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Evaluating Rubber Aging on Tire Durability: Quantitative Evaluation of Rubber Aging

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Evaluating Rubber Aging on Tire Durability: Quantitative Evaluation of Rubber Aging

I affirm that this report represents work performed by me and I assume full responsibility for originality, comprehension, and accuracy of all aspects of the report.

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Executive Summary

Rubber is considered one of the most important polymers in the world due to its variety of uses for industries such as automotive, clothing and adhesives. There are many different conditions that can affect the useful life of rubber including oxygen, humidity, temperature and mechanical load. The goal of this project is to test samples of rubber that have been provided by Ford Motor Company by varying the length of testing as well as the temperature that the samples are tested to see the tire durability. While there has been research conducted on the aging of rubber by a variety of universities, there has been little research into how the length of time and temperature of testing can affect the mechanical loading on the rubber.

For testing that was conducted in Dr. Zhu's lab, the eXpert ADMET Mechanical Testing System was used to accelerate the aging of the rubber sample. This is due to the slow aging rate of rubber in a natural environment which can result in a slow degradation for the rubber sample. The eXpert ADMET Mechanical Testing System allowed the testing to be conducted where the amount of time could be varied for each rubber sample. The first step was to cut the samples to the specified dimensions 25mm x 5mm x 2mm. Once the samples were cut and prepared, the sample was placed into the testing system and run for a specified amount of time including 2 hours, 5 hours, 10 hours, 15 hours, 20 hours and 40 hours. The testing was then ran for the specified time using cyclic motion where each hour of testing equated to 300 cycles. The sample was pulled at a constant rate for each sample regardless of length of testing to keep a consistent speed. After testing was completed at room temperature, the temperature was adjusted to see how the temperature may affect the rubber samples. A special chamber was created so that heat guns could accurately specify a certain temperature during testing with minimal fluctuation. The temperatures that were experimented included room temperature, 30°C, 40°C, 50°C, 60°C and

70°C. For the 40 hour testing, the eXpert ADMET Mechanical Testing System was not adequate as the machine was not set up to handle such extensive testing. As a result, graduate students Yifan Li and Xufeng Guo created a new setup which included a temperature chamber with a program that collected the data needed for the study. Once the new setup was in place, the rubber samples could be tested for an extended period of time such as 40 hours.

The results from the mechanical performance data showed that while cycling stress occurred, the higher temperature and longer period of time resulted in a lower normalized stress on the rubber sample. Normalized stress is considered the stress of the aged rubber sample at 100% elongation divided by the stress of the unaged rubber sample at 100% elongation. Therefore, a higher normalized stress value is desired. From the data collected for one time period at the different temperatures, the testing showed that a higher temperature resulted in more elongation in the rubber and thus a higher amount of stress measured in MPa which would result in a decrease in the tire durability. From the data collected at one temperature for the various times tested, the testing showed that a longer time period resulted in a larger amount of elongation and thus a decrease in the tire durability. As a result, more stress was put on a sample for forty hours than a sample tested for only two hours.

Throughout the time working in the lab there were many career skills that were gained from this project. Before working in the lab, I had not experienced research and development. Throughout working in the lab, I was able to gain experience working with the eXpert ADMET Mechanical Testing System and how the system can be used to collect data for the samples tested. In addition, I learned more details about the stress strain curves that were produced from the samples and how they can be beneficial when looking at the data. The results that were found can be beneficial to society because this could possibly allow in the future for the rubber compounds to be created to have a longer useful life. For future work, more in depth analysis can be completed for how the mechanical loading can affect the rubber samples. In addition, a variety of rubber samples could be tested as only one type of rubber was experimented on during the research. Finally, the data and information that was collected for the honors project was sent to Yifan Li where more in depth data analysis occurred to create a model for the mechanical loading on different rubber aging conditions.

From the honors project that was conducted on evaluating the rubber aging on tire durability, many lessons were learned including using various machines in the laboratory including the eXpert ADMET Mechanical Testing System. From the data that was collected, I was able to learn more about rubber aging using the stress strain curves that were produced, and how they can relate to the rubber samples tested at different temperatures and with various times. For other students that may work on these types of projects in the future, it is important to learn as much as you can from the graduate students working in the laboratory, as most undergraduate students do not get the experience that was gained from working on my honors project.

Introduction/ Background

Rubber is considered to be one of the most useful polymers in the world as it can be used for a variety of applications in various industries including aerospace, chemical, and automobiles. While each industry will have various factors affecting the rubber based off of the application being used, aging is a universal factor that affects the rubber quality and useful lifetime of the product. Different factors that affect the aging of rubber can include the rubber exposure to ozone, mechanical force, heat and amount of oxygen.[1,2] When the rubber is exposed to the varying factors, the structure of the rubber will be altered and as a result the performance of the rubber will decrease. An example of this is the performance of an automobile tire. When new, the tread and performance is considered to be at its peak. However, after being used on the road and enduring factors such as mechanical loading and oxygen, the tread on the tire decreases and the performance of the tire has been shortened.

Many factors have been considered and studied for the degradation of rubber including research into how rubber is affected by oxygen, heat, and humidity. There are many individuals that have researched how the aging of rubber can be affected by factors such as heat, oxygen, ozone, and light radiation. Some of the individuals include R. Behnke,[3] C. Naumann,[4] J. Budzien,[5] and M. Gigliotti.[6] Examples of these studies include the research by Behnke where the thermal properties of rubber were researched,[3] and Naumann who created a thermo-oxidative model for rubber by looking at diffusion reaction kinetics.[4] While many properties of rubber have been researched in hopes of increasing the useful life of rubber, mechanical force has not been researched in depth. This project focuses on how mechanical force can affect the useful life of rubber by varying the temperature on the rubber sample.

For this research, the Ford Motor Company provided samples of styrene butadiene rubber that were used in experimentation. The mechanical force and properties were compared both before and after testing. The testing was completed by creating a chamber in where the cycling time and temperature could be adjusted. The cycling times were adjusted due to rubber aging at a relatively slow rate under normal environmental conditions. As a result, the testing chamber allowed for accelerated testing to be completed to better find how mechanical force affects rubber.

Experimental Methods

The testing that was completed in the lab used styrene butadiene rubber sheets that were supplied by the Ford Motor Company. The sheets that were given were larger than what was needed for each test, so the first step was to cut the samples into a size of 25mm by 5 mm by 2mm. **Figure 1** below shows a sample of the rubber that was used for both the dynamic aging tests and for the performance based tests as well as the sheets that were supplied by Ford.

Figure 1 shows a rubber sample that was used during the dynamic aging test and the performance based tests and the sheet that was supplied by Ford.

