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Aging Model for Commercial Polymers

Kevin J. Ford

Thesis submitted to the
College of Engineering and Mineral Resources
at West Virginia University
in partial fulfillment of the requirements
for the degree of

Master of Science
in
Mechanical Engineering

Ever J. Barbero, Ph.D., Chair

Wade W. Huebsch, Ph.D.

Jacky Prucz, Ph.D.

Department of Mechanical and Aerospace Engineering

Morgantown, West Virginia

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thermoset, thermoplastic

ABSTRACT

Aging of Commercial Polymers

Kevin J. Ford

Physical aging of polyvinyl chloride, high-density polyethylene, and polyester reinforced with polyester fibers specimens have been investigated. These materials are commercially available and are currently used in trenchless relining of sewer pipes. The analysis uses the effective-time theory and time-temperature superposition (TTSP) methods proposed by Struik, as well as variations of these methods, as proposed by Chai and McCrum, Guerdoux et al. and others. The creep data generated by this study show that the time-dependant creep properties of these materials can be modeled within experimental error with slight changes to the above methods. To predict the creep behavior of full-scale specimens; these properties were then shifted from their testing age and temperature to the testing age and temperature of the full-scale specimens. It was shown that a rotation, along with a horizontal shift of the aging data, is needed to obtain the ageing parameter of the materials.

DEDICATION

This thesis is dedicated to my grandparents, the late John and Anna Kondik and the late Ross and Martha Ford. Without their influence in my life this would not have been possible, thanks.

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CHAPTER 1 INTRODUCTION AND LITERATURE REVIEW

1.1 Introduction

The Urban Wet-Weather Federal Advisory Committee (FAC) and the Environmental Protection Agency (EPA) are developing a new set of standards and regulations that the current sewer systems in the United States must comply with. These new standards and regulations will require municipalities to invest heavily on the rehabilitation of the collection sewer systems. Due to high costs and traffic disruptions, trenchless lining of existing pipes is being used. In trenchless lining, a polymer or reinforced-polymer is applied to the inside of the existing host-pipe, without disturbing the soil or any aboveground facilities (Fig. 1.1). Several technologies offer various solutions, including thermoplastic and thermoset polymers and composites, which can be cured within the host-pipe or mechanically installed to fit the host pipe. No accepted unbiased testing procedure has yet been established that allows a fair comparison of the various products for a particular field installation.

The main purpose of the liner is to prevent water leakage into the sewer pipe. Therefore, a liner encased by a host sewer pipe is subject to hydrostatic external pressure, but it may also carry some soil pressure if the host pipe is deteriorated severely. Regardless of the source of external pressure, the encased liner fails by creep-buckling under external pressure. If the time-dependent properties of the liner are known, realistic predictions of the buckling pressure of a liner can be done by rigorous numerical modeling of the buckling of a confined pipe.

1.2 Literature Review

There has been a significant amount of work previously conducted that relates to the prediction of time-dependent properties of materials, particularly PVCs and composite materials. This literature review discusses the relevant studies to this project.

Lakes [1] describes a viscoelastic material as those for which the relationship between stress and strain depends on time. He further explains that some phenomena of viscoelastic materials are: 1) if the stress is held constant, the strain increases with time (creep) and 2) if the strain is held constant, the stress decreases with time (relaxation). He defines the creep compliance as

$$J(t) = \frac{\varepsilon(t)}{\sigma_o} \quad (1.1)$$

where J is the torsional compliance, $\varepsilon(t)$ is the strain as a function of time, and σ is stress.

Struik [2] has shown that creep curves of quenched polymers are nearly horizontally shifted towards longer times with increase in aging time. He postulates that the retardation spectrum is shifted without any modification during aging. Furthermore, he postulates that the $\log(t_e)$ vs. $\log(a_e)$ plot is linear with slope μ , called the aging parameter. In addition, μ may or may not be a function of temperature in the temperature range of interest for the use of the material.

His effective-time theory for long-term creep makes the following assumptions. First, all mechanical relaxation times change in the same way. They increase by a horizontal shift factor, a_e , which he defines as

$$a(t'_e, t_e) = \frac{M(t'_e)}{M(t_e)} \quad (1.2)$$

where a_e is the horizontal shift factor, M denotes the segmental mobility, and t_e is the age of the material.

Second, the acceleration factor, a_e , varies with the age of the material, t_e , according to a power law. He theoretically derived and confirmed by experiments that the power laws remain valid and the exponent μ remains constant for very long periods of time. He defines an effective time interval $d\lambda$ by

$$d\lambda = a(t)dt \quad (1.3)$$

where λ is the effective time and $a(t)$ is the acceleration factor. This is based on the fact that at creep time t , the shift factor is less than unity. All relaxation processes are $1/a_e$ times slower than at $t=0$. Based on this, the effective time, λ , was defined as

$$\lambda = \frac{t_e}{1-\mu} \left[\left(1 + \frac{t}{t_e} \right)^{1-\mu} - 1 \right] \quad (1.4)$$

where λ is the effective time, μ is the aging parameter, t_e is the age of the material, and t is time.

To obtain a momentary creep curve in order to predict the creep behavior of the material Struik proposes that the time-temperature superposition method, TTSP, be used. He discusses the physical meaning of the TTSP curve. He uses the argument that for all polymers the TTSP method works very well, therefore it cannot be considered an arbitrary data reduction method.

Sharma [3] explains that creep is one of the simplest experiments that can be used to describe the viscoelastic behavior of polymers. He further discusses that the retarded elastic deformation is due to the interplay of elastic and viscous effects and is a

characteristic of polymers. Creep compliance monotonically increases with time as the material moves from the *glassy region* (perfect elastic behavior). For a linear viscoelastic solid, creep strain can be related to the stress by

$$\varepsilon_{xy} = J(t) \sigma_{xy} \quad (1.5)$$

where $J(t)$ is the torsional compliance, ε is the strain, and σ is stress.

He further explains that the stress is found to decrease with time when a material is subjected to an instantaneous strain ε_{xy} and can be expressed by the relation

$$\sigma_{xy} = G(t) \varepsilon_{xy} \quad (1.6)$$

where $G(t)$ is the relaxation modulus function. In stress relaxations the material behaves like an elastic solid at very short times and over time the material shows viscoelastic behavior. Sharma states, “The retardation spectrum, $J(\lambda)$ does not represent the response of the materials in any specific test. The retardation spectrum gives the closest representation of molecular processes occurring in viscoelastic deformation.”

Wang, et al. [4] investigated the effect of physical aging on the viscoelastic creep properties of a thermoplastic-toughened cyanate ester resin (Fiberite 954-2) and its IM8/954-2 composites, and a semi-crystalline thermoplastic (Fiberite ITX) and its IM8/ITX composites. These tests were performed using dynamic mechanical analysis (DMA) and tensile creep tests. Creep tests were conducted up to an aging time of 54 hr with the logarithmic aging shift rate, μ , and its dependence on sub-glass transition temperature, being determined. Momentary creep tests were conducted on both material systems at temperatures between 140 °C and 200 °C to study the effect of long-term aging. Master curve plots were drawn from these momentary creep tests using the time-temperature superposition principle (TTSP). Effective time theory (ETT) was then used

to modify the TTSP and incorporate physical aging effects. Their study concluded that physical aging had a significant effect on the creep behavior of the 954-2 and ITX resin-based composite systems. They determined that as the aging time increased, the creep compliance decreased consistently. ETT was then used to predict the long-term creep behavior of the ITX system with reasonable accuracy. Due to the difficulties in rejuvenation, possible post-curing, degradation, and possible phase separation in the cyanate ester system, ETT could not be applied to Fiberite 954-2. Instead, their experimental results indicated that at longer creep times, $t > 26000$ s, the creep curve could be modeled using the power law

$$J_{\beta}(t) = J_{\beta_o} + m_1 t^n \quad (1.7)$$

where $J_{\beta}(t)$ is the creep compliance in the b region, J_{β_o} is the initial compliance, m_1 is the linear coefficient, t is time, and n is the relaxation time. While at shorter creep times, $1 < t < 3475$ s, the creep compliance is best represented by Struik's relationship for tensile creep compliance

$$J_{\alpha}(t) = J_{\alpha_o} \exp\left(\frac{t}{t_o}\right)^m \quad (1.8)$$

where J_{α_o} is the initial compliance, t is time, and t_o is a characteristic retardation time, and m is a shape parameter for each creep curve.

Knox, et al. [5] investigated creep analysis of adhesively bonded connections in glass reinforced epoxy pipes. Their approach concluded that the time-temperature superposition principle and the time-temperature stress superposition principle do not take into account physical aging and they are generally not applicable in the region of practical concern, under the glass transition temperature. They further validate the use of

Findley's power law [6] to model the creep behavior over a long time span. The basic form of this approach is the power law with non-linear coefficients

$$\varepsilon(t) = \varepsilon_o + mt^n \quad (1.9)$$

where $\varepsilon(t)$ is the strain at time t , ε_o the time independent strain, m the coefficient of time dependent term and n is a constant independent of stress. Their data showed that viscoelastic deformation occurs and that creep occurs instantaneously. Their experimental results demonstrated that the creep rates have a definite dependency on temperature and stress.

Bradshaw and Brinson [7] present an analytic method based on error minimization, for the data reduction of the study of physical aging and for time-aging time superposition. Their analytic method used error minimization to determine the momentary curves for a set of test data, and to find the associated shift factors and master curve. Their computer program uses the Kohlrausch model

$$S(t; S_o, \tau, \beta; t_e) = S_o \exp\left(\frac{t}{\tau}\right)^\beta \quad (1.10)$$

presented in Struik to model their data, where S_o is the initial compliance, t is time, and τ is a characteristic retardation time, and β is a shape parameter for each creep curve. When shifting data to the momentary curve to obtain a master curve, they select the longest aging time curve as the reference curve, since it spans the longest test time range. They further incorporate a total reference curve, which uses all of the short-term compliance curves to determine the parameters. They felt that the information about the shape of each curve is not fully represented by choosing one curve as a reference curve. Our experience with their computer program was disappointing.

