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Results of Load-Deflection Testing at LLNL as Part of a Multi-Site Assessment Study

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Overview

Kansas City National Security Campus (KCNSC) provided a set of nine (9) direct-ink-write (DIW) printed samples and a load-deflection test plan (Appendix A) to multiple sites to assess variations in methods and results among the sites. Each site received a separate set of test samples; the same set was not shared among sites. Information on each sample was provided by KCNSC (Appendix B). The samples were intended to be identical, though there was some minor variation among samples. This report describes the methods used and results obtained at Lawrence Livermore National Laboratory (LLNL).

LLNL Test Method

All testing was conducted at LLNL in B132S R2729 on 04/23/2018 by Ward Small. Room temperature was 21°C and humidity was 22% (measured by a VWR temperature/humidity meter).

Prior to load-deflection testing, the thickness of each sample was measured using a digital thickness gauge (Checkline MTG-DX, S/N 4171) with a 28.7-mm-diameter foot (measurement stress ~0.6 kPa). The values obtained at LLNL were in good agreement with those provided by KCNSC (Table 1). A photograph of one of the samples is shown in Fig. 1. Additional sample information can be found in Appendices A and B.

An Instron 5967 dual-column electromechanical test machine (S/N R5447) with a 5 kN static load cell (Instron 2580-5KN, S/N 137001) was used for load-deflection testing. A PC with Bluehill 3 software was used to operate the machine and acquire data. A 28.68-mm-diameter (1.129-inch-diameter) fixed lower platen (Wyoming Test Fixtures) and a 50-mm-diameter spherical seat upper platen with locking bolts (Wyoming Test Fixtures) were used. Data was acquired at 50 Hz.

Prior to testing the samples, a platen-to-platen compression test was performed to measure instrument compliance. A polynomial was fit to the resulting crosshead position vs. load curve (Fig. 2). During the load-deflection tests of the samples, the compliance was calculated (using the polynomial fit) at the given load for each data point and subtracted from the raw crosshead position data by the Bluehill 3 software in real-time to obtain compliance-corrected compressed thickness of the samples. Because (1) the compliance was quite low (~0.05 μm/N), (2) the applied load did not exceed 30 N, and (3) the compliance curve passed through zero at a load of 19 N (i.e., "zero gap" position was previously set at a load of 19 N with the platens touching), the compliance correction was negligible.

The sample was centered on the lower platen for testing (sample was larger than the lower platen). Whether the top or bottom surface of each printed sample faced up or down was unknown. Three load-unload cycles to a maximum compressive strain of 0.62 were performed at a test speed of 0.05 in/min (1.27 mm/min). The original thickness h_0 measured by KCNSC and the compliance-corrected compressed thickness h were used to calculate the engineering strain ε during the test:

$$\varepsilon = (h_0 - h)/h_0$$

The engineering stress σ was calculated by

$$\sigma = F/A$$

where F is the applied load and A is the loading area (taken as the area of the lower platen, 1.00 in^2).

Results

Load-deflection curves are shown in Fig. 3 (U.S. customary units) and Fig. 4 (SI units); all curves are overlaid. Individual curves for each sample are shown in Appendices C and D (U.S. customary units) and Appendices E and F (SI units). All plots include compliance-corrected values of compressed thickness and strain. Stress at 0.62 strain during the third loading cycle is given in Table 2. Sample X081 is an outlier, as was expected based on the cross-section sag reported by KCNSC (Appendix B).

Acknowledgments

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Table 1: Sample Thickness Measured by KCNSC and LLNL

Number	Sample	Thickness (in)		Thickness (mm)	
		KCNSC	LLNL	KCNSC	LLNL
1	BBN-X008-717	0.1083	0.1079	2.751	2.741
2	BBN-X023-717	0.1115	0.1114	2.832	2.830
3	BBN-X028-717	0.1092	0.1091	2.774	2.771
4	BBN-X033-717	0.1103	0.1100	2.802	2.794
5	BBN-X041-717	0.1095	0.1093	2.781	2.776
6	BBN-X047-717	0.1043	0.1045	2.649	2.654
7	BBN-X081-717	0.1053	0.1052	2.675	2.672
8	BBN-X100-717	0.1051	0.1049	2.670	2.664
9	BBN-X057-717	0.1066	0.1068	2.708	2.713

Table 2: Engineering Stress at 0.62 Engineering Strain During the Third Loading Cycle

Number	Sample	Stress at 0.62 Strain During 3rd Load	
		(psi)	(kPa)
1	BBN-X008-717	3.3746	23.267
2	BBN-X023-717	3.3567	23.144
3	BBN-X028-717	4.2379	29.219
4	BBN-X033-717	3.3567	23.144
5	BBN-X041-717	3.7737	26.019
6	BBN-X047-717	3.4054	23.479
7	BBN-X081-717	6.4250	44.299
8	BBN-X100-717	4.3150	29.751
9	BBN-X057-717	3.8574	26.596

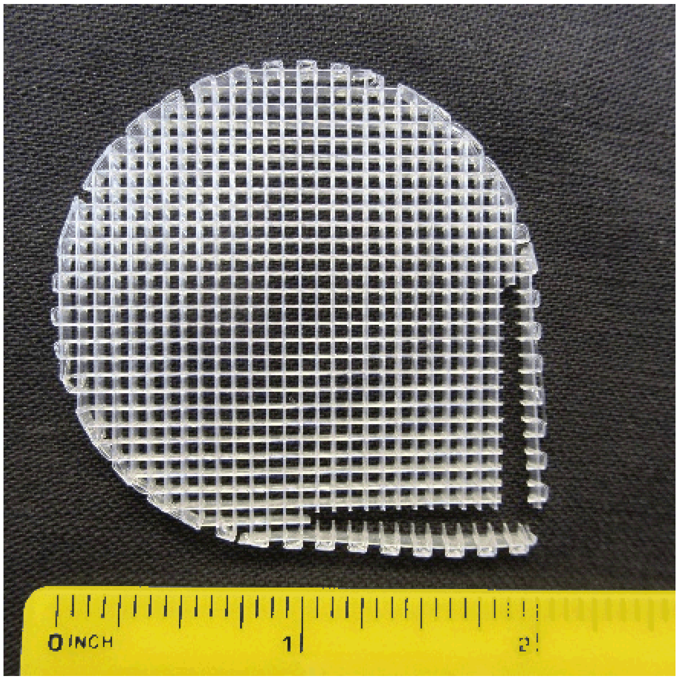


Figure 1. Photograph of a sample as-received at LLNL.

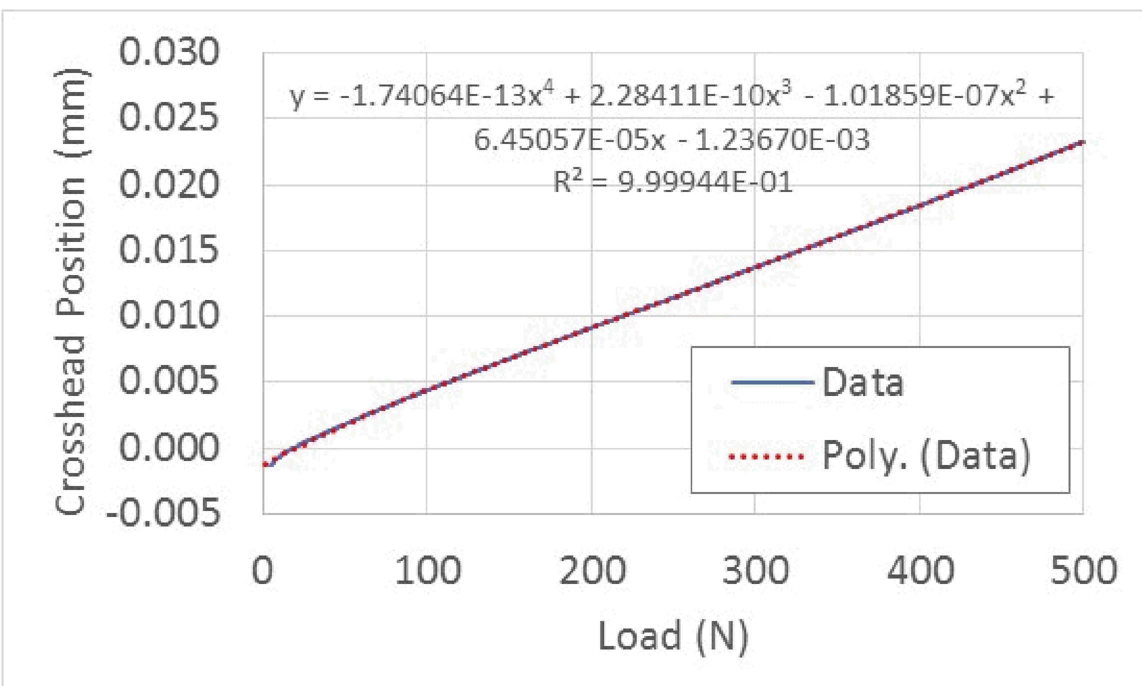
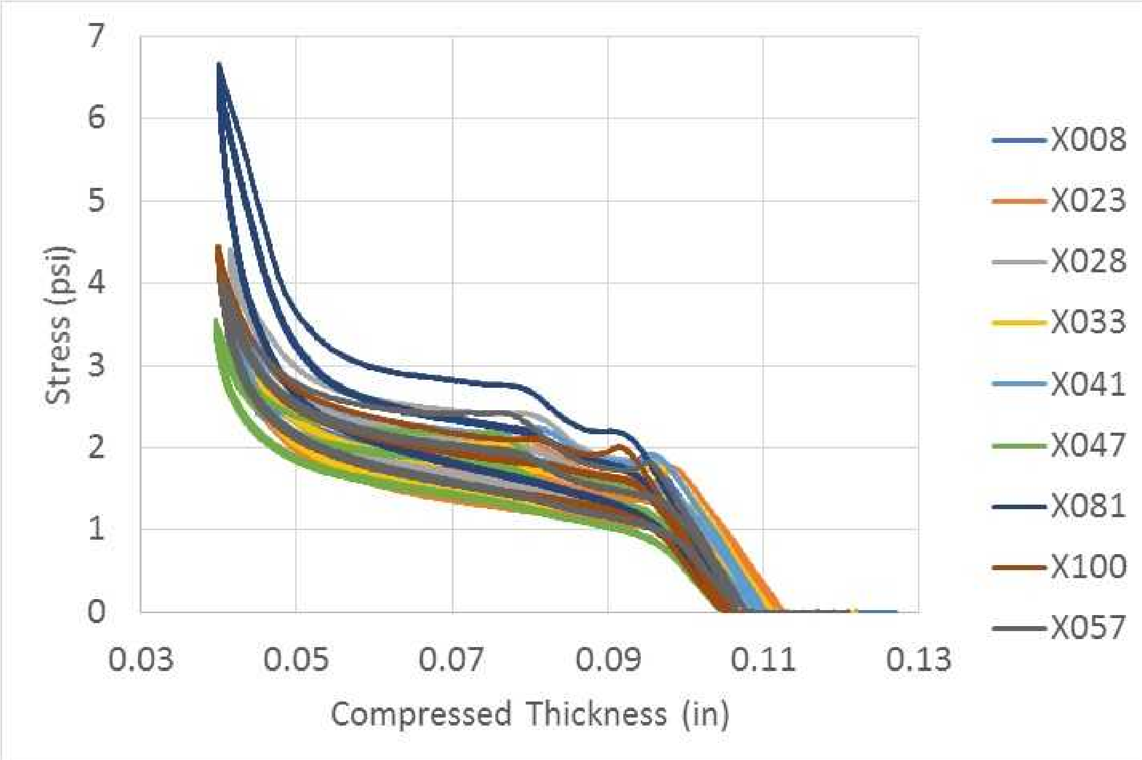


