



DuPont Advanced Fibers Systems

KEVLAR[®] Engineered Elastomer
for Reinforcement of Rubber Roll Covers

by

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KEVLAR® Engineered Elastomer for Reinforcement of Rubber Roll Covers

ABSTRACT

KEVLAR® engineered elastomer, a composite of KEVLAR® pulp and elastomer, enables incorporating high-surface-area para-aramid pulp reinforcement to rubber compounds. It affords the rubber chemist opportunities to go beyond present limits in designing rubber compounds. It not only provides a vehicle for aramid pulp reinforcement of rubber compounds; but also, by its proprietary manufacturing process, maximizes the effectiveness of aramid pulp reinforcement.

Engineered elastomer builds tensile and compressive modulus at low loadings allowing compounds to be re-engineered to enhance properties. It is possible to obtain very high modular anisotropy by extruding or milling a compound into a thin sheet. Tear resistance can be increased, and tear propagation can be reduced. Compounds reinforced with engineered elastomer have excellent dynamic properties. It enables building modulus without significantly increasing hysteresis. It is also highly effective as a processing aid by increasing compound green strength.

Rubber roll cover compounds reinforced with engineered elastomer have been developed and are in routine use in several industries. Rolls covered with these compounds have demonstrated reduced abrasion, better cut resistance, and lower cut growth resistance – and thus a longer life in use.

INTRODUCTION

DuPont™ KEVLAR® brand fiber was introduced in the 1970's. KEVLAR®, the world's first para-aramid fiber, is known for its high strength to weight ratio, high modulus, and excellent chemical and thermal stability. Initially, it was offered in continuous filament form, and soon found applications in tires, mechanical rubber goods, bullet resistant vests, and composites. In the 1980's, short forms of the fiber - staple, floc, and pulp - were introduced and quickly found acceptance in cut-resistant protective apparel, gaskets, and friction materials. Photographs of these three product forms are shown in **Figure 1**.

Once short forms of KEVLAR® and Akzo's (now Teijin Twaron's) para-aramid TWARON® were introduced, they were evaluated for rubber reinforcement. Using short fibers (such as cellulose, cotton linters, cut scrap denim, polyester, and nylon) to reinforce rubber is common in the rubber industry. They improve green strength, provide dimensional stability prior to cure, and improve mechanical properties of the vulcanizate. Compounders found that they could incorporate para-aramid floc (we define floc as short uncrimped fiber less than 6 mm long) into rubber using an internal mixer or a roll mill, often with difficulty. An electron photomicrograph showing floc in a rubber compound may be found in **Figure 2**. Incorporating the high-surface-area pulp product (**Figure 3**) proved to be exceedingly difficult. Para-aramid pulp is a low bulk density, static-prone material that is hard to handle in a rubber plant. A few people were able to adequately disperse pulp into a rubber compound. Their work did demonstrate the superior reinforcement potential of aramid pulp if the dispersion limitation were overcome. Compounds reinforced with pulp had 3-5x higher modulus at a given loading than those reinforced with floc. Pulp reinforced compounds also had lower heat build up in dynamic applications, and they had better processing characteristics. An electron photomicrograph showing pulp in a rubber compound may be found in **Figure 4**.

The rubber industry frequently utilizes dispersion or masterbatch technology to incorporate materials that are difficult to mix into a rubber compound. This was quickly identified as the preferred method for incorporating aramid pulp into a rubber compound.

DuPont initiated studies to define a method to disperse para-aramid pulp into rubber, and this effort led to development of a unique new technology platform for dispersing pulp into an elastomer matrix. Products produced via this technology showed superior dispersion of aramid pulp in rubber compounds. Two samples of rubber compound having identical compositions were analyzed using an ultrasonic scanning technique that measures relative porosity; the two scans are shown in **Figure 5**. In the sample on the left, the pulp was introduced using engineered elastomer; in the sample on the right, the pulp was added directly into the rubber. Both compounds were mixed using a laboratory scale internal mixer. A uniform color indicates a homogenous mixture. The sample made by compounding pulp directly into the rubber shows significant color differences indicating relatively poor fiber dispersion; the sample prepared using engineered elastomer is nearly a uniform color, demonstrating its excellent dispersion.

Product made via this new technology enabled dispersion of pulp into rubber so well that it was given a new name, 'KEVLAR® engineered elastomer.' Initial evaluation in the rubber industry confirmed that engineered elastomer was far easier to process than dry para-aramid pulp, and confirmed the improved dispersability of pulp made possible by using this offering. Initial adoptions for engineered elastomer were in power transmission belts. This industry had experience with short-fibers, a common ingredient in belt formulations.

REINFORCEMENT EFFICIENCY

One of the first rubber chemists who evaluated engineered elastomer found it highly effective in rubber reinforcement. This person described the offering as having...

“an intimacy between the rubber and particle never before reached via conventional compounding.”

We also learned that several other customers who had been able to achieve good dispersion of dry para-aramid pulp in rubber found better reinforcement when using engineered elastomer to introduce pulp into their compound. They obtained up to 20% higher modulus at the same fiber content when using engineered elastomer rather than using raw pulp. Internal DuPont data illustrating the improved reinforcement efficiency is shown in **Figure 6**. The NR/SBR tire tread compound reinforced with engineered elastomer had about an 8% higher modulus than an identical compound reinforced with dry pulp.

We proposed a hypothesis to explain the basis for this improved reinforcement; the hypothesis is based on:

- Superior dispersion of the fiber,
- Openness of the fiber, and
- The microstructure of para-aramid fiber.

The importance of good dispersion of fillers in a rubber compound is well known in the rubber industry. Dispersing fibers into a rubber compound can be more challenging than using traditional fillers. Fibers can form tangles (called neps in the fiber industry) that are not likely to be removed in rubber mixing. It is also important that the concentrate be well dispersed (mixed) into the final rubber compound. Both fiber neps and undispersed concentrate can form defect sites that can lead to failure of the rubber compound. An example of both tangles and undispersed concentrate in a compound is shown in **Figure 7**. Eliminating defects like those shown in **Figure 7** requires that the technology used to prepare the concentrate treat the pulp in a manner to avoid forming tangles, and that the rubber mixing technology subject the concentrate to sufficient shear to blend the concentrate into the compound.

Our quality policy states that “The KEVLAR® organization will be recognized as providing superior value and continual improvement in all the customer services and products supplied.” We strive for continual improvement in our engineered elastomer product. All products are tested for dispersion of pulp into the concentrate. We have reduced the number of apparent ‘defects’ in our product by over 30%. We have changed the physical form of the offering to a more ‘user friendly’ form that more easily incorporates into a rubber compound. We continually look for improvements in mixing procedures to make the mixing process easier and suggest these improvements to our customers.

Openness is also essential to maximize the reinforcement potential of aramid pulp. Note the number of fine fibrils present in the electron micrograph of the pulp shown in **Figure 3**. Having these fibrils 'open' and extended is essential. Photographs of two compound samples illustrating openness of pulp are shown in **Figure 8**. The photo on the right is of a compound reinforced with KEVLAR[®] engineered elastomer. Note the number of extended fibrils present in the photograph. An identical compound formulation, mixed by the same procedure, is shown on the left. The aramid pulp was incorporated using a concentrate prepared by a technology different from that used to produce engineered elastomer. Note that the pulp is not as extended and, in some cases, even appears somewhat compacted.

Openness is essential to achieve interaction between the fiber and rubber. The polymer base for para-aramid is poly(p-phenylene terephthalamide); a rigid rod molecule. When spun into fiber, the polymer becomes highly oriented and highly crystalline. The high orientation allows extensive hydrogen bonding between the carbonyl and 'N-H' functionality in the amide groups of adjacent polymer chains (**Figure 9**.) KEVLAR[®] fiber is spun from highly concentrated sulphuric acid. Free SO₃⁻ in the solvent sulphonates some of the aromatic rings, and studies within DuPont suggest that the resulting sulphonic acid groups tend to be accessible at the fibril surface. Thus, the pulp fibril surface contains polar groups (amide and sulphonic acid on the polymer backbone as well as amine and carboxylic acid end groups) that can associate with a group on an elastomer.

We believe that the well-dispersed, well-opened pulp fiber present in KEVLAR[®] engineered elastomer can associate with the elastomer matrix. Evidence for this association of the elastomer with charged groups on the fibril surface is provided by gravimetric determination of fiber content of engineered elastomer. When engineered elastomer grades in neoprene that contain 23% fiber on a weight basis are analyzed by gravimetric analysis, they average about 26% fiber. Gravimetric analysis of 'apparent' fiber content of engineered elastomer in the more polar NBR matrix averages 29.1% fiber, although the nominal fiber concentration is 23 weight percent. Non-fiber containing controls, subjected to our process, show no fiber present.

We propose that the gravimetric analyses provide the evidence for 'bound rubber' in engineered elastomer, similar to bound rubber in carbon black. Bound rubber theories for carbon black assume that segments of elastomer molecules adhere to 'active sites' or 'reactive sites' on the filler particles. Leblanc describes this theory in a recent publication ⁽¹⁾. A similar mechanism could certainly be operative in engineered elastomer.

(1) J. L. Leblanc, *J. Applied Polymer Science*, **66**, 2257 (1997).

The key requirement for our hypothesis is high accessibility of the surface of the pulp to the elastomer. The patented process used to prepare engineered elastomer presents the pulp to the elastomer in a way that the fiber is fully open to allow the elastomer to completely wet the fibrils. The engineered elastomer process maximizes the wetting of the pulp allowing it to reinforce with maximum efficiency. If pulp is mixed directly in an internal mixer or roll mill, or if a 'masterbatch' of pulp in rubber is made by other technologies, the pulp can become compacted to some degree, and its reinforcing potential can not be fully realized. The process by which engineered elastomer is manufactured creates the intimacy between the rubber and particle. Engineered elastomer is more than a simple masterbatch or dispersion of pulp in elastomer.

REQUIREMENTS IN ROLL COVERS

One 'product need' for a roll cover is that it has long life in service. Service life can be affected by a number of factors. Certainly, the elastomer matrix is critical; the elastomer must be stable to the chemical environment and temperature in which the roll will operate. Other important considerations are the physical properties of the compound; its hardness, abrasion resistance, tear resistance, compression set, and dynamic properties.

There are many references that summarize the chemical and thermal resistance of different elastomer matrixes, included the Rubber Roller Group Handbook, a benefit of being a member of the Rubber Roller Group. KEVLAR[®] pulp is a remarkably chemically stable material. It is stable in most organic solvents, salt solutions, petroleum products, and many dilute acids and bases over a broad temperature range. Its limitations are primarily strong aqueous acids, bases and bleach over long periods of time and at elevated temperatures.

Once the elastomer matrix for a roll cover is selected, the goal is often to maximize the abrasion and tear resistance of the rubber compound. The dynamics of a roll cover are complex; a schematic is shown in the Roller Group Handbook. A good discussion of a possible mechanism for abrasion of a rubber covered roll is described in an article published by Metlikovic and Meineke⁽²⁾. Abrasion results from pressure on the working roll, which causes a stress on the rubber covering. This stress leads to a strain, or deformation of the rubber. The strain causes a bulge in the rubber as it approaches the pressure point (roll nip.) The shape of the roll cover changes from the dotted line to the solid line as shown in **Figure 10**.

(2) P. Metlikovic and E. Meineke, "Stesses, Slip and Abrasion of Rubber Covered Conveyor Rollers, A Review", Paper 66, ACS Rubber Division Meeting, Louisville, 1996.

The rubber moves rapidly in the entry bulge as the turning roll approaches the point of maximum stress. The rubber is subjected to a tangential shear stress and a normal friction stress. Since the shear stress is greater than the friction stress between points A and B, the rubber slips in this region. This slipping under stress can lead to abrasion of the roll cover. A similar situation exists in the exit bulge and slipping occurs between points C and D. The theory presented in Melokovic and Meineke's paper predicts that abrasion is inversely proportional to compound modulus; abrasion resistance can be improved by increasing compound modulus.

EFFECT OF ENGINEERED ELASTOMER ON COMPOUND PROPERTIES

KEVLAR[®] engineered elastomer builds compound modulus very efficiently. The effect of aramid pulp on modulus in a SBR/BR treadstock is shown in **Figure 11**. Modulus increases dramatically at low fiber loading.

Para-aramid pulp has a high L/D aspect ratio. This geometry makes possible an orientation of the particle when sheared in processing. Calendering or extruding compounds reinforced with aramid pulp leads to modular anisotropy – a difference in modulus between the machine direction (MD) and cross machine direction (XMD.) This modular anisotropy is illustrated in the data shown in **Figure 11**. MD modulus is about 5X that of XMD modulus in 2-mm test pieces of this NR/SBR tire tread compound. Samples calendered or extruded to thinner sheets will display even higher anisotropy. Some users of engineered elastomer routinely achieve MD/XMD ratios greater than 10.

Using engineered elastomer to reinforce a roll cover compound can help reduce wear due to slipping and abrasion. By designing the roll so fibers are aligned in the circumferential direction (a strip builder for rolls will achieve this orientation), the modulus or stiffness of the compound can be increased in this direction. The strain at a given stress will be reduced, so the entrance and exit bulge in a running roll will be reduced. However because of the modular anisotropy possible with aramid pulp reinforcement, radial and axial moduli are increased to a lesser extent.

The ability of engineered elastomer to efficiently build compound modulus was mentioned previously. As seen in **Figure 12**, aramid pulp builds modulus about 3 to 5 times more efficiently than short fibers or flocs that are often used in neoprene power transmission belt compounds. **Figure 13** illustrates the effect of adding both carbon black and pulp to a NR tire compound. The lowest curve is a gum rubber compound. The next three stress-strain curves show the increase in modulus by adding 30, 45 and 60 phr N330 carbon black. The upper two curves show the dramatic increase in modulus achieved by adding 1 and 3 phr aramid pulp to the compound. Aramid pulp addition of only 1 phr gives a greater increase in modulus than 15 parts of N330.

Increasing compound modulus using traditional stiffening agents typically results in an increase in compound hardness. For a roll cover, an increase in hardness may mean a sacrifice in roll grip since a harder roll may have less desirable frictional properties. Engineering the rubber compound by balancing the relative content of aramid pulp and other reinforcing agents allows for increased modulus without an increase in hardness. This is illustrated in a NBR roll compound formulation in **Figure 14**. Compounds were prepared at different loadings of silica and aramid pulp. The control (no fiber compound) has a Shore 'A' durometer hardness of 81. A compound of 80 durometer was prepared with >6X higher modulus (13.1 vs 2.1 MPa) by addition of 9 phr aramid pulp while decreasing silica from 45 to 15 phr.

Additional data from this compound study are shown in **Figure 15**. Incorporating engineered elastomer into the rubber compound enabled an improvement in both tear and abrasion – two key properties for improved performance in a rubber covered roll. Aramid pulp enables desirable improvements in modulus, tear and abrasion resistance without affecting hardness or affecting processability. Mooney viscosity of these NBR roll cover compounds is shown in **Figure 16**. The modulus increase in the neoprene power transmission belt compounds (**Figure 12**) was accompanied by a lower increase in Mooney viscosity than when using flocs.

Compounds reinforced with engineered elastomer display modular anisotropy, a great increase in modulus in the machine direction, and a far smaller increase in modulus in the cross-machine direction. In contrast, tear resistance increases in both the machine (MD) and cross-machine (XMD) direction. Data from the SBR/BR heavy duty treadstock study are shown in **Figure 17** (trouser tear) and **Figure 18** (Die C Tear.) We attribute the isotropic increase in tear resistance in compounds reinforced with engineered elastomer to the three dimensional nature of aramid pulp, and to the openness of the pulp which results from our manufacturing process.

Compounds reinforced with engineered elastomer behave quite differently than their no-fiber controls in tear testing. Control compounds will stretch in the tensile test machine, and then suddenly fail. A compound reinforced with engineered elastomer will stretch as it is pulled in the tensile tester; one or more 'notches' will form on one side as stretching continues. Ultimately, the compound reinforced with engineered elastomer will fail – at a higher tear strength than the no-fiber control. Photographs of a tear test are shown in **Figure 19**. The photo on the left is of the control compound; this EPDM based roofing compound failed at 183 lbs/inch. The photo on the right is of the same compound reinforced with engineered elastomer. Note the notch that has developed. This compound had a tear strength of 230 lbs/inch, a 26% improvement over the no-fiber control.

In general, it is important to reformulate a compound to make best use of engineered elastomer reinforcement. It is unlikely that one can achieve property goals by simply dropping aramid pulp into an existing formulation.

Roll covers are a dynamic application. The rubber compound will see cyclic stress-strain behavior in the end-use. We have conducted an extensive study to determine the behavior of a compound reinforced with engineered elastomer in cyclic, dynamic conditions.

The cyclic stress-strain behavior of para-aramid pulp reinforced NR compounds was observed over 10 cycles up to 2.5, 10, and 50% strain. In these tests, the first cycle was at the given strain, and subsequent cycles at the (constant) force required to achieve this strain in the first cycle. Some of the test details are described in **Figure 20**. Typical curves from the test at 10% ultimate strain are shown in **Figure 21**; the curves for the first and tenth cycle are shown.

The energy loss fraction (fraction of energy dissipated in each cycle as shown in **Figure 22**) was calculated from the stress-strain curves for each cycle (**Figure 23**.) The energy loss fraction was:

- Nearly constant after the first cycle;
- Nearly the same in the machine and cross-machine direction, and
- Nearly independent of the fiber concentration in the compound (**Figure 24**.)

The stress-strain behavior of engineered elastomer reinforced compounds after cycling was also measured. These tests were conducted at 10, 30, 50 and 100% strain, and after 2, 10 and 100 cycles. Measurements were made in both the machine and cross-machine direction (with and against fiber orientation.) A description of the test is shown in **Figure 25**. The stress-strain curves in the machine direction for the reference (no fiber compound) after 2, 10 and 100 cycles at 10% strain and for the compound containing 1 phr para-aramid pulp are shown in **Figures 26 and 27**. The effect of cycling on stress-strain behavior is nearly identical for both compounds. Similar nearly identical results were obtained with samples cycled to other strains, and those measured in the cross-machine direction.

Short-term dynamic properties in compression were measured using plied-up cylinders (disks.) The specimens were precompressed to 10%, and were measured from 0.1% to 5% dynamic strain at 1, 10 and 100 Hz, and at 20° and 100°C.

Curves for compound containing 1 phr aramid are shown in **Figure 28** (20° C) and **Figure 29** (100°C). Stiffness at 1 and 3 phr aramid content at 1% dynamic strain is shown in **Figure 30**. Stiffness, as expected, increases with increasing fiber content. Loss angle was almost totally independent of fiber content as shown in **Figure 31**.

Short-term dynamic properties in tension were measured using molded strips prestressed to 5%. Samples were measured at 0.1% to 5% dynamic strain at 1, 10 and 100 Hz, and at 20° and 100°C.

Results were quite similar to those of the short-term dynamic properties in compression. Curves at 20° and 100°C are shown in **Figure 32** and **Figure 33**. Stiffness increased with increasing fiber content (**Figure 34**) while loss angle was relatively independent of fiber content (**Figure 35**.)

Both dynamic tests, compression and tension, showed that loss angle was nearly independent of fiber content. This is in contrast to carbon black reinforcement where loss angle is quite dependent upon concentration (**Figure 36**.)

In general, engineered elastomer enables developing high modulus compounds with reduced potential for heat generation. High modulus power transmission belt compounds in neoprene were developed with lower tan delta than comparable compounds reinforced with flocs (**Figure 37**.) The dynamic modulus of a NR/SBR treadstock was increased by use of engineered elastomer with no increase in tan delta over a broad frequency range (**Figure 38**.)

The stress-strain curves of compounds reinforced with para-aramid pulp are nearly linear with 'high modulus' at low strain, and at again with 'lower modulus' at high strain. Tensile modulus in the direction of fiber orientation (machine direction - MD) is higher than that perpendicular to the direction of orientation (cross-machine direction – XMD.) The MD/XMD modulus difference (anisotropy) of the compounds peaks near 50% strain. **Figure 39**, shows the relationship between modular anisotropy, strain and fiber content where anisotropy is calculated from the absolute stress values at a given strain. Anisotropy peaks at about 60% strain for the compound reinforced with 1 phr of para-aramid pulp, and at about 50% strain for the compound with 3 phr reinforcement. **Figure 40** shows an identical plot where modular anisotropy is calculated by the tangential stiffness at a given strain. Anisotropy peaks at about 40% for the compound with 1 phr of pulp, and at about 30% for the compound containing 3 phr pulp. The transition or inflection in the stress-strain curve always occurs around 50% strain. Acoustic emission tests were conducted on a number of compounds, both with and without engineered elastomer reinforcement. Specimens were pulled at a constant rate of 2 inches per minute, and the acoustic output monitored throughout. Key observations made during the testing included:

- Each material (non-pulp-reinforced and pulp-reinforced) showed detectable acoustic activity.
- The amount of acoustic activity, as measured by the total number of events, was roughly proportional to the amount of pulp present (**Figure 41**).
- The amplitude (intensity) of the acoustic events was similar; that is, the fiber compounds reinforced with pulp did not produce louder events, just more of them.