Beckmann et al. [8] performed creep experiments in uniaxial extension to explore the kinetics of the physical aging process in semicrystalline syndiotactic polystyrene (sPS) having two processing histories. Their test revealed that classical time-aging time superposition, TAS, behavior was found for both materials at temperatures from 70 to 95°C with the shift rate, μ , decreasing as temperature was increased. They represented the creep behavior at each time using a Kohlraush-Williams-Watts (KWW) function

$$D(t) = D_o \exp\left(\frac{t}{\tau_o}\right)^\beta \quad (1.11)$$

where τ_o is a characteristic retardation time and β a shape parameter for each creep curve, and D_o is a fitting parameter. They found the time shift factor a_{te} using the methods described by Struik. The mechanical tests were carried out in uniaxial extension in creep conditions. The load was controlled using a computer-controlled servo-hydraulic testing machine, equipped with an oven for temperature control. Sample strain was measured with an extensometer attached to the sample. Their aging experiments were carried out by first annealing the specimens at 160 °C for 1 hr. They then placed the samples in the test machine at the aging temperature, and began applying the “probe” stresses. Experiments were performed at aging test temperatures of 60, 70, 80, 82.5, 85, 90, 95, 100, 110, and 120 °C following Struik’s protocol for the loading history.

They concluded that if the shape of the creep curve is unaltered as the aging time progresses, that TAS can apply. Thus, the TAS is not limited to the KWW type of creep function and can be represented by any function that describes the data. Their experimental observations suggest that the sPS behaves much like an amorphous polymer below T_g , while above T_g the response is unlike either amorphous materials or other semicrystalline polymers.

Sullivan [9] demonstrated that physical aging is an important factor in the viscoelastic behavior of composites. He looked at the short-term creep behavior of a unidirectional composite material and of its corresponding resin. Next, he used time-aging time superposition to form momentary creep master curves and discussed the effect of temperature on the physical aging process. The author discusses the appropriateness of TTSP for use in making both momentary and long term creep master curves in polymer composites. The effective-time theory of Struik is used in the prediction of long-term creep behavior.

Sullivan tested a unidirectional glass fiber reinforced thermosetting resin system. It was comprised of 30 vol.% glass fibers and Dow Derakane 470-36 resin. The T_g for this system is around 125-130 °C. All test were conducted in tension using tensile strips of dimensions 150 mm x 13 mm x 3 mm. Both short term (momentary) and long term creep tests were conducted. For the short-term test Sullivan followed Struik's snap shot assumption and in long term creep tests, aging occurs simultaneously with the creep. Annealing and rejuvenation of test specimens was done at 170 °C for 2 hrs.

Sullivan concluded that the creep compliance curves are dependent on the aging time, much like the results reported for glassy polymers. Shifting the momentary compliance curves outlined by Struik formed the momentary master curves. Using both horizontal and vertical shifting, his data showed excellent superposition.

Chai and McCrum [10] studied the mechanism of physical aging in crystalline polymers by thermally stimulated creep and by creep superposition. Their goal was to model an experiment where the specimen was heated to a temperature, T_2 , then quenched to and maintained at T_1 . The specimen's viscoelastic parameters then changed with time

due to aging. They observed that aging for an elapsed time had no effect on retardation elements at τ for $\tau \gg t_e$.

McCrum [11] describes the computer modeling of physical aging using the Sequential Aging Theory. Chai and McCrum did not support the Sequential Aging Theory with numerical modeling, but this paper proposes a numerical application of the theory. He noticed considerable changes if the specimen is quenched to liquid nitrogen temperature and data was taken on the run as the temperature increased. Quenching increases the magnitudes of the β - and γ -relaxations and if there is a shift of viscoelastic spectra produced by quenching, it isn't large.

Menard [12] characterizes the γ , β , and α relaxations in the following way:

The gamma transition is where the material begins to heat up and expand. Here, bending and stretching and side chain movements can occur due to an increase in the free volume. The beta transition is where the material begins to develop toughness. This occurs as the material continues to heat up and the whole side chains and localized groups of four to eight backbone atoms start to have enough space to move. The alpha transition is a slippage of the crystallites past each other.

McCrum further explains that small shifts of the spectrum in polymeric solids due to quenching and aging are conceivable. Sequential aging begins after a quench to temperature T where the viscoelastic elements with very small retardation times are aging. The elements are moving to their appropriate values corresponding to the temperature. The sequential aging theory was proposed to explain two experimental facts:

- The pronounced change in shape of the retardation spectrum produced by aging, first observed by Kovacs et al. [13] and others [14], [10].
- Observations from thermally stimulated creep experiments in which, during aging up to a time t_e , the retardation times at τ greatly in excess of t_e do not age [10].

McCrum concludes that physical aging is not restricted to the temperature region between the alpha- and beta-relaxations, as originally proposed by Struik.

Guerdoux et al. [15] studied the physical aging properties of polycarbonate and poly (methyl methacrylate). They measured the aging properties by dynamic mechanical experiments at different temperatures. They argue that the horizontal shift proposed by Struik to superpose the experimental curves for different aging times is only a first approximation. They state, “Struik proposed that the primary mechanism of physical aging arises from changes in molecular mobility of the polymer segments. This results in a proportionate increase in all retardation times, which can be represented by a shift with aging time of the retardation time spectra towards longer times. Thus, creep curves in the linear viscoelastic region can be superposed by a ‘nearly horizontal’ shift along the $\log(\text{time})$ axis.” The aim of their study was to see if Struik’s proposal could be generalized from creep to embrace stress relaxation and dynamic mechanical experiments. They measured the torsional viscoelastic properties of polymers with a Rheometrics mechanical spectrometer. They tested specimens with both cylindrical and rectangular cross-sections. The effective length of the cylindrical specimens was 40 mm and their diameter was 5 mm. The parallelepipeds had the following dimensions: length

40 mm, width 11 mm, thickness 4 mm. The specimens were annealed for one hour at 20 °C above their T_g . The specimens were then quenched to near ambient conditions.

Their testing procedure followed the snapshot assumption of Struik. They measured the relaxation modulus, $G'(\omega)$ and the dynamic modulus, $G''(\omega)$. They tried to superimpose the curves using only horizontal shifts and obtained different values of a_v for the three types of measurements. They concluded that the simple hypothesis of Struik is not valid for these data. They then used the model proposed by Chai and McCrum. In this model, it is assumed that the limiting values of the viscoelastic function vary with aging time. This hypothesis gives directly by a simple calculation the three following equations

$$\begin{aligned} G^{t_{v_0}}(t) &= C_v G^{t_v}(ta_v) + B_v \\ G^{t_{v_0}}(\omega) &= C_v G^{t_v}\left(\frac{\omega}{a_v}\right) + B_v \\ G^{t_{v_0}}(\omega) &= C_v G^{t_v}\left(\frac{\omega}{a_v}\right) \end{aligned} \quad (1.12)$$

where t_{v_0} is the reference aging time, B_v and C_v describe changes in the relaxed and unrelaxed moduli. These equations imply that to superimpose the experimental curves it is necessary to make a vertical shift and a rotation, as well as the horizontal shift a_v . They conclude that the horizontal shift proposed by Struik to superimpose $G(t)$, $G'(\omega)$ of $G''(\omega)$ for different aging times is only a first approximation and is not valid for the entire range of time or frequency.

Dean et al. [16] studied the creep behavior for poly(butylene terephthalate, PBT) over a range of elapsed times, t_e , between quenching from 80 °C and the start of the creep test. They tested specimens of PBT (POCAN B1505) that were 145 mm x 12 mm x 6 mm for creep tests and 145 mm x 10 mm x 3 mm for dynamic tests. They then heated the

specimens to 80 °C for 30 min, quenched them in water at room temperature then stored them at 23 °C for various periods of time. They used the following equation to model the compliance in the α region

$$D_{\alpha}(t) = (D_{R_{\alpha}} - D_{U_{\alpha}}) \left[1 - \exp\left(-\left(\frac{t}{\tau_{\alpha}}\right)^m\right) \right] \quad (1.13)$$

where m is a parameter characterizing the width of the retardation time spectrum of the mechanism and $D_{U_{\alpha}}$ and $D_{R_{\alpha}}$ are compliances for the α process. They then expanded the exponential term in this function as a power series which gives

$$D_{\alpha}(t) = \Delta D_{\alpha} \left[\left(\frac{t}{\tau_{\alpha}}\right)^m \left(1 - \frac{1}{2} \left(\frac{t}{\tau_{\alpha}}\right)^m + \dots \right) \right] \quad (1.14)$$

Their results indicated a small variation in m with elapsed time. Analyses in which m was considered to vary with t_e were significantly more complicated than when m was constant. They then used a constant, average value of m to fit the data.

1.3 Objectives

The purpose of this study was to develop a low-cost, short-term testing procedure to predict the time dependent properties of commercial PVCs and High Density Polyethylene over the lifetime of the installation (50 years). Bending tests, in accordance with ASTM D6272-98 were used to produce momentary curves of creep compliance at various aging times, t_e , and temperatures T_i . Aging times were chosen following Struik's snapshot assumption. Data taken at the different temperatures (TTSP) and the effective-time theory (ETT) were then used to develop a model predicting the time-dependent properties of the liner.

1.4 Organization

This thesis is organized into six chapters. The first presents the scope of the project, a literature review of relevant work, and the project's objectives. Chapter two discusses the materials tested and the process in which they were tested. The research itself was divided into parts. Chapter three presents the testing method and data reduction of the effective-time theory. The testing method and data reduction for the time temperature superposition principle is discussed in chapter four. Chapter five compares the data from long-term testing at different temperatures and compares the data with full-scale tests. Lastly, chapter six presents a summary of the findings and recommendations.

Figure 1.1. Illustration of trenchless lining of a pipe.

Figure 1.2. Idealized temperature scan of a polymer [Fig. 5.4, 12].

CHAPTER 2 EXPERIMENTAL PROCEDURES

2.1 Introduction

The relationship between stress and strain depends on time due to creep [1] and physical aging [2]. In a related study [17], creep and aging were studied in the frequency domain using Dynamic Mechanical Analysis (DMA). However, two drawbacks of Dynamic Mechanical Analysis (DMA) testing motivate long-term bending (LTB): specimen¹ size and test duration. DMA specimens are small on the order of (10 mm x 1.5 mm x 15 mm) and they must be cut from the pipe wall. Instead, LTB specimens use the full thickness of the pipe wall with a maximum testing size of (50 mm x material thickness x 231 mm). The larger size of the LTB specimens allows for a better representation of the material properties to be tested. Running long-term tests on a DMA ties up the machine and is costly. Therefore, another, less expensive method to test specimens needed to be developed. The LTB fixture was designed to perform inexpensive, long-term creep testing under ASTM D6272-98 four-point bending conditions.

2.2 Experimental Approach

2.2.1 Testing Method

All tests were performed using a four-point loading system, which uses two loading points with a spacing equal to one third of the support span. Testing was done in accordance to ASTM D6272-98.

