# Sustainable Rubber Compound Research for Automotive Applications

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# Author's Note

This senior thesis is submitted as partial fulfillment of the graduation requirements of Kettering University needed to obtain a Bachelor of Science in Chemical Engineering. The conclusions and opinions expressed in this thesis are from myself and do not necessarily represent the position of Kettering University or anyone else affiliated with this culminating undergraduate experience. Although this thesis represents the compilation of my own efforts, I would like to acknowledge and extend my sincere gratitude to the following individuals for their valuable time and assistance, without whom the completion of this thesis would not have been possible:

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- Dr. Stefania Schamber, Manager, Material Technologies Expert, Surface Treatment.
- Ryan O'Neil, Material Lab Technician II.
- Roderick Morrison, Process Development Technician III.

# Abstract

This project aims to develop and test three new rubber compounds with recovered carbon black and sustainable oils as alternatives to Vibracoustic's standard carbon black compound. Mechanical, rheological, and heat-age performance metrics were compared to assess feasibility. Within the timeframe allowed, the results demonstrate measurable progress toward a more sustainable compound and provide recommendations for future development.

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Sustainable Rubber Compound Research for Automotive Applications

# Introduction

## Rubber Compounds

Rubber compounds are made up of raw elastomeric[1] materials, additives, reinforcements, curing agents, and stabilizers. These elements define the final rubber product's flexibility, hardness, durability, and performance. This is achieved by selecting a base polymer, curing system, fillers, and stabilizers to meet requirements.

The base polymer – natural or synthetic rubber – provides the primary elasticity, flexibility, and mechanical strength. Common synthetic rubbers include Styrene-Butadiene rubber (SBR), Nitrile rubber (NBR), and Ethylene Propylene Diene Monomer (EPDM) (Patel, 2025). For this project, however, natural rubber was selected. Derived from Hevea Brasiliens trees, these compounds are known for their exceptional elasticity, tensile strength, and abrasion resistance.

After selecting the polymer, fillers are added to adjust the hardness, flexibility, and performance of the rubber compound. Reinforcing agents like carbon black and silica improve tensile strength and durability, while other fillers, such as clay and calcium carbonate, act as plasticizers and softeners, improving processability (Patel, 2025).

To further enhance long-term performance, chemical additives such as antioxidants[2] and antiozonants[3] protect rubber compounds from degradation caused by

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[1] A rubber-like solid with elastic properties.

[2] A substance that prevents or slows down degradation caused by oxygen.

[3] A substance that prevents or slows down degradation caused by ozone.

oxygen, ozone, heat, and UV exposure. These agents prevent cracking, brittleness, and loss of elasticity over time (Patel, 2025).

In addition to polymer, filler, and additive selection, vulcanization is another essential factor for the characteristics of rubber compounds. This chemical process cross-links polymer chains, improving rubber strength, elasticity, and resistance to wear. Accelerators are typically used to ensure an even, consistent cure of the rubber, ensure structural stability, and reduce cure time (Patel, 2025). Because rubber components in automotive applications encounter harsh environments, resistance to heat, chemicals, weather, and mechanical stress is imperative (Patel, 2025).

## Literature Review

Vibracoustic is a leading global noise, vibration, and harshness expert. The company aims to ensure a smooth, safe, and quiet ride by reducing noise and vibrations originating from the engine, motor, drive train, and road surfaces, and transmitted into the chassis (Vibracoustic, 2024). To reduce NVH, it is important to use a cushion, typically rubber in automotive applications.

Historically, Vibracoustic only used natural rubber (NR) combined with carbon black, standard oils, and fillers. However, because sustainability has become a growing concern worldwide, reliance on conventional compounds has raised environmental and ethical issues. These challenges drove the company to reevaluate its material choices and explore more sustainable options.

In response to these concerns, the Material Technologies team launched the Green Rubber Project in 2016 at Vibracoustic's lab in Weinheim, Germany. The team focused on identifying sustainable raw materials, reducing environmental impact, and improving recyclability. To address these, the team shifted from synthetic rubber derived from fossil fuels to natural rubber (NR). This approach was considered more sustainable if deforestation and intense working conditions are avoided (Maust, 2026). In addition to the polymer selection, the oil used in the rubber was replaced with a more sustainable bio-oil derived from end-of-life tire pyrolysis. The oil has a renewable carbon content of 30%, shows improvements in tensile strength, curing time, and elongation at low temperatures, and complies with PAH regulations. At the same time, carbon black was partially replaced with recycled carbon black (rCB), an alternative that reduces emissions and improves recyclability (Plaettner, 2023).

Pyrolysis, by definition, is the thermal decomposition of organic substances under inert conditions (absence of oxygen) at high temperatures between 400-800˚C. The process starts with pretreating the tires to remove impurities, then they are fed into a shredder and into a pyrolysis reactor, where they are heated. The oil and gas mixture generated enters a separator, where it is separated based on temperature and pressure differences. The oil is cooled in a condenser and collected as liquid in a storage tank. The gas enters a processing system for purification, recovery, or utilization, and the carbon black is collected from the bottom of the furnace where the tires are heated (GEP ECOTECH, 2025). Overall, the pyrolysis process increases the recycled content in the product, reduces the carbon footprint, and helps address waste tire pollution. Unlike incineration, this process yields higher material recovery and lower emissions of airborne particles and contaminants (Costa, 2022).

Using these more sustainable rubber components, the Material Technologies Team developed two sets of recipes to test against a control group in the first phase of the project. The first set of recipes had one modification, which changed either the rCB material or the oil. The second set of recipes applied both changes: rCB and oil. Both sets were tested against the control group, NR-C010A-560, with standard carbon black and oil. The tests performed were tensile strength, elongation, compression, TeCo, and durability. Tension-compression (TeCo) testing provides the static[4] and dynamic[5] stiffnesses of a rubber sample. These showed promising results with an increase in sustainable content to about 60%, and 5-15% recycled or renewable content. The compounds also showed strong durability and tensile strength and were considered an option when quoting new customer parts (Maust, 2026).

For this phase of the project, the goal was to increase the sustainability content in the rubber using three new carbon blacks and a new bio-oil provided by Dr. Stephanie Deike and Dr. Stephania Schamber. The plan focused on refining the carbon black-to-recovered carbon black ratio to decrease the amount of carbon black and increase the recovered carbon black in the recipe. This allows for more rubber solutions for customers in the future, helps lower the company's carbon footprint, and increases recyclability. The limitations of this project included timing, location, and workload. The time available to collect data for this project was six weeks, and the research was conducted at the

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[4] Test that involves applying a constant load under sustained pressure (DataCalculus).

[5] Test that involves applying varying loads (DataCalculus).

Vibracoustic Material Technologies lab in South Haven. The team that originally began work on the Green Rubber Project worked out of Weinheim, Germany, so communication while in different time zones proved difficult. Time was split between working on this project and supporting the application team, which proved slightly challenging, as there were many critical tasks to complete on other teams.

The control group used in this phase consisted of a rubber compound containing carbon black, standard oil, fillers, raw rubber, and plasticizers. The experimental recipes included three new carbon black compounds: Bolder Black, Greenblack 7200, and Continua 8000SCM. Bolder Black and Continua 8000SCM are both produced from end-of-life (EOL) tires and rubber scrap. Bolder Black requires 90% less water than other processes and produces 90% fewer greenhouse gases (Bolder Industries). Continua 8000SCM also provides significant environmental benefits, with a net-negative carbon footprint, as it recovers steel and produces renewable fuels. 1 ton of Continua 8000SCM reduces $CO_2$ emissions by 0.73 tons. In contrast, Greenblack 7200 is not produced from EOL tire pyrolysis but instead by a plasma process using raw materials. Although it is not a recovered carbon black, the process to create Greenblack 7200 is still more environmentally friendly than traditional manufacturing processes (Monolith Materials).

These compounds were combined with a newer, more sustainable oil, natural rubber, and standard fillers and plasticizers. The difference in this phase of testing in South Haven is that the compounds were created as a single set, with both recipe changes. TeCo or durability testing were also not completed due to time constraints and machine availability. Through the development of these new recipes, it was expected that the new compounds would exhibit greater correlation to the original carbon black compound while increasing the sustainable content.

## Method

Before testing began, general lab safety training had to be completed for the Material Technologies Lab. The PPE required for this project included close-toed shoes, safety glasses, a lab coat, and latex gloves. After completing lab safety training, a lab technician had to provide training for the machines used in this project. Once all training was completed, testing progressed as discussed in the following sections.

### Mixing

Alessandra Siqueira first assessed the recipes provided by the Weinheim Material Technologies team; then the chemicals in each recipe were mixed and given to Rodrick Morrison, who added the ingredients to the Francis Shaw K1 Intermix machine (Figure M-1). Then, the vulcanized rubber was rolled into the Lab Tech two-roll mixing machine, which extrudes the rubber to a specified thickness of about 1mm (Figure M-2). Once rolled out, a large slab of rubber was cut from the roller.

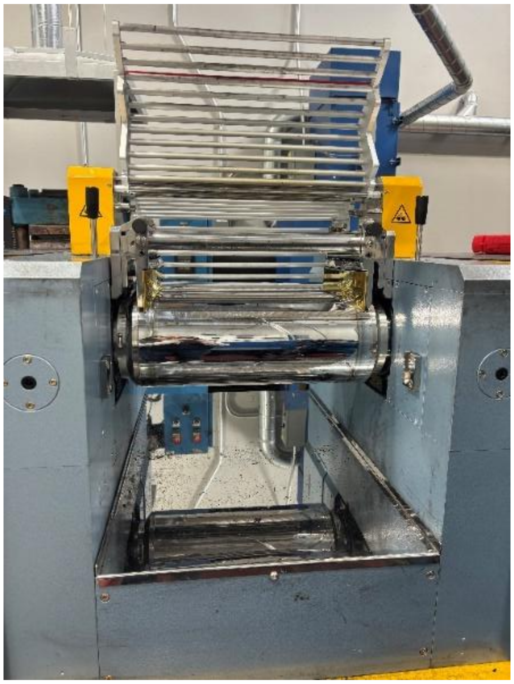
**Figure M-1.**

*Francis Shaw Intermix machine.*

*Note.* Raw materials are fed in the top and mixed by the screw, producing vulcanized rubber in the bottom tray.

**Figure M-2**

*Lab Tech Two-Roll Mixing Machine*



*Note.* Rolls out rubber to 1mm thickness.