There were two main tests that were conducted by using the eXpert ADMET Mechanical Testing System. The first test that was done was the dynamic aging test where the rubber sample was placed into the machine and cyclic stress was applied for several different sets of times. The schematic for the testing completed can be seen in **Figure 2.**

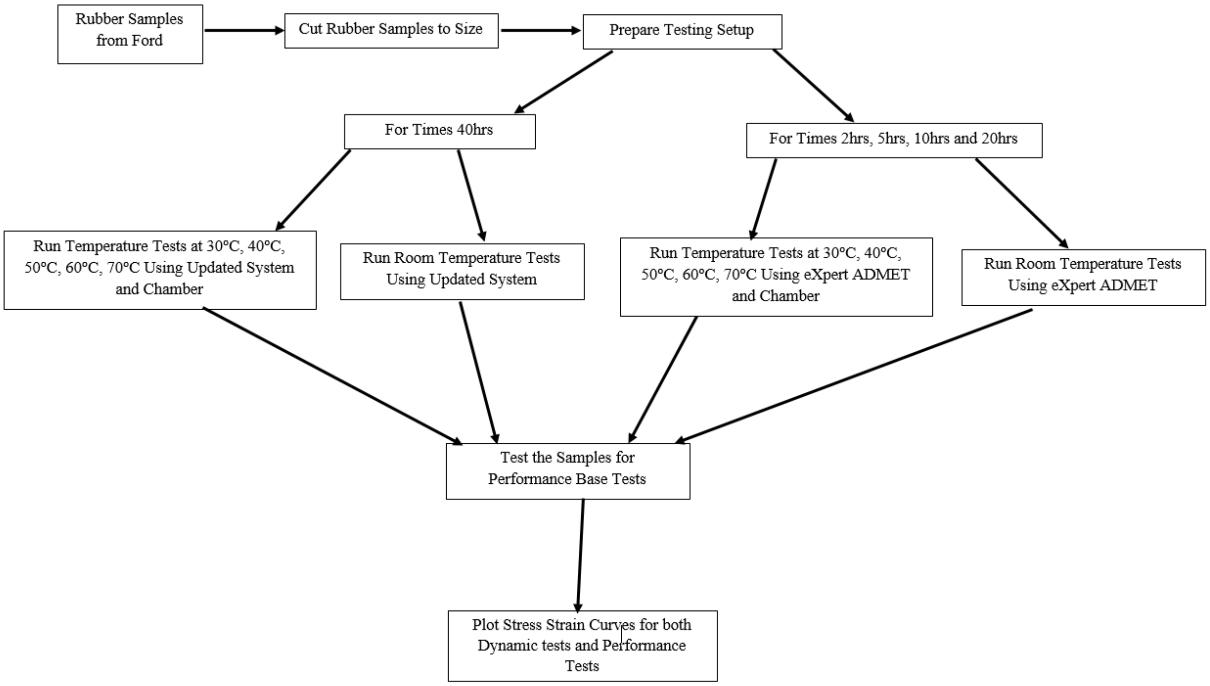

Figure 2 shows the schematic for the testing that was completed during the study.

The amount of time was varied which included times of 2 hours, 5 hours, 10 hours, 15 hours, 20 hours and 40 hours. In addition to varying the amount of time for cyclic stress on the rubber sample, the temperature was also adjusted. For room temperature, no adjustment was needed to be made at the various times. However, when testing the samples at different temperatures including 30°C, 40°C, 50°C, 60°C, and 70°C, an environmental chamber was created to ensure that the temperature was constant. **Figure 3** below shows the eXpert ADMET Mechanical Testing System without the heating chamber and **Figure 4** below shows the heating chamber that was used with the eXpert ADMET Mechanical Testing System to monitor the temperature during testing.

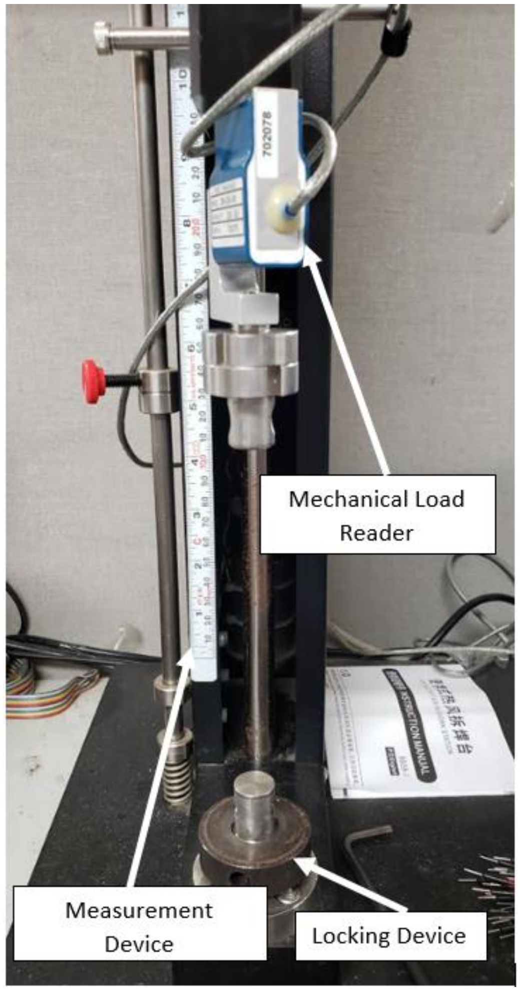

Figure 3 shows the eXpert ADMET Mechanical Testing System without the heating chamber attached to the system.

Figure 4 shows the heating chamber that was created for the eXpert ADMET Mechanical Testing System. The system allowed the temperature to be monitored and maintained during testing.

It was important that the environmental chamber had no leaks that could result in an inaccurate reading of the temperature. As a result, the chamber was created using polycarbonate and an insulating material surrounding the outside of the chamber. For the heating element, two heat guns were used which allowed the temperature to be set and maintained for the duration of the test. The temperature guns had a temperature sensor attached to them so that the inside temperature in the chamber would remain constant throughout the duration of the test.

For the dynamic aging test, there were a variety of conditions that needed to be met and verified before starting the test. The first condition was making sure that the rubber sample was cut to the appropriate measurements. To verify that the rubber sample was correct, calipers were used and an average width and thickness was measured in millimeters. The samples were cut to have dimensions of 5mm by 2mm by 20 mm. In order to make sure that the samples were consistent from each test, any measurement with more than 5% error was not used. After the rubber sample dimensions were verified, the setup for the test needed to be set. For all dynamic aging tests where cyclic conditions were occurring, the grip separation between the two clamps needed to be 20mm apart before the start of the testing. An example of the grip separation is shown in **Figure 5.**

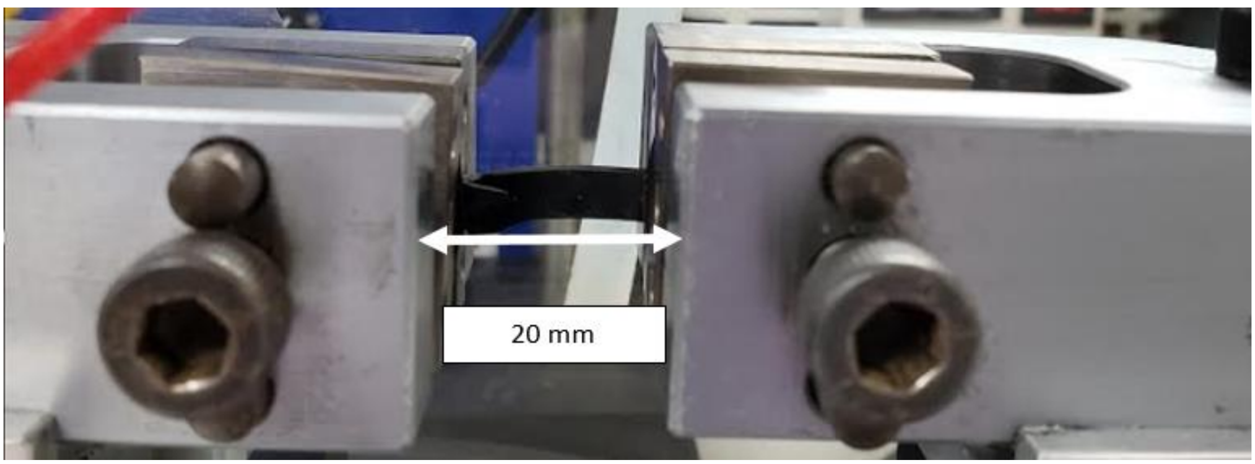

Figure 5 shows the grip separation device that was used in the system. Before the testing was started, the distance between the grip separation device was measured to be 20 mm.