Figure 2. Instrument compliance curve. The polynomial fit (dotted line) is shown. Note that the crosshead position values go from negative to positive as compression increases, passing through zero at 19 N (load at which the crosshead position was set to zero with the platens touching). Compliance was approximately 0.05 µm/N.

(a)



(b)

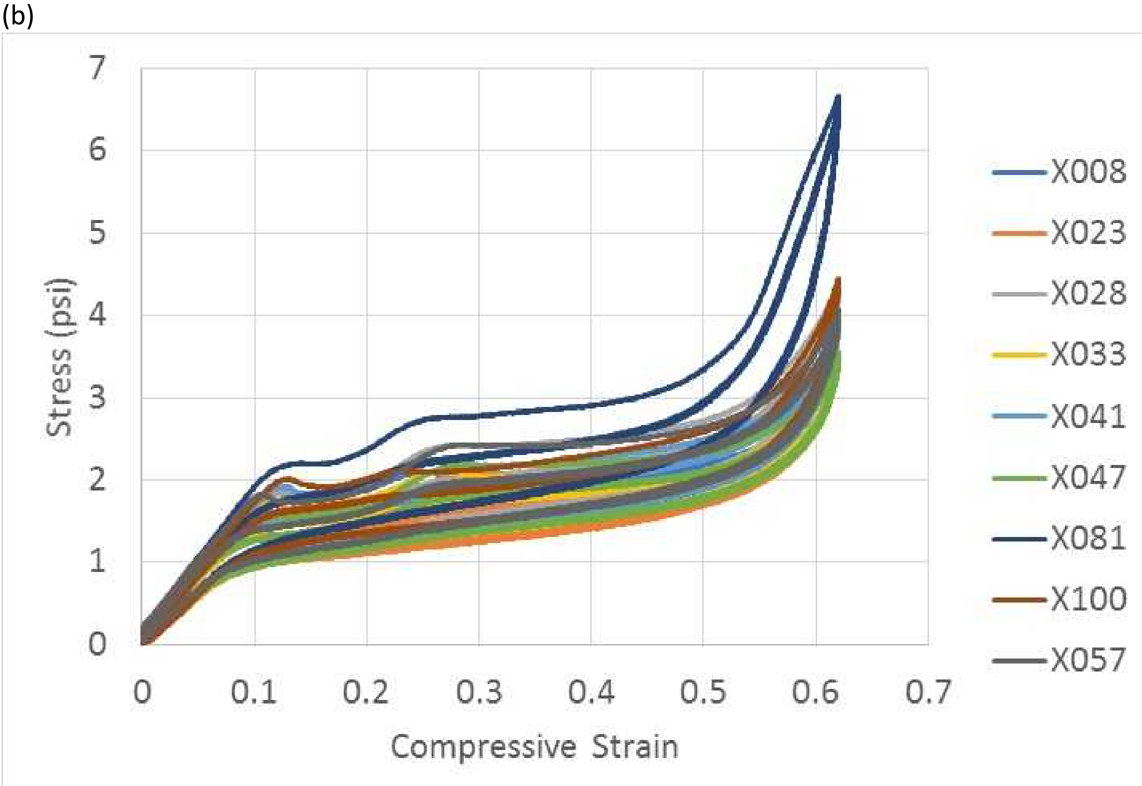
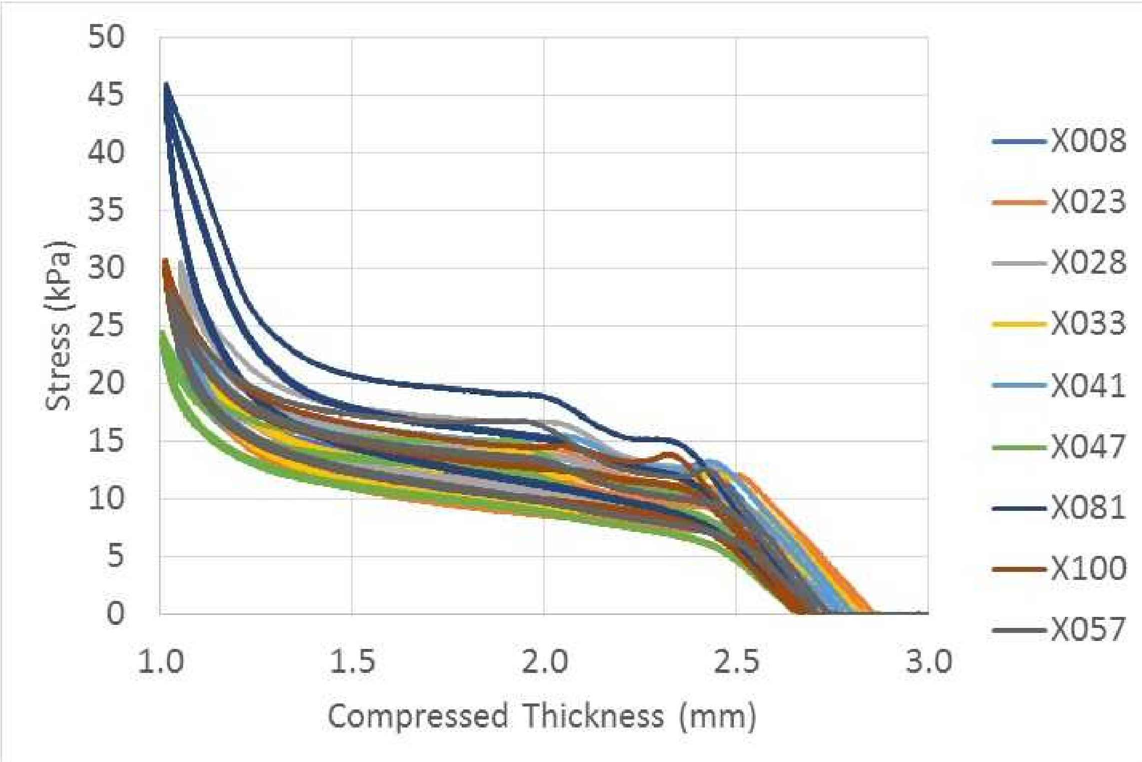


Figure 3. Engineering stress vs. (a) compressed thickness and (b) engineering strain. All 3 load-unload cycles are shown for each sample. Values in U.S. customary units.

(a)



(b)

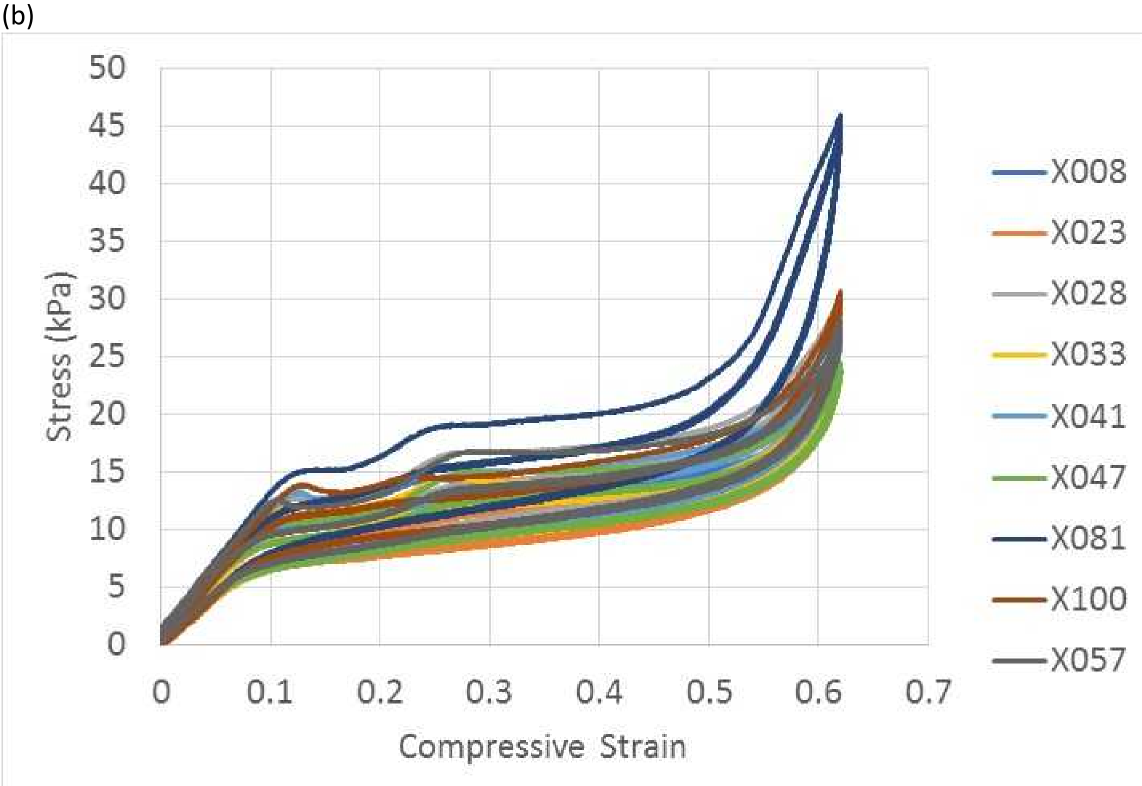


Figure 4. Engineering stress vs. (a) compressed thickness and (b) engineering strain. All 3 load-unload cycles are shown for each sample. Values in SI units.