The peak acoustic activity was determined by plotting the data as ‘hits’ per strain interval (**Figures 42 and 43.**) We found that peak acoustic activity occurs in the range 40-60% strain; this corresponds to the region where the stress-strain curve changes slope. The onset and peak of acoustic activity for the three compounds is summarized below:

<u>Pulp concentration (phr)</u>	<u>0</u>	<u>1</u>	<u>3</u>
Onset of acoustic activity			
% Strain	14-38	26-36	24-37
Stress (lbs)	<10	16-18	26-30
Peak of acoustic activity			
% Strain	51-85	60	47-54
Stress (lbs)	8-15	22-23	38-40

We hypothesize that reinforcement of elastomers by para-aramid pulp involves association between charged groups on the fibril surfaces and those in the elastomer, a mechanism similar to bound rubber theories for carbon black. It is our belief that acoustic emission testing is recording the disruption of the association between the charged groups on fibrils and elastomers. We therefore recommend that engineered elastomer be considered primarily in applications where strain does not exceed 40 to 50%.

ROLL COVER PERFORMANCE

Engineered elastomer is used in a number of commercial roll cover applications. Actual end-use performance data and case histories are, of course, proprietary to each customer and can not be reported in this paper. However, in summary, the following can be stated regarding performance of roll covers reinforced with KEVLAR® engineered elastomer:

- Roll life improvement ranged from 2x to 10x.
- Tear resistance was improved.
- Tear growth potential was reduced.

Engineered elastomer is available in a number of elastomer matrixes. A list is included in **Figure 44.**

CONCLUSIONS

- Engineered elastomer can be used to significantly reinforce rubber compounds for roll cover applications.
- The reinforcement efficiency is significantly greater than that of other commonly used reinforcing materials such as carbon black and silica.
- A high level of modular anisotropy can be introduced to a compound by conventional processing techniques.
- Hysteretic properties are nearly unaffected by the concentration of engineered elastomer pulp used in the compound.
- Stress-strain and acoustic emission data suggest that association between elastomer and fiber exists up to 40-50% strain.
- Tear resistance can be improved by incorporation of engineered elastomer into a compound.
- Tear growth resistance can be improved by incorporation of engineered elastomer in a roll cover compound.
- KEVLAR[®] engineered elastomer reinforcement should be considered for demanding roll cover applications.

Product safety information is available upon request.

This information corresponds to our current knowledge on the subject. It is offered solely to provide possible suggestions for your own experimentations. It is not intended, however, to substitute for any testing you may need to conduct to determine for yourself the suitability of our products for your particular purposes. This information may be subject to revision as new knowledge and experience becomes available. Since we cannot anticipate all variations in actual end-use conditions, DUPONT MAKES NO WARRANTIES AND ASSUMES NO LIABILITY IN CONNECTION WITH ANY USE OF THIS INFORMATION. Nothing in this publication is to be considered as a license to operate under or a recommendation to infringe any patent right.

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Fax: 81-3-3242-3183

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Figure 1

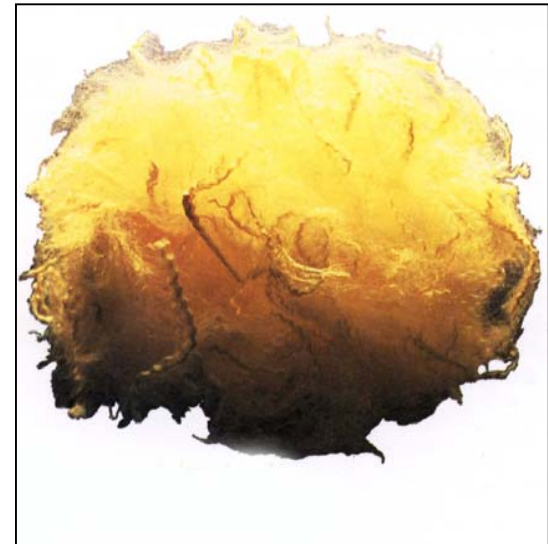
Commercial Forms of KEVLAR®



Pulp



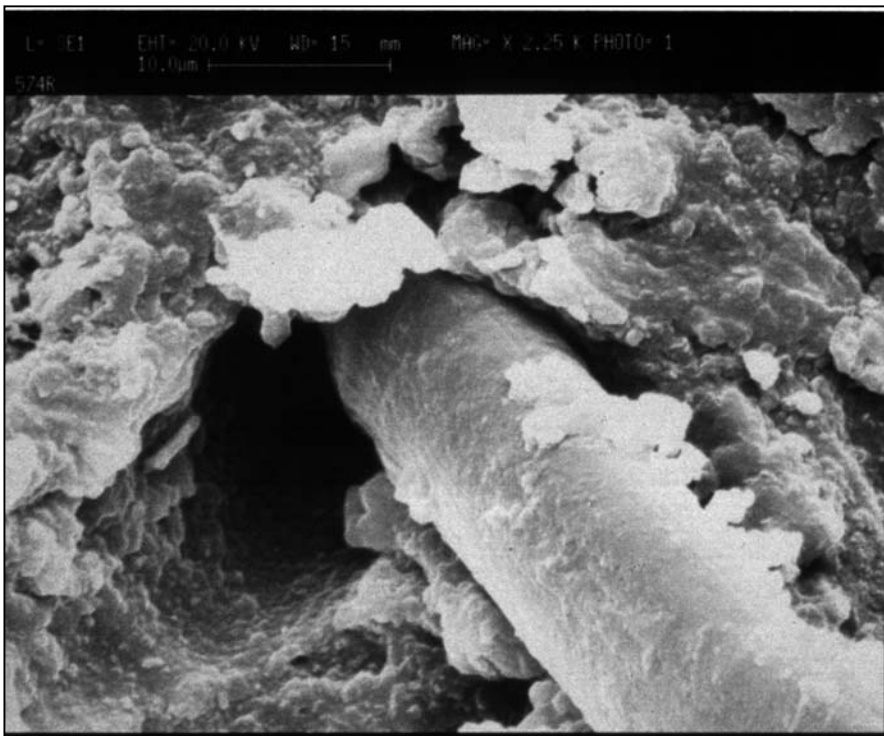
Filament



Staple

Figure 2

Aramid Floc in Rubber



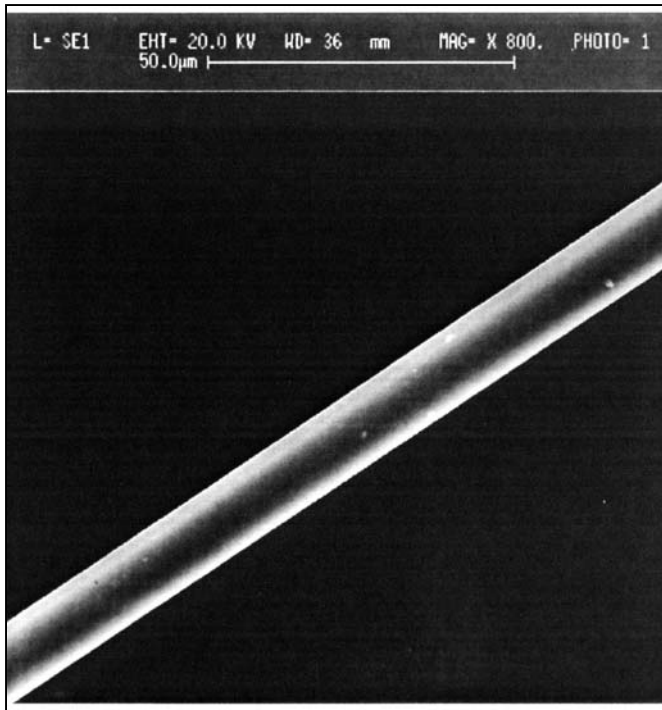
**Staple on V-belt
surface**



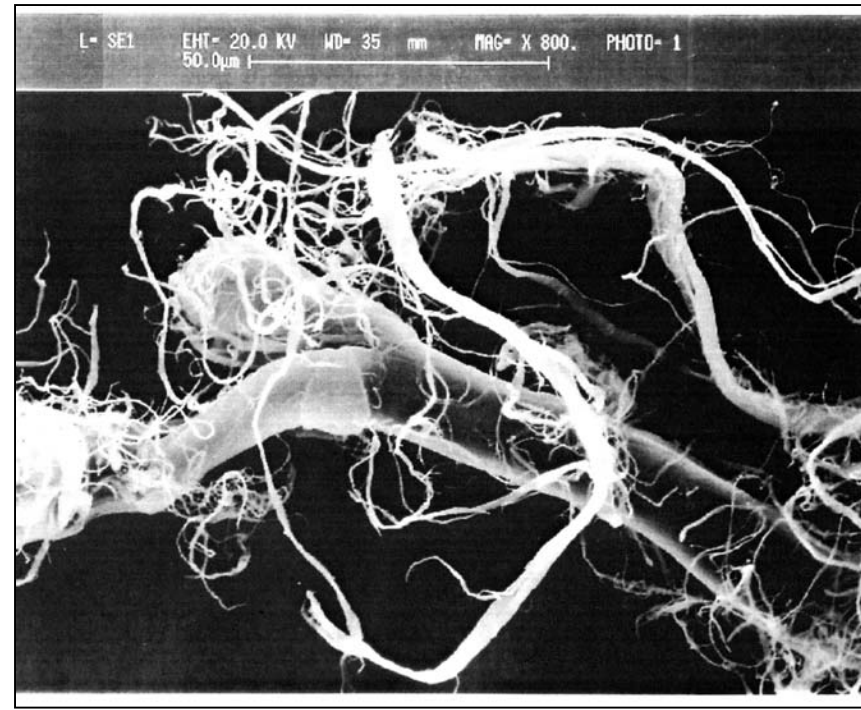
**Staple in V-belt
compound**

Figure 3

Pulp Versus Floc Fiber Form



0.1-0.3 m²/g



7-9 m²/g

Figure 4

Pulp Fiber in Rubber

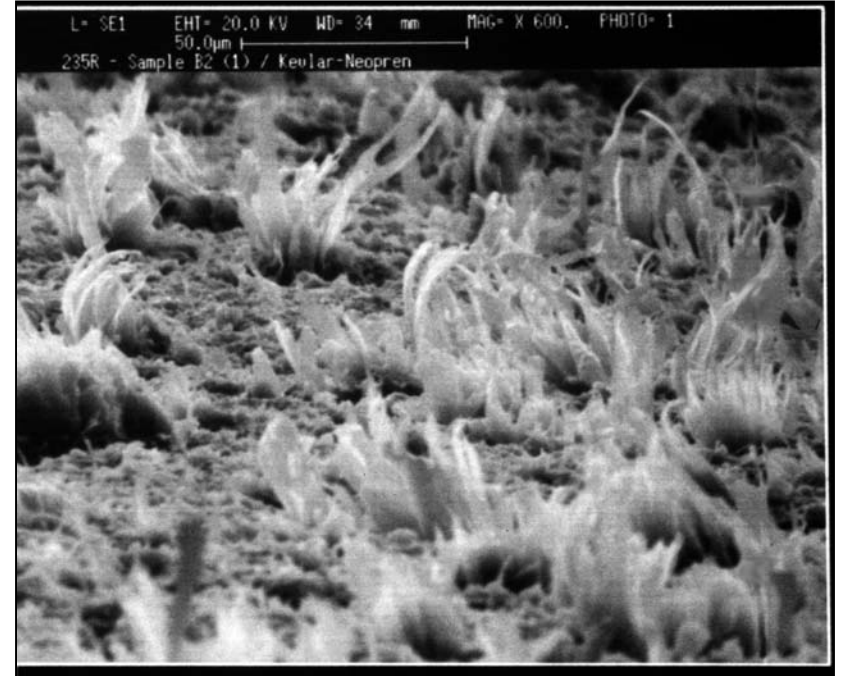
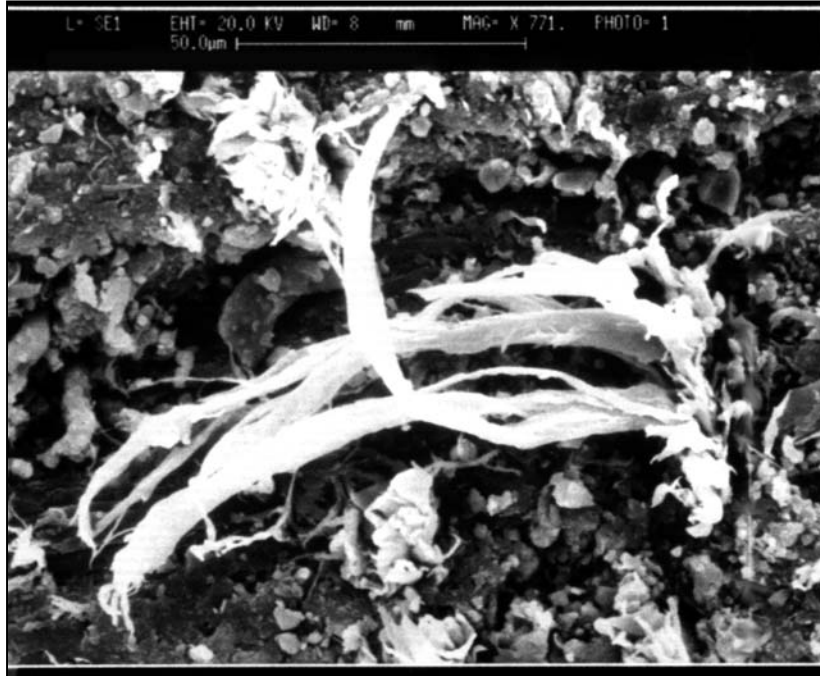


Figure 5

Fiber Dispersion and Uniformity with and without use of KEVLAR[®] Engineered Elastomer