After the rubber sample was verified and the layout of the system was setup, the data was input and verified in the eXpert ADMET Mechanical Testing System. The rubber width, thickness and the grip separation were also recorded. In addition, the stress rate was set to a value of 200 mm/min. Finally, the time was set based on the sample that was being run. After this was in place, the system was started and was allowed to run for the time needed for that sample. A stress strain curve was plotted in the system from the data collected.

The eXpert ADMET Mechanical Testing System was used for the dynamic aging testing while the chamber was used to adjust the temperatures. While the testing system worked well when testing up to 20 hours, the system did not work well exceeding the 20 hour time frame. This was due to the fact that the eXpert ADMET Mechanical Testing System did not plot data for extended periods of time such as the 40 hours that needed to be tested. As a result, a new testing chamber needed to be created for tests that lasted longer than 20 hours. This testing chamber was created by Yifan Li, and a program was also created by Xufeng Guo that allowed the data to be collected. **Figure 6** below shows the testing chamber that was used for any test lasting longer than 20 hours.

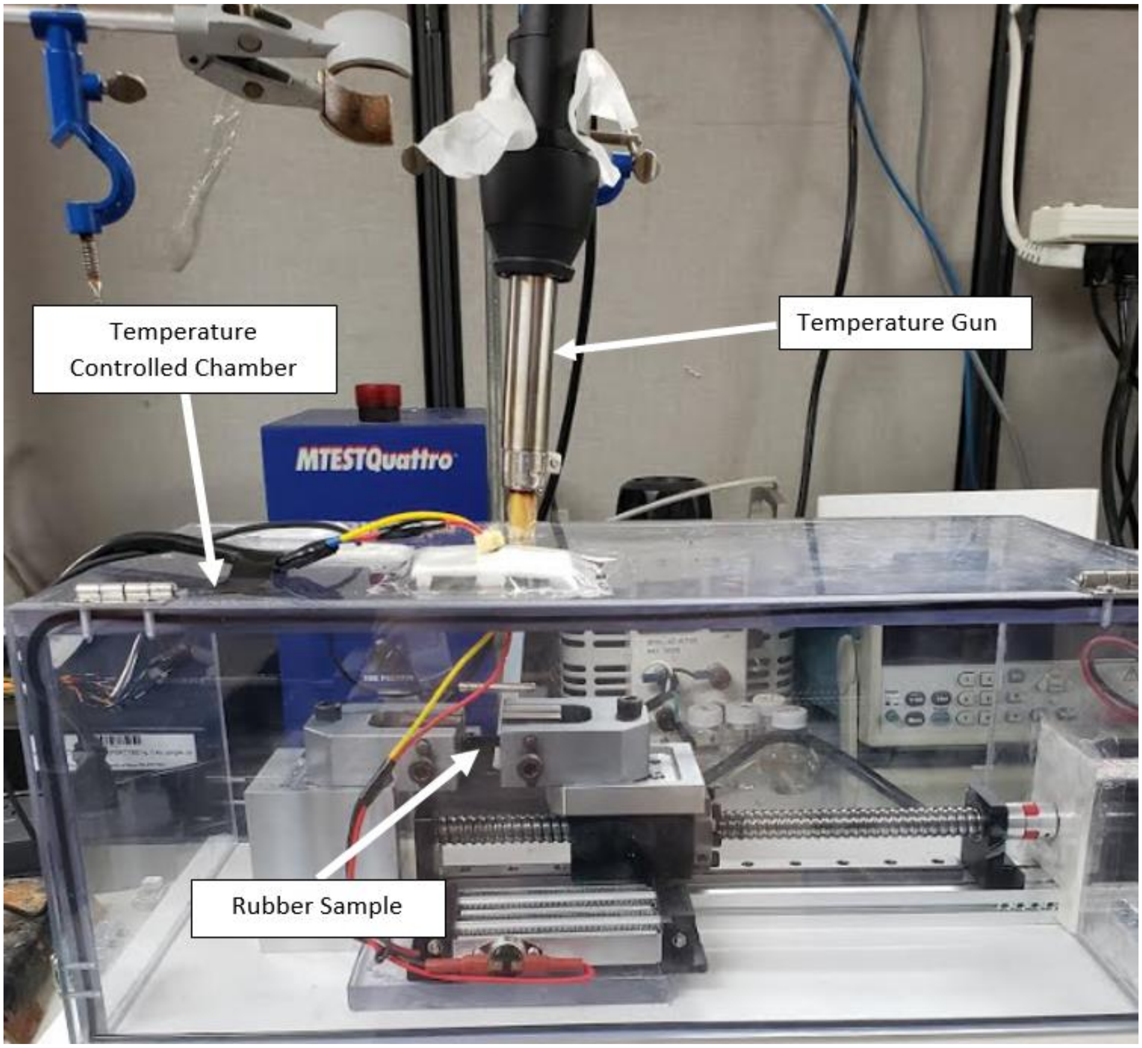

Figure 6 shows the testing chamber that was created for testing that needed to exceed 20 hours. The chamber was created to also monitor the temperature during testing.

As seen in the picture, the testing chamber is enclosed to allow the temperature to be steadily maintained throughout the duration of the test. The same heat guns and grip devices were used to allow for constant measurements and to minimize sources of error.

Finally, after the dynamic aging test was completed using one of the two chambers depending on the time length of the test, the performance based testing then needed to be conducted. It was important to let the sample sit for a few days before testing the performance based testing. This was to ensure that the rubber sample had reached its oxidative state after the extensive testing and would not be affected from the previous testing done on the sample. In the performance based testing, the eXpert ADMET Mechanical Testing System was used again, but different specifications were needed. The main difference between the dynamic aging test and performance based test is that the performance based testing is not cyclic and thus is completed in only a few seconds. As an example, a dynamic based test that was completed at five hours had a total of 1500 cycles during the testing time, with 300 cycles occurring per hour. However, the performance based test was only stretched outward, and thus only half of one cycle occurs for this testing. As compared to the dynamic aging test, the time for the test was not a factor because it could be completed in only a few seconds. A limit position was set at 45mm in the system which allowed the elongation of the rubber to expand by about 200% (assuming the rubber sample was around 20mm in length.) After testing, a single stress strain curve was generated from the data.

Data and Results

After the data was collected by using the eXpert ADMET Mechanical Testing System, the stress strain curve was plotted. A sample of the raw data can be found for the dynamic based testing in **Appendix A** and a sample of the raw data can be found for the performance based testing in **Appendix B**. Over 50 stress strain curves were produced and an example of a stress strain curve for the dynamic aging testing and performance based testing can be seen in **Figure 7** and **Figure 8,** respectively. The dynamic based testing occurred at a variety of lengths of time. It was determined that for each hour of testing conducted, 300 cycles were occurring during that time period. The experiment shown in **Figure 7** had a length of 15 hours and a total of 4,500 cycles during the testing. As a result, it can be seen that the bottom line in the dynamic based testing has error. This is due to the elongation of the rubber sample as the testing continued. When each cycle would be coming down, the length of the rubber sample would slightly increase resulting in a slightly different curve than the last one produced on the graph. This explains the trend for the dynamic aging test shown below and for the other samples that were tested at varied temperatures and times.

