Lab 4: Creep, Stress-Strain Response, and Stress Relaxation of Polymer Samples in Tensile Loading

Diana L. Nelson (d.nelson@ufl.edu)

***Abstract*—This report presents and analyzes data collected in Lab 4a and Lab 4b. In Lab 4a, creep in a polymeric fishing line was examined. An LVDT (Linear Variable Displacement Transducer) was used to detect voltage readings which were sent to and OOTB DAQ device (Out of the Box Data Acquisition Device). A LabView program (VI) was written to compile voltage readings and applied loads and then use that information to develop a stress vs. strain diagram. In Lab 4b, an Instron 5967 Universal Testing Machine (UTS) with a 30 kN load cell was used to apply uni-axial tension to Nylon 6-6 and Ultra High Molecular Weight Polyethylene (UHMW PE). Data from the UTS was used to determine stress-strain behavior of Nylon 6-6 and UHMWPe.**

***Index Terms*— Instron UTS, OOTB DAQ, LVDT, Nylon 6-6, UHMWPe, creep**

I. Introduction

STRESS strain diagrams can give much insight into a materials' mechanical properties. By developing a stress strain diagram of a material, one can determine its modulus of elasticity, toughness, yield stress, ultimate strength, breaking strength, percent elongation, and more. Creep diagrams are plots of the strain that a material experiences over time when the stress is held constant. It is important to account for measurement uncertainties when deriving material properties from these measurements.

The objectives of Lab 4a were to examine the creep properties of a nylon monofilament fishing line, use the information measured to develop characterization of creep for the material, and develop uncertainties for the measurements.[1]

The objectives of the Lab 4b were to examine the tensile properties of Nylon 6-6 and UHMW PE, and to use the information measured to develop stress-strain diagrams of the materials under differing strain rates.[2]

II. Procedure

A. VI and OOTB DAQ Collaboration

In order to obtain tangible data from the OOTB DAQ in Lab 4a, a VI was created. A Mathscript node was placed within a while loop and the LVDT voltage signal from the OOTB DAQ was used as an input value. A series of equations derived from the voltage readings were then formed and are reviewed in the discussion section of this report.

B. Calibrating the LVDT and Setting up the Wire

The calibration constant of the LVDT, k, was provided by the lab to be 491.13 mV/mm. The diameter of the line was found on the spool of the fishing line.

Next, the sample wire was set up. The wire was wrapped around the top of the tensile loading fixture and tightened down. The other end of the wire was wrapped around the weight carrier and tightened down. The initial length, L_0, was measured with a metric ruler. In order to ensure that the LVDT was reading voltages within range, the LVDT was raised while monitoring the voltage. The piece holding the LVDT body was tightened back down once the LVDT was measuring an appropriate voltage (i.e. $-6<V<6$).

C. Loading the wire

With the VI running and an acquisition time of 0.1 seconds and sample rate of 100 Hz, a brass mass was placed on the LVDT weight hanger. The mass, m, was an input control on the front panel of the VI. A 400 g mass was used in the first run and a 700 g mass was used in the second run. A creep diagram was displayed on the front panel of the VI and used to monitor the strain experienced by the wire over time. After the primary creep phase, the acquisition time was reduced to 15 seconds during the secondary creep phase. After 15 minutes in the secondary creep phase, the load was removed and the acquisition time was changed to one second for 30 seconds. After that 30 seconds passed, the acquisition time was changed to 10 seconds for the final 4.5 minutes of the test. All data from each trial (400g and 700g) was stored to a spreadsheet. This was the end of the first experiment

D. Measuring the cross section of test specimens and marking the test specimen

The first step of Lab 4b was to measure the cross-sectional area of each test specimen. A micrometer was used for the thickness measurements and calipers were used for the width measurements. There were initially four test specimens (two samples of UHMW PE and two samples of Nylon 6-6). Each one was measured 10 times by 10 different people. Ten length and ten width measurements of each sample were recorded. The mean area of each specimen was calculated with these values.

E. Preparing Sample for Loading

Next, the sample was mounted into the wedge grips of the UTS. The sample length between the grips was measured with a pair of calipers and recorded as the initial length, L_{0b}. A mark was placed at the grip of each sample.

F. Loading the Sample, Measuring Relaxation

A constant cross-head displacement rate of 5mm/min was applied to the sample for two minutes. The displacement was collected from the cross-head displacement of the testing machine and the load data was collected from the load cell. After two minutes of loading, the sample was immediately removed and the distance between the clamp marks was measured. A measurement was taken every 5 minutes for 12 minutes and recorded. This was performed for both the Nylon 6-6 and UHMW. This process was repeated at 100 mm/min with new samples of Nylon and UHMW, however, strain relaxation was not recorded for these samples.

