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EVALUATION OF THE HOT MIX ASPHALT COMPACTABILITY UTILIZING THE IMPACT COMPACTION METHOD

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I am submitting herewith a thesis written by Pawel Andrzej Polaczyk entitled "EVALUATION OF THE HOT MIX ASPHALT COMPACTABILITY UTILIZING THE IMPACT COMPACTION METHOD." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Civil Engineering.

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EVALUATION OF THE HOT MIX ASPHALT COMPACTABILITY UTILIZING THE IMPACT COMPACTION METHOD

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Abstract

This study investigates possibility of utilizing an accelerometer to evaluate compactability of Hot Mix Asphalt compacted with an impact hammer. For over 50 years Marshall Asphalt Mix Design has been the principal choice for asphalt mix designers around the world. Although the United States has almost entirely moved to Superpave Mix Design, the rest of the world nations still choose the Marshall Method. The investigation was conducted with the accelerometer placed on the falling mass of the Marshall Hammer and acceleration data was stored and analyzed. Data obtained from the accelerometer was filtered and the asphalt mix response after each blow was analyzed. Results from the study showed that during impact compaction, a so-called locking point exists. This point is defined as the first blow when peak acceleration and impact time become stable. When this point is reached, further compaction has a noticeably lower effect on decreasing air void content. A Superpave Gyratory Compactor was used to confirm the results obtained with the impact hammer, and a correlation was established.

Table of Contents

List of Tables

List of Figures

Abbreviations and Symbols

CBR	California Bearing Ratio
CDI	Construction Densification Index
G_{mb}	Bulk Specific Gravity of Asphalt Mix
G_{mm}	Theoretical Maximum Specific Gravity
HMA	Hot Mix Asphalt
JMF	Job Mix Formula
RAP	Reclaimed Asphalt Pavement
RAS	Reclaimed Asphalt Shingles
SGC	Superpave Gyratory Compactor
TDI	Transportation Densification Index
TDOT	Tennessee Department of Transportation

CHAPTER ONE

INTRODUCTION

Compaction is an important part of the asphalt pavement life. Regardless of the asphalt mix design method, it is a process that uses weight of the rollers to decrease the volume of asphalt mix mass to the required density in relation to the maximum density. During compaction, aggregates are brought together creating skeleton that provides resistance to deformations and at the same time limits permeability by reducing air void content that prolong the life of the pavement. Inadequate compaction can lead to premature damage in the asphalt course and underlying layers.

The compaction process can be affected by many factors such as asphalt cement and aggregates properties, mix type, compaction temperature, lift thickness, base course properties and environmental conditions. Asphalt cement properties change with temperature, which means that there is a specific range where viscosity permits adequate compaction by providing lubrication between particles during the compaction process. Low temperature prevents aggregate particles from moving, and the required density is not possible to achieve.

Another key factor of successful compaction is mix design. The history of asphalt mix design dates to the beginning of the twentieth century when pioneers that worked with asphalt, based on their previous experiences, realized the importance of adequate dosage of mix components. Asphalt mix design is the process of determining the optimum

proportions of asphalt cement, coarse aggregates, and fine aggregates, that permits creating well-performing and long-lasting pavements [1].

The first method to determine optimum binder content in the asphalt mix was the pat test, which was highly imprecise as it was based on visual appraisement, but for the earliest asphalt mix designers, it permitted high advancement in quality and performance [2]. Around the same time, the bitulithic pavement was developed and patented by Federick Warren. This mix incorporated large stones up to three inches, allowing lower asphalt cement consumption and a lower price [3].

The threshold for development of asphalt industry was Bruce Marshall's invention of a new design method. For over 50 years, Marshall Asphalt Mix Designs dominated the United States and the world paving industry. Internationally, the Marshall method is still the principal choice for designers. Two generations of engineers, specialists and experts utilized this design method without profound understanding of the impact compaction process.

The Superpave mix design method brought new challenges and opportunities to the compaction process. Superpave is permitting better understanding of the compaction process by introducing the Superpave Gyratory Compactor (SGC), which allows monitoring of specimen height after each gyration and provides better simulation of compaction than previous compactors [1]. Therefore, a reasonable compaction effort for mix design can be determined so that over-compaction can be avoided. For the impact hammer compaction, there is no method available to characterize and analyze the behavior of an asphalt mixture during compaction.

1.1 Literature Review

In the last 30 years, there were attempts to utilize accelerometers to calibrate the Marshall Hammer, but due to the high level of noise in the signal from the accelerometer, it was not possible to evaluate the data and calibrate the hammer. Siddiqui et al. 1988 [4] conducted research to determine the possibility of using accelerometers to calibrate the Marshall Hammer. Their objective was to eliminate error in the results when different hammers are used. The analysis of the acceleration data indicated that there was limited variability between each blow, and from the measurements, only blow strength increased. The structural ringing made it impossible to analyze the impact of the hammer. The filter applied to the signal can reduce ringing but also alter the signal. Cassidy et al. 1994 [5] made a similar attempt to calibrate the Marshall hammer using an accelerometer, load cell and LVDT. Similarly, like Siddiqui et al. 1988 [4], they encountered strong structural ringing and decided to utilize only the data from the load cell and LVDT. Except for the work cited above, there has been little effort to describe the compaction process of the asphalt mixtures when an impact hammer is used, due to equipment limitation and work scope. The work of Siddiqui et al. 1988 [4] and Cassidy et al. 1994 [5] was focused on finding a calibration method for the Marshall hammer, not on describing compaction properties of asphalt mixtures.

Another approach for utilizing accelerometers was the development of a Clegg Impact Tester. In this approach, at the initial stage of research a standard Proctor-type hammer was equipped with an accelerometer and utilized to measure deceleration of the falling

hammer mass. The Clegg Tester can be used to determine hardness of compacted soil and the results can be correlated with a CBR value. The standard procedure consists of dropping a hammer four times in the same place and identifying the highest deceleration value. A higher value of the peak deceleration indicates stiffer material. Currently, the Clegg hammer is not limited to standard Proctor-type hammer. There are several models with different hammer weights. The weight of the hammer is based on the type of soil to be tested. The Clegg Impact Tester provides basic strength values at a relatively small cost and requires low technical abilities [6, 7, 8, 9].

The success of the Clegg Hammer can be attributed to direct contact between the falling mass of the Proctor hammer and the soil during impact. The construction of the Marshall Hammer does not allow direct contact between a falling mass and the asphalt mix because the falling mass hits a metal head before the metal head hits asphalt mix. This impact between the two metal parts of the Marshall Hammer produces structural ringing (noise) that is difficult to eliminate. Figure 1 presents the Clegg Hammer, Proctor Hammer and Marshall Hammer.

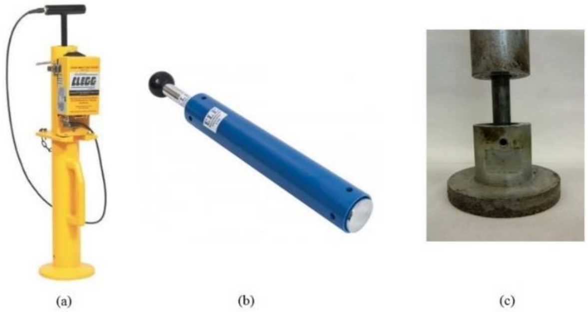

Figure 1: (a) Clegg Hammer [10], (b) Proctor Hammer [11], (c) Marshall Hammer.

One key achievement of the Strategic Highway Research Program (SHRP) was the introduction of the Superpave Gyratory Compactor (SGC). The SGC improves our understanding of the compaction process: the new compactor allows us to monitor the specimen height after each gyration and provides better simulation of compaction than previous compactors. Since the introduction of the gyratory compactor, various researchers have attempted to use a densification curve, which is obtained from specimen height change, to determine compactability of the asphalt mix. Bahia et al. 1998 [12] introduced the concept of the Construction Densification Index (CDI) and the Transportation Densification Index (TDI). The CDI is te area under the SGC densification curve from 88%G_{mm} to 92%G_{mm}, where G_{mm} is defined as theoretical maximum specific gravity of the asphalt mix. The TDI is the area under the SGC densification curve from 92%G_{mm} to 98%G_{mm}. It is desirable that an asphalt mix possess a low value of CDI, because it represents low effort required in the compaction process. The CDI is meant to represent the energy that is used by a roller during compaction to achieve required compaction. Figure 2 presents densification curve, CDI and TDI.

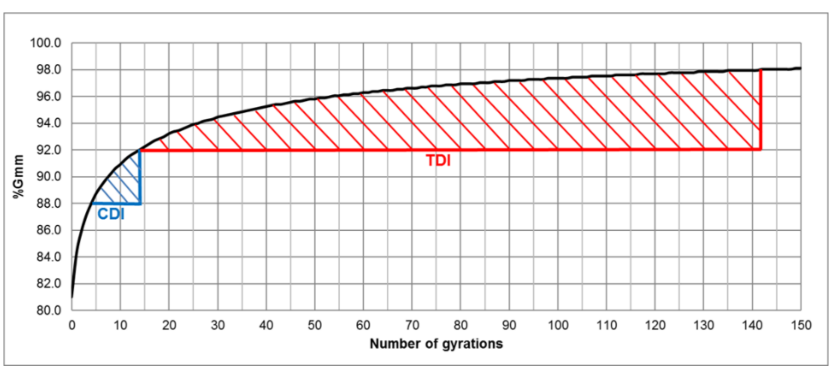

Figure 2: Determination of CDI and TDI from a densification curve.

Anderson et al. 2002 [13] introduced a slope of densification curve to describe compactability. The compaction slope can indicate the shear resistance of the aggregates structure in the asphalt mix. Higher slope means higher resistance to compaction. Mallick 1999 [14] indicated that it is commonly accepted and required by most agencies that the target compaction of an asphalt lift in the field should reach 8% of air voids. The value of required air voids can be taken as a borderline between expectations regarding compactibility of the asphalt mix. It is desired for the mix to compact easily until it reaches 92%G_{mm} and that it should become hard to compact when it exceeds 92%G_{mm}. In the first case, it is desirable by contractors to have a mix that does not require high compaction effort. In the second case, after the mix reaches 8% of air voids, it should be hard to compact as it permits higher resistance to the traffic and a longer period of service.

