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EFFECT OF KRAFT CELLULOSE PROCESSING ON HIGH STRAIN RATE BEHAVIOR OF RADFORD PROPELLANT DEVELOPMENT-596 GUN PROPELLANT

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14. ABSTRACT

Uniaxial compression testing at high strain rates was performed on several lots of RPD-596 gun propellant with varying processing technique for manufacturing nitrocellulose, and the sourcing of those materials, to evaluate the behavior under loading at various temperatures. Experimental lots of RPD-596 gun propellant grains were manufactured, substituting the traditional method of sulfite cellulose with the kraft process, for producing kraft cellulose. Additional source materials of wood pulp were used to evaluate the material behavior under compression at a high strain rate. Gun propellants are subject to harsh and extreme conditions during the initial launch process for munitions. Testing on specimens were conducted at strain rates on the order of 200/s and temperatures ranging -45°, -32°, 23°, and 63°C.

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INTRODUCTION

The gun launch environment is a harsh and dynamic event in which propellant grains are subject to high loads and pressures. Grains are subject to pressure waves, collision with other grains, and impact on the chamber wall at high speeds. The formulation of gun propellants is designed to tailor characteristics such as the grain size, perforations, and burn rate/pressurization based on the surface area. The internal ballistics of a firing event and these materials are driven to be optimized for a specific system. The mechanical properties of these materials are of interest due to the potential fracture of large propellant grains and increase in surface area. A significant increase in surface area can greatly affect the pressurization rate and burn characteristics during launch.

Two lots of Radford Propellant Development (RPD)-596 gun propellant made with nitrocellulose (NC) kraft (sulfate) cellulose from two different suppliers and one lot of RPD-596 made with pressurized boiled NC (lot BS016A-S73266) were tested in compression at high rates to determine any changes in mechanical behavior due to new sourcing and type of NC used in manufacturing.

The gun propellant formulation RPD-596 is a double base formulation composed mainly of NC, and nitroglycerin (NG). This composition is used in systems such as 120-mm M1002 target practice multi-purpose with tracer cartridges. A total of four lots of RPD-596 gun propellant were created to evaluate their response under compression at high rates (table 1). The baseline lot BS014C-S73191 has been manufactured with sulfite cellulose. The three experimental lots: (1) BS015J-S573245, (2) BS015J-S573246, and (3) BS016A-S573266 were all composed using the kraft cellulose process, each with different sourcing of wood pulp (table 2).

Table 1
Lot process and sourcing of ingredients

Propellant lot	Process	Source
BS014C-S73191	Sulfite cellulose	Reference lot
BS015J-S573245	Kraft cellulose	Buckeye sulfate pulp
BS015J-S573246	Kraft cellulose	Reyonier sulfate pulp
BS016A-S73266	Kraft cellulose	Pressurized boiled

Table 2
RPD-596 formulation ingredients

RPD-596 composition	
Material	Ratio
NC	63.5 to 69.5%
NG	20 to 25.5%
Acetyltriethyl citrate	8.5 to 11%
Akardite II	.5 to .9%
Other	<1%

TEST SETUP

An Instron very high strain rate hydraulic testing apparatus located at the U.S. Army Armament Research, Development and Engineering Center, Picatinny Arsenal, NJ, was used to conduct the uniaxial compression of the RPD-596 gun propellant samples. The devices can achieve actuator velocities up to 20 m/s. A Kistler pezioletric transducer was used to measure the load on the sample during these short time duration impact tests. A high-speed camera was used to measure the actuator displacement during each test. The load measurements were used to determine compressive stress, and the actuator displacement was used to determine the strain the specimen undergoes during testing. During each test, the actuator will apply loading on the grain specimen. Upon reaching a desired displacement, or sample strain, the load is then transferred to a steel fixture to prevent further compression of the sample.

Prior to testing, the sample grains are prepared by using a Buehler Isomet saw to face the end surfaces so they are flat and parallel. The ends of the individual grains were faced to achieve a 1:1 length to diameter ratio. This is ideal to ensure there is uniform loading across the samples. Dimensions of the samples are recorded including length, diameter, and perforation size and number if present. Samples of RPD-596 propellant grains ranged from 6.3 to 6.5 mm in length and were 6.4 mm in diameter. The grains are placed in a large steel compression fixture, and placed in a temperature conditioner for 2 hr at temperature to equilibrate. The steel fixtures were removed from the conditioning chamber and placed on the material testing device at desired velocities (fig. 1).