## Test Slabs

Using the rubber slab from the two-roll mixing machine, four slabs were cut for each recipe, ensuring each was consistent in weight. The slabs were placed in the Alan Bradley press by Ryan O'Neil for four to five minutes to create rubber slabs for testing (Figure M-3). In this process, because the slabs do not match the cavity size, they developed bubbles after molding. If the slab had only a few bubbles, samples could be cut around them, leaving enough for testing. If the slab had many bubbles, mixing and molding of the test slabs were repeated. The slabs were then cooled for around three hours.

**Figure M-3**

*Alan Bradley Press*

*Note.* Molds uncured rubber into even 1mm thick slabs.

### RPA and MDR

Using the MonTech Sample Cutter VS3000 (Figure M-4), two circular samples were cut from the same uncured rubber slab as used in the mixing section and placed in the MonTech MDR 2000 and D-RPA 3000 machines. The D-RPA machine, or the Rubber Process Analyzer shown in Figure M-5, evaluates the molecular structure and viscoelastic[6] behavior of the rubber. The machine applies shear stress[7] to a rubber sample and measures the resulting deformation or flow. The test used for the D-RPA machine was the isothermal curing at variable strain test. It provided a torque-versus-time graph that showed higher oscillation angles for the softer materials and lower oscillation angles for the stiffer materials. Manufacturers can use these characteristics to adjust the formulation more precisely (MonTech USA).

**Figure M-4**

*MonTech Sample Cutter VS3000*

*Note*. Cuts samples from uncured rubber to test in the D-RPA machine.

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[6] A substance that exhibits both elastic and viscous behavior when deformed.
[7] Force applied to a material along the surface rather than pressing directly into it.

**Figure M-5**

*MonTech D-RPA Machine*

*Note.* Provides the dynamic stiffness and damping properties of the rubber.

The MonTech MDR 2000 machine (Moving Die Rheometer), shown in Figure M-6, measures the viscoelastic properties of rubber compounds before, during, and after cure. This test provided information about processability, cure characteristics, cure speed, and behavior after cure at fixed strain rates, and is essential for maintaining batch-to-batch consistency (MDR 3000).

**Figure M-6**

*MonTech MDR 2000*

*Note*. Provides cure characteristics like scorch time, vulcanization time, and max torque difference.

### Tensile/Elongation/Durometer Testing

From one of the four cured slabs, samples for tensile, durometer, and elongation testing were cut using a press with a dumbbell-shaped cutting attachment. To evaluate mechanical performance, tensile strength[8] was measured. This test followed the ASTM D2000 test specifications (see Appendix A-2). Evaluating the rubber's mechanical performance is important because compounds with high tensile strength exhibit excellent

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[8] The maximum stress the rubber can withstand while being stretched before breaking, expressed in megapascals (MPa)

elasticity and flexibility, enabling them to withstand repeated stretching and mechanical loads – essential for automotive applications. Hence, these compounds also typically exhibit excellent compression-set resistance (Patel, 2025).

Hardness, or durometer, describes a rubber's resistance to deformation under applied pressure. This project evaluated hardness using the Shore A hardness scale. The material's hardness affects its compression set, elasticity, and durability. The higher the hardness value, the greater the compound's wear resistance and load-bearing capacity. Softer rubber offers greater flexibility and rebound resistance, making it a better fit in some cases for cushioning and vibration damping.

Before placing the samples in the Alpha Technologies Tensometer 2020, they were measured for hardness and thickness. The hardness was measured by lining up the Rex Durometer with the dumbbell end, lightly pressing down, and simultaneously rolling the tip (Figure M-7). The hardness was recorded on the dumbbell and on the test setup screen.

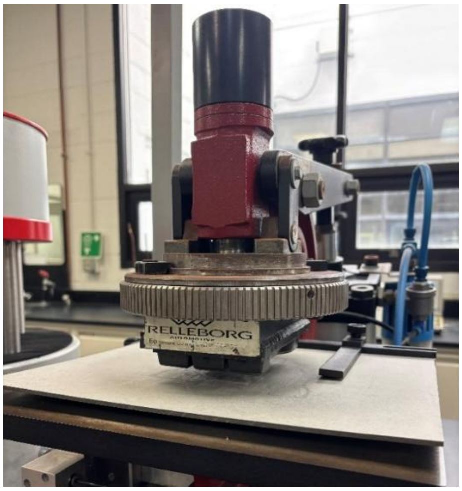
**Figure M-7**

*Rex Durometer Gauge*

*Note*. Takes hardness measurements of rubber compounds.

**Figure M-8**

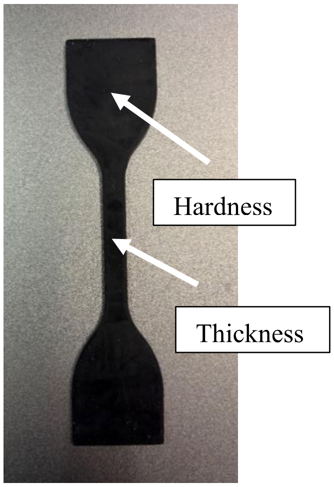
*Dumbbell Press*



*Note*. Cuts rubber into dumbbell shapes.

**Figure M-9**

*Rubber Dumbbell*



*Note.* This figure shows the locations where hardness and thickness measurements were taken.

The thickness of the dumbbells was taken using the SPI Thickness Gauge by placing the sample so that the thin part of the dumbbell was underneath the meter (Figure M-10). The meter was then pressed down, and the thickness was recorded on the sample and on the test setup screen.

**Figure M-10**

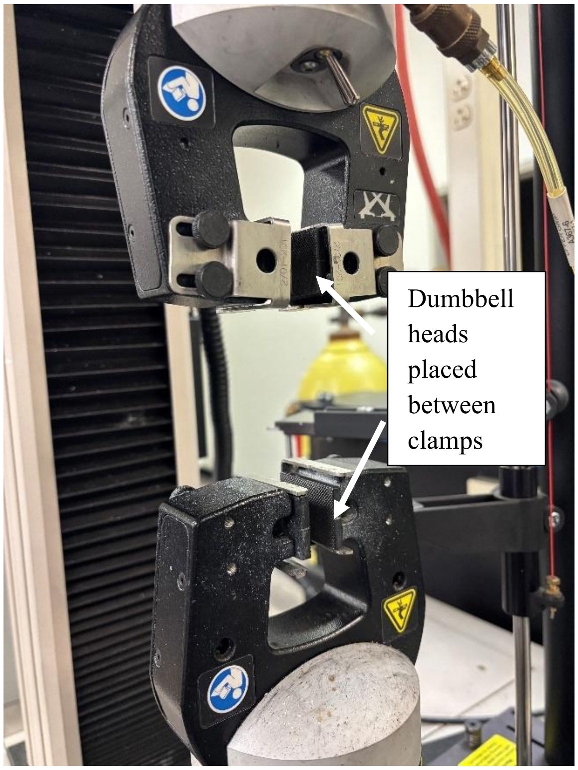
*SPI Thickness Gauge*

*Note*. The figure shows the locations of thickness measurements on the rubber dumbbells.

Once all measurements were recorded, testing was initiated. The dumbbell was placed between the clamps of the Tensometer, and the prongs were clamped onto the dumbbell just underneath the heads of the dumbbell to continuously measure the length of the rubber before and at break (Figure M-11). Once the sample was secured in the machine, the test ran until the rubber broke, and the procedure was repeated for all other samples.

**Figure M-11**

*Tensometer*



*Note.* Set up for tensile and elongation testing.

### Compression Set Testing

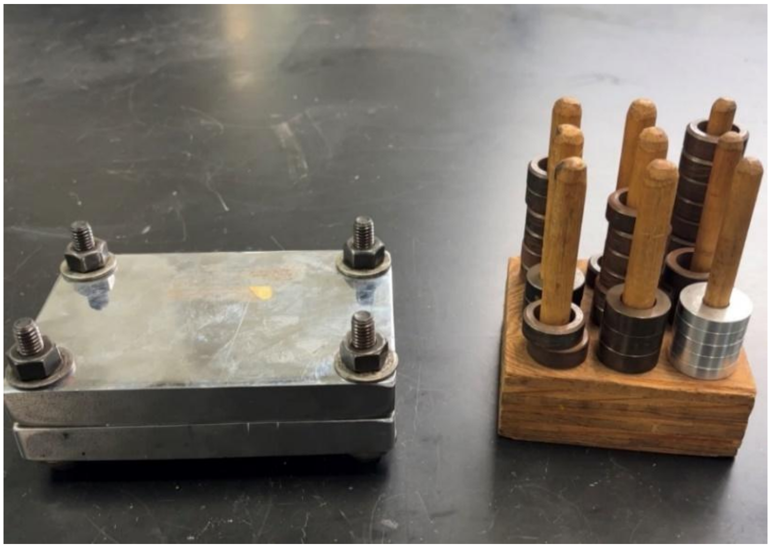
Using a different molded rubber slab, the press attachment was switched to a circular one, and 16 pieces were cut for compression testing. The test only required 12-15 pieces; however, extras were created as backups. On a piece of paper, the compound number, hours to test, and temperature required for testing were written down.

Then, for each of the three stacks, the Mitutoyo Thickness Gauge was used to measure thickness, and the values were recorded on the same sheet (Figure M-13). For the compression test to be accurate, the thickness of the stacks must be within 0.005mm of each other. The backup samples were used if the stack thicknesses were not equivalent. Using the recovery percentage specified in ASTM D2000, the spacer height was calculated for the compression test plates using Equation 1.

$$thickness \times 0.75 = spacer\ height \tag{1}$$

**Figure M-12**

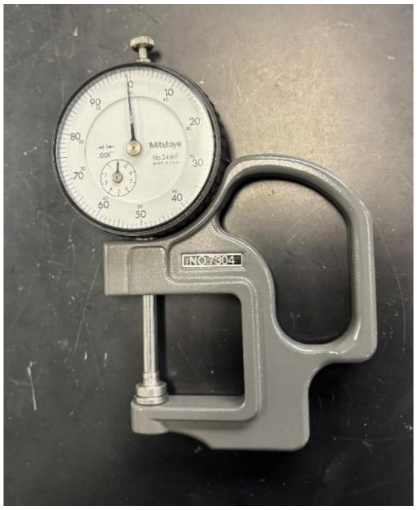
*Compression Set Plates and Spacers*



*Note*. Compression set plates on the left and spacers on the right.

**Figure M-13**

*Mitutoyo Thickness Gauge*



*Note*. Measures hardness in 0.001”.