The most common concept that is used to evaluate compactability of the asphalt mix is a gyratory locking point. This concept is based on change of the specimen height during the gyratory compaction. Originally, the gyratory locking point was proposed by William J. Pine while working with the Illinois Department of Transportation [15]. The gyratory locking point defines a threshold on the densification curve beyond which the mix structure starts to resist further compaction and aggregates can be fractured. Different mixtures lock up at different number of gyrations and at different air void contents. There are many definitions of the gyratory locking point by different researchers and agencies. Mohammad and Shamsi 2007 [16] reported that the Alabama Department of Transportation defined the locking point “as the point where the sample being gyrated

loses less than 0.1 mm in height between successive gyrations". Georgia DOT defined the locking point "as the number of gyrations at which, in the first occurrence, the same height has been recorded for the third time". Louisiana Transportation Research Center (LTRC) denotes "the number of gyrations after which the rate of change in height is equal to or less than 0.05 mm for three consecutive gyrations" as the locking point. In this study, the locking point was defined as the first gyration in the first set of three gyrations at the same height preceded by two sets of two gyrations at the same height. It is the most widely accepted definition presented by Vavrik and Carpenter 1998 [17]. Table 1 presents an example of locking point defined by Vavrik and Carpenter.

Table 1: Example of gyratory locking point determination [17].

Gyrations	Height (mm)
33	65.1
34	65.0
35	65.0
36	64.9
37	64.8
38	64.8
39	64.7
40	64.7
41	64.6
42	64.6
43	**64.5**
44	64.5
45	64.5

1.2 Objective and Scope

Since the Marshall method is still the principal choice for engineers around the world, the objectives of this study are 1) to develop a method to characterize the compaction behavior of asphalt mixtures using Marshall Hammer compaction; and 2) to evaluate compactibility of the different asphalt mixtures used in Tennessee. A shock accelerometer was used to determine responses of the HMA at different stages of compaction. Two types of asphalt binders (a PG64-22 non-modified binder and a PG76-22 modified binder), two different gradations (D (½") and BM-2 (1¼")), mixes with virgin asphalt, and mixes with reclaimed asphalt pavement (RAP) and with reclaimed asphalt shingles (RAS) were considered.

CHAPTER TWO

LABORATORY EXPERIMENTS

2.1 Materials

A total of eight HMAs were utilized in this study. The material was collected from asphalt plants in different regions of the State of Tennessee. Two asphalt binders (PG64-22 and PG76-22), two types of gradation (½” and 1¼”), virgin asphalt, RAP and RAS were selected. The asphalt mix design was elaborated by contractors and accepted by the Tennessee Department of Transportation (TDOT). All aggregates and asphalt cement properties met the specifications of TDOT [18]. A summary of raw materials and compaction temperatures is presented in Table 2. Gradation of the aggregates and mixtures are in included in appendix (A-16 – A-23).

2.2 Equipment

The compaction of asphalt mix specimens was performed with a Humboldt Marshall Mechanical Compactor and 4” molds. The data were acquired with a National Instrument data acquisition system with a sampling rate of 10,000 Hz.

A PCB Piezotronics 5000g accelerometer was installed on the compaction hammer. A Pine Instrument Company AFGC125X Superpave Gyratory Compactor was used to compact 150 mm diameter samples that work as the reference for data obtained during the impact hammer compacting process.

Table 2: The summary of raw materials and compaction temperatures used in this study.

Mix No.	Mix Type	PG	Material	Compaction Temperature
1	411 D	64-22	Granite D-Rock	280°F
			Soft Limestone	
			Natural Sand	
			Baghouse Fines	
2	411 D	76-22	Hard Limestone #7	265°F
			Slag	
			Hard Limestone #10	
			Soft Limestone #10	
			Natural Sand	
			RAP ½	
3	307 BM-2	76-22	Soft Limestone #57	305°F
			Soft Limestone #7	
			Soft Limestone #10	
			RAP ½	
4	411 D	76-22	Gravel	295°F
			Soft Limestone #10	
			Natural Sand	
5	307 BM-2	64-22	Soft Limestone BM-2	270°F
			Soft Limestone #7	
			Natural Sand	
			RAP ¾	
			RAS ⅜	
6	411 D	64-22	Gravel	290°F
			Soft Limestone	
			Natural Sand	
7	307 BM-2	76-22	Gravel BM-2 Rock	290°F
			Soft Limestone #57	
			Natural Sand	
			Soft Limestone #10	
			RAP ½	
			RAP 5/16	
8	411 D	76-22	Gravel	315°F
			Soft Limestone	
			Natural Sand	
			RAP ½	
			RAP 5/16	

2.3 Test Procedure

The Marshall mix design method was used to design the mixtures utilized for this study. The design process was conducted by contractors and approved by TDOT. Mixes were produced in eight different asphalt plants, accepted and collected by TDOT staff, and delivered to the research laboratory.

Once asphalt mixtures were delivered to the laboratory, the testing process has started. First, the theoretical maximum specific gravity (G_{mm}) was determined following the AASHTO T 209 specification [19]. Next, asphalt mixtures were reheated for two hours to a temperature that permits air void content at 4% after completing 150 blows (75 blows to each side) with an impact hammer. A standard sample weight of 1,230 grams was used. HMAs were compacted utilizing the 10-lb. Marshall hammer and 75 blows to each side with the accelerometer placed on the hammer in the vertical direction of hammer drop (Figure 3).

Figure 3: Accelerometer installed on the impact hammer.

The accelerometer was then connected to the National Instrument data acquisition system with a coaxial cable. A LabVIEW System Design Software was used to receive and store the acceleration data. Once the compaction process was concluded, bulk specific gravity (G_{mb}) was determined by AASHTO T 166 [20]. Data obtained from the accelerometer were later filtered with five points moving average, and the response from the mix after each blow was plotted in the time domain, analyzed, and compared to data obtained from Superpave Gyratory Compactor (SGC) densification curve.

The analysis of the accelerometer data exhibited the existence of a point similar to the SGC locking point: when crossing this point the HMA resists further compaction. In this study, the impact locking point was defined as the number of blows that after which the response of the mix sent to the accelerometer becomes stable with change neither in peak acceleration nor impact time.

CHAPTER THREE

RESULTS AND DISCUSSION

3.1 Impact Hammer Locking Point

In the light of the studies mentioned in the Literature Review Chapter, the author of this study used acceleration data in the time domain after each of the 150 blows to identify patterns that can allow determination of the impact locking point. The idea of the locking point is based on the assumption that during the compaction process, the skeleton of the asphalt mix is gradually developed until the point where course aggregates interlock and resist further compaction. In this research, the impact locking point is defined as the number of hammer blows at which the acceleration-time history curve stops fluctuating and values of the acceleration and impact time become stable. Figure 4 presents a typical example of the different stages in the compaction process obtained from the acceleration data. The initial stage (Figure 4a) is characterized by a relatively long impact time, a low acceleration peak and the existence of more than one peak. As the density of the asphalt mixture increases, the stiffness also increases, causing changes in the acceleration response. During the middle compaction stage, the impact time becomes shorter, peak acceleration increases and multiple acceleration peaks evolve in to just one peak (Figure 4b).The final compaction stage (Figure 4c) is taken, in this study, to be the impact locking point. When the asphalt mixture reaches this stage, the peak acceleration and impact time become stable, which means there in no further significant increase in compaction.

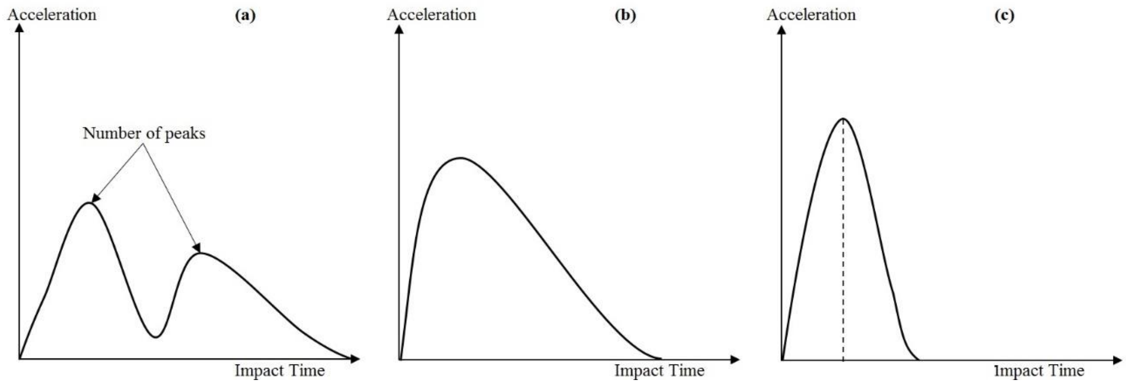

Figure 4: Typical shapes of response plots in different compaction stages: (a) initial, (b) middle, (c) at impact locking point

The analysis described above was conducted for all eight mixtures (two samples for each mixture). The three compaction stages were determined for seven of them.

One mix (No. 3) reached the second compaction stage after 150 blows, so no impact locking point could be determined. The locking point was marked as >150. For the seven mixes that reached the final compaction stage, the locking point ranged from 108 to 146 blows. The summary of locking points is presented in Table 3.

Table 3: The summary of the impact locking points

Mix No.		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Locking Point (blows)	Sample 1	144	106	>150	112	112	145	117	142
	Sample 2	146	110	>150	113	111	147	116	140
	Average	**145**	**108**	**>150**	**113**	**112**	**146**	**117**	**141**

In Table 2, it can be observed that for two different samples of the same asphalt mixture, the results are varying between one and four blows, which can suggest that the results may be repeatable. However further study should be performed to confirm.

Figure 5 presents an example of data analysis and interpretation, in this case, for mixture No. 2, Sample 1. This asphalt mixture sample was evaluated to have the lowest locking point of 106 blows. From Figure 5, the three compaction stages described above can be identified. The initial stage ranges from blow 1 to blow 30 and is characterized by two acceleration peaks. In this stage, the peak acceleration ranged from 250g to 350g, and the impact time decreased from the initial 50 ms to 20 ms. The second stage began with the 30th blow and lasted until the 106th blow. In this stage, the acceleration peak increased from 350g to 550g, and the impact time decreased from 20 ms to 15 ms. After the final stage was reached, the acceleration peak was maintained at the same level of 550g and impact time of 15 ms until the last (150th) blow. The Appendix contains acceleration data for all eight mixtures.

The locking point describes the point during compaction process that is a boundary between easy and difficult compaction. In this study, the impact locking point is defined as a point when the response from the accelerometer becomes stable. It is assumed that when the response becomes stable there will be no further major changes in the stiffness of the asphalt mix, which implies that there will be no major changes in density or air voids.