2.2.2 Design and Fabrication of Testing Apparatus

Tests were conducted using the West Virginia University Long-Term Bending Fixture (LTB) based on ASTM D6272-98. This fixture uses two loading points with a

spacing of 64 mm (2.52 in) or one third of the support span spacing of 192 mm (7.56 in). Four fixtures can support a specimen with a maximum width of 50 mm (1.96 in) while four other fixtures can support a specimen with a maximum width of 25 mm (0.98 in). All four-load points have a radius of 7.94 mm (0.313 in), which allow for a minimum specimen depth of 4.96 mm (0.195 in) according to ASTM D6272-98 Section 6.2. Load-point displacement is measured with a linear optical encoder with an accuracy of 0.005 mm and a maximum travel of 50 mm. The optical encoder, model LDK-4-4-B and spar and scale assembly, model B36679-4-0-50.0 were purchased from Dynamics Research Corporation. The majority of the testing apparatus was constructed out of aluminum, except for the load supports and the vertical rods where stainless steel was used. Linear bearings were used to allow the carriage to descend freely and apply the load to the specimen (refer to Appendix A for fixture schematics). A picture of the fixture with an untested specimen is shown in Fig. 2.2. Fig. 2.3 is a picture of the testing fixture with a tested specimen. Six fixtures shown during testing are in Fig. 2.4. Each specimen is fixed to the load points with rubber bands, as shown in Fig. 2.5. This allows the top of the specimen to remain in contact with the bottom of the loading arms at all times during the test. Refer to Fig. 2.6 for a depiction of four point bending. Further, this allows an accurate measuring of the deflection of the specimen, since the specimen may not always be flat and enables the fixture to measure the relaxation.

2.2.3 Data Acquisition

Data was acquired from the testing fixtures using an ACS-Tech80 5312B ISA, Encoder Interfacing card with four axes. A Pentium 166mhz and Pentium 150mhz computer were used to read the card and store the data (Fig. 2.7). Software drivers

provided by the DAQ manufacturer were modified to write data to files in specific time increments using Visual Basic 6.0. Refer to Appendix B for the modified Visual Basic code.

2.3 Test Environmental Conditions

All tests were performed in West Virginia University's environmental chamber located in room G86 of the Engineering Science Building. The environmental chamber is a Cincinnati Sub-Zero model Z-32 (Fig. 2.8) that uses a Chromalox 2030 microprocessor controller.

2.4 Sample Preparation

2.4.1 Materials

In this study five different materials were tested, three of which are PVCs, one is High Density Polyethylene, and the other is Polyester with reinforced felt. The glass transition temperature and melting temperature of the materials were obtained from testing by Dynamic Mechanical Analysis at West Virginia University [17] (Table 2.1). These materials are commercially available, to avoid bias, the materials were designated with the letters A, B, C, D, and E.

2.4.2 Sample Collection

New liner samples were produced at the vendor facility or field installation of each material. In either case, the samples were taken from rounded pipe and processed into a cylindrical configuration (Fig. 2.1). All liner samples were cut perpendicular to the direction of extrusion and had a minimum length of 3 ft. If the installation prohibited the removal of samples at this length, three samples not less than 1 ft in length each were

provided. The 3 ft samples collected from the field were cut into three pieces, each with a length of 1 ft.

For the purpose of measuring the thickness of the bagging material used on material E, the vendor also provided two samples at least 930 cm² of un-impregnated hose comprising both main hose and the lining hose. Due to the nature of the thermoset liners, the liner test section had at least one flat surface.

2.4.3 Flattening of Samples

Next, the samples, except for material D, were flattened. First, the pipe section was cut longitudinally into three equal sections. These sections were then placed, concave side down, on a piece of flat aluminum with a thickness of 12.7 cm (1/2 in) and overall dimensions slightly greater than the sample and placed in an oven. The orientation of the sample indicated the hoop-wise direction of the sample as shown in Fig. 2.9. A second identical aluminum plate was placed on top of the sample and additional weights were added to it. The samples, aluminum plates and additional weights were then heated to T_H and maintained at that temperature for not less than 48 hours. The specimen heating temperature, T_H , was determined to be 15 °C above the glass transition temperature (T_g) of the material, but below its melting point (T_m).

2.4.4 Sample Sizing and Preparation

The specimens had a minimum aspect ratio of 16 to 1 and had a maximum width of 50 mm and a minimum depth of 4.96 mm. All specimens were cut to width using a band saw (Fig 2.10).

The thickness and width of each specimen were measured at both ends and at the center of the span using a micrometer as per Section 6.3 of ASTM D790 and then

averaged. In the case of the thermoset specimen, the thickness of the bagging material was subtracted from the total thickness. The specimens, except for the HDPE, were annealed in an oven at temperature T_H for at least 30 min. The HDPE was annealed at the temperature used to expand the liner during installation. They were then quenched between steel plates for approximately 5 min. After the specimens were quenched, they were placed in the fixture and held in place with rubber bands wrapped around the inner loading nodes. Next, the spar and scale assembly was placed in the fixture. Using the software the fixtures were then zeroed, the test filename and path were entered and the data was then recorded.

Table 2.1. Material Properties.

Material	T_g (°C)	T_H (°C)	T_M (°C)
<i>A</i>	70	85	~
<i>B</i>	90	105	~
<i>C</i>	85	100	~
<i>D</i>	-30	93	116
<i>E</i>	135	150	~

Figure 2.1. Illustration of the location from which the samples are removed.

Figure 2.2. LTB fixture with untested specimen.

Figure 2.3. LTB fixture with bent specimen.

Figure 2.4. LTB fixtures in environmental chamber under testing.

Figure 2.5. Specimen held in place with rubber bands.

Figure 2.6. Illustration of specimen under four-point bending, the dashed line represents the deformed specimen due to loading.

Figure 2.7. Computers used for data acquisition.

Figure 2.8. Environmental chamber.

Figure 2.9. Illustration of one-third of pipe between two plates for flattening purposes.

Figure 2.10. Band saw used to cut specimens.

Figure 2.11. Ovens used to anneal specimens.

CHAPTER 3 AGING STUDY

3.1 Introduction

Physical aging starts when a polymer is quenched to a temperature below its T_g , regardless of whether or not the material is under load. Physical aging is accompanied by increases in stiffness, yield stress, density, and viscosity, and decreases in creep and stress relaxation rates.

The equivalent time theory (ETT) of Struik [2] assumes that physical aging can be explained by a single shift, a_e , of the entire relaxation spectrum. In a typical Struik-type experiment, the sample is quenched from above the glass-transition temperature, T_g , to the testing temperature, T_i , and maintained at that temperature for the aging time, t_e . Tests are then performed for a short time interval: one-tenth the age, t_e , of the specimen. This method of testing takes a *snapshot* of the viscoelastic state, which prevents the data from being tainted by physical aging.

3.2 Testing Procedure

Each specimen was prepared as described in Section 2.4.3. Tests were performed at a temperature, T_i , of 40 °C. Due to room conditions and the capabilities of the environmental chamber the value of T_i ranged from 39.5 °C to 40 °C. The width of the specimens was in the range of 7 mm to 10 mm. The testing temperature and specimen width were determined by doing several practice tests to achieve a deflection large enough that the error in the optical encoder does not interfere with the results. The specimens were tested according to Struik's *snapshot* assumption. This assumes that if the test time is less than one-tenth the age of the specimen, physical aging is not observed

during the test time. The testing schedule varied with each study due to other activities, but the snapshot assumption was always followed.

Tests were conducted at eight intervals during the aging experiment. A typical testing schedule is shown in Table 3.1. Conducting an aging study and calculating the shift factors, a_e , determined the number of test. Using these shift factors, μ was calculated and tests were performed until the value of μ remains constant; that is, the slope of the $\log(a_e)$ vs. $\log(t_e)$ does not change by adding another data point. For all materials tested, this is accomplished with eight intervals of testing over approximately four days.

3.3 Data Analysis

Data reduction was performed using Microsoft Excel 2000 and Microcal Origin 6.0. The files from the Long-Term Bending software were opened in Microsoft Excel. The load was removed after each snapshot test, allowing the sample to relax, but the initial shape is not recovered. This occurs because the relaxation time is finite and because a portion of the viscoelastic behavior is that of a fluid [18]. Each snapshot test starts from a deflected initial position, which is easily found since the optical encoder reads deflection during the relaxation as well as during the creep (snapshot) test. Once the initial deflection was established for each snapshot test, the relative deflection data vs. time represents a snapshot creep curve.

The stiffness of the material increases with age, reducing the amount of deflection observed during the test. Therefore, with each successive test the deflection vs. time curves should lie under one another. This was not observed with the first two tests (refer to Fig. 3.2). This occurrence is thought to be the result of mechanical conditioning,

where the specimen must adjust and settle onto the load supports. Therefore, the first two tests for each aging study were not used in the calculation of μ .

Next, the compliance $D(t)$ was calculated for each point. The equation for the compliance under true four-point bending was derived using the method outlined below. Referring to Figure 2.6, the maximum deflection of a beam under four-point bending with 1/3 load span is [19]

$$d1 = \frac{-P/2b(L^2 - b^2)^{3/2}}{9\sqrt{3}EI} + \frac{-P/2a(L^2 - a^2)^{3/2}}{9\sqrt{3}EI} \quad (3.1)$$

where P is the load, L is the distance of the support span, E is the modulus of elasticity, I is the moment of inertia, $a = L/3$ and $b = L/3$.

The deflection at the load supports is [19]

$$d2 = \frac{P/2a^2b^2}{3EI} + \frac{P/2b}{6EI} [x^3 - (L^2 - b^2)x] \quad (3.2)$$

where $a = L/3$, $b = 2L/3$, and $x = L/3$. The deflection delta is:

$$\delta = d1 - d2 \quad (3.3)$$

The moment of inertia of a rectangle is

$$I = \frac{1}{12}bh^3 \quad (3.4)$$

where b is the width of specimen and h is the height of the specimen.

Thus the compliance is

$$D = \frac{243(64\sqrt{6} + 135)\delta wh^3}{2117PL^3} \approx \frac{33.491\delta wh^3}{PL^3} \quad (3.5)$$

where d is the deflection of the specimen, w is the width of the specimen, h is the thickness of the specimen, P is the load, and L is the distance of the support span.