Figure 1
High-rate material testing device with high-speed camera measuring actuator displacement

EXPERIMENTAL

Three samples from each lot were compressed at high rates to determine stress-strain response under various temperatures. The RPD-596 grains were compressed approximately 50% of their length. Loading and displacement profiles were recorded during each test. This data was used to calculate the stress and strain of each sample, and then plotted to evaluate their behavior. The strain rates observed during testing were approximately 200/s. The plotted results of the samples were then measured to determine the modulus, peak stress, strain at peak stress, and the work hardening or softening slope. Several tests were conducted for each lot at temperatures of 63°, 23°, -32°, and -45°C. The results were tabulated to determine averages and standard deviation for results. An example of a typical stress-strain plot of a material being compressed is shown in figure 2.

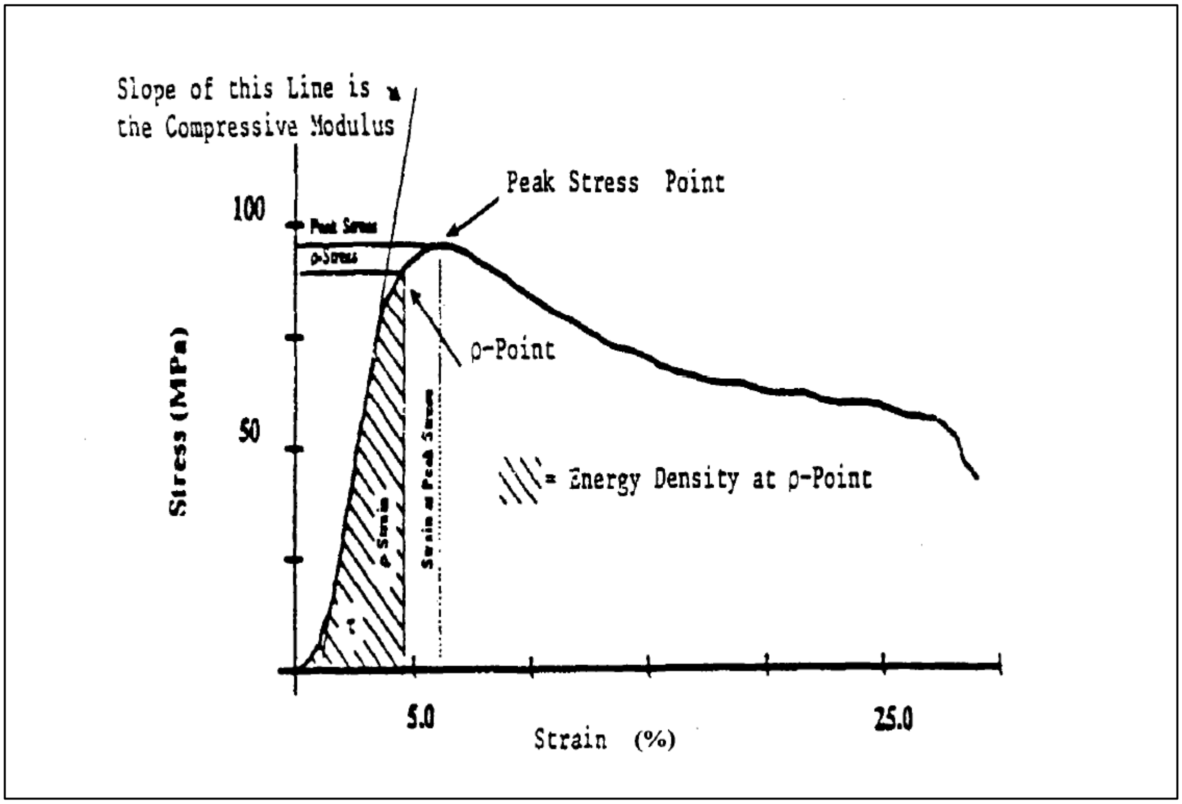

Figure 2
Example of typical stress-strain plot of sample under compression found in North Atlantic Treaty Organization (NATO) standardization agreement (STANAG) 4443

Engineering strain calculation:

$$\varepsilon = \frac{\Delta l}{L} \tag{1}$$

Engineering stress calculation:

$$\sigma = \frac{F}{A} \tag{2}$$

A number of important characteristics can be determined from stress-strain plots of these tests. The characteristics evaluated in this study include: (1) the modulus, (2) peak compressive stress, (3) strain at corresponding peak compressive stress, and (4) the failure slope. The modulus is a measure of the initial slope described as the elastic region of the material. It is a measure of the material's stiffness or spring constant prior to reaching the point in which the material begins to fail and undergo permanent damage. The peak compressive stress is a measure at which the maximum stress is highest during the loading period. The strain at peak compressive stress is the amount of strain the sample has undergone at which the peak compressive stress is located along the stress-strain curve. The failure modulus describes the slope and behavior of the curve in the region beyond the peak compressive stress. A negative slope indicates work softening such as figure 2. This negative slope indicates that the material cannot continue to support loading while failing. A positive slope in this region indicates the material has failed and is undergoing work hardening, a process in which the material is able to continue to support increased loading and stress with its geometry changing to decrease in height and increase in diameter (assuming a constant volume and density).

