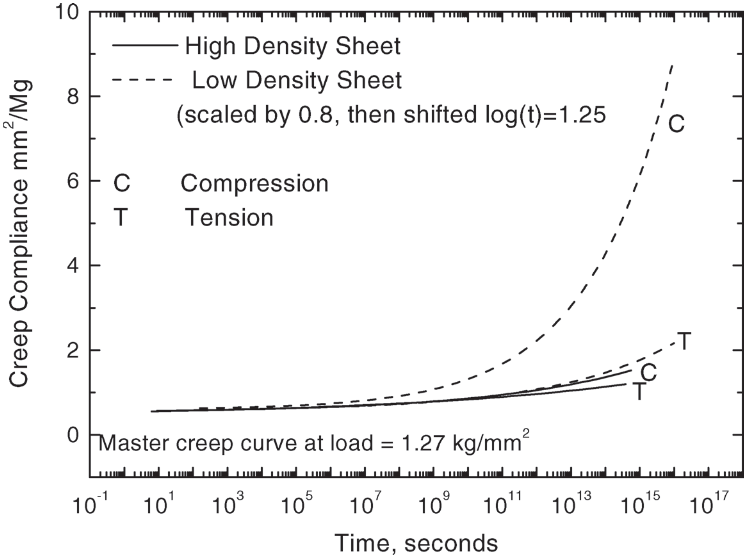

Figure 47 Comparison Low and high density master creep curves scaled and shifted to account for efficiency factor.

And the text on page 717 should read:

Figure 47 shows the comparison of master creep curves after the scaling and shifting. The tensile curve for the low density sheet now superimposes with the curves for the high density sheets. The master curve for compression does not superimpose.

DISCUSSION CONTRIBUTIONS

Christopher Dodson University of Manchester

Doug, one or more of those graphs seem to have 10^{16} seconds on and that is a very long time.

Douglas Coffin

It is because once you shift, to make a master creep curve you shift the high load at short time all the way to the long time.

Christopher Dodson

But it did have data points on.

Douglas Coffin

Because you shift the data points in time. Because it is a time shift, it is just translating it out to a larger scale.

Christopher Dodson

It is a little bit worrying for a mathematician to have things creeping for about the age of the universe.

Douglas Coffin

It just means we can predict it.

Jukka Ketoja KCL Science and Consulting

Thank you for a very nice talk. It certainly clarified things, at least in my mind. I would just like to make a comment about the effect of moisture content. We have found[1] that actually the same sort of master curve formalism applies to the moisture content. What is interesting is that you can, for instance, analyse Brezinski's data, and it turns out that 1% change in moisture content corresponds to about one order of magnitude in time, which causes extremely fast creep at a high moisture content. It means that creep does not apply only to box failure but other things as well.

[1] S. Lehti *et al.*, International Paper Physics Conference, Victoria 2003

Douglas Coffin

That's right. I did not show Brezinski's moisture data, but he formed master curves with that. But one of the things I advocate is normalised creep compliance. With respect to moisture, he found that for secondary creep, the slope of that curve was the same for the compliance and not normalised compliance, even though we know the modulus changes. So there is something interesting there with the moisture and secondary creep that needs more investigation.

Tom Lindström STFI-Packforsk AB

We have this accelerated creep problem, so what should we look for in order to alleviate the problem? I mean you can improve bonding, you can crosslink, you can also look for stress concentrations on different structural levels like, drying stress in the z-direction. You have microcompressions, you may have shives – all creating stress concentrations. Add free volume considerations and you have an action list. So, what should we look for?

Douglas Coffin

I think what you should do is take your chemicals and not just improve the bonding between fibres, but actually change the shear transfer between the fibres. I think that would be beneficial.

Tom Lindström

What do you mean by that? Explain to a chemist.

Douglas Coffin

When we think about bonds, we assume a very thin layer or no layer, it is just how the fibres are attached, there is nothing there, but we know that all the deformation has to be transferred by shear between fibres. We have to get the load from fibre to fibre. The deformation is through the whole fibre wall and not just the bond and if you can change that behaviour, you get a change of fundamental behaviour of the paper. You might be able to improve say stretch, while also improving stiffness, which is going to reduce creep compliance giving you much longer lifetimes. Whereas, you see, if we harden the fibre itself we are not getting anything because we are reducing the strain at failure.

We can improve bonding all we want, but we also want to go one step further and improve the material response at the same time.