Next, new samples were cut from the drawn section of the specimens that underwent a 100 mm/min strain rate. The new samples were cut to be approximately the same length as the original samples. The drawn Nylon was placed in the UTS and strained at a rate of 5 mm/min for 6 minutes. The drawn UHMW was strained at a rate of 5 mm/min for the first three minutes and then at 100 mm/min for the remainder of the time (~1 min).

III. Results

Raw measurements taken in Lab 4a that were used to solve for strain are listed in Table I below.

TABLE I
RAW DATA FROM LAB 4A FOR EACH LOAD

Applied mass, m [g]	*Mass of weight hanger[g]*	*Tare Voltage, V_t [V]*	*Initial Length, L_0 [m]*	*Fishing Line Diameter, d [m]*
400	101	4.93	.072	2.28E-4
700	101	4.97	.067	2.28E-4

Figs. 1 and 2 are plots of the percent strain over time for the fishing line loaded with a 400g mass. The stages of creep are labeled.

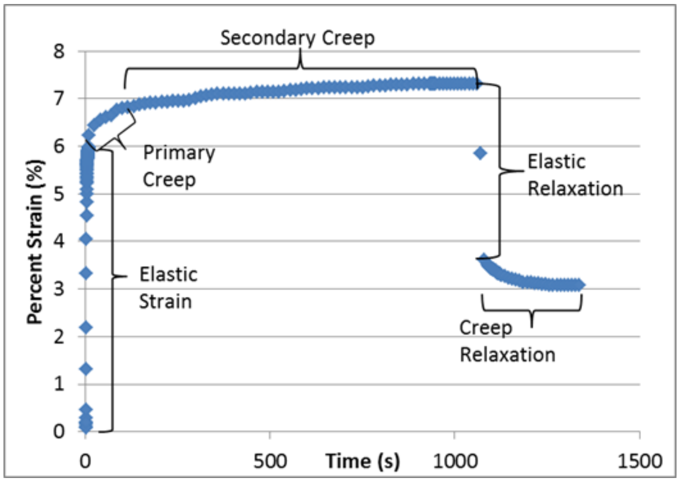

Figure 1 Creep Diagram for 400g load with labeled creep stages

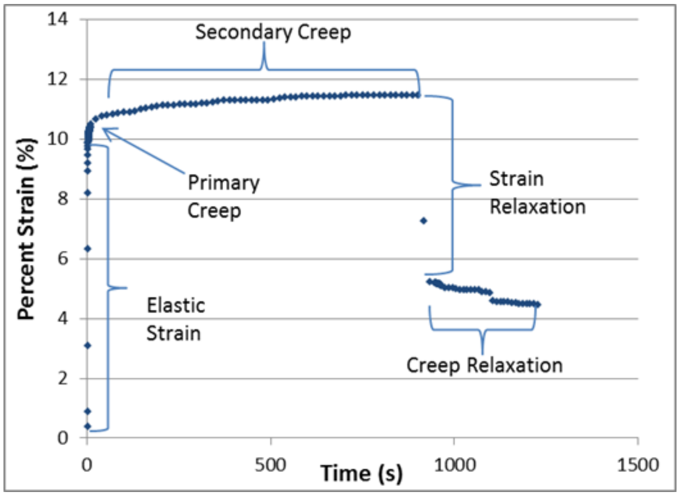

Figure 2 Creep Diagram for 700g load with labeled creep stages

Figs. 3 and 4 are graphs of the logarithmic strain over the logarithmic time for each load. These plots were obtained by taking samples of data in the secondary creep phase of Figs. 1 and 2 respectively.

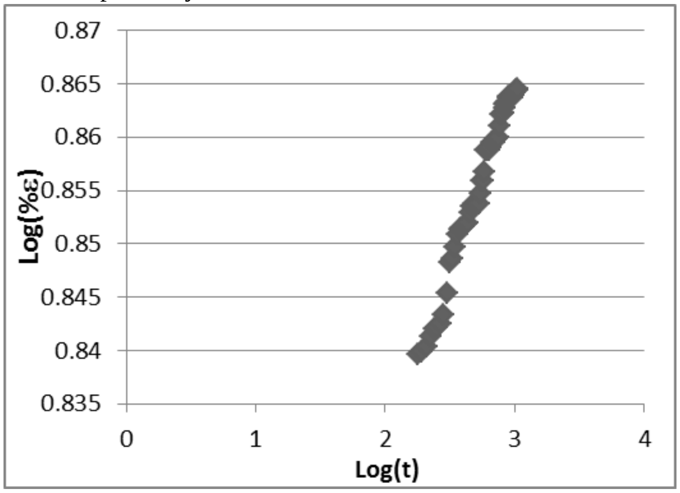

Figure 3 Log (% Strain) vs. Log (time) for the secondary creep phase with the 400g load applied