The next step was to fit a model to the data to obtain an equation for each test. Several models were fit to determine the best fit for the data. These methods included the Standard Linear Solution, Maxwell Model, *Dean's Equation* [16], and the Modified Power Law. It was determined that a one term Modified Power Law best fit the data. Figure 3.2 is a typical curve fit of the data. The Modified Power Law is represented by the following equation

$$D = D_o + D_1 t^m \quad (3.6)$$

where D_o is the initial compliance, D_1 is the linear coefficient, and t is the time, and η is the relaxation time. All data fitting parameters were obtained using Microcal Origin 6.0.

Once all of the curves were fit using the Modified Power Law, the next step was to shift the curves to obtain the shift factors and aging value μ for each material. Shifting the curves turned out to be quite complicated. Dividing each time by a shift factor, a_e , the curves were to be shifted on top of the reference curve. However each of the curves could only be shifted so that a few points would match, creating the problem of which points should be used to align the curves onto the reference curve. To solve this problem it was observed that a straight line in double log scale using the Power Law could represent the data. The Modified Power Law can be transformed into the standard Power Law by the following method

$$\begin{aligned} D &= D_o + D_1 t^m \\ D - D_o &= D_1 t^m \\ \log(D - D_o) &= \log(D_1 t^m) \end{aligned} \quad (3.7)$$

Finally,

$$\log(D - D_o) = \log(D_1) + m \log(t) \quad (3.8)$$

This approach is similar to Dean et al. Using equation 1.8 and expanding the exponential to only one term, the Modified Power Law can be derived as follows:

$$\begin{aligned} D - D_o &= D_1 \left[\left(\frac{t}{2} \right)^m - \frac{1}{2} \left(\frac{t}{2} \right)^{2m} + \dots \right] \\ D - D_o &\sim D_1 \left(\frac{t}{\tau} \right)^m = \left(\frac{D_1}{\tau^m} \right) t^m \\ D_1 &= \left(\frac{D_1}{\tau^m} \right) \\ D &= D_o - D_1 t^m \end{aligned} \quad (3.9)$$

where m is a constant, equal to the average of all the values m_i of the aging study, where $i=1 \dots N$, N being the number of snapshot test available. The difference between m_i and the average m represents a rotation of the line. Chai and McCrum and [10] Guerdoux et al. [15] also discussed the need for rotating the data in addition to horizontal shifting to calculate a_e . Again looking at the Modified Power Law equation (3.6), m is the slope of the line, therefore averaging this value is the same as performing a rotation of each curve.

Once the data was represented by a straight line, it was noticed that the slopes of each curve did not match. The problem again was which point should be used for the curve shifting. To solve this problem the values of m_i (the slope of the curve) were averaged and the data for each snapshot test was refit keeping the value of m constant and equal to the average (Figs 3.4 through 3.8). This produced good results; each curve now was a straight line with the same slope and could be easily shifted on top of one another (Figs. 3.9 through 3.13). Each shift factor was analytically calculated using the following

method. First, an arbitrary value of $\log(D-D_o)$ was selected. Next, $\log(t)$ was calculated for each test using the following equation

$$\log(t)_{test} = \frac{\log(D-D_o)_{arbitrary} - \log(D_{test})}{m} \quad (3.10)$$

where D_{test} was obtained from the curve fit of the corresponding test. Then using the last test as a reference, $a_e=1$, a_e of each test was calculated using the following formula:

$$a_{e_{test}} = \frac{\log(t)_{test}}{\log(t)_{lasttest}} \quad (3.11)$$

where $\log(t)_{test}$ is the log base-10 of the time of the snapshot curve to me shifted and $\log(t)_{lasttest}$ is the log base-10 of the time of the reference snapshot curve. Since m is the same for all snapshot tests, the value of $\log(D-D_o)$ does not affect the results of (3.11). Below is a flowchart describing the process of calculating the shift factors.

An aging study was done on three specimens separately. For each specimen, all of the snapshot curves were shifted to the longest age(hr). The three specimens had a slightly different longest age due to differences in the testing schedule. Therefore, all age factors for all snapshot tests in a given specimen were shifted so that $a_e=1$ corresponds to $t_e=15$ min. This was done for each specimen independently using its own $a_e(t_e)$ curve. Then the three specimens have the same reference age, $t_e=15$ min with $a_e=1$. Next, a_e values of every snapshot for all specimens can be plotted together, Figs. 3.14 through 3.18. Linear regression of $\log(a_e)$ vs. $\log(t_e)$ as in Figs. 3.14 through 3.18 yields a linear equation that allows us to predict the shift factor $a_e(t_e)$ for any age t_e , including the age of the full-size samples tested by Barbero and Rangarajan [20]. The slope of the line is the aging parameter μ . Tables 3.2 through 3.6 compare the values of μ for each aging study preformed for each material and give the standard deviation and coefficient of variation of each study with the master μ . An aging study was preformed for materials A, B, and C at 21.1 °C to observe if temperature had any effect on the aging parameter, μ . As can be seen in Tables 3.7 through 3.9 temperature has not effect on the aging parameter.

Table 3.1. Typical testing schedule for an aging study.

	day and time test began	t_e (min)	test duration (min)
test 1	01/23/02 10:11:25 AM	11.42	1.14
test 2	01/23/02 10:16:39 AM	16.65	1.67
test 3	01/23/02 10:30:13 AM	30.22	3.02
test 4	01/23/02 11:33:23 AM	93.38	9.34
test 5	01/23/02 02:57:41 PM	297.68	29.77
test 6	01/24/02 09:54:18 AM	1434.30	143.43
test 7	01/25/02 09:53:56 AM	2873.93	287.39
test 8	01/26/02 01:12:58 PM	4512.97	451.30

Table 3.2. Comparison of aging studies of material A.

$\mu = 0.481$		
specimen	μ	% diff
A1	0.510	6.09
A2	0.481	0.02
A3	0.465	3.31
A41	0.490	1.96
A42	0.492	2.38
average	0.488	
standard deviation	0.0166	
coefficient of variation	3.40%	

Table 3.3. Comparison of aging studies of material B.

$\mu = 0.720$		
specimen	μ	% diff
B1	0.717	0.47
B2	0.722	0.20
B3	0.728	1.05
average	0.722	
standard deviation	0.0055	
coefficient of variation	0.76%	

Table 3.4. Comparison of aging studies of material C.

$\mu = 0.718$		
specimen	μ	% diff
C2	0.709	1.15
C3	0.712	0.76
C4	0.678	5.59
C5	0.793	10.57
C6	0.636	11.40
average	0.706	
standard deviation	0.0580	
coefficient of variation	8.21%	

Table 3.5. Comparison of aging studies of material D.

$\mu = 0.177$		
specimen	μ	% diff
D1	0.196	10.78
D2	0.169	4.27
D3	0.169	4.46
average	0.178	
standard deviation	0.0154	
coefficient of variation	8.69%	

Table 3.6. Comparison of aging studies of material E.

$\mu = 0.602$		
specimen	μ	% diff
E1	0.592	1.69
E2	0.496	17.63
E3	0.698	15.92
E4	0.551	8.41
E5	0.630	4.65
E6	0.605	0.47
E7	0.577	4.19
average	0.595	
standard deviation	0.1010	
coefficient of variation	16.97%	

Table 3.7. Comparison of master μ at 21.1 °C and 40 °C for material A.

T °C	μ
40	0.481
21.1	0.519
<i>average</i>	0.500
<i>standard deviation</i>	0.027
<i>coefficient of variation</i>	5.42%

Table 3.8. Comparison of master μ at 21.1 °C and 40 °C for material B.

T °C	μ
40	0.720
21.1	0.717
<i>average</i>	0.719
<i>standard deviation</i>	0.003
<i>coefficient of variation</i>	0.35%

Table 3.9. Comparison of master μ at 21.1 °C and 40 °C for material C.

T °C	μ
40	0.718
21.1	0.634
<i>average</i>	0.676
<i>standard deviation</i>	0.059
<i>coefficient of variation</i>	8.80%

Figure 3.1. Deflection versus time for aging study test.

Figure 3.2. Illustration of the reasoning for mechanical conditioning.

Figure 3.3. Fit of the data using the Modified Power Law.

Figure 3.4. Aging study data transformed into the Power Law for material A.

Figure 3.5. Aging study data transformed into the Power Law for material B.

Figure 3.6. Aging study data transformed into the Power Law for material C.

Figure 3.7. Aging study data transformed into the Power Law for material D.

Figure 3.8. Aging study data transformed into the Power Law for material E.

Figure 3.9. Aging study data shifted to obtain μ for material A.

Figure 3.10. Aging study data shifted to obtain μ for material B.

Figure 3.11. Aging study data shifted to obtain μ for material C.

Figure 3.12. Aging study data shifted to obtain μ for material D.

Figure 3.13. Aging study data shifted to obtain μ for material E.

Figure 3.14. Theoretical and experimental values of the aging shift factors for material A

Figure 3.15. Theoretical and experimental values of the aging shift factors for material B.

Figure 3.16. Theoretical and experimental values of the aging study shift factors for material C.

Figure 3.17. Theoretical and experimental values of the aging shift factors for material D.

Figure 3.18. Theoretical and experimental values of the aging shift factors for material E.

CHAPTER 4 TIME-TEMPERATURE SUPERPOSITION PRINCIPLE

4.1 Introduction

The time temperature superposition principle (TTSP) is a method used to predict the behavior of a material for times longer than the test time. This method accelerates the creep of the material by an increase in the temperature. It assumes that this increase in temperature can accelerate but not change the material property being investigated, in our case compliance.

Creep compliance is measured at each temperature over a span of time shorter than $t_e/10$ so that the curve is free of physical aging effects. Test data at each temperature plotted on a base-10 log-log scale versus time. One temperature is chosen as a reference temperature. The remaining curves are superimposed onto the reference curve by a shifting with a horizontal shift factor a_T . Once all of the curves are shifted, a master curve that spans longer time than the actual testing time is created. This master curve can then be shifted to any temperature, and used to predict the value of compliance over time. Since every individual test is free of physical aging, the master curve is free of physical aging even if it spans a time range much larger than $t_e/10$.

4.2 Testing Procedure

For TTSP testing the materials were prepared as described in Section 2.2.3. They were then placed in the testing fixture at the desired testing temperature to let them age. Each specimen was aged 60 min and then tested for 6 min, following the snapshot assumption to avoid the effects of physical aging. During the aging process, two one-minute tests were performed at $t_e = 20$ min and $t_e = 25$ min. This mechanically conditioned the specimen as described in Section 3.3 before the actual test at $t_e = 60$ min.