Each stack was numbered and placed between the compression plates (Figure M-12). A press was used to hold the compression plates in place while the bolts were tightened as much as possible (Figure M-14).

**Figure M-14**

*Hydraulic Press*

*Note*. Used to hold compression plates in place while tightening bolts.

**Figure M-15**

*Thermo Scientific Heratherm Heat Chamber*

*Note*. Samples were left in the heat chamber for 24 hours at 70˚C for compression set and heat aging.

The compression plates were placed in the Thermoscientific Heratherm Heat Chamber for 24 hours at 70˚C (Figure M-15). Sticky notes were placed on the heat chamber doors with the compound numbers and whether each compound was in the front or back of the chamber to keep track of each compound. Once complete, the plates were pulled out, and the thicknesses were measured immediately after. The recovery percentage was calculated using Equation 2 and recorded for each compound.

$$C_B = \left[\frac{t_0 - t_i}{t_0 - t_n}\right] * 100 \qquad (2)$$

$C_B = compression\ set\ expressed\ as\ percentage\ of\ the\ original\ deflection$

$t_0 = original\ thickness\ of\ specimen$

$t_i = final\ thickness\ of\ specimen$

$t_n = thickness\ of\ the\ spacer\ bar\ used$

**Heat Age Testing**

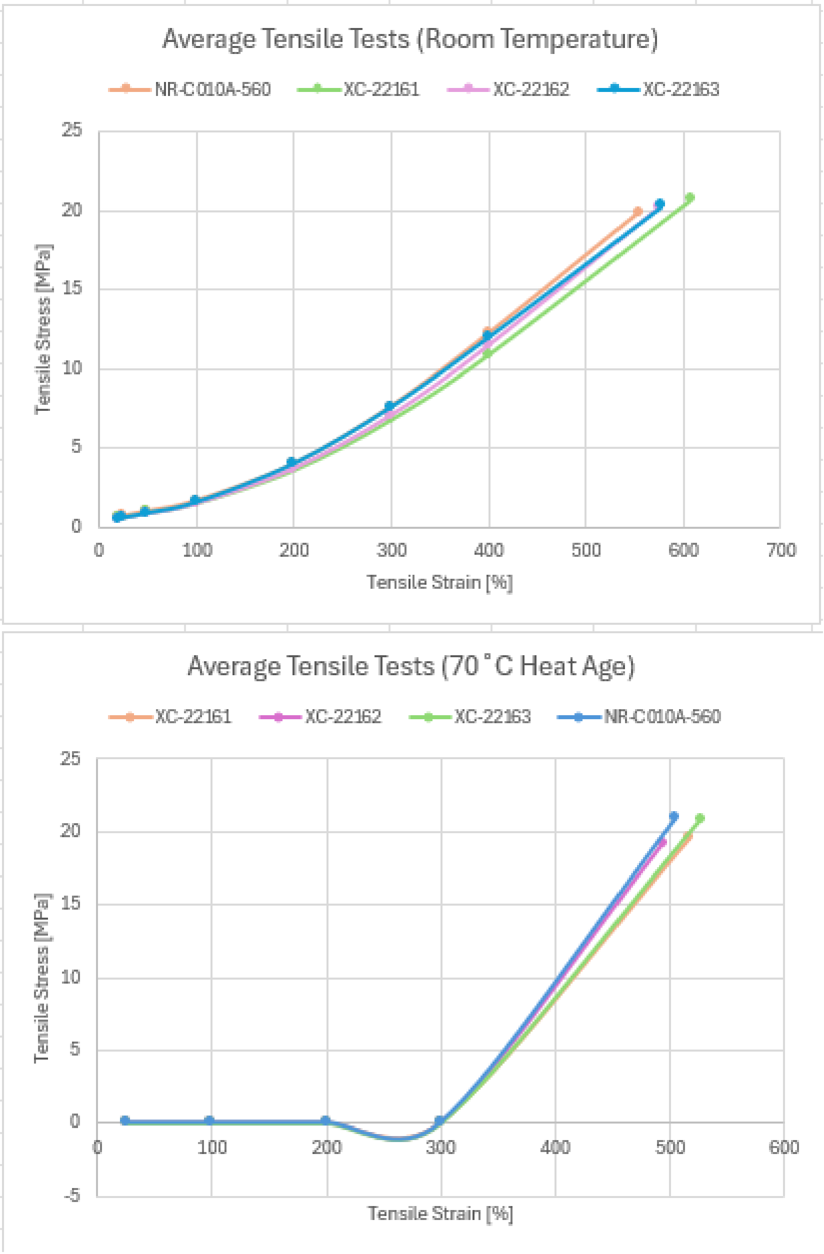
Another three dumbbells were cut out of the third cured slab, and the compound number, heat age time, and temperature were written on the dumbbells. The thickness measurement was taken using the SPI Thickness gauge and recorded on the dumbbells. Before performing the second round of tensile testing, the dumbbells were placed in binder clips and hung in the heat chamber for 24 hours at 70˚C. These were placed in the heat chambers at the same time as the compression sets for efficiency. After the heat-age test, the dumbbells were removed, and hardness and thickness measurements were taken and recorded. Then, the tensile and elongation tests were performed, and the results were recorded.

All testing was performed for each of the four rubber compounds. After collecting the results for each test, the data was compared with the control group using graphs, other collected data, and previous testing conducted by Vibracoustic, which are presented in the following sections.

# Results

**Figure R-1**

*Average Tensile and Elongation at Room Temperature and 70°C.*



*Note.* Results of the average tensile stress versus strain for the room temperature samples and the 70°C heat age samples.

**Table R-1**

*Room Temperature Tensile and Elongation Test Values*

| Room Temperature Samples | Duro | Mean Tensile Stress at Break (MPa) | Mean Elongation at Break (%) |
|---|---|---|---|
| **NR-C010A-560** | 49 | 19.853 | 554.782 |
| **XC-22161** | 50 | 20.675 | 607.942 |
| **XC-22162** | 51 | 20.238 | 576.437 |
| **XC-22163** | 51 | 20.313 | 578.25 |

**Table R-2**

*Heat Age Tensile and Elongation Test Values*

| Heat Age Samples | Duro | Mean Tensile Stress at Break (MPa) | Mean Elongation at Break (%) |
|---|---|---|---|
| **NR-C010A-560** | 52 | 20.935 | 505.130 |
| **XC-22161** | 53 | 19.505 | 516.910 |
| **XC-22162** | 52 | 19.150 | 494.780 |
| **XC-22163** | 53 | 20.815 | 527.250 |

For all tensile and elongation testing, the ASTM D2000-08 standards were followed (see Appendix A-2). Based on Table 6 Suffix A13 in the standards, the maximum amount of hardness point change allowed is +10 ShA, the maximum percentage of tensile strength change allowed is -25%, and the maximum percentage of elongation allowed is -25%. Based on these standards, all room temperature and heat-aged samples passed. The compound that exhibited the highest resistance to mechanical stress was XC-22163 with an average tensile strength of 20.3 MPa at room temperature and 20.8 MPa at 70°C, and an average elongation percentage of 578.3% at room temperature and 527.3% at 70°C.

## Compression Set Tests

**Table R-3**

*Compression Set Trial 1 Results*

| COMPOUND | NR-C010A-560 | | | XC-22161 | | | XC-22162 | | | XC-22163 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 |
| **Orig. Thickness (0.001”)** | 392 | 388 | 391 | 409 | 411 | 410 | 412 | 413 | 413 | 396 | 394 | 393 |
| **Spacer Thickness (0.001”)** | 295 | 295 | 295 | 305 | 305 | 305 | 310 | 310 | 310 | 300 | 300 | 300 |
| **Final Thickness (0.001”)** | 314 | 325 | 316 | 384 | 386 | 388 | 386 | 387 | 385 | 369 | 369 | 366 |
| **% Comp Set** | 80.4 | 67.7 | 78.1 | 24 | 23.6 | 21 | 24.5 | 25.2 | 27.2 | 28.1 | 26.6 | 29 |

**Table R-4**

*Compression Set Trial 2 Results*

| COMPOUND | NR-C010A-560 | | | XC-22161 | | | XC-22162 | | | XC-22163 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 |
| **Orig. Thickness (0.001”)** | 395 | 385 | 393 | 415 | 414 | 412 | 401 | 403 | 402 | 398 | 399 | 400 |
| **Spacer Thickness (0.001”)** | 295 | 295 | 295 | 310 | 310 | 310 | 300 | 300 | 300 | 300 | 300 | 300 |
| **Final Thickness (0.001”)** | 356 | 359 | 360 | 382 | 386 | 376 | 374 | 378 | 376 | 367 | 365 | 371 |
| **% Comp Set** | 39 | 28.9 | 33.7 | 31.4 | 26.9 | 35.3 | 26.7 | 24.3 | 25.5 | 31.6 | 34.3 | 29 |

For all compression testing, the same ASTM standards were used as references. Based on Table 6 Suffix B13 of the standard, the maximum compression set for a 22-hour test at 70°C is 25%. For this phase of the project, it was expected that the recovery percentage would be between 15 and 20 percent. Table R-3 and R-4 summarize the percent compression set for each stack of samples across all compounds.