APPENDIX A
Project Test Plan Provided by KCNSC

Project Test Plan (PTP)

Program Name:	Assessment of Load Deflection Testing Methods Used at the NSE and AWE
Scheduled Start Date:	7/30/2017
Scheduled Completion Date:	9/30/2017

Project Scope Description:

The goal is to assess site to site differences in load deflection testing methodologies using SE1700 printed in the W88D07 structure. Each site will be provided five 2-inch diameter teardrops SE1700 W88D07-structure pads printed at KCNSC. The teardrop shape was chosen to allow for cross sectioning of the pads prior to load testing. Each site will use its standard load defection methodology to analyze physical behavior. The data will be shared between all of the sites to determine variations between equipment and techniques.

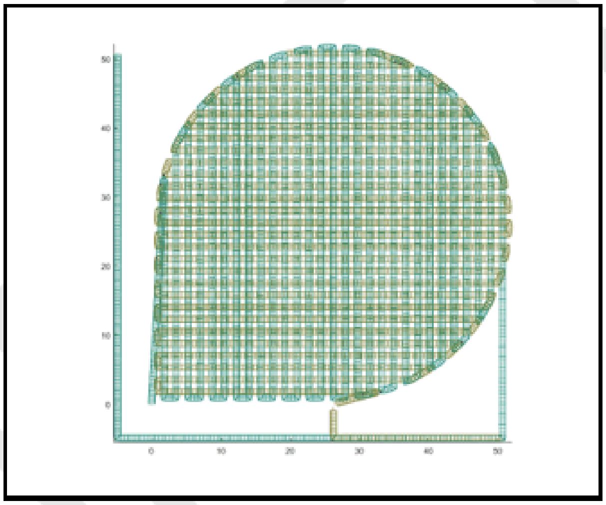


Figure 1: Sample shape to allow for cross sectioning as well as load defelection testing.

Material and Part Structure Summary

SE1700 is the current standard material for Direct Ink Write (DIW) printing and is currently in development for the W88 AF&F compression pads. This material consists of a part A base material and a part B catalyst material, all from the same lot. The material is mixed using a planetary thinky mixer at a 10:1 ratio with a 1% tolerance on the weights. To ensure proper mixing, the material is mixed in 45-second cycles at 2000 rpm until the material is homogeneous. After mixing, the material is hand loaded into syringes and placed into a centrifuge for 15 minutes at 4000 rpm. The syringes are then inserted into the DIW printer and the material is extruded with a Nordson EFD pump (model 7017179) using a 0.001158 cc/s flowrate with a print speed of 24 mm/s. The structure that is printed is summarized in Table 1.

Table 1. Compression Pad Structure

Structure	Spacing (center to center)	Nozzle Size	Nozzle Type	Layers
BCC	1.75 mm	250 µm*	Nordson EFD Plastic	13

*Nozzle inner diameter were examined under a microscope and determined to be 250±10 µm

The Z-coordinate at which each layer is printed is presented in Table 2. These values have been experimentally determined to decrease part-to-part variation.

Table 2. Layer to Layer *z* Height Variation of Printed Structure

Layer 1	Layer 2 (sum height)	Layer 3 (sum height)	Layer 4 through 13 (sum height)
0.2500 mm	0.4875 mm	0.725 mm	0.725 + (n-3)*0.225 where n=current layer number

Test Method

Load deflection testing will be carried out using methods defined at each site. Environmental and critical testing parameters will be recorded. Any method used to ensure Instrument compliance should be noted and verified that it does not affect results. If a correction is allied to the data post testing, both the raw and corrected data should be provided.

Critical Parameters

These are testing parameters that need to be matched in order to eliminate potential variables between our systems:

Platen Size	Loading Velocity	Unloading Velocity	Cycles	Cycle Point*
1.129 in	0.05 in/min)	0.05 in/min	3	62% or 8 psi

*Maximum deflection is 62% or the maximum applied force is 8psi

KCNSC Load Deflection Testing Methodology

KCNSC will use the standard production testing instrumentation and method during this load deflection assessment study.

KCNSC tests for load deflection using model TE5675 Gilmore systems. Testing occurs at 23°C ± 3°C and at 50% ± 10% relative humidity. Two Gilmore instruments are used at KCNSC to test compression pads; both systems are calibrated and yield matching load deflection data. Prior to load deflection analysis, each sample thickness is measured. The thickness of the sample pad is entered into the Gilmore software to ensure 62% deflection of each individual pad. For this cross site validation study, the following critical testing parameters will be used.

Table 3. KCNSC Gilmore Load Deflection Testing Parameters

Sample Position	Platen Size	Loading Velocity	Unloading Velocity	Cycles	Cycle Point*
Sample is centered on the platen	1.129 in	0.05 in/min (+/- 0.001)	0.05 in/min (+/-0.001)	3	62% (+/-1)

*Maximum deflection is 62%

For each sample, a single test consisting of 3 cycles will be performed. Complete stress/strain curves will be collected for each of the 3 loading and unloading cycles.

Data Reporting

At a minimum, the raw data should include the following:

- Test date
- Test operator
- Instrument used
- Environmental testing conditions (temperature, °C, and percent relative humidity)
- Testing parameters, such as those described in Table 3
- Sample identification provided by KCNSC
- Sample dimensions (diameter, thickness, etc.)
- Stress/strain data for each cycle
- Crosshead Positional data

All data should be sent to John Durivage at KCNSC, who will collate the data and then distribute the data to each site.

A final report will be written summarizing the testing methods, conditions, and results.

Project Contacts:

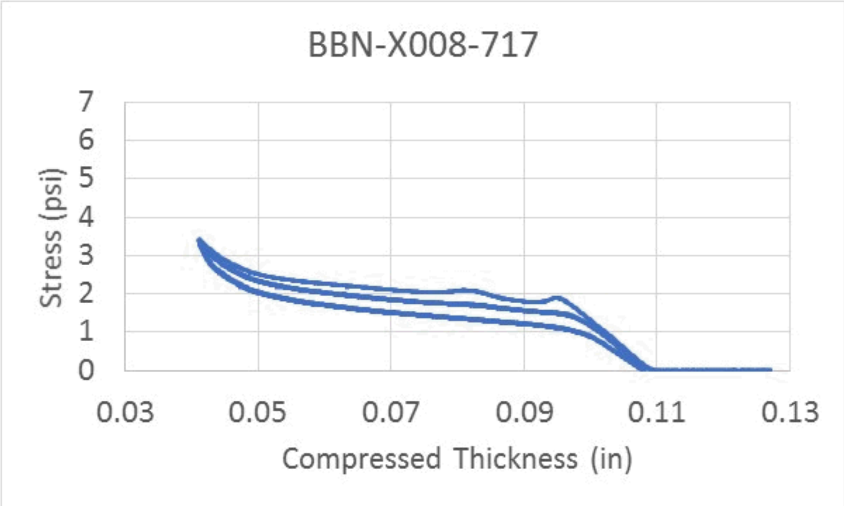
Name	Location	Phone	Email
John Durivage	KCNSC	816-488-3706	jdurivage@kcp.com
Denisse Ortiz-Acosta	LANL	505-606-1947	denisse@lanl.gov
Tom Wilson	LLNL	925-422-5519	wilson97@llnl.gov
Robert Bernstein	SNL	505-284-3690	rbernst@sandia.gov
Preeya Lakhani	AWE		preeya.lakhani@awe.co.uk

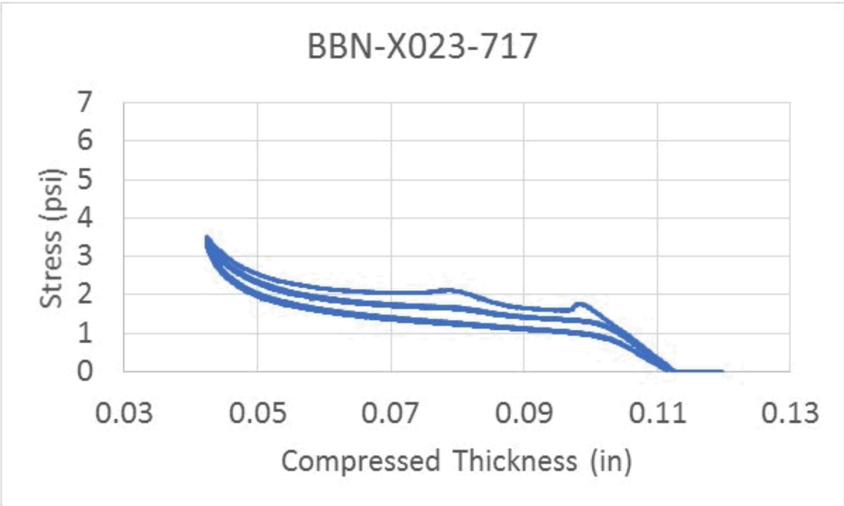
APPENDIX B
Sample Data Provided by KCNSC