4.3 Data Analysis

Three specimens of each material were tested across the temperature range, approximately 21.1 °C to 57 °C for each material. Next, the log base-10 of the time and compliance was calculated and plotted for each material. The lowest temperature was used as a reference temperature. Data was then superimposed on to this curve using a horizontal shift factor, a_T .

The curves were shifted by minimizing the difference in shifted time $\left(t_{ref} - \frac{t_i}{a_{Ti}} \right)$, where t_{ref} is the reference time, t_i is the time, and a_{Ti} is the shift factor, between the two curves on a base-10 log-log scale. Testing temperatures were chosen so that the compliances would overlap. For the materials in this study, it was found that a change every 5 to 7 °C was sufficient. A temperature schedule was formulated for testing at intervals of about 5 to 7 °C apart. The testing temperature did not exceed the T_g of the material. Three specimens were tested at or near the nominal temperature in the testing schedule. The data sets were designated T_{1a} , T_{1b} , T_{1c} through T_{nc} where n is the number of different temperatures tested. Then all the data sets were shifted until they overlap with the data of the previous temperature, taking the lowest temperature as a reference temperature ($a_T=1$). Due to material variability and experimental error each set of data at a particular temperature did not lie on top of each other. In order to correct for this the following method was used to shift the data:

1. Data for each curve at the lowest tested temperature T_{1a} , T_{1b} , and T_{1c} were used as a reference temperature ($a_T=1$).

2. One curve at the next (higher) temperature T_{ia} , where i is the number of the data set being shifted, was then shifted to each previous curve $T_{(i-1)a}$, $T_{(i-1)b}$, $T_{(i-1)c}$ producing three shift factors.
3. This is then done for the next two curves T_{ib} and T_{ic} producing six more shift factors.
4. The shift factors are then averaged giving one shift factor for the data at T_i .
5. Data for T_{ia} , T_{ib} , and T_{ic} are then shifted using the averaged shift factor, a_T .

In the case of material D it was noticed that each set of data was a straight line on log base-10 scale. This allowed the data to be fit with a Power Law equation to represent the master curve. To get the equation of the TTSP curve at a particular temperature the data for each specimen tested at that temperature was fit with a Power Law. The parameters of each of these curve fits were then averaged. Material E was tested using a Dynamic Mechanical Analyzer (DMA). This was done to avoid moving the material between tests. It was observed that the composition of the material was not uniform and a change in the material's location on the support and loading nodes produced varied results. Testing the material on the DMA allowed the material to be annealed and quenched without having to move the specimen. Data for the TTSP of material E was obtained from Barbero and Julius [17]. The moving average of the master curve of each material was then taken to reduce the number of data points. The master curve of each material is shown in Figs. 4.1 through 4.5. Linear regression of $\log(a_T)$ vs. temperature as in Figs. 4.6 through 4.10 yields a linear equation that can be used to predict the shift factor $a_T(T)$ for any temperature.

Figure 4.1. TTSP graphs and master curve shifted to 21.1 °C of material A.

Figure 4.2. TTSP graphs and master curve shifted to 20.27 °C of material B.

Figure 4.3. TTSP graphs and master curve shifted to 20.28 °C of material C.

Figure 4.4. TTSP graphs and master curve shifted to 21.9 °C of material D.

Figure 4.5. TTSP graphs and master curve shifted to 40 °C of material E.

Figure 4.6. Theoretical and experimental values of the TTSP shift factors for material A at 21.1 °C.

Figure 4.7. Theoretical and experimental values of the TTSP shift factors for material B at 20.27 $^{\circ}\text{C}$.

Figure 4.8. Theoretical and experimental values of the TTSP shift factors for material C at 20.28 $^{\circ}\text{C}$.

Figure 4.9. Theoretical and experimental values of the TTSP shift factors for material D at 21.9°C .

Figure 4.10. Theoretical and experimental values of the TTSP shift factors for material E at 40°C .

CHAPTER 5 LONG-TERM TESTING AND CORRELATION WITH FULL SIZE SPECIMENS

5.1 Introduction

The goal of this project was to be able to predict the ageing of the five materials and compare them with data from full-scale samples [20]. In order to compare the prediction and long-term tests with the full-scale samples, the data needed to be shifted for age and temperature outside the range of age and temperature used in the accelerated tests. In addition, sample size and testing conditions of full-size test are quite different from bending test. Long-term tests on the order of four or six days and a t_e of 1 hr were conducted using the LTB fixtures to give another set of data for comparison. The main advantage of doing long-term tests with the Long-Term Bending fixtures is that more of the test parameters could be controlled. This reduces the number of possible errors when trying to compare the results. By testing in this manner, we can tell if the predictions match long-term bending tests where both accelerated test and long-term bending tests correspond to samples of the same age albeit test durations are quite different. Performing LTB tests at two different temperatures also gives the opportunity to shift the creep compliance for temperature as well. Data taken in this study was shifted using the shift factors obtained from TTSP testing to 21.1 °C. LTB data was then shifted to compensate for the difference in age and for temperature where needed. Data taken in this study was shifted using the shift factors obtained from TTSP testing Section 4.3 to 21.1 °C. Table 5.1 is a list of the aging times, t_e , for each of the full-scale pipes.

5.2 Testing Procedure

The testing procedure is similar to that of the ageing study and the TTSP. First, the specimens are annealed and then quenched. Next, they are aged one hour with two tests being performed at $t_e = 20$ min and $t_e = 25$ min to mechanically condition the specimen. Finally, the test is started and data is recorded. Tests were performed at both 21.1 °C and 40 °C with a $t_e = 1$ hr. Data was recorded every 30 seconds and then a moving average was taken to reduce the number of points, making the data more manageable in Excel.

5.3 Data Analysis

5.3.1 Shifting for Age and Temperature

Struik [2] proposed that the equivalent time could be predicted using the following equation

$$t = t_e \left[\left[\left(\frac{\lambda \alpha}{t_e} \right) + 1 \right]^{\frac{1}{\alpha}} - 1 \right] \quad (5.1)$$

where t is the equivalent time to compensate for ageing, λ is the unaged time on the TTSP curve, $\alpha=1-\mu$, and t_e is the age (time at which the LTB test was started). The compliance is then read on the TTSP curve and plotted against the times calculated using equation (5.1). Creep behaviors were predicted at both 21.1 °C and 40 °C.

Next, the creep vs. time data taken at 21.1 °C was shifted to 40 °C and the data taken at 40 °C was shifted to 21.1 °C. When shifting the data for temperature one must take into account that the stiffness of the material changes with temperature as well as with age. To shift data for temperature first calculate the unaged time, λ , using the following equation

$$\lambda = \left(\frac{t_e}{\alpha} \right) \left[\left(\frac{t}{t_e} + 1 \right)^\alpha - 1 \right] \quad (5.2)$$

where t is the test time, t_e is the age of the material, and $\alpha=1-\mu$. The unaged time, λ , can be shifted for temperature and or age by dividing the unaged time by the corresponding shift factor (a_T to shift for temperature and or a_e to shift for age) as shown in the following equation

$$\lambda' = \frac{\lambda}{a_T} \text{ or } \frac{\lambda}{a_e} \text{ or } \frac{\lambda}{a_T a_e} \quad (5.3)$$

Once the unaged time is shifted the effective time or aged time can be calculated using the following equation

$$t = t_e \left[\left[\left(\frac{\lambda' \alpha}{t_e} + 1 \right)^{\frac{1}{\alpha}} - 1 \right] \right] \quad (5.4)$$

The following flowchart illustrates the process of shifting the data for temperature and or age.

Figs. 5.1 through 5.5 contain the data from this study shifted from 21.1 °C ($t_e = 1$ hr) to 40 °C ($t_e = 1$ hr). Figs. 5.6 through 5.9 contain the data shifted from 40 °C ($t_e = 1$ hr) to 21.1 °C ($t_e = 1$ hr). In order to compare the LTB data with the full-scale data the TTSP curve was shifted from an age of 1 hr to the age of the pipes when testing began and the equivalent times, *prediction*, were calculated using equation 5.1. Figs. 5.10 through 5.14 are the comparisons of the full-scale data and the prediction based on Struik's effective-time theory.

5.3.2 Calculating Ageing Shift Factors

Using the ageing parameters obtained from Section 3.3 and the linear regression of the $\log(a_T)$ vs. $\log(t_e)$, the ageing factor a_e can be calculated as

$$a_e = 10^{(b + \mu \log(t_e))} \quad (5.5)$$

where b is the y intercept, μ is the ageing parameter, and t_e is the age of the material. Since any ageing time can be used as reference time, we can take the age of the material on the TTSP as a reference (1 hr in this study). For the reference age $a_e=1$ so

$$b = -\mu \log(t_e) \quad (5.6)$$

5.3.3 Calculating Temperature Shift Factors

Linear regression of $\log(a_T)$ vs. temperature yields a linear equation that allows us to predict the shift factor $a_T(T)$ for any temperature. Using the linear regression equations obtained in Figs. 4.6 through 4.10 the temperature shift factor can be calculated using the following equation

$$a_T = 10^{(b + \gamma(T))} \quad (5.7)$$

where b is the y intercept, γ is the slope of the curve fit, and T is the temperature. This method is similar to the method used to calculate a_e described above.

Table 5.1. Start date for testing of full-scale pipes.

Material	Manufacture Date	Test Date	T_e (hr)	a_e
A	10/11/2000	12/04/2000	1.30E+03	3.19E-02
B	02/01/2001	05/02/2001	2.16E+03	3.96E-03
C	02/01/2001	05/02/2001	2.16E+03	4.05E-03
D	12/07/2001	04/03/2002	2.81E+03	2.46E-01
E	11/29/2001	04/01/2002	2.95E+03	8.16E-03

Figure 5.1. TTSP and prediction at 40 °C and $t_e = 1$ hr for material A.

Figure 5.2. TTSP and prediction at 40 °C and $t_e = 1$ hr for material B.

Figure 5.3. TTSP and prediction at 40 °C and $t_e = 1$ hr for material C.

Figure 5.4. TTSP and prediction at 40 °C and $t_e = 1$ hr for material D.

Figure 5.5. TTSP and prediction at 40 °C and $t_e = 1$ hr for material E.

Figure 5.6. TTSP and prediction at 21.1 °C and $t_e = 1$ hr for material A.

Figure 5.7. TTSP and prediction at 21.1 °C and $t_e = 1$ hr for material B.