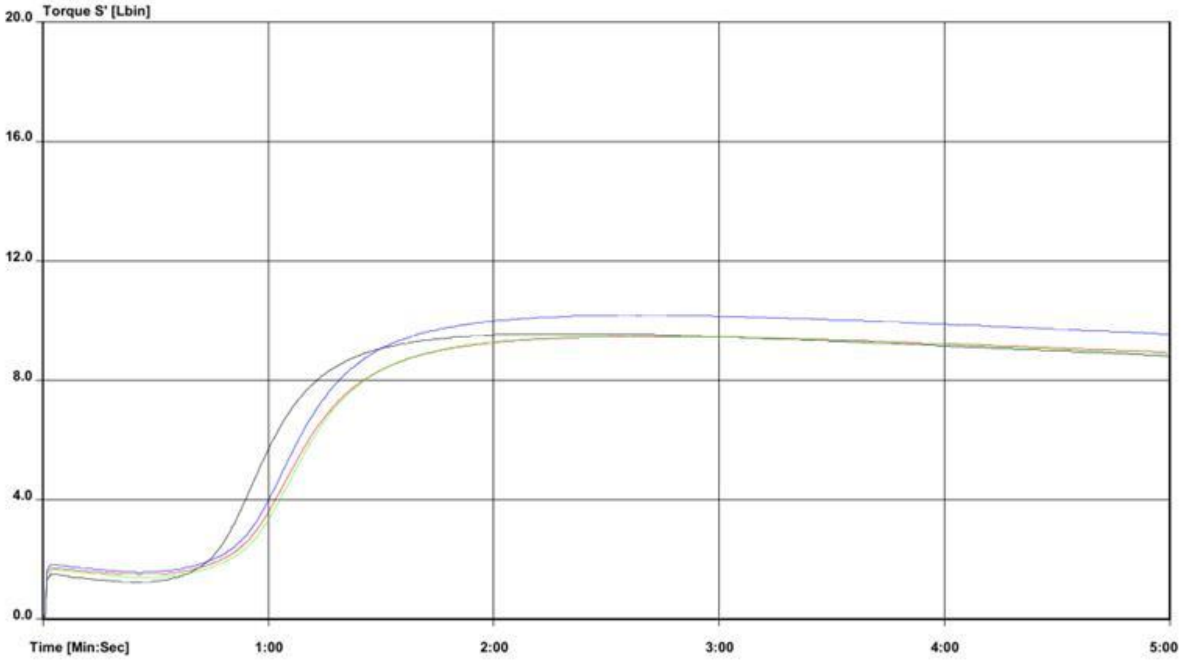
The values in Table R-3 for trial 1 were averaged to compare the new recipes to the control group. The compound that exhibited compression characteristics most like the control group was XC-22161 with an average compression percent of 32.03%. The control group’s average recovery was 75.4%. The three new recipes had consistent averages; however, the average for the control group was considered an outlier. This was a result of leaving the compression set samples in the Thermo Scientific Heratherm Heat

Chamber for 168 hours instead of the 24 hours specified in the ASTM standard. Because of this error, the results in Table R-3 can be disregarded.

Contrary to the first trial, the second trial was left in the heat chamber for 24 hours, and the results shown in Table R-4 were considered comparable. The compound that exhibited compression characteristics most similar to the control group was XC-22163, with an average compression set of 31.6% compared to the control group's 33.9%.

**Figure R-2**

*MDR (5 min @ 350°C)*



*Note*. Rheometer test results graph showing torque versus time. This provides the scorch time and TC 90 times for rubber samples.

**Table R-5**

*MDR Test Results*

| Compound | Scorch Time (TS 2) (Min: Sec) | TC 90 (Min: Sec) |
|---|---|---|
| **NR-C010A-560** | 0:50 | 1:21 |
| **XC-22161** | 0:59 | 1:35 |
| **XC-22162** | 0:59 | 1:35 |
| **XC-22163** | 0:58 | 1:33 |

Table R-5 summarizes the results of the MDR test. The TC 90 value is the time required for each compound to reach 90% of its maximum torque, listed in Appendix A-4. The Appendix also includes the TC 20 and TC 50 times, or the times required to reach 20% and 50% of the maximum torque, respectively. Scorch time indicates how long raw rubber stays processable before it begins to vulcanize.

Based on the results in Table R-5, the three new compounds had higher scorch times and TC 90 times than the control group. A longer scorch time is ideal because it provides a wider processing window; however, a shorter TC 90 time is preferred for efficient curing. The compound XC-22163 meets these constraints, with a scorch time of 58 seconds and a TC 90 time of 1 minute and 33 seconds, compared to the control group's scorch time of 50 seconds and TC 90 time of 1 minute and 21 seconds.

## Strain (RPA) Test

**Table R-6**

*RPA Test Results*

| Compound | G* (kPa) | Phase (°) |
|---|---|---|
| NR-C010A-560 | 916.377 | 3.6701 |
| XC-22161 | 968.5662 | 3.6339 |
| XC-22162 | 913.3043 | 3.7016 |
| XC-22163 | 985.8234 | 4.3674 |

Based on the results of the RPA test in Table R-6, all compounds were relatively similar to the control group, with phase angles differing by 0.1°. One outlier, XC-22163 was observed to have a phase angle of 4.3674°, indicating high damping. Its dynamic stiffness (G*) was slightly higher than that of the control group, indicating a stiffer compound. While XC-22163 would typically be the preferred option, however, XC-22162 may be recommended if a customer required a softer compound due to its lower stiffness and adequate damping characteristics.

# Discussion

## Test Slab Curing

During curing, the slabs did not completely match the mold dimensions, so some molded samples developed bubbles. If the slab had a small number of bubbles, samples could be cut around them, leaving enough for testing. If the slab had many bubbles, mixing and molding of the test slab sections were repeated. This introduced unavoidable challenges when producing consistent test slabs.

## Tensile and Elongation Testing

In Figure R-1, the heat-age graph showed zero tensile stress until the samples reached 200% strain. Under normal conditions, the graph should show consistent positive exponential behavior beginning at a value of zero for stress and strain; however, this deviation occurred due to machine error. The data collected at break for all heat-age samples were considered reliable based on previous testing and the ASTM D2000-08 standard, whereas the modulus at 100%, 200%, and 300% strain was considered inaccurate. This error could have resulted from improperly set Tensometer clamps or an error with the testing software. Because the elongations at break were accurate, the heat-aged and room-temperature samples remained comparable.

### Compression Set

With the compression set testing, a few errors occurred in the procedure, affecting the consistency of the two trials. The first trial failed because the samples were left in the oven for 168 hours instead of 24 hours, and measurements were taken immediately after removal from the oven rather than allowing the 30-minute dwell time required by ASTM standards. This caused the recovery percentage of the NR-C010A-560 to be much higher than that of the three other recipes. The second trial failed because measurements were taken immediately after removal. Because both trials conducted did not include a dwell time, the results from trial 2 were still comparable, and were used as part of the project analysis.

## Conclusions and Recommendations

The project analysis concluded that XC-22163 closely resembled the performance of the control compound while increasing sustainable content and performance in some areas. This conclusion was drawn from an analysis of tensile, durometer, elongation, compression set, and heat-age tests. Overall, the three new compounds had a calculated sustainable content of 66.5% and 3.05% of recycled or renewable content. Compared to previous testing, there was a 6.5% increase in sustainable content. It was found that substituting more sustainable oil and adding new recovered carbon black types increased the overall sustainable content of the rubber. More specifically, one of the three new recovered carbon black additions was the most promising. The XC-22163 compound was the closest match to the control group, NR-C010A-560, and even had improved elongation and damping properties.

Following the research in South Haven, TeCo tests, durability, and fatigue testing will need to be performed to determine whether these compounds can be used in production. Depending on those results, one of the three rubber compounds could be used in production at Vibracoustic's Carmi Mixing facility. For future research and development, it's suggested that the percentage of recovered carbon black be increased and the maximum allowable increase that would not alter the rubber properties be established.

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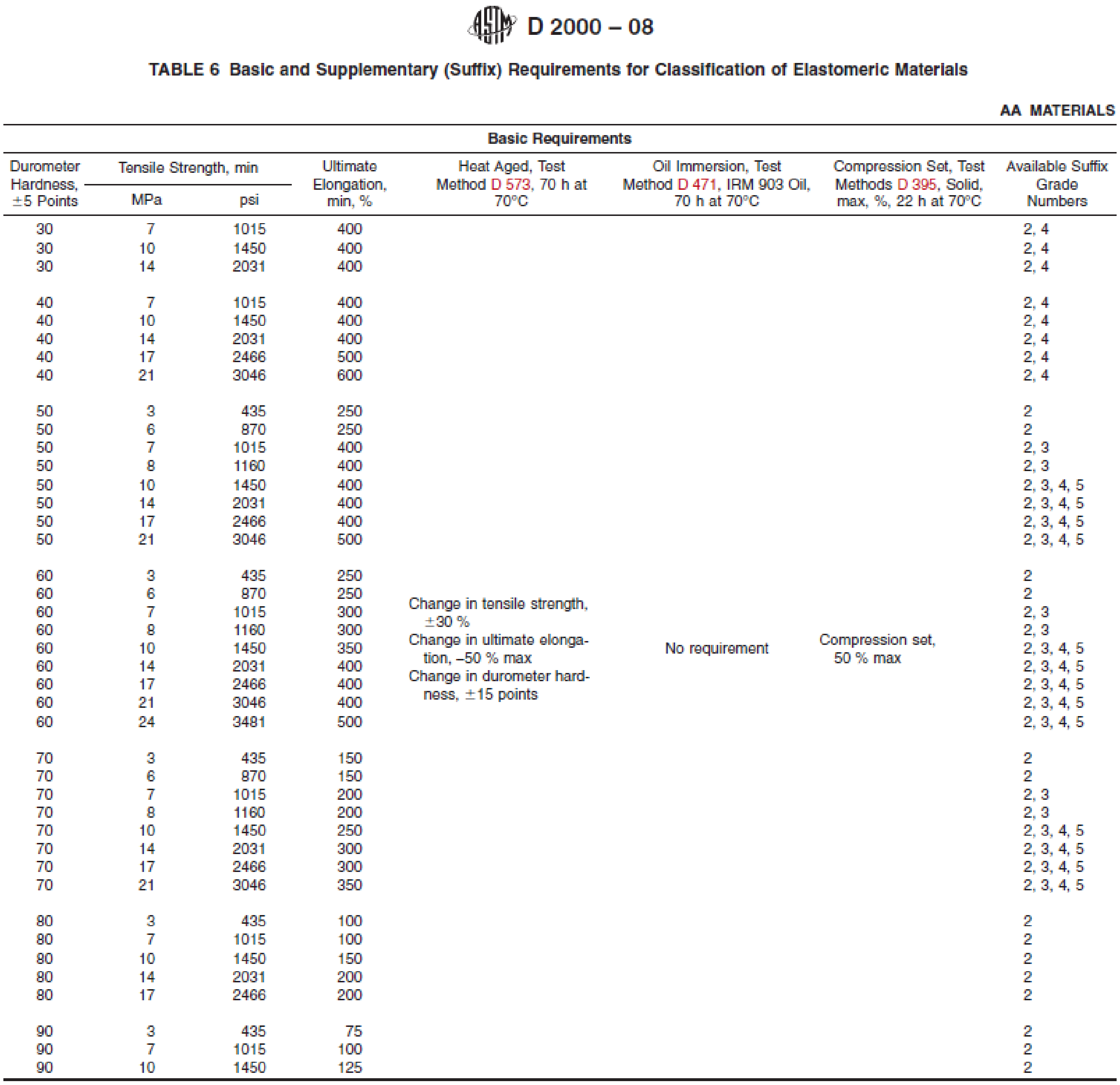
# Appendices