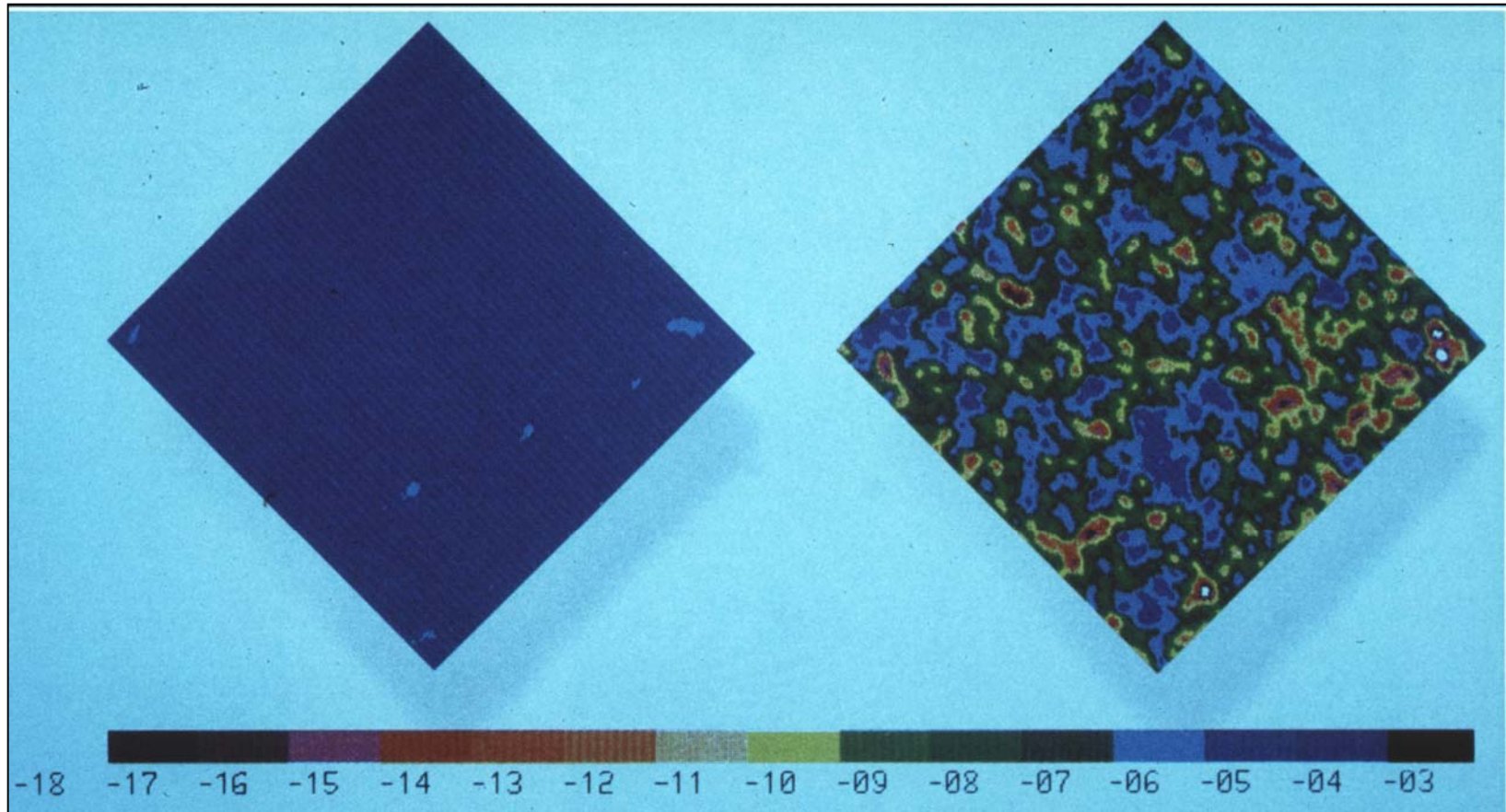


Figure 6

Improved Reinforcement from Engineered Elastomer vs Dry Pulp

MODULUS AT 20% ELONGATION

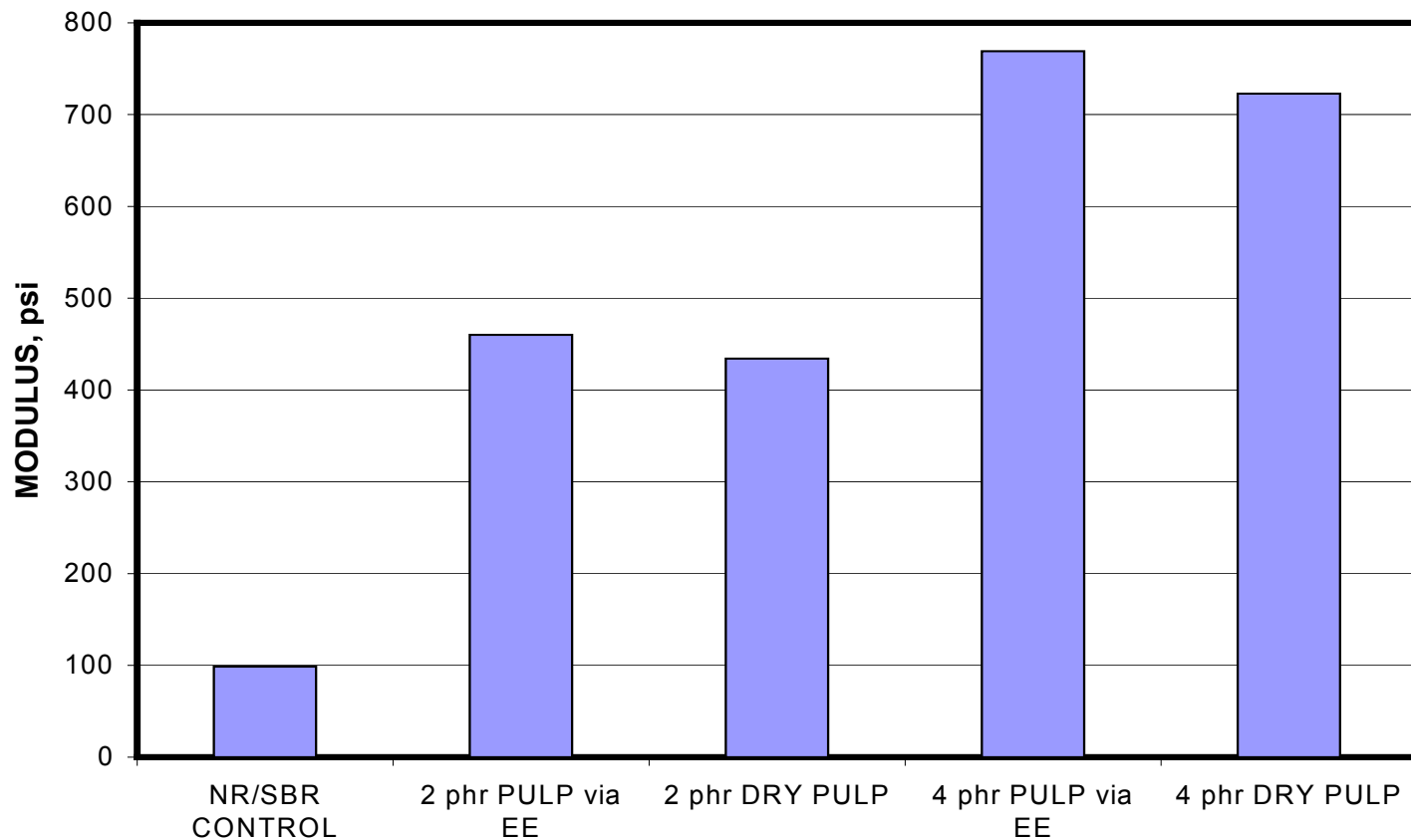
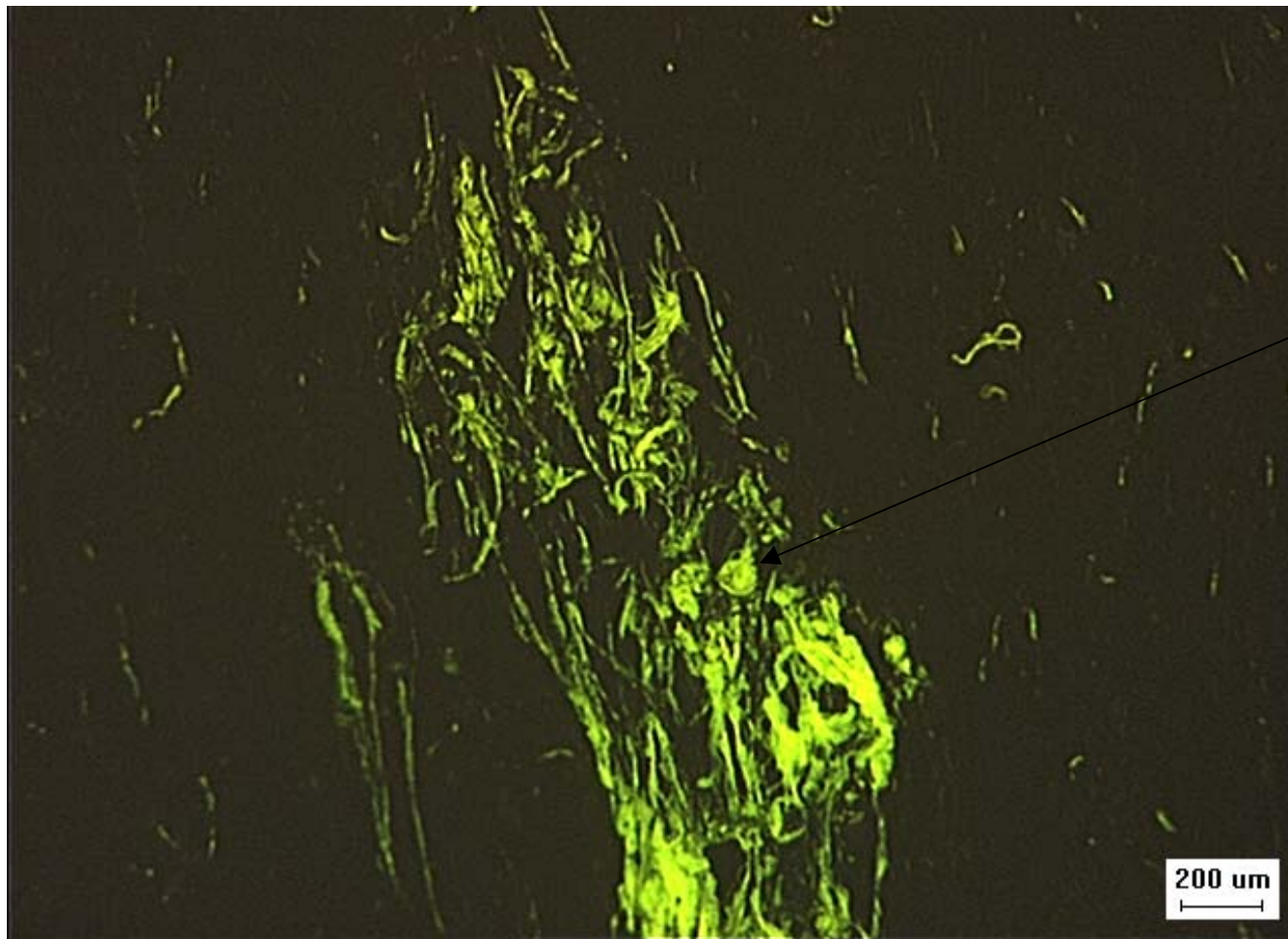


Figure 7

Compound with Undispersed Concentrate



Tangled
Fiber

Figure 8

Compound Samples Illustrating Degree of Openness

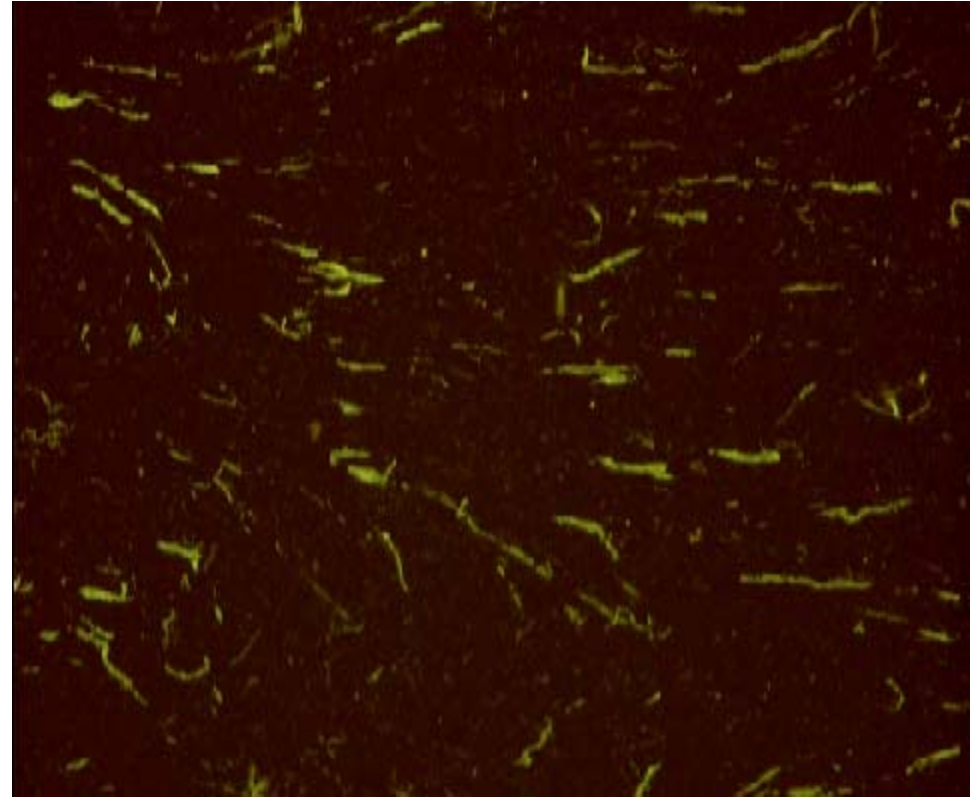
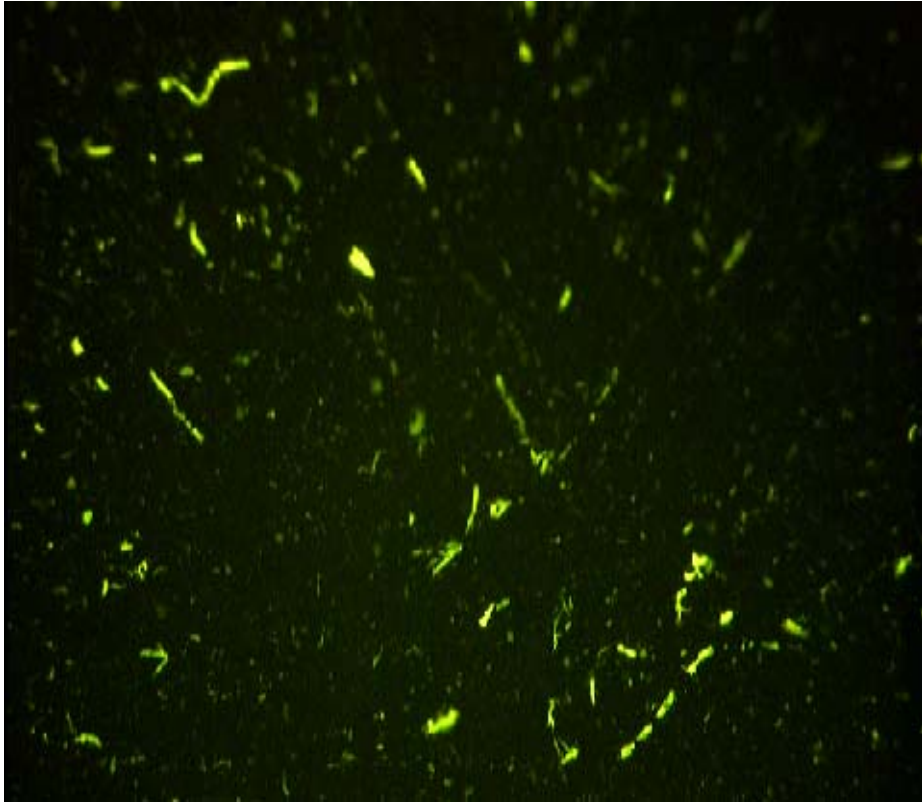


Figure 10

Roll Cover Dynamics

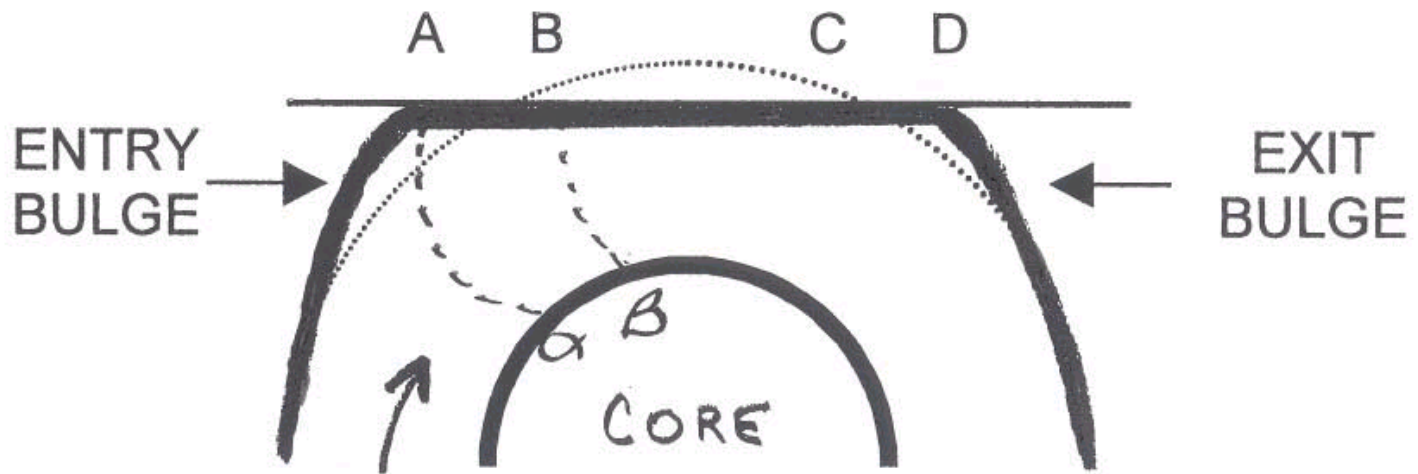


Figure 11

Effect of Engineered Elastomer On Compound Modulus

MODULUS AT 20% ELONGATION
CROSS MACHINE DIRECTION

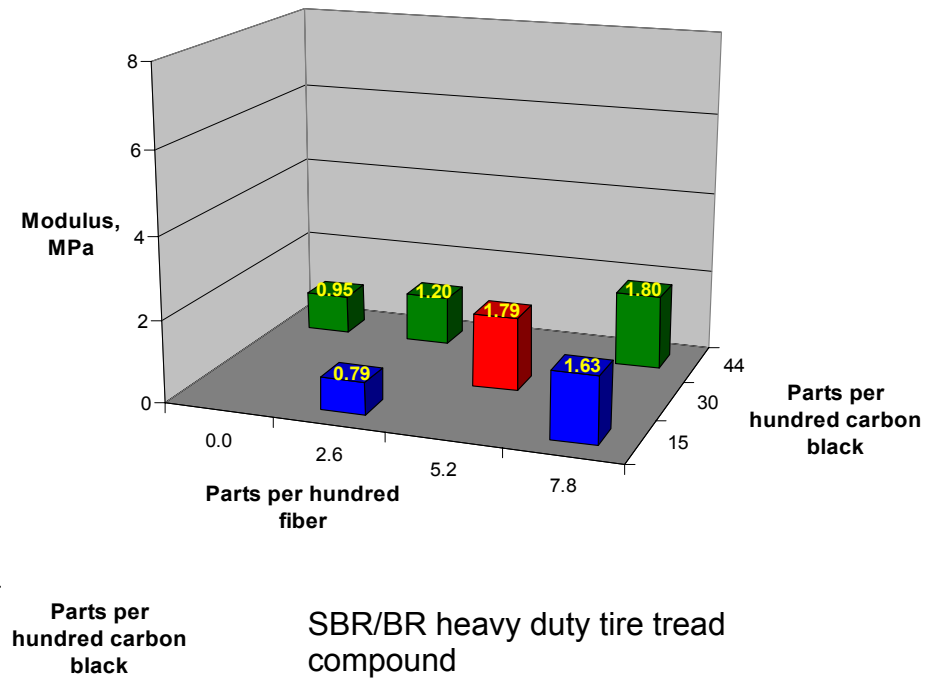
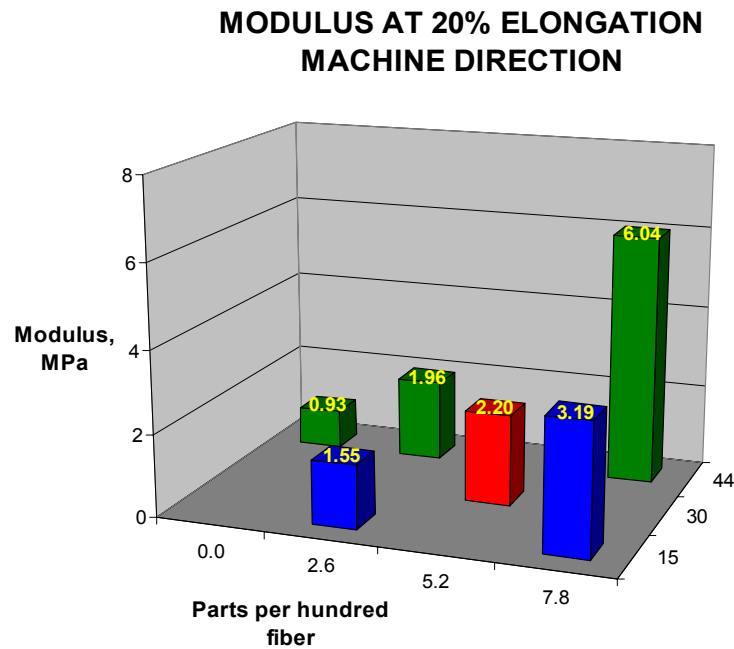


Figure 12

Reinforcement and Mooney Comparison Between Engineered Elastomer and Various Flocs

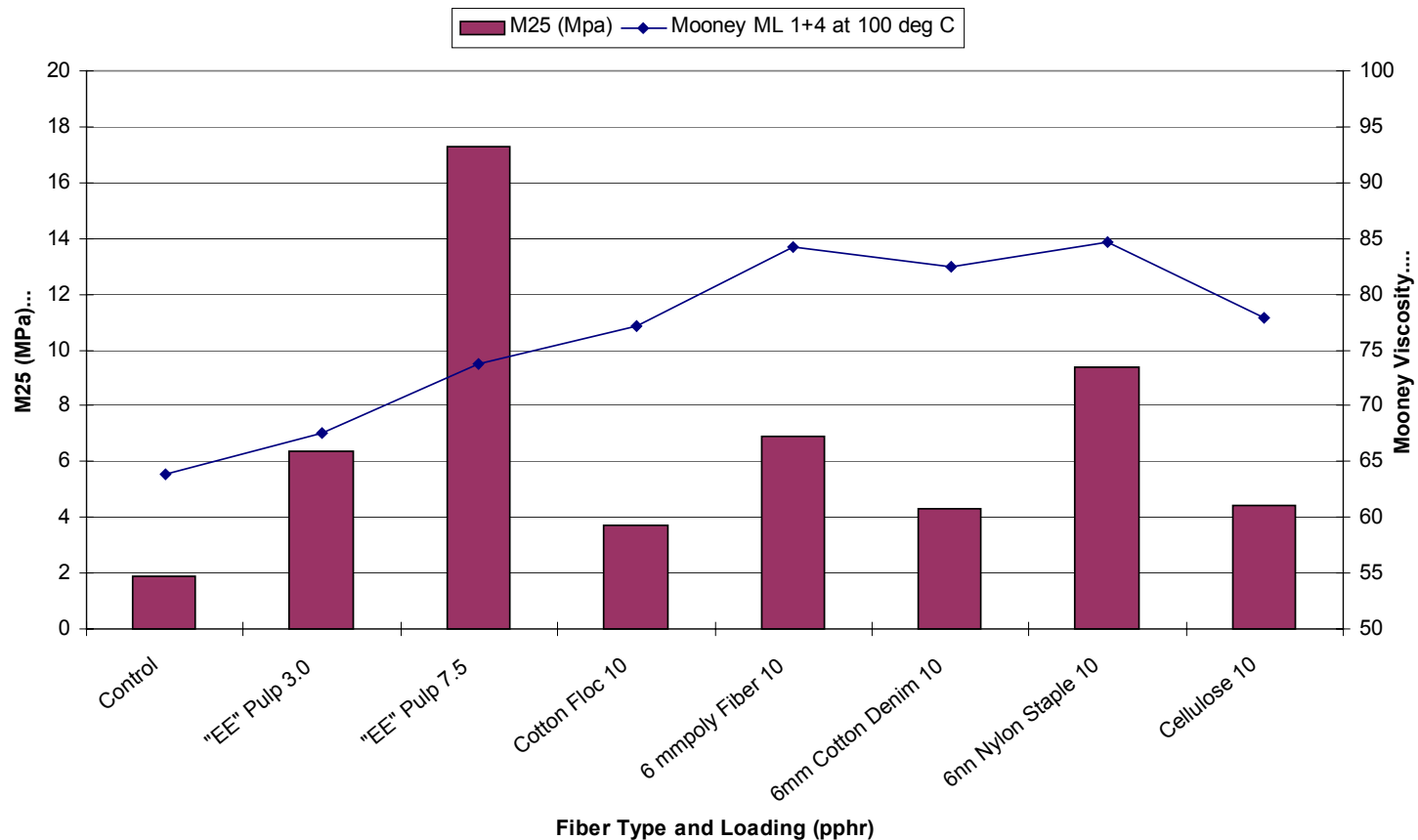


Figure 13

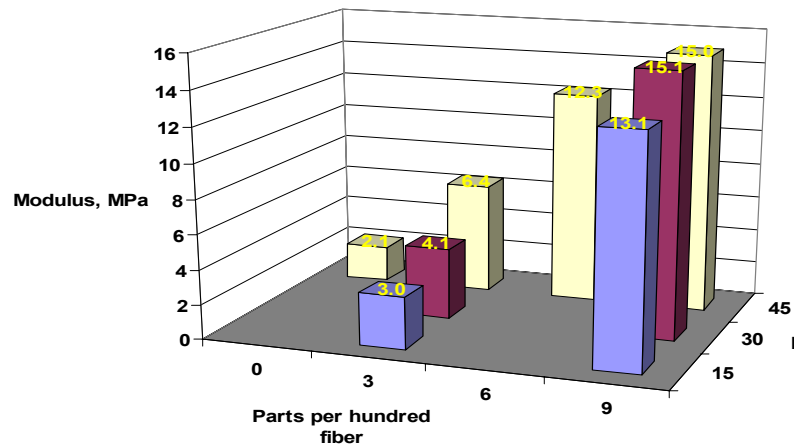
Comparison between carbon black and p-aramid pulp reinforcement of NR



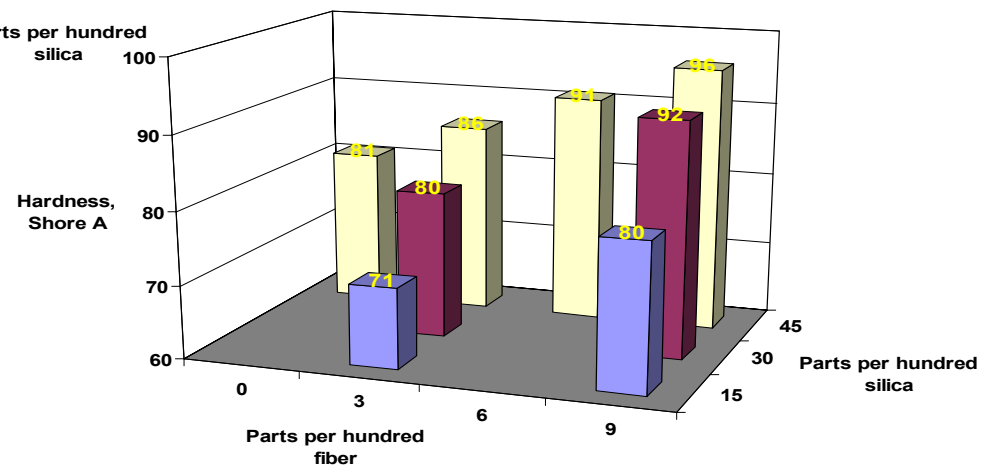
Figure 14

Effect of Engineered Elastomer on Modulus and Hardness of a Roll Cover Compound

MODULUS AT 25% ELONGATION



HARDNESS



NBR Roll Cover

Figure 15

Effect of Engineered Elastomer on Tear and Abrasion Resistance of a Roll Cover Compound