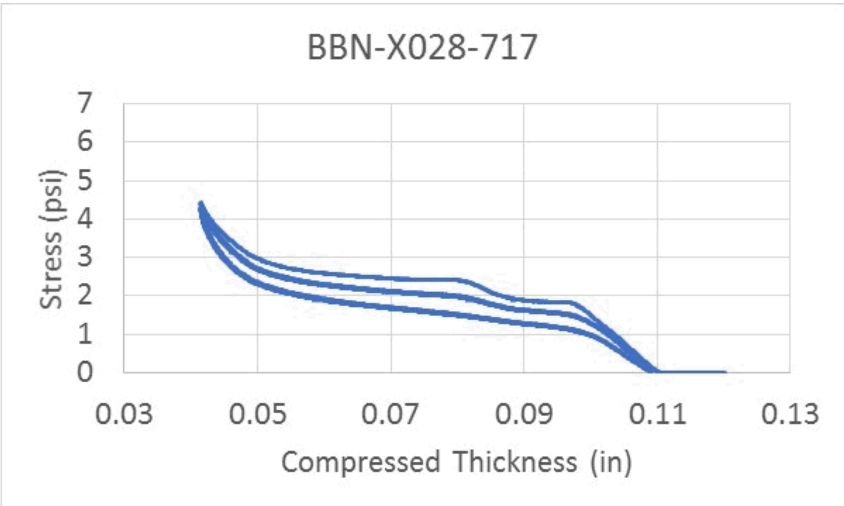
LLNL								
Number	DOM	Site	Sample	Quadrant	Mix ratio	Order	Thickness	Cross Section Sag
1	7/11/2017	LLNL	X008	1	10.0062	11	0.1083	None
2	7/11/2017	LLNL	X023	2	10.0062	14	0.1115	None
3	7/11/2017	LLNL	X028	3	10.0062	3	0.1092	None
4	7/11/2017	LLNL	X033	3	10.0062	11	0.1103	None
5	7/11/2017	LLNL	X041	4	10.0062	11	0.1095	None
6	7/12/2016	LLNL	X047	1	10.00816	1	0.1043	None
9	7/12/2016	LLNL	X057	1	10.00816	11	0.1066	None
7	7/12/2016	LLNL	X081	3	10.00816	3	0.1053	1st and 2nd Sag
8	7/12/2016	LLNL	X100	4	10.00816	7	0.1051	Flat
						Average	0.1078	
						St. Dev	0.0024	

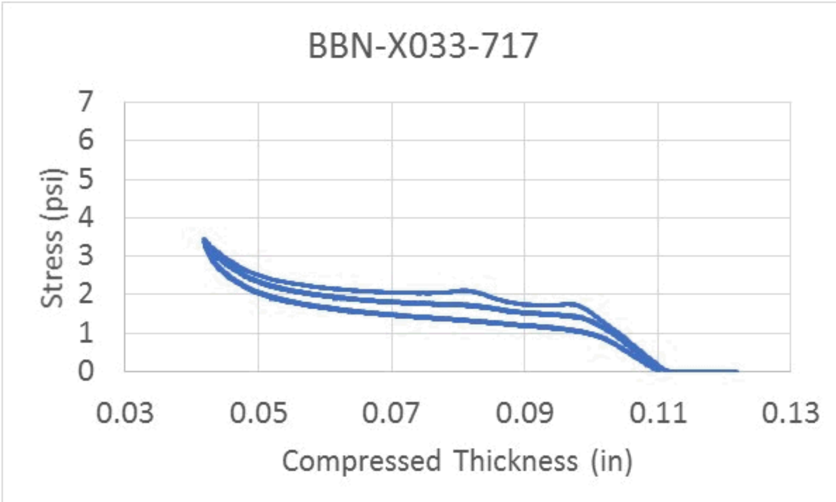
Thickness is in inches. Nine (9) samples were provided. The samples are not numbered consecutively in the above table (far left column). The year of the date of manufacture (DOM) for samples X047, X057, X081, and X100 may be incorrectly listed as 2016 (likely should be 2017).

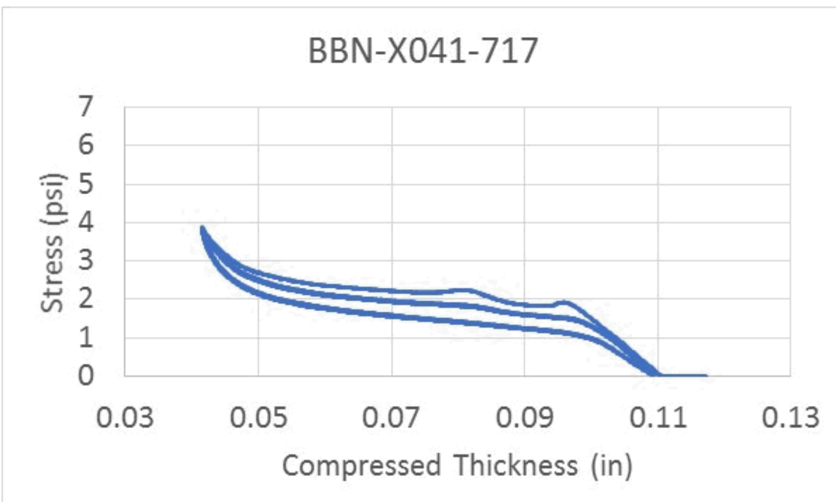
APPENDIX C
Individual Engineering Stress vs. Compressed Thickness Curves (U.S. Customary Units)

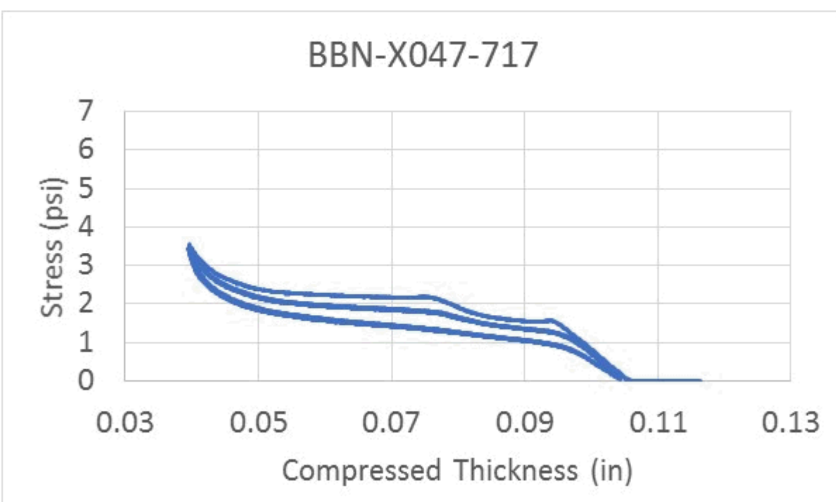


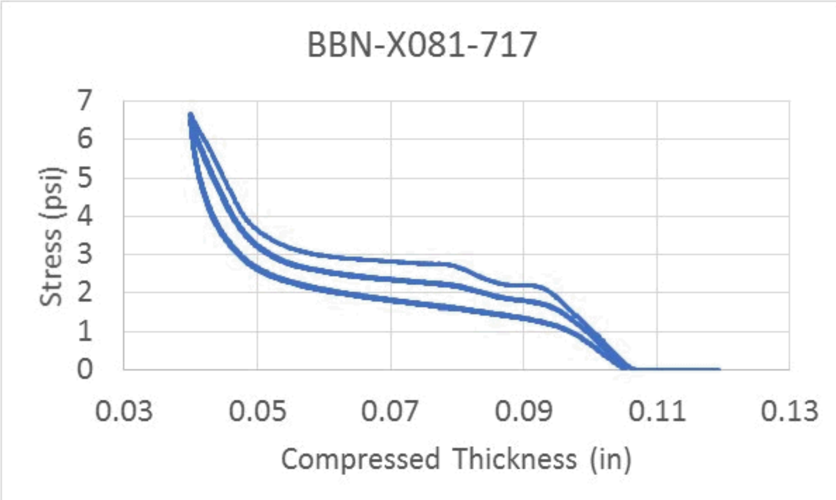


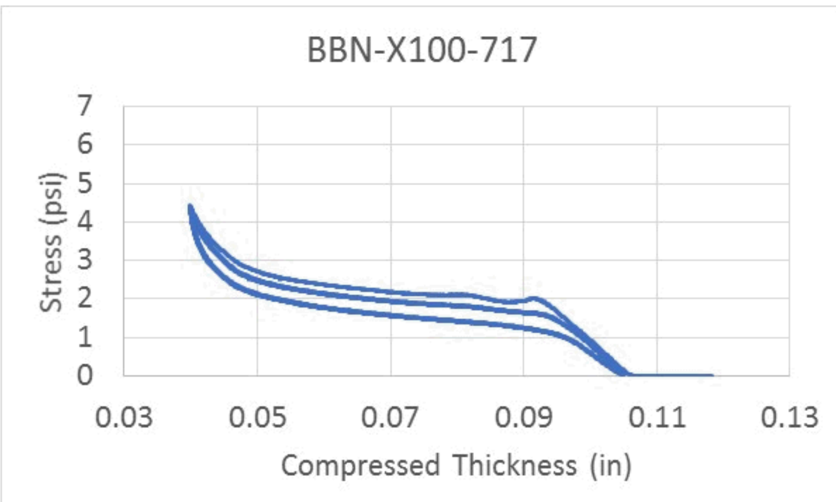


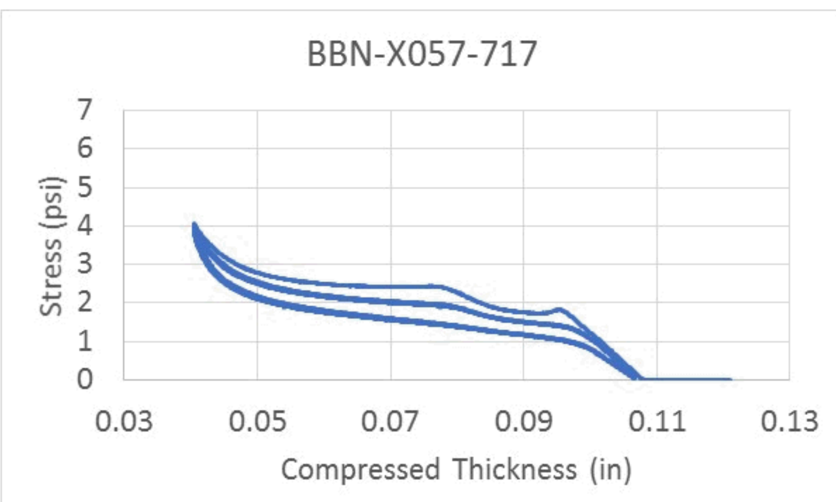

BBN-X033-717
Stress (psi)
Compressed Thickness (in)
0
1
2
3
4
5
6
7
0.03
0.05
0.07
0.09
0.11
0.13