RESULTS

A number of common trends occurred over the range of conditions while performing the testing. The modulus and peak stress of each lot had increased as the conditioning temperature was decreased. At 63° and 23°C, samples that had undergone work hardening continue to support loading after reaching a peak stress and deformed under additional deformation. Under the conditions at -32° and -45°C, the samples had begun failing, exhibiting work softening with the samples breaking up into pieces under additional deformation. Pieces of the samples post-tests are shown in figures 3 through 6 alongside an undeformed grain. At the colder temperature of -45°C, it appears that each sample breaks up into a higher number of smaller shards. This trend increase in surface area at colder temperatures is the concern for specifically gun propellants, as they may affect the pressurization rate of the chamber during initial launch.

Figure 3
RPD-596 samples post-test at 63°C and an undeformed grain on the right

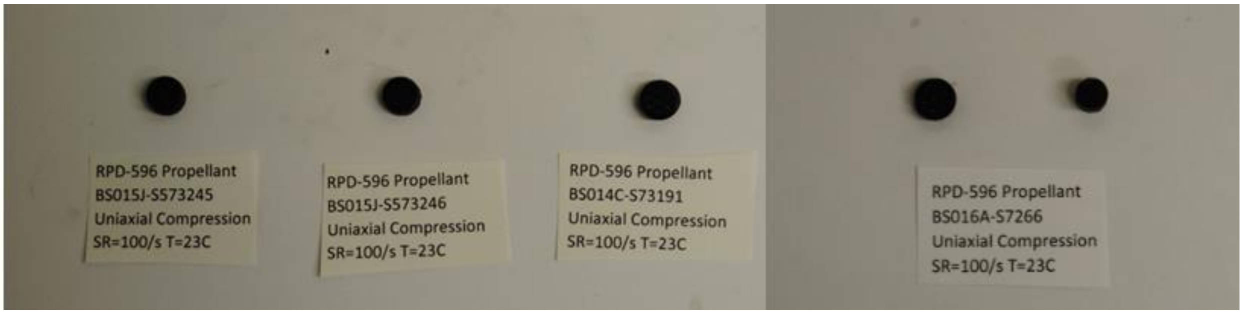

Figure 4
RPD-596 samples post-test at 23°C and an undeformed grain on the right

Figure 5
RPD-596 samples post-test at -32°C and an un-deformed grain on the right

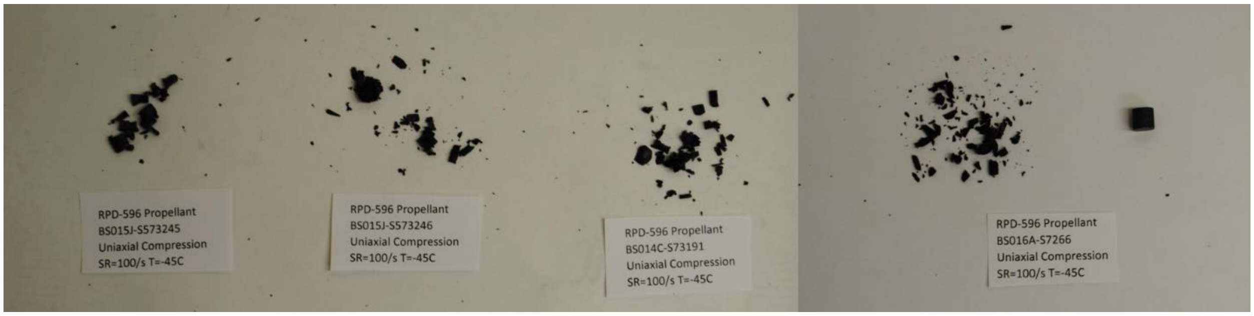

Figure 6
RPD-596 samples post-test at -45°C and an un-deformed grain on the right

The lots of RPD-596 propellant grains all appeared to be similar in their responses under loading. The behavior and trends at each temperature were consistent with each other, and no significant deviations were observed due to the different kraft versus sulfite processing and mill source of the propellant. The results and parameters of each lot are shown in table 3. Some important characteristics of each lot material such as the modulus, peak stresses, and strains at peak stresses appear to be within standard deviations of each other. Example plots of a specimen from each lot that were plotted along with other tests at each condition are shown in figures 7 through 10. Due to the brittle behavior at lower temperatures, the range and standard deviation in characteristics shown in table 3 increase, introducing more variability in the behavior and results.