To validate this line of reasoning, specimens were compacted at various numbers of hammer blows. The first set of samples was compacted with the 150 standard blows to

reach 4% air voids. The second set of samples was compacted with the number of blows defined previously as the locking point.

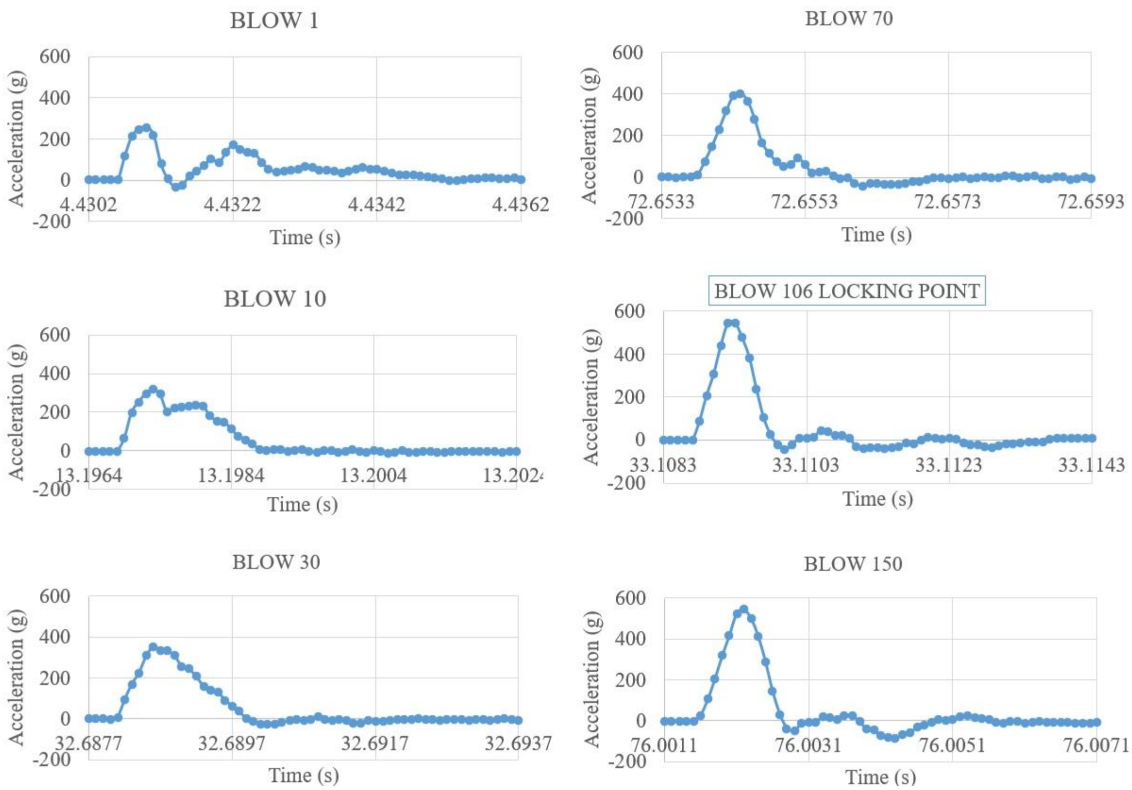

Figure 5: Example of data obtained from accelerometer. Mixture 2, Sample 1

The expectation was that the air void content in these two sets would be similar. The last set of samples was compacted at 15 blows below the impact locking point. The expectation was that air voids content would be higher than in two previous sets. The summary of the validation samples is shown in Figure 6. Mixture 3 is not included in the summary because the impact locking point for this mix was not defined in the range of

the 150 blows. As presented in Figure 6, once the locking point was achieved, further compaction caused minimal change in air voids for all tested mixtures. On average, the air void content was 0.19% higher at the locking point than at 150th blow. The average difference between air voids at the 150th blow and 15 blows below locking point was 1.2%. From the air void data, it can be concluded that the locking point found with the accelerometer is in fact the point where the asphalt mix changed compaction properties and became more difficult to compact.

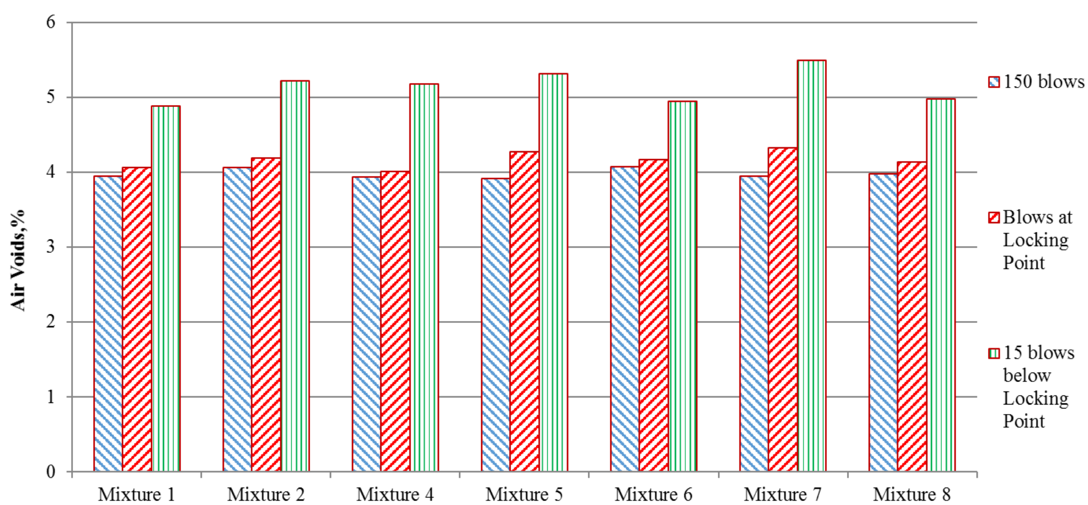

Figure 6: Comparison of air voids at 150 blows, at the locking point, and 15 blows below the locking point.

3.2 Gyratory Locking Point

Since the concept of locking point was developed for gyratory compactor, in this study, this idea was used to compare the results obtained with the impact hammer and the accelerometer. The purpose of this comparison was to evaluate if there is relation between gyratory and impact locking point. Specimens for all eight mixtures (two samples per mix) were compacted using the Pine Instrument Company AFGC125X Superpave Gyratory Compactor (SGC), 150 mm molds, and the same temperatures as previously used with the impact hammer. After the specimens cooled, the bulk specific gravity was determined by AASHTO T 166. Next, utilizing the theoretical-maximum specific gravity and specimen height change data obtained during compaction from the superpave gyratory compactor, densification curves were plotted and the gyratory locking point was determined for each mix utilizing 2-2-3 method. The summary of the gyratory locking point is presented in Table 4.

Table 4. Comparison of the impact hammer locking point and the gyratory locking Point

Mix No.	Impact Locking Point (blows)	Gyratory Locking Point 2-2-3 (gyrations)
1	145	76
2	108	51
3	>150	83
4	113	56
5	112	53
6	146	74
7	122	56
8	141	73

Locking points that were obtained with the SGC a have similar trend as the locking points obtained from the impact hammer and the accelerometer. The highest value of 83 gyrations obtained with Mixture 3 also has the highest value of impact locking point, defined as >150 blows. Similarly, Mixture 2 has the lowest gyratory locking point of 51 gyrations and the lowest impact locking point of 108 blows.

Figure 7 presents relationship between the locking point results acquired with the gyratory compactor and the impact hammer. The coefficient of determination (R^2) for the set of data obtained is 0.97. It can be concluded that there exists a correlation between the locking points from the different methods of compaction included in this research.

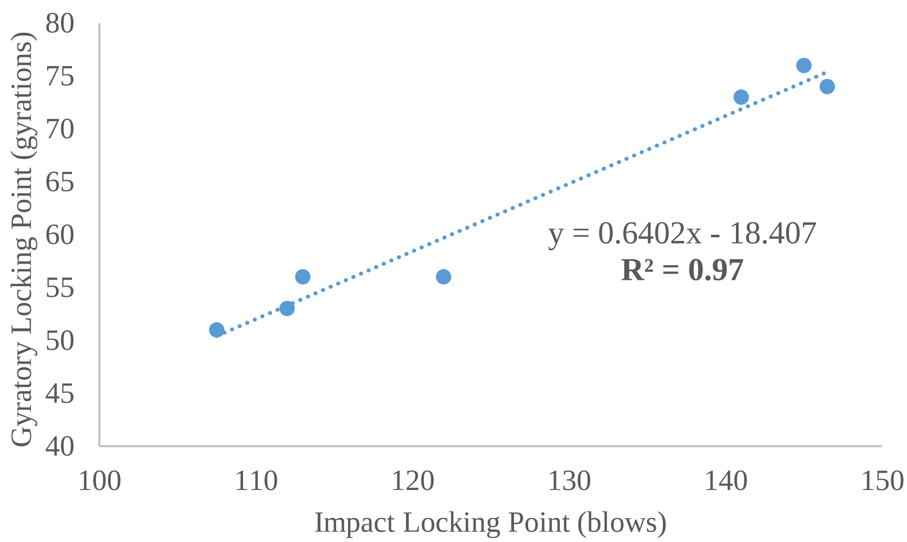

Figure 7: Relationship between Gyratory and Impact Locking Point

CHAPTER FOUR

SUMMARY AND CONCLUSIONS

4.1 Summary

In this study, eight different asphalt mixes from different regions of Tennessee State were analyzed with the objectives to (1) develop a method to characterize the compaction behavior of asphalt mixtures using Impact Hammer compaction and (2) evaluate the compactibility of the different asphalt mixtures used in Tennessee. An accelerometer was used to acquire changes in acceleration data during the compaction process. In the last 30 years, there have been only a few attempts to use accelerometers to calibrate the Marshall impact hammer, all without success.

To achieve the objectives the accelerometer was placed on the falling mass of the Marshall Hammer. Obtained data were filtered with the five-points moving average. The response of the HMA after each blow was analyzed, and it was determined that different stages in the compaction process can be established based on changes in the peak acceleration and the impact time. It was found that for the impact hammer compaction method, there exists a locking point defined as the first of blow when the peak acceleration and the impact time become stable. When this point is reached, further compaction is considerably less effective in reducing air void content. For each of the mixtures, the impact locking point was established and the range was from 108 to 146 blows. One mixture did not reach locking point during 150 blows; the locking point for

this mix was marked as >150. Once the values of the locking point were established, the verification process included a comparison of air void contents during different compaction stages: 15 blows before the locking point is reached, at the locking point and after the final compaction at 150 blows. The results confirmed that after exceeding the locking point, the asphalt mix becomes harder to compact as the air void content decreases at a lower rate than before reaching the locking point. Next, the Superpave Gyratory Compactor was used to compact specimens at the same temperatures as was done for the impact hammer. The results acquired from the SGC confirmed the impact hammer results, and a correlation could be established with the coefficient of determination of 0.97.