Stress Strain Curve: Dynamic Based Testing

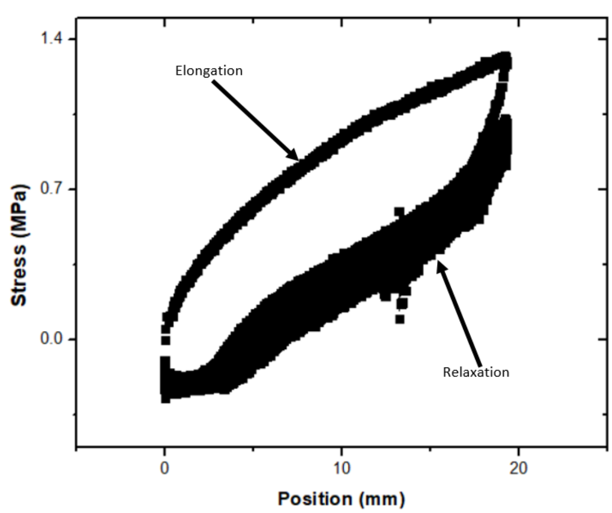

Figure 7 shows an example of a stress strain curve for a rubber sample that was tested at 30°C for 15 hours for dynamic based testing.

Stress Strain Curve: Performance Based Testing

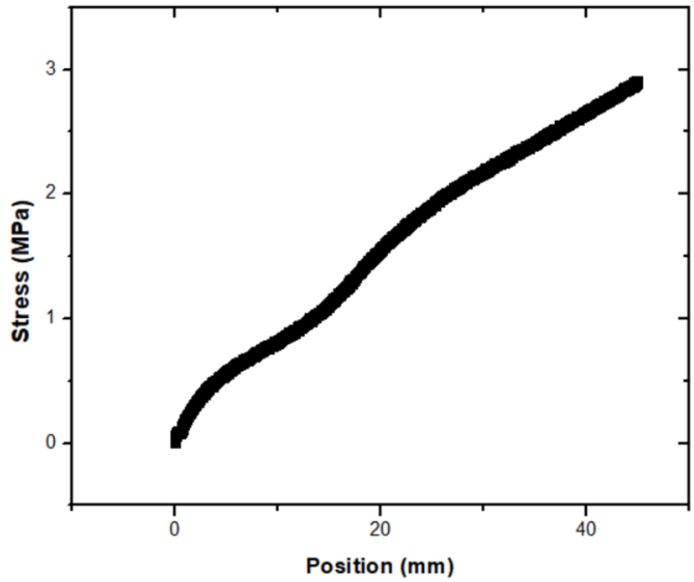

Figure 8 shows a stress strain curve for a rubber sample that was tested at 30°C for 15 hours for performance based testing.

Figure 9 shows the dynamic based testing for 15 hours for the six different temperatures that were tested. From the graph, it can be seen that each temperature has an upper and lower limit. These are connected from using the eXpert ADMET Mechanical Testing System. At the greatest point, the position is maximized and the rubber sample is experiencing the most significant stress. Once the maximum is reached, the rubber sample then returns to its beginning position as seen by the lowest point. The reason for the differences is because of the error that may be involved. For the longer tests, the rubber sample had a larger elongation throughout the duration of the test which resulted in a larger error that can be seen by the 70°C line. The performance based testing was also measured for 15 hours with the same temperature variations as the dynamic based testing. The data shown in **Figure 10** shows that the higher temperature resulted in a larger stress for 200% elongation. Overall, both graphs show that as the temperature is increased for the same duration of the testing, there is more stress on the rubber sample.

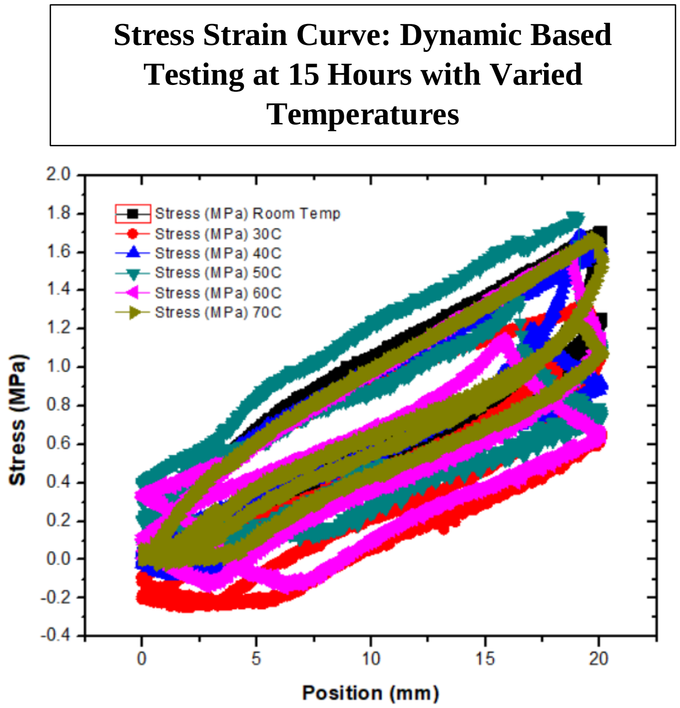

Figure 9 shows the dynamic based testing for 15 hours at the different temperatures testing including room temperature, 30°C, 40°C, 50°C, 60°C, and 70°C.

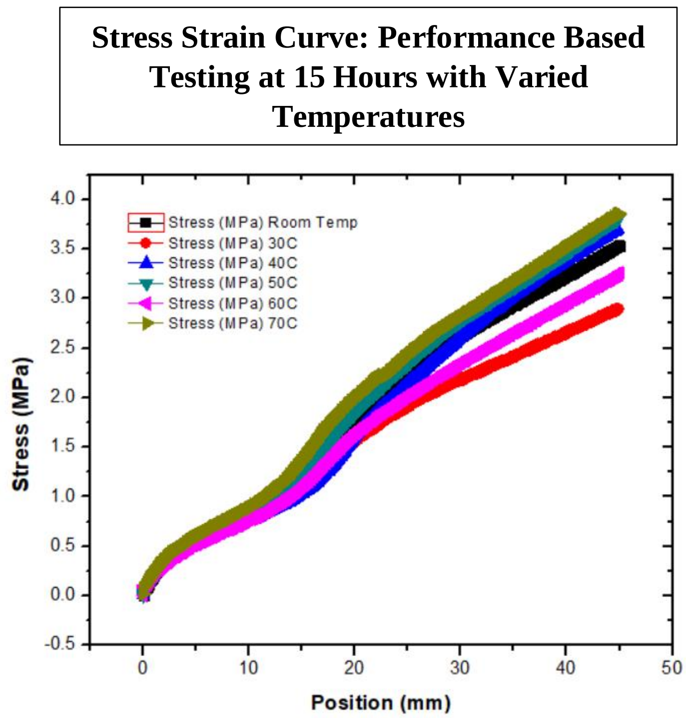

Figure 10 shows the performance based testing for 15 hours at the different temperatures including room temperature, 30°C, 40°C, 50°C, 60°C, and 70°C.