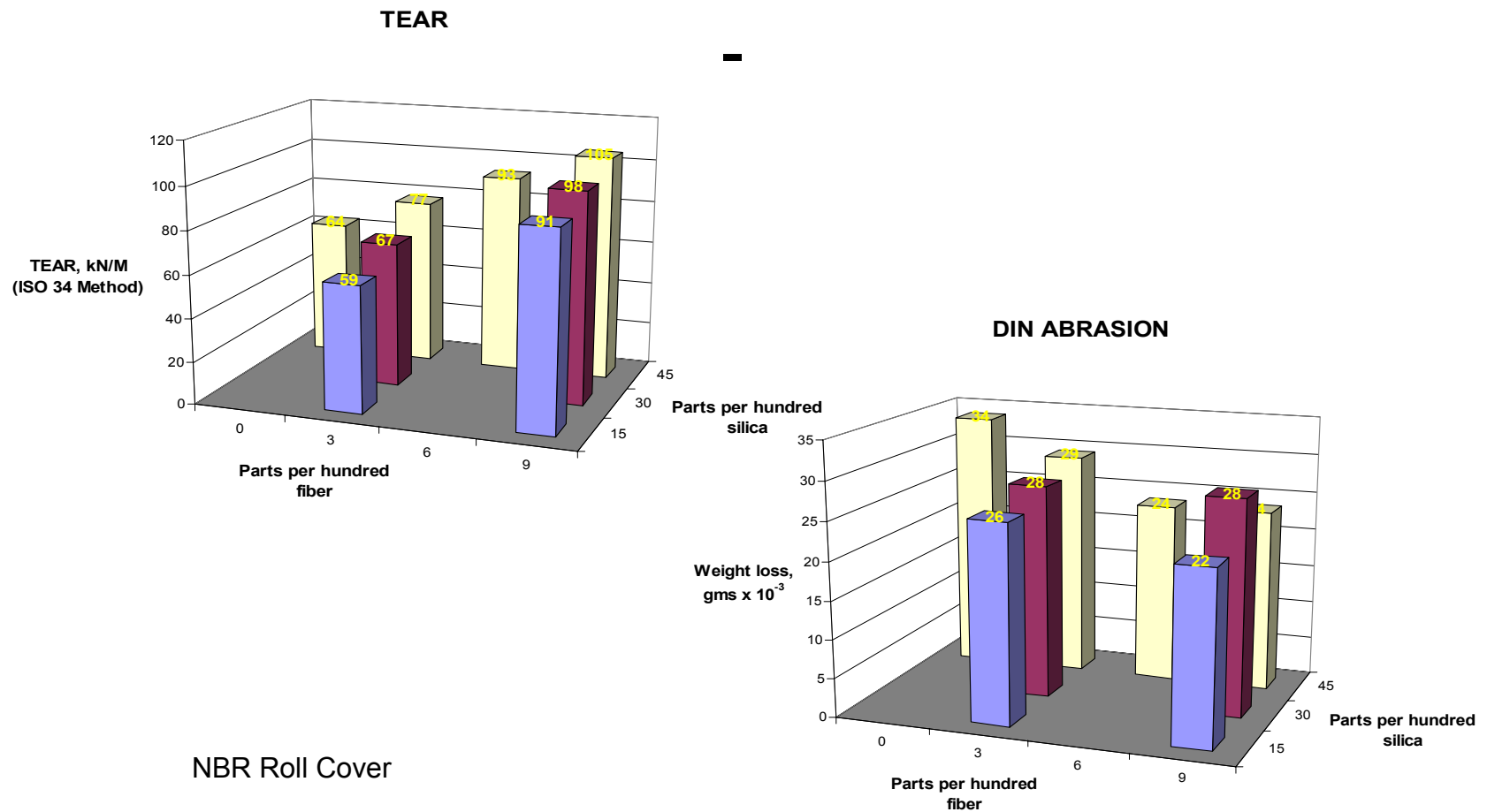
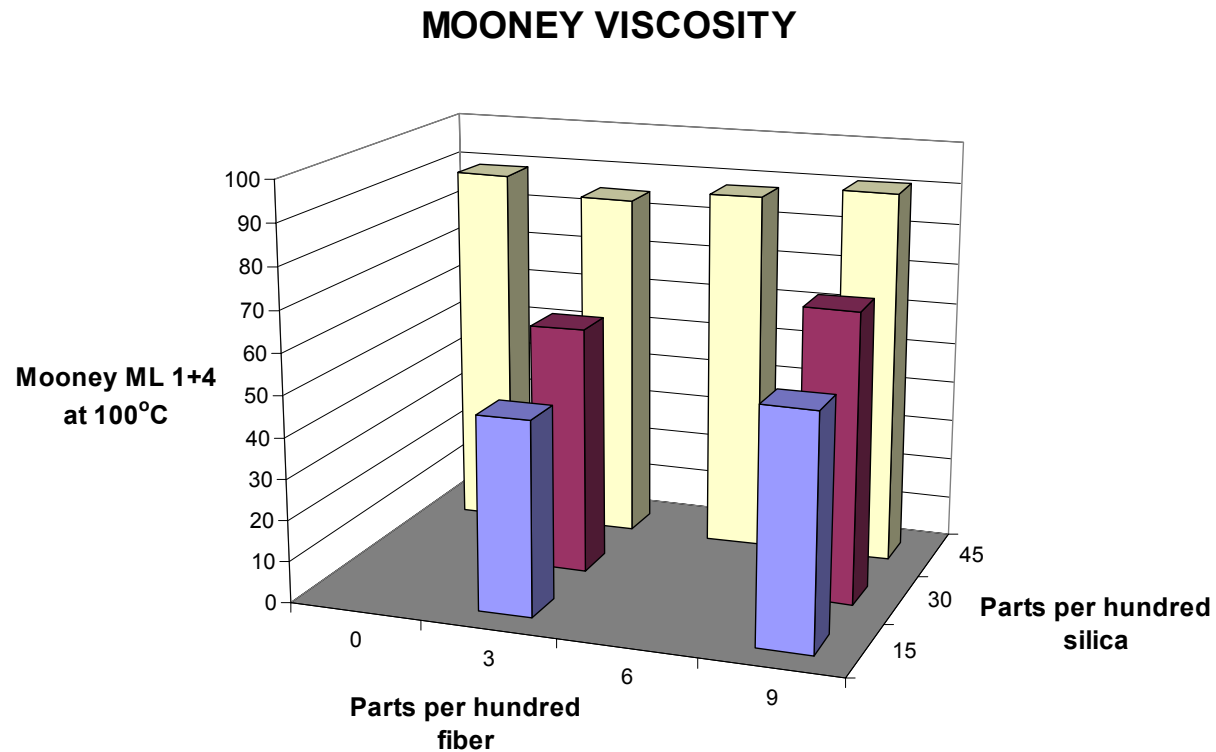


Figure 16

Effect of Engineered Elastomer on Mooney Viscosity of a Roll Cover Compound



NBR Roll Cover

Figure 17

Effect of Engineered Elastomer and Carbon Black Loadings on Trouser Tear

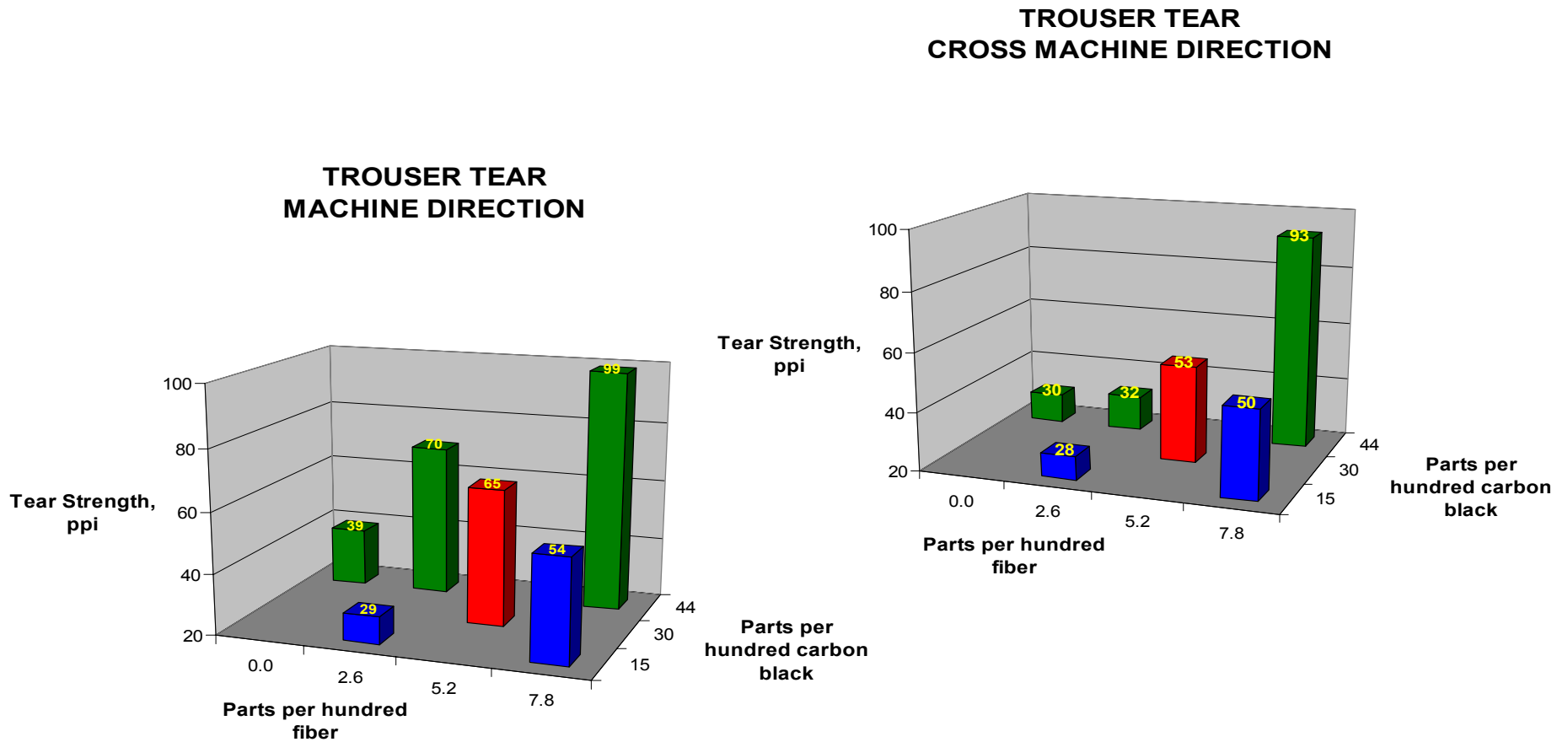


Figure 18

Effect of Engineered Elastomer and Carbon Black Loadings on Die C Tear

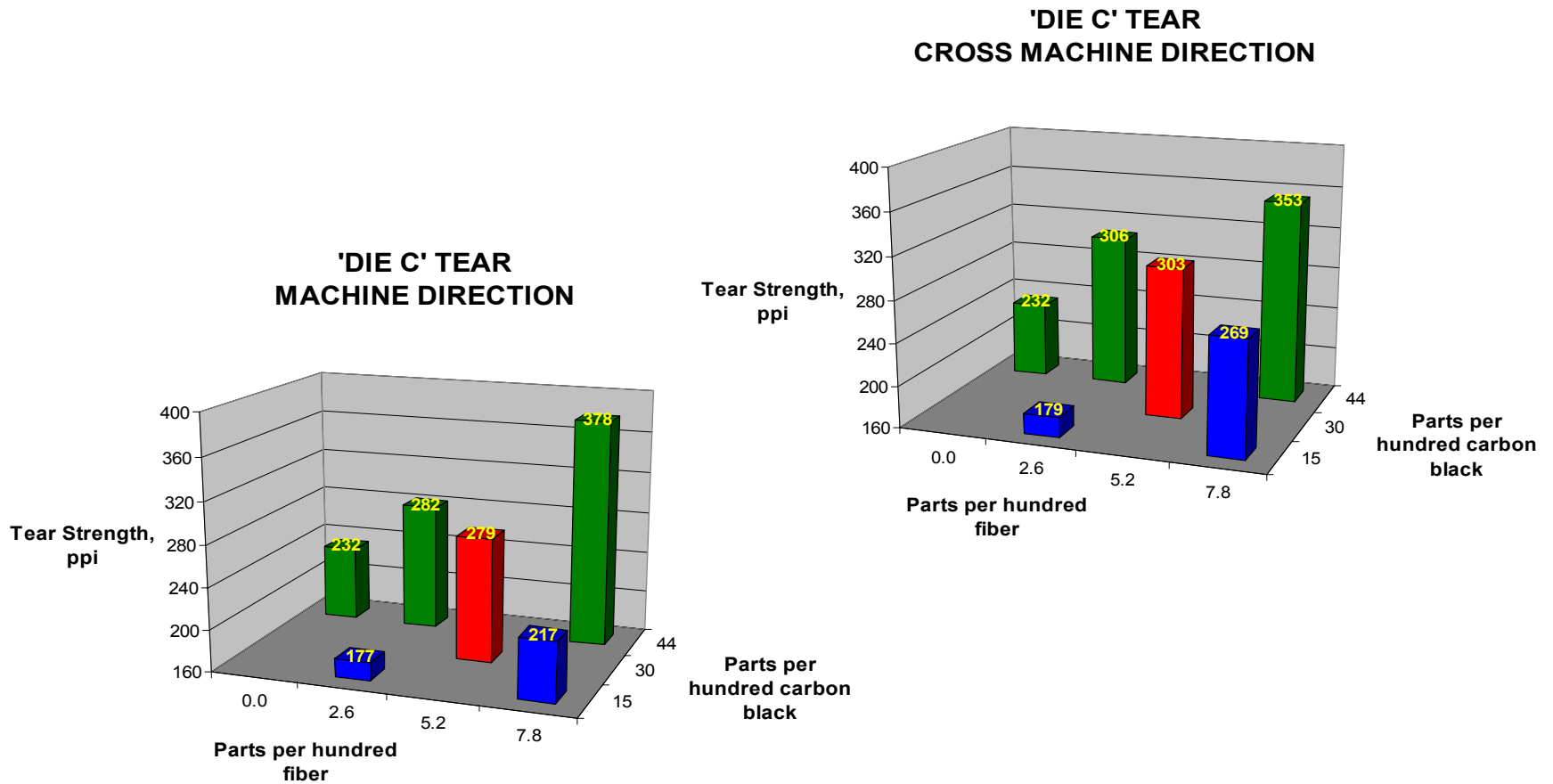


Figure 19

Photographs of Die C Tear Test



Figure 20

Cyclic Stress-strain Conditions

- Pull Speed: 25mm/min
- Position: cross-head displacement calibrated for pull speed
- First Cycle at constant Strain
- Subsequent Cycles at constant Force
- Test pieces: Bongos (100 x 3.2 x 2 mm)

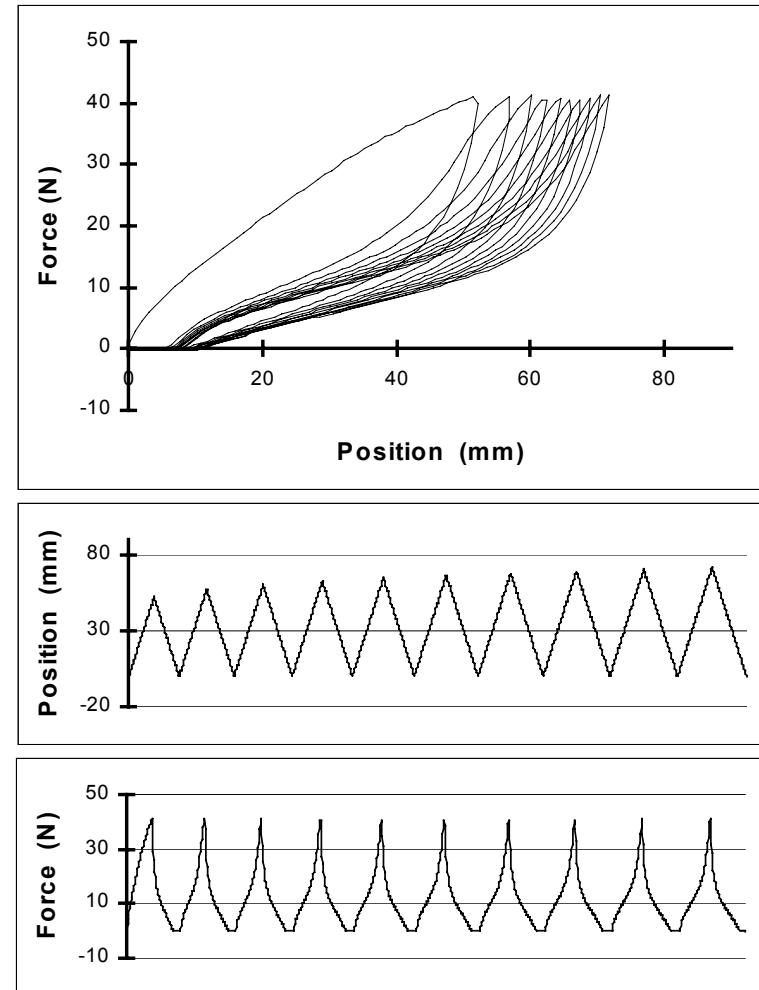


Figure 21

Cyclic stress-strain

Effect of fiber loading on 1st and 10th hysteresis cycles, cycled up to 10% strain

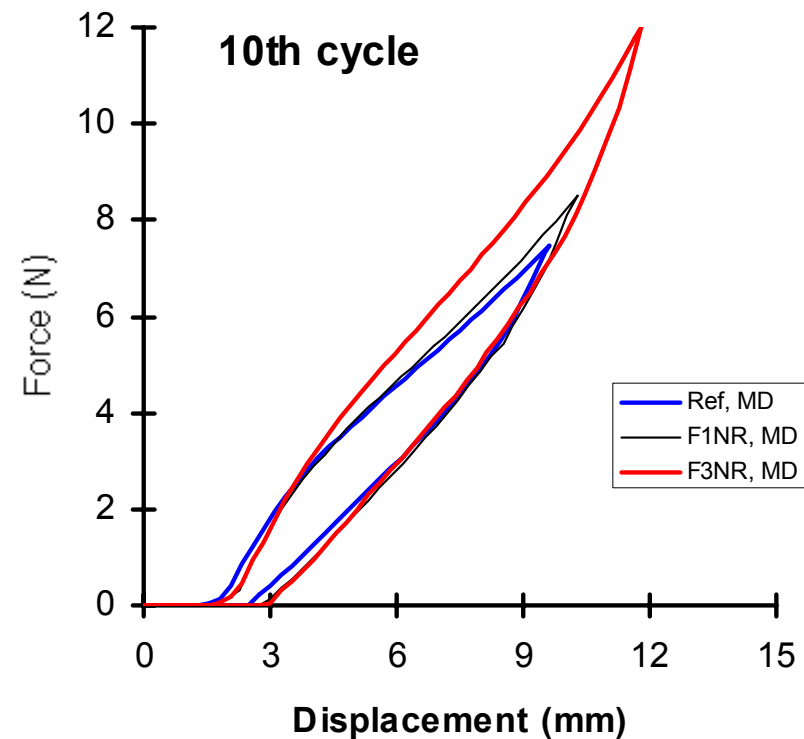
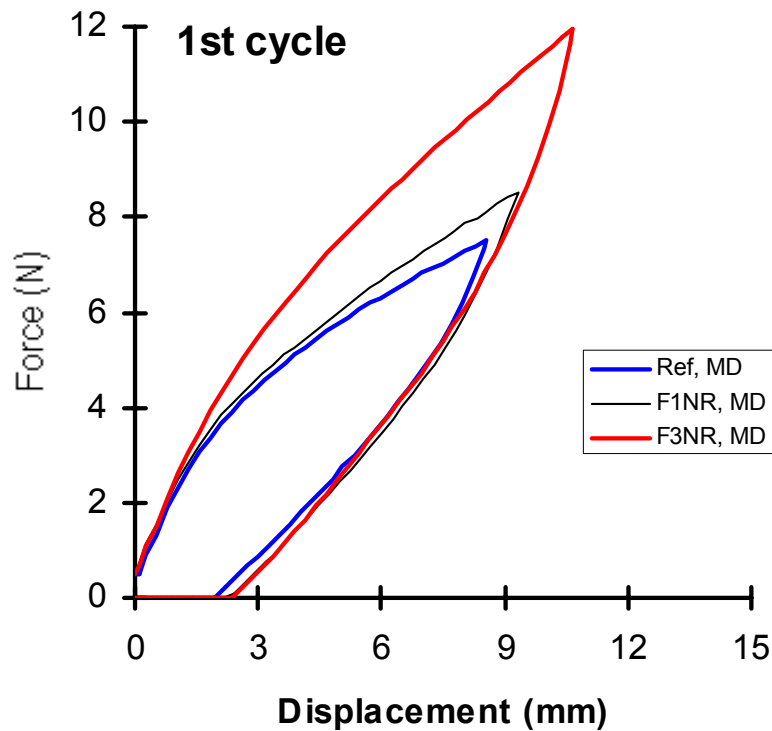