Table 3
Results of RPD-596 high-rate compression tests

Temp (deg C)		Modulus (MPa)	Peak Compressive Stress (MPa)	Strain at Peak Stress	Work Hardening/ Softening Slope (MPa)
Lot BS014C-S73191					
63C	Avg	474	29	0.072	112
	Std Dev (+/-)	154	5.2	0.0159	23
23C	Avg	1205	78.7	0.0899	111
	Std Dev	138	3.5	0.0093	53
-32C	Avg	2044	162.1	0.11	-901
	Std Dev	365	35.9	0.0071	1029
-45C	Avg	2245	182.5	0.1005	-2495
	Std Dev	416	65.9	0.0516	111
Lot BS015J-S73245					
63C	Avg	505	31.1	0.0713	111
	Std Dev	135	2.6	0.014	7
23C	Avg	1035	76.8	0.0994	98
	Std Dev	139	4.7	0.0183	92
-32C	Avg	2197	193.1	0.1306	-2183
	Std Dev	345	37.2	0.0618	525
-45C	Avg	1971	218.1	0.1337	-2307
	Std Dev	28	15.1	0.0123	215
Lot BS015J-S73246					
63C	Avg	611	33.1	0.0667	126
	Std Dev	136	5.1	0.0045	26
23C	Avg	985	76.5	0.1135	154
	Std Dev	179	3.7	0.012	39
-32C	Avg	2038	186.2	0.108	-2459
	Std Dev	400	23.4	0.0046	508
-45C	Avg	2204	245.2	0.1474	-2473
	Std Dev	118	23.4	0.0249	1935
Lot BS016A-S7266					
63C	Avg	500	29.5	0.0704	161
	Std Dev	28	2.6	0.0032	29
23C	Avg	1069	72.8	0.093	186
	Std Dev	56	1.7	0.007	15
-32C	Avg	1834	183	0.1293	-531
	Std Dev	313	13	0.0346	217
-45C	Avg	2359	158.1	0.0795	-2565
	Std Dev	255	31.5	0.0219	379