It was also important to look at how the length of the test affected the rubber sample by plotting a stress strain curve for the different times. **Figure 11** shows the testing that was completed for the room temperature testing. It can be seen that while the graphs have an overlay, there is the most significant difference for the 40 hour testing. This can be seen at the position mark of 20mm, where the stress at 1MPa results in a move where the rubber sample started to experience more variation as the time went on for the test. In addition to the dynamic testing for varied times, the performance based testing was also completed at room temperature for the six different time periods as shown in **Figure 12**. This graph shows that during the 2 hours duration, the stress was most significant with a value of over 4MPa. However, as the duration increased to 40 hours, the maximum stress decreased to a value of just under 3MPa. This can be explained due to the fact that the rubber sample at 40 hours has endured a much larger cycle time, and thus the elongation of the sample is much greater than that of the 2 hour test. As a result, the maximum stress for the longer time period will be less because the sample has more aging and the rubber sample cannot handle the maximum amount of stress that the shorter sample can handle. The graph shows that the longer test duration resulted in lower maximum stress for the performance based testing.

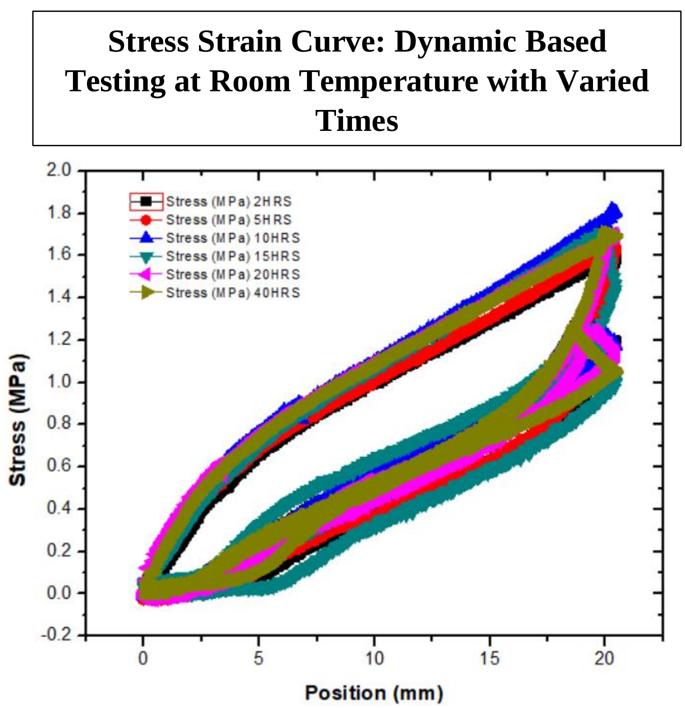

Figure 11 shows the dynamic based testing that was completed at room temperature for the times of 2 hours, 5 hours, 10 hours, 15 hours, 20 hours, and 40 hours.

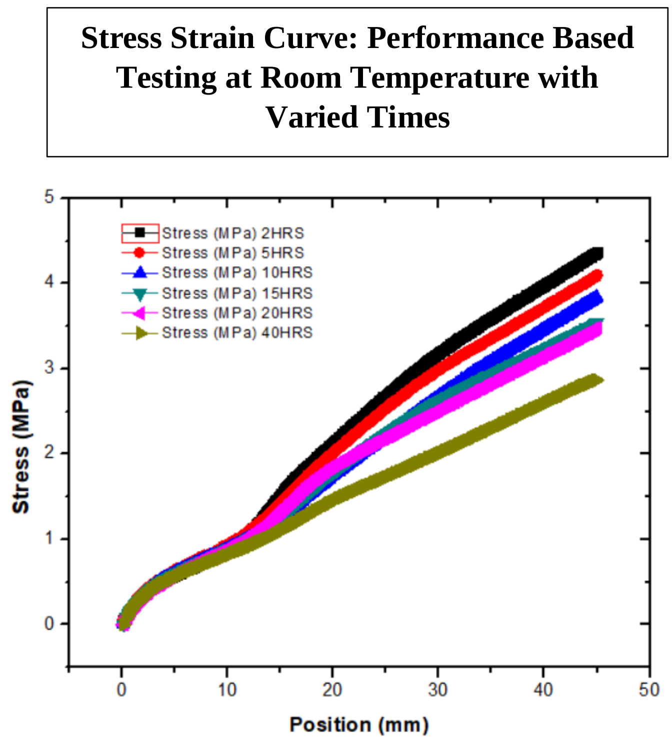

Figure 12 shows the performance based testing that was completed at room temperature for the times of 2 hours, 5 hours, 10 hours, 15 hours, 20 hours, and 40 hours.

From the stress strain data curve, a comparison was made for the rubber that was aged and the mechanical behaviors that occurred for three different systems including (a) static aging without stress; (b) dynamic aging with fixed stress and (c) dynamic aging with cycling stress. The results for the three different tests can be seen in **Figure 13**. Normalized stress is calculated as the stress at an elongation of 100% for the aged rubber divided by the stress at an elongation of 100% for the unaged rubber.

Aging Time vs. Normalized Stress

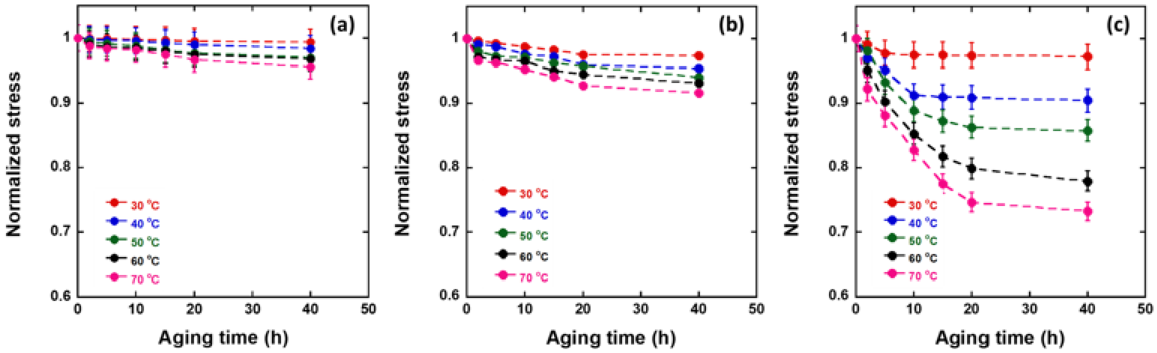

Figure 13 shows the mechanical performance that was measured by normalized stress for (a) static aging without stress, (b) dynamic aging with fixed stress and (c) dynamic aging with cycling stress.[7]

Figure 13 shows that without stress on the rubber, the normalized stress is minimal and there is a very small change regardless of the temperature or aging time that was used. However, when the dynamic aging with fixed stress was tested, there was a lower value for normalized stress. Finally, cycling stress resulted in the lowest normalized stress, where a higher temperature resulted in a lower normalized stress. The lowest normalized stress occurs at 70°C and 40 hours, where the mechanical property for the rubber sample was found to be 73% of the rubber sample before testing. Also observed was that under cycling stress, all temperatures see a significant drop in normalized stress within the first 20 hours which then flattens out during the 40 hour sample test.

Finally, the mechanical performance for the real-time data needed to be compared with that from the recovery of the rubber sample. **Figure 14** shows the data for the real-time comparison with that of the recovery for the rubber sample at the five different temperatures that were tested. These temperatures included (a) 30°C, (b) 40°C, (c) 50°C, (d) 60°C and (e) 70°C.