Figure 22

Definition of Energy Loss Fraction

Energy Loss Fraction = $A1 / (A1+A2)$ = Hysteresis Energy / Stored Elastic Energy

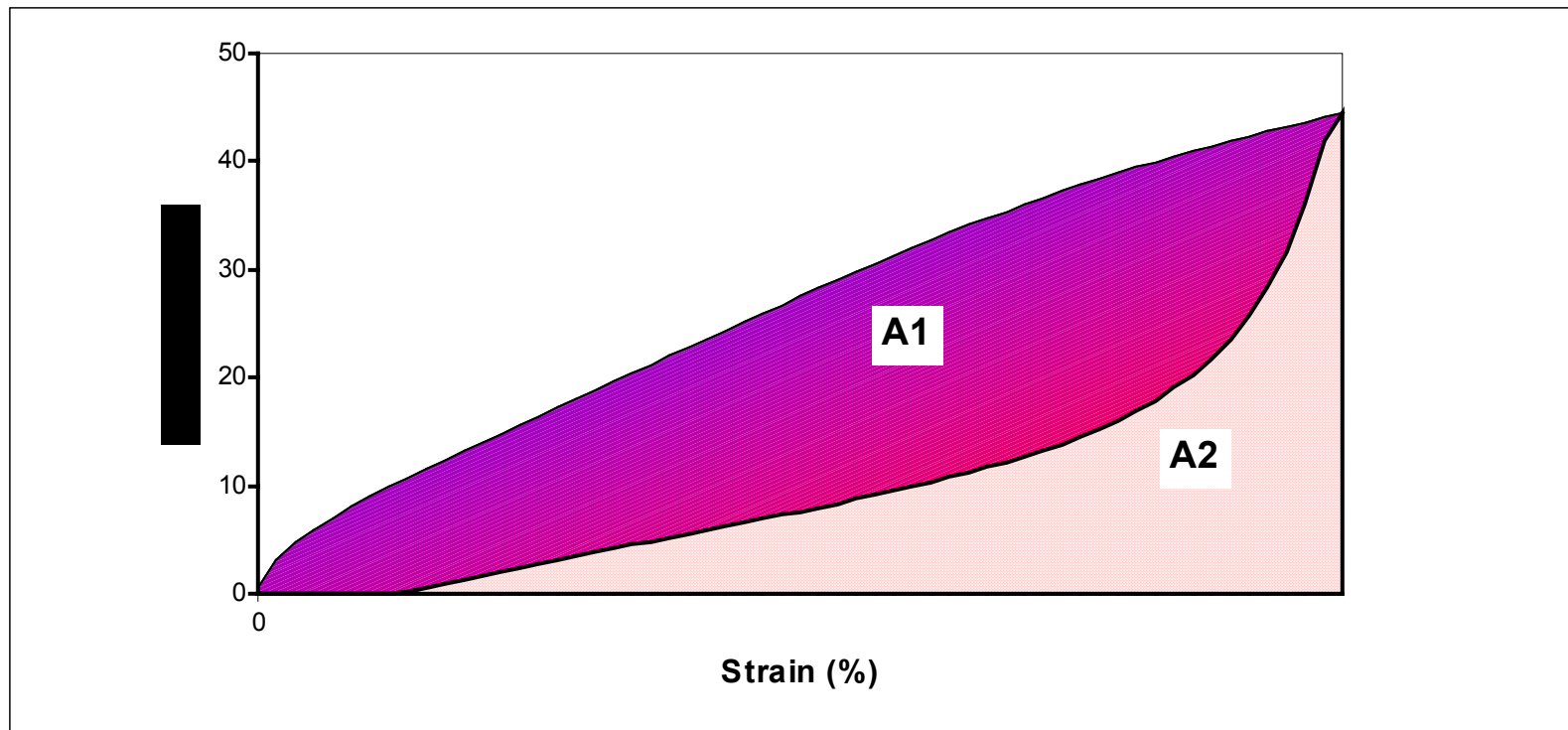


Figure 23

Cyclic stress-strain Effect of number of cycles upon Energy Loss Fraction

F1NR Compound – Cycles up to 10% Strain

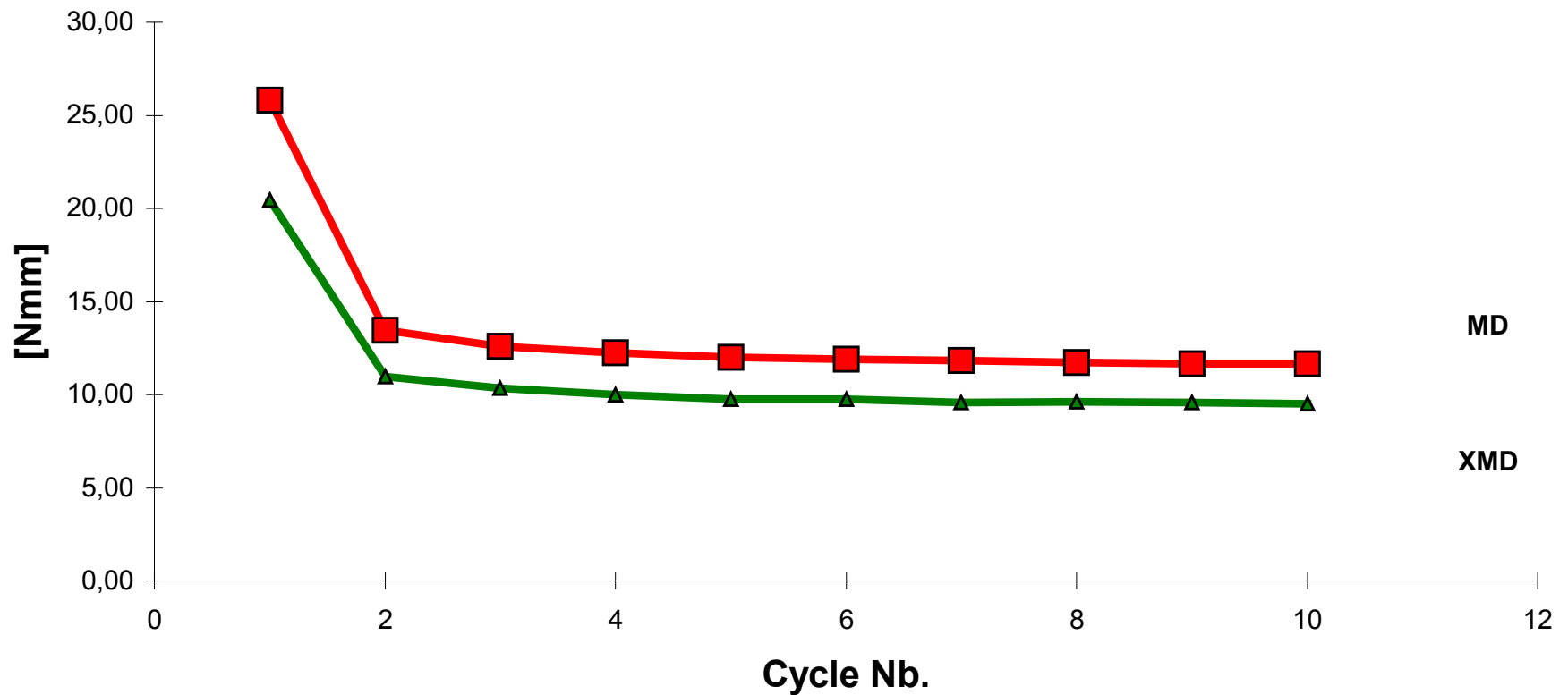


Figure 24

Cyclic stress-strain Energy loss fraction vs. fiber loading Cycled up to 10% strain

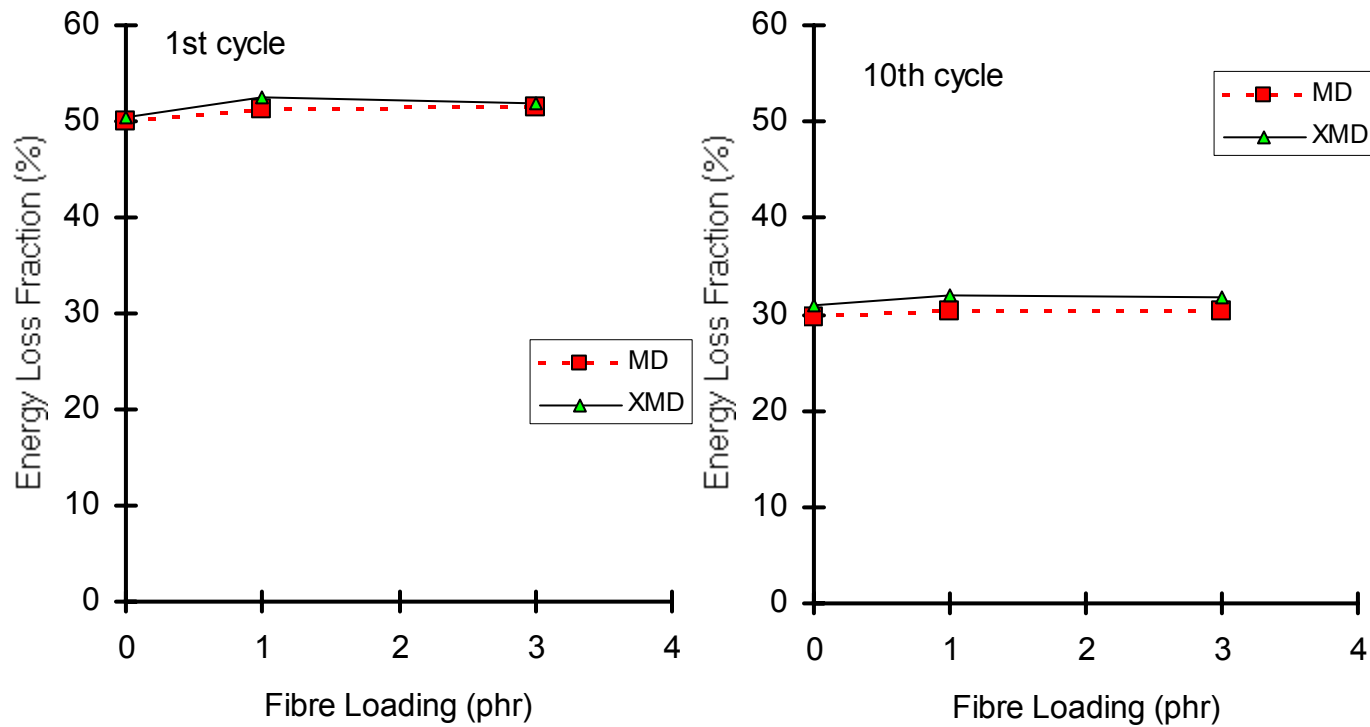


Figure 25

Cycles Were Performed At Constant Force

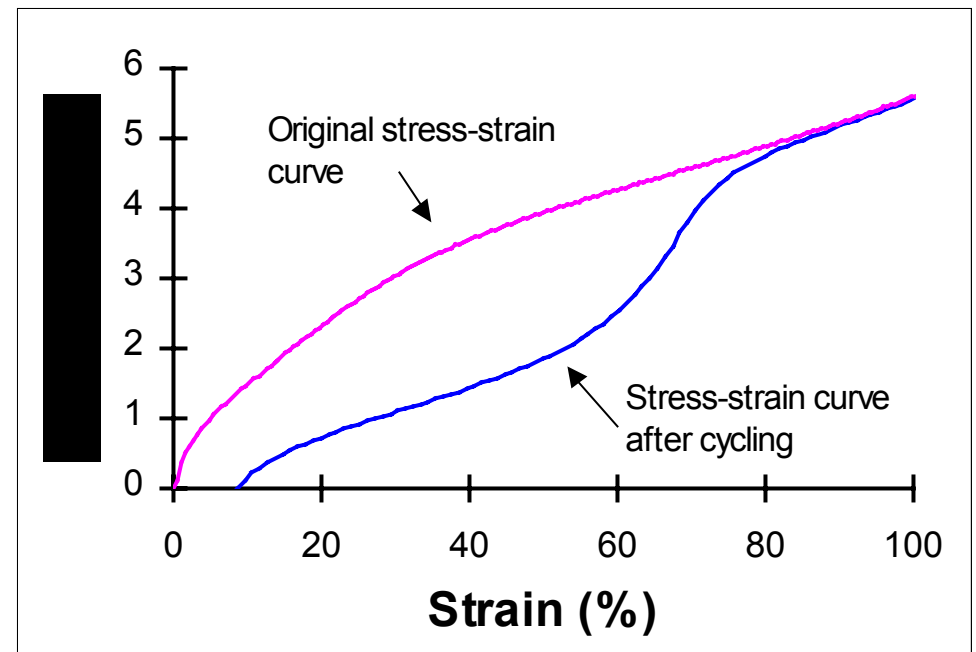
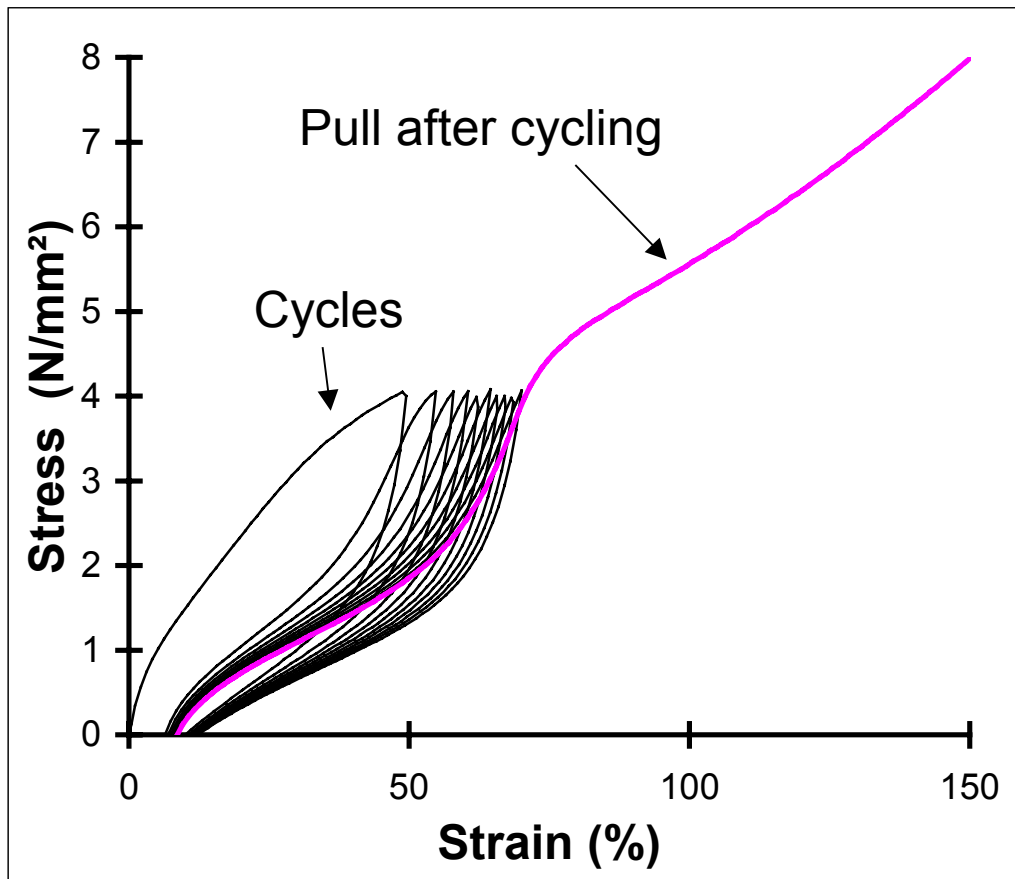