BBN-X041-717
Stress (psi)
Compressed Thickness (in)
0
1
2
3
4
5
6
7
0.03
0.05
0.07
0.09
0.11
0.13

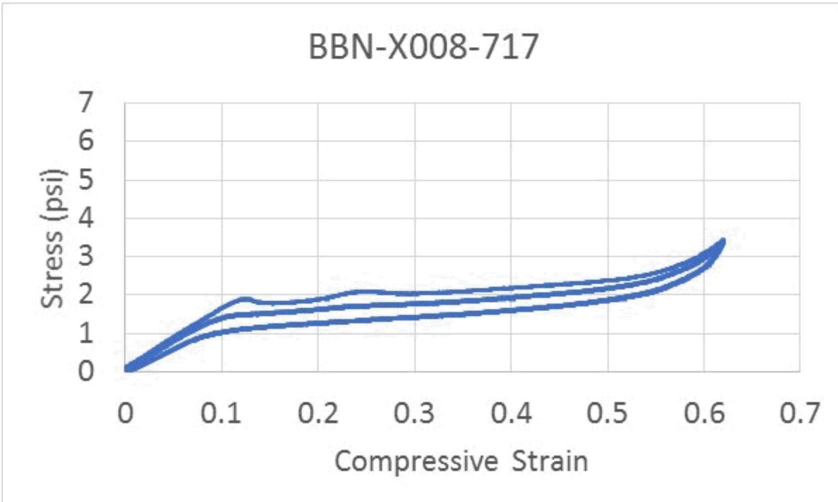

BBN-X047-717
Stress (psi)
Compressed Thickness (in)
0
1
2
3
4
5
6
7
0.03
0.05
0.07
0.09
0.11
0.13

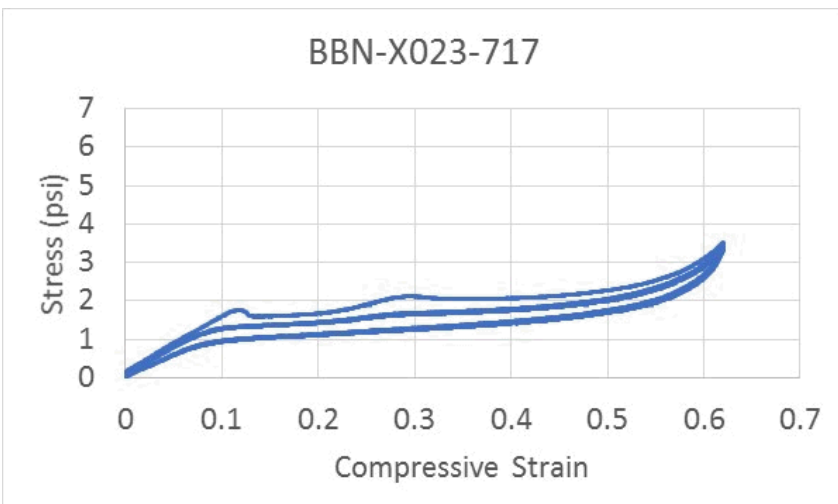

BBN-X081-717
Stress (psi)
0
1
2
3
4
5
6
7
0.03
0.05
0.07
0.09
0.11
0.13
Compressed Thickness (in)

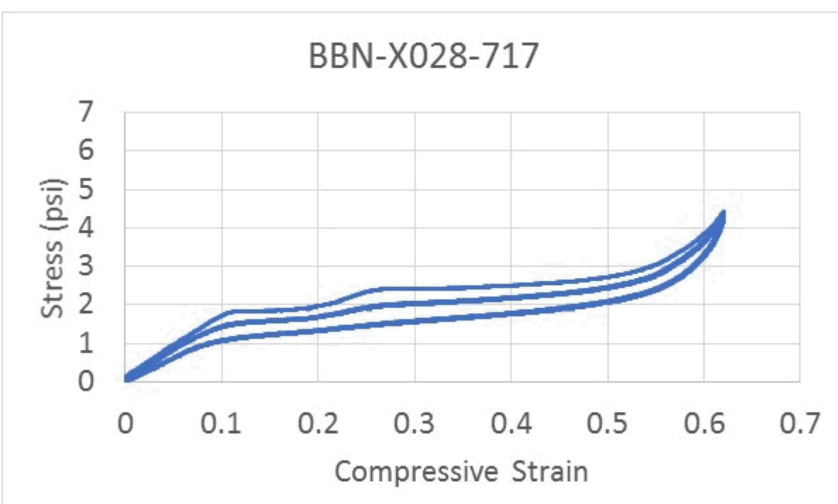

BBN-X100-717
Stress (psi)
0
1
2
3
4
5
6
7
0.03
0.05
0.07
0.09
0.11
0.13
Compressed Thickness (in)

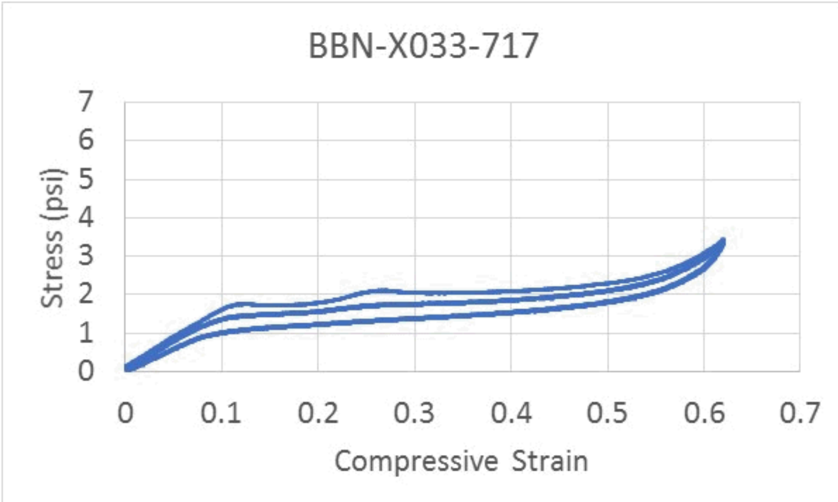

BBN-X057-717
Stress (psi)
0
1
2
3
4
5
6
7
0.03
0.05
0.07
0.09
0.11
0.13
Compressed Thickness (in)

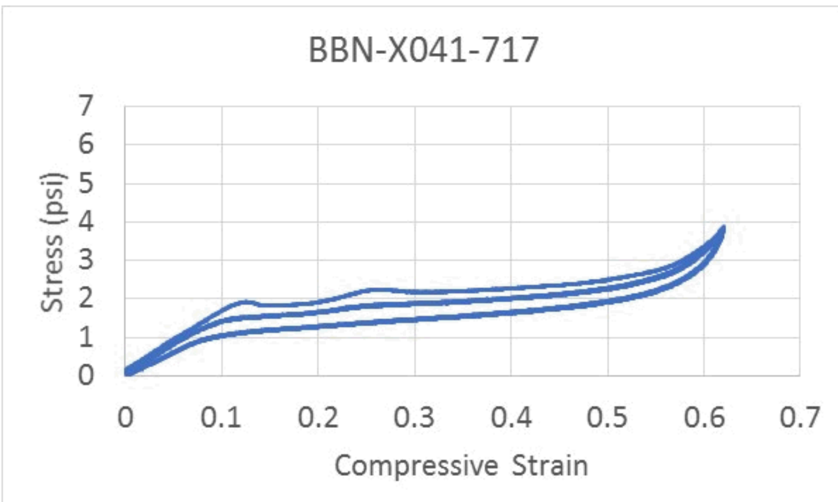
APPENDIX D
Individual Engineering Stress vs. Engineering Strain Curves (U.S. Customary Units)