## Contents

## A-1. Compound descriptions.

| Compound | Description |
|---|---|
| NR-C010A-560 | Control group & standard oil |
| XC-22161 | Bolder Black & bio-oil |
| XC-22162 | Greenblack & bio-oil |
| XC-22163 | Continua 8000SCM & bio-oil |

## A-2. ASTM D2000-08 Standards



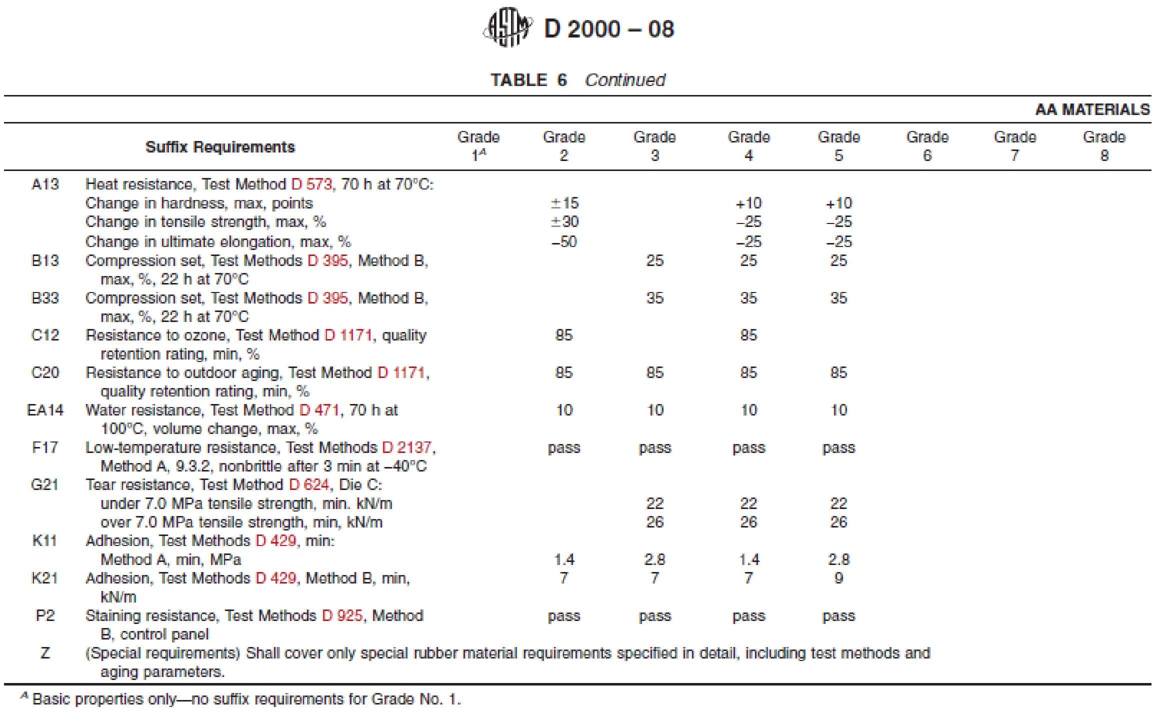
D 2000 – 08

TABLE 6 Basic and Supplementary (Suffix) Requirements for Classification of Elastomeric Materials

AA MATERIALS

Basic Requirements

| Durometer Hardness, ±5 Points | Tensile Strength, min MPa | Tensile Strength, min psi | Ultimate Elongation, min, % | Heat Aged, Test Method D 573, 70 h at 70°C | Oil Immersion, Test Method D 471, IRM 903 Oil, 70 h at 70°C | Compression Set, Test Methods D 395, Solid, max, %, 22 h at 70°C | Available Suffix Grade Numbers |
|---|---|---|---|---|---|---|---|
| 30 | 7 | 1015 | 400 | Change in tensile strength, ±30 %<br>Change in ultimate elongation, −50 % max<br>Change in durometer hardness, ±15 points | No requirement | Compression set, 50 % max | 2, 4 |
| 30 | 10 | 1450 | 400 | | | | 2, 4 |
| 30 | 14 | 2031 | 400 | | | | 2, 4 |
| 40 | 7 | 1015 | 400 | | | | 2, 4 |
| 40 | 10 | 1450 | 400 | | | | 2, 4 |
| 40 | 14 | 2031 | 400 | | | | 2, 4 |
| 40 | 17 | 2466 | 500 | | | | 2, 4 |
| 40 | 21 | 3046 | 600 | | | | 2, 4 |
| 50 | 3 | 435 | 250 | | | | 2 |
| 50 | 6 | 870 | 250 | | | | 2 |
| 50 | 7 | 1015 | 400 | | | | 2, 3 |
| 50 | 8 | 1160 | 400 | | | | 2, 3 |
| 50 | 10 | 1450 | 400 | | | | 2, 3, 4, 5 |
| 50 | 14 | 2031 | 400 | | | | 2, 3, 4, 5 |
| 50 | 17 | 2466 | 400 | | | | 2, 3, 4, 5 |
| 50 | 21 | 3046 | 500 | | | | 2, 3, 4, 5 |
| 60 | 3 | 435 | 250 | | | | 2 |
| 60 | 6 | 870 | 250 | | | | 2 |
| 60 | 7 | 1015 | 300 | | | | 2, 3 |
| 60 | 8 | 1160 | 300 | | | | 2, 3 |
| 60 | 10 | 1450 | 350 | | | | 2, 3, 4, 5 |
| 60 | 14 | 2031 | 400 | | | | 2, 3, 4, 5 |
| 60 | 17 | 2466 | 400 | | | | 2, 3, 4, 5 |
| 60 | 21 | 3046 | 400 | | | | 2, 3, 4, 5 |
| 60 | 24 | 3481 | 500 | | | | 2, 3, 4, 5 |
| 70 | 3 | 435 | 150 | | | | 2 |
| 70 | 6 | 870 | 150 | | | | 2 |
| 70 | 7 | 1015 | 200 | | | | 2, 3 |
| 70 | 8 | 1160 | 200 | | | | 2, 3 |
| 70 | 10 | 1450 | 250 | | | | 2, 3, 4, 5 |
| 70 | 14 | 2031 | 300 | | | | 2, 3, 4, 5 |
| 70 | 17 | 2466 | 300 | | | | 2, 3, 4, 5 |
| 70 | 21 | 3046 | 350 | | | | 2, 3, 4, 5 |
| 80 | 3 | 435 | 100 | | | | 2 |
| 80 | 7 | 1015 | 100 | | | | 2 |
| 80 | 10 | 1450 | 150 | | | | 2 |
| 80 | 14 | 2031 | 200 | | | | 2 |
| 80 | 17 | 2466 | 200 | | | | 2 |
| 90 | 3 | 435 | 75 | | | | 2 |
| 90 | 7 | 1015 | 100 | | | | 2 |
| 90 | 10 | 1450 | 125 | | | | 2 |



D 2000 – 08

**TABLE 6** *Continued*

**AA MATERIALS**

| | **Suffix Requirements** | Grade 1[A] | Grade 2 | Grade 3 | Grade 4 | Grade 5 | Grade 6 | Grade 7 | Grade 8 |
|---|---|---|---|---|---|---|---|---|---|
| A13 | Heat resistance, Test Method D 573, 70 h at 70°C: | | | | | | | | |
| | Change in hardness, max, points | | ±15 | | +10 | +10 | | | |
| | Change in tensile strength, max, % | | ±30 | | −25 | −25 | | | |
| | Change in ultimate elongation, max, % | | −50 | | −25 | −25 | | | |
| B13 | Compression set, Test Methods D 395, Method B, max, %, 22 h at 70°C | | | 25 | 25 | 25 | | | |
| B33 | Compression set, Test Methods D 395, Method B, max, %, 22 h at 70°C | | | 35 | 35 | 35 | | | |
| C12 | Resistance to ozone, Test Method D 1171, quality retention rating, min, % | | 85 | | 85 | | | | |
| C20 | Resistance to outdoor aging, Test Method D 1171, quality retention rating, min, % | | 85 | 85 | 85 | 85 | | | |
| EA14 | Water resistance, Test Method D 471, 70 h at 100°C, volume change, max, % | | 10 | 10 | 10 | 10 | | | |
| F17 | Low-temperature resistance, Test Methods D 2137, Method A, 9.3.2, nonbrittle after 3 min at −40°C | | pass | pass | pass | pass | | | |
| G21 | Tear resistance, Test Method D 624, Die C: | | | | | | | | |
| | under 7.0 MPa tensile strength, min. kN/m | | | 22 | 22 | 22 | | | |
| | over 7.0 MPa tensile strength, min, kN/m | | | 26 | 26 | 26 | | | |
| K11 | Adhesion, Test Methods D 429, min: | | | | | | | | |
| | Method A, min, MPa | | 1.4 | 2.8 | 1.4 | 2.8 | | | |
| K21 | Adhesion, Test Methods D 429, Method B, min, kN/m | | 7 | 7 | 7 | 9 | | | |
| P2 | Staining resistance, Test Methods D 925, Method B, control panel | | pass | pass | pass | pass | | | |
| Z | (Special requirements) Shall cover only special rubber material requirements specified in detail, including test methods and aging parameters. | | | | | | | | |

[A] Basic properties only—no suffix requirements for Grade No. 1.