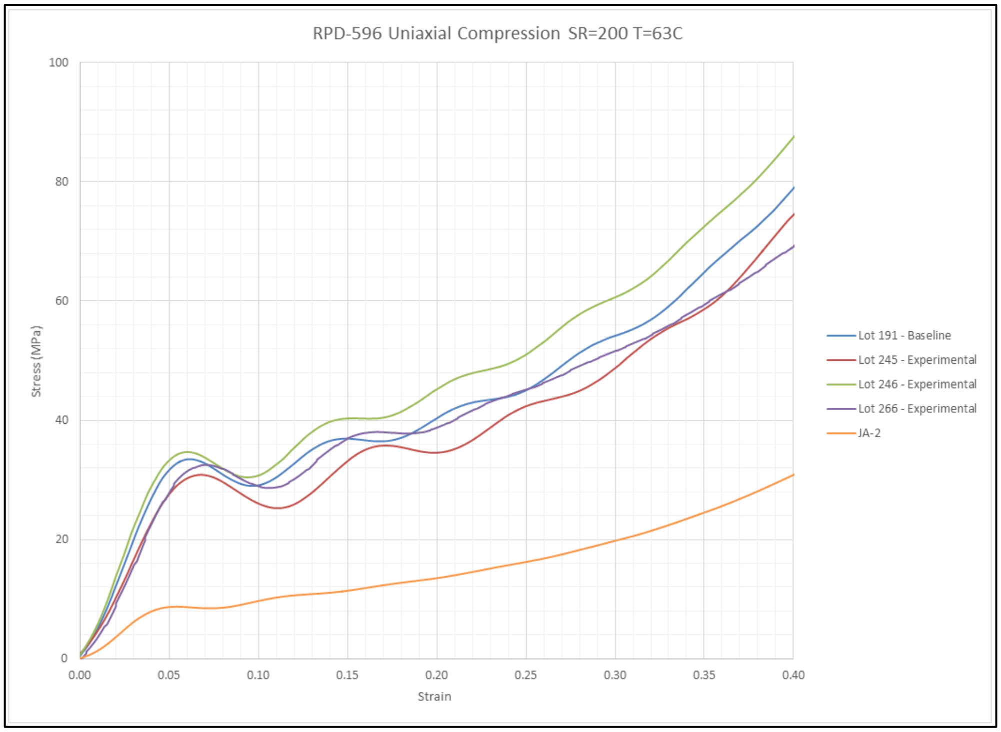

Figure 7
Stress-strain behavior of RPD-596 lots at 63°C under compression

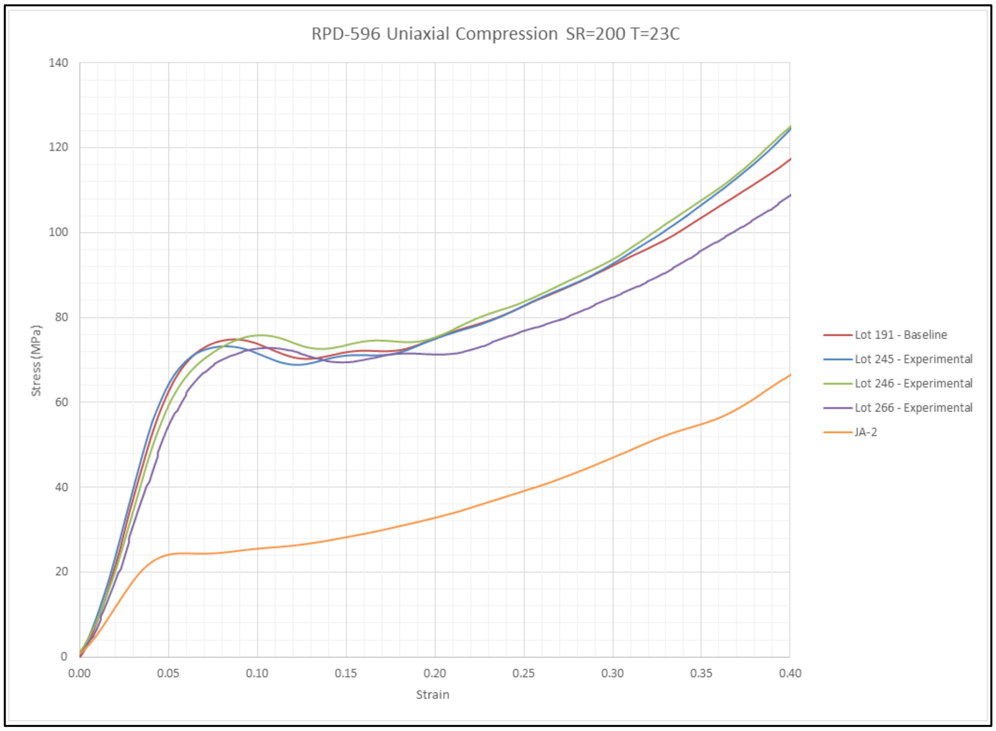

Figure 8
Stress-strain behavior of RPD-596 lots at 23°C under compression

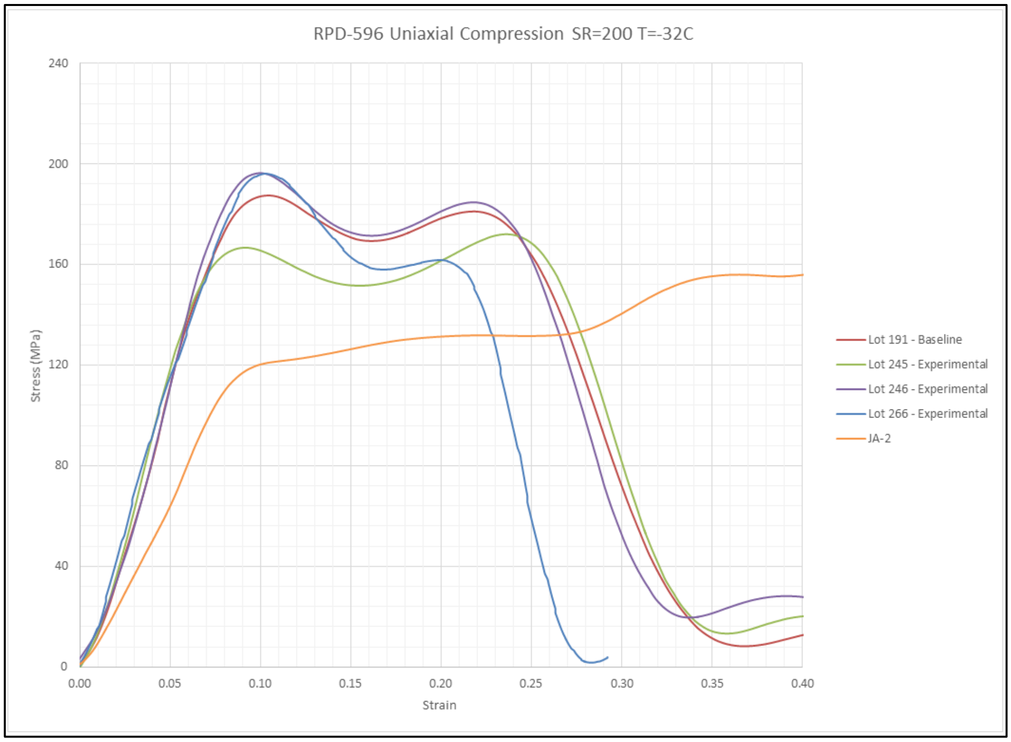

Figure 9
Stress-strain behavior of RPD-596 lots at -32°C under compression

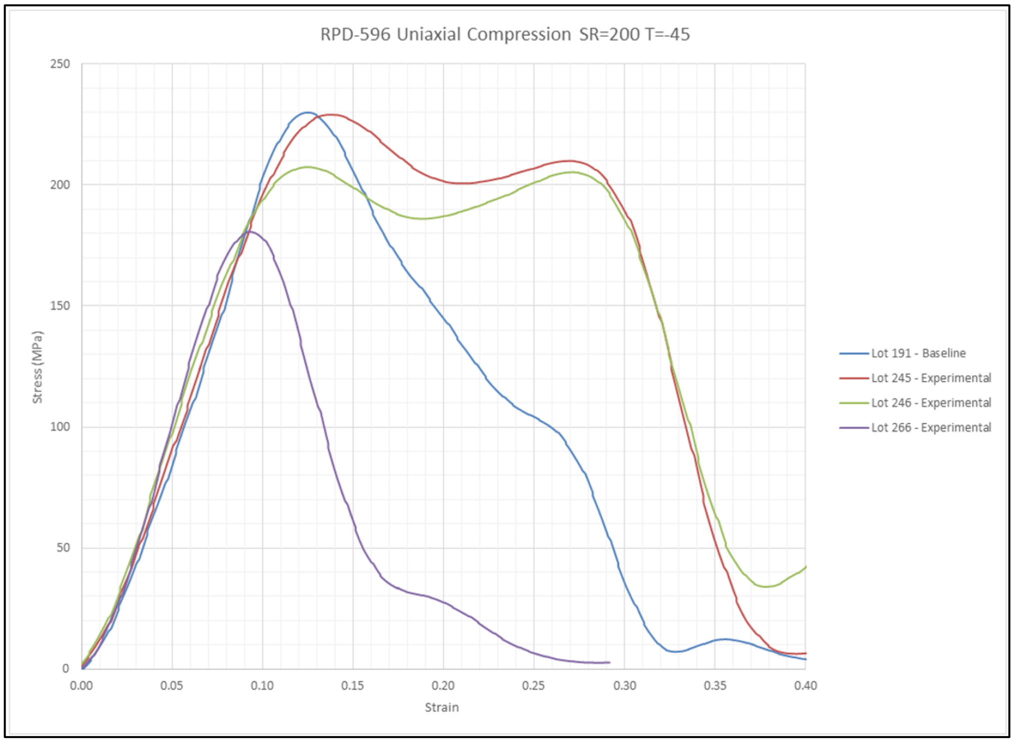

Figure 10
Stress-strain behavior of RPD-596 lots at -45°C under compression

Performing testing at both temperatures 63° and 23°C showed similar behavior of grains under compression. All lots of the sample material appeared to have similar behavior with regard to values of their modulus, peak stress, corresponding strains at peak stresses, and their work hardening slopes at each temperature. Both temperatures had shown the grain to continually deform after reaching its peak stress. This ability to continue to deform, absorb energy, and load had continued up until 50% strain was achieved on the sample. Post-test photographs of both temperatures did not show any signs of fracture among the grains. Average peak stresses had ranged from 29 MPa to 33.1 MPa for 63°C and 72.8 MPa to 78.7 MPa for 23°C. In both cases, their ranges and standard deviations don't appear to be significantly different. Plotted results of stress-strain curves in figures 7 and 8 appear to be very similar for both temperatures.