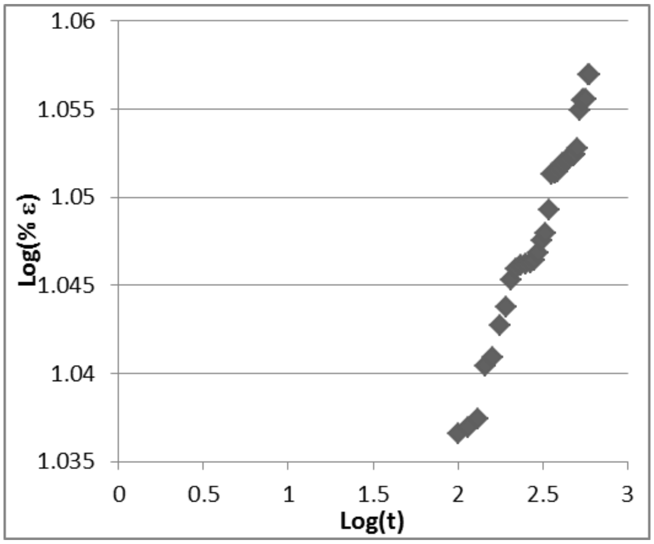

Figure 4 Log (% strain) vs. Log (time) in the secondary creep phase when the 700g load was applied

Table II summarizes the mean width and thickness measurements taken for each sample in Lab 4b. The mean area is simply the product of the width and thickness. The initial length measurements of the fishing line are recorded in the last column of Table II. The extension rate and material of each sample is provided in Table III.

TABLE II
LAB 4B SPECIMEN GEOMETRY DATA

Sample	Mean Width [m]	Mean Thickness [m]	Mean Area [m^2]	Initial Length, L_{0b} [mm]
1	0.026	.001623	4.138E-5	106
2	.0255	.001702	4.345E-5	118
3	.0253	.001625	4.108E-5	115
4	.0254	.001702	4.334E-5	135
5	.0154	.000787	1.216E-5	106
6	.0157	.001181	1.852E-5	101

TABLE III
LAB 4B SPECIMEN MATERIALS AND EXTENSION RATES

Sample	*Material*	*Extension Rate (mm/min)*
1	Nylon 6-6	5
2	UHMWPe	5
3	Nylon 6-6	100
4	UHMWPe	100
5	Nylon 6-6	5
6	UHMWPe	5 (3 min), 100 (2 min)

The length between the two sharpie marks on each sample was measured immediately after being loaded by the UTS. This length is represented in Table IV in the first row of data (time=0 minutes). Subsequent measurements were taken every two minutes to obtain relaxation data.

TABLE IV
LAB 4B STRAIN RELAXATION OF SAMPLES 1 AND 2

	Nylon 6-6	***UHMWPe***
Time (min)	*Length (in)*	*Length (in)*
0	4.409	4.877
2	4.396	4.807
4	4.355	4.796
6	4.346	4.735
8	4.336	4.734
10	4.336	4.734
12	4.336	4.734

The stress-strain response of each specimen and the stress relaxation of each material are graphed in Figs. 5-12. The stress-strain responses of all of the Nylon samples are listed first, followed by the stress-strain responses of the UHMWPe samples.