Figure 5.8. TTSP and prediction at 21.1 °C and $t_e = 1$ hr for material C.

Figure 5.9. TTSP and prediction at 21.1 °C and $t_e = 1$ hr for material D.

Figure 5.10. Comparison of full-size pipes and prediction for material A.

Figure 5.11. Comparison of full-size pipes and prediction for material B.

Figure 5.12. Comparison of full-size pipes and prediction for material C.

Figure 5.13. Comparison of full-size pipes and prediction for material D.

Figure 5.14. Comparison of full-size pipes and prediction for material E.

CHAPTER 6 SUMMARY AND RECOMMENDATIONS

6.1 Summary

This study was aimed at developing a short-term test that is an alternative to DMA testing to predict the time-dependent creep behaviors of commercial polymers. The proposed test procedure can be implemented regardless of the type of polymer material used for the liner. The liner materials used for testing are commercially available blends of polymers that are used in typical field installations.

It was determined that horizontal shifting alone is not enough to superimpose the creep curves obtained from an aging study as proposed by Struik [2]. A rotation is needed as proposed by Chai and McCrum [10] and Guerdoux et al. [15]. Through the fitting of the data with the Modified Power Law and then transforming the data into a straight line (Power Law) the data can be analytically superimposed. The aging parameter, μ , is not affected by temperature, at least in the range of this study.

Shifting the data for temperature was performed quite well using the shift factors obtained from the TTSP curve. Struik's method for predicting the creep behavior correlated well with the experimental data from the LTB and full-size specimens. Materials A, B, D, and E followed the prediction for the time period tested. Material C however did not compare well with the prediction. It is believed that the full-size specimens yielded during testing, due to high strains.

6.2 Contributions of this Thesis

This thesis examined the physical aging behavior of five different materials: polyvinyl chloride, high-density polyethylene, and polyester reinforced with polyester fibers specimens. The objective of designing a short-term testing fixture capable of

conducting the necessary experiments to predict the physical aging behavior of full-size specimens has been met using Struik's effective-time theory. It was shown that a horizontal shift alone is not enough to calculate the aging parameter of a material. A rotation as well as a horizontal shift of the data is needed. A method for shifting data to compensate for age and temperature was also presented.

6.3 Recommendations

The present study examined a method to predict the time-dependent creep behavior of five commercial products used in trenchless lining of pipes. The effective-time theory and time temperature superposition principle were used for the basis of this study. In addition to the above procedure, certain other areas of testing and theoretical analysis can be performed on materials to evaluate their structural behavior over time. Based on this study the following recommendations are made:

1. Investigate the sequential aging theory proposed by Struik to determine if the results are the same.
2. Study the effect of moisture on the long-term material properties of the liner.
3. Further analysis on the effect of annealing material D relative to its aging properties should be conducted.
4. More uniform specimens of material E should be obtained to improve the results of TTSP testing using the LTB.
5. Tests to determine the mechanical properties such as yield stress with a $t_e = 1$ hr should be conducted. This would serve as a reference as to the maximum load to be applied during long-term testing.

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APPENDICES

Appendix A – Drawing Package of Testing Apparatus

Figure A1 Testing fixture base

Figure A2 Testing fixture load support arm side view

Figure A3 Testing fixture load support arm bottom view

Figure A4 Test fixture ball bearing guide

Figure A5 Test fixture carriage assembly top and outside views

Figure A6 Testing fixture carriage assembly inside view

Figure A7 Testing fixture spar and mirror measuring device

Figure A8 Testing fixture load support

Appendix B – Software Package

Visual Basic Code for the form frmSelections

This form was added to the drivers that came with the DAQ card, it allowed the user to select the file to write data to and the time interval in which it wrote the data, Fig. B.1 is a screen shot of this form.

```
Private Sub cmdExit_Click()  
Unload F5312  
Unload frmSelections  
End
```

```
End Sub
```

```
Private Sub cmdRecord1_Click()  
If filenamechange1 = 0 Then  
frmChangefilename.Show  
Else  
Open frmSelections.CommonDialog2.FileName For Output As #2  
Print #2, Date  
Print #2, Time  
AXIS1data = Val(F5312.Text31Val)  
Print #2, Date; Time; " "; Format(AXIS1data, "00.000")  
j = Timeintervalinput  
Timer2.Enabled = True  
Timer2.Interval = Timeintervalinput * 1000  
End If
```

```
End Sub
```

```
Private Sub cmdRecord0_Click()  
If filenamechange0 = 0 Then  
frmChangefilename.Show  
Else  
Open frmSelections.CommonDialog1.FileName For Output As #1  
Print #1, Date  
Print #1, Time  
AXIS0data = Val(F5312.Text30Val)  
Print #1, Date; Time; " "; Format(AXIS0data, "00.000")  
i = Timeintervalinput  
Timer1.Enabled = True  
Timer1.Interval = Timeintervalinput * 1000  
End If
```

```
End Sub
```

```
Private Sub cmdRecord2_Click()  
If filenamechange2 = 0 Then  
frmChangefilename.Show  
Else  
Open frmSelections.CommonDialog3.FileName For Output As #3
```

```

Print #3, Date
Print #3, Time
AXIS2data = Val(F5312.Text32Val)
Print #3, Date; Time; " "; Format(AXIS2data, "00.000")
k = Timeintervalinput
Timer3.Enabled = True
Timer3.Interval = Timeintervalinput * 1000
End If

End Sub

Private Sub cmdRecord3_Click()
If filenamechange3 = 0 Then
frmChangefilename.Show
Else
Open frmSelections.CommonDialog4.FileName For Output As #4
Print #4, Date
Print #4, Time
AXIS3data = Val(F5312.Text33Val)
Print #4, Date; Time; " "; Format(AXIS3data, "00.000")
l = Timeintervalinput
Timer4.Enabled = True
Timer4.Interval = Timeintervalinput * 1000
End If

End Sub

Private Sub cmdSave0_Click()
CommonDialog1.DefaultExt = ".crp"
CommonDialog1.Filter = "crp files (*.crp)|*.crp"
CommonDialog1.ShowSave 'display Save dialog
filenamechange0 = 2
End Sub

Private Sub cmdSave1_Click()
CommonDialog2.DefaultExt = ".crp"
CommonDialog2.Filter = "crp files (*.crp)|*.crp"
CommonDialog2.ShowSave 'display Save dialog
filenamechange1 = 2
End Sub

Private Sub cmdSave2_Click()
CommonDialog3.DefaultExt = ".crp"
CommonDialog3.Filter = "crp files (*.crp)|*.crp"
CommonDialog3.ShowSave 'display Save dialog
filenamechange2 = 2
End Sub

Private Sub cmdSave3_Click()
CommonDialog4.DefaultExt = ".crp"
CommonDialog4.Filter = "crp files (*.crp)|*.crp"
CommonDialog4.ShowSave 'display Save dialog
filenamechange3 = 2
End Sub

Private Sub cmdStop0_Click()

```

```

Timer1.Enabled = False
Print #1, Time
Print #1, Date
Close #1
i = 0
End Sub

```

```

Private Sub cmdStop1_Click()
Timer2.Enabled = False
Print #2, Time
Print #2, Date
Close #2
j = 0
End Sub

```

```

Private Sub cmdStop2_Click()
Timer3.Enabled = False
Print #3, Time
Print #3, Date
Close #3
k = 0
End Sub

```

```

Private Sub cmdStop3_Click()
Timer4.Enabled = False
Print #4, Time
Print #4, Date
Close #4
l = 0
End Sub

```

```

Private Sub Form_Load()
filenamechange0 = 0
filenamechange1 = 0
filenamechange2 = 0
filenamechange3 = 0

End Sub

```

```

Private Sub ReadCmd_Click()
Dim ret1 As Integer
Dim ResetTemp As Long

'--Reload the counter reset all register's for all Axis.
ret1 = te5312LoadCntr(0, 0)
ResetTemp = te5312ReadCntr(0)
Text1Val.Text = ResetTemp
Text2Val.Text = Hex(ResetTemp)
ret1 = te5312WriteCmd(-1, TE5312MCR_FLAG_RST)
ret1 = te5312WriteCmd(-1, TE5312MCR_CMP_RST)
End Sub

```

```

Private Sub Timer1_Timer()
AXIS0data = Val(F5312.Text30Val)
Print #1, Date; Time; " "; Format(AXIS0data, "00.000")

```

```

i = i + Timeintervalinput
End Sub

Private Sub Timer2_Timer()
    AXIS1data = Val(F5312.Text31Val)
    Print #2, Date; Time; " "; Format(AXIS1data, "00.000")
    j = j + Timeintervalinput
End Sub

Private Sub Timer3_Timer()
    AXIS2data = Val(F5312.Text32Val)
    Print #3, Date; Time; " "; Format(AXIS2data, "00.000")
    k = k + Timeintervalinput
End Sub

Private Sub Timer4_Timer()
    AXIS3data = Val(F5312.Text33Val)
    Print #4, Date; Time; " "; Format(AXIS3data, "00.000")
    l = l + Timeintervalinput
End Sub

Private Sub txtTimeinterval_Change()
    Timeintervalinput = Val(txtTimeinterval)
End Sub