Figure 26

Ref MD cycled at 10% for 2, 10 and 100 cycles

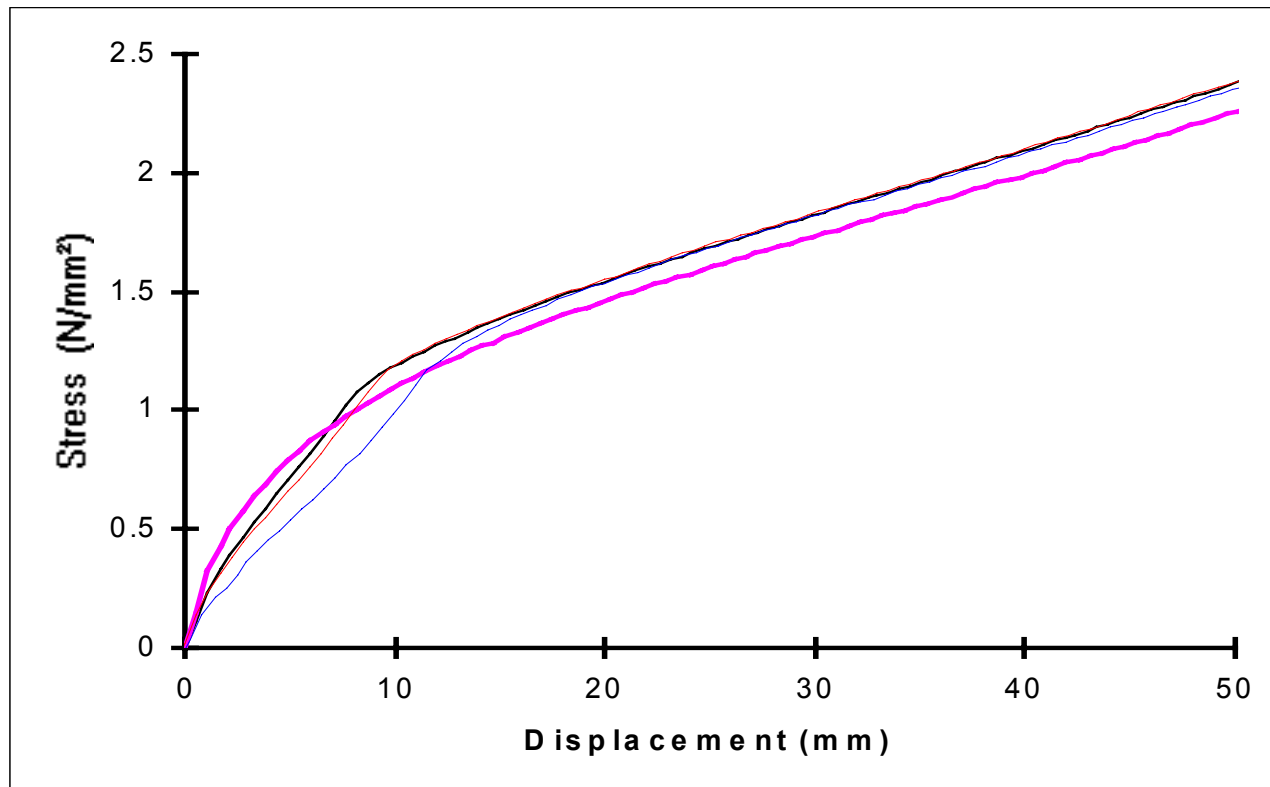


Figure 27

F1NR MD cycled at 10% for 2, 10 and 100 cycles

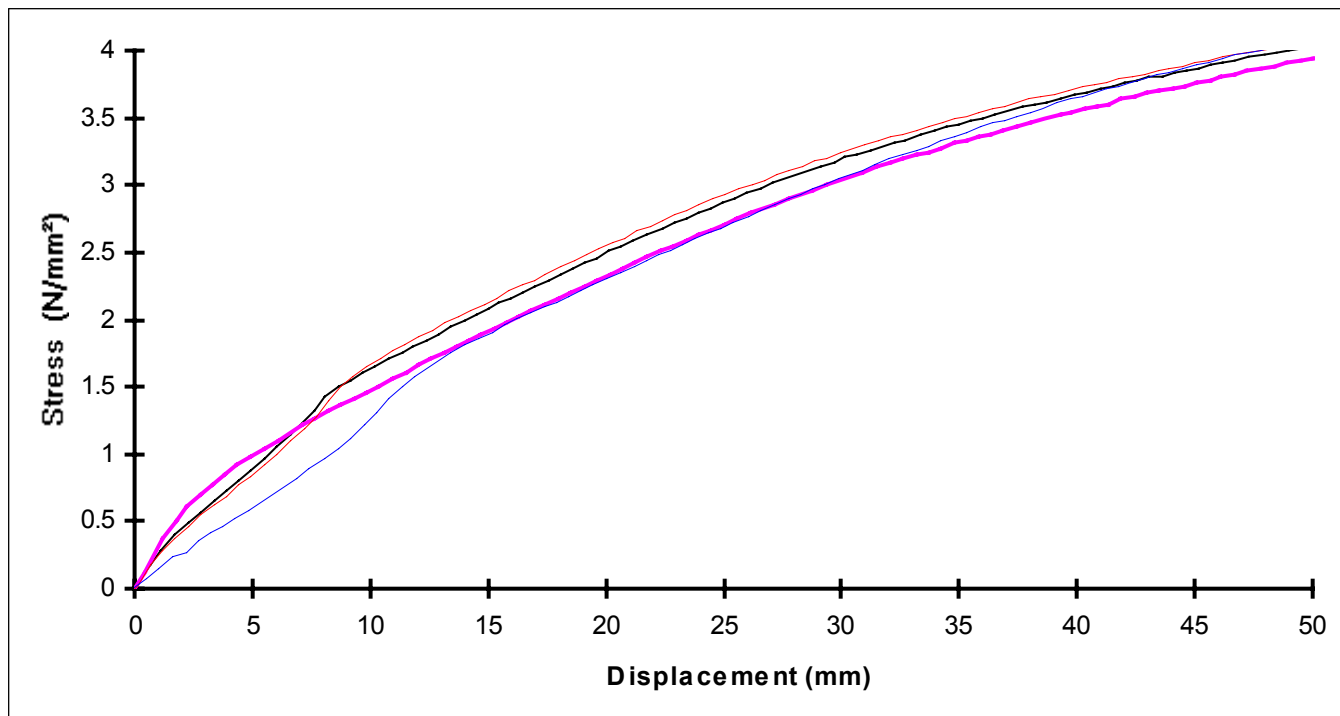


Figure 28

Short-Term Dynamic Compression F1NR Compound 20°C Plied Up Discs

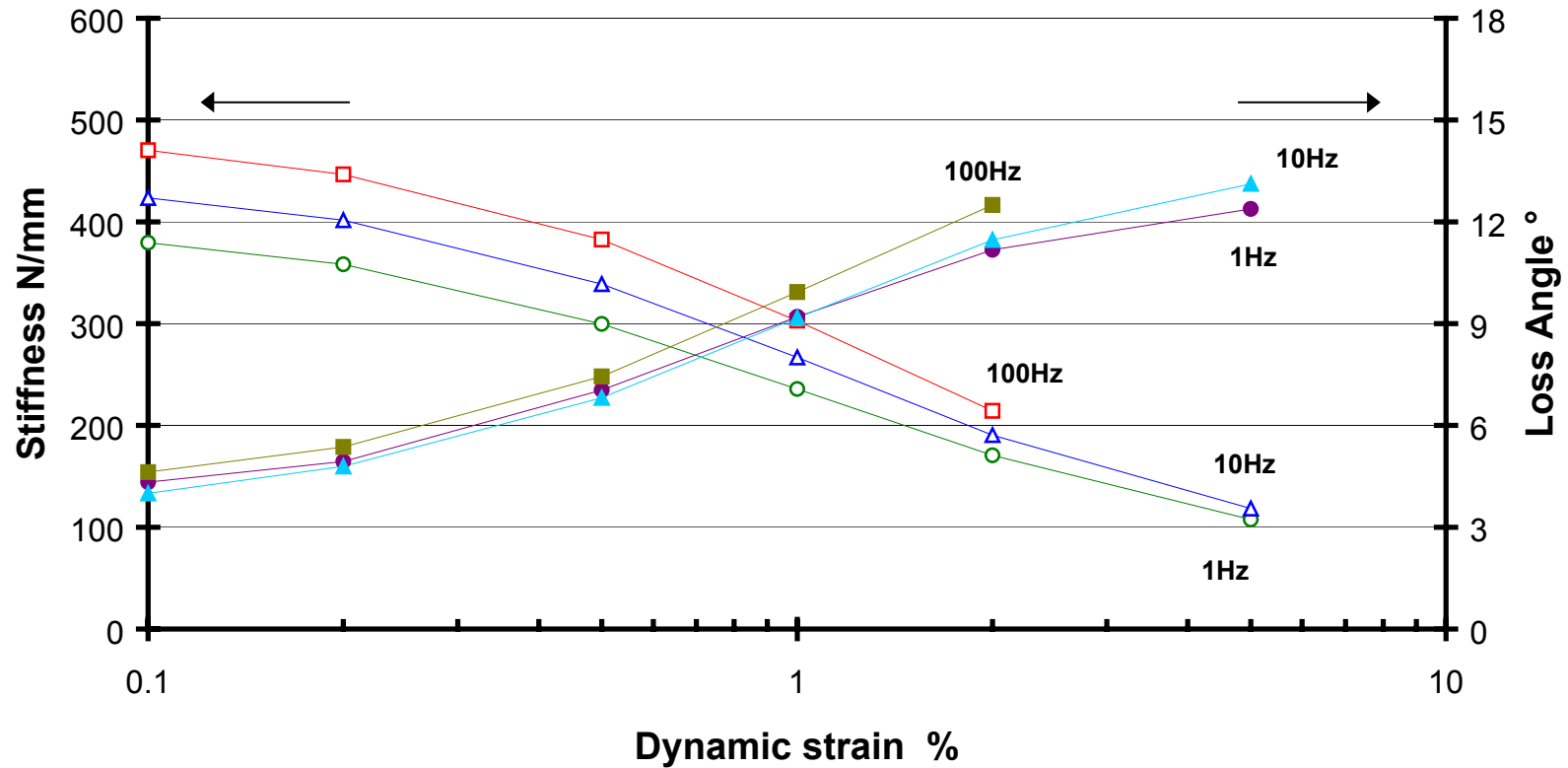


Figure 29

Short-Term Dynamic Compression
F1NR Compound 100°C Plied Up Discs

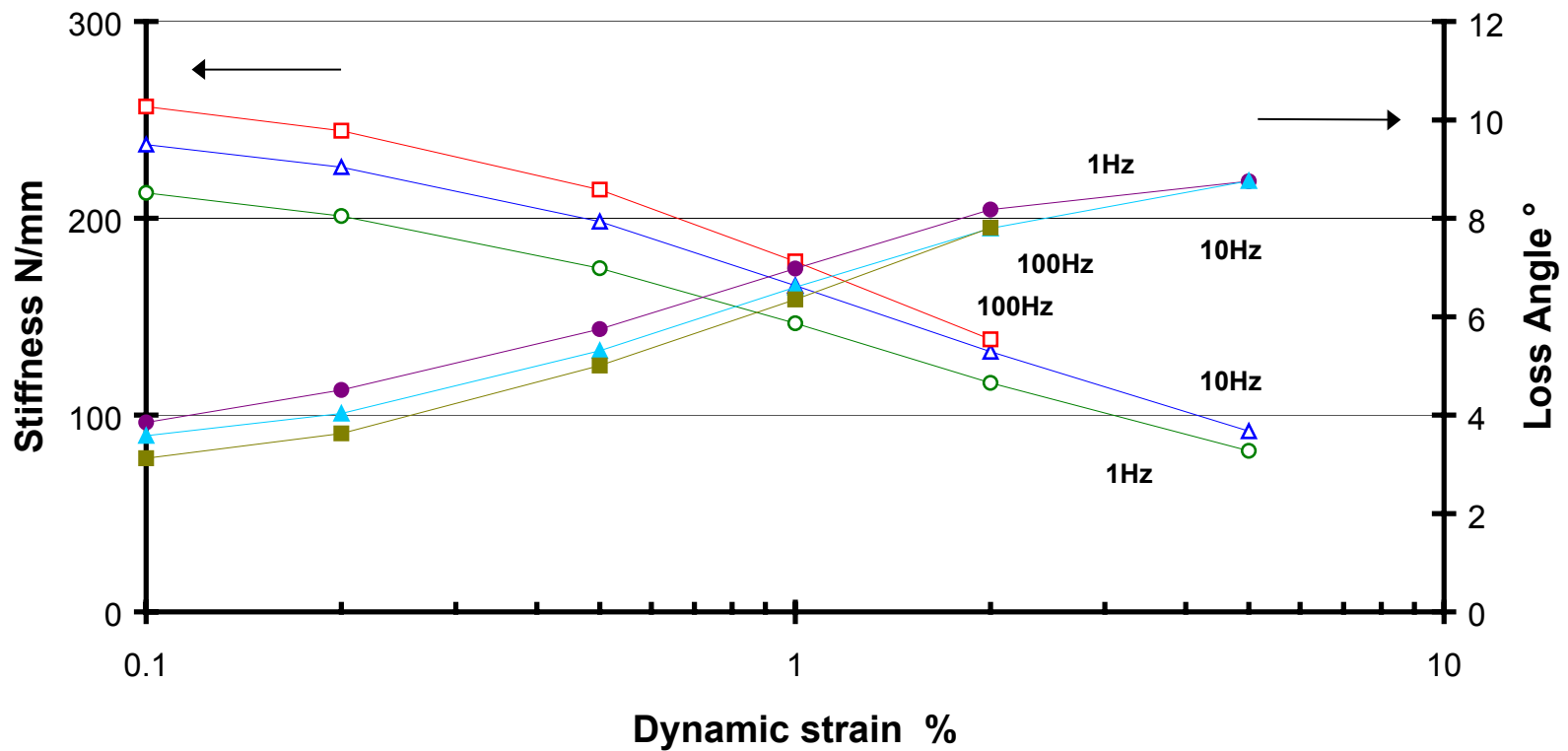


Figure 30

Short-Term Dynamic Compression Stiffness vs. Fiber Loading

Piled Up Discs 20°C and 100°C at 1% Dynamic Strain

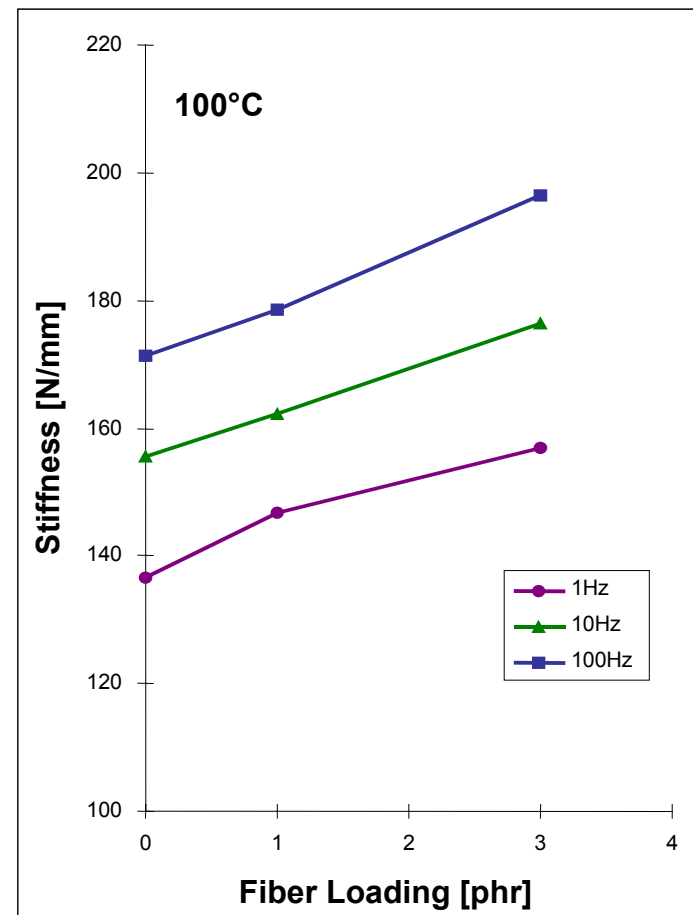
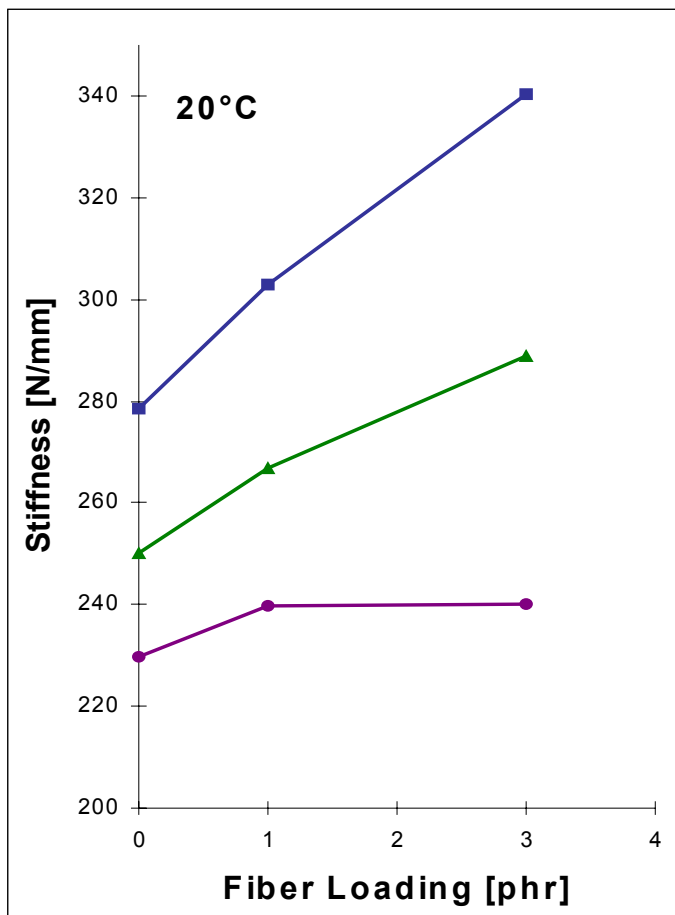


Figure 31

Short-Term Dynamic Compression Loss Angle vs. Fiber Loading Piled Up Discs 20°C and 100°C at 1% Dynamic Strain

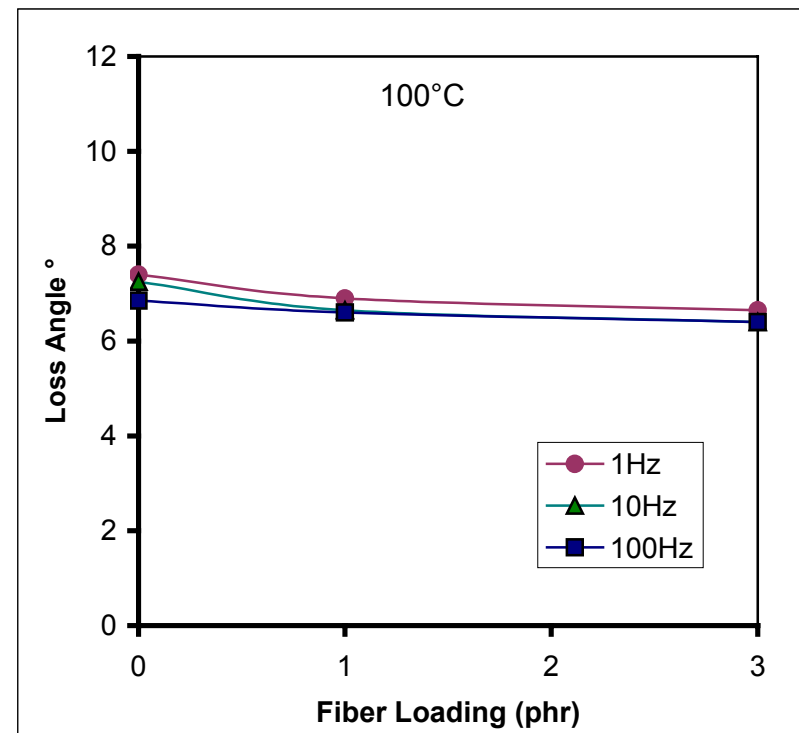
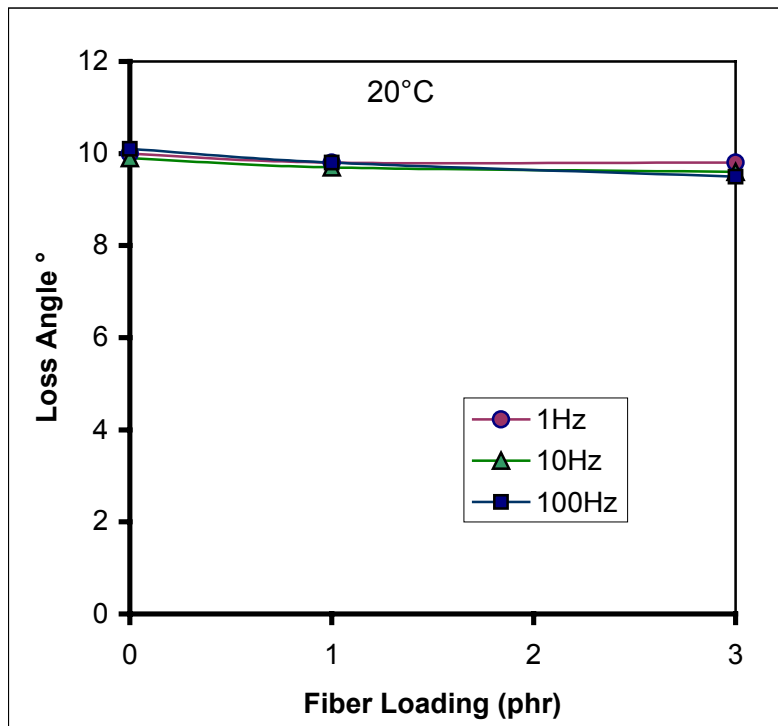


