THE EFFECT OF PAPER STRUCTURE ON THE DEVIATION BETWEEN TENSILE AND COMPRESSIVE CREEP RESPONSES

A thesis submitted by

Adisak Vorakunpinij

B.ChE. 1994, King Mongkut’s University of Technology Thonburi, Bangkok, Thailand
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ABSTRACT

The contribution of paper structure and properties to box lifetime is unclear. Certainly the intrinsic compressive creep behavior of the liners and medium play an important role. Unfortunately, compressive creep testing of paper is inherently difficult because of the low buckling resistance, but it is essential to build up knowledge based on how the sheet structure and material properties affect compressive creep. Furthermore, it is aimed to have a correlation between tensile and compressive creep, using knowledge about the specific structure of the sheet.

The research presented in this dissertation documents the initial investigation of the influence of sheet structure on the differences in uniaxial tensile and compressive creep behavior of paper. Factors controlled in the experiment are fiber orientation, sheet density, lateral force, creep load and stress direction. To carry out the objectives, a multi-station tensile-compressive creep tester is designed and constructed. The design is based on the PAPRICAN compressive strength instrument, which uses flat plates for lateral support. The advantage of this apparatus is a simple device that allows for creep to be studied in both tension and compression under similar conditions. It is limited to constant relative humidity testing. Friction is the main complication of the testing and methods to minimize friction between paper and the aluminum plates are tested. As an indication of the potential frictional forces, a load cell is used to measure lateral forces that developed during the test. Creep strain is calculated from displacement measurements taken from
two Hall-effect sensors utilizing two small magnets attached to the sample. The new apparatus show satisfactory and repeatable results in both stress directions.

The concept of forming master creep curves with sufficient lateral force provides excellent comparisons between tensile and compressive master creep curves even though the effect of friction could not be totally eliminated. The results demonstrate that a prediction of compressive creep by tensile creep at the same load strongly correlates to the sheet structure. However, the compressive master creep is greater than the tensile master creep when the structure has less buckling resistance.
CHAPTER I  
INTRODUCTION  

On a macroscopic level, paper is treated as a inhomogeneous and viscoelastic material, which is composed of cellulosic fibers bonded in the network structure. The mechanical properties of paper depend on both fiber properties and network characteristics generated by wood fiber properties as altered by the manufacturing processes. Therefore, process variables impact mechanical behavior and end-use performance. After being manufactured, paper is transported from one place to another for its usage before it finally goes to recycle mills or landfills. Thus, the lifecycle of paper is significantly influenced by the external environments of manufacture or usage. It is evident that the mechanical properties of paper generally decrease over time by hysteresis of relative humidity. This degradation usually inhibits paper performance. It is suggested that the performance of paper products is a function of mechanical properties, which include the viscoelastic properties, and time.

Creep is defined as a viscoelastic property and is a major contributor to the demise of performance over time. Although it has been investigated for over 40 years, no one is certain how to overcome creep because it is a natural phenomenon present in most materials. As one of pioneers in the study of paper rheology, Mason (1948) stressed that creep in many circumstances was more important than the true elastic strain which usually comprised only a small portion of the total strain. Part of the reason for this lack
of progress is that until recently, the mechanics of creep was not clearly understood. Furthermore, characterizations of creep behavior in thin materials have almost invariably come from uniaxial tensile testing rather than in edgewise compressive testing. This is because of the experimental simplicity under tension and the occurrence of buckling in compression. In the case of metals, it may be reasonably assumed that tension data will suffice for compression data. In the case of polymers, with their complex structures, it would seem to be desirable to make an actual comparison of tensile and compressive creep behavior before using tensile data universally in a structural design. A prediction of intrinsic compressive creep could improve product performance. However, measuring the intrinsic compressive creep response of paper is a major task. A greater knowledge of the viscoelastic behavior of paper under tensile and compressive stresses is required for designing finished products with long-term durability. A correlation between tensile and compressive creep could help papermakers improve life service of paper products by better estimating properties from tensile creep data. However, there are only a few studies of both tensile and compressive creep data for paper (de Ruvo et al., 1975; Gunderson, 1981). Finally, it is still questionable about which mechanisms of creep would be appropriate for an explanation in paper.

The motivation of this study is to determine if tensile creep behavior along with other properties can be used to predict compressive creep. This investigation is the first step in which a method to measure both tensile and compressive creep is developed, and an experimental investigation of the influences of sheet structure on both tensile and compressive creep is conducted. Correlations between two creep responses are addressed from a structural viewpoint.
In Chapter II, the previous creep investigations in polymers, fibers and paper are reviewed. Some deformation mechanisms in tensile and compressive strength are also described to provide a background for creep mechanisms. Furthermore, some creep models in tension and compression are presented.

In Chapter III, the hypothesis and objectives of this research are given based on the reviewed literature.

In Chapter IV, the development of a new tensile-compressive creep apparatus and a technique to reduce the static frictional coefficient are described. Then some preliminary results will be discussed briefly. Finally, the experimental procedures, the characterizations of sheets and the creep measurements are explained.

In Chapter V, the experimental results of the tensile and compressive creep are reported. This section also illustrates some SEM micrographs, comparing the sheet structure before and after creep. Then treatments of the data, including construction of master creep curves and the possibility of frictional correction, are presented.

In Chapter VI, major findings, the significance of the results and current problems from this study are summarized. Finally, recommendations for future works are provided in Chapter VII.
2.1 Structure of Wood, Fiber, and Paper

The physical and chemical properties of wood fibers are quite different among wood species. Although fibers consist of three major polymers: (1) lignin, (2) hemicellulose and (3) cellulose, the amounts of each vary from one location to another in the same fiber. When looking at a fiber in terms of the morphological structure, a fiber is composed of five distinct layers: (1) the intercellular substance or middle lamella, (2) the primary wall, (3) the outer layer of the secondary wall or S1 layer, (4) the central layer of the secondary wall or S2 layer, and (5) the inner layer of the secondary wall or S3 layer. This description indicates that a wood fiber is a naturally heterogeneous structure. Furthermore, chemical and physical characteristics of fibers would be further changed by the chemical and mechanical treatments in the pulping and papermaking processes before fibers are manufactured into paper. Table 1 summarizes the general relationships between properties and operations (Kline, 1982). A plus (+) in any point indicates that the operation can positively influence the sheet properties, whereas a minus (-) indicates a negative influence in the sheet properties. A result of heterogeneous structure could affect physical and chemical behaviors of the end-use products. As fibers lie primarily in the planar direction, their orientation creates an orthotropic material that also has non-uniform distribution of strength and optical properties along the principle axes. Because
of hysteresis, the characteristics of paper products change when they are subjected to different environmental conditions.

Table 1. Relationships between operations and properties (Kline, 1982).

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*G=gray       Y=yellow       B=blue       W=white
2.2 Creep Characterization

2.2.1 Stages of Creep

Creep is defined as the continuous deformation of a material under constant stress over a long period of time. In other words, creep is the time-dependent behavior of a material under a quasi-static stress. When a material has time-dependent behavior, it generally exhibits viscoelastic behavior. The viscoelastic behavior combines elastic and viscous properties. The creep phenomena are generally classified into three stages, as depicted in Fig. 1. The first stage is called primary creep, where strain rate increases instantaneously with the application of load, then decreases gradually. When strain rate is constant, creep enters into the secondary creep. This steady stage is the most important in structural design against creep since the period of this stage is considerably longer than the primary creep. When the strain rate begins increasing again, the final stage or tertiary creep has been reached. In the tertiary creep stage, deformation continues on until creep rupture occurs.

2.2.2 Creep in Polymeric Materials

The creep rate of polymers is relatively large when the temperature is above the glass transition temperature ($T_g$). It has been postulated that polymeric materials creep by the action of molecular chains sliding past another in a viscous manner (as having weak bonds, hydrogen and van der Waals, to hold the carbon chains) (Findley, 1960; Dowling, 1993). The rate of viscous flow increases with stress and temperature, as depicted in Eq. 2.1.
Figure 1. Typical creep curve.

\[
\dot{\varepsilon} = C \sigma e^{-Q/(R T)} \tag{2.1}
\]

where

- \( \dot{\varepsilon} \) = rate of strain
- \( \sigma \) = stress
- \( Q \) = activation energy
- \( T \) = temperature
- \( R \) = gas constant
- \( C \) = constant
An increase in the amorphous content of polymers leads to viscous flow, orienting the polymer chains in the direction of stress. This viscous behavior (fluid-like deformation) is reduced, and the material becomes more creep resistant if the material has a higher crystalline content, a more cross-linked network or bulkier side groups in the polymer chains. Three-dimensional network polymers have greater creep resistance than other polymers, due to the strong primary bonds in the network structure (Findley, 1960). The action of molecular sliding also depends upon the polymer structure and the nature of the applied stress. For example, dislocation and diffusion phenomena in crystal lattice of a polymer should affect the defects of a polymer in the same manner as in metals. Diffusion creep involves point defects, which result from the movement of vacancies (holes) in the crystal lattice. On the other hand, dislocation creep involves line defects caused by the motion of dislocations in the crystalline part.

O’Connor and Findley (1962) investigated creep strain of polyethylene and rigid unplasticized polyvinyl chloride copolymer in tension and compression. The experiments were performed at 75°F and 50% RH for 2000 hr. A rectangular specimen with 9/16-in thickness was supported laterally by rollers under compressive loads. The results showed that the creep curves for polyethylene under tension and compression were similar. However, for the polyvinyl chloride copolymer, the tensile creep strains were mostly greater than the compressive creep strains. The calculated elastic modulus for tension and compression from 20-s strain curves were similar for polyethylene, resulting in similar tensile and compressive creep. On the other hand, a higher tangent elastic modulus in compression for polyvinyl chloride resulted in lower compressive creep strains. They hypothesized that shear stresses would have a strong impact on creep in weaker materials
such as unplasticized polyvinyl chloride copolymer, which caused the differences in tension and in compression.

Benham and Hutchison (1971) investigated three thermoplastic polymers (polymethyl methacrylate, polyacetal and polypropylene) subjected to constant loads in tension and compression. In order to avoid the buckling effect in compression, a cylindrical specimen (3.675-in long with 0.995-in diameter) with ½” gage length diameter was selected. All three polymers crept up to 3% strain within $10^5$ seconds at 21°C and 55% RH. Their results showed that the creep resistance for all three of the thermoplastic polymers was higher in compression than in tension. The polymethly methacrylate showed the lowest creep strain while polypropylene had the highest value. They described how the free volume in chain segments caused different creep behavior between tension and compression. The reduction of free volume under compression resulted in greater restriction of chain movement. Therefore, an increase of free volume in tension for the same stress allowed more mobility and higher creep strain.

### 2.2.3 Creep in Paper and Fiber

Researchers (Mason, 1948; Brezinski, 1955, 1956) have hypothesized on cause of the time-dependent mechanical response of paper. The possible explanations of the mechanical response in paper span mechanisms which occur within the fibers, within the interfiber bonds, or within the full network structure. Typically, physical properties of paper are strongly influenced by the orientation of the structural element. Van den Akker (1950) hypothesized that the effect of stress distribution would be more significant in a
heterogeneous material, such as paper. Later on, Page (2000) discussed that both bond breaking and deformed fibers should result in plastic deformation of paper under a load.

2.2.3.1 Tensile Creep

Brezinski (1955, 1956) illustrated that the primary creep of alpha-pulp handsheets subjected to an applied stress at constant conditions (73°F and 50% RH) was correlated to initial stresses. The effects of increasing initial stress could be described in a master creep curve by shifting the creep curves in log time until they fit into a single curve. It was postulated that the creep curve at any stress level was ideally a portion of the total creep response in the master creep curve. However, a large increase of deformation could be caused by small initial stresses at higher relative humidity. Also, some creep curves with changing relative humidity conditions could not be fitted into a master creep curve. An attempt to determine creep properties on sheet structure was made. Handsheets at different solid fractions were manufactured by changing the degrees of beating and wet pressing. At similar solid fractions, results suggested that an increased refining level caused a delay in creep strain. Moreover, an increase in the solid fraction by wet pressing was very effective in decreasing the creep response in the lower solid-fraction range. Based on the experimental data, Brezinski hypothesized that primary creep behavior in tension resulted from molecular reconfiguration in the amorphous section of fibers.

Schulz (1961a, 1961b) observed the effect of unidirectional wet straining on viscoelastic behavior of handsheets made from a Rayonier softwood alpha pulp at 73°F and 50% RH. An increase in wet straining of a certain percent resulted in a decrease of creep response. It was noted that total deformation decreased as wet straining increased.
However, total deformation would increase if wet straining was greater than 4%. The explanation of how this effect delayed the creep response was not fully described. Nevertheless, Page et al. (1985) pointed out that stretching curled fibers by wet straining could improve the tensile strength of paper because of higher straightness of fibers in the direction of straining. This explanation could be used to describe the findings in Schulz’s study. The stronger a sheet is, the less creep it will show.