4.2 Conclusions

Laboratory experiments were conducted to determine compactability of the HMA utilizing the impact hammer and the accelerometer. Based on the results the following conclusions can be drawn:

- An accelerometer can be used to determine different stages in the compaction process. The response received from the asphalt mix via the accelerometer is similar for two samples of the same asphalt mix, which can indicate repeatability of this method, but further study should be conducted.
- The locking point for HMA can be determined as the point where the acceleration and the impact time become stable. For seven out of the eight evaluated mixes the locking

point was established between the 108th and 146th blow. For one mix, the locking point was higher than 150 blows.

- The locking points obtained from the Superpave Gyratory compactor confirmed the results obtained with the impact hammer, and a correlation could be established.

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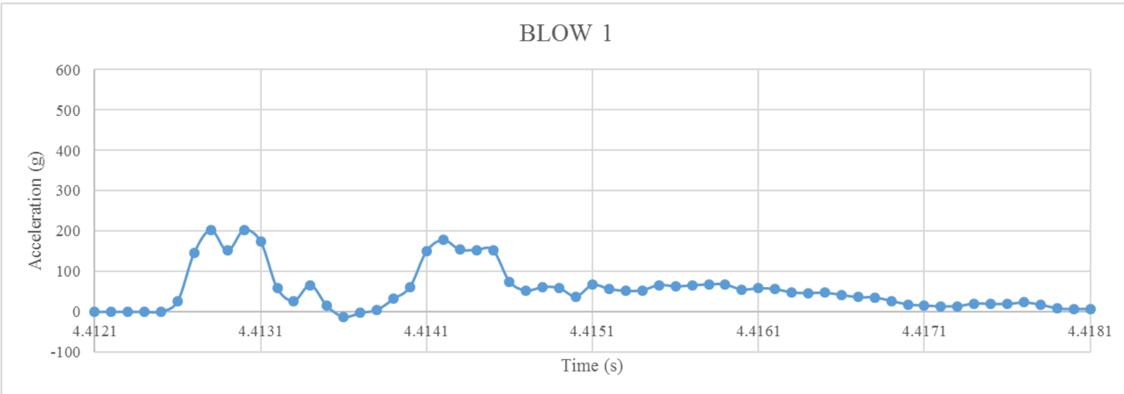
[18] Tennessee Department of Transportation. Standard Specifications for Road and Bridge Construction (2015).

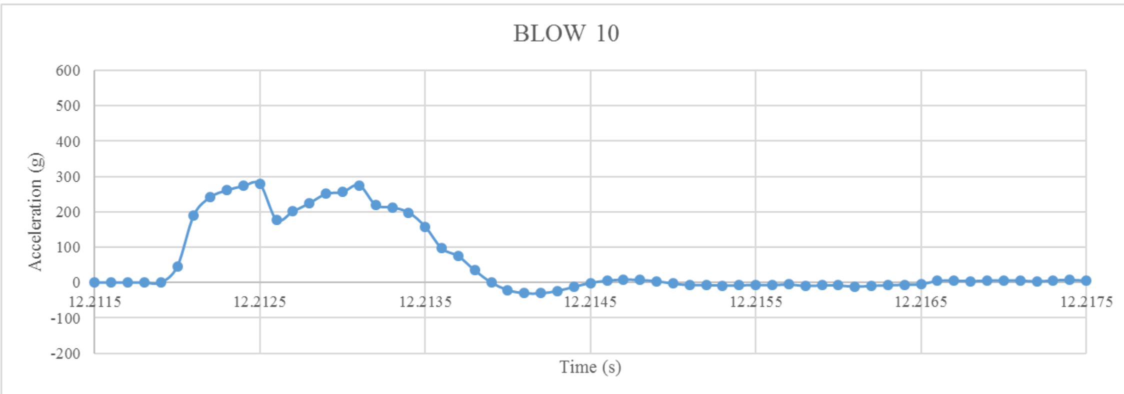
[19] AASHTO T 209 Theoretical Maximum Specific Gravity and Density of Hot Mix Asphalt. American Association of State Highway and Transportation Officials

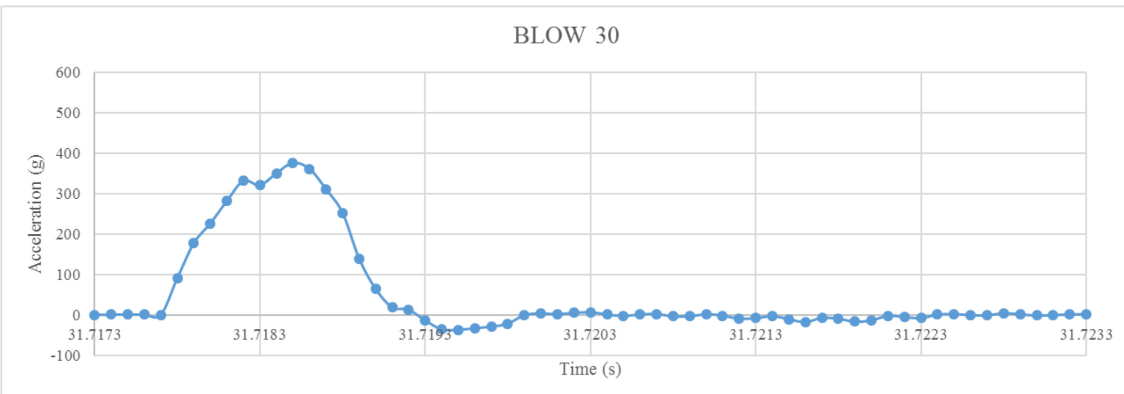
[20] AASHTO T 166 Bulk Specific Gravity of Compacted Asphalt Mixtures Using Saturated Surface-Dry Specimens. American Association of State Highway and Transportation Officials