The recovery tests were conducted after letting the sample sit for 72 hours. For each sample at all five temperatures, there was a significant drop for the normalized stress during the first 10 hours of testing. The normalized stress was calculated by finding the stress elongation of aged rubber at 100% divided by the stress elongation of the unaged rubber at 100%. The real-time sample data that was found indicated that the normalized stress at 30°C was found to be around 0.80 while the normalized stress at 70°C was found to be around 0.65, the lowest of the five experiments.

Aging Time vs. Normalized Stress

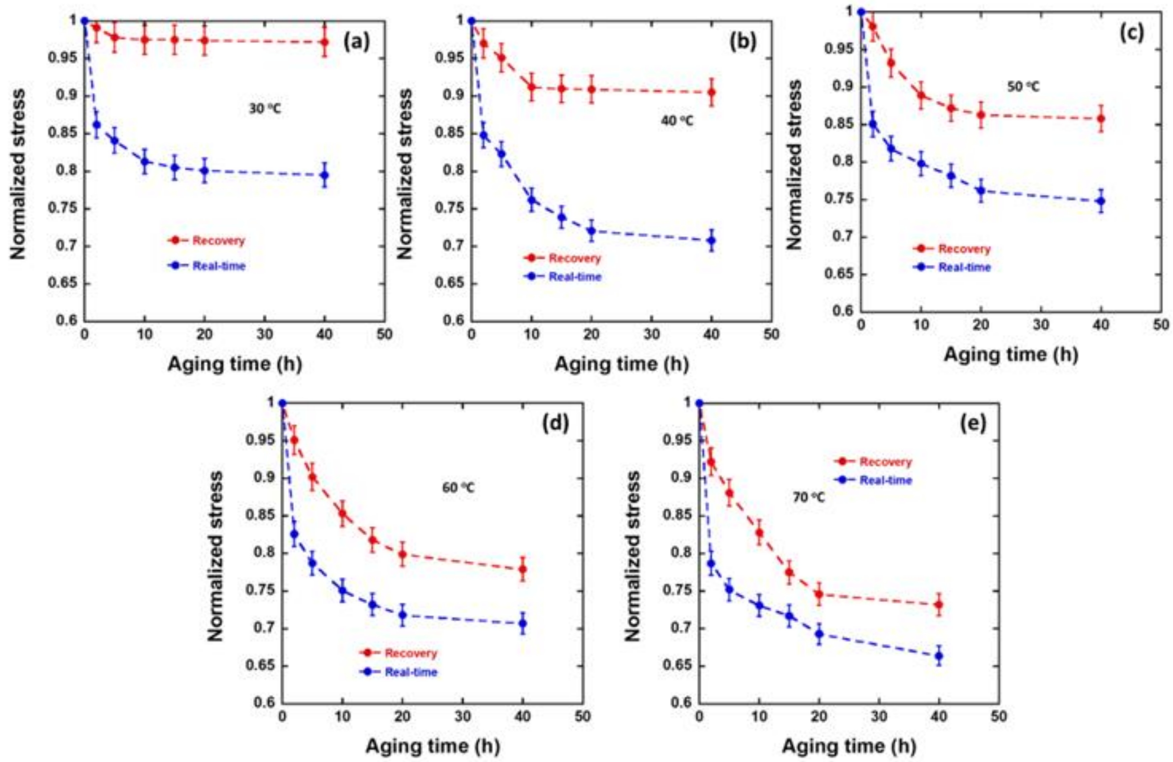

Figure 14 shows the difference in mechanical performance between the real-time and recovery rubber samples under the following temperatures (a) 30°C, (b) 40°C, (c) 50°C, (d) 60°C and (e) 70°C.[7]

Discussion/Analysis

The first data that was collected from the eXpert ADMET Mechanical Testing system was the dynamic based testing. From the system, a stress strain curve was plotted for both the performance based testing as well as the dynamic based testing. The importance of these curves was to verify and make sure that the results collected from the computer system were accurate with no errors. An example of an error that was found during testing was when the rubber sample was torn. As a result, the stress strain curve did not look similar to that shown above, and the sample was discarded and a new sample was retested. After verification of the data collected, the values of normalized stress and peak ratio could then be calculated for each sample tested at the different temperatures and time periods. As shown in **Figure 13**, the normalized stress was found for the samples for static aging without stress, dynamic aging with a fixed stress and dynamic aging with a cycling stress. As expected, there was little difference between the samples for the static aging with no stress. This can be seen in **Figure 13** where the normalized stress at 30°C is 1.0 where the normalized stress at 70°C is 0.96. This shows that there is only a 4% difference between the lowest temperature tested compared to the highest temperature tested. This shows that regardless of the aging time or temperature, a rubber sample with no stress will not degrade quickly. For the dynamic aging with a fixed stress amount, the samples were found to have a lower normalized stress than the static aging showing that the stress caused a faster degrading of the rubber sample. Finally, the dynamic aging with cycling stress showed that there was a significant difference between the temperature and aging time, where the longer time and higher temperature resulted in a lower normalized stress. This can be expected due to the continuous amount of stress that was being put on the sample, so the sample was degrading at a much faster rate than that of the static testing.

In conclusion, the testing conducted showed that the longer time period for cycling stress resulted in a lower normalized stress on the rubber sample. In addition, the higher temperature also resulted in a lower normalized stress. As a result, the lower normalized stress showed that there would be more elongation for the sample which would lead to a decrease in tire durability. When varying the temperatures while keeping the time period constant, the higher temperature showed a higher amount of stress measured in MPa. When varying the time while keeping the temperature constant, the testing found that a longer time period resulted in a larger elongation of the rubber sample which would also lead to a decrease in tire durability. In future research, different types of rubber could be tested which would give a larger amount of data showing how stress and elongation can lead to a decrease in tire durability.

Literature Cited

1. Baldwin, J.M.; Bauer, D.R.; Ellwood, K.R., Rubber aging in tires. Part 1: Field results. *Polymer Degradation and Stability* **2007**, 92 (1), 103-109.

2. Bauer, D.R.; Baldwin, J.M.; Ellwood, K.R., Rubber aging in tires. Part 2: Accelerated oven aging tests. *Polymer Degradation and Stability* **2007**, 92 (1), 110-117.

3. Behnke, R.; Kaliske, M., Numerical modeling of thermal aging in steady state rolling tires. *International Journal of Non-Linear Mechanics* **2018**, 103, 145-153.

4. Naumann, C.; Ihlemann, J., Simulation von oxidativen Alterungsprozessen in Elastomerbauteilen. *Kautschuk Gummi Kunststoffe* **2014**, 10, 68-75.

5. Budzien, J.; Rottach, D.R.; Curro, J.G.; Lo, C.S.; Thompson, A.P., A new constitutive model for the chemical aging of rubber networks in deformed states. *Macromolecules* **2008**, 41 (24), 9896-9903.

6. Gigliotti, M.; Minervino, M.; Lafarie-Frenot, M.; Grandidier, J., Effect of thermos-applications. *Mechanics of Materials* **2016**, 101, 118-135.

7. Li, Y.; Guo, X.; Dong, Y.; Zhu, J., Investigating the thermal-mechanical coupling effect during rubber aging process: a combined experimental and modeling approach. *The University of Akron* **2020**, 1, 1-27.