```

Visual Basic code for the form frmF5312

This code was modified so that the driver recorded in quadrature mode at all times. It is used to zero the system and allows the user to get to the frmSelections file, Fig. B.2 is a screen shot of this form.

```
Private Sub BrdAdr_Click()

    Addr.Show

End Sub

Private Sub cmdRecordData_Click()
    If filenamechange = 1 Then
        frmChangefilename.Show
    End If

    If filenamechange = 2 Then
        '---Stop reading the counter.
        Timer1.Enabled = False

        '---If "Don't show dialog" is not checked, show it.
        If Demo1Chk = False Then
            Demo1Dlg.Show 1
        End If

        '---Write the registers for Quadrature operation
        argument2 = TE5312CMD_ICR Or TE5312ICR_ENABLE Or TE5312ICR_LATCH
        retval = te5312WriteCmd(ALLAXIS, argument2)

        argument2 = TE5312CMD_OCCR Or OCCR_Qrd
        retval = te5312WriteCmd(ALLAXIS, argument2)

        '---If no dialog box appears, initial count is 0
        If Demo1Chk = True Then
            retval = te5312LoadCntr(AXIS0, 0)
            retval = te5312LoadCntr(AXIS1, 0)
            retval = te5312LoadCntr(AXIS2, 0)
            retval = te5312LoadCntr(AXIS3, 0)
        End If

        Text29Val.Text = Demo1String

        '---Start reading the counter.
        Timer1.Enabled = True

        Graph.Show
    End If

End Sub
```

```

Private Sub cmdSaveAs_Click()
CommonDialog1.DefaultExt = "dat"
CommonDialog1.Filter = "dat files (*.dat)|*.dat"
CommonDialog1.ShowSave    'display Save dialog
filenamechange = 2
End Sub

Private Sub cmdSelections_Click()
'---Stop reading the counter.
Timer1.Enabled = False

'---If "Don't show dialog" is not checked, show it.
If Demo1Chk = False Then
Demo1Dlg.Show 1
End If

'---Write the registers for Quadrature operation
argument2 = TE5312CMD_ICR Or TE5312ICR_ENABLE Or TE5312ICR_LATCH
retval = te5312WriteCmd(ALLAXIS, argument2)

argument2 = TE5312CMD_OCCR Or OCCR_Qrd
retval = te5312WriteCmd(ALLAXIS, argument2)

'---If no dialog box appears, initial count is 0
If Demo1Chk = True Then
retval = te5312LoadCntr(AXIS0, 0)
retval = te5312LoadCntr(AXIS1, 0)
retval = te5312LoadCntr(AXIS2, 0)
retval = te5312LoadCntr(AXIS3, 0)
End If

Text29Val.Text = Demo1String

'---Start reading the counter.
Timer1.Enabled = True
F5312.Hide
frmSelections.Show
End Sub

Private Sub cmdTime_Click()
Unload frmSelection
frmSelection.Show
End Sub

Private Sub Command1_Click()
Form1.Show
End Sub

Private Sub Demo1_Click()
""This is what we are using!!""

'---Stop reading the counter.
Timer1.Enabled = False

'---If "Don't show dialog" is not checked, show it.
If Demo1Chk = False Then

```

```

Demo1Dlg.Show 1
End If

'---Write the registers for Quadrature operation
argument2 = TE5312CMD_ICR Or TE5312ICR_ENABLE Or TE5312ICR_LATCH
retval = te5312WriteCmd(ALLAXIS, argument2)

argument2 = TE5312CMD_OCCR Or OCCR_Qrd
retval = te5312WriteCmd(ALLAXIS, argument2)

'---If no dialog box appears, initial count is 0
If Demo1Chk = True Then
    retval = te5312LoadCntr(AXIS0, 0)
    retval = te5312LoadCntr(AXIS1, 0)
    retval = te5312LoadCntr(AXIS2, 0)
    retval = te5312LoadCntr(AXIS3, 0)
End If

Text29Val.Text = Demo1String

'---Start reading the counter.
Timer1.Enabled = True

End Sub

Private Sub Demo2_Click()

'---Stop reading the counter.
Timer1.Enabled = False

'---If "Don't show dialog" is not checked, show it.
If Demo2Chk = False Then
    Demo2Dlg.Show 1
End If

'---Write the registers for Quadrature operation
argument2 = TE5312CMD_ICR Or ICR_Count
retval = te5312WriteCmd(ALLAXIS, argument2)

argument2 = TE5312CMD_OCCR Or OCCR_NotQrd
retval = te5312WriteCmd(ALLAXIS, argument2)

'---If no dialog box appears, initial count is 0
If Demo2Chk = True Then
    retval = te5312LoadCntr(AXIS0, 0)
    retval = te5312LoadCntr(AXIS1, 0)
    retval = te5312LoadCntr(AXIS2, 0)
    retval = te5312LoadCntr(AXIS3, 0)
End If

Text29Val.Text = Demo2String

'---Start reading the counter.
Timer1.Enabled = True

```



```

End Sub

Private Sub Demo3_Click()

'---Stop reading the counter.
Timer1.Enabled = False

'---If "Don't show dialog" is not checked, show it.
If Demo3Chk = False Then
Demo3Dlg.Show 1
End If

'---Write the registers for Quadrature operation
argument2 = TE5312CMD_ICR Or ICR_Quad
retval = te5312WriteCmd(ALLAXIS, argument2)

argument2 = TE5312CMD_OCCR Or OCCR_NotQrd
retval = te5312WriteCmd(ALLAXIS, argument2)

'---If no dialog box appears, initial count is 0
If Demo3Chk = True Then
retval = te5312LoadCntr(AXIS0, 0)
retval = te5312LoadCntr(AXIS1, 0)
retval = te5312LoadCntr(AXIS2, 0)
retval = te5312LoadCntr(AXIS3, 0)
End If

Text29Val.Text = Demo3String

'---Start reading the counter.
Timer1.Enabled = True

End Sub

Private Sub Demo4_Click()

'---Stop reading the counter.
Timer1.Enabled = False

'---If "Don't show dialog" is not checked, show it.
If Demo4Chk = False Then
Demo4Dlg.Show 1
End If

'---Write the registers for Quadrature operation
argument2 = TE5312CMD_ICR Or ICR_Quad
retval = te5312WriteCmd(ALLAXIS, argument2)

argument2 = TE5312CMD_OCCR Or OCCR_Qrd
retval = te5312WriteCmd(ALLAXIS, argument2)

'---If no dialog box appears, initial count is 0
If Demo4Chk = True Then
retval = te5312LoadCntr(AXIS0, 0)
retval = te5312LoadCntr(AXIS1, 0)
retval = te5312LoadCntr(AXIS2, 0)

```

```

retval = te5312LoadCntr(AXIS3, 0)
End If

Text29Val.Text = Demo4String

'---Start reading the counter.
Timer1.Enabled = True

End Sub

Private Sub Demo5_Click()

'---Stop reading the counter.
Timer1.Enabled = False

'---If "Don't show dialog" is not checked, show it.
If Demo5Chk = False Then
Demo5Dlg.Show 1
End If

'---Write the registers for Quadrature operation
argument2 = TE5312CMD_ICR Or ICR_Quad
retval = te5312WriteCmd(ALLAXIS, argument2)

argument2 = TE5312CMD_OCCR Or OCCR_Ord
retval = te5312WriteCmd(ALLAXIS, argument2)

'---If no dialog box appears, initial count is 0
If Demo5Chk = True Then
retval = te5312LoadCntr(AXIS0, 0)
retval = te5312LoadCntr(AXIS1, 0)
retval = te5312LoadCntr(AXIS2, 0)
retval = te5312LoadCntr(AXIS3, 0)
End If

retval = te5312LoadPr(AXIS0, FieldArray(0).PreLoadCnt)
retval = te5312LoadPr(AXIS1, FieldArray(1).PreLoadCnt)
retval = te5312LoadPr(AXIS2, FieldArray(2).PreLoadCnt)
retval = te5312LoadPr(AXIS3, FieldArray(3).PreLoadCnt)

Text29Val.Text = Demo5String

'---Start reading the counter.
Timer1.Enabled = True

End Sub

Private Sub Exit_Click()
Unload F5312

End

End Sub

Private Sub ExitCmdMnu_Click()

```

```

Unload F5312

End

End Sub

Private Sub Form_Unload(Cancel As Integer)

    retval = CloseTheDriver()

End Sub
Private Sub Form_Load()
'Lengthoftest = 60
'Timeinterval = 1
filenamechange = 1
End Sub

Private Sub ReadCmd_Click()
Dim ret1 As Integer
Dim ResetTemp As Long

'--Reload the counter reset all register's for all Axis.
ret1 = te5312LoadCntr(0, 0)
ResetTemp = te5312ReadCntr(0)
Text1Val.Text = ResetTemp
Text2Val.Text = Hex(ResetTemp)
ret1 = te5312WriteCmd(-1, TE5312MCR_FLAG_RST)
ret1 = te5312WriteCmd(-1, TE5312MCR_CMP_RST)
End Sub

Private Sub ResetAllMnu_Click()
Dim ret1 As Integer
Dim ResetTemp As Long

'--Reload the counter reset all register's for all Axis.
ret1 = te5312LoadCntr(0, 0)
ResetTemp = te5312ReadCntr(0)
Text1Val.Text = ResetTemp
Text2Val.Text = Hex(ResetTemp)
ret1 = te5312WriteCmd(-1, TE5312MCR_FLAG_RST)
ret1 = te5312WriteCmd(-1, TE5312MCR_CMP_RST)
End Sub

Private Sub SaveAsCmdMnu_Click()
CommonDialog1.DefaultExt = ".dat"
CommonDialog1.Filter = "dat files (*.dat)|*.dat"
CommonDialog1.ShowSave 'display Save dialog
End Sub

Private Sub ShwDlgMnu_Click()

Demo1Dlg.Check1.Value = 0
Demo1Chk = False
Demo1Dlg.Check1.Value = 0

```

```

Demo2Chk = False
Demo1Dlg.Check1.Value = 0
Demo3Chk = False
Demo1Dlg.Check1.Value = 0
Demo4Chk = False
Demo1Dlg.Check1.Value = 0
Demo5Chk = False

End Sub

Private Sub Text1Val_GotFocus()
'---Hide the caret, display only data.
LRetVal = HideCaret(Text1Val.hWnd)
End Sub

Private Sub Timer1_Timer()
'-----
'Read Axis 0
'-----
'Read the counter
'-----

If (AXISN And 1) <> 1 Then
FieldArray(AXIS0).count = te5312ReadCntr(AXIS0)
Text1Val.Text = FieldArray(AXIS0).count
If FieldArray(AXIS0).count > 10600 Then
Text30Val.Text = (16777216 - FieldArray(AXIS0).count) * -0.005
Else
Text30Val.Text = FieldArray(AXIS0).count * 0.005
End If
Text2Val.Text = Hex(FieldArray(AXIS0).count)

'-----
'Read the status.
'-----

StatusWord = te5312ReadSts(AXIS0) 'Get the status word
FieldArray(AXIS0).Borrow = &H1 And StatusWord "'Borrow" = LSB
Text7Val.Text = FieldArray(AXIS0).Borrow
FieldArray(AXIS0).Carry = &H2 And StatusWord "'Carry" = Bit 1
If FieldArray(AXIS0).Carry = 0 Then
Text6Val.Text = "0"
Else
Text6Val.Text = "1"
End If

FieldArray(AXIS0).Compare = &H4 And StatusWord "'Compare = Bit 2
If FieldArray(AXIS0).Compare = 0 Then
Text5Val.Text = "0"
Else
Text5Val.Text = "1"
End If

FieldArray(AXIS0).Sign = &H8 And StatusWord "'Sign = Bit 3
If FieldArray(AXIS0).Sign = 0 Then