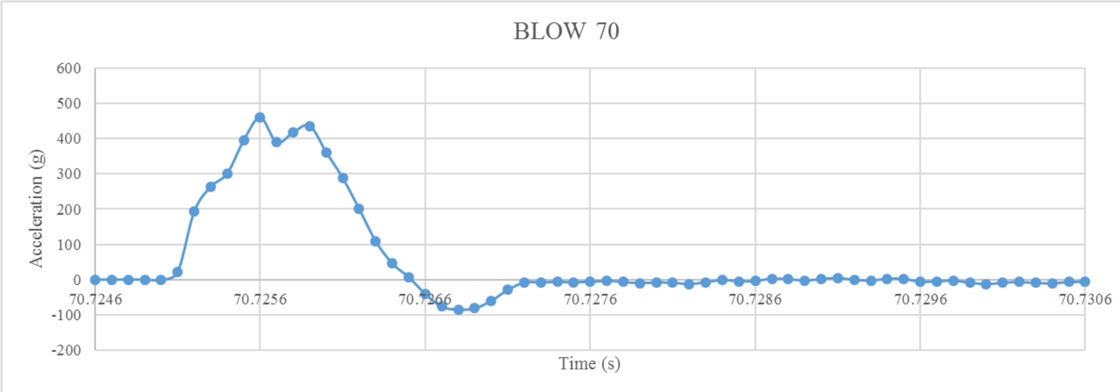
APPENDIX

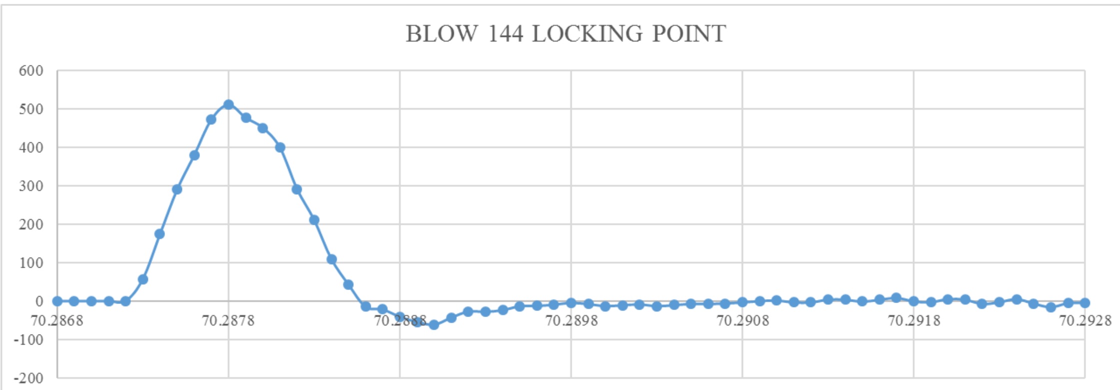
A-1 Mixture 1 Sample 1

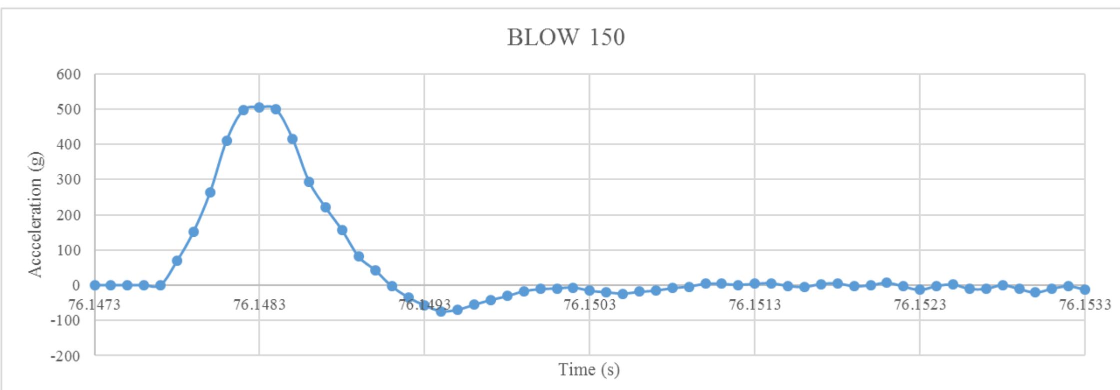




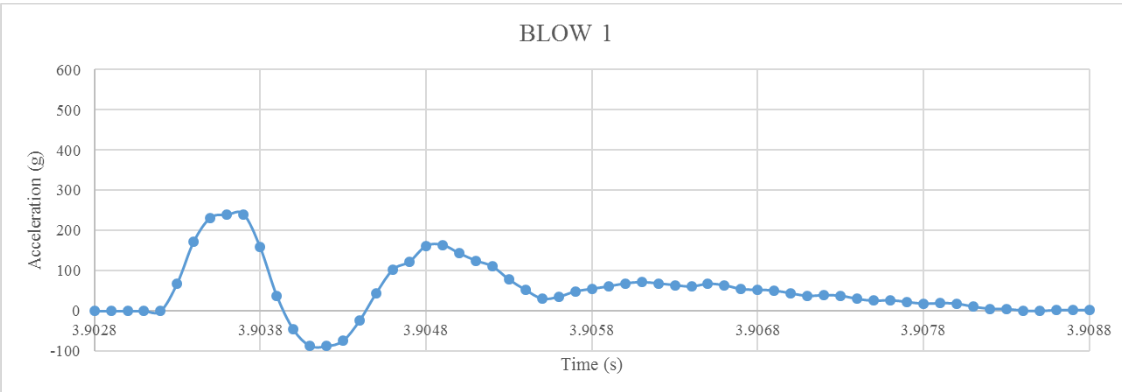


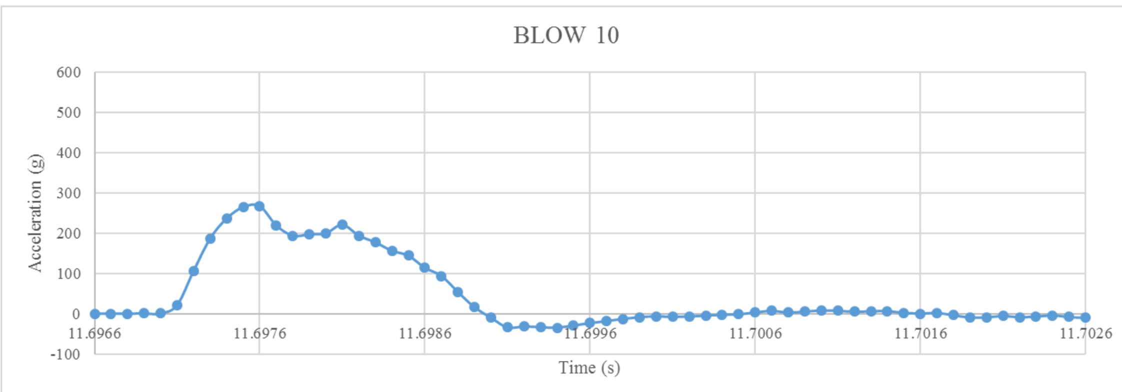

BLOW 70
Acceleration (g)
600
500
400
300
200
100
0
-100
-200
70.7246
70.7256
70.7266
70.7276
70.7286
70.7296
70.7306
Time (s)

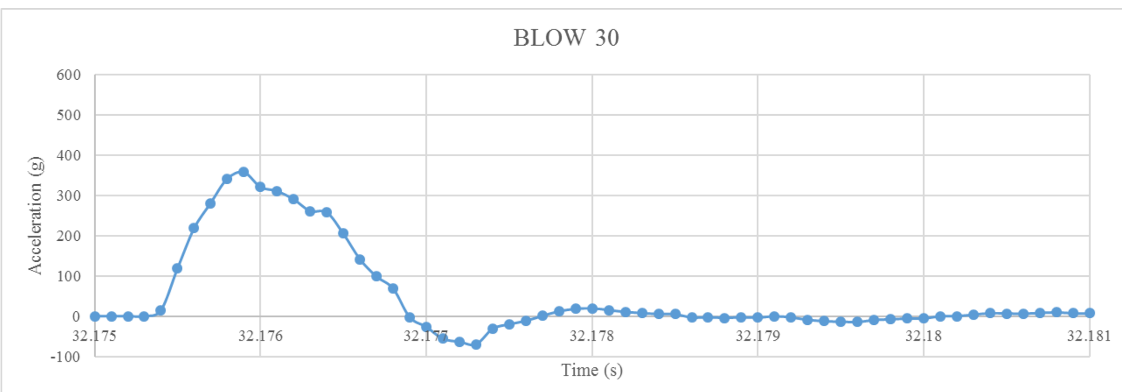

BLOW 144 LOCKING POINT
600
500
400
300
200
100
0
-100
-200
70.2868
70.2878
70.2888
70.2898
70.2908
70.2918
70.2928

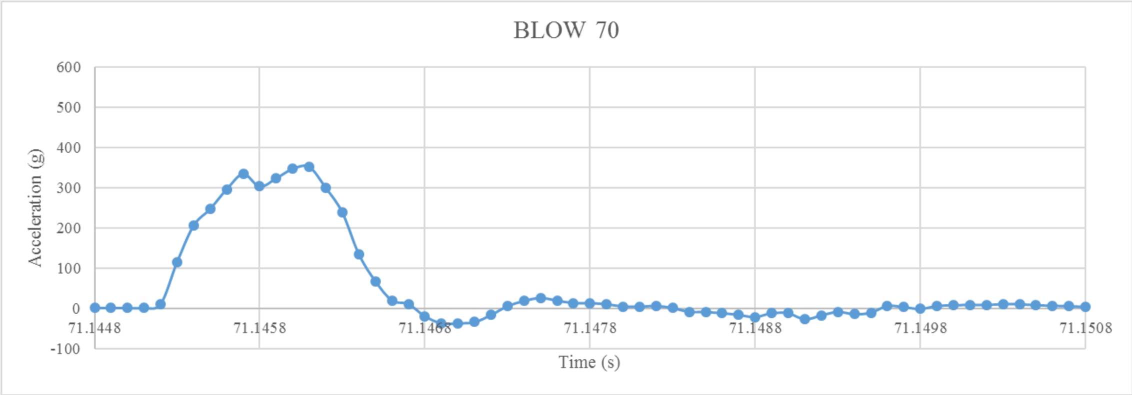

BLOW 150
Acceleration (g)
600
500
400
300
200
100
0
-100
-200
76.1473
76.1483
76.1493
76.1503
76.1513
76.1523
76.1533
Time (s)

A-2 Mixture 1 Sample 2

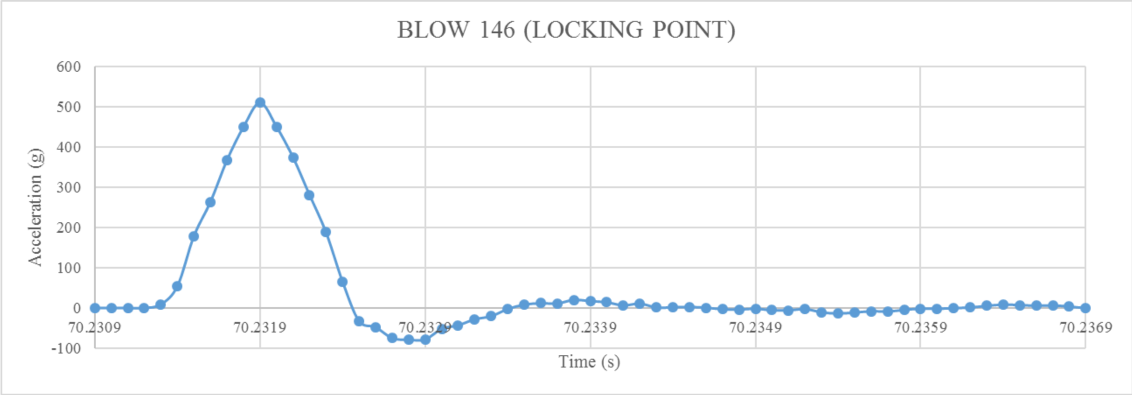




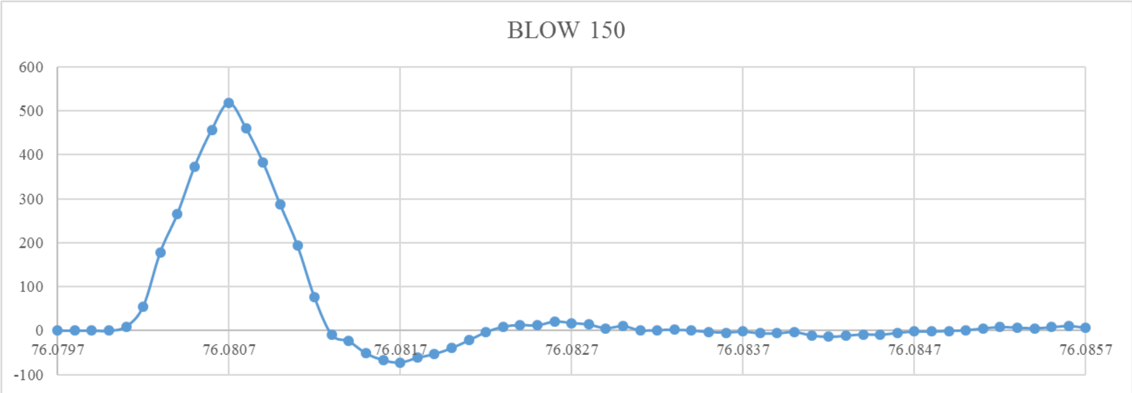




BLOW 70
Acceleration (g)
600
500
400
300
200
100
0
-100
71.1448
71.1458
71.1468
71.1478
71.1488
71.1498
71.1508
Time (s)