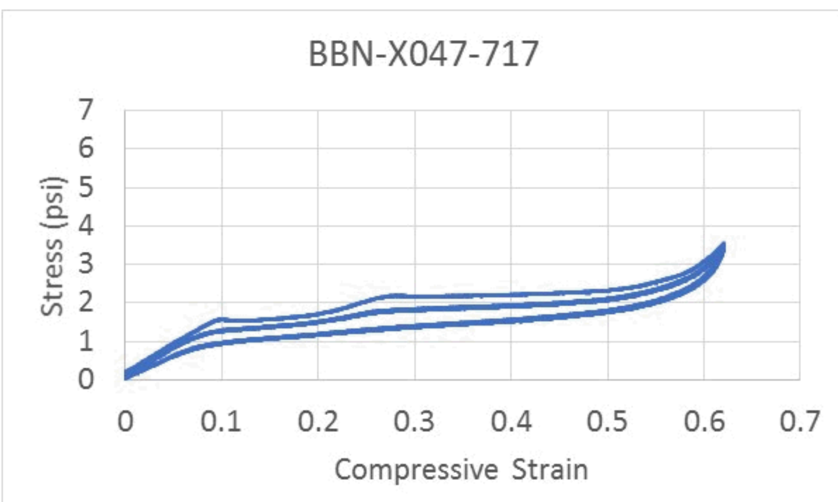


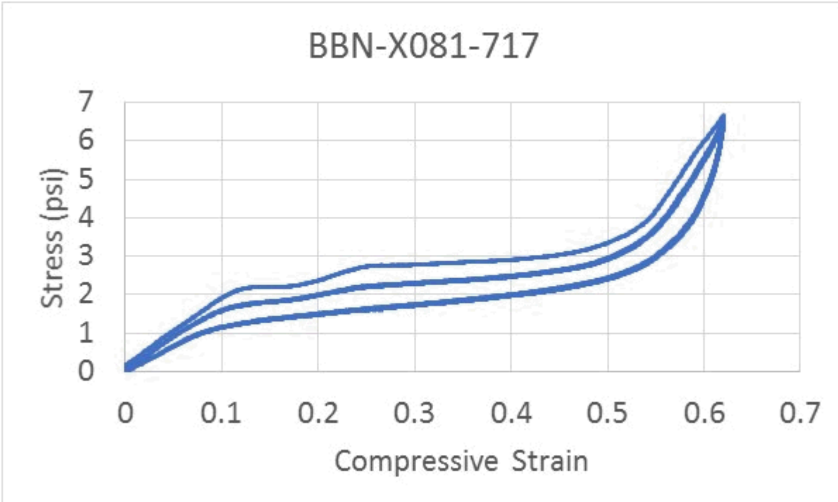


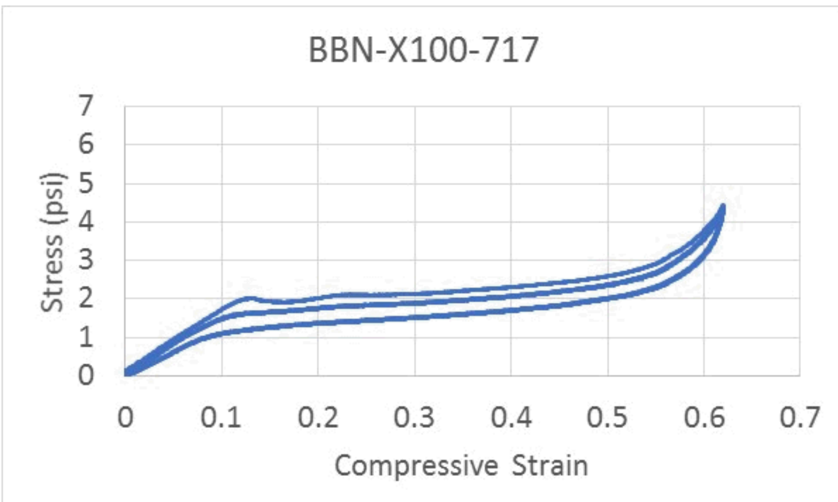


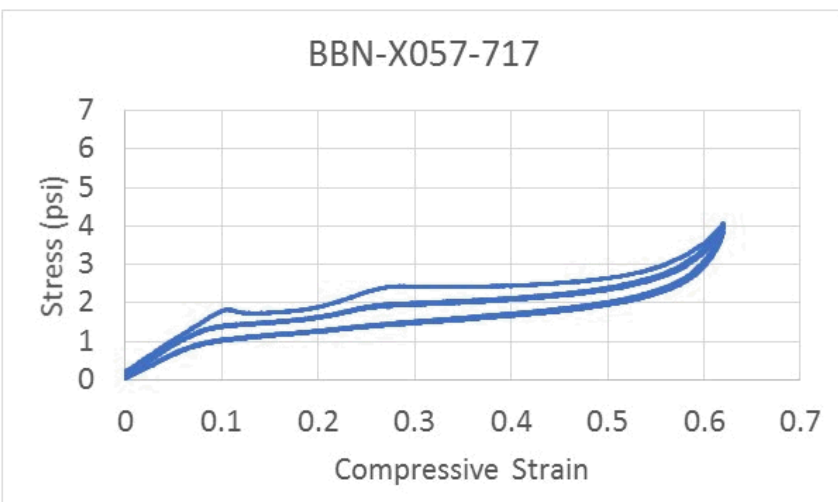

BBN-X033-717
Stress (psi)
7
6
5
4
3
2
1
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Compressive Strain


BBN-X041-717
Stress (psi)
7
6
5
4
3
2
1
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Compressive Strain

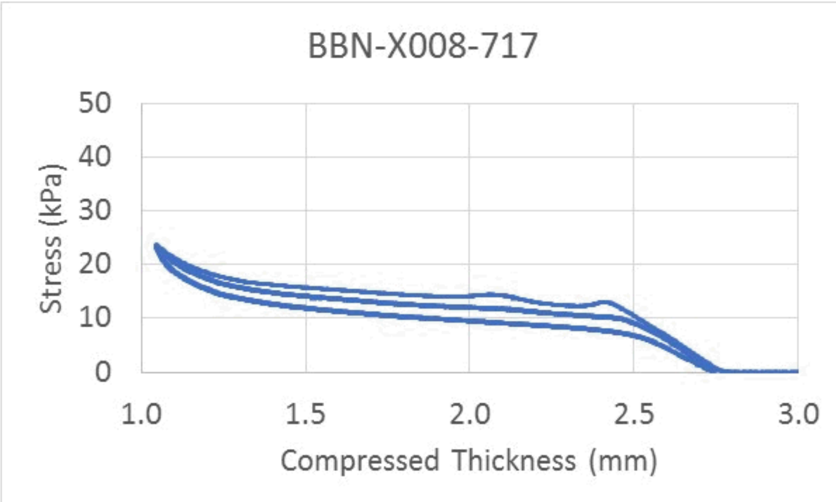

BBN-X047-717
Stress (psi)
7
6
5
4
3
2
1
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Compressive Strain

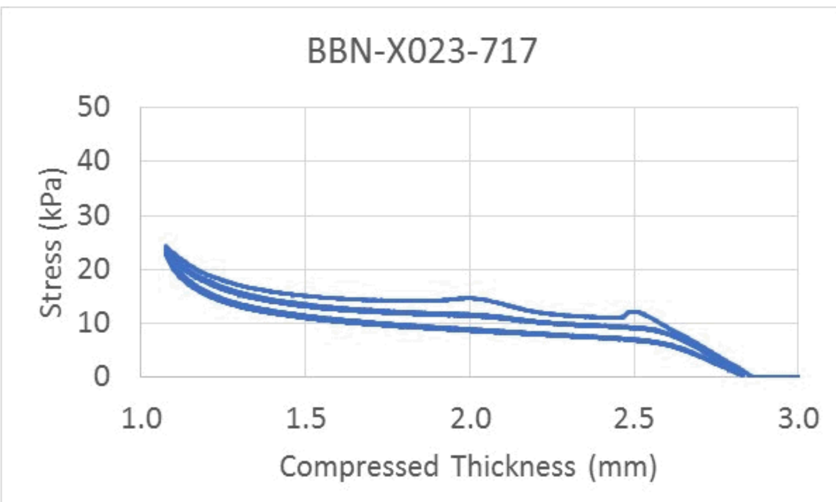

BBN-X081-717
Stress (psi)
Compressive Strain
0
1
2
3
4
5
6
7
0.1
0.2
0.3
0.4
0.5
0.6
0.7

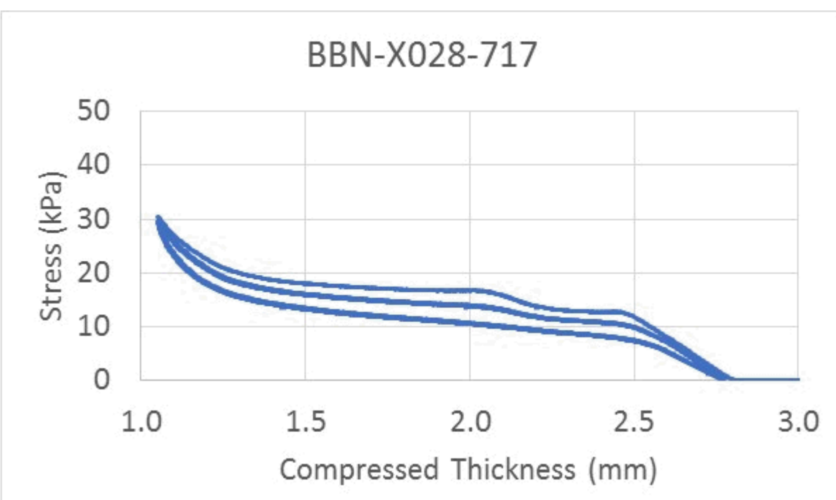

BBN-X100-717
Stress (psi)
Compressive Strain
0
1
2
3
4
5
6
7
0.1
0.2
0.3
0.4
0.5
0.6
0.7

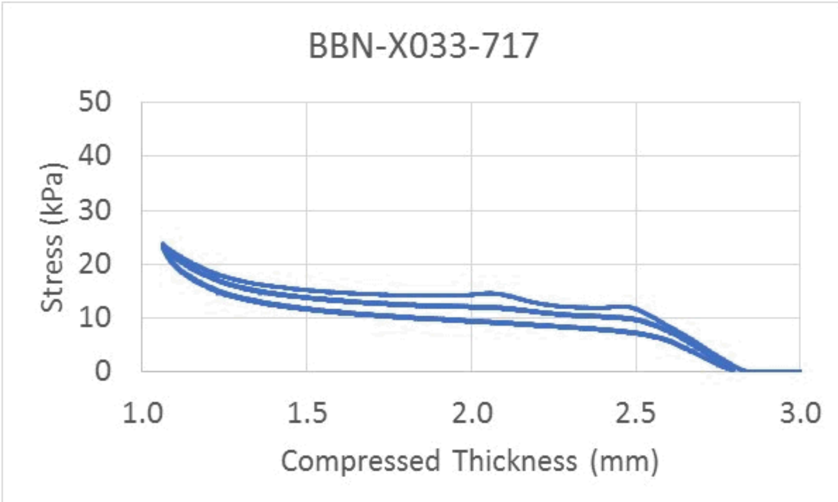

BBN-X057-717
Stress (psi)
Compressive Strain
0
1
2
3
4
5
6
7
0.1
0.2
0.3
0.4
0.5
0.6
0.7