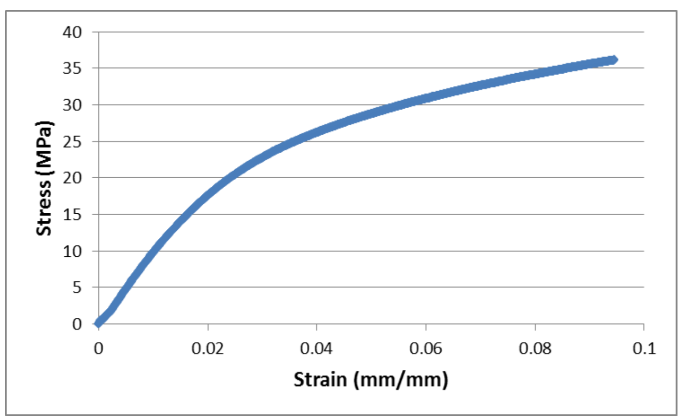

Figure 5 Stress vs. Strain Nylon 6-6 at 5 mm/min extension rate

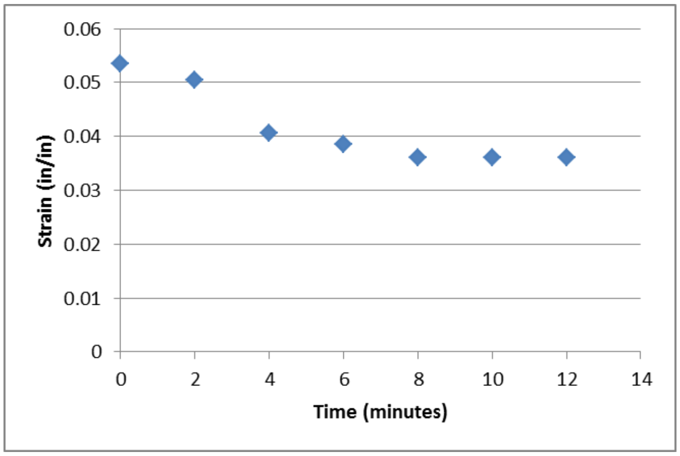

Figure 6 Strain Relaxation of Nylon 6-6 at 5 mm/min extension rate

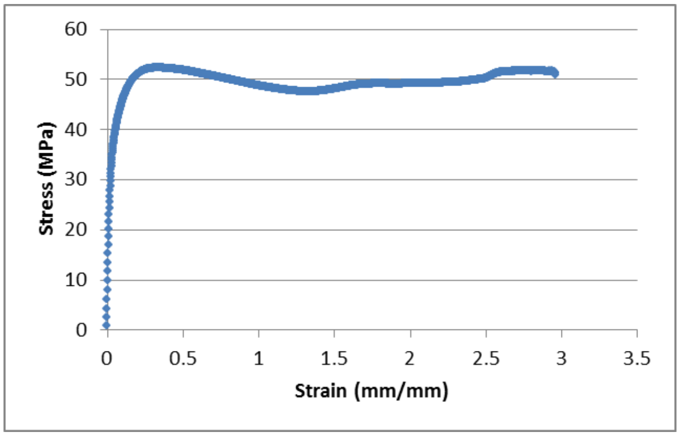

Figure 7 Stress vs. Strain of Nylon 6-6 at 100 mm/min extension rate

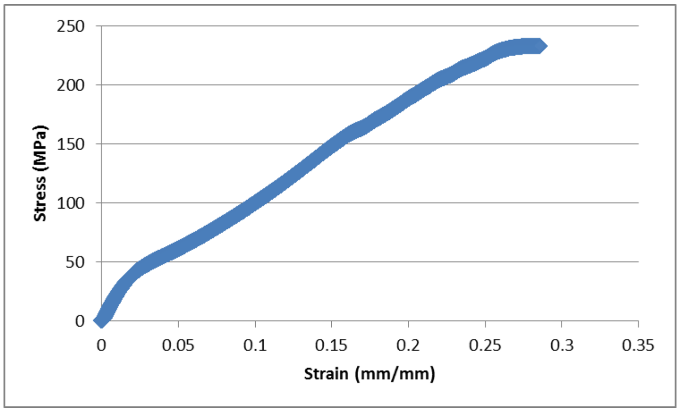

Figure 8 Stress vs. Strain of drawn Nylon 6-6 at 5 mm/min extension rate

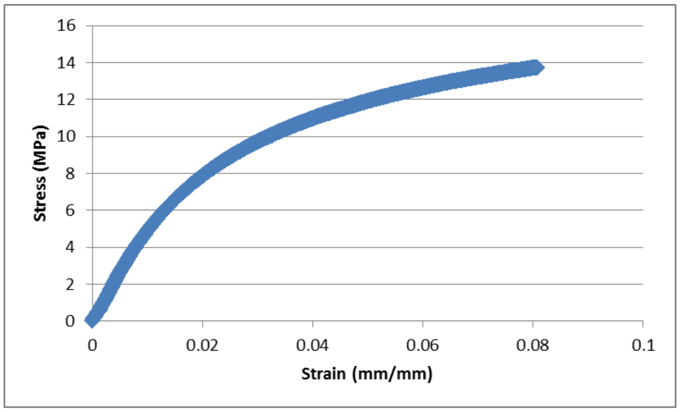

Figure 9 Stress vs. Strain of UHMWPe at 5 mm/min extension rate

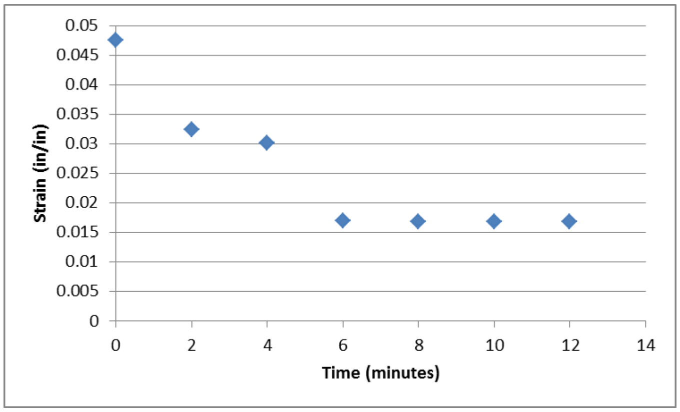

Figure 10 Strain Relaxation of UHMWPe at 5mm/min extension rate

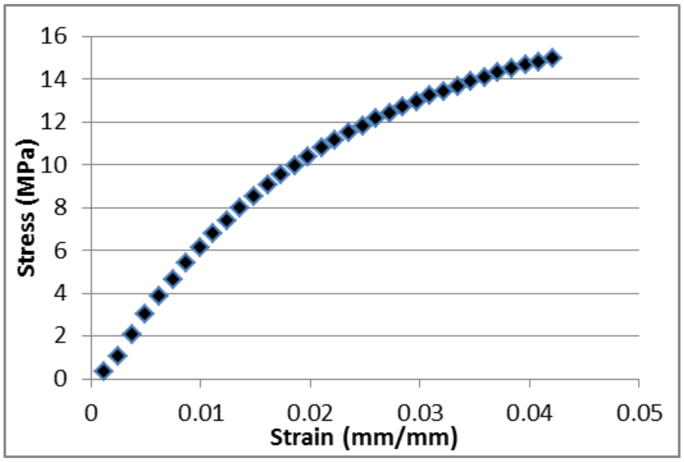

Figure 11 Stress vs. Strain of UHMWPe at 100 mm/min extension rate

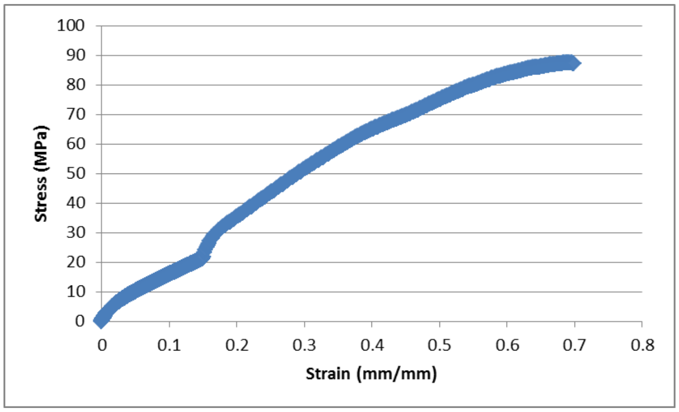

Figure 12 Stress vs. Strain of drawn UHMWPe strained at a rate of 5 mm/min for the first 3 minutes and 100 mm/min for the remaining time.

IV. Discussion

The variables used to calculate stress and strain in Lab 4a are defined below along with their corresponding equations.

V=Voltage [V]
V_t=Tare Voltage [V]
dL=Elongation [mm]
L_0=Initial Length of the wire [mm]
k=calibration constant=491.13 [mV/mm]
F=Force [N]
m=mass [g]