Another investigation of creep behavior in paper by Sanborn (1961, 1962) was performed at 73°F and 50% RH. His 100-g/m² sheets were made from mixed never-dried bleached sulfite pulp (60-80% spruce, 10-20% hemlock, 10-20% balsam fir, 5-10% larch fiber). Changes in both optical and porous properties were used as criteria to investigate structured changes after 48-hr creep recovery cycles (24 hr of creep and 24 hr of recovery). He discovered that deformed specimens showed significant changes in pore size distribution and light scattering. An increase in pore size distribution could imply that the applied stress caused some changes in intrafiber and bonded areas. However, changes in scattering and energy loss depended upon the duration of testing. In addition, he suggested that energy loss from deformation could not be used to calculate the energy absorbed precisely if some energy was absorbed by fibers during sheet deformation.

A study by Hill (1967a, 1967b) describing the creep response of southern pine holocellulose fibers at 23°C and 50% RH showed that there were structural changes within the fiber after tensile creep. Using an X-ray diffraction method, the fibrillar orientation decreased in fibers subjected to applied loads of 10 and 20 g per fiber for 14 hr. Nevertheless, there were no significant changes in the crystallinity of treated fibers. If the crystalline cellulose in fibers reorientated along the stress direction, their elastic
modulus should increase. Hill hypothesized that there were two types of structural changes occurring during creep tests: (1) The molecules in the amorphous region had stress relaxation from minute fibrillar movement. (2) Some movement in large segments of cellulosic fibrils contributed to further fiber deformation after stress relaxation that occurred in the first stage.

Byrd (1971, 1972) examined the effect of relative humidity changes on tensile creep. His results illustrated that deformations would be greater under cyclic relative humidity (35% ↔ 90% RH) with 500-min intervals than under a constant relative humidity (90% RH) for all applied stress levels. Changing moisture content during testing caused more load-deformation due to structural change within fibers. He argued that both partial bond breaking and stress redistribution could affect the rate of deformation as stress increased. It was shown that fibril angles of fibers, taken from crept sheets and then measured by X-ray diffraction, decreased at constant RH but increased with cyclic RH.

Olsson and Salmen (2001) recorded spectra from the mid- and near-IR in creep tests. The creep experiments for 15-g/m² sheets were performed at constant 90% RH and under cyclic humidity between 90 and 30% RH with 70-min intervals. Three different stresses (2.2, 3.5 and 6.1 MPa) were selected. Their data illustrated that dynamic elastic modulus increased, except at the lowest stress level. Evidence from the mid-IR spectra at 1184 and 1030 cm⁻¹, which was assigned to CH₂, CH and C-O, indicated sliding between the cellulose chains. Then they argued that the change was due to the reorientation of the cellulose molecules towards the tensile load. This is in agreement with Hill’s and Byrd’s X-ray results at constant relative humidity testing. The microscopic results also seem to
agree with Brezinski’s hypothesis that creep strain was largely due to molecular reconfiguration in the amorphous region of the polymer.

2.2.3.2 Compressive Creep

A study by de Ruvo et al. (1975) related mechanisms of compressive failure in paper by creep. Their result suggested that strain for the three basis weight sheets tested (380-410 g/m²) was greater in compression than in tension. Then they postulated that the deformation mechanisms of plastic components in compression were considerably larger than in tension due to the instability of the load bearing elements in compression, a buckling phenomenon. However, their results do not provide insight into how changes in sheet properties or sheet structure influence structural instabilities.

Donega and colleagues (1990) examined compressive creep of 270-g/m² virgin and recycled paperboard made by blending 90% eastern Canadian hardwood species (45% birch and 45% poplar) and 10% softwood (mainly white pine). Cylindrical compressive creep measurements were performed at 25°C for 240 min. The compressive creep was carried out at different testing conditions: fiber orientation (MD or CD), fiber type (virgin or recycle), load (25% or 60% of maximum load at 90% RH), and relative humidity (constant 90% RH or cyclic between 35 and 90% RH with 48-min intervals). At constant and cyclic RH, the cross machine direction showed more creep for both virgin and recycled sheets. Nevertheless, deformation of recycled paper was much smaller in both machine direction and cross machine direction compared to the results from virgin paper. As expected, creep under cyclic RH showed higher creep rates for all testing conditions than under constant RH.
Haraldsson and co-workers (1993) constructed isochronous curves to compare compressive creep of commercial linerboard (185-g/m²) in machine direction (MD) and cross machine direction (CD). From the isochronous curves, the compressive creep of MD linerboard was less than that of CD at both 1 and 10,000 s. Furthermore, they depicted in the 10-second isochronous curves that the initial slope of curves was the same in tension and compression, and later both curves deviated from each other, as depicted in Fig. 2.

![Figure 2](image.png)  
**Figure 2.** Tensile and compressive isochronous curves for commercial linerboard in MD and CD at 10 seconds (Haraldsson et al., 1993).

Creep is affected not only by paper properties but also by the environment of the testing conditions. Considine et al. (1994) investigated the effect of a humid environment on compressive creep behavior for linerboard and corrugating medium. It was shown that
strength properties of specimens at 90% RH were lower than at 50% RH. The mean maximum creep rates of both samples at 90% RH were two or three times greater than at 50% RH. High moisture content would plasticize the fibers and bonds, which then cause lower compressive strength, lower stiffness and greater creep. Their results showed, as expected, that creep in the cross machine direction (CD) was greater than in the machine direction (MD) for all RH conditions.

2.3 Compressive Creep Measurement

The tensile creep measurements are generally much simpler than compressive creep measurements. Although they both employ dead-weight loading and use a strain gauge to measure the relative displacement for paper creep over time, tensile testing requires no additional lateral support. However, compressive creep testing is experimentally more difficult because of the low buckling resistance of a sheet of paper. There is always the possibility that differences in techniques may cause some of the observed difference in behavior (Coffin and Fellers, 2001). In order to avoid buckling, many researchers have applied various lateral restraint techniques to investigate paper creep in compression. Adding unnecessary force to inhibit compressive deformation of the sheet is unwanted, but sufficient force must be used to inhibit buckling. It is believed that the intrinsic compressive strength and creep could be measured with appropriate lateral support. The concept of a compressive creep tester was basically developed from existing compressive strength apparatus. It has been known that the compression strength of paper is primarily based on the configuration of the specimen, the slenderness ratio of the unsupported portion of the specimen, and the straightness of the specimen (Fellers,
1983). Nonetheless, no existing edgewise compressive strength instrument has been widely accepted for the intrinsic compressive creep measurements in paper. Since the slenderness ratio was a major concern in a measurement of the intrinsic compressive strength, the free span of a specimen, excepting cylindrical tests, was typically shorter than 5 in. Fellers suggested that the differences among compression strength values of thin uneven material, such as paper, as measured by the different methods, should be explained in terms of the different abilities of the methods to prevent the sheet from becoming unstable. Moreover, undulations possibly occurred in between lateral supports in the final parts of a compression deformation unless the lateral supports were sufficiently stiff and tightly pressed against the specimen. From the compressive strength apparatus, there are four different types of lateral supports that could be used in compressive creep measurements as follows: (1) cylindrical support, (2) vacuum restraint, (3) blade support, and (4) plate support.

2.3.1 Cylindrical Support Test

Forming a cylindrical sheet for a compressive creep test helps increase the stability of a specimen, as shown in Fig. 3. To minimize the buckling effect, however, Setterholm and Gertjejansen (1965) inserted an additional inner cylinder and glued the ends to avoid crushing the ends. They pointed out that the diameter of a cylindrical specimen affected the measured compressive strength. Their results illustrated that the maximum compressive strength achieved was with a 1-in diameter cylinder for low to medium paper thickness. It was very difficult to form small diameter cylinders from very thick boards at TAPPI standard testing conditions. Uesaka et al. (1982) suggested
preparation of cylindrical specimens under high humidity in order to minimize damage from bending when a cylinder was formed. Then Ueseka (1983) provided the conservative criteria for cylindrical geometry in Eqs 2.2 and 2.3.

\[
\frac{t}{R} \leq 0.04 
\]

\[
L > l_g + 4R
\]

where

\[
t = \text{sheet thickness} \\
R = \text{diameter of a cylindrical specimen} \\
L = \text{height of a cylindrical specimen} \\
l_g = \text{gage length}
\]

**Figure 3.** Cylindrical support test with coupled mirror and knife edge-type compressometer for measuring compressive deformation (Setterholm and Gunderson, 1983).
Some researchers (Gunderson, 1981; Fellers, 1983; Donega et al., 1990) hypothesized that the multi-component stress state would affect the test results when testing paper in a cylindrical shape. Due to incomplete theories for cylindrical geometry, they argued that the applied compressive load in the cylindrical form was lower than in a flat sheet. It is questionable whether the cylindrical shape is suitable for cyclic humidity creep testing. Since some residual stresses resulting in cylindrical formation appear perpendicular to the loading direction, accelerated creep may show various responses.

2.3.2 Vacuum Restraint Test

A lateral restraint concept was developed by Gunderson (1981) at the Forest Product Laboratory (FPL) in Wisconsin, USA. They utilized a light vacuum to increase buckling resistance of a specimen to in-plane deformation, as depicted in Fig. 4. 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. A cross machine direction linerboard was used to test the apparatus under constant and cyclic humidity, but no comparison to other methods was given. Nevertheless, their preliminary results suggested that this instrument should be appropriate for paperboard materials or thicker sheets due to the vacuum pressure. However, the pressure difference between the two sides of a specimen could result in a moisture gradient across the thickness direction. Later on, the restraint system was further modified by using vertical rods (3.2-3.3 by 3.2-3.3 by 115-152 mm) (Gunderson, 1983; Considine et al., 1994).
2.3.3 Blade Support Test

The blade support test was developed by two independent groups: (1) at the Swedish Pulp and Paper Research Institute, STFI, (Cavlin and Fellers, 1975) and (2) at the Weyerhaeuser Company (Stockmann, 1976), as depicted in Fig. 5. The idea of this support type was to use the fingers to support the specimen laterally in order to avoid buckling in the compressive strength test while exerting minimal force on the sample. Calvin and Fellers found that buckling of micro elements triggers the failure in compression. However, no information was provided on the spacing between the steel fingers, which caused buckling. The main disadvantages of this concept were its high sensitivity to the spacing between fingers, the difficulty in direct strain measurement on the sample because of the test configuration, and the friction between the specimen and the fingers (Uesaka et al., 1982). Haraldsson et al., (1994) further developed the STFI apparatus to measure stress-strain and creep curves by extending the free span from 20 mm to 60 mm and increasing blade thickness to 3 mm (see Fig. 6). They showed that the influence of lateral force to the compressive strength index was up to 60 N. When the
force was higher than 60 N, the stress-strain curve reached a plateau. Therefore, a 60-N lateral force was selected in the creep experiments. Their compressive creep curves did not show any buckling of 185-g/m² MD linerboard when load was applied up to a limit of 10 kN.m/kg. However, samples quickly deformed when the applied load was greater than 10 kN.m/kg. It is hypothesized that the rupture in creep curves could result in local buckling between blades.

Figure 5. Weyerhaeuser finger support test (Stockmann, 1976).
2.3.4 Plate Support Test

2.3.4.1 PAPRICAN Plate Support Test

The equipment from the Weyerhaeuser edgewise compressive strength apparatus (Fig. 5) was modified by Seth and Soszynski (1979) at the Pulp and Paper Research Institute of Canada (PAPRICAN). The PAPRICAN plate support apparatus was initially used to measure the intrinsic compressive strength of paper. However, this concept could be adapted for creep testing under compression as well (Fellers, 1983).

The modification was employing flat aluminum plates instead of fingers for the lateral support, as shown in Fig. 7. The lateral force that developed during compression was determined by measuring the deflection of a beam that rested against the movable support. Therefore, the frictional resistance of the lateral supports could be assessed, as illustrated in Fig. 8.
Figure 7. PAPRICAN plate support test (Seth et al., 1979).

Figure 8. Load-deformation curves in compression and the lateral forces developed according to the PAPRICAN plate support test (Seth and Soszynski, 1979).
2.3.4.2 STFI Plate Support Test

The solid plate support idea was developed by Fellers (1980, 1983) at the Swedish Pulp and Paper Research Institute (STFI). A schematic of the apparatus is depicted in Fig. 9. The free span was selected at 1 mm in order to prevent buckling of the unsupported section of the specimen. Fellers pointed out that the uneven thickness of a thin sheet would develop small amplitude waves in compression. Therefore, clearance between lateral support and the specimen typically was a predominant source of error in the measurement. He also described that the sensitivity of clearance would depend on basis weight, orientation and thickness uniformity of the paper. The relative error in strength was less than 5% if the clearance was kept between 0 and -0.01 mm in the compression measurement. Although Fellers suggested this type of apparatus could be useful for compressive creep, he could not find a way to improve its performance for the creep measurements. It is possible that the friction at the paper-plate interface was a major factor at that time.