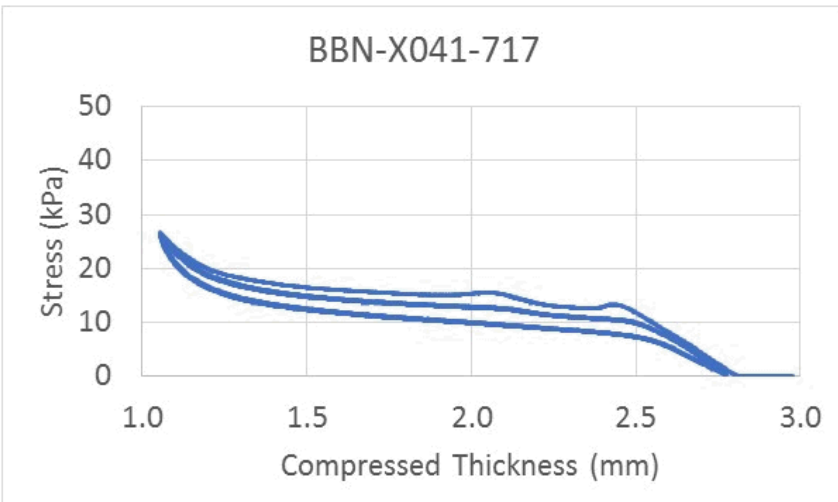
APPENDIX E
Individual Engineering Stress vs. Compressed Thickness Curves (SI Units)

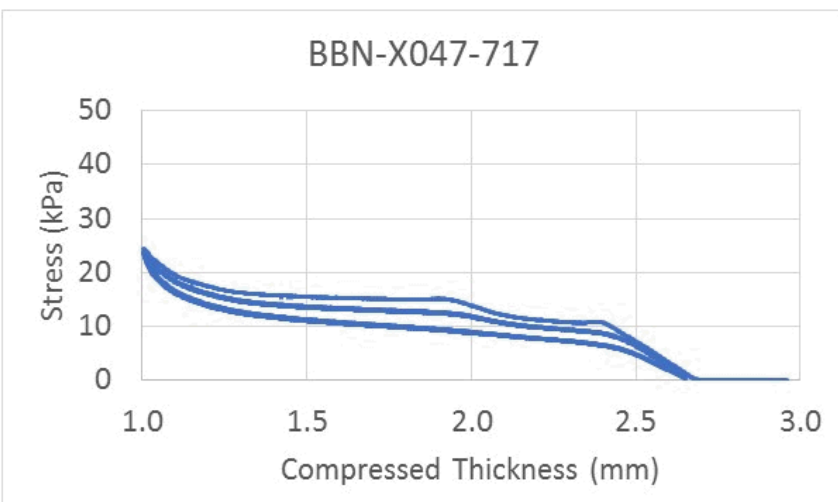


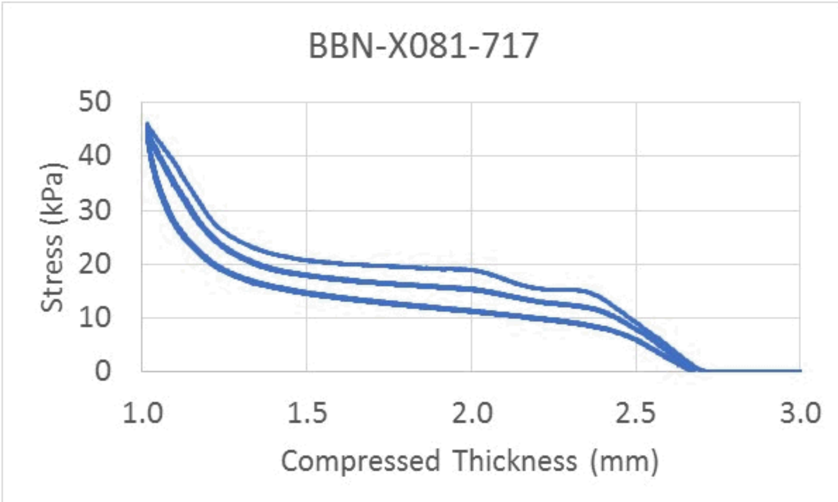


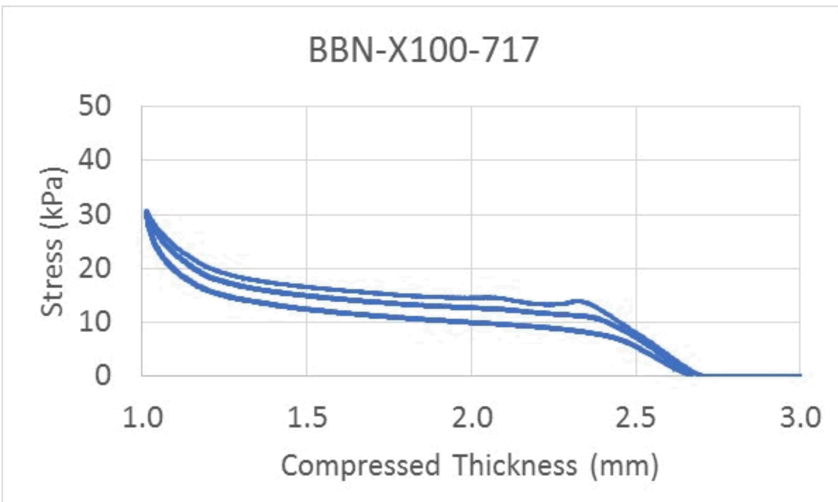


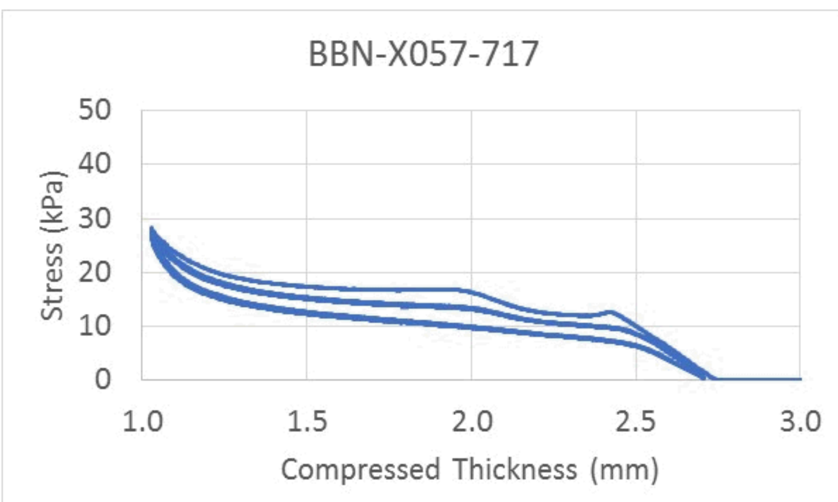

BBN-X033-717
Stress (kPa)
50
40
30
20
10
0
1.0
1.5
2.0
2.5
3.0
Compressed Thickness (mm)


BBN-X041-717
Stress (kPa)
50
40
30
20
10
0
1.0
1.5
2.0
2.5
3.0
Compressed Thickness (mm)

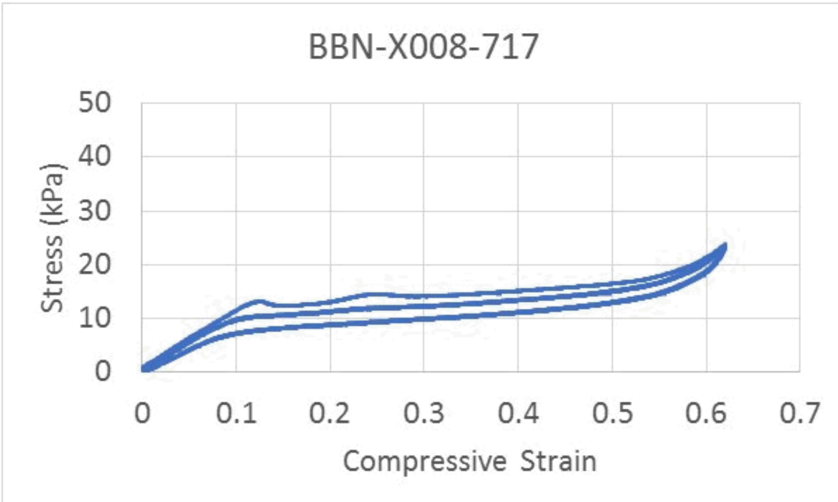

BBN-X047-717
Stress (kPa)
50
40
30
20
10
0
1.0
1.5
2.0
2.5
3.0
Compressed Thickness (mm)

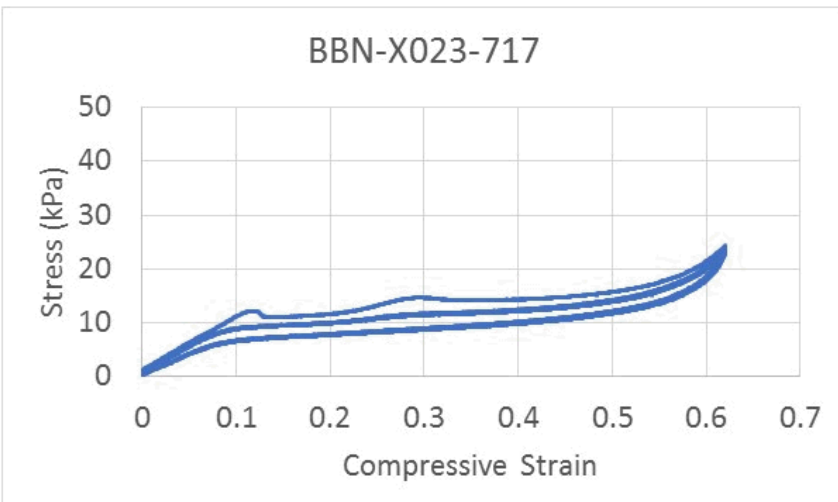

BBN-X081-717
Stress (kPa)
50
40
30
20
10
0
1.0
1.5
2.0
2.5
3.0
Compressed Thickness (mm)