Compression tests performed at -32°C appeared to have fairly consistent results among the lots tested. The range of peak stresses at this temperature had ranged from 162.1 to 193.1 MPa; however, the standard deviation for some of these lots had been between +/-13-37.2 MPa. Other values for parameters appear to be similar among the lots at this temperature. One significant change in the response of the RPD-596 at colder temperatures is it failing and undergoing work softening after reaching its peak stress. The lots appear to each take some loading under additional deformation past its peak stress, prior to undergoing work softening. This negative slope for the work softening behavior indicates that the samples can no longer support additional loading thus begin to fracture and break up into smaller pieces. The post-test photographs in figure 5 show the samples that break up into similar size shards.

The testing of RPD-596 lots at -45°C had shown to have a slight increase in their modulus, peak stress, and their work softening slopes. The range of average peak stresses had been from 158.1 to 245.2 MPa with standard deviations ranging from 15.1 to 61.8. These ranges of both are increased compared to results at higher temperatures; however, for lots 266 and 191, only two samples were available for testing at this condition. Additional samples at this condition could help to increase confidence in values for their range and deviation in results. Another notable difference is when the sample reaches its peak stress, the curves appear to begin failing more abruptly with each specimen breaking up into smaller pieces. As shown in figure 6, the fracture shards collected post-test appear to be smaller in size and greater quantity compared to conditions tested at -32°C. The relation indicates the rate of failure and drop in stress to the severity of damaged grain specimens with larger surface areas created.

Material data of JA-2 was conducted in past experiments and added to the plots at conditions of 63°, 23°, and -32°C for comparison against the RPD-596. The composition of JA-2 has been widely used in a number of legacy items for the U.S. Army. The composition contains 59% NC and 15% NG both of which, in comparison, are less than the amount in the RPD-596. Although JA-2 appears to have a lower modulus, and peak stress in comparison the RPD-596 materials, it shows signs of work hardening and deformation under loading at 63°, 23°, and -32°C. At the-32°C temperature testing conditions, JA-2 showed no signs of fracture or breakup while undergoing large compressive strains compared to the RPD-596 where fracture does occur (figs. 11 through 13).