![A schematic of STFI solid support test (Fellers, 1983).](image)

**Figure 9.** A schematic of STFI solid support test (Fellers, 1983).
2.4 Deformation Mechanisms in Tension and Compression

It is hypothesized that the same mechanisms that determine tensile and compressive strength are activated for tensile and compressive creep, respectively. An explanation of creep mechanisms in terms of fiber and bond deformation could be based on the progress of failure mechanisms as stress distributes through the sheet. To better understand creep mechanisms in tension and compression, it would be appropriate to explore tensile and compressive stress-stain relationships. In the literature, there have been two explanations about the rheological behavior of paper under stresses: (1) the structural approach and (2) the molecular approach. However, this dissertation will only focus on the structural approach.

Figure 10. Typical tensile and compressive deformation behavior of paper (Waterhouse, 1990).
A general stress-strain curve of paper in tension and compression is shown in Fig. 10. As mentioned previously, a measurement of compressive strength requires some means of lateral support to prevent specimen buckling. Waterhouse (1990) anticipated that the mechanisms controlling deformation and failure of paper in compression would be different from those in tension because the maximum load and strain in compression was approximately one-third to one-half of that in tension.

2.4.1 Deformation Mechanisms in Tension

Page and Tydeman (1961) described how microcompressions at the bond sites were pulled out when the sheet was stretched. Simultaneously, the cross fibers were stretched transversely. They argued that a point would be reached when the shear bond strength was exceeded, and bond breakage would begin. If bonds broke slowly, the microcompressed regions were released, allowing a greater extension and greater permanent deformation. Using Page’s equation (Page, 1969), the tensile-strength mechanism of an isotropic sheet is a combination of fiber deformation and bond breakage. The rupture processes occurs in two parts depending upon whether fiber or bond strength is exceeded. When fibers are stronger, the bond areas are first deformed by bending, stretching and shearing of fibers in the rupture zone. After bond breakage, the stress would transfer from certain fibers to adjacent ones until the catastrophic failure of the load-bearing fibers occur. On the other hand, fiber segments would break first if the bond strength is stronger. Then bonds would hold stresses until they are broken.

Furukawa and co-workers (1985, 1991) studied structural changes in well-beaten 80-g/m² NBKP machine-made paper under tension when samples were loaded in the
cross machine direction. The scanning electron micrographs of plastic deformation on the paper surface appeared to show partial and random debonding at the interfiber crossing, which then developed into small cracks. If stress was increasing, the breakage was continuous, not only at bonded areas, but also in the fibers segments. The damaged areas were obvious when strains were 2% or more. They pointed out that the load bearing within a sheet depended upon components and matrix structure, in which cracks were scattered over the observed areas.

2.4.2 Deformation Mechanisms in Compression

De Ruvo and co-workers (1975) described how failure in compression was initiated by the instabilities of the load bearing elements on different structural levels. Their results demonstrated that creep rate and stress relaxation in compression were higher than ones in tension. Fellers (1983) pointed out that the intrinsic compressive strength could be examined if the loading conditions and specimen straightness were close to ideal. The critical stress for the Euler equation could be calculated from the correlation between elastic modulus and slenderness ratio of plate, as depicted in Eq. 2.4.

\[
\sigma_c = k \frac{\pi^2 E}{\lambda^2}
\]  

(2.4)

where

- \( \sigma_c \) = critical stress
- \( E \) = elastic modulus
- \( \lambda \) = slenderness ratio = \( \sqrt{3} \frac{L}{t} \)
- \( k \) = buckling coefficient
Sachs and Kuster (1980) used microscopic techniques to study the compressive failure mechanism of southern pine linerboards using the short span method. The apparatus was built in the specimen chamber of a scanning electron microscope, and it allowed videotaping in the electron beam of the microscope while unidirectional compressive force was applied. The results showed that the failure mechanism was a combination of enlarging voids, tearing fiber cell walls, and separating fiber layers. The deformation finally led to delamination of the fiber. As showing that buckling of fibers occurred after maximum load was achieved, they described it as a postfailure phenomenon.

Fellers and coworkers (Cavlin and Fellers, 1975; Fellers et al., 1980; Fellers, 1983) proposed two complementary failure mechanisms in compression. Failure was triggered either (1) by buckling of the fibrous structure (predominant in low-density sheets) or (2) by shear dislocations of the fiber walls caused by flow of microfibrils (predominant in high-density sheets).

Perkins and McEvoy (1980) proposed mechanisms of edgewise compressive strength in paper from a mechanical point of view at failure. They used sheets of various densities with different spacing between adjacent fingers (1.5-3.25 mm) in the Weyerhaeuser edgewise compression apparatus. They found three phenomena of compression failure in the photomicrographs: (1) shear slip plane mode, (2) bending mode, and (3) bulging mode, as depicted in Fig. 11. Due to inherent imperfections in
paper, these three localized buckled forms were predominated in compression. In contrast, the characteristic features of bending failure were irregular. The sheet thickness increased between two adjacent pairs from lateral support fingers as sheet delamination. This is an effect of deformation presumably related to a gradual transition from shear to bending failure.

![Figure 11](image.png)

**Figure 11.** Compressive failure modes: (1) shear slip plane mode, (2) bending mode, and (3) bulging mode (Perkins and McEvoy, 1980).

A theory developed by Habeger and Whitsitt (1983) considered a sheet as a composite of laminae, whose thickness was of the order of a fiber thickness. They assumed that bending of the critical laminae caused prebuckling deformations under compressive load. However, buckling of the critical lamina would not appear since it was resisted by the stiffness of the medium. With an assumption that the stress on the critical lamina was equal to the overall compressive stress, the critical lamina was not necessarily the weakest layer, but rather its failure could lead to the structure collapse. Therefore, compressive failure of the sheet occurred when the maximum shear stress in the medium exceeded a limit.
Page (Back, 1985; Page and Seth, 1990) argued that when the matrix in a microcompressed region of a fiber in a sheet yielded under compression, the amplitude of the microcompressions increased by further flow. This hypothesis was different from Page’s description for tensile strength mechanism, in which the yield point and plastic flow in paper was caused by the yield of the matrix as the microcompressed regions of fibers were extended.

Another mechanistic explanation was from investigating edgewise compressive loading of 240-g/m² NBKP machine-made paper with cylindrical support (Mark et al., 1984; Furukawa et al., 1991). The results showed that compression failure was a localized three-dimensional phenomenon in which fiber debonding and fiber buckling were obvious. However, such damage only appeared around the crease area. There was no structural change unless creasing occurred.

2.5 Creep Models for Paper

2.5.1 Tensile Creep Models

Brezinski (1956) proposed two types of primary creep models under tension at low and high initial stresses, as shown in Eqs. 2.5 and 2.6, respectively. The power-law equation was used to describe creep curves at low initial stresses, whereas the logarithmic equation would fit at higher initial stresses.

\[
\frac{y}{L_0} = B * t^\alpha + C \tag{2.5}
\]

\[
\frac{y}{L_0} = K * \log(t) + D \tag{2.6}
\]
where

\[ y = \text{total first-creep deformation} \]
\[ L_0 = \text{initial specimen length} \]
\[ t = \text{time of loading} \]
\[ B, a, C, K, D = \text{constants} \]

A model of the master creep curve was presented by Pecht et al. (1984). This model was developed from the concept of simple stress rheology, in which creep curves could be shifted to form a master creep curve. Equations (2.7) and (2.8) illustrate the desired creep strain expression.

\[
\frac{\varepsilon(t)}{\sigma_0} = \frac{1}{E} + k \log[1 + g(t) \cdot f(\sigma_0)] \tag{2.7}
\]

\[
g(t) \cdot f(\sigma_0) = \left(\frac{t \cdot 10^A \cdot (\sigma_0 - \sigma_R)}{t_0}\right)^n \tag{2.8}
\]

where

\[ \varepsilon(t) = \text{strain} \]
\[ \sigma_0 = \text{initial stress} \]
\[ \sigma_R = \text{reference stress that forms the basis of the master creep curve} \]
\[ E = \text{elastic modulus} \]
\[ k = [\text{creep strain at } t = t_0 \cdot (1/E)]/\log(2) \]
\[ t_0, n = \text{material properties} \]
\[ A = \text{shift factor} \]

\[ g(t) = \text{time-shift function assumed to have the form of a power law } (t/t_0)^n \]

\[ f(\sigma_0) = \text{simple form of the stress shift function} \]

If \( g(t) \cdot f(\sigma_0) \ll 1 \), then Eq. 2.7 could be simplified to Eq. 2.9, which is similar to the exponential creep model of Brezinski (Eq. 2.5). On the other hand, Eq. 2.7 could be approximated by Eq. 2.10 if \( g(t) \cdot f(\sigma_0) \gg 1 \), which matches to the logarithmic creep model of Brezinski (Eq. 2.6).

\[
\frac{\varepsilon(t)}{\sigma_0} \bigg|_{g(t) \cdot f(\sigma_0) \ll 1} = \frac{1}{E} \left( k \cdot 10^{A \cdot n \cdot (\sigma_0 - \sigma_R)} \right) \cdot t^n \quad (2.9)
\]

\[
\frac{\varepsilon(t)}{\sigma_0} \bigg|_{g(t) \cdot f(\sigma_0) \gg 1} = \frac{1}{E} + k \cdot n \cdot \log \left( \frac{t}{t_0} \right) \quad (2.10)
\]

Pommier et al. (1992) proposed an analogy-based model formed by a Maxwell system connected with two Kelvin Voigt elements. This function was used to predict the rheological behavior of paper creep, as shown in Eq. 2.11.

\[
\frac{\varepsilon(t)}{\sigma_0} = \frac{1}{E_1} \cdot \left( 1 + \frac{t}{\tau_1} \right) + \frac{1}{E_2} \cdot \left( 1 + e^{-t/\tau_2} \right) + \frac{1}{E_3} \cdot \left( 1 + e^{-t/\tau_3} \right) \quad (2.11)
\]

where

\[ \varepsilon(t) = \text{strain} \]

\[ \sigma_0 = \text{initial stress} \]

\[ E_i = \text{elastic modulus; } i = 1, 2, \text{ and } 3 \]
2.5.2 Compressive creep models

Haraldsson et al. (1993) performed uniaxial creep experiments on linerboard with a finger-support apparatus. They fitted a hyperbolic tangent equation to the edgewise compressive creep, as shown in Eqs 2.12 and 2.13.

\[
\sigma = \left( \frac{t}{t_1} \right)^n \alpha_1 \tanh \left( \frac{\varepsilon \alpha_2}{\alpha_1} \right) 
\]

(2.12)

\[
\sigma = \left( 1 - m \log \left( \frac{t}{t_1} \right) \right) \beta_1 \tanh \left( \frac{\varepsilon \beta_2}{\beta_1} \right) 
\]

(2.13)

where

\[ \sigma = \text{specific stress [force/(width*grammage)]} \]

\[ \varepsilon = \text{strain} \]

\[ t = \text{creep time} \]

\[ t_1 = \text{creep time at 1 second} \]

\[ m, n, \alpha_1, \alpha_2, \beta_1, \beta_2 = \text{material constants} \]
Using a vacuum restraint apparatus, Chalmers (2000) showed the best fit of a creep curve in 90% RH with the power-law model, as depicted in Eq. 2.14. This approximation was similar to Eq. 2.5 presented by Brezinski (1955, 1956).

\[ E_c(t) = a \cdot t^b \]  
\[ (2.14) \]

where

- \( E_c(t) = \) compressive strain
- \( t = \) creep time
- \( a, b = \) constants

Urbanik (2002) further developed compressive creep models for corrugated containers. Using a linear load rate \((p = r \cdot t)\) to correlate the stress-strain relationship, that model described each stage of creep strain components for paper in compression, as shown in Eqs. 2.15 - 2.18.

\[ E_c = E_{c1} + E_{c2} + E_{c3} \]  
\[ (2.15) \]

\[ E_{c1} = \frac{\tau_1 \cdot (1 - \alpha_1) \cdot q_0 \cdot (e^{q_1 \cdot r \cdot t} - 1)}{1 - \tau_1 \cdot q_1 \cdot r} - \tau_1 \cdot (1 - \alpha_1) \cdot q_0 \cdot (e^{-t / \tau_1} - 1) \]  
\[ (2.16) \]

\[ E_{c2} = \frac{q_0}{q_1 \cdot r} \left( e^{q_1 \cdot r \cdot t} - 1 \right) \]  
\[ (2.17) \]

\[ E_{c3} = \int_{0}^{t} \left( \beta_0 + \beta_1 \cdot q_0 \cdot e^{q_1 \cdot r \cdot t} \right) \cdot e^{-a \cdot e^{-b \cdot r \cdot t / \tau_3} \cdot \frac{3}{t / \tau_3}} \cdot dt \]  
\[ (2.18) \]

If the \( p \) is constant, creep strains are presented in Eqs. 2.19 - 2.21.
\[ \varepsilon_{c1} = \tau_1 * (R_2 - R_1) * \left( e^{-t/\tau_1} - 1 \right) \] (2.19)

\[ \varepsilon_{c2} = R_2 \times t \] (2.20)

\[ \varepsilon_{c3} = \tau_3 * R_3 * e^{-t_b/\tau_3} * \left( e^{t/\tau_3} - 1 \right) \] (2.21)

where

- \( \varepsilon_{c1}, \varepsilon_{c2}, \varepsilon_{c3} \) = creep strain at primary, secondary and tertiary stage, respectively
- \( \tau_1, \tau_2, \tau_3 \) = time constant at primary, secondary and tertiary stage, respectively
- \( R_1 \) = primary creep rate = \( q_0 \times (1 - \alpha_1) + \alpha_1 \times R_2 \)
- \( R_2 \) = secondary creep rate = \( q_0 e^{q_1 \times p} \)
- \( R_3 \) = tertiary creep rate = \( \beta_0 + \beta_1 \times R_2 \)
- \( t_b \) = time to failure
- \( p \) = load
- \( r \) = rate of load
- \( t \) = time
- \( a, b, q_0, q_1, \alpha_1, \beta_0, \beta_1 \) = constants
CHAPTER III
THESIS HYPOTHESIS AND OBJECTIVES

The public literature provides relatively few studies of primary creep for paper in both tension and compression at constant relative humidity. Furthermore, there is little available information to illustrate how changing paper structure results in different creep characteristics between tension and compression. In fact, no complete study enables one to prescribe a correlation between creep in tension and compression. It has been noted that the strength of fibers is controlled by fibril angle, defects and chemical composition (Page et al., 1972; Page and El-Hosseiny, 1976a, 1976b), and the strength of paper is governed by the strength of both fibers and bonds (Page et al., 1979; Page and Seth, 1979).