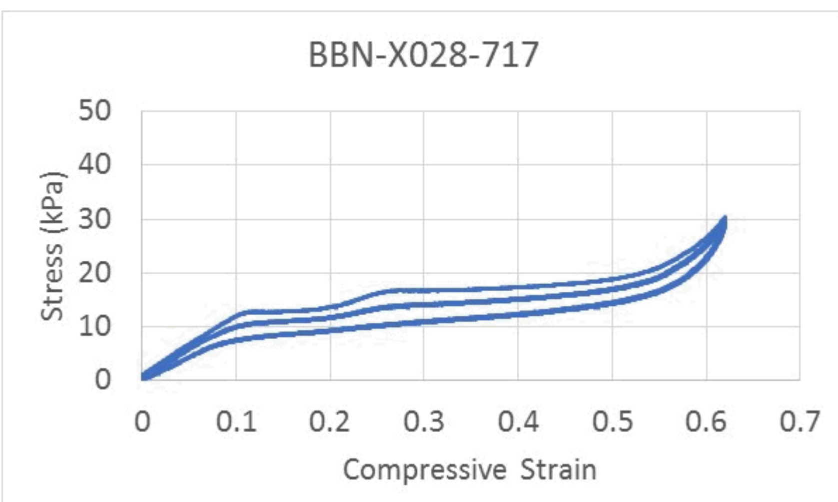

BBN-X100-717
Stress (kPa)
50
40
30
20
10
0
1.0
1.5
2.0
2.5
3.0
Compressed Thickness (mm)

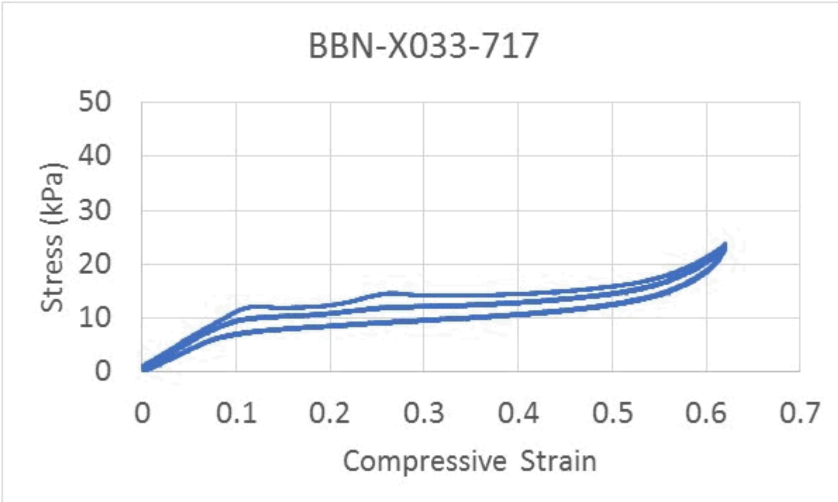

BBN-X057-717
Stress (kPa)
50
40
30
20
10
0
1.0
1.5
2.0
2.5
3.0
Compressed Thickness (mm)

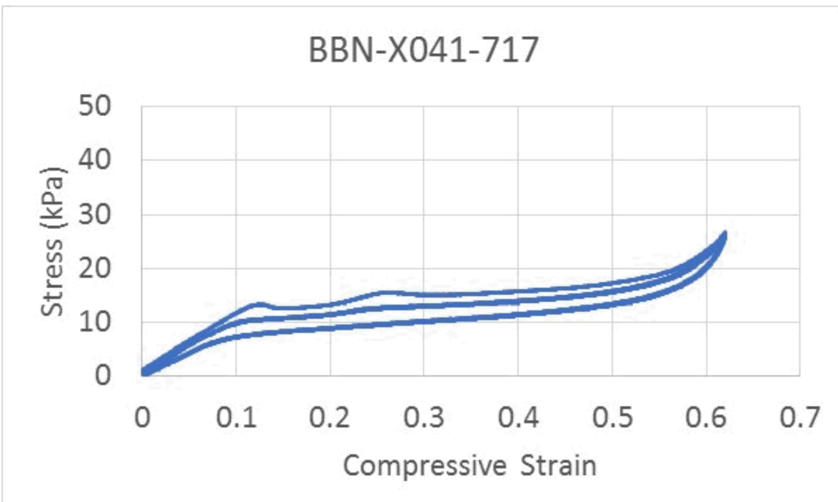
APPENDIX F
Individual Engineering Stress vs. Engineering Strain Curves (SI Units)

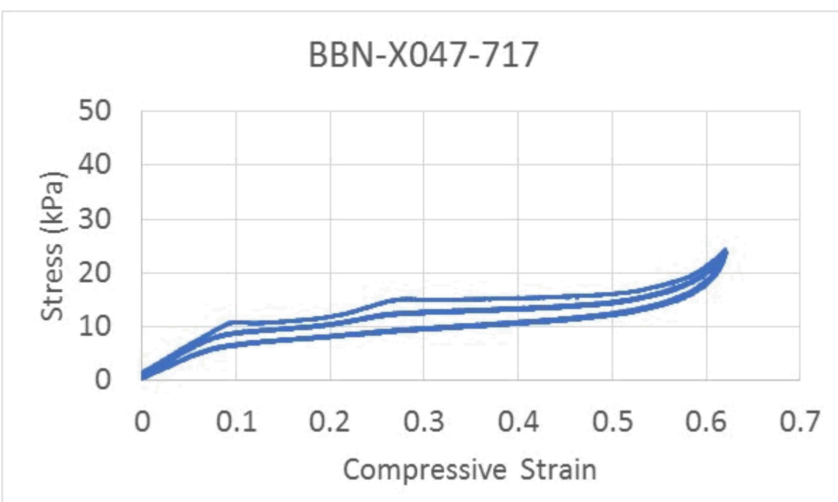


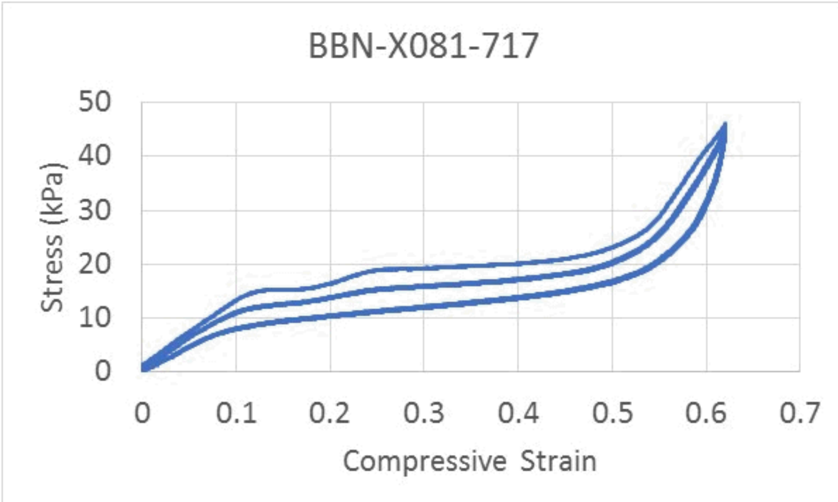


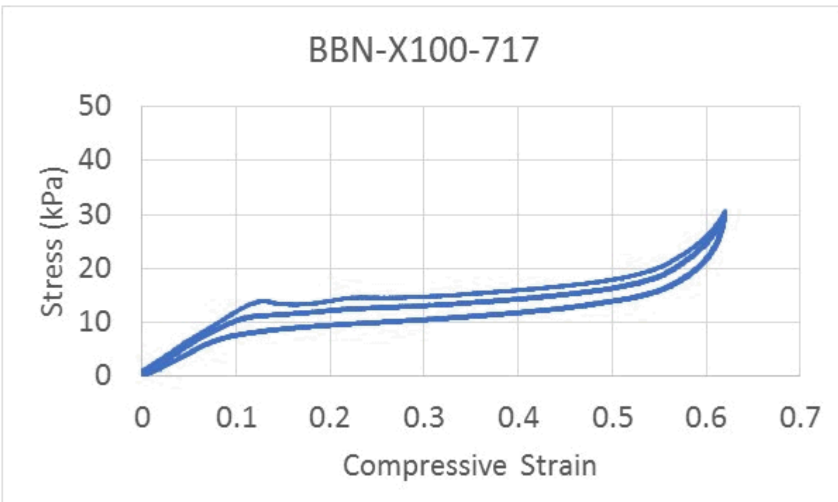


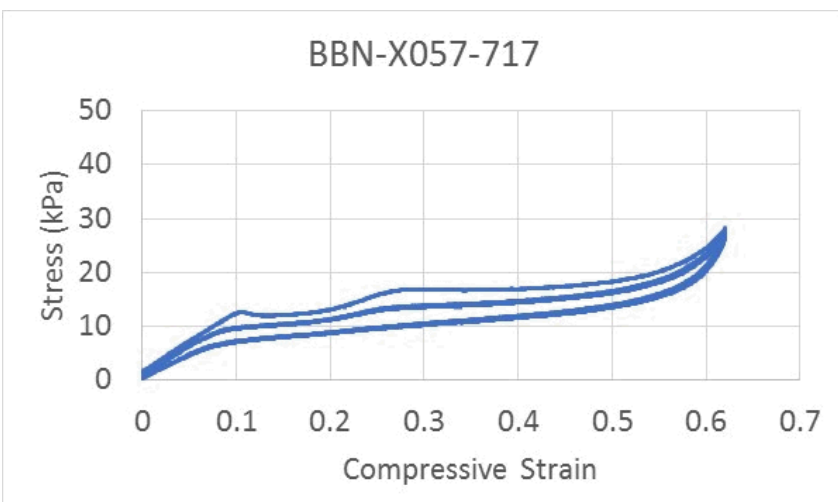

BBN-X033-717
Stress (kPa)
50
40
30
20
10
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Compressive Strain


BBN-X041-717
Stress (kPa)
50
40
30
20
10
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Compressive Strain


BBN-X047-717
Stress (kPa)
50
40
30
20
10
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Compressive Strain


BBN-X081-717
Stress (kPa)
50
40
30
20
10
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Compressive Strain


BBN-X100-717
Stress (kPa)
50
40
30
20
10
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Compressive Strain


BBN-X057-717
Stress (kPa)
50
40
30
20
10
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Compressive Strain