## A-3. Individual tensile test graphs and data tables.

**Figure 1**

*Tensile Test for NR-C010A-560 at Room Temperature*

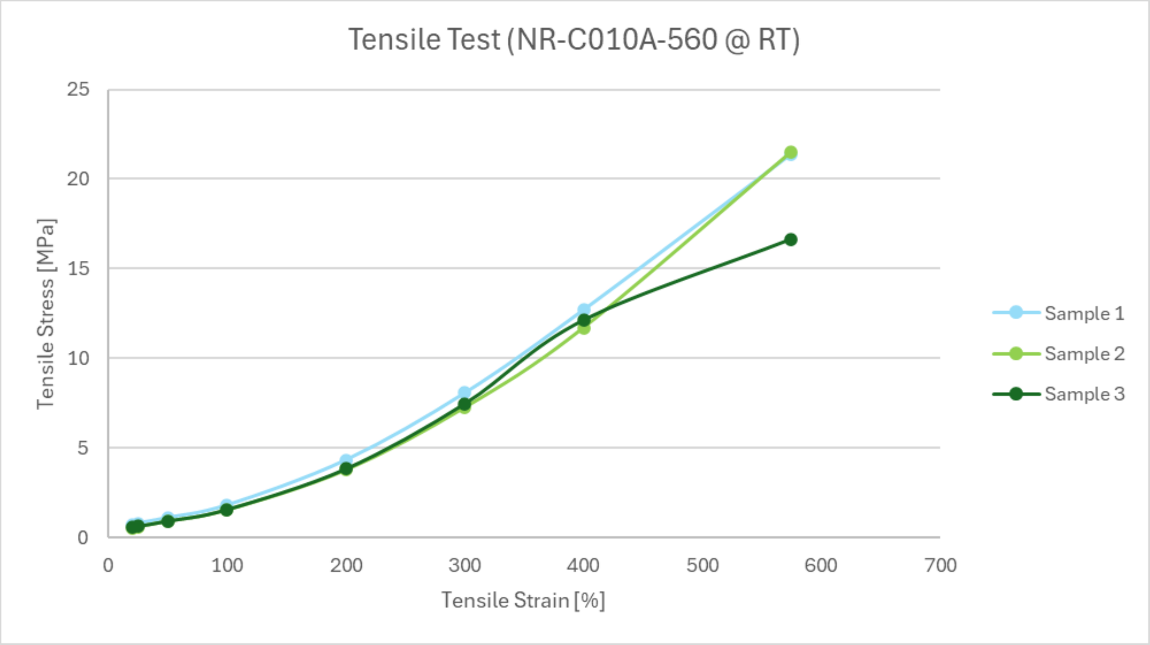


**Table 1**

*NR-C010A-560 Room Temperature Data*

| | Tensile Stress at Break | Tensile Strain at Break | Extension at Break (Standard) | Modulus @ 20% | Modulus @ 50% | Modulus @ 200% | Modulus @ 400% | Thickness |
|---|---|---|---|---|---|---|---|---|
| | MPa | % | mm | MPa | MPa | MPa | MPa | mm |
| **1** | 21.392 | 574.759 | 310.607 | 0.746 | 1.129 | 4.338 | 12.705 | 2.052 |
| **2** | 21.524 | 600.456 | 324.749 | 0.554 | 0.922 | 3.775 | 11.723 | 2.035 |
| **3** | 16.643 | 489.13 | 270.59 | 0.583 | 0.948 | 3.854 | 12.137 | 2.029 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **S.D.** | 2.78 | 58.29 | 28.091 | 0.104 | 0.113 | 0.305 | 0.493 | 0.012 |
| **Mean** | 19.853 | 554.782 | 301.982 | 0.628 | 1 | 3.989 | 12.189 | 2.039 |
| **Median** | 21.392 | 574.759 | 310.607 | 0.583 | 0.948 | 3.854 | 12.137 | 2.035 |

**Figure 2**

*Tensile Test for XC-22161 at Room Temperature*

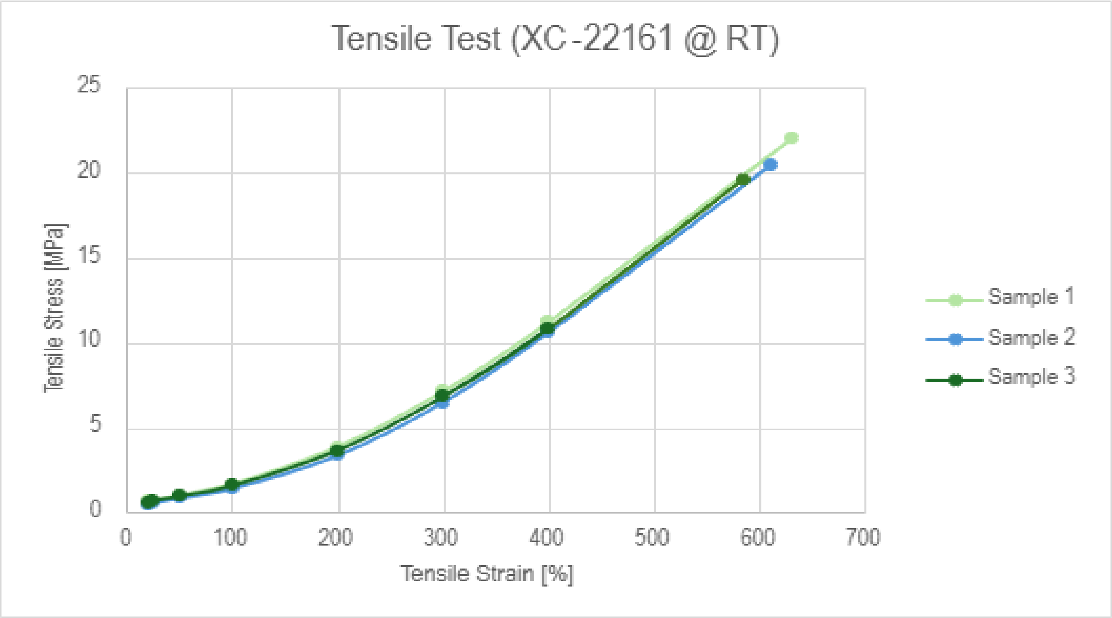


**Table 2**

*XC-22161 Room Temperature Data*

| | Tensile Stress at Break | Tensile Strain at Break | Extension at Break (Standard) | Modulus @ 20% | Modulus @ 50% | Modulus @ 200% | Modulus @ 400% | Thickness |
|---|---|---|---|---|---|---|---|---|
| | MPa | % | mm | MPa | MPa | MPa | MPa | mm |
| **1** | 21.392 | 574.759 | 310.607 | 0.746 | 1.129 | 4.338 | 12.705 | 2.052 |
| **2** | 21.524 | 600.456 | 324.749 | 0.554 | 0.922 | 3.775 | 11.723 | 2.035 |
| **3** | 16.643 | 489.13 | 270.59 | 0.583 | 0.948 | 3.854 | 12.137 | 2.029 |
| **S.D.** | 2.78 | 58.29 | 28.091 | 0.104 | 0.113 | 0.305 | 0.493 | 0.012 |
| **Mean** | 19.853 | 554.782 | 301.982 | 0.628 | 1 | 3.989 | 12.189 | 2.039 |
| **Median** | 21.392 | 574.759 | 310.607 | 0.583 | 0.948 | 3.854 | 12.137 | 2.035 |

**Figure 3**

*Tensile Test for XC-22162 at Room Temperature*

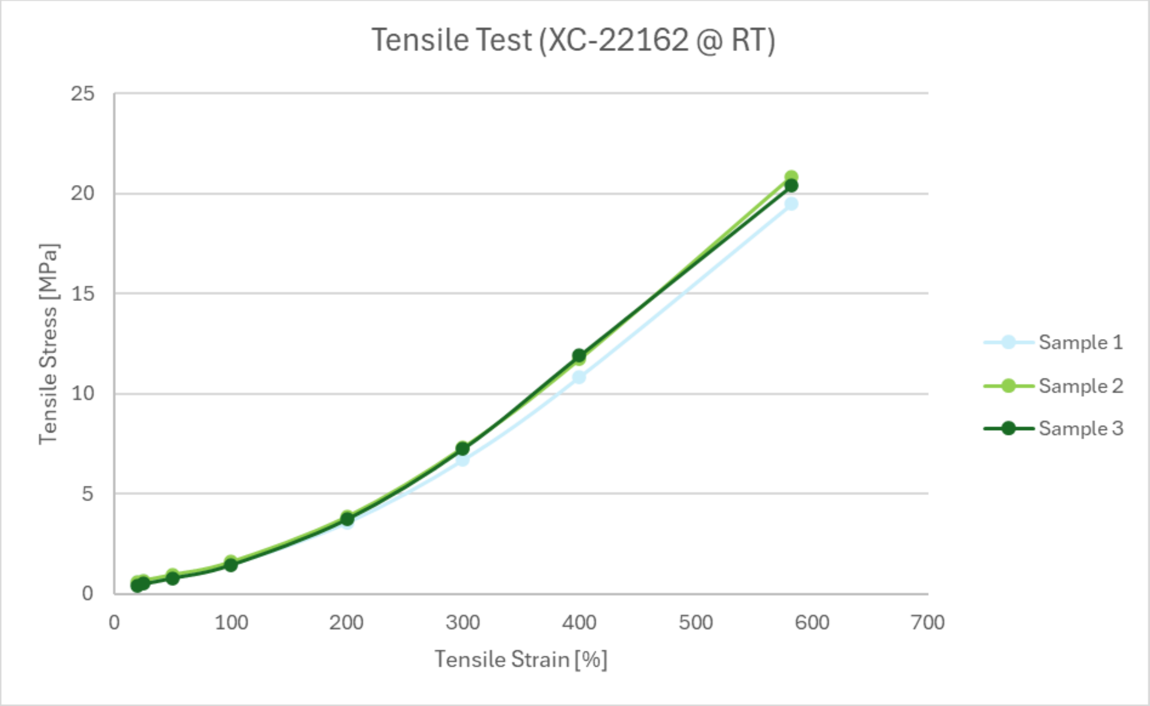


**Table 3**

*XC-22162 Room Temperature Data*

| | Tensile Stress at Break | Tensile Strain at Break | Extension at Break (Standard) | Modulus @ 20% | Modulus @ 50% | Modulus @ 200% | Modulus @ 400% | Thickness |
|---|---|---|---|---|---|---|---|---|
| | MPa | % | mm | MPa | MPa | MPa | MPa | mm |
| **1** | 19.487 | 582.794 | 328.712 | 0.566 | 0.886 | 3.569 | 10.839 | 2.051 |
| **2** | 20.845 | 582.149 | 324.948 | 0.592 | 0.943 | 3.839 | 11.705 | 2.091 |
| **3** | 20.383 | 564.369 | 316.324 | 0.422 | 0.775 | 3.72 | 11.884 | 2.087 |
| **S.D.** | 0.69 | 10.457 | 6.351 | 0.091 | 0.085 | 0.135 | 0.559 | 0.022 |
| **Mean** | 20.238 | 576.437 | 323.328 | 0.527 | 0.868 | 3.709 | 11.476 | 2.076 |
| **Median** | 20.383 | 582.149 | 324.948 | 0.566 | 0.886 | 3.72 | 11.705 | 2.087 |