Since a sheet of paper generally has low buckling resistance, the measurement of intrinsic compressive creep is difficult. Fiber types, the pulping process, the papermaking process, and end-use environmental conditions are always factors affecting creep response. The complexity of these factors is a major impediment for a complete understanding how these factors contribute to similarities and differences between tensile and compressive creep. Nevertheless, it is a fact that a weaker sheet of paper tends to show more deformation because stress distribution after either fibers or bonds failed is limited unlike a stronger sheet. Until now, a major obstacle in creep experiments under edgewise compression is to prevent the specimen from buckling before its failure. Paper
physicists are still proposing alternative techniques for improving lateral supports. Ideally, the lateral support should avoid adding unnecessary stresses while keeping a sheet flat during tests. Some normal stresses exist when the lateral supports contact a specimen. To simplify the analysis, however, most previous work has neglected the effect of friction. If this effect could be accounted for, the implication of intrinsic compressive creep should be clarified. Furthermore, comparisons of compressive creep behavior with tensile creep data would be more significant. The evidence from isochronous curves showed that creep curves of a commercial linerboard in tension and compression are similar for a few seconds (Haraldsson et al., 1993). Therefore, it is hypothesized that there would be some similarities between tensile and compressive creep in the early stage, and then different creep-failure mechanisms resulting from the stress direction would cause a differentiation at longer time or large deformation. The hypotheses guiding the research can be stated as follows:

1. Tensile and compressive creep at low load levels and short time frames are the same.

2. At large load levels and long time, different structural deformation such as fiber-segment or fibril buckling will cause compressive creep to be higher than tensile creep.

3. The extent of structural deformation will vary with changes in sheet density and fiber orientation and in turn create differences between tensile and compressive creep.
The fundamental research work recorded in this dissertation was separated into two parts. In the first part, the design and development of a new tensile-compressive creep apparatus was completed. The second part concentrated on how paper structure and creep variables influenced creep behavior at a constant relative humidity. In particular, the effects of lateral force were investigated.
CHAPTER IV
EXPERIMENTAL METHODS

The experiments were divided into two phases: (1) the development of a new tensile-compressive creep apparatus and (2) experiments of tensile and compressive creep for papers with varying structure. Details of the first phase including the research approach, development of creep apparatus, and some preliminary results are described. Then experimental procedure and variables for this research are presented in the second phase.

4.1 Development of Tensile and Compressive Creep Apparatus

4.1.1 Creep Apparatus

In prior research (Gunderson, 1981; Donega et al., 1990; Haraldsson et al., 1993, 1994), the compressive creep behavior had been studied mostly from edgewise compression strength apparatus. Due to the difficulty in fundamentals, there is no proven and widely accepted instrument for measuring compressive strain of paper (Gunderson, 1981). Paper is a thin material with low buckling resistance, so such an instrument should have good lateral support.

The creep testing apparatus in this research was modified from the flat plate support in the PAPRICAN compressive strength instrument (Seth and Soszynski, 1979). It was constructed specifically for this study. This apparatus was able to test creep either
in tension or in compression depending on how the sample was mounted. The principal
design had rigid flat aluminum plates supporting the specimen laterally to prevent
buckling of the specimen under compressive load. Because the creep tests were of
extended duration, testing multiple specimens at the same time provided increased time
efficiency. Four testing units were constructed and placed on a table and enclosed by a
chamber allowing for a controlled humidity environment, as shown in Fig. 12. Dead
weight was applied underneath the table. A program written with LabView was created to
control the humidity and record all voltage signals into a computer. The program and
schematic diagrams are shown in Appendix A.

Figure 12. Four units of creep testes in the humidity chamber.

Figure 13 shows a schematic of flat plate support consisting of two pairs of plates,
i.e., (1) a set of fixed plates mounted on low-friction linear bearings and (2) a pair of
removable flat plates. The fixed plates were used to laterally support the removable plates and a specimen. The plate A was fixed to the base and could move freely along the load direction with a low-friction linear bearing. The plate B was suspended over a low-friction linear bearing attached to the base and had free lateral movement. The dimensions of a sample holder were 8 inches in length by 1.5 inches in width by 0.5 inch in thickness. The sample holder C would be mounted to the plate A, while the sample holder D would be fixed to the plate B. The sample holder D had two small rectangular openings (1 inch in length by 0.20 inch in width). These openings were to allow free movement of magnets mounted directly to the specimen and used in the displacement measurements. An eyelet bolt was attached to the plate A. A wire, contacting a low-friction pulley and passing through a hole on the table, was connected between the eyelet and a hook. The hook was used to attach a dead load. The weight of hook and wire was approximately 23 grams.

A 100-N compressive miniature load cell from Entran Devices was placed between the plate B and a micrometer in order to measure the amount of lateral force. A micrometer head was soldered into a hole and attached to the load cell. When the micrometer was advanced forward, the plate B moved closer to the plate A, the voltage of compressive force was sent to a computer. The power supplies used to provide the excitation voltage for the compressive load cell was ±15 to 18 volts.
4.1.2 Relative Humidity Control

A water column (3 inches in diameter by 5 feet in height) supplied wet air to the chamber. The relative humidity in the chamber was controlled by a customized feedback-loop-control program written in LabView. The relative humidity control program and its schematic diagrams are depicted in the Appendix B. The wet air was produced by bubbling air through the water column. Wet air traveled from the top of the water column through a cap. Then the wet air was divided into four tubes and injected underneath the chamber at each corner. The wet air was mixed with dry air near each corner to provide
the proper relative humidity to the chamber. In general, equilibrium conditions were reached within 20 to 30 minutes. Temperature and relative humidity were measured by the HMP 233 transmitter from Vaisala, which sent signals to a computer through an analog/digital board (A/D board). Because the designed system had no temperature control, all equipment was placed in a room at TAPPI standard testing conditions (73°F and 50% RH).

4.1.3 Measurement of Creep Deformation

There were two independent sets of displacement gauges for each testing unit. Each set consisted of a sensor and a magnet. The sensor, a HAL805 Hall sensor from Micronas GmbH, measured changes of the magnetic field between the sensor and the magnet (HAL805 Data Sheet, 1999). The power supply used to provide the excitation voltage for the HAL 805 sensor was ±15 volts. All voltage signals from sensors were sent through an A/D board, which was connected to a computer. The HAL805 is a magnetic field sensor with a voltage output based on the Hall effect. The sensor was calibrated by modulating the supply voltage from a two-point calibration in which the magnetic field was then converted to the output voltage. A calibration was also made against the actual displacement from a micrometer in order to obtain a calibration curve. The distance between the sensor and the magnet was calibrated in the range of 0.5 and 1.0 cm. Figure 14 is a calibration curve for a HAL805 sensor and is typical for all sensors. It should be noted that the correlation of reading voltage and actual displacement is nonlinear. The correlation is described by a power-law model as shown in Eq. 4.1.
where x is the reading voltage and y is the actual displacement between the magnet and the sensor. A HAL805 sensor was mounted to the plate B on one side of rectangles (Fig. 15), while two magnets were attached to the paper surface by two-sided tape, as described in the section on sample mounting (4.1.4). Total gauge length was the distance between the two magnets. Then creep strain was calculated from displacement changes of the two magnets, which was relative to the HAL805 sensors. Calculations of deformation were expressed as “percent strain.” This value was obtained by dividing the absolute deformation, produced by the creep load, by the gauge length of the specimen. The result was displayed as a percentage. In all cases, absolute strain was calculated using the initial gage length of the specimen, and no correction was made for the change in length during the test.

\[ y = \frac{1.05446}{x^{0.5}} - \frac{0.05692}{x} + 0.01534 \]  

(4.1)

**Figure 14.** Calibration curve for a HAL805 sensor.
4.1.4 Sample Mounting

Since the creep apparatus was able to measure both tensile and compressive creep, the sample mounting depended upon the direction of the creep test, as depicted in Fig. 16. Mounting adhesive was prepared by mixing equal parts of a two component Epoxy 907 from Miller-Stephenson Chemical. All specimens were cut to 1 in by 8 in. Then a thin layer of the adhesive was applied on the paper surface at one side of each end (0.5-in long). Next, the paper was sandwiched between the sample holders without external pressure. The adhesive in the sandwich was generally allowed to cure at least 12 hours. After curing, each magnet mounted to lightweight plastic blocks was attached on the
paper surface by two-sided tape in between two drilled rectangles of the sample holder D. The distance between the magnet and the sensor was adjusted by the level of creep load.

![Schematic of sample preparation.](image)

**Figure 16.** Schematic of sample preparation.

### 4.1.5 Reducing Frictional Effects

Due to the design of flat plate support, friction could impact on the creep results. Furthermore, previous work (Whitsitt et al., 1982; Inoue et al., 1990; Back, 1991; McDonald et al., 1996; Fellers et al., 1998; Backstrom et al., 1999; Garoff et al., 1999) showed the effects of sheet properties, papermaking factors and chemicals on the frictional coefficient of paper. For a preliminary study of static friction coefficient in this research, many chemicals were tested by applying them on a sheet of 75-g/m² copy paper. Copy paper was used as a reference because it was generally smoother than other
commercial samples. If a potential chemical were applied on the paper surface, a decrease in the static frictional coefficient (COF) should be distinguishable from the others. The static frictional coefficient was measured by the Amontons II apparatus according to ISO test method 15359. A photograph of Amonton II is shown in Fig. 17.

![Amontons II: static and kinetic friction apparatus.](image)

**Figure 17.** Amontons II: static and kinetic friction apparatus.

Teflon coating provided a coefficient of friction less than 0.10 in the dry state (Larsen-Basse, 1990). It was found that Teflon could significantly reduce friction at the paper-aluminum plate interface if the aluminum plates were covered. In the frictional measurement, a Teflon tape was mounted on a stationary sled. A selected chemical was applied on the surface of copy paper before the sheet was placed on a movable horizontal table. There were three selected chemicals with four testing conditions. For the first condition, a stearic acid was used. Utilization of this chemical was similar to its use in previous work for reducing frictional coefficient (Garoff et al., 1999). The stearic acid
was prepared at 5 mmol/L by dissolving it in acetone. After complete mixing, the solution was sprayed on a sheet of paper. The sheet was then dried under restraint at 73°F and 50% RH. Paraffin wax was tested in the second condition. This paraffin wax was used in the cold corrugating process (Whitsitt et al., 1982). It was produced by mixing stearin, graphite and silicone oil and by then molding the mixture into solid bars. A treatment could be accomplished by abrading the paraffin agent onto the sheet. The number of paraffin passes could cause differences in static coefficients of friction, as shown in Table 2. The third condition used commercial graphite powder. The powder was distributed on the sheet surface before measurement. The last condition was to abrade paraffin wax and then to additionally spray commercial graphite powder onto the paper surface. The results of first frictional coefficient were compared with a control experiment, in which no chemical was applied on the paper surface (see Table 3).

Table 2. Number of paraffin-wax passes on the first static frictional coefficient.

<table>
<thead>
<tr>
<th>Number of Passes on Paraffin Wax Treatment</th>
<th>Static Frictional Coefficient ± S.D.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.257 ± 0.016</td>
</tr>
<tr>
<td>2</td>
<td>0.167 ± 0.006</td>
</tr>
<tr>
<td>3</td>
<td>0.169 ± 0.015</td>
</tr>
<tr>
<td>10</td>
<td>0.177 ± 0.010</td>
</tr>
</tbody>
</table>
Table 3. Preliminary results of static frictional coefficient.