g=gravitational constant=9.81 [m/s^2]
ε=strain [mm/mm]
σ=stress [Pa]
d=diameter of fishing line [m]

$$dL = \frac{(V_t - V)}{k} = \frac{\Delta V}{k} \quad (1)$$

$$\varepsilon = \frac{dL}{L_0} \quad (2)$$

$$F = m \times g \quad (3)$$

$$\sigma = \frac{F}{A} = \frac{4F}{\pi d^2} \quad (4)$$

The uncertainties in the measuring devices used in Lab 4a are listed below, where $U_{\Delta V}$ is the uncertainty in the voltage measured by the DAQ and U_{L_0} is the uncertainty in the ruler. The uncertainty in the calibration constant, U_k, was provided to us by the lab instructor. These uncertainties can be substituted into (5) to get the uncertainty in the percent strain.

$$U_{\Delta V} = \pm .001\ V \quad U_k = \pm 1.0\ \frac{mV}{mm} \quad U_{L_0} = \pm .0005\ m$$

$$U_{\%\varepsilon} = [\left(\frac{\partial \varepsilon}{\partial \Delta V}\right)^2 U_{\Delta V}{}^2 + \left(\frac{\partial \varepsilon}{\partial L_0}\right)^2 U_{L_0}{}^2 + \left(\frac{\partial \varepsilon}{\partial k}\right)^2 U_k{}^2]^{\frac{1}{2}} \times 100 \quad (5)$$

The uncertainties in percent strain at the point of maximum strain for both the 400g trial and 700g trial are shown in Table III along with the values used in the uncertainty equation at maximum strain.