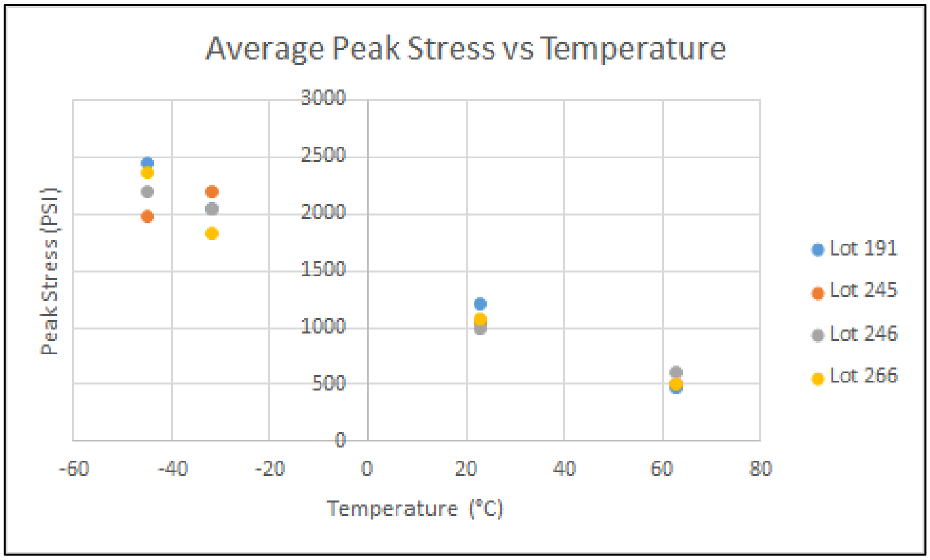

Figure 11
Average peak stress of lots versus temperature

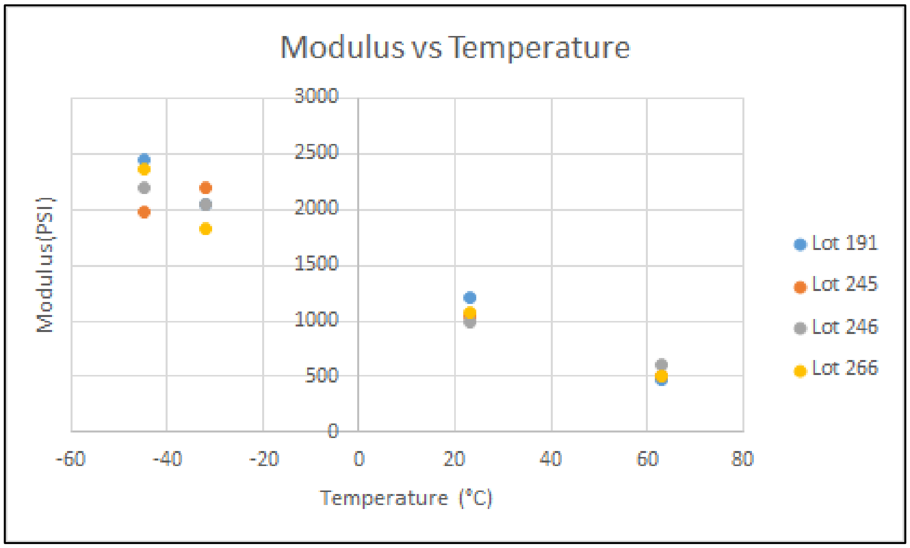

Figure 12
Average modulus of lots versus temperature

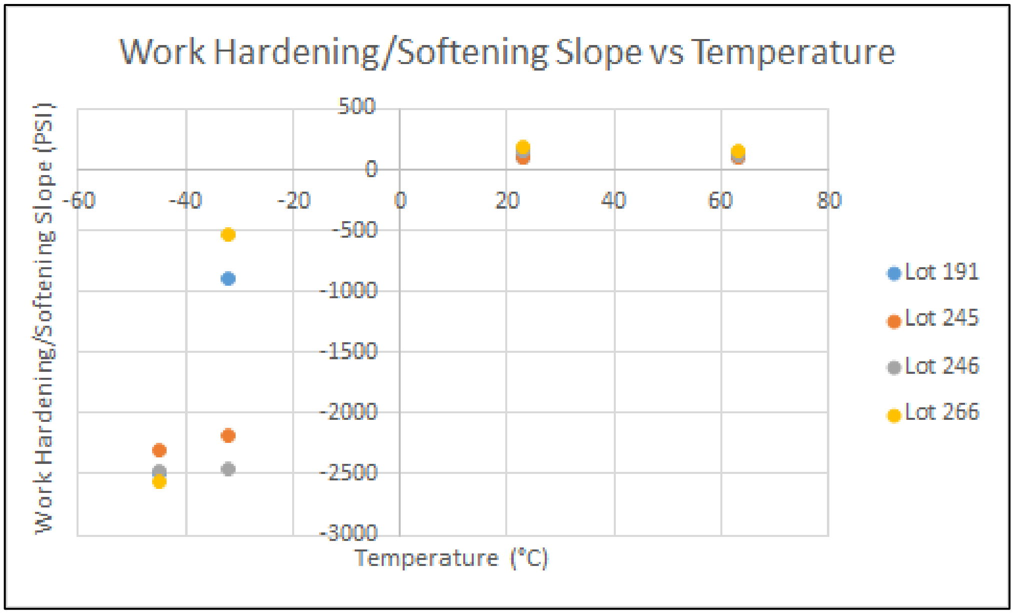

Figure 13
Average work hardening/softening slope of lots versus temperature

When comparing some of the average results of each lot across the temperatures, their relationship with temperature can be observed better. The temperature appears to have an indirect effect on both the modulus and peak stresses for the lots. The values of modulus and peak stresses among the lots have a good linear relationship with a change in temperature that can likely be accurately predicted across the temperatures tested. The failure behavior related to the work hardening and work softening slopes seems to be a polynomial fit when plotted against temperature. The values at 23° and 63°C appear very similar. As temperature decreases below 23°C toward -32° and -45°C, the failure behavior result becomes more sensitive to the temperature change.

CONCLUSIONS

Samples of Radford Propellant Development (RPD)-596 gun propellant were produced with sulfite and kraft nitrocellulose to determine behavioral changes due to sourcing and processing location. The material was evaluated under varying conditions and compared to evaluate its results. Several samples were shown to have a wider range of response at cold temperatures. Additional testing on more samples at this condition could improve the standard deviation. Overall, the behavior of experimental RPD-596 lots appeared to exhibit consistently similar results with the baseline material. Additional work such as behavioral changes due to aging may also be beneficial to investigate long-term effects on the material response with different source materials and processing effects. The kraft process for manufacturing cellulose appears to produce material that has the same consistent behavior as the traditional sulfite processing method.

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5. STANAG – 4443 Uniaxial Compression Test for Energetic Materials.

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