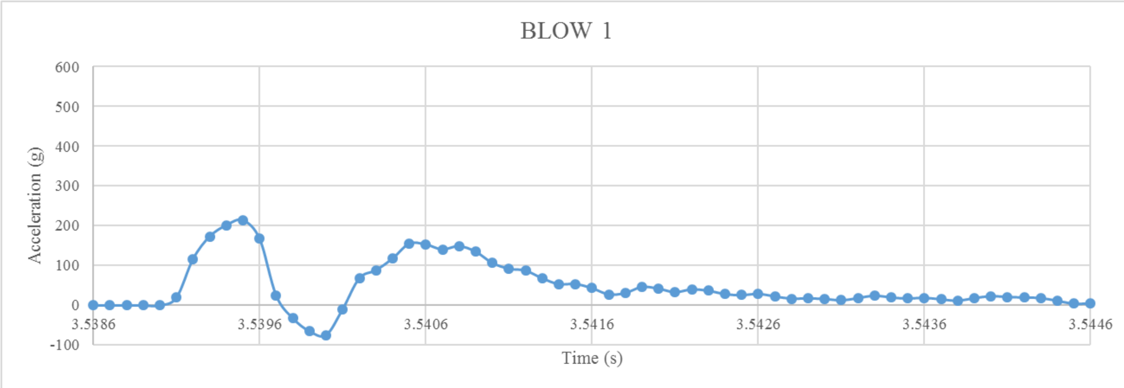


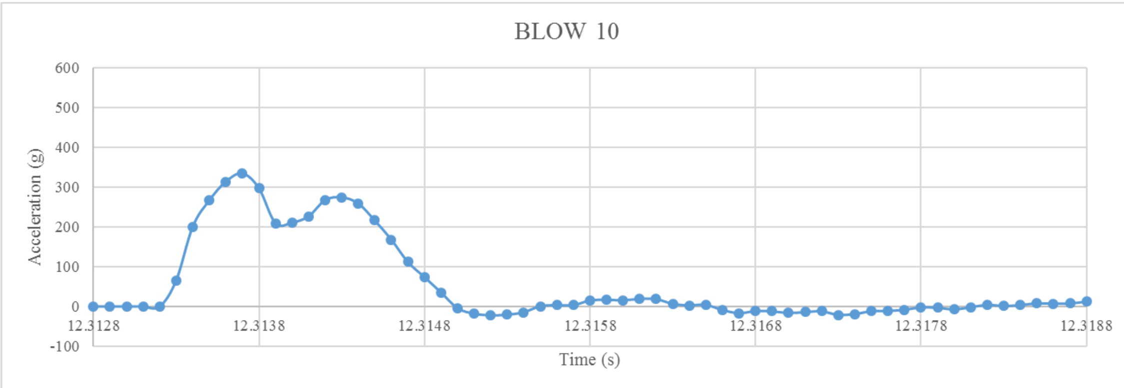
BLOW 146 (LOCKING POINT)
Acceleration (g)
600
500
400
300
200
100
0
-100
70.2309
70.2319
70.2329
70.2339
70.2349
70.2359
70.2369
Time (s)

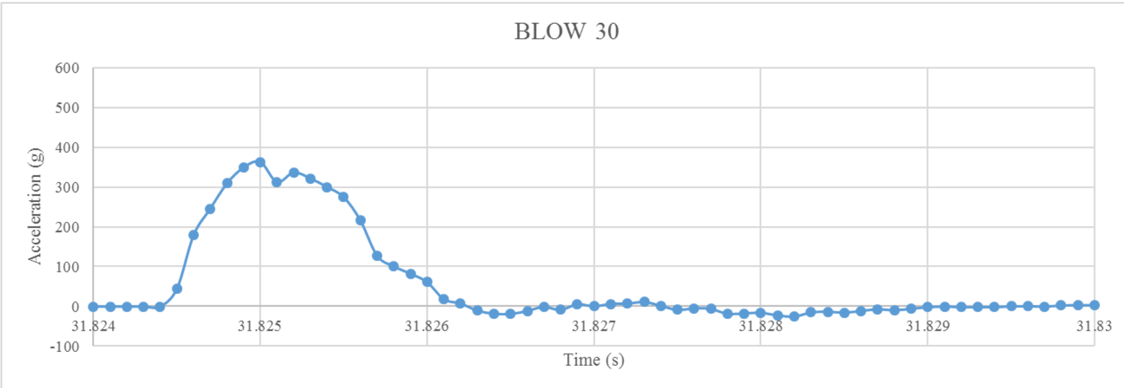


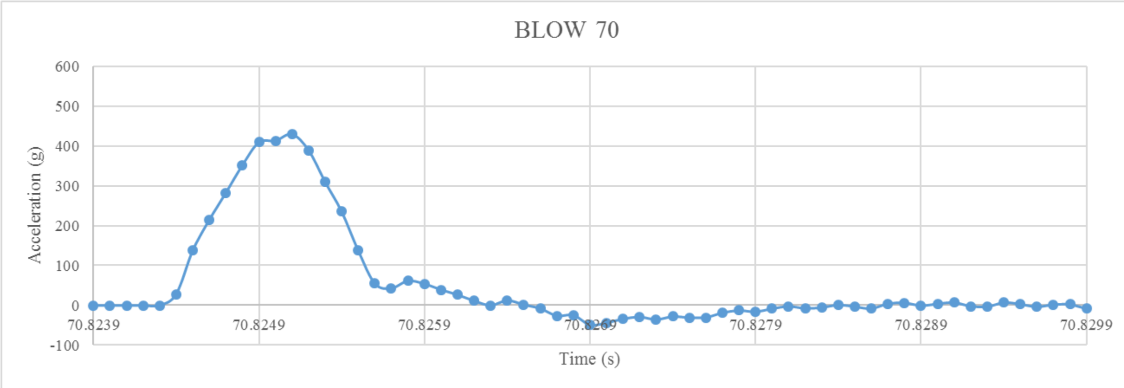
BLOW 150
600
500
400
300
200
100
0
-100
76.0797
76.0807
76.0817
76.0827
76.0837
76.0847
76.0857

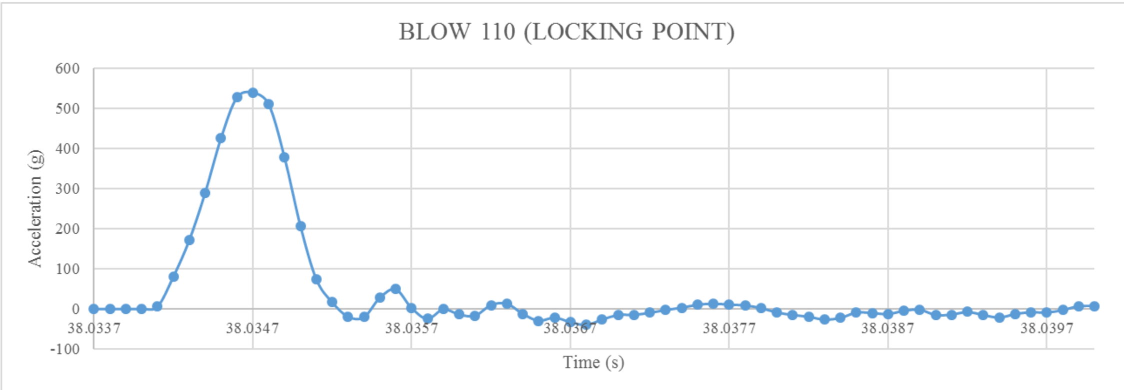
A-3 Mixture 2 Sample 2

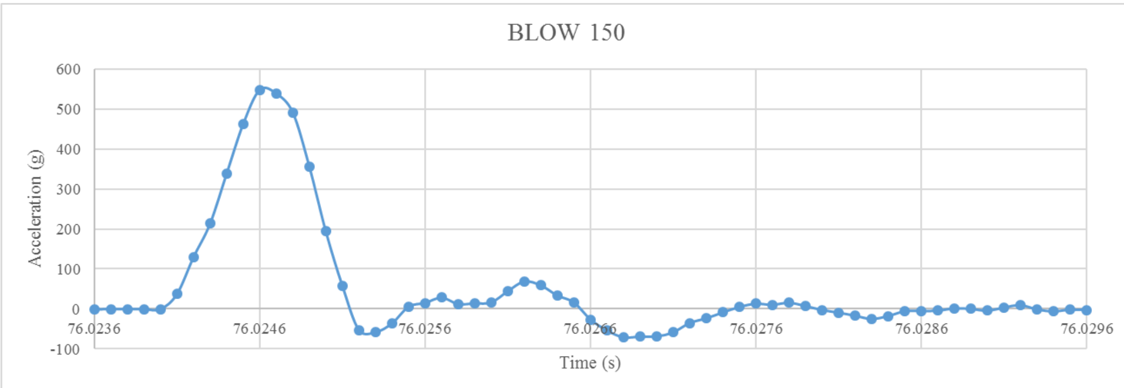




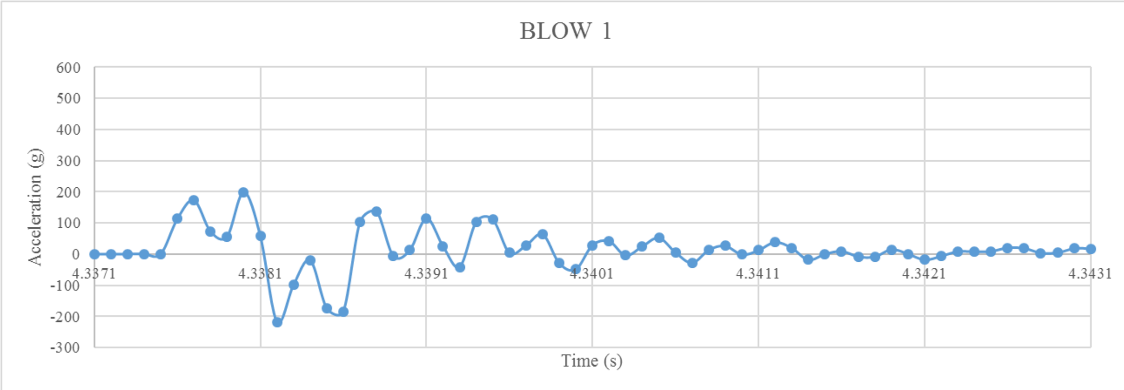


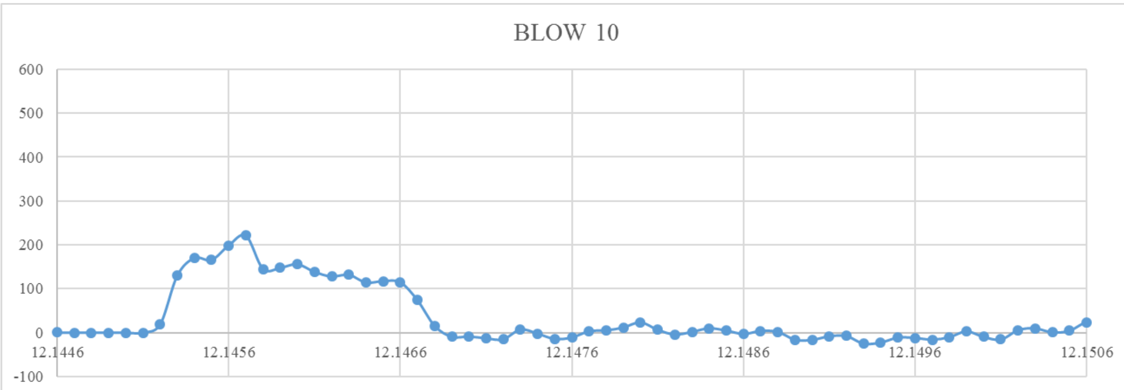

BLOW 70
600
500
400
300
200
100
0
-100
Acceleration (g)
70.8239
70.8249
70.8259
70.8269
70.8279
70.8289
70.8299
Time (s)