Appendices

Appendix A: Original Data Sample for Dynamic Aging Testing

	A	B	C	D	E	F	G	H
1	Time (sec)	"Load (N)"	"Position (mm)"	"AxialStrain (mm)"	"TransverseStrain (mm)"	"Auxiliary ()"	"Control Out (V)"	"Stress (MPa)"
2	0	0.01689821	0	NaN	NaN	NaN	0.18128549	0.001817715
3	0.011	0.87870693	0.009471186	NaN	NaN	NaN	3.8558261	0.09452121
4	0.021	0.69282657	0.06898898	NaN	NaN	NaN	3.4590735	0.07452633
5	0.030999999	0.8111141	0.14023812	NaN	NaN	NaN	2.6313863	0.087250344
6	0.041000001	0.7604194	0.20998049	NaN	NaN	NaN	1.8830495	0.0817972
7	0.050999999	1.2504675	0.2656237	NaN	NaN	NaN	1.4203748	0.13451095
8	0.061000001	1.1828747	0.3095356	NaN	NaN	NaN	1.2580113	0.12724008
9	0.071000002	1.2842641	0.34322286	NaN	NaN	NaN	1.2555698	0.13814639
10	0.081	1.3518568	0.37346607	NaN	NaN	NaN	1.3324788	0.14541724
11	0.090999998	1.3011621	0.40209487	NaN	NaN	NaN	1.4496734	0.13996409
12	0.101000004	1.60533	0.43029317	NaN	NaN	NaN	1.5790758	0.17268297
13	0.111000001	1.4532461	0.46258134	NaN	NaN	NaN	1.6315693	0.15632354
14	0.120999999	1.7405157	0.49777538	NaN	NaN	NaN	1.6144785	0.1872247
15	0.130999997	1.689821	0.5324313	NaN	NaN	NaN	1.5778551	0.18177155
16	0.141000003	1.9094977	0.5671949	NaN	NaN	NaN	1.5680889	0.20540184
17	0.150999993	1.5208389	0.6026042	NaN	NaN	NaN	1.5900629	0.1635944
18	0.160999998	2.1122763	0.6363991	NaN	NaN	NaN	1.6071538	0.22721444
19	0.171000004	1.774312	0.66857964	NaN	NaN	NaN	1.6559849	0.19086011
20	0.180999994	2.1798692	0.70248216	NaN	NaN	NaN	1.6681926	0.23448528
21	0.191	1.8081084	0.7389678	NaN	NaN	NaN	1.6144785	0.19449554
22	0.201000005	2.2474618	0.77566856	NaN	NaN	NaN	1.5680889	0.24175616
23	0.210999995	2.1967673	0.81161606	NaN	NaN	NaN	1.5265825	0.23630302
24	0.221000001	2.1798692	0.84584147	NaN	NaN	NaN	1.5241408	0.23448528
25	0.231000006	2.1967673	0.87909824	NaN	NaN	NaN	1.5314655	0.23630302
26	0.240999997	2.3488512	0.91149396	NaN	NaN	NaN	1.5656474	0.25266245
27	0.250999987	2.3488512	0.9436745	NaN	NaN	NaN	1.605933	0.25266245
28	0.261000007	2.7206118	0.9770389	NaN	NaN	NaN	1.6205823	0.29265222
29	0.270999998	2.3657494	1.0127711	NaN	NaN	NaN	1.5815175	0.25448015
30	0.280999988	2.5516298	1.0483958	NaN	NaN	NaN	1.5412318	0.27447504
31	0.291000009	2.7713063	1.0822982	NaN	NaN	NaN	1.5229201	0.29810533
32	0.300999999	2.653019	1.1156626	NaN	NaN	NaN	1.5351279	0.28538132

Figure A1 shows a sample of the data that was collected from the eXpert ADMET Mechanical Testing System. Due to the thousands of data points, all data points are not shown in this appendix. The data can then be used to plot a stress strain curve for the sample of rubber being tested for the dynamic aging testing.

33	0.31099999	2.6361208	1.1479508	NaN	NaN	NaN	1.5717512	0.2835636
34	0.32100001	2.585426	1.178732	NaN	NaN	NaN	1.605933	0.27811044
35	0.331	2.9740849	1.2144643	NaN	NaN	NaN	1.605933	0.31991792
36	0.340999991	2.669917	1.2486897	NaN	NaN	NaN	1.5558811	0.28719905
37	0.351000011	3.0416777	1.2854983	NaN	NaN	NaN	1.5363487	0.3271888
38	0.361000001	2.6192224	1.3202618	NaN	NaN	NaN	1.5192578	0.28174588
39	0.370999992	3.1768634	1.3527652	NaN	NaN	NaN	1.5412318	0.3417305
40	0.381000012	2.9233904	1.3853761	NaN	NaN	NaN	1.5607642	0.31446478
41	0.391000003	3.21066	1.4169109	NaN	NaN	NaN	1.6095953	0.34536594
42	0.400999993	3.0416777	1.4507059	NaN	NaN	NaN	1.6193615	0.3271888
43	0.411000013	3.3458455	1.4849312	NaN	NaN	NaN	1.5729719	0.35990763
44	0.421000004	3.058576	1.520771	NaN	NaN	NaN	1.5326864	0.3290065
45	0.430999994	3.5148277	1.5551041	NaN	NaN	NaN	1.5216993	0.37808484
46	0.441000015	3.0078814	1.58976	NaN	NaN	NaN	1.550998	0.32355335
47	0.451000005	3.4810314	1.6224786	NaN	NaN	NaN	1.5778551	0.3744494
48	0.460999995	3.2444563	1.6537982	NaN	NaN	NaN	1.6291277	0.34900138
49	0.470999986	3.531726	1.6879159	NaN	NaN	NaN	1.6266862	0.3799025
50	0.481000006	3.548624	1.7245092	NaN	NaN	NaN	1.5583227	0.38172022
51	0.490999997	3.3627436	1.7595956	NaN	NaN	NaN	1.5253617	0.3617254
52	0.500999987	3.6331153	1.7933905	NaN	NaN	NaN	1.5216993	0.39080885
53	0.510999978	3.5148277	1.8246024	NaN	NaN	NaN	1.5400109	0.37808484
54	0.521000028	3.785199	1.8566753	NaN	NaN	NaN	1.5766343	0.40716827
55	0.531000018	3.6500134	1.8887482	NaN	NaN	NaN	1.6144785	0.39262655
56	0.541000009	3.7345042	1.9252337	NaN	NaN	NaN	1.6071538	0.4017151
57	0.550999999	3.5655222	1.9619346	NaN	NaN	NaN	1.5448941	0.38353795
58	0.56099999	4.106265	1.9963753	NaN	NaN	NaN	1.5143746	0.44170487
59	0.57099998	3.6331153	2.0298471	NaN	NaN	NaN	1.4899591	0.39080885
60	0.58099997	3.9879775	2.0623507	NaN	NaN	NaN	1.5094916	0.42898086
61	0.591000021	3.68381	2.0941007	NaN	NaN	NaN	1.5436733	0.396262
62	0.601000011	4.3597383	2.1250973	NaN	NaN	NaN	1.5937252	0.46897057
63	0.611000001	3.7345042	2.1571703	NaN	NaN	NaN	1.5998291	0.4017151
64	0.620999992	4.1738577	2.1925795	NaN	NaN	NaN	1.5595434	0.44897574

Figure A2 shows a sample of the data that was collected from the eXpert ADMET Mechanical Testing System. Due to the thousands of data points, all data points are not shown in this appendix. The data can then be used to plot a stress strain curve for the sample of rubber being tested for the dynamic aging testing.