```

```

    Text4Val.Text = " +"
Else
    Text4Val.Text = " -"
End If

FieldArray(AXIS0).Direction = &H10 And StatusWord ""Direction = Bit 4
If FieldArray(AXIS0).Direction = 0 Then
    Text3Val.Text = " Down"
Else
    Text3Val.Text = " Up"
End If
Else
Text2Val.BackColor = &H80000000
Text3Val.BackColor = &H80000000
Text4Val.BackColor = &H80000000
Text5Val.BackColor = &H80000000
Text6Val.BackColor = &H80000000
Text7Val.BackColor = &H80000000
Text1Val.BackColor = &H80000000
End If ' axisn 0
'-----
'Read Axis 1.
'-----
'-----
'Read the counter.
'-----
'Dim var222
'var222 = AXISN
'AXISN = 6
If AXISN < 8 Then
If (AXISN = 0) Or (AXISN = 1) Or (AXISN = 4) Or (AXISN = 5) Then
GoTo testt
Else
Text8Val.BackColor = &H80000000
Text9Val.BackColor = &H80000000
Text10Val.BackColor = &H80000000
Text11Val.BackColor = &H80000000
Text12Val.BackColor = &H80000000
Text13Val.BackColor = &H80000000
Text14Val.BackColor = &H80000000
End If
Else
If (AXISN = 8) Or (AXISN = 9) Or (AXISN = 12) Or (AXISN = 13) Then
testt:
FieldArray(AXIS1).count = te5312ReadCntr(AXIS1)
Text8Val.Text = FieldArray(AXIS1).count
If FieldArray(AXIS1).count > 10600 Then
Text31Val.Text = (16777216 - FieldArray(AXIS1).count) * -0.005
Else
Text31Val.Text = FieldArray(AXIS1).count * 0.005
End If
Text9Val.Text = Hex(FieldArray(AXIS1).count)

'-----
'Read the status.
'-----

```

```

StatusWord = te5312ReadSts(1) 'Get the status word
FieldArray(AXIS1).Borrow = &H1 And StatusWord "'Borrow" = LSB
Text14Val.Text = FieldArray(AXIS1).Borrow

FieldArray(AXIS1).Carry = &H2 And StatusWord "'Carry" = Bit 1
If FieldArray(AXIS1).Carry = 0 Then
    Text13Val.Text = "0"
Else
    Text13Val.Text = "1"
End If

FieldArray(AXIS1).Compare = &H4 And StatusWord "'Compare" = Bit 2
If FieldArray(AXIS1).Compare = 0 Then
    Text12Val.Text = "0"
Else
    Text12Val.Text = "1"
End If

FieldArray(AXIS1).Sign = &H8 And StatusWord "'Sign" = Bit 3
If FieldArray(AXIS1).Sign = 0 Then
    Text11Val.Text = "+"
Else
    Text11Val.Text = "-"
End If
FieldArray(AXIS1).Direction = &H10 And StatusWord "'Direction" = Bit 4
If FieldArray(AXIS1).Direction = 0 Then
    Text10Val.Text = " Down"
Else
    Text10Val.Text = " Up"
End If

Else
Text8Val.BackColor = &H80000000
Text9Val.BackColor = &H80000000
Text10Val.BackColor = &H80000000
Text11Val.BackColor = &H80000000
Text12Val.BackColor = &H80000000
Text13Val.BackColor = &H80000000
Text14Val.BackColor = &H80000000
End If
End If ' Axisn 1

'-----
'Read Axis 2.
'-----
'-----
'Read the counter.
'-----
'Dim var222
'var222 = AXISN
'AXISN = 10
If AXISN < 8 Then
If AXISN = 0 Or AXISN = 1 Or AXISN = 2 Or AXISN = 3 Then
GoTo tt
Else
Text15Val.BackColor = &H80000000

```

```

Text16Val.BackColor = &H80000000
Text17Val.BackColor = &H80000000
Text18Val.BackColor = &H80000000
Text19Val.BackColor = &H80000000
Text20Val.BackColor = &H80000000
Text21Val.BackColor = &H80000000
End If
Else
If AXISN = 8 Or AXISN = 9 Or AXISN = 10 Or AXISN = 11 Then
tt:
FieldArray(AXIS2).count = te5312ReadCntr(AXIS2)
Text15Val.Text = FieldArray(AXIS2).count
If FieldArray(AXIS2).count > 10600 Then
Text32Val.Text = (16777216 - FieldArray(AXIS2).count) * -0.005
Else
Text32Val.Text = FieldArray(AXIS2).count * 0.005
End If
Text16Val.Text = Hex(FieldArray(AXIS2).count)

'-----
'Read the status.
'-----
StatusWord = te5312ReadSts(AXIS2) 'Get the status word
FieldArray(AXIS2).Borrow = &H1 And StatusWord "'Borrow" = LSB
Text21Val.Text = FieldArray(AXIS2).Borrow
FieldArray(AXIS2).Carry = &H2 And StatusWord "'Carry" = Bit 1
If FieldArray(AXIS2).Carry = 0 Then
Text20Val.Text = "0"
Else
Text20Val.Text = "1"
End If

FieldArray(AXIS2).Compare = &H4 And StatusWord "'Compare = Bit 2
If FieldArray(AXIS2).Compare = 0 Then
Text19Val.Text = "0"
Else
Text19Val.Text = "1"
End If

FieldArray(AXIS2).Sign = &H8 And StatusWord "'Sign = Bit 3
If FieldArray(AXIS2).Sign = 0 Then
Text18Val.Text = "+"
Else
Text18Val.Text = "-"
End If

FieldArray(AXIS2).Direction = &H10 And StatusWord "'Direction = Bit 4
If FieldArray(AXIS2).Direction = 0 Then
Text17Val.Text = " Down"
Else
Text17Val.Text = " Up"
End If

Else
Text15Val.BackColor = &H80000000
Text16Val.BackColor = &H80000000

```

```

Text17Val.BackColor = &H80000000
Text18Val.BackColor = &H80000000
Text19Val.BackColor = &H80000000
Text20Val.BackColor = &H80000000
Text21Val.BackColor = &H80000000
End If ' axisn 2
End If

'-----
'Read Axis 3.
'-----
'-----
'Read the counter.
'-----
If AXISN < 8 Then
FieldArray(AXIS3).count = te5312ReadCntr(AXIS3)
Text22Val.Text = FieldArray(AXIS3).count
If FieldArray(AXIS3).count > 10600 Then
Text33Val.Text = (16777216 - FieldArray(AXIS3).count) * -0.005
Else
Text33Val.Text = FieldArray(AXIS3).count * 0.005
End If
Text23Val.Text = Hex(FieldArray(AXIS3).count)

'-----
'Get Axis 3 status.
'-----
StatusWord = te5312ReadSts(AXIS3) 'Get the status word
FieldArray(AXIS3).Borrow = &H1 And StatusWord "'Borrow" = LSB
Text28Val.Text = FieldArray(AXIS3).Borrow

FieldArray(AXIS3).Carry = &H2 And StatusWord "'Carry" = Bit 1
If FieldArray(AXIS3).Carry = 0 Then
Text27Val.Text = "0"
Else
Text27Val.Text = "1"
End If

FieldArray(AXIS3).Compare = &H4 And StatusWord "'Compare" = Bit 2
If FieldArray(AXIS3).Compare = 0 Then
Text26Val.Text = "0"
Else
Text26Val.Text = "1"
End If

FieldArray(AXIS3).Sign = &H8 And StatusWord "'Sign" = Bit 3
If FieldArray(AXIS3).Sign = 0 Then
Text25Val.Text = "+"
Else
Text25Val.Text = "-"
End If

FieldArray(AXIS3).Direction = &H10 And StatusWord "'Direction" = Bit 4
If FieldArray(AXIS3).Direction = 0 Then
Text24Val.Text = " Down"

```



```

Else
    Text24Val.Text = " Up"
End If
Else
Text22Val.BackColor = &H80000000
Text23Val.BackColor = &H80000000
Text24Val.BackColor = &H80000000
Text25Val.BackColor = &H80000000
Text26Val.BackColor = &H80000000
Text27Val.BackColor = &H80000000
Text28Val.BackColor = &H80000000
End If' axisn 3

End Sub

Private Sub TimeSelectMnu_Click()
frmSelection.Show
End Sub

```

Visual Basic code for the module variable

This module was added to the original code, it contains defines all of the variables that were added to the software.

```
Public testvar As Integer
```

```
Public AXIS0data!  
Public AXIS1data!  
Public AXIS2data!  
Public AXIS3data!
```

```
Public graphx() As Double  
Public graphy1() As Double  
Public graphy2() As Double  
Public graphy3() As Double  
Public graphy4() As Double
```

```
Public selec As Integer  
Public testcheck As Integer  
Public timecheck As Integer  
Public filenamechange0 As Integer  
Public filenamechange1 As Integer  
Public filenamechange2 As Integer  
Public filenamechange3 As Integer  
Public Lengthoftestinput!  
Public Timeintervalinput!  
Public Lengthoftest!  
Public Timeinterval!  
Public i As Long  
Public j As Long  
Public k As Long  
Public l As Long
```

```
Public counterp  
Public AXIS0datap
```

```
Public displacement
```

```
Public c0 As Integer  
Public c1 As Integer  
Public c2 As Integer  
Public c3 As Integer
```

```
Public l0!  
Public l1!  
Public l2!  
Public l3!
```

The screenshot shows a software window titled "WVU 4pt bending software". It contains two columns of controls for four different axes. The left column handles Axis 0 and Axis 2, while the right column handles Axis 1 and Axis 3. For each axis, there are three buttons: "Save", "Record", and "Stop" data. Below these buttons is a text input field for the filename. At the bottom of the window, there is a "Time interval" label, a text input field, and a constraint "< or = 30 sec". An "Exit Program" button is located in the bottom right corner.

Axis	Save Data	Record Data	Stop Data	Filename
Axis 0	Save AXIS0 Data	Record AXIS0 Data	Stop AXIS0	
Axis 1	Save AXIS1 Data	Record AXIS1 Data	Stop AXIS1	
Axis 2	Save AXIS2 Data	Record AXIS2 Data	Stop AXIS2	
Axis 3	Save AXIS3 Data	Record AXIS3 Data	Stop AXIS3	

Time interval < or = 30 sec Exit Program

Figure B.1 Screen shot of the form frmSelections, which allows users to enter the filename to write to and select the time interval to write the data.

Figure B.2 Screen shot of the from frmF5312 which allows users to zero the system.