TABLE V
LAB 4A UNCERTAINTY IN % STRAIN AT MAXIMUM STRAIN

Load [g]	ε_{max}[in/in]	V [V]	ΔV [V]	$U_{\%\varepsilon}$[%]
400	.0732	2.342	2.588	.053
700	.1145	1.203	3.767	.0886

Figures (3) and (4) are plots of the log (%ε) vs. log (t) during the secondary creep phase of each trial. The slope of each graph, *m*, was found by inserting a linear fit through the points and having Excel calculate the slope of this fit line. The uncertainty in the slope was found by using the Monte Carlo simulation which required the input of four representative points during the secondary creep phase and their corresponding uncertainties. Figure 13 shows the output graph of the Monte Carlo simulation for the 700 g load. Equations (6) and (7) were used to find the uncertainty in the log (%ε) and log (t) input values for the Monte Carlo simulation.

$$u(\log(\%\varepsilon)) = \log(\%\varepsilon + u(\%\varepsilon)) - \log(\%\varepsilon) \quad (6)$$

$$u(\log(t)) = \log(t + u(t)) - \log(t) \quad (7)$$

Where u(%ε) is the uncertainty in the percent strain found in Table V and u(t) in the uncertainty in the time which was found by taking 1% of the smallest measurable time. A millisecond was the smallest time that was able to be measured so u(t) was 1E-5 seconds. The slopes and uncertainties are summarized in Table IV.

TABLE VI
SLOPE OF LOG (%STRAIN) VS. LOG (TIME) AND THEIR MONTE CARLO UNCERTAINTIES

Mass [g]	Calculated slope, *m*	Monte Carlo avg. slope	Uncertainty, *U(m)*
400	.035	.0369	±.0047
700	.0259	.0236	±.0059

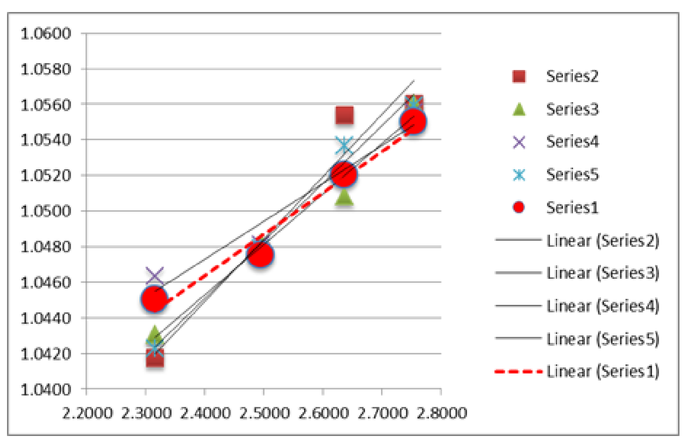

Figure 13 Monte Carlo uncertainty of the slope, m, during the secondary creep phase of the 700 g trial

The slope values in Table VI are representative of the rate of creep during the secondary creep phase. There are no units on these values since they are logarithmic values. When the fishing line was loaded with 400g, the slope was greater than when the 700g load was applied. This suggests that as the load applied increases, the secondary phase creep rate decreases. It's important to note, however, that by observing Figs. 1 and 2 one can see that the strain rate was greater during the elastic strain phase with the 700g load and the rate of primary creep was also greater with the 700g load.

Temperature also plays a role on the rate of creep. In general, increasing temperature leads to increasing creep rates. Room temperature was maintained throughout the duration of this experiment so we will infer that no major differences in creep rate were due to temperature.

The amount of recovered creep strain after the load was removed can be found in Figs. 1 and 2 by locating the initial strain value during the creep relaxation phase, and by locating the strain value where the creep relaxation curve plateaus. The recovered creep strain is the difference between these two values. As shown in Table VII, the percent of recovered creep strain increases as the load increases.