<table>
<thead>
<tr>
<th>Lubricant Materials</th>
<th>Static Frictional Coefficient of Paper(^{(1)}) Against Teflon-Tape Surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>No chemical – controlled experiment</td>
<td>0.374</td>
</tr>
<tr>
<td>Stearic acid in acetone</td>
<td>0.284</td>
</tr>
<tr>
<td>Paraffin wax(^{(2)})</td>
<td>0.167</td>
</tr>
<tr>
<td>Graphite powder</td>
<td>0.259</td>
</tr>
<tr>
<td>Paraffin wax(^{(2)}) + graphite powder</td>
<td>0.230</td>
</tr>
</tbody>
</table>

\(^{(1)}\) Sample was copy paper.
\(^{(2)}\) Paraffin wax was applied on paper surface with two passes.

The preliminary tests for static frictional coefficients shown in Table 3 suggest that paraffin wax provided a minimum value of the first static frictional coefficient. Therefore, the paraffin wax on the sheet and aluminum plates covered with Teflon tape were selected for the creep studies in this research.

4.1.6 Preliminary Results

4.1.6.1 Results of Tensile Creep

To verify the results of tensile creep, two different samples were tested and then compared with results from a traditional tensile creep tester at the Institute of Paper Science and Technology (Habeger and Coffin, 2000). The samples were a 160-g/m\(^2\) handsheet and a 205-g/m\(^2\) commercial linerboard. For the handsheet, the furnish was a never-dried bleached northern softwood pulp (70% black spruce and 30% jack pine) supplied by Domtar Inc. and refined in a laboratory Valley beater to 550 CSF. After the 8”x 8” Noble and Wood handsheet was formed, it was pressed at 50 psi for 5 and 2 min,
respectively, before being fully restraint-dried for 20 min in the Emerson dryer. The same 9027-g tensile load was applied to each sample. The linerboard was only tested in the cross machine direction (CD). The load was equal to 30% of the handsheet’s 50% RH tensile strength and 53% of the CD linerboard’s 50% RH tensile strength, respectively. All tensile creep experiments were performed at 73°F and 50% RH.

A major difference between the modified creep tester (tensile-compressive creep apparatus) and the traditional tensile creep tester was the lateral support. In order to compare tensile creep results, the applied lateral force from this modified creep tester had to be minimized. However, there was a limit for increasing the gap between the sample holders C and D because a sample would not be parallel to the loading direction. This caused some error in the strain measurement. Furthermore, only the tensile creep curves were compared, after eliminating any initial deformation, since different loading techniques between the two instruments could cause different initial deformation.

Figures 18 and 19 illustrate good reproducibility of tensile creep curves for the handsheet and CD linerboard specimens, respectively. However, the variation of creep strain for both samples tended to be larger as time increased. It may be primarily attributed to a variation in the sheet. The results of mean tensile creep curves showed in Figures 20 and 21 indicated good comparisons between two different testers for both samples. In fact, mean tensile creep curves from the handsheet completely coincide with each other. Note that the handsheet exhibited less creep strain than the CD linerboards, showing that the correlation between the two testers is good for both small and large creep strain.
Figure 18. Tensile creep curves for 160-g/m² Noble & Wood handsheets at 30% of the 50% RH breaking load: (a) from tensile-compressive creep tester and (b) from traditional tensile creep tester. The mean curve and its 95% confidence intervals are included.
Figure 19. Tensile creep curves for 205-g/m² CD linerboard at 53% of the 50% RH breaking load: (a) from tensile-compressive creep tester and (b) from traditional tensile creep tester. The mean curve and its 95% confidence intervals are included.
Figure 20. Comparison of mean tensile creep curves for the 160-g/m$^2$ Noble & Wood handsheets from two apparatuses at 30% of the 50% RH breaking load.

Figure 21. Comparison of mean tensile creep curves for the 205-g/m$^2$ CD linerboard from two apparatuses at 53% of the 50% RH breaking load.
4.1.6.2 Results of Compressive Creep

Attempts to verify the apparatus for compressive creep were made using 185 g/m² laboratory formette sheets at TAPPI standard conditions (73°F and 50% RH). This basis weight should allow comparison of the results with previous research (Haraldsson et al., 1994) even though both sheets were manufactured differently. In the previous research, Haraldsson et al. examined a 185-g/m² commercial linerboard in the machine direction (MD) at 50% RH. The MD compressive strength index of their specimen was 27.4 N.m/g.

Sheets in this study were produced from a commercial never-dried and fully bleached kraft pulp provided by Domtar Inc. The wood furnish was a blend of northern softwood species, consisting 60-70% black spruce and 30-40% jack pine. The weight length average of the unrefined pulp, as measured by the fiber quality analyzer, was 2.24 mm. The curl index was 0.187. The pulp was beaten to a freeness level of 550 CSF in a laboratory Valley beater according to TAPPI Standard T-200 sp-01. Sheets were formed by the Formette Dynamique sheet former at a condition with low fiber orientation. Each wet sheet was couched off the wire with blotters and transferred to the KMW drum dryer. The felt tension of the KMW drum dryer was set at 20 psig. At the dryer, each wet sheet was fed in while the felt was moving. When a sheet was completely sandwiched in between the drum and the felt, the motor for the felt drive was stopped for restraint drying of the wet sheet. A sheet was completely dried after 20 min. The sheets were conditioned at 90% RH for 24 hr in order to remove any residual stress. After that, they were stored at 20% RH for 24 hr. Finally the sheets were held at 50% RH for at least one week before the creep tests were performed. During all of these conditioning steps, the temperature
was held at 73°F. The average basis weight of this formette sheet was 184.4 g/m², and the MD compressive strength index was 26.4 N.m/g.

Figure 22. Compressive creep curves at different initial compressive stresses with an average initial lateral force of 26.24 N.

For these preliminary results of compressive creep tests, it was decided that all tests would be performed at 73°F and 50% RH. The compressive creep tests needed to have some lateral forces applied to the sample to minimizing buckling. After the sample was glued and mounted on the creep tester, the system was allowed 24 hr to reach steady state conditions before creep loading began. At steady state, the lateral forces were defined as “initial lateral forces”. Figure 22 shows compressive creep curves with an average of 26.24 N of initial lateral force at various initial stresses. Each compressive strain curved upward. Total strain gradually increased over time. At a lower initial lateral force, total strain increased dramatically as initial compressive stress. In fact, total strain
increased dramatically when paper began to buckle between the plates. At the buckling point, the slope of a creep curve change immediately. These results are in agreement with a previous study on compressive creep (Haraldsson et al., 1994), as shown in Fig. 23. Compressive stress could be applied to a specimen up to some values at a specific lateral force before the buckling occurred. The column lateral support may require higher force to prevent early localized buckling compared with this flat plate support. However, neither kind of lateral support could protect a sample if it buckles.

![Compressive stress vs. Total Strain](image)

**Figure 23.** Compressive creep of a 185-g/m² linerboard in MD: (a) stress index and (b) strain (Haraldsson et al., 1994).

### 4.2 Experimental Procedures

#### 4.2.1 Preparation of Specimens

For tensile and compressive creep experiments, all samples were made from a commercial never-dried and fully bleached kraft pulp, whose furnish consisted of 60-70% black spruce and 30-40% jack pine. The pulp was beaten to a freeness level of 550 CSF
in a laboratory Valley beater according to TAPPI Standard T-200 sp-01. A sample of the refined fibers was dyed using Chlorazol Black E (Ingalsbe, 2001). Each forty grams of oven dry (o.d.) fibers was diluted to 800 ml and then mixed with 1200 ml of hot deionized water. The 0.8 g of Chlorazol Black E power was dissolved in hot water before being added to the pulp slurry. The slurry was agitated by a stirring rod for 10 minutes, and then 8 g of NaCl was added to the pulp suspension. After that, the suspension was allowed to cool for 12 hr before washed in the Bauer-McNett fiber classifier. In the washing process, the 100-mesh screen was put in the first position and the dyed pulp was washed for a total of 25 min. The washing process would remove fines and unattached dyed fibers from the pulp. The dyed fibers were removed from the classifier, dewatered, and then placed in a sealed plastic bag. The bag was stored in a cold room at approximately 12 % of consistency until the dyed fibers were used for sheet making.

Table 4. Papermaking conditions.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Formette Dynamique Sheet Former</th>
<th>KMW Drum Dryer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pump Pressure</td>
<td>Jar Speed</td>
</tr>
<tr>
<td>A</td>
<td>2.5</td>
<td>900</td>
</tr>
<tr>
<td>B</td>
<td>2.5</td>
<td>900</td>
</tr>
<tr>
<td>C</td>
<td>0.8</td>
<td>1600</td>
</tr>
</tbody>
</table>

An amount of dyed fibers equal to 0.01% of the total oven dry fiber content was added to the dilute pulp stock before sheets were formed. The Formette Dynamique sheet former was used at different fiber-orientation conditions. The target sheet basis weight
was 185 g/m² at TAPPI standard testing conditions (73°F and 50% RH). After a wet sheet was formed in the Formette Dynamique sheet former, each one was couched off the wire with blotters and transferred to the KMW drum dryer. The felt tension of the KMW drum dryer was set at 20 psig. There was a pressure nip, which would use to control sheet density for high-density samples before restrained drying. Table 4 shows the papermaking conditions for all three samples. After being dried for 20 min, each sheet was placed in a series of RH conditions (90% RH for 24 hours → 20% RH for 24 hours → 50% RH at least a week) at constant temperature of 73°F before creep experiments were performed.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Sample A</th>
<th>Sample B</th>
<th>Sample C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basis Weight (g/m²)</td>
<td>184.36</td>
<td>184.96</td>
<td>183.12</td>
</tr>
<tr>
<td>Thickness (mm)</td>
<td>0.3908</td>
<td>0.2098</td>
<td>0.3623</td>
</tr>
<tr>
<td>Sheet Density (kg/m³)</td>
<td>472</td>
<td>882</td>
<td>505</td>
</tr>
<tr>
<td>MD Tensile Index (N.m/g)</td>
<td>93.75</td>
<td>130.73</td>
<td>165.38</td>
</tr>
<tr>
<td>MD Compressive Index (N.m/g)</td>
<td>26.42</td>
<td>42.19</td>
<td>40.44</td>
</tr>
<tr>
<td>MD/CD Stiffness Ratio (ultrasonic)</td>
<td>1.19</td>
<td>1.19</td>
<td>3.35</td>
</tr>
<tr>
<td>MD Bending Stiffness (gf⋅cm)</td>
<td>62.51</td>
<td>25.55</td>
<td>99.55</td>
</tr>
<tr>
<td>COF(1), static (wire side)</td>
<td>0.31</td>
<td>0.28</td>
<td>0.32</td>
</tr>
<tr>
<td>COF(1), static (felt side)</td>
<td>0.29</td>
<td>0.27</td>
<td>0.30</td>
</tr>
<tr>
<td>COF(2), static (wire side)</td>
<td>0.18</td>
<td>0.17</td>
<td>0.19</td>
</tr>
<tr>
<td>COF(2), static (felt side)</td>
<td>0.17</td>
<td>0.17</td>
<td>0.18</td>
</tr>
</tbody>
</table>

(1) No paraffin wax was applied on the surface of formette sheets.
(2) Paraffin wax was applied on the surface of formette sheets with three passes.
After conditioning, the properties of formette sheets were measured at 73°F and 50% RH. The reported properties of the formette sheets are averages for the specimens of each condition. Table 5 displays the averaged properties of the formette sheets at the three different conditions.

4.2.2 Characterization of Formette Sheets Before and After Creep

Images from scanning electron microscopy (SEM) may provide a means to determine how the structure of the sheet changed in the sheets. An exploratory technique was used to observe the changes in sheet structure that occurred during creep testing. The SEM used in this research was the JEOL model JSM-6400. The SEM allowed for observation of the samples in three dimensions. For the cross section, Williams and Drummond (1994) provided procedure for preparing the SEM large sections. At first, each pre-cut specimen was placed in epoxy resin. Before the resin was cured in an oven for a day, removal of any trapped air bubbles in the block was required. Then the cured block was polished by a dry grinding method, using abrasive paper of different grits. Then the polished block surface was immersed into a solvent for resin removal. The solvent was a mixture of 4-gram KOH pellets, 100% methyl alcohol, and 10% of propylene oxide. After resin removal, the block was placed under a vacuum for removing the volatiles before examination in the SEM.

4.2.3 Creep Testing

In all tests, all specimens were cut along the machine direction, and their dimensions were 1-in wide by 8-in long. Each test was conducted at 73°F and 50% RH.
The relative humidity inside the chamber was controlled in the manner previously described.