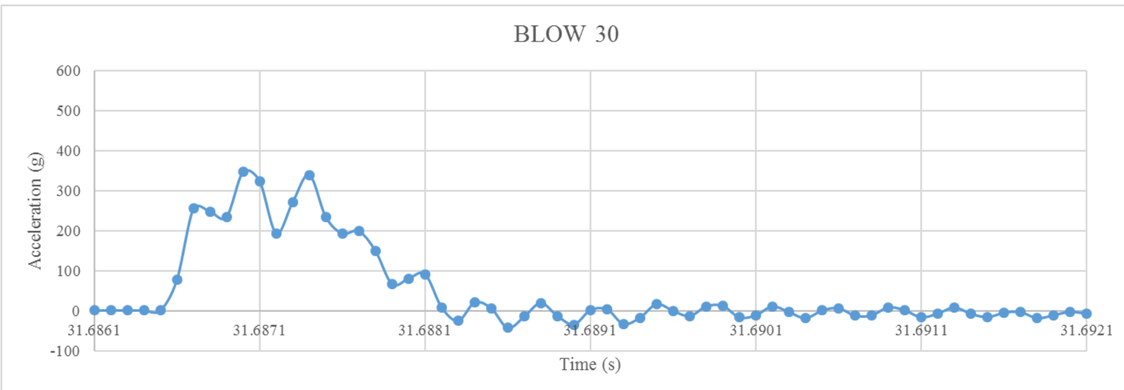

BLOW 110 (LOCKING POINT)
600
500
400
300
200
100
0
-100
Acceleration (g)
38.0337
38.0347
38.0357
38.0367
38.0377
38.0387
38.0397
Time (s)

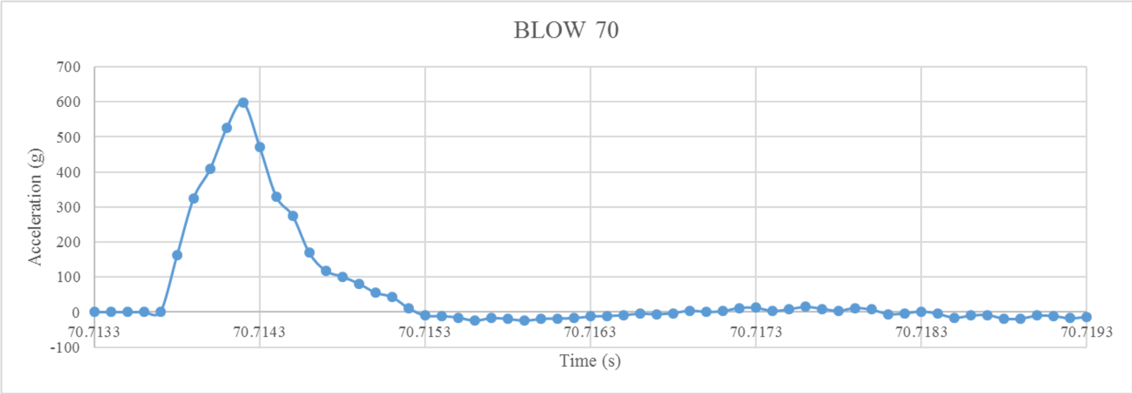

BLOW 150
600
500
400
300
200
100
0
-100
Acceleration (g)
76.0236
76.0246
76.0256
76.0266
76.0276
76.0286
76.0296
Time (s)

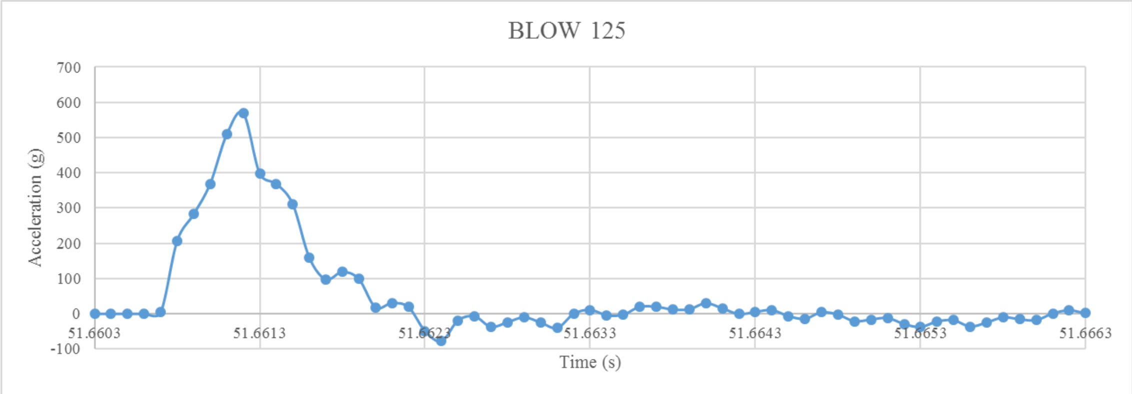
A-4 Mixture 3 Sample 1

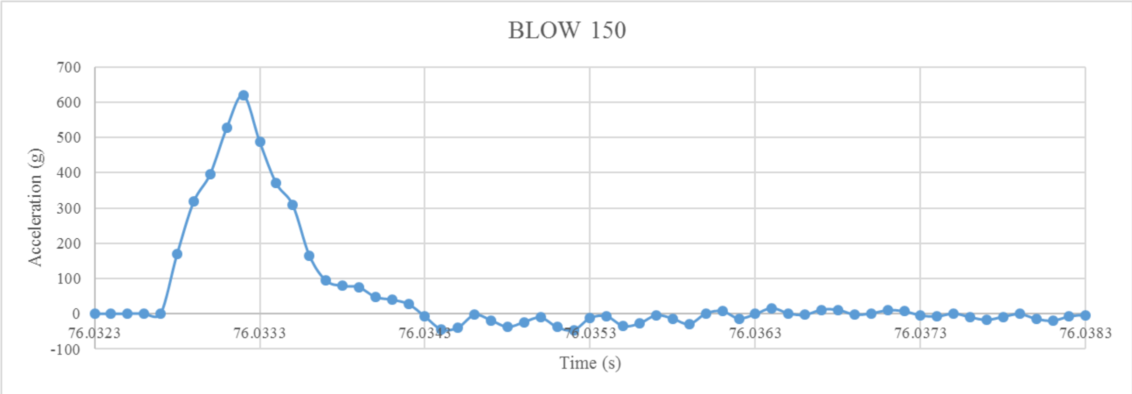




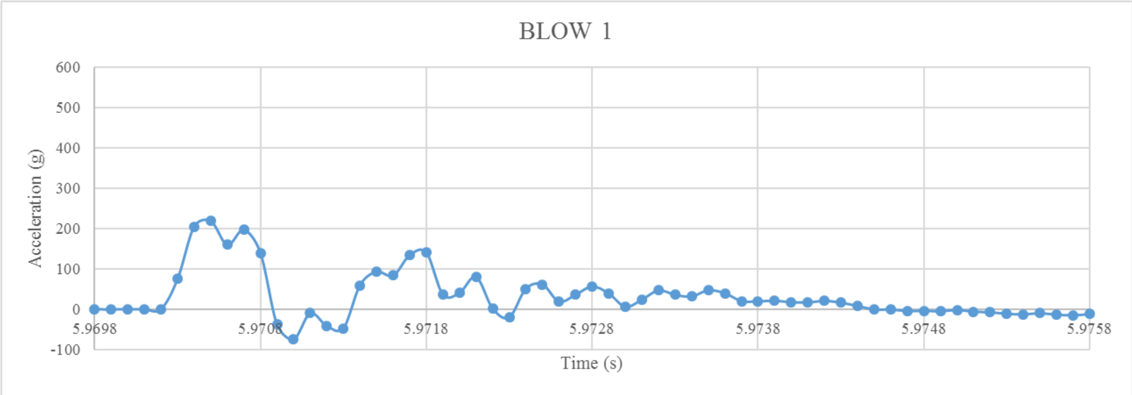


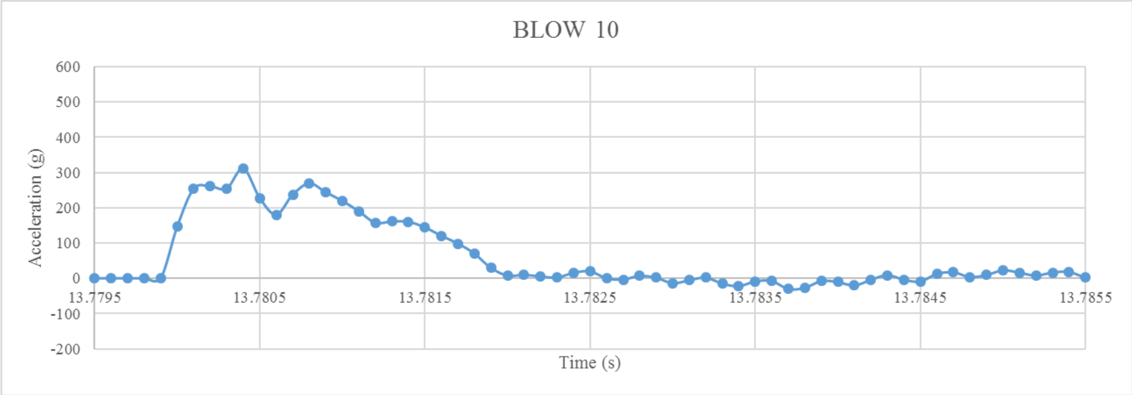

BLOW 70
700
600
500
400
300
200
100
0
-100
Acceleration (g)
70.7133
70.7143
70.7153
70.7163
70.7173
70.7183
70.7193
Time (s)