Appendix B: Original Data Sample for Performance Based Testing

	A	B	C	D	E	F	G	H
1	Time (sec)	"Load (N)"	"Position (mm)"	"AxialStrain (mm)"	"TransverseStrain (mm)"	"Auxiliary ()"	"Control Out (V)"	"Stress (MPa)"
2	0	0.30416778	0.009578812	NaN	NaN	NaN	3.890008	0.025650848
3	0.01	0.6759284	0.07124915	NaN	NaN	NaN	6.518342	0.05700189
4	0.02	1.4532461	0.19502032	NaN	NaN	NaN	6.233901	0.12255406
5	0.03	1.2166711	0.33568895	NaN	NaN	NaN	3.993774	0.10260339
6	0.04	1.7405157	0.45311013	NaN	NaN	NaN	2.165049	0.14677987
7	0.05	1.6391264	0.531355	NaN	NaN	NaN	1.1566868	0.13822958
8	0.06	1.774312	0.57515925	NaN	NaN	NaN	0.8698041	0.14962995
9	0.07	1.926396	0.60486436	NaN	NaN	NaN	0.94549227	0.16245538
10	0.08	2.0446835	0.6302644	NaN	NaN	NaN	1.1542453	0.17243072
11	0.09	2.1798692	0.65265083	NaN	NaN	NaN	1.3666606	0.18383108
12	0.1	2.1798692	0.68138725	NaN	NaN	NaN	1.5265825	0.18383108
13	0.11	2.1798692	0.7144287	NaN	NaN	NaN	1.5632057	0.18383108
14	0.12	2.2305639	0.74908465	NaN	NaN	NaN	1.5436733	0.18810622
15	0.13	2.2136655	0.78513974	NaN	NaN	NaN	1.500946	0.18668118
16	0.14	2.416444	0.81925756	NaN	NaN	NaN	1.4936215	0.20378174
17	0.15	2.4671388	0.8524067	NaN	NaN	NaN	1.5107123	0.20805688
18	0.16	2.500935	0.88512534	NaN	NaN	NaN	1.5424526	0.21090698
19	0.17	2.5347316	0.9171982	NaN	NaN	NaN	1.5827382	0.21375707
20	0.18	2.5178335	0.9480872	NaN	NaN	NaN	1.621803	0.21233203
21	0.19	2.6361208	0.9852185	NaN	NaN	NaN	1.605933	0.22230734
22	0.2	2.653019	1.0218118	NaN	NaN	NaN	1.5424526	0.22373238
23	0.21	2.7206118	1.0576515	NaN	NaN	NaN	1.496063	0.2294326
24	0.22	2.7882047	1.0911236	NaN	NaN	NaN	1.4887383	0.23513277
25	0.23	2.8557975	1.1240575	NaN	NaN	NaN	1.5058292	0.24083297
26	0.24	2.889594	1.1562381	NaN	NaN	NaN	1.5448941	0.24368306
27	0.25	2.8726957	1.1885262	NaN	NaN	NaN	1.5876213	0.24225801
28	0.26	2.9233904	1.219738	NaN	NaN	NaN	1.5973876	0.24653316
29	0.27	3.0247796	1.2566541	NaN	NaN	NaN	1.5778551	0.2550834
30	0.28	3.1937616	1.2901262	NaN	NaN	NaN	1.5412318	0.2693339
31	0.29	3.1937616	1.3258584	NaN	NaN	NaN	1.5461149	0.2693339
32	0.3	3.1937616	1.3590075	NaN	NaN	NaN	1.5558811	0.2693339

Figure B1 shows a sample of the data that was collected from the eXpert ADMET Mechanical Testing System. Due to the thousands of data points, all data points are not shown in this appendix. The data can then be used to plot a stress strain curve for the sample of rubber being tested for the performance based testing.

33	0.31	3.2275581	1.3916186	NaN	NaN	NaN	1.5680889	0.272184
34	0.32	3.2782528	1.4236914	NaN	NaN	NaN	1.6095953	0.27645916
35	0.33	3.4134383	1.4580244	NaN	NaN	NaN	1.6047122	0.2878595
36	0.34	3.531726	1.4940795	NaN	NaN	NaN	1.5558811	0.29783484
37	0.35	3.379642	1.5299194	NaN	NaN	NaN	1.5229201	0.2850094
38	0.36	3.3965402	1.5628532	NaN	NaN	NaN	1.4948422	0.28643447
39	0.37	3.5655222	1.597832	NaN	NaN	NaN	1.5143746	0.30068496
40	0.38	3.548624	1.6311965	NaN	NaN	NaN	1.529024	0.2992599
41	0.39	3.616217	1.6633769	NaN	NaN	NaN	1.5668681	0.3049601
42	0.4	3.5824206	1.6946964	NaN	NaN	NaN	1.6181407	0.30211
43	0.41	3.7007082	1.7298905	NaN	NaN	NaN	1.5815175	0.31208533
44	0.42	3.8358936	1.7651922	NaN	NaN	NaN	1.5497772	0.3234857
45	0.43	3.7683008	1.7998482	NaN	NaN	NaN	1.5302447	0.3177855
46	0.44	3.9034867	1.8340735	NaN	NaN	NaN	1.5326864	0.32918587
47	0.45	3.852792	1.8652855	NaN	NaN	NaN	1.5448941	0.32491076
48	0.46	3.9541812	1.897143	NaN	NaN	NaN	1.5876213	0.33346102
49	0.47	4.0724688	1.931799	NaN	NaN	NaN	1.6144785	0.34343636
50	0.48	3.9710793	1.9683921	NaN	NaN	NaN	1.5644265	0.33488607
51	0.49	4.123163	2.0038013	NaN	NaN	NaN	1.5204785	0.3477115
52	0.5	4.123163	2.0377042	NaN	NaN	NaN	1.4985045	0.3477115
53	0.51	4.1400614	2.0716066	NaN	NaN	NaN	1.4716474	0.34913656
54	0.52	4.241451	2.1038947	NaN	NaN	NaN	1.4936215	0.35768685
55	0.53	4.3259416	2.135537	NaN	NaN	NaN	1.533907	0.36481208
56	0.54	4.3090434	2.1671793	NaN	NaN	NaN	1.5900629	0.363387
57	0.55	4.3428397	2.2017276	NaN	NaN	NaN	1.5766343	0.3662371
58	0.56	4.3428397	2.2360609	NaN	NaN	NaN	1.5143746	0.3662371
59	0.57	4.3766365	2.2725465	NaN	NaN	NaN	1.4899591	0.3690872
60	0.58	4.478026	2.3059108	NaN	NaN	NaN	1.4875176	0.3776375
61	0.59	4.5287204	2.3386292	NaN	NaN	NaN	1.4948422	0.38191262
62	0.6	4.478026	2.369626	NaN	NaN	NaN	1.5314655	0.3776375
63	0.61	4.4611278	2.4007304	NaN	NaN	NaN	1.5815175	0.37621245
64	0.62	4.6132116	2.43431	NaN	NaN	NaN	1.5912837	0.38903788

Figure B2 shows a sample of the data that was collected from the eXpert ADMET Mechanical Testing System. Due to the thousands of data points, all data points are not shown in this appendix. The data can then be used to plot a stress strain curve for the sample of rubber being tested for the performance based testing.