Each test would take 48 hr, which consisted of 24 hr of preconditioning and 24 hr of creep. At the start of the preconditioning stage, the applied lateral force for each creep unit was adjusted by moving the micrometer forward. After preconditioning (24 hr), the lateral force, defined as “initial lateral force”, was recorded. After loads were applied, all measurements were recorded every second for the first 5 min and then every 15 s until the experiments were completed. Nevertheless, the first creep measurement from the instant of the load application was recorded after about 12 s had elapsed. There were three variables included in this creep study: (1) initial lateral force, (2) creep load, and (3) creep direction, which are illustrated in Tables 6-8. In each condition, a creep curve would have at least 3 replicates. In this study, it was decided to use the same loads in tension and compression for comparisons. The compressive strength is typically one-third to one-half the tensile strength. Therefore, the ratio of creep load to tensile strength was much less than the ratio of creep load to compressive strength. The ranges of initial loads were approximately 6 to 17% of the 50% RH breaking loads in tension and 21 to 59% of the 50% RH breaking loads in compression, as shown in Table 9.

### Table 6. Creep variables for sample A.

<table>
<thead>
<tr>
<th>Initial lateral force (N)</th>
<th>Creep Load in Tension (N)</th>
<th>Creep Load in Compression (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>39.2</td>
<td>39.2</td>
</tr>
<tr>
<td>8.90</td>
<td>39.2</td>
<td>39.2</td>
</tr>
<tr>
<td>26.70</td>
<td>39.2</td>
<td>39.2</td>
</tr>
</tbody>
</table>
Table 7. Creep variables for sample B.

<table>
<thead>
<tr>
<th>Initial lateral force (N)</th>
<th>Creep Load in Tension (N)</th>
<th>Creep Load in Compression (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>39.2</td>
<td>53.9</td>
</tr>
<tr>
<td>8.90</td>
<td>39.2</td>
<td>53.9</td>
</tr>
<tr>
<td>26.70</td>
<td>39.2</td>
<td>53.9</td>
</tr>
</tbody>
</table>

Table 8. Creep variables for sample C.

<table>
<thead>
<tr>
<th>Initial lateral force (N)</th>
<th>Creep Load in Tension (N)</th>
<th>Creep Load in Compression (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>39.2</td>
<td>58.5</td>
</tr>
<tr>
<td>8.90</td>
<td>39.2</td>
<td>58.5</td>
</tr>
<tr>
<td>26.70</td>
<td>39.2</td>
<td>58.5</td>
</tr>
</tbody>
</table>

Table 9. Creep loads in terms of percent in tensile and compressive strength.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Creep Load (N)</th>
<th>% of Tensile Strength</th>
<th>% of Compressive Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>39.2</td>
<td>9.40</td>
<td>33.35</td>
</tr>
<tr>
<td>A</td>
<td>53.9</td>
<td>12.93</td>
<td>45.86</td>
</tr>
<tr>
<td>A</td>
<td>68.6</td>
<td>16.45</td>
<td>58.37</td>
</tr>
<tr>
<td>B</td>
<td>39.2</td>
<td>6.74</td>
<td>20.89</td>
</tr>
<tr>
<td>B</td>
<td>53.9</td>
<td>9.27</td>
<td>28.72</td>
</tr>
<tr>
<td>B</td>
<td>68.6</td>
<td>11.80</td>
<td>36.55</td>
</tr>
<tr>
<td>C</td>
<td>39.2</td>
<td>5.33</td>
<td>21.79</td>
</tr>
<tr>
<td>C</td>
<td>58.5</td>
<td>7.99</td>
<td>32.69</td>
</tr>
<tr>
<td>C</td>
<td>80.9</td>
<td>10.99</td>
<td>44.95</td>
</tr>
</tbody>
</table>
CHAPTER V
RESULTS AND DISCUSSION

In the following, changes in the creep behavior for both tension and compression resulting from changes in sheet structure, creep load, initial lateral force, and loading direction are presented. The impact of creep on structural changes in the sheet is illustrated with images from a scanning electron microscope. Comparisons of the constructed master creep curves for the various experimental settings are discussed. Finally, an attempt to correct for effects of lateral force on tensile creep is described.

Due to variations in the sheet structure leading to different creep behavior, Hill (1967a) pointed out two independent methods of data analysis in his study: (1) combining the data using the master creep curve concept and (2) averaging the deformations at selected times for all tests at a given initial stress. Those two methods yielded the same curves, except for a time shift. He suggested that the data fitted the average curve much better than they did the master creep curve when he plotted a correlation between initial stresses and required time shift. Since the averaged data reduced some variations before constructing the master creep curve, this technique was applied in this research.

All the results presented as following represented the average of first-creep curves for three different formette sheets. Each curve was obtained with the tensile-compressive creep apparatus by the techniques described in the previous chapter. First-creep curves
defined by Brezinski (1955, 1956) are “those obtained on specimens, which have not
been subjected to previous mechanical tests.”

5.1 Tensile Creep

5.1.1 Influence of Initial Tensile Stresses

Tensile creep curves depicted in Appendix C show the total first-creep strain, as a
percentage of the initial gage length, versus the logarithm of time in seconds. Note that
the plotted strain is the total strain, which includes the initial elastic strain. Each of the
figures was distinguished by the papermaking history (different paper structure), degrees
of initial lateral forces and initial stresses over time. For the same specimen, tensile creep
curves with different degrees of initial lateral forces were displayed. In each of these
figures, every curve was characterized with the degree of initial tensile stress to which it
was subjected. In each specimen, the apparent initial tensile stresses were represented in
terms of stress indices [creep load*acceleration of gravity / (sample width*basis weight)].

The results to be presented showed that an increase in creep strain, with respect to
the initial stress, was substantial for all three samples. Higher initial stress resulted in
more total tensile first-creep deformation. This observation is in general agreement with
previous creep data (Brezinski, 1955, 1956; Schulz, 1961a, 1961b; Sanborn, 1961, 1962;
Hill, 1967a, 1967b; Byrd, 1971, 1972; Olsson and Salmen, 2001). However, an increase
in the initial lateral force reduced total tensile first-creep strain for each specimen. Figures
24-26 depict total tensile first-creep strain as percentage of initial gage length versus the
logarithmic time in seconds with varying initial lateral forces and tensile loads for all of
three specimens. Each creep curve is shown the standard deviation for only 30 points.
Figure 24. Influence of initial lateral force on tensile creep curves for Sample A at different tensile loads: (a) 39.2 N, (b) 53.9 N, and (c) 68.6 N.
Figure 25. Influence of initial lateral force on tensile creep curves for Sample B at different tensile loads: (a) 39.2 N, (b) 53.9 N, and (c) 68.6 N.
**Figure 26.** Influence of initial lateral force on tensile creep curves for Sample C at different tensile loads: (a) 39.2 N, (b) 58.5 N, and (c) 80.9 N.
In each graph, sheets were subjected to three levels of initial lateral forces with keeping the same tensile load constant. The results suggest that increasing initial lateral force tended to lower total first-creep strain. It is expected that fibers and bonds in a sheet move less in the direction of tensile load at higher lateral force because of the friction from the lateral restraint. Tensile creep curves of Sample A did not show any statistical difference among others for short period of creep as changing initial lateral forces and tensile loads, except conditions at zero initial lateral force. Then the effect of initial lateral force resulted in differences among curves at longer time. This effect appeared at all three levels of tensile loads. At the highest tensile load (68.6 N) depicted in Fig. 24c, by contrast, tensile creep curves were not different at the low levels of initial lateral forces if variations from one creep curve were included. Tensile creep curves of Samples B and C at zero initial lateral force shown in Figs. 25 and 26, respectively, were substantially different from the others at each tensile load.

5.1.2 Influence of Initial Lateral Forces

A study of the intrinsic edgewise compressive strength of paper with a flat-plate support (Seth et al., 1979; Seth and Soszynski, 1979) showed that deformation was accompanied by an increase of the actual lateral force. It has been shown in previous studies with a flat-plate support that lateral force developed after a certain amount of deformation and compressive load. The average actual lateral forces at two levels of initial lateral forces versus time for all three specimens in tension are given in Figs. 27-29. It has been understood that the first reliable strain in a creep test should be recorded at a certain time after loading due to the effect of the loading procedure. Therefore, it was
Figure 27. Lateral force vs. time in tension for Sample A at: (a) low initial lateral force and (b) high initial lateral force.
Figure 28. Lateral force vs. time in tension for Sample B at: (a) low initial lateral force and (b) high initial lateral force.
Figure 29. Lateral force vs. time in tension for Sample C at: (a) low initial lateral force and (b) high initial lateral force.
arbitrarily decided in this study that the recording of the creep started at 12 seconds after a stress was applied. In essence, an instantaneous change of lateral force was proportional to the amount of tensile load. It is hypothesized that the instantaneous change in lateral force is attributed by tensile stress either to stretch fibers or to break bonds in paper. A study by Ohrn (1965) showed that the sheet thickness increased while paper was stretched. Therefore, the results seem to agree with his findings. An effect of the highest initial stress was more pronounced to instantaneous change. The degree of response also varied substantially among specimens. For example, the Sample A seemed to have the smallest change in instantaneous lateral force for all testing conditions. Data shown in Figs. 27-29 suggest that actual lateral forces at each initial tensile stress decreased slowly over time. This effect should result in gradual stress relaxation of specimens in the thickness direction while creeping in tension.

5.2 Compressive Creep

5.2.1 Influence of Initial Compressive Stresses

The compressive first-creep strain versus the logarithm of time in seconds is plotted in Appendix D. Curves were obtained by changing the same variables as for tensile first-creep curves: (1) paper structure, (2) initial lateral forces and (3) initial stresses. Again, the apparent initial compressive stresses were represented in terms of stress indices [creep load*acceleration of gravity / (sample width*basis weight)]. Some creep experiments were terminated due to buckling of the specimens.
Figure 30. Influence of initial lateral force on compressive creep curves for Sample A at different compressive loads: (a) 39.2 N, (b) 53.9 N, and (c) 68.6 N.
Figure 31. Influence of initial lateral force on compressive creep curves for Sample B at different compressive loads: (a) 39.2 N and (b) 53.9 N.
Figure 32. Influence of initial lateral force on compressive creep curves for Sample C at different compressive loads: (a) 39.2 N, (b) 58.5 N, and (c) 80.9 N.
The results depicted in Figs. 30-32 suggest that total strains of all three specimens increased substantially during creep as compressive loads were increased. Since the ratio of applied load and breaking load in compression was higher than a ratio in tension, data clearly show that total first-creep strain in compression was greater than one in tension. In a compressive creep experiment, undulations occurred when a sample had insufficient lateral support. It was because a sample was unstable in compression with inadequate lateral force. This phenomenon is a part of failure for paper under a compressive load. After undulations appeared, some curves displayed discontinuity of creep strain. Since magnets were attached to paper surface, they could be moved by either creep or undulation. If undulations caused magnets move, total creep strain would show some sudden changes. It is postulated that movement of undulations depends upon weak areas, which cause interfiber bonds to disintegrate. Therefore, the criterion for averaging creep curves in compression was that any selected compressive creep curve showed no disruption in total first-creep strain over extended duration. In contrast, having inadequate lateral support under some creep conditions caused a sample to buckle easily. For example, an average of compressive creep curve for Sample A (see Fig. 30c and D.1) showed a sudden change in total strain due to buckling at a low initial lateral force when specimens were subject to the highest compressive load (68.6 N). Likewise, an average of compressive creep curve for Sample B could not be obtained because of poor replication at a low initial lateral force when the highest compressive load (68.6 N) was applied. Having the lowest bending stiffness, Sample B would have low stability during edgewise compression with insufficient lateral support. Therefore, this may result in lack of repeatability.
By comparing results at the same compressive load, each specimen exhibited different outcomes. The standard deviation for 30 points was included in each curve. Figure 31 illustrates only two different levels of compressive loads since consistent creep curve at the highest compressive load (68.6 N) was not reproducible. Data of Sample A demonstrate that every curve showed significantly different results in total compressive first-creep strain at each experimental condition. For Sample B, there were large variations in an average creep curve at a condition of low compressive load and low initial lateral force (Fig. 31a). When including standard variations at the lowest compressive load (39.2 N), both curves were not different in total compressive first-creep strain with changing initial lateral force. It is hypothesized that variation in the paper structure of Sample B could cause a larger error at this condition. On the other hand, substantial difference between curves appeared at greater compressive loads. When considering Sample C, data indicate no statistical difference with varying initial lateral forces at a constant compressive load. Having higher fiber orientation in the sheet, changes in initial lateral forces seem to have smaller influence on total first-creep strain than changes in compressive load. Interestingly, Samples B and C showed less creep. This may be because both structures provide more resistance under compression than a structure in Sample A. The results demonstrate that changes in paper structure would show (1) larger variations in total compressive first-creep strain and (2) insignificant differences between curves in some cases.
5.2.2 Influence of Initial Lateral Forces

As mentioned previously, Seth and his colleagues (Seth et al., 1979; Seth and Soszynski, 1979) showed that the lateral force increased when the deformation in compression extended beyond a certain point. Results of lateral forces over time in tension also demonstrated none of any lateral force increase. In fact, lateral force in tensile creep gradually decreased during creep, resulting in stress relaxation. In compressive creep experiments, the instantaneous change of lateral force still appeared as a result of loading. The amount of instantaneous change in lateral force seems to depend upon the magnitude of compressive load and initial lateral force. As a result of different instrumental configuration, no one has ever showed a correlation between applied loads and changes of lateral forces over time.