Figure 32

Short-Term Dynamic Tension F1NR Compound 20°C Moulded Strip

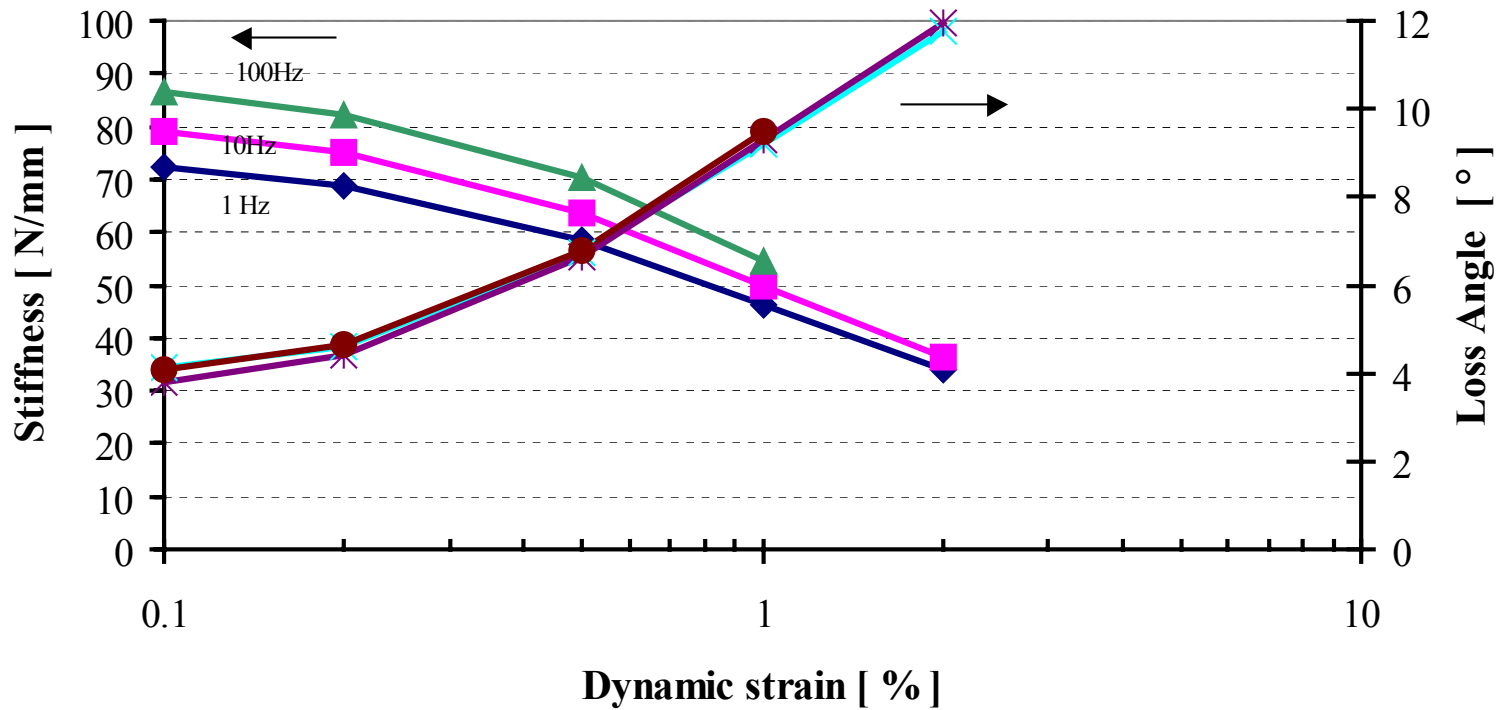


Figure 33

Short-Term Dynamic Tension F1NR Compound 100°C Moulded Strip

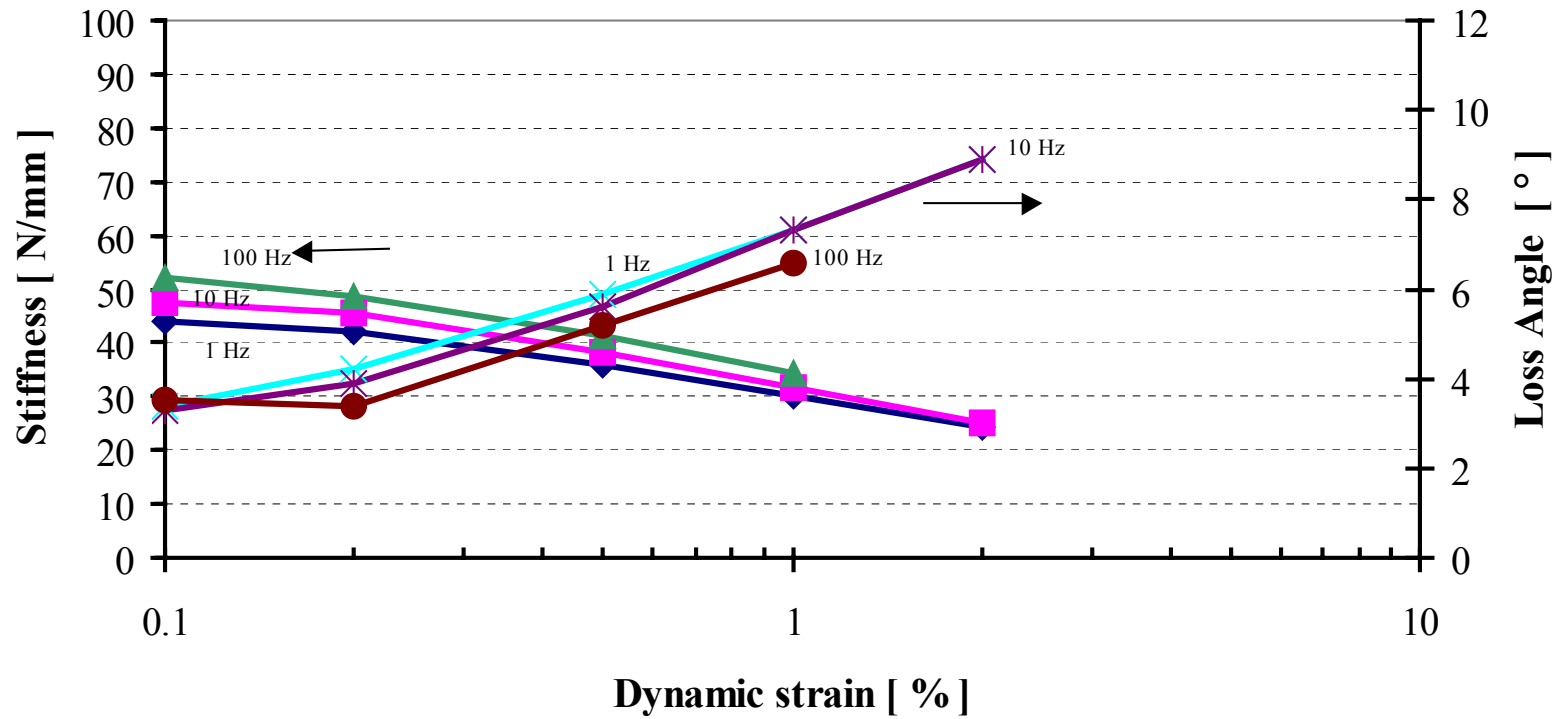


Figure 34

Short-Term Dynamic Tension Stiffness vs. Fiber Loading Moulded strip at 1% Dynamic Strain

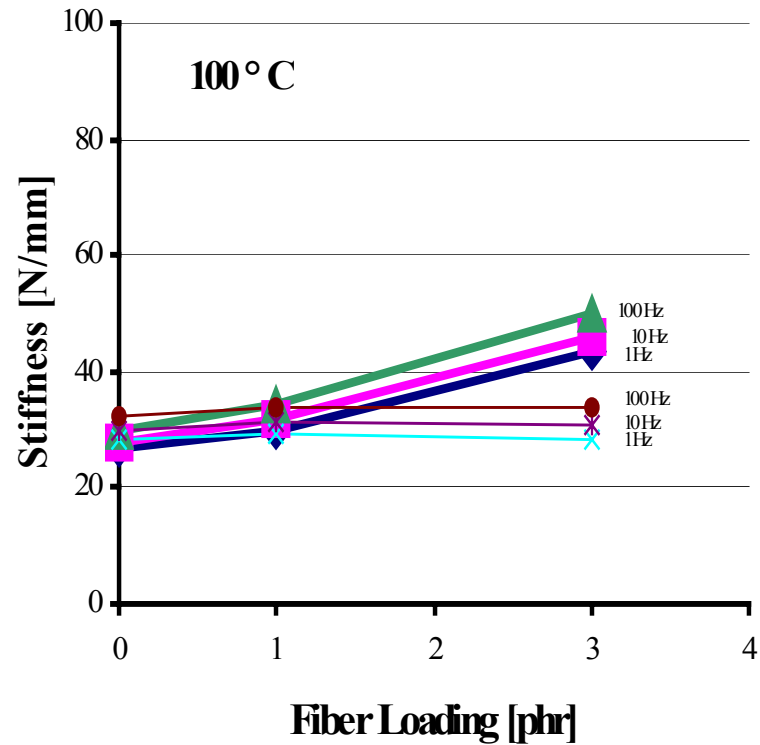
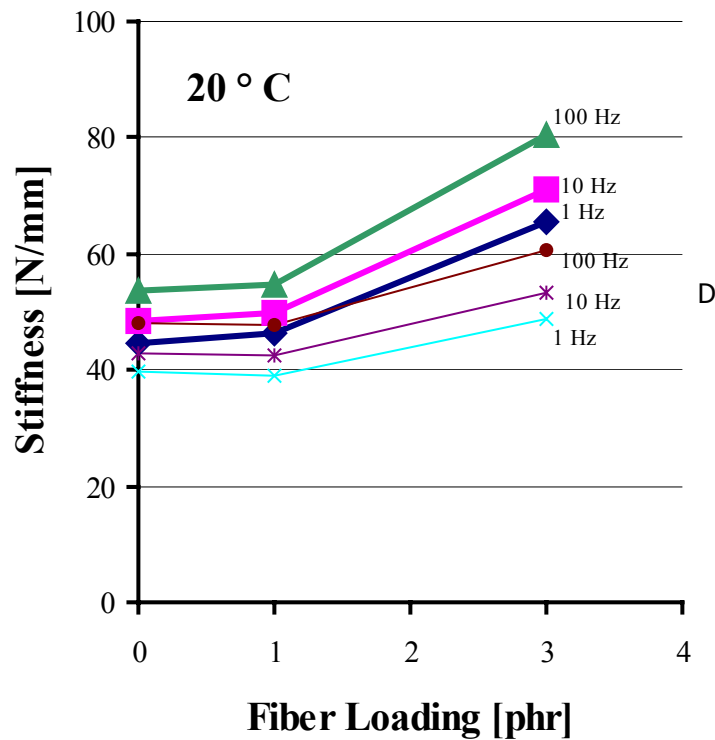


Figure 35

Short-Term Dynamic Tension Loss Angle vs. Fiber Loading (MD only) Moulded strip at 1% Dynamic Strain

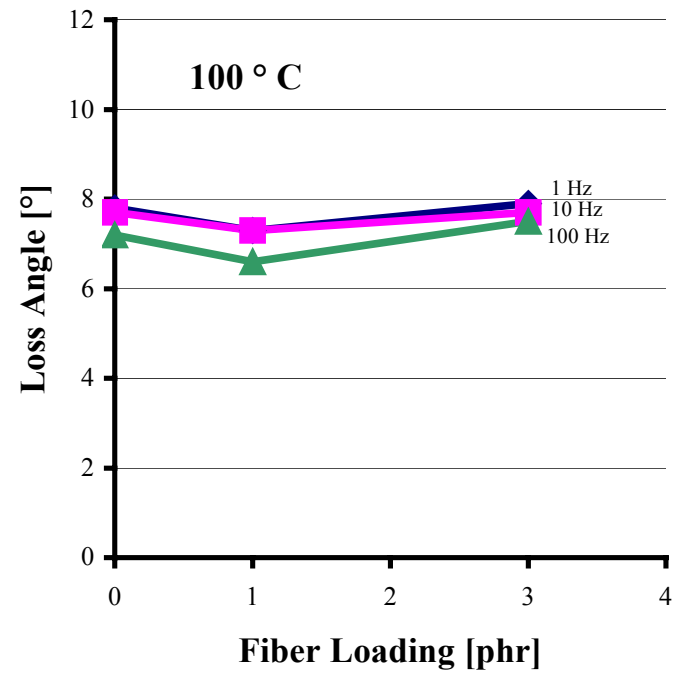
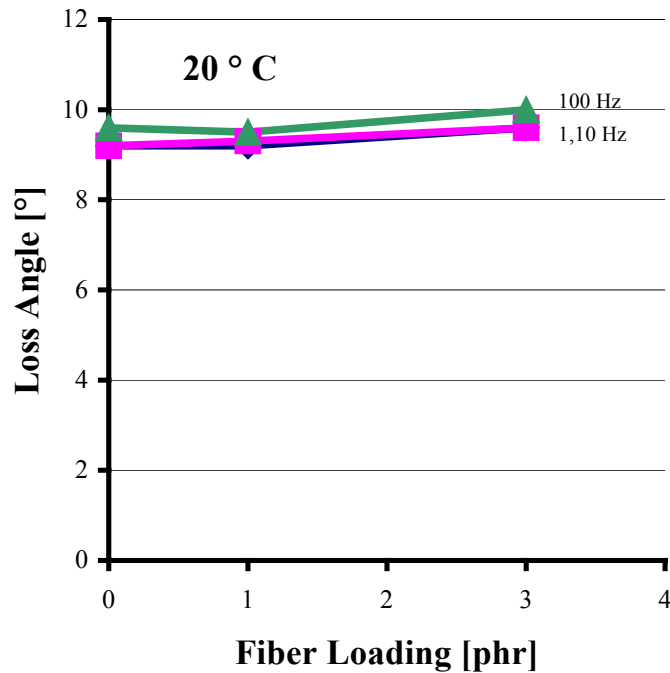
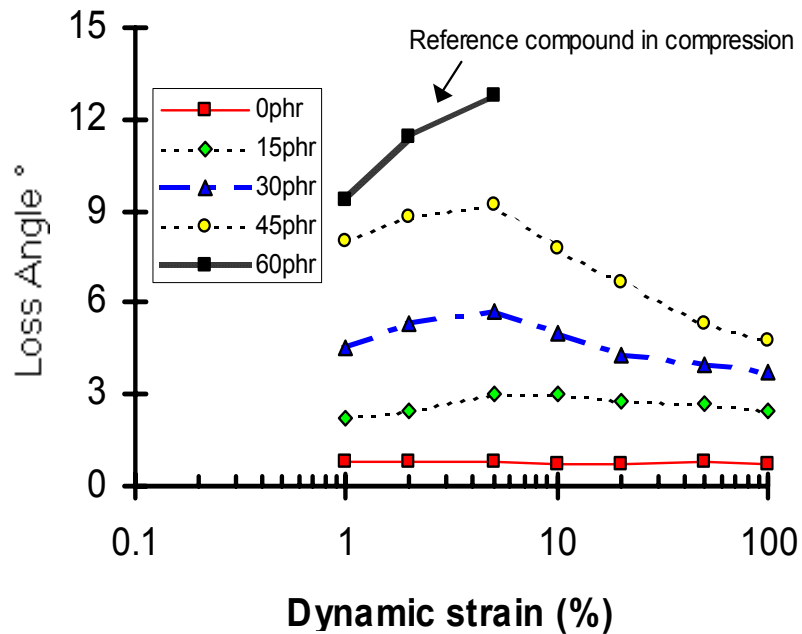


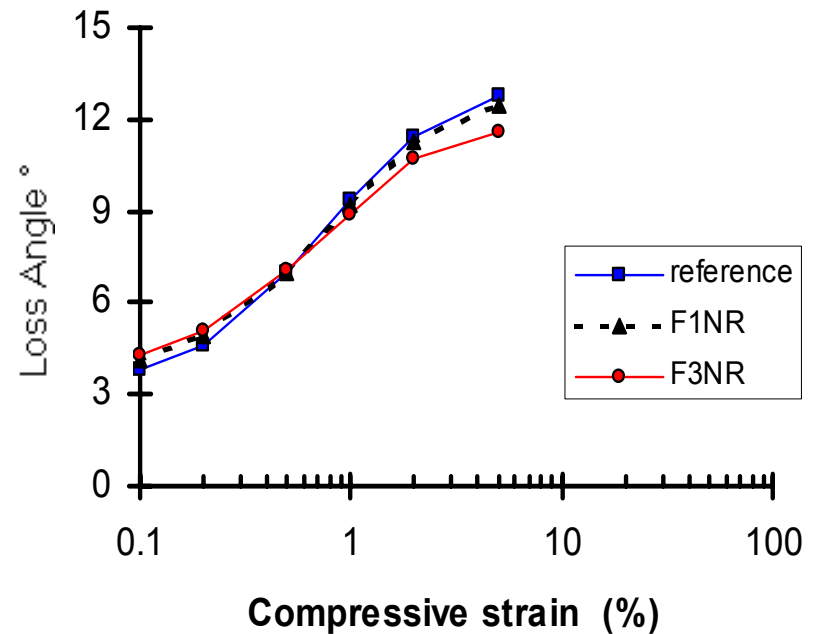
Figure 36

Comparison between effects of carbon black and para-aramid fibers upon loss angle

Effect of N330 carbon black upon Loss Angle
Dynamic Shear, Frequency 1Hz, 23°C



Effect of fibre loading on Loss Angle
Dynamic compression, Frequency 1Hz, 20°C



Data from MRPRA, Engineering Data Sheets©

Figure 37

Reinforcement and Tan Delta Comparison Between Engineered Elastomer and Various Floccs

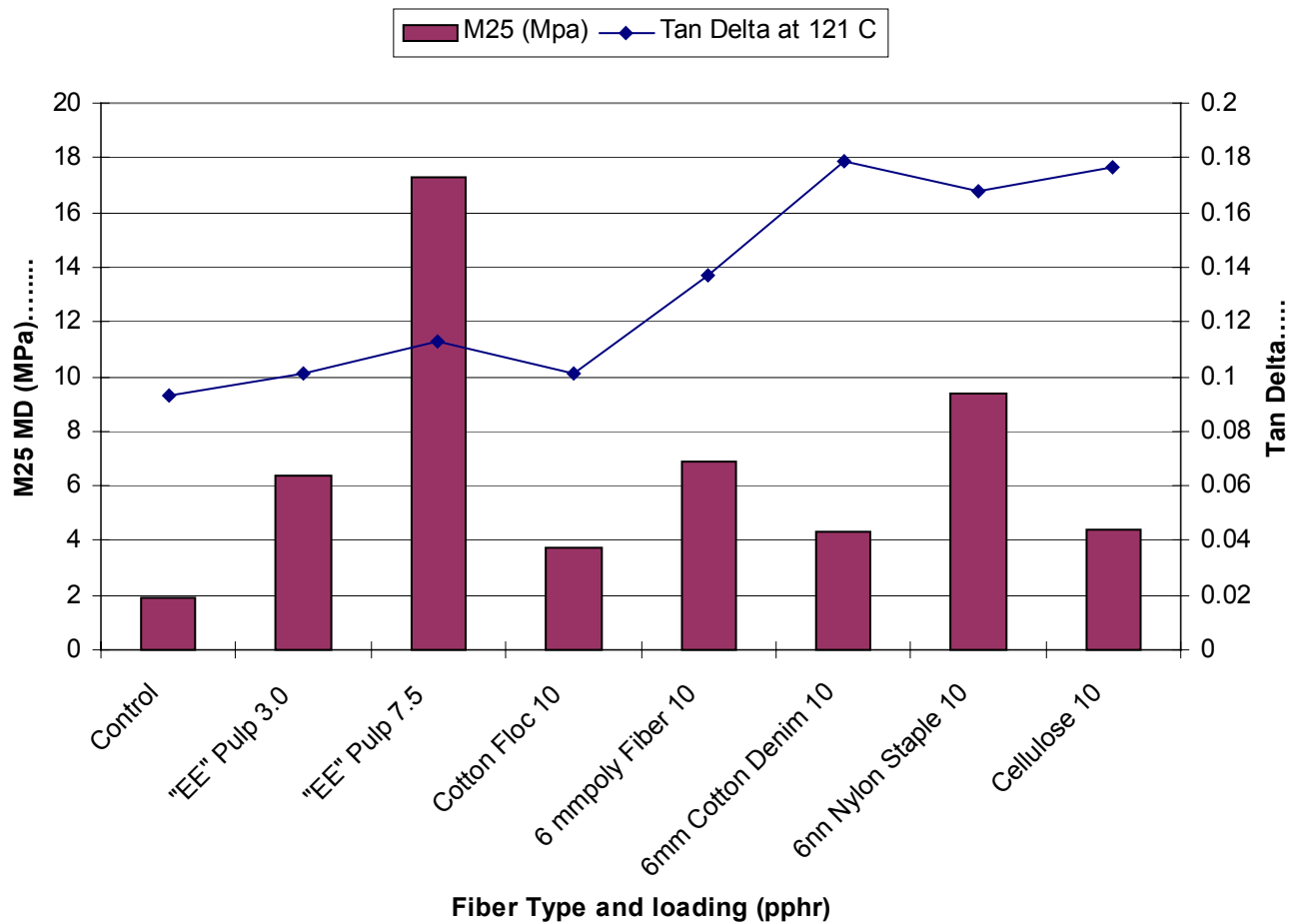
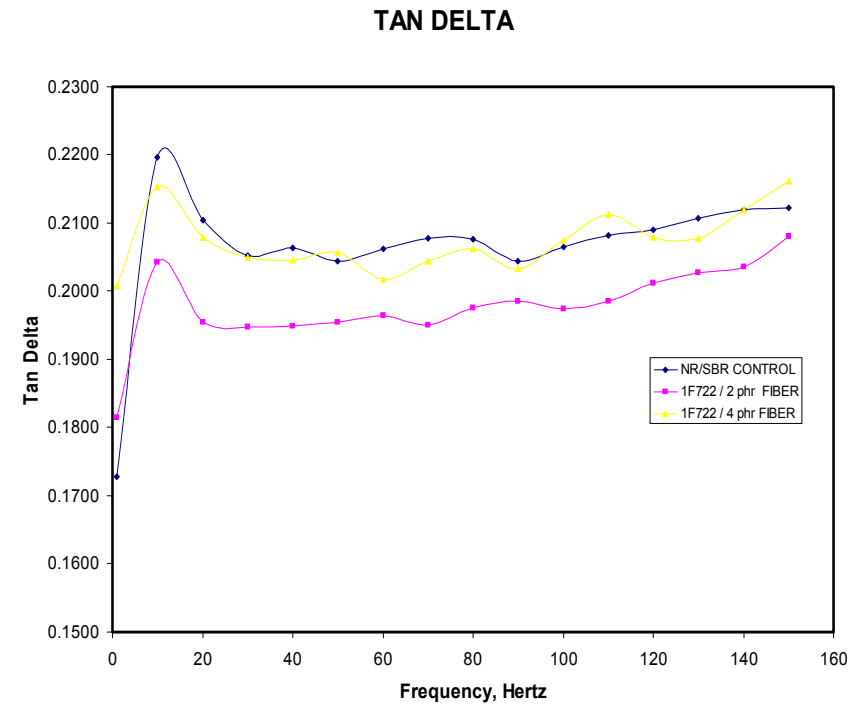
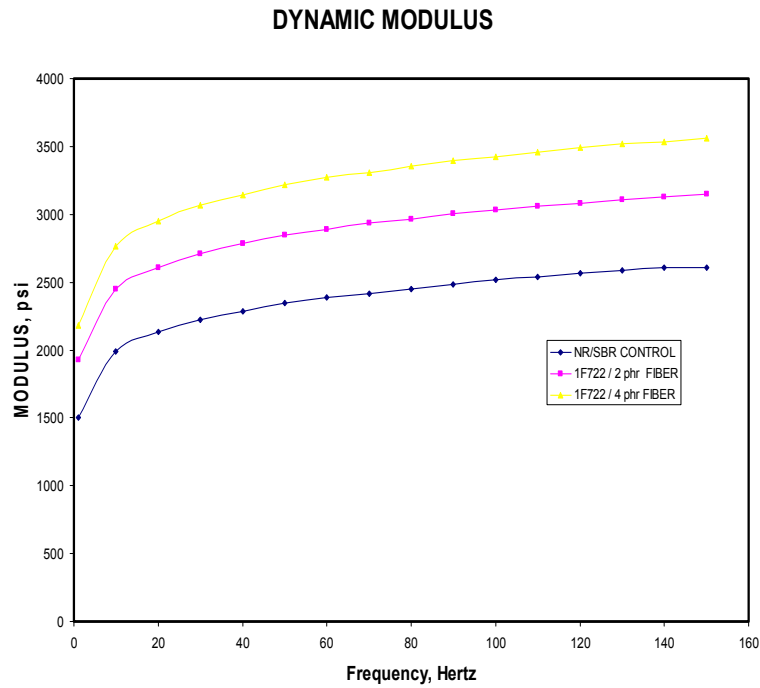