TABLE VII
RECOVERED CREEP STRAIN % AFTER LOAD WAS REMOVED

Load [g]	Recovered Creep Strain (%)
400	.53
700	.72

In Lab 4b, the stress-strain responses of each specimen were plotted as well as the strain relaxation of the first two samples (Figs. 5-12). The percent strain used in these graphs was found by (8) using the initial length of each specimen, L_{0b}, found in Table II as well as the displacement output by the UTS, L_{UTS}.

$$\%\varepsilon = \frac{L_{UTS}}{L_{0b}} \times 100 \tag{8}$$

Force values were obtained from the load cell of the UTS and were used in conjunction with the area of the specimens (Table II) to calculate stress (9).

$$\sigma = \frac{F}{A} \tag{9}$$

The modulus of elasticity, E, of each specimen was found by taking the average slope of the elastic region of the stress-strain diagram for each specimen. The 0.2% offset yield point was found by making a line offset by 0.2% on the x-axis of the stress-strain diagram with a slope equal to the modulus of elasticity of the material. The stress value where this line intersected the stress-stress diagram was recorded as the 0.2% offset yield strength. The ultimate strength was found on the stress-strain diagrams by locating the highest strength that was reached. The breaking strength was located on the stress-strain diagrams as the final stress that the specimen underwent before breaking. Only one specimen in this experiment broke so we were unable to find accurate ultimate strength and breaking strength values for the other five specimens. The percent elongation was found two different ways. The first way was by taking the final strain reading, ε_f, and multiplying it by 100 (10). The second way was by using the initial length of each specimen, L_{0b}, listed in Table II, and the final length, L_f, measured between the sharpie marks immediately after the sample was removed from the grips (11). L_f can be found in Table IV by the length measurement at zero minutes.

$$\%\,\Delta L_{\varepsilon} = \varepsilon_f \times 100 \tag{10}$$

$$\%\Delta L_{sharpie} = \frac{L_f - L_{0b}}{L_{0b}} \times 100 \tag{11}$$

The toughness (12) was found by calculating the area underneath the stress-strain diagram.

$$\sum_i^n \frac{(\sigma_i + \sigma_{i+1})}{2} \times (\varepsilon_i + \varepsilon_{i+1}) \tag{12}$$

A summary of these findings is shown in Table VIII. Tables II and III in the results section list what material each sample was and the extension rate that was applied to them. The material properties found in Table VIII indicate that increasing the strain rate will increase the modulus of elasticity, the 0.2% offset yield strength, the % elongation, and the toughness of both Nylon 6-6 and UHMWPe. Since our samples of Nylon and UHMWPe did not break at 5mm/min we cannot draw any conclusions about their breaking strength and ultimate strength. We can, however, examine their stress strain diagrams in Figs. 5 and 9 and estimate whether or not these values increased with increasing strain rate. The curve in Fig. 5 appears to be approaching 40 MPa and its slope is decreasing so with our knowledge of stress-strain diagrams we can make an educated guess that the sample may have reached about 40 MPa before breaking. Nylon strained at 100 mm/min had an ultimate strength of 52.3 MPa. By analyzing the behavior of these graphs we hypothesize that the ultimate strength would not have reached this value and therefore would have a smaller ultimate strength than the 100 mm/min sample. The UHMWPe performed similarly so the same hypotheses can be applied to this material.

When comparing sample 1 to sample 5, all of the material properties we found for the drawn Nylon 6-6 were greater in value when compared to those found for the "as supplied" Nylon 6-6 at 5 mm/min. When the UHMWPe drawn sample was loaded in the Instron, there was a 5 mm/min strain rate applied initially and then the strain rate was increased to 100 mm/min after 3 minutes. This change in strain rate made it harder to compare the drawn UHMW to one of the "as supplied" samples of the UHMWPe.

When comparing sample 6 to sample 2 (5 mm/min), the only material property of the UHMW that decreased in the drawn sample was the 0.2% offset yield strength. However, when comparing sample 4 (100 mm/min) with sample 6, the drawn sample has a higher estimated ultimate strength and a lower modulus of elasticity, lower yield point, and lower percent elongation. It makes more physical sense to compare sample 6 to sample 4 because the results suggest that the drawn UHMWPe behaves more like a brittle material while the "as supplied" UHMWPe behaves like a ductile material. This is due to changes in the molecular structure of the material. The "as supplied" material has non-crystalline structure at the molecular level and as a load is applied to it, the bonds become aligned form crystalline structure which results in strain hardening. The aforementioned variations in material properties can also be seen by examination of the stress-strain diagrams of the respective materials. The drawn materials have a curve that is almost linear throughout the entire load until failure. In contrast, the "as supplied" materials have curves with a more distinct linear elastic region followed by an inelastic strain hardening region.