Records of creep in Figs. 33-35 showed after a compressive load was applied for 12 seconds. Compressive creep data show two opposite trends as follows: (1) the lateral force was slightly reduced during creep at low compressive loads, and (2) the lateral force increased over time at greater compressive loads. The gradual decrease in lateral force during creep could be caused by stress relaxation of paper in the thickness direction as well. This tendency is similar to results for tensile creep. From a structural viewpoint, a sheet could bear some compressive loads with sufficient lateral support up to certain strain. Hence, lateral force could gradually decrease during creep in this circumstance. On the other hand, increasing compressive load beyond a certain point would create instability in sheets under edgewise compression. A study of compressive strength by Haraldsson et al. (1994) showed that the failure zones appeared more frequently around the middle of the span. Their results could imply that insufficient lateral support causes
Figure 33. Lateral force vs. time in compression for Sample A at: (a) low initial lateral force and (b) high initial lateral force.
Figure 34. Lateral force vs. time in compression for Sample B at: (a) low initial lateral force and (b) high initial lateral force.
Initial compressive stress index, kN.m/kg

- 8.41
- 12.56
- 17.25

(a)

Lateral Force, N

Time, s

Initial compressive stress index, kN.m/kg

- 8.34
- 12.38
- 17.02

(b)

Lateral Force, N

Time, s

Figure 35. Lateral force vs. time in compression for Sample C at: (a) low initial lateral force and (b) high initial lateral force.
specimens to buckle as the compressive load increases. Furthermore, some previous studies in compressive failure showed that the thickness of a paper increased if a sheet buckled (Sachs and Kuster, 1980; Uesaka and Perkins, 1983). Therefore, an increase of lateral force over time would indicate some changes in a sheet as a result of buckling.

5.3 Microscopic Observations

Micrographs depicted three different samples subjected to the highest creep load in two different loading directions (tension and compression). The condition of a high initial lateral force applied to each sample was photographed in order to avoid seeing structural failure. Any significant change observed in the sheet structure was expected to be permanent deformation since examinations were not done immediately after creep tests.

Unlike the measurement of tensile and compressive strength, creep deformation develops slowly under constant ambient conditions. In previous sections, creep data indicated small total first-creep deformation in both tension and compression. Therefore, it was anticipated to have minute change in the paper structure, particularly in tension. The SEM observations reveal that deformation appeared localized and random. Basically, the enlargement of voids occurred as a result of creep. Compared with a sample before creep, an increase of voids could lead to bond breakage and then delamination between fiber layers in samples after tensile or compressive creep, as depicted in Figs. 36-44. In the figures, the arrows indicate some large voids, which could appear either before or after creep. Furthermore, the rectangular boxes demonstrate bond breakage or delamination of fiber layers. It is postulated that shear stress would cause delamination in
Figure 36. Cross section of Sample A in the cross machine direction before creep. Magnification: 200X.

Figure 37. Cross section of Sample A in the cross machine direction after tensile creep. Magnification: 200X.
Figure 38. Cross section of Sample A in the cross machine direction after compressive creep. Magnification: 200X.

Figure 39. Cross section of Sample B in the cross machine direction before creep. Magnification: 200X.
Figure 40. Cross section of Sample B in the cross machine direction after tensile creep. Magnification: 200X.

Figure 41. Cross section of Sample B in the cross machine direction after compressive creep. Magnification: 200X.
Figure 42. Cross section of Sample C in the cross machine direction before creep. Magnification: 200X.

Figure 43. Cross section of Sample C in the cross machine direction after tensile creep. Magnification: 200X.
Figure 44. Cross section of Sample C in the cross machine direction after compressive creep. Magnification: 200X.

both the directions of creep. However, the magnitude of deformation would be less in tensile creep. Unfortunately, the enlarging voids were not often detected in the porous structure (Samples A and C). On the other hand, the enlarging voids and delamination were easily noticed in the dense structure (Sample B). From thickness measurements in the SEM micrographs, it was not clearly seen for all samples that the enlargement of voids and delamination attributed to the thickness increment in both tensile and compressive creep, compared with samples before creep. It is possible that small deformation appeared in this study. Furthermore, micrographs were not taken from the same location. The disadvantage of SEM in this study was unable to explore obvious changes in fibrous structure. To further examine changes at the fibrous level, the
transmission electron microscopy (TEM) would be recommended. However, this technique was not used in this study.

5.4 Master Creep Curves

In previous studies, successful constructions of the master creep curves for handsheets and fibers have been limited to tension (Brezinski, 1955, 1956; Sanborn, 1961, 1962; Schulz, 1961a, 1961b; Hill, 1967a, 1967b). Unfortunately, no one has ever created a master creep curve in compression. The construction of a master creep curve began by normalizing total strain by a factor of the initial stress. Brezinski described those normalized curves as the reduced curves. The initial stress calculated as defined by Brezinski and Sanborn is depicted in Eq 5.1.

\[
\text{Stress} = \frac{(\text{Creep Load}) \times (\text{Density of fiber})}{(\text{Specimen basis weight}) \times (\text{Specimen width})}
\]  

(5.1)

where the density of the fiber was assumed to be 1.5 g/cm³. At each lateral force, the lowest stress was chosen arbitrarily as a basis for the construction of the master creep curve. Then the other creep curves were shifted along the logarithmic time axis to form the master creep curve. Interestingly, Figures 45-50 illustrate that a power-law model could fit the master creep curves well in all cases. However, Sample A has the worst fit for a compressive master creep curve, especially at the lowest initial lateral force; probably due to the effect of buckling. It is shown that tensile and compressive master creep at zero initial lateral forces was different from ones with initial lateral forces. As a result of variation in total strain for Samples B and C (see Figs. 25 and 26), master creep
**Figure 45.** Master creep curves in tension for Sample A at three different initial lateral forces.

**Figure 46.** Master creep curves in compression for Sample A at two different initial lateral forces.
Figure 47. Master creep curves in tension for Sample B at three different initial lateral forces.

Figure 48. Master creep curves in compression for Sample B at two different initial lateral forces.
Figure 49. Master creep curves in tension for Sample C at three different initial lateral forces.

Figure 50. Master creep curves in compression for Sample C at two different initial lateral forces.
curves with excluded zero initial lateral force are considered similar in tension, as shown in Figs. 47 and 49. With the same reason (Fig. 32), moreover, compressive master creep curves with initial lateral forces for Sample C also did not showed statistical difference, as depicted in Fig. 50. Larger variations of total deformation would cause differences in logarithmic time required to form master creep curves in tension and compression, respectively. The results of master creep indicate that it requires longer period of creep time for a higher initial lateral force to reach the same deformation as one at a lower initial lateral force. Moreover, changes in initial lateral forces substantially alter the shapes of the compressive master creep curves but shows slightly different shapes in the tensile master creep curves.

Because of the small deformation in total tensile first-creep response, Brezinski neglected to examine a correlation of the time-shift requirement at lower initial stresses by assuming its linearity. Figures 51-53 depict time relative shift of the creep curves required to form a master creep curve as a linear function of initial stress. Each graph was plotted by varying stress directions and initial lateral forces. Using a linear regression fit between the time-shift requirement and initial stress, the $R^2$ from a linear curve fit (see Appendix F) reveals that the relationship between the time-shift requirement and initial stress was linear for all of the studied conditions. Therefore, these observations were in agreement with Brezinski’s hypothesis.
Figure 51. Time shift required to form master creep curves versus initial stress for Sample A: (a) tensile stress with no initial lateral force, (b) tensile stress with 8.93-N initial lateral force, (c) tensile stress with 27.06-N initial lateral force, (d) compressive stress with 8.84-N initial lateral force, and (e) compressive stress with 26.63-N initial lateral force.
Figure 52. Time shift required to form master creep curves versus initial stress for Sample B: (a) tensile stress with no initial lateral force, (b) tensile stress with 9.65-N initial lateral force, (c) tensile stress with 27.02-N initial lateral force, and (d) compressive stress with 27.70-N initial lateral force.
Figure 53. Time shift required to form master creep curves versus initial stress for Sample C: (a) tensile stress with no initial lateral force, (b) tensile stress with 8.99-N initial lateral force, (c) tensile stress with 26.96-N initial lateral force, (d) compressive stress with 9.15-N initial lateral force, and (e) compressive stress with 27.03-N initial lateral force.
A construction of the master creep curves provides two noteworthy aspects: (1) the master creep curves of each specimen are shown to be different when changing initial lateral forces, particularly to compressive creep. Under these investigations, the mechanism of first-creep response should be different when paper was subjected to different loading directions. (2) For the same conditions, total first-creep deformation in compression is an order of magnitude greater than that observed in tension because of low buckling resistance in compression.

5.5 Comparisons of Tensile and Compressive Master Creep Curves

The previous section demonstrated that the successful construction of master creep curves could be useful to compare results between tensile and compressive creep. However, the effect of initial lateral force was a major concern since the low initial lateral force could lead to sheet buckling. Therefore, it was suggested that a comparison of tensile and compressive master creep curves need to set at a specified level of initial lateral force, which was a high level of initial lateral force in this study.

Comparisons of tensile and compressive master creep curves as results of the changes in paper structure (sheet density and fiber orientation) and stress direction are given in Figs. 54-56. For Sample A, representing low sheet density and random sheet, total reduced strain (total first-creep strain per unit initial stress) in the compressive master creep curve was greater than total reduced strain in the tensile master creep curve over time, as depicted in Fig. 54. In fact, a creep rate in compression was faster than that in tension as a result of buckling in fibers when stress increased. This observation is in agreement with the earlier findings by Haraldsson et al. (1993). They showed in the 10-
second isochronous curves that compressive creep was greater than tensile creep in a commercial linerboard. For Sample B, representing high sheet density, the tensile master creep curve coincided with the compressive master creep curve, as shown in Fig. 55. This result suggests that paper having higher sheet density would show the same creep behaviors in tension and compression up to certain reduced strain. As increasing fiber orientation in the sheet (Sample C), the master creep curves demonstrate that the initial part of the compressive master creep curve concurred with the tensile master creep curve, as shown in Fig. 56.

![Figure 54. Comparison of tensile and compressive master creep curves of Sample A at high initial lateral force.](image)
Figure 55. Comparison of tensile and compressive master creep curves of Sample B at high initial lateral force.

Figure 56. Comparison of tensile and compressive master creep curves of Sample C at high initial lateral force.
The changes in paper structure indicate a significant effect to the master creep curves in tension and compression. The results of Sample A demonstrate that compressive master creep was greater than tensile master creep. The structure of Sample A, a bulky and random sheet, would have lower buckling resistance. Thus, it results in faster creep as compressive load increases. When increasing sheet density (Sample B), total reduced strain in tension and compression were similar. Because of the packed structure, fiber segments are more restricted from lateral movement. Moreover, the stress distribution in the dense sheet would be more uniform than a bulky structure. With these two effects, the alignment of fibers expects to be the same under both stresses. Hence, tensile and compressive responses appear similarly. If increasing fiber orientation in the sheet (Sample C), both master creep curves displayed similar in a short period. Then, the compressive master creep was higher over time. A trend of master creep curves in Sample C were similar to Sample A that compressive master creep was greater than tensile master creep. It is probably that fiber segments or fibrils in the sheet start buckling, deformation becomes greater in compression. This evidence strongly supports the hypothesis in this study that some similarities between tensile and compressive creep would show in the early stage, and then different loading directions would cause a differentiation between those curves at longer time or larger deformation.

5.6 Corrections of Frictional Effects

An attempt was made to account for the effect of friction on creep behavior so that any tensile creep curve at any level of lateral force could be extrapolated to a level of zero lateral force. If this approach was applicable, it was hypothesized that compressive master
creep curves could be extrapolated to a level of no lateral force. Hence, a comparison between master creep curves without an effect of lateral force could be made.

![Diagram showing load schematic and free-body force diagram for tensile creep test.](image)

**Figure 57.** Load schematic and free-body force diagram for tensile creep test.

From a free-force body diagram (Fig. 57), $F_1$ will be equal to $F_2$ at the equilibrium condition. The actual load at a specified time ($F_1$ or $F_2$) was obtained by subtracting the frictional component (static frictional coefficient multiplied by actual lateral force at that time) from the tensile load, as shown in Eq. 5.2. Then using Eq. 5.1 calculated the actual applied stress.