**Figure 4**

*Tensile Test for XC-22163 at Room Temperature*

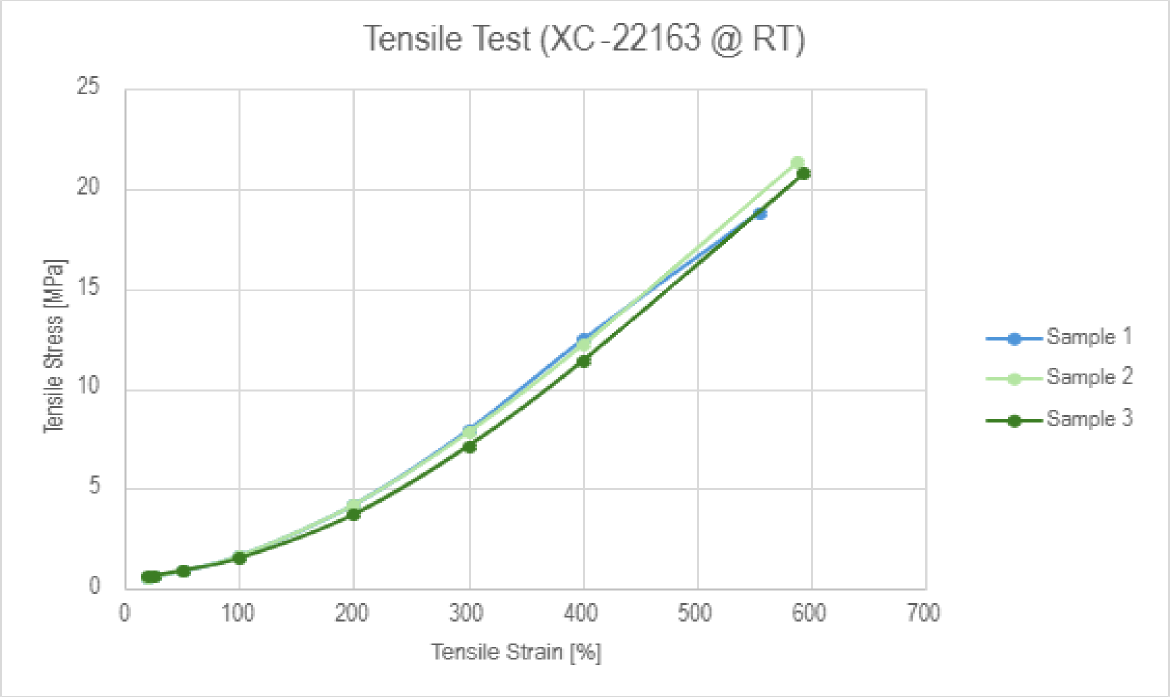


**Table 4**

*XC-22163 Room Temperature Data*

| | Tensile Stress at Break | Tensile Strain at Break | Extension at Break (Standard) | Modulus @ 20% | Modulus @ 50% | Modulus @ 200% | Modulus @ 400% | Thickness |
|---|---|---|---|---|---|---|---|---|
| | MPa | % | mm | MPa | MPa | MPa | MPa | mm |
| **1** | 18.826 | 554.056 | 309.825 | 0.508 | 0.882 | 4.19 | 12.444 | 2.167 |
| **2** | 21.343 | 587.453 | 324.827 | 0.505 | 0.885 | 4.192 | 12.188 | 2.13 |
| **3** | 20.77 | 593.241 | 319.769 | 0.569 | 0.914 | 3.712 | 11.404 | 2.213 |
| **S.D.** | 1.319 | 21.151 | 7.633 | 0.036 | 0.017 | 0.276 | 0.542 | 0.042 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Mean** | 20.313 | 578.25 | 318.14 | 0.527 | 0.894 | 4.031 | 12.012 | 2.17 |
| **Median** | 20.77 | 587.453 | 319.769 | 0.508 | 0.885 | 4.19 | 12.188 | 2.167 |

**Figure 5**

*Tensile Test for NR-C010A-560 at 70°C*

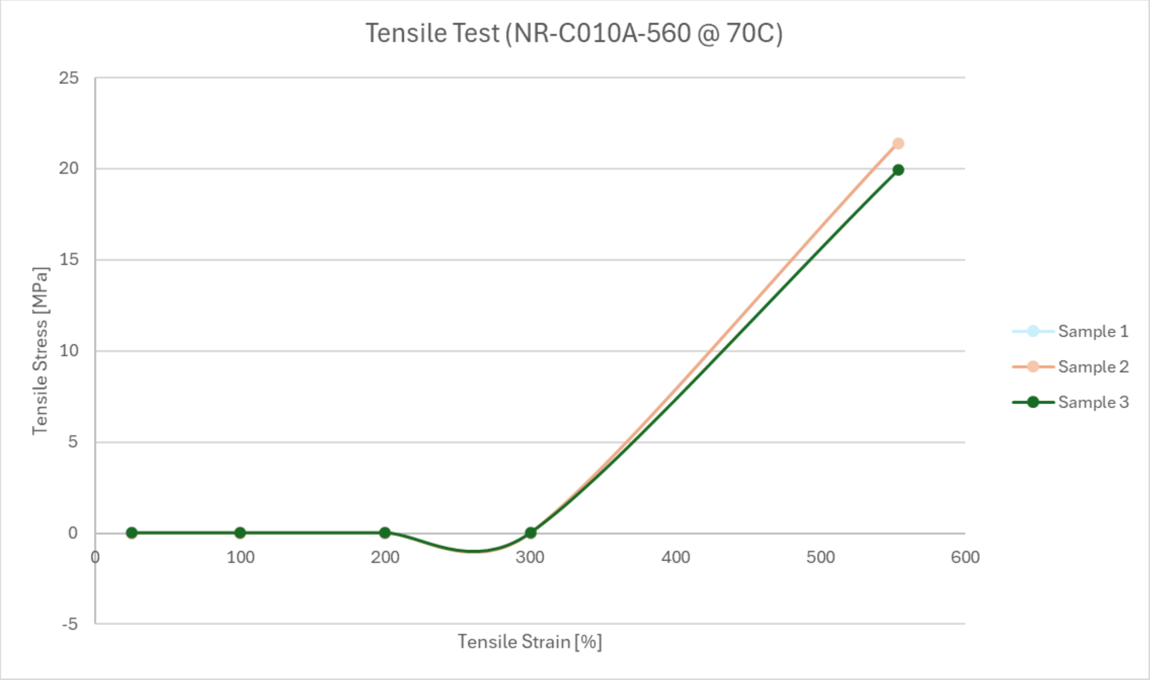


**Table 5**

*NR-C010A-560 at 70°C Data*

| | **Tensile Stress at Break** | **Tensile Strain at Break** | **Extension at Break (Standard)** | **Modulus @ 25%** | **Modulus @ 100%** | **Modulus @ 200%** | **Modulus @ 300%** | **Thickness** |
|---|---|---|---|---|---|---|---|---|
| | MPa | % | mm | MPa | MPa | MPa | MPa | mm |
| **1** | 21.390 | 553.290 | 257.28183 | 0.002 | 0.002 | 0.002 | 0.002 | 2.083 |
| **2** | 21.477 | 508.120 | 293.81046 | 0.007 | 0.007 | 0.007 | 0.007 | 2.117 |
| **3** | 19.938 | 454.000 | 243.58034 | 0.005 | 0.005 | 0.005 | 0.005 | 2.109 |
| **S.D.** | 0.865 | 49.711 | 25.965 | 0.003 | 0.003 | 0.003 | 0.003 | 0.018 |
| **Mean** | 20.935 | 505.130 | 264.89087 | 0.004 | 0.004 | 0.004 | 0.004 | 2.103 |
| **Median** | 21.390 | 508.120 | 257.28183 | 0.005 | 0.005 | 0.005 | 0.005 | 2.109 |

**Figure 6**

*Tensile Test for XC-22161 at 70°C*

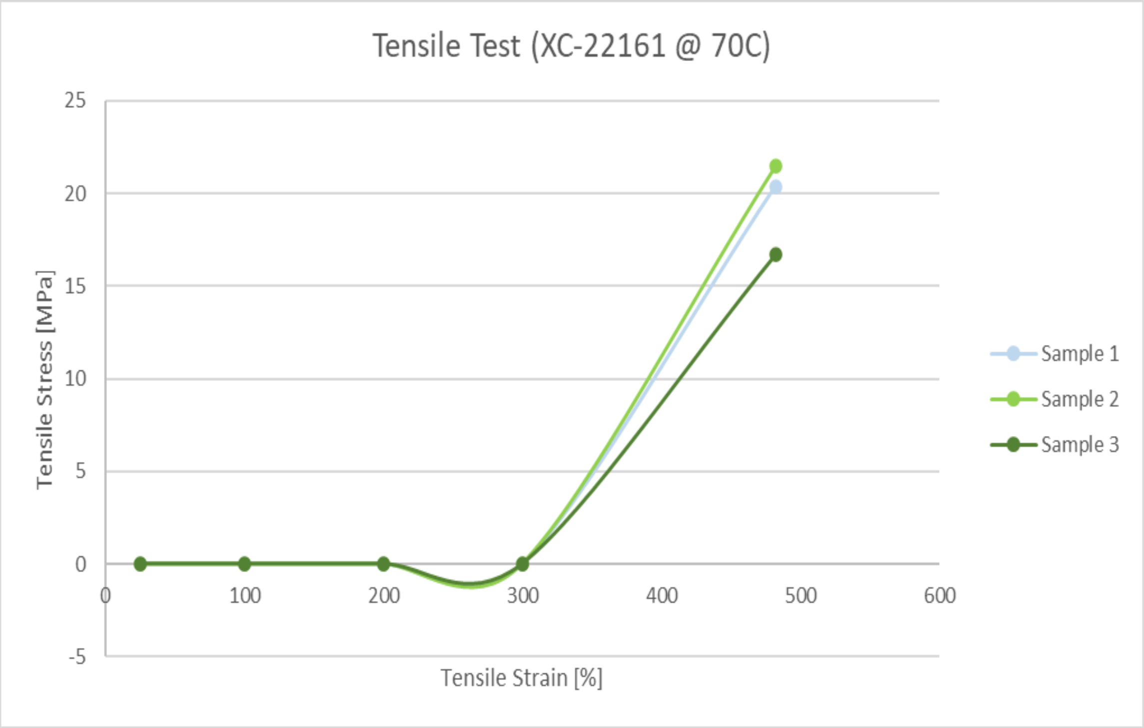


**Table 6**

*XC-22161 at 70°C Data*

| | Tensile Stress at Break | Tensile Strain at Break | Extension at Break (Standard) | Modulus @ 25% | Modulus @ 100% | Modulus @ 200% | Modulus @ 300% | Thickness |
|---|---|---|---|---|---|---|---|---|
| | MPa | % | mm | MPa | MPa | MPa | MPa | mm |
| **1** | 20.363 | 482.19 | 288.73013 | 0 | 0 | 0 | 0 | 2.078 |
| **2** | 21.468 | 517.78 | 297.19711 | 0 | 0 | 0 | 0 | 2.045 |
| **3** | 16.686 | 550.76 | 272.64365 | 0.003 | 0.003 | 0.003 | 0.003 | 2.09 |
| **S.D.** | 2.504 | 34.294 | 12.472 | 0.002 | 0.002 | 0.002 | 0.002 | 0.023 |
| **Mean** | 19.505 | 516.91 | 286.1903 | 0.001 | 0.001 | 0.001 | 0.001 | 2.071 |
| **Median** | 20.363 | 517.78 | 288.73013 | 0.001 | 0.001 | 0.001 | 0.001 | 2.078 |