TABLE VIII
MATERIAL PROPERTIES OF SAMPLES TESTED IN LAB 4B

Sample	*Modulus of Elasticity [GPa]*	*0.2% Offset Yield Strength [MPa]*	*Ultimate Strength [MPa]*	*Breaking Strength [MPa]*
1	1	16	*-	*-
2	0.53	5.83	*-	*-
3	1.3	23.3	52.3	51.3
4	0.7	7.7	*-	*-
5	2.5	27.5	*-	*-
6	0.6	2.7	**-	**-
Sample	% ΔL_{ε} [%]	%$\Delta L_{sharpie}$ [%]	*Toughness* $[MPa \times \sqrt{m}]$	
1	9.5	5.35	2.4	
2	8.1	4.75	0.8	
3	30.0	***-	145.3	
4	340.4	***-	78.3	
5	28.6	***-	38.9	
6	70.0	***-	37.2	

*Specimens did not break so breaking stress and ultimate stress were not found
**The specimen slipped out of the grips before breaking
***Sharpie marks were not measured

Equation (13) was used to propagate the uncertainty for the strain in Lab 4b. The uncertainty of the calipers is represented as U_{L0b} and the accuracy of the Instron position measurement device is represented as U_L. According to Instron[3], the accuracy of the position measurement is either ±0.01 mm or 0.05% of the displacement (whichever is greater). This means that once the displacement measurement is over 20 mm, the uncertainty increases with increasing displacement. In this case there was a broad range of maximum extension values so the uncertainty in strain was found for each sample at the point of maximum strain. A summary of the uncertainties in stress and strain is provided in Table IX.

$$U_{\varepsilon} = ((\frac{\partial \varepsilon}{\partial L_{0b}})^2 U_{L0b}{}^2 + (\frac{\partial \varepsilon}{\partial L_{UTS}})^2 U_{L_{UTS}}{}^2)^{\frac{1}{2}} \quad (13)$$

Equations (14) and (15) solve for the propagation of uncertainty for the stress in Lab4b. The uncertainty in the load, U_{LC}, is the load cell precision of the Instron which is given by the manufacturer.[3] The uncertainty in the area is due to the uncertainty in the micrometer and calipers used to measure the thickness and width of the samples. The uncertainty in stress was calculated using the data point of maximum force.

$$U_{LC} = \pm 0.5\% \; of \; reading$$
$$U_t = \pm 5 \times 10^{-7} \; m$$
$$U_w = \pm .00005 \; m$$
$$U_A = [\left(\frac{\partial A}{\partial w}\right)^2 U_w{}^2 + \left(\frac{\partial A}{\partial t}\right)^2 U_t{}^2]^{\frac{1}{2}} \quad (14)$$

$$U_{\sigma} = [\left(\frac{\partial \sigma}{\partial F}\right)^2 U_{LC}{}^2 + \left(\frac{\partial \sigma}{\partial A}\right)^2 U_A{}^2]^{\frac{1}{2}} \quad (15)$$

TABLE IX
PROPAGATED UNCERTAINTIES IN STRESS AND STRAIN FOR SAMPLES 1-6 OF LAB 4B

Sample	U_{ε}*	U_{σ} [MPa]**
1	±0.00009	±1.1
2	±0.00008	±0.4
3	±0.00150	±1.6
4	±0.00170	±0.8
5	±0.00014	±14.8
6	±0.00035	±3.7

*Propagated at point of maximum extension
**Propagated at point of maximum force

V. CONCLUSION

From the experiment conducted in Lab 4a we were able to identify the stages of creep in a polymeric fishing line. We also concluded that as the load is increased on the fishing line, the voltage read by the LVDT increases and consequently the uncertainty in the strain increases. In Lab 4b we were able to use the stress-strain response diagrams of Nylon 6-6 and UHMWPe to derive their material properties. We concluded that with increasing strain rates, the material properties of both Nylon 6-6 and UHMWPe increased. We also concluded that a drawn sample of Nylon 6-6 had material properties greater in value than an "as supplied" sample of Nylon 6-6 strained at 5 mm/min. The drawn UHMW exhibited brittle behavior while it's "as supplied" counterpart exhibited ductile behavior.

REFERENCES

[1] J.K. Author, "Lab 4A Creep Behavior in Polymeric Line," EML3301C – Mechanics of Material Laboratory-Fall 2013, unpublished.
[2] J.K. Author, "Lab 4B Strain Rate-Dependent Behavior of Bulk Polymers and Strain Relaxation," EML3301C –Mechanics of Material Laboratory-Fall 2013, unpublished.
[3] "5960 Dual Column Tabletop Universal Testing Systems," Instron. <http://www.instron.us/wa/product/details.aspx?PageID=652> J.K.