Actual force ($F = F_1 = F_2$) = Tensile load - $\mu N$  

\[ F = F_1 = F_2 = \text{Tensile load} - \mu N \quad (5.2) \]

where

$F_1$, $F_2$ = actual forces at glue site

$\mu$ = coefficient of friction
\( N \) = lateral force

Although McDonald et al. (1996) showed that the kinetic coefficient of friction was independent on the normal pressure (2.0 to 480 kPa) and sled speed (0.6 to 1000 mm/s), the static frictional coefficient was still selected over the kinetic frictional coefficient. It is because the creep rate at constant ambient conditions is typically slow. A reduced curve was obtained from each of the tensile first-creep strains at a specified time divided by the actual applied stress. Then tensile master creep curves were re-constructed as described earlier. Next, each corrected master creep curve was shifted along the time axis by using a relationship of logarithmic time shift and initial stress, as given in Figs. 51-53. Hence, all corrected curves could be comparable at the same basis stress. Figures 58-60 depict the corrected master creep curves in tension for all three specimens. The results indicate that this correction did not fully account for the effect of friction on tensile first-creep response. However, it is still an improvement as the gaps between the curves were smaller. There are two plausible hypotheses: (1) the actual coefficient of friction in the first order approximation is greater than measured, or (2) the relationship between the frictional component and initial stress in creep is not uniform throughout the length of the sheet. To check the first hypothesis, the frictional coefficient in the first order approximation was recalculated from Eq. 5.3-5.5.
Figure 58. Correction of frictional effect for tensile master creep curves of sample A. The mean curves are power law fits to the data.

Figure 59. Correction of frictional effect for tensile master creep curves of sample B. The mean curves are power law fits to the data.
Figure 60. Correction of frictional effect for tensile master creep curves of sample C. The mean curves are power law fits to the data.

\[ E_{\text{CAL}} = \frac{\sigma_C}{\varepsilon} \]  \hspace{1cm} (5.3)

\[ \varepsilon_C = \frac{\varepsilon_0 \cdot E_0}{E_{\text{CAL}}} \]  \hspace{1cm} (5.4)

\[ \mu_{\text{CAL}} = \left( L - \frac{\text{basis weight} \cdot \text{sample width} \cdot E_0 \cdot \varepsilon_C}{\text{fiber density}} \right) \frac{g}{N} \]  \hspace{1cm} (5.5)

where

\begin{align*}
 E_0 &= \text{Young’s modulus at 4 s with no applied lateral force, kg/mm}^2 \\
 E_{\text{CAL}} &= \text{calculated Young’s modulus at 4 s, kg/mm}^2 \\
 L &= \text{creep load, kg} \\
 \varepsilon_0 &= \text{strain at 4 s with no applied lateral force, %}
\end{align*}
\[ \varepsilon = \text{strain at 4 s with applied lateral force, \%} \]
\[ \varepsilon_C = \text{corrected strain at 4 s with applied lateral force, \%} \]
\[ g = \text{gravity force} = 9.81 \text{ m/s}^2 \]
\[ \mu = \text{static coefficient of friction measured by Amontons II} \]
\[ \mu_{\text{CAL}} = \text{calculated coefficient of friction} \]
\[ N = \text{initial lateral force, N} \]
\[ \sigma_C = \text{corrected initial stress at 4 s after subtracting initial stress by } \mu \ast N, \text{ kg/mm}^2 \]

All values of calculated frictional coefficient displayed in Table 10 were greater than ones shown in Table 5. Therefore, it concludes that the first order approximation by using static frictional coefficient is not good enough to shift curves at different initial lateral forces back to one at no lateral force.

Table 10. Calculated frictional coefficient from Eq.5.5.

<table>
<thead>
<tr>
<th>Sample</th>
<th>8.90-N initial lateral force</th>
<th>26.70-N initial lateral force</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.38</td>
<td>0.16</td>
</tr>
<tr>
<td>B</td>
<td>1.00</td>
<td>0.43</td>
</tr>
<tr>
<td>C</td>
<td>0.66</td>
<td>0.44</td>
</tr>
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</table>

To check the second hypothesis, the frictional correction was fitted by a nonlinear equation (Eq. 5.6). The values of constants a and b are shown in Table 11. It is revealed that adding a nonlinear term for calculating actual force was able to shift each corrected
tensile creep curves back to one at no lateral force for all of three samples, as shown in Figs. 61-63.

\[
\text{Actual force, } F = \text{Tensile load} - \mu N - aN^b
\]  

(5.6)

where

\[
a, b = \text{constants}
\]

**Table 11.** Constant values for nonlinear frictional curve fit.

<table>
<thead>
<tr>
<th>Sample</th>
<th>a</th>
<th>b</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.03</td>
<td>2</td>
</tr>
<tr>
<td>B</td>
<td>0.09 - 0.4</td>
<td>2 - 2.3</td>
</tr>
<tr>
<td>C</td>
<td>0.06 - 0.25</td>
<td>2</td>
</tr>
</tbody>
</table>

**Figure 61.** Corrected tensile creep curves for Sample A by using Eq. 5.6.
Figure 62. Corrected tensile creep curves for Sample B by using Eq. 5.6.

Figure 63. Corrected tensile creep curves for Sample C by using Eq. 5.6.
From the investigations of both frictional hypotheses, it demonstrates that the frictional effect would not be simple as expected, and the frictional coefficient was not the same value as measured by the Amonton II. The further experiments for measuring the friction are strongly recommended so that a truly applied stress could be determined.

Although the nonlinear frictional equation in Eq. 5.6 seems to work well for corrected tensile master creep curves, it was not used to correct compressive master creep curves. This is because the lowest level of initial lateral force was not high enough to support samples in compressive creep. At the low initial lateral force, Sample A experienced buckling, and poor repeatability existed for Sample B. Therefore, the amount of initial lateral force needs to be greater than 8.90 N in order to restrict the sample buckling in compression. This left only one set of creep curves at the highest lateral forces. Instead of shifting the master creep curve to account for frictional effects, the tensile and compressive creep curves were compared at the same level of lateral load.
A new apparatus using the flat plate support was constructed for measuring tensile and compressive creep. This lateral support prevented global buckling of the sample and allowed for creep testing to larger strains. The equipment construction and preparation of samples used in the experiment was simple. An alternative strain measurement, using magnetic sensors, was capable of calculating creep deformation. The preliminary results showed satisfactory comparisons in both tensile and compressive creep.

The creep behaviors under tensile and compressive loads were studied with this apparatus. Three different structural samples were manufactured by varying sheet density and fiber orientation. Three creep variables were examined: creep load, lateral force and stress direction. As expected, a higher creep load resulted in larger creep deformation for all specimens. At the same creep load, compressive creep showed higher total first-creep strain than tensile creep. However, increasing initial lateral force reduced total first-creep strain in both tension and compression. For tensile creep, lateral force would perhaps decrease fiber stretching and bond breaking along the loading direction. For compressive creep, the flat plate support mostly prevented paper buckling. Nonetheless, the effect of buckling still existed because of the instability of paper in compression with insufficient lateral support.
The creep analysis using SEM micrographs were utilized to look for structural changes in the sheets. This revealed creep deformation as seen by the enlargement of voids and the delamination between fibers in both tensile and compressive creep. For small deformation, by contrast, the SEM technique did not seem to be well suited for investigating changes in the fibers.

To describe the continuous creep deformation over time, master creep curves were constructed and they showed satisfactory results. The master creep rate in compression was higher than the master creep rate in tension at the same creep load. The frictional force along the specimen, induced by the lateral support, greatly impacted both tensile and compressive creep. The effect of friction could not be neglected on the creep measurement when using the flat plate support. With sufficient amount of lateral force, the master creep curves demonstrated that tensile and compressive creep tended to coincide up to a certain point of strain for a denser sheet. With a restricted movement in the thickness direction, prebuckling of fiber segments had not occurred yet, which suggests that the fiber alignment was still similar in tensile and compressive creep. For a bulky sheet, the compressive master creep would be higher than the tensile master creep. In an unrestricted structure, fiber segments have low internal buckling resistance, so they enable to bend and buckle easily under compressive load. Then its compressive master creep was greater than tensile master creep. However, an increase of fiber orientation demonstrated that the master creep curve creep curves for tension and compression coincided only for low strains. Then, the master compressive creep was higher since some fiber segments had experienced in buckling. Based on the results, it is suggested that the
effect of sheet density had more pronounced to tensile and compressive master creep than the effect of fiber orientation.

In summary, studies reported in this research provide some knowledge base of primary tensile and compressive creep behaviors caused by changing the sheet structure and creep variables. This research has shown that there are direct relationships between the creep characteristics and the sheet structure in both tension and compression.
CHAPTER VII
FUTURE WORK AND RECOMMENDATIONS

There are two main suggestions that could be useful for continued work in this area:

*Equipment*

The development of creep apparatus should be continued. The flat plate support has showed potential uses in the research for tensile and compressive creep even though the effect of friction could not be totally neglected. Three recommendations are:

- Some automatic controls such as loading and micrometer adjustment should be installed to obtain more precise measurements and fewer errors.
- Some chemicals or new methods for improving the surface friction at paper-aluminum plate interface should be considered.
- A number of load cells measuring lateral force along the aluminum plate should be increased. Thus, a non-linear profile of actual lateral force along the sample length could be investigated.

*Experiments*

This research indicated two mechanical properties (sheet density and fiber orientation) that significantly affected tensile and compressive creep. Further studies with a wide range of sheet density and fiber orientations should be completed, with density being the most important. Additional papermaking variables resulting in changes of
structure or mechanical history in paper should be extensively studied. Finally, differences in short time deformation for samples with no lateral load and lateral load need further investigated. Hence, the overall pictures of tensile and compressive creep related to the structural influence will be better understood.
ACKNOWLEDGMENTS

I would like to take this opportunity to share my gratitude to the following people and organizations for helping me achieve this major goal of my life.

First of all, I like to thank my research committee, Dr. Douglas Coffin, Dr. Charles Habeger, and Dr. Preet Singh. I would like to express my special gratefulness to my advisor, Dr. Douglas Coffin, and my co-advisor, Dr. Charles Habeger, for their great help and advice. Their valuable guidance and discussions are essential throughout the course of this work. I would like to recognize Dr. Hiroki Nanko for his help in the scanning electron microscopy. I also acknowledge the members of the Institute of Paper Science and Technology for the financial support through this research. Moreover, I would like to express my deep appreciation to the Domtar Inc. for pulp supplied for this study.

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Last but not least is the most gratefulness to my family for their love and support, especially my parents, Chuchai and Suwanna. Without them, I would not accomplish in this work.
LITERATURE CITED


Figure A.1. Controlling and recording panel of creep tests written in Labview.
Figure A.2.  Block diagrams of a main controlled program written in LabView.
APPENDIX B
PROGRAM FOR RELATIVE HUMIDITY CONTROL

Figure B.1. Relative humidity control panel for creep tests written in LabView.
Figure B.2. Block diagrams of a humidity control program written in LabView.
Figure B.3. Diagram of humidity generator.
Figure C.1. Tensile creep curves of sample A without initial lateral force.
Figure C.2. Tensile creep curves of sample A at a low initial lateral force.

Figure C.3. Tensile creep curves of sample A at a high initial lateral force.
Figure C.4. Tensile creep curves of sample B without initial lateral force.

Figure C.5. Tensile creep curves of sample B at a low initial lateral force.
Figure C.6. Tensile creep curves of sample B at a high initial lateral force.

Figure C.7. Tensile creep curves of sample C without initial lateral force.
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Figure D.2. Compressive creep curves of sample A at a high initial lateral force.

Figure D.3. Compressive creep curves of sample B at a low initial lateral force.
Figure D.4. Compressive creep curves of sample B at a high initial lateral force.

Figure D.5. Compressive creep curves of sample C at a low initial lateral force.
Figure D.6. Compressive creep curves of sample C at a high initial lateral force.
APPENDIX E
SHIFTS IN LOG TIME TO FORM MASTER CREEP CURVES

Table F.12. Summary of master creep curves for sample A.

<table>
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<tr>
<th>Creep Direction</th>
<th>Average Basis Weight (g/m²)</th>
<th>Lateral Force (N)</th>
<th>Creep Load (kNm/kg)</th>
<th>Initial Stress* (kg/mm²)</th>
<th>Shift in Log Time to form Master Creep</th>
<th>R² for a linear curve fit</th>
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* Initial stress was calculated from Eq. 5.1.
Table F.13. Summary of master creep curves for sample B.

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<th>Creep Direction</th>
<th>Average Basis Weight (g/m²)</th>
<th>Lateral Force (N)</th>
<th>Creep Load (kNm/kg)</th>
<th>Initial Stress* (kg/mm²)</th>
<th>Shift in Log Time to form Master Creep</th>
<th>R² for a linear curve fit</th>
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</tbody>
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* Initial stress was calculated from Eq. 5.1.
N.A. = no available data
Table F.14. Summary of master creep curves for sample C.

<table>
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<tr>
<th>Creep Direction</th>
<th>Average Basis Weight (g/m²)</th>
<th>Lateral Force (N)</th>
<th>Creep Load (kNm/kg)</th>
<th>Initial Stress* (kg/mm²)</th>
<th>Shift in Log Time to form Master Creep</th>
<th>R² for a linear curve fit</th>
</tr>
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* Initial stress was calculated from Eq. 5.1.
Table F.15. Power-law fitting the master creep curves: $\varepsilon(t) = a + b t^c$.

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<th>Sample</th>
<th>Creep Direction</th>
<th>Avg. Initial Lateral Force (N)</th>
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<th>b</th>
<th>c</th>
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