**Figure 7**

*Tensile Test for XC-22162 at 70°C*

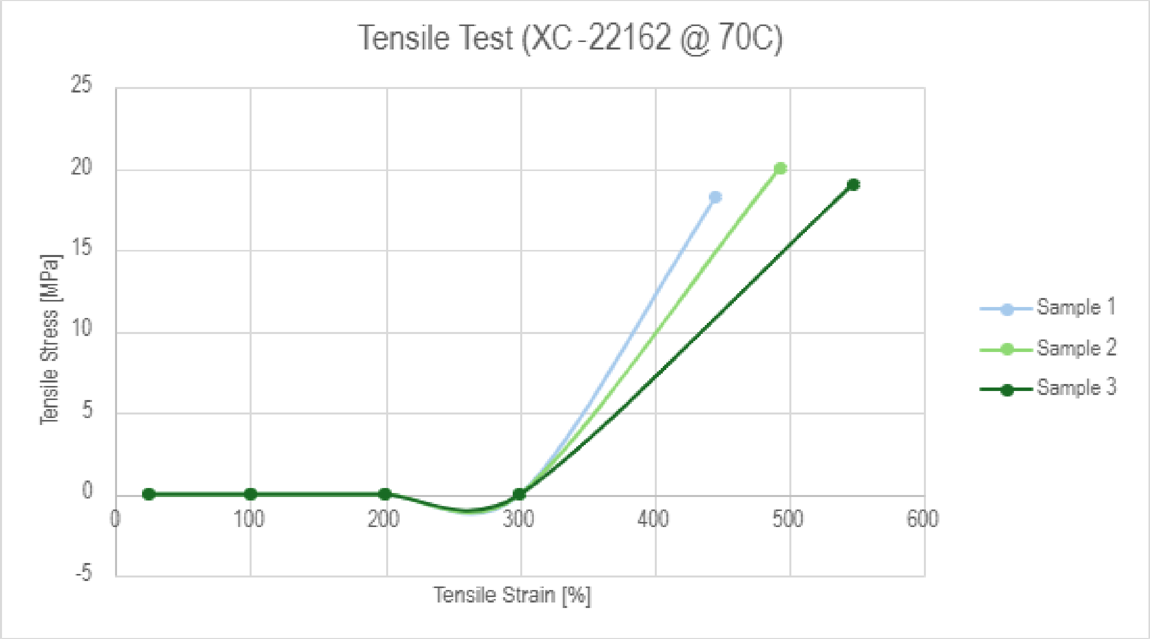


**Table 7**

*XC-22162 at 70°C Data*

| | Tensile Stress at Break | Tensile Strain at Break | Extension at Break (Standard) | Modulus @ 25% | Modulus @ 100% | Modulus @ 200% | Modulus @ 300% | Thickness |
|---|---|---|---|---|---|---|---|---|
| | MPa | % | mm | MPa | MPa | MPa | MPa | mm |
| **1** | 18.3 | 445.14 | 271.79721 | 0 | 0 | 0 | 0 | 2.085 |
| **2** | 20.091 | 492.59 | 290.42361 | 0.001 | 0.001 | 0.001 | 0.001 | 2.059 |
| **3** | 19.059 | 546.62 | 281.11041 | 0 | 0 | 0 | 0 | 2.065 |
| **S.D.** | 0.899 | 50.778 | 9.313 | 0 | 0 | 0 | 0 | 0.014 |
| **Mean** | 19.15 | 494.78 | 281.11041 | 0.001 | 0.001 | 0.001 | 0.001 | 2.07 |
| **Median** | 19.059 | 492.59 | 281.11041 | 0.001 | 0.001 | 0.001 | 0.001 | 2.065 |

**Figure 8**

*Tensile Test for XC-22163 at 70°C*

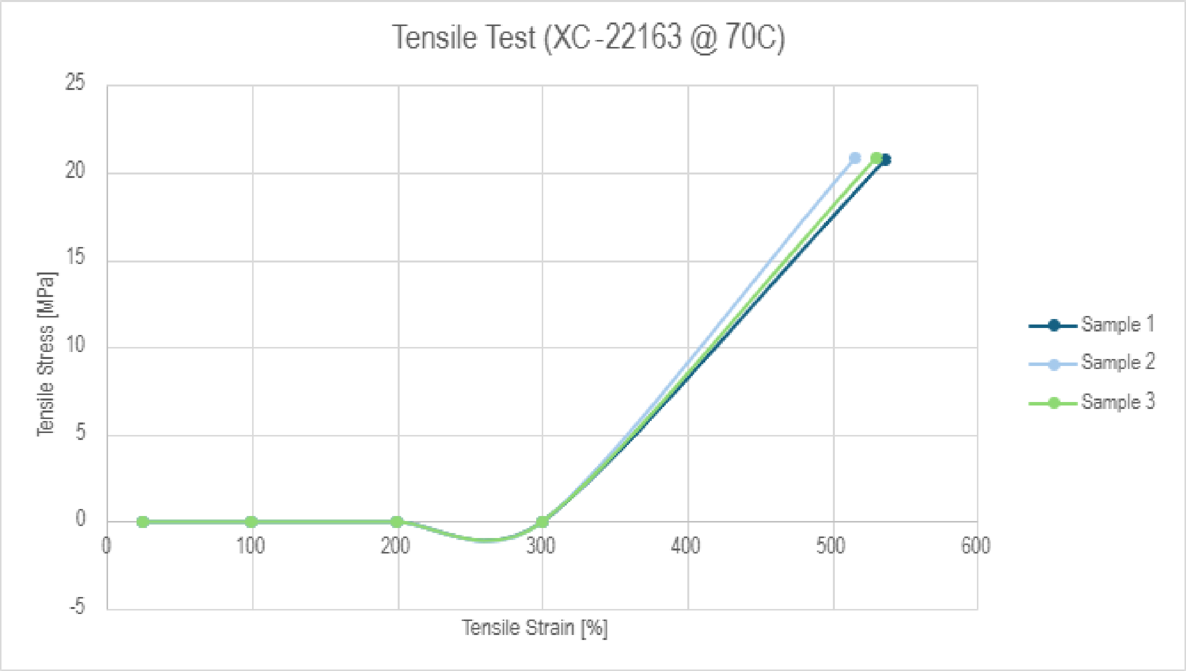


**Table 8**

*XC-22163 at 70°C Data*

| | Tensile Stress at Break | Tensile Strain at Break | Extension at Break (Standard) | Modulus @ 25% | Modulus @ 100% | Modulus @ 200% | Modulus @ 300% | Thickness |
|---|---|---|---|---|---|---|---|---|
| | MPa | % | mm | MPa | MPa | MPa | MPa | mm |
| **1** | 20.755 | 536.42 | 288.73016 | 0.001 | 0.001 | 0.001 | 0.001 | 2.293 |
| **2** | 20.85 | 515.55 | 287.03687 | 0.003 | 0.003 | 0.003 | 0.003 | 2.294 |
| **3** | 20.839 | 529.79 | 281.11044 | 0.001 | 0.001 | 0.001 | 0.001 | 2.305 |
| **S.D.** | 0.052 | 10.665 | 4.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.007 |
| **Mean** | 20.815 | 527.25 | 285.62582 | 0.002 | 0.002 | 0.002 | 0.002 | 2.297 |
| **Median** | 20.839 | 529.79 | 287.03687 | 0.001 | 0.001 | 0.001 | 0.001 | 2.294 |

**A-3. Additional RPA and MDR data.**

**Table 9**

*MDR Data*

| Compound | S' Min | S' Max | Scorch Time (TS 2) | TC 10 | TC 50 | TC 90 |
|---|---|---|---|---|---|---|
| | Lbin | Lbin | Min:Sec | Min:Sec | Min:Sec | Min:Sec |
| **NR-C010A-560** | 1.22 | 9.55 | 0:50 | 0:44 | 0:58 | 1:21 |
| **XC-22161** | 1.46 | 9.45 | 0:59 | 0:50 | 1:07 | 1:35 |
| **XC-22162** | 1.38 | 9.47 | 0:59 | 0:51 | 1:08 | 1:35 |
| **XC-22163** | 1.55 | 10.16 | 0:58 | 0:50 | 1:06 | 1:33 |

*Note.* Samples ran for five minutes at 350°C.

**Table 10**

*RPA Data*

| Compound | Document Links |
|---|---|
| **NR-C010A-560** | https://tbvc-my.sharepoint.com/personal/rachel_kelsey_vibracoustic_com/Documents/THESIS/TESTING%20DATA/NR-C010A-560%20RPA.xlsm |
| **XC-22161** | https://tbvc-my.sharepoint.com/personal/rachel_kelsey_vibracoustic_com/Documents/THESIS/TESTING%20DATA/XC-22161%20RPA.xlsm |
| **XC-22162** | https://tbvc-my.sharepoint.com/personal/rachel_kelsey_vibracoustic_com/Documents/THESIS/TESTING%20DATA/XC-22162%20RPA.xlsm |
| **XC-22163** | https://tbvc-my.sharepoint.com/personal/rachel_kelsey_vibracoustic_com/Documents/THESIS/TESTING%20DATA/XC-22163%20RPA.xlsm |

## A-4. Abbreviations.

NVH – Noise, vibration, and harshness.

NR – Natural rubber.

rCB – Recovered carbon black.

CB – Carbon black.

PAH – Polycyclic aromatic hydrocarbons.

TeCo – Tension and compression.

EOL – End of life.

ShA – Shore A hardness unit.

S.D. - Standard deviation.