Figure 38

Hardness, Modulus, Tear Balance as affected by pulp and carbon black loadings



NR/SBR Tire Tread Compound

Figure 39

Stress Ratio Anisotropy vs. Strain

Stress ratio anisotropy is the ratio of MD/XMD absolute stress values at a given strain

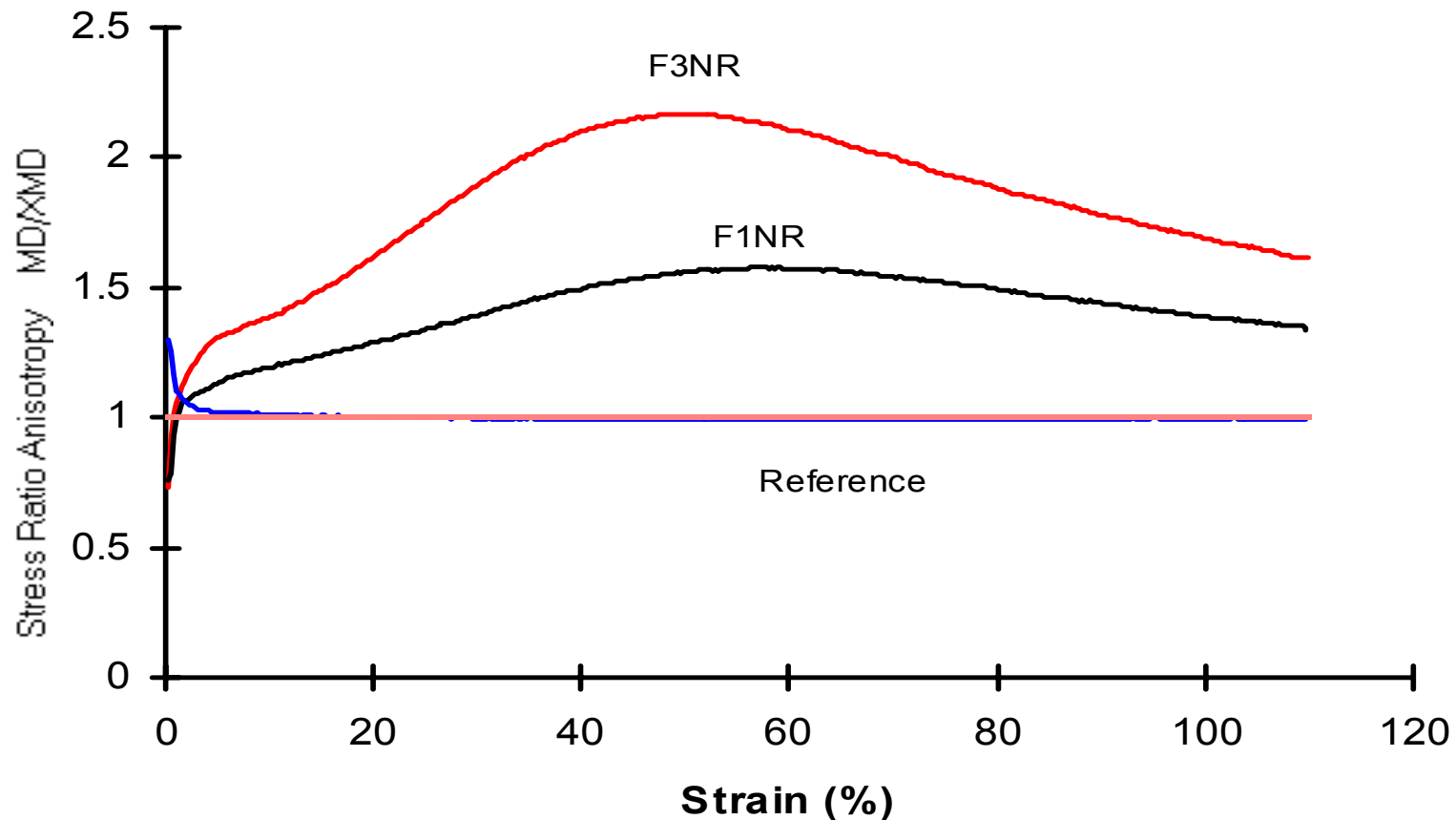


Figure 40

Modular Anisotropy vs. strain

Modular anisotropy is ratio of MD/XMD tangential stiffness at a given strain

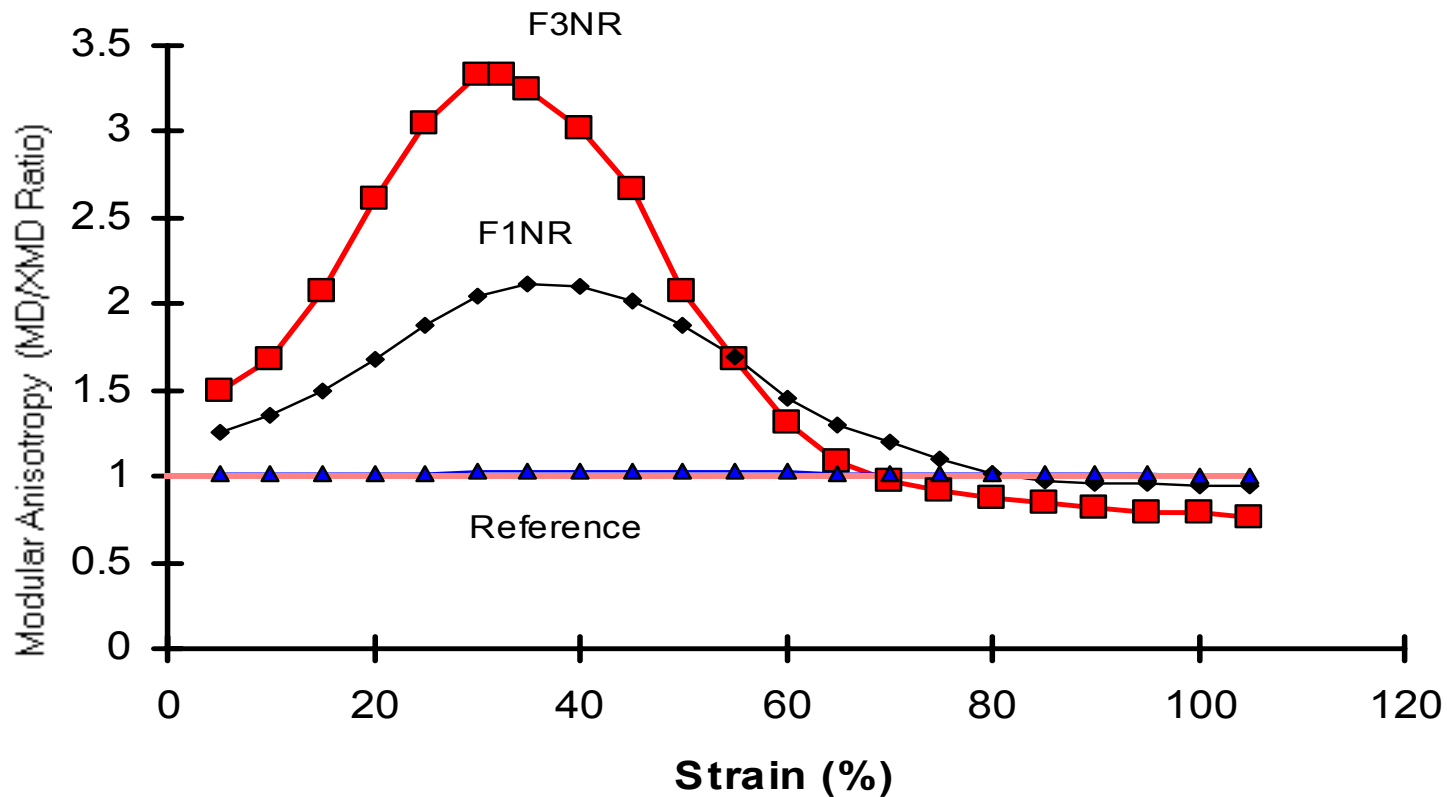


Figure 41

Acoustic Emission Tests

Acoustic Events are proportional to Fiber Loading

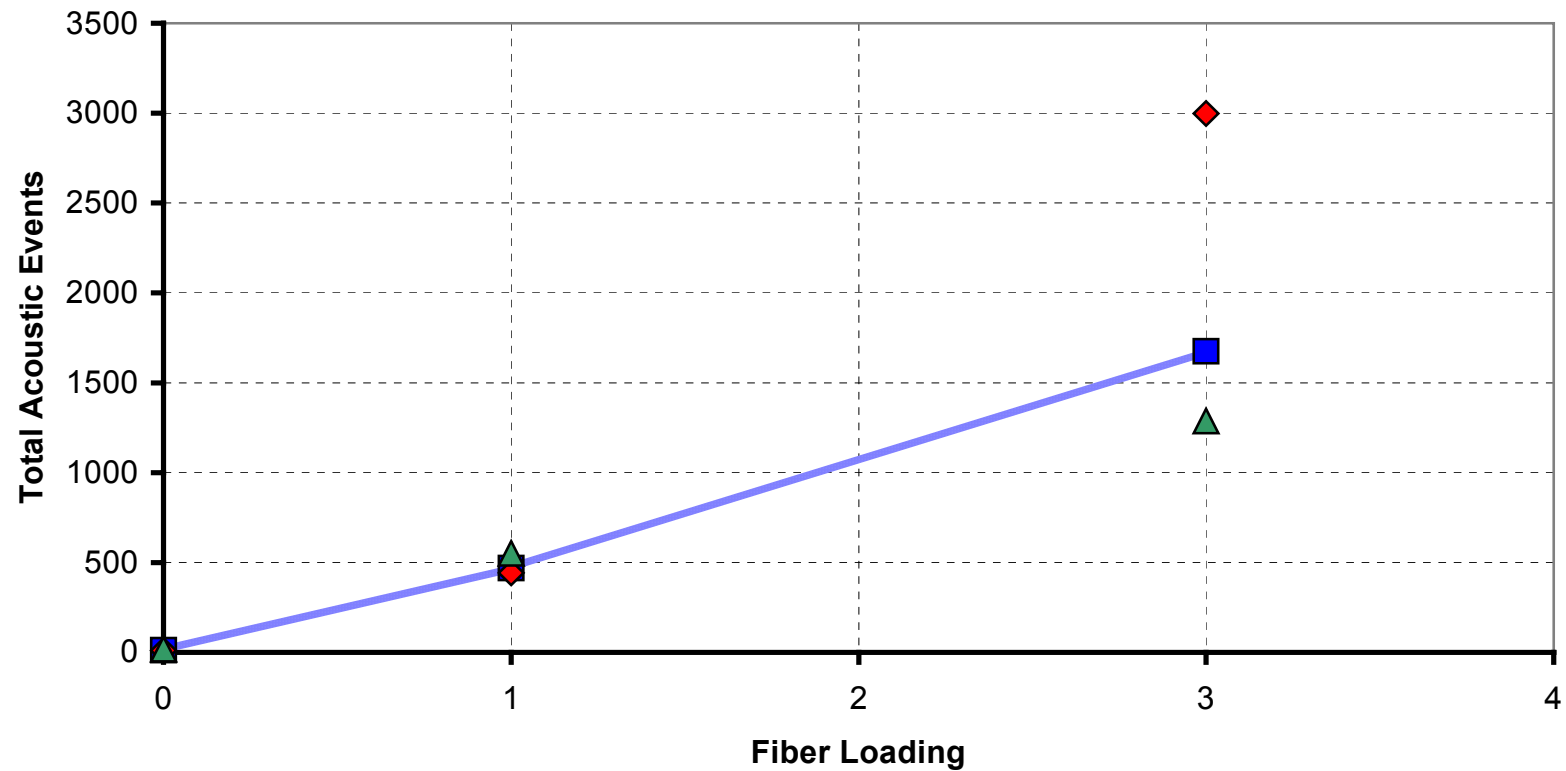


Figure 42

Acoustic Emission Tests Acoustic Activity for F1NR

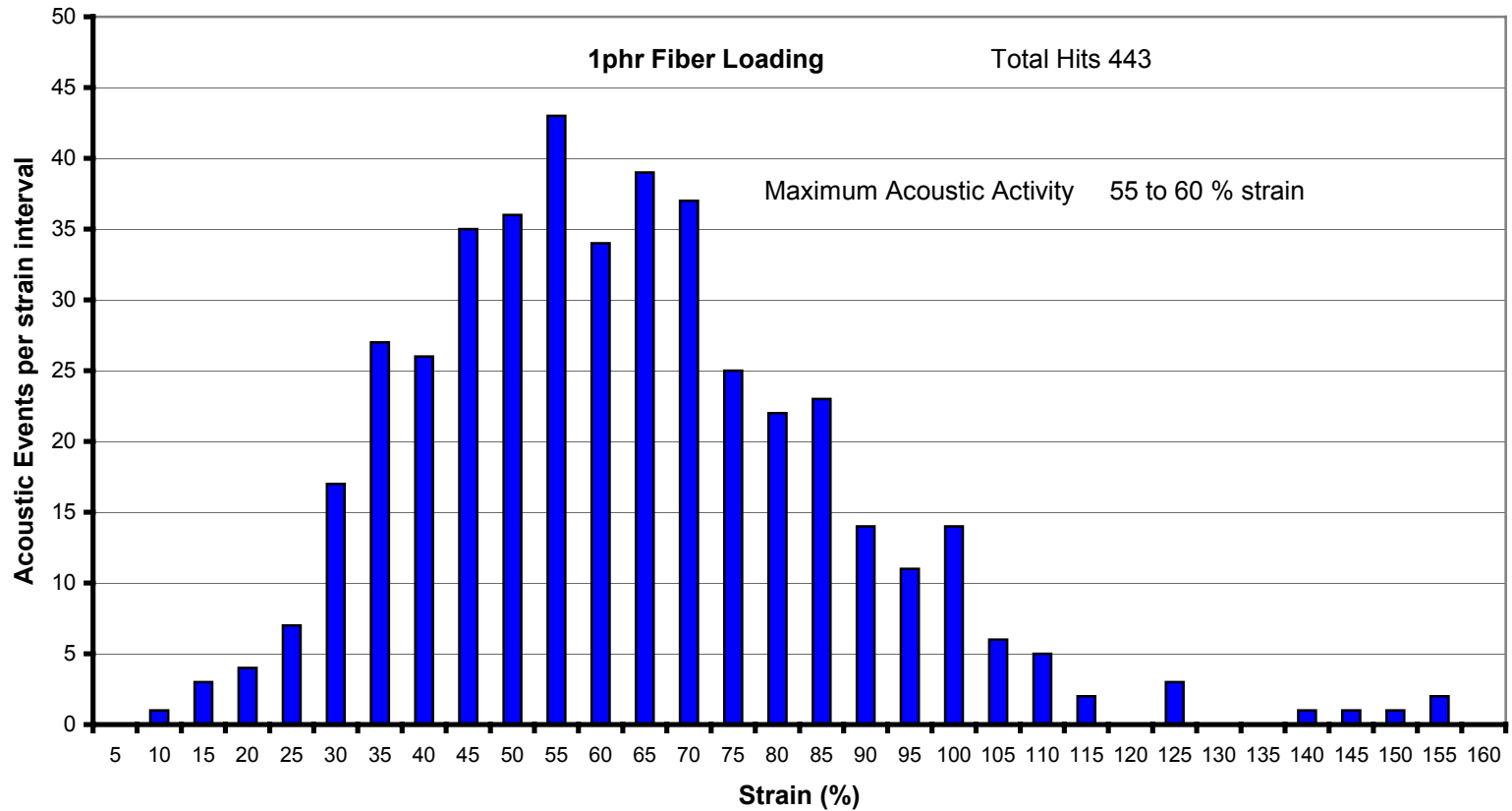


Figure 43

Acoustic Emission Tests Acoustic Activity for F3NR

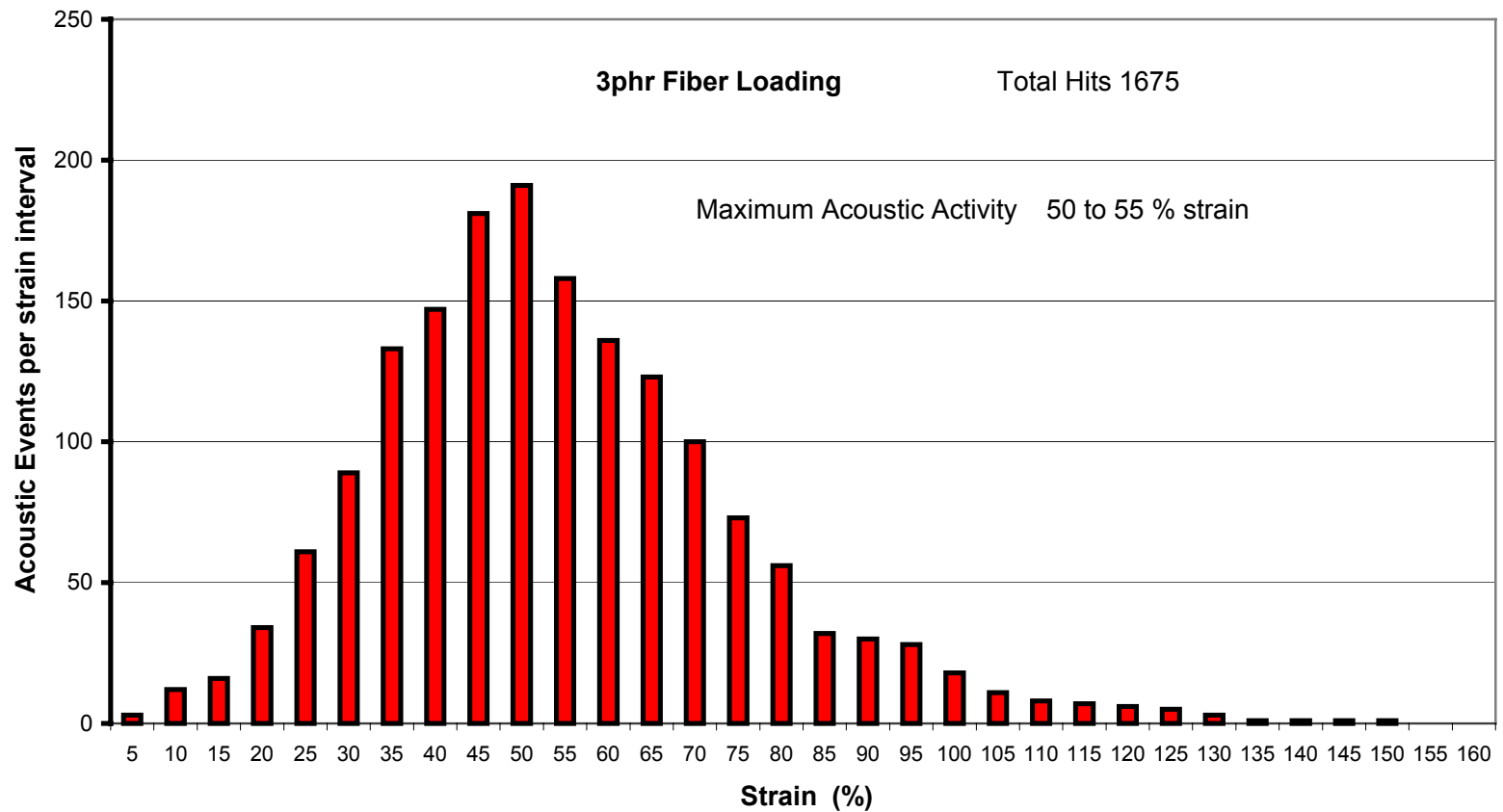


Figure 44

KEVLAR[®] brand engineered elastomer

An elastomeric composite of KEVLAR[®] brand pulp and elastomer

Product Number	1F722	1F724	1F770	1K1239
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Properties

Matrix elastomer	Natural Rubber	SBR 1502	NBR Med ACN	ENGAGE [®] 8400
Pulp concentration	23%	23%	23%	61.5%
Specific gravity	1.05	1.05	1.10	1.22
Physical form	nugget	nugget	nugget	granule

Product Number	1F723	1F1234	1F735	1F1168	1F819
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Properties

Matrix elastomer	Neoprene GW	Neoprene GW	Neoprene GRT	Neoprene GRT	Neoprene WRT
Pulp concentration	23%	28.6%	23%	28.6%	23%
Specific gravity	1.28	1.29	1.28	1.29	1.28
Physical form	nugget	nugget	nugget	nugget	nugget

General Recommendations

KEVLAR[®] engineered elastomer enables the compounder and designer to achieve performance, properties and designs not possible in the past. Compounds have been engineered to improve wear and abrasion, achieve better frictional properties, improve tear, improve shear resistance, replace reinforcing fabric, reduce part thickness, or lower rolling resistance.