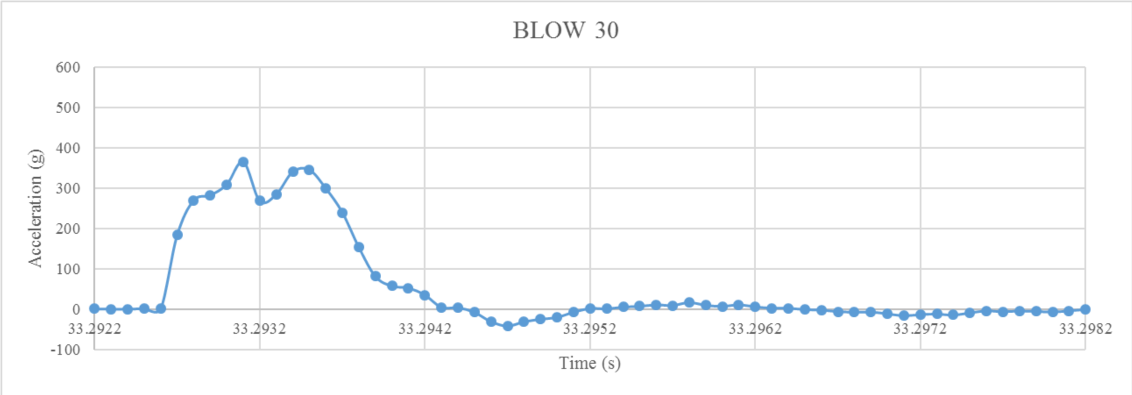

BLOW 125
700
600
500
400
300
200
100
0
-100
Acceleration (g)
51.6603
51.6613
51.6623
51.6633
51.6643
51.6653
51.6663
Time (s)

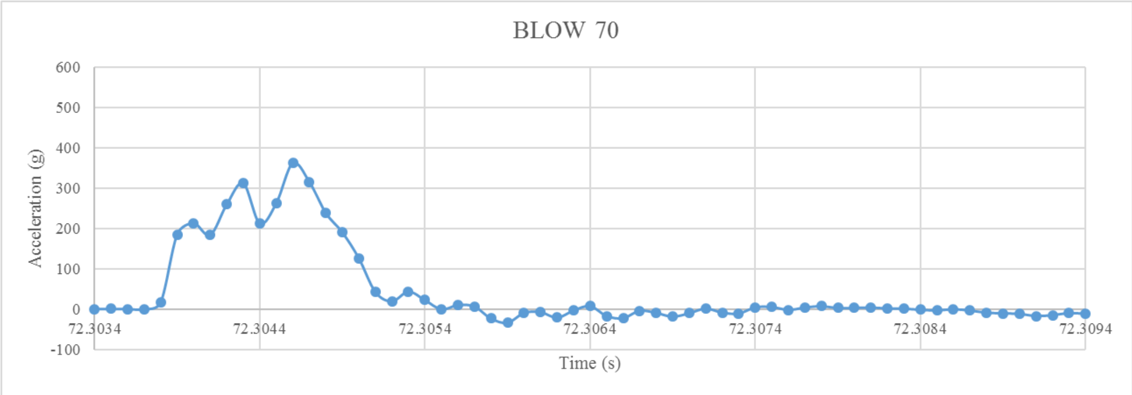

BLOW 150
700
600
500
400
300
200
100
0
-100
Acceleration (g)
76.0323
76.0333
76.0343
76.0353
76.0363
76.0373
76.0383
Time (s)

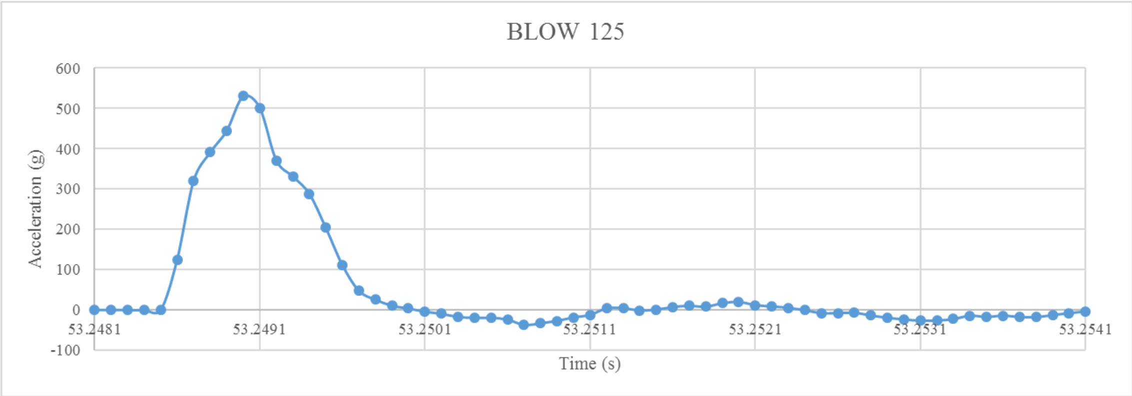
A-5 Mixture 3 Sample 2

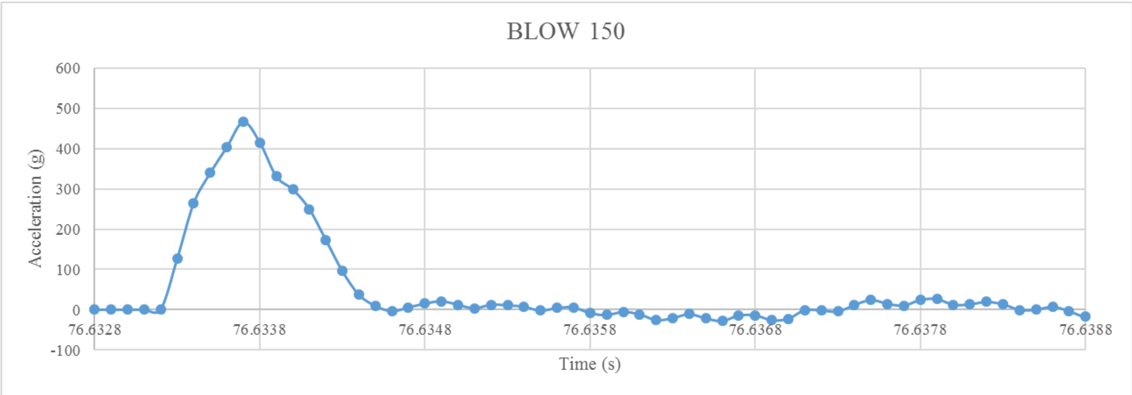




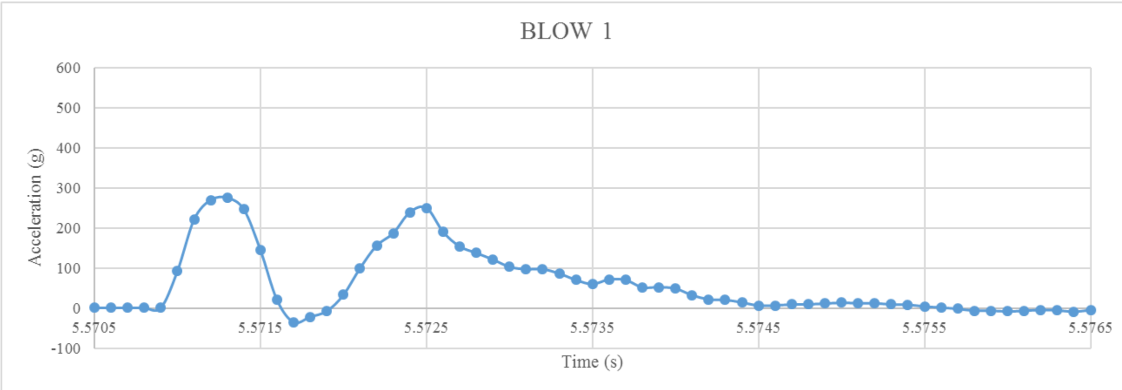


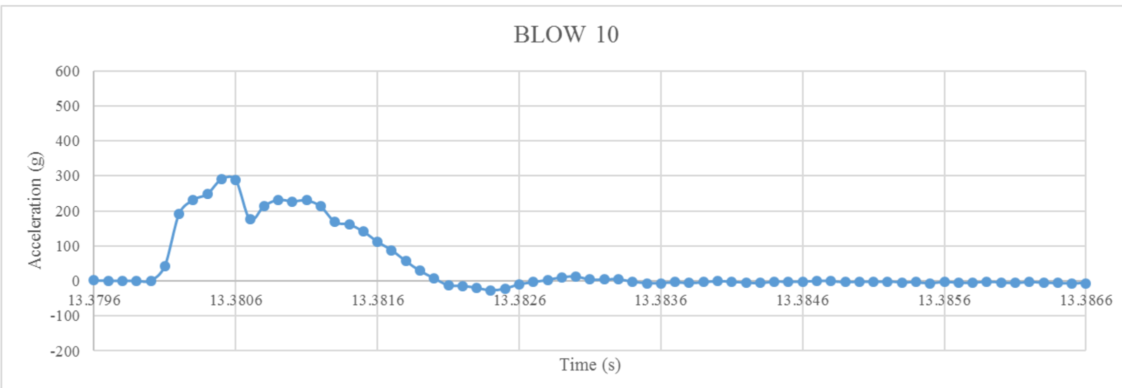

BLOW 70
Acceleration (g)
Time (s)
600
500
400
300
200
100
0
-100
72.3034
72.3044
72.3054
72.3064
72.3074
72.3084
72.3094

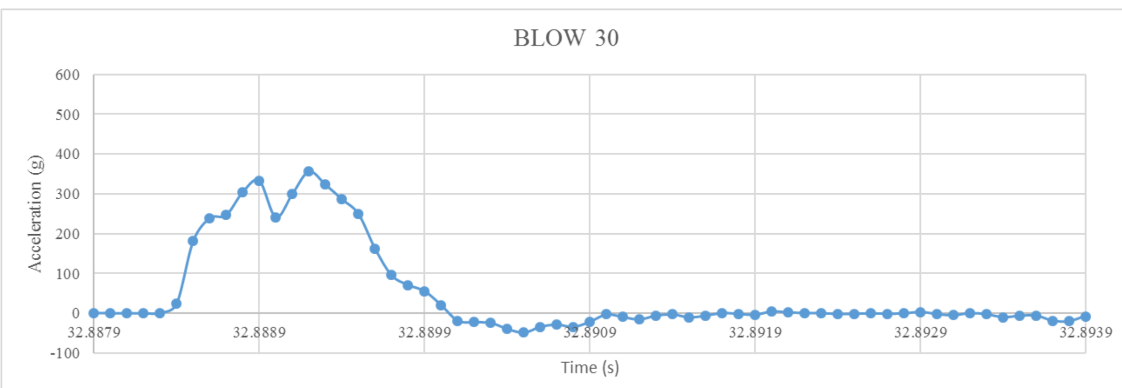

BLOW 125
Acceleration (g)
Time (s)
600
500
400
300
200
100
0
-100
53.2481
53.2491
53.2501
53.2511
53.2521
53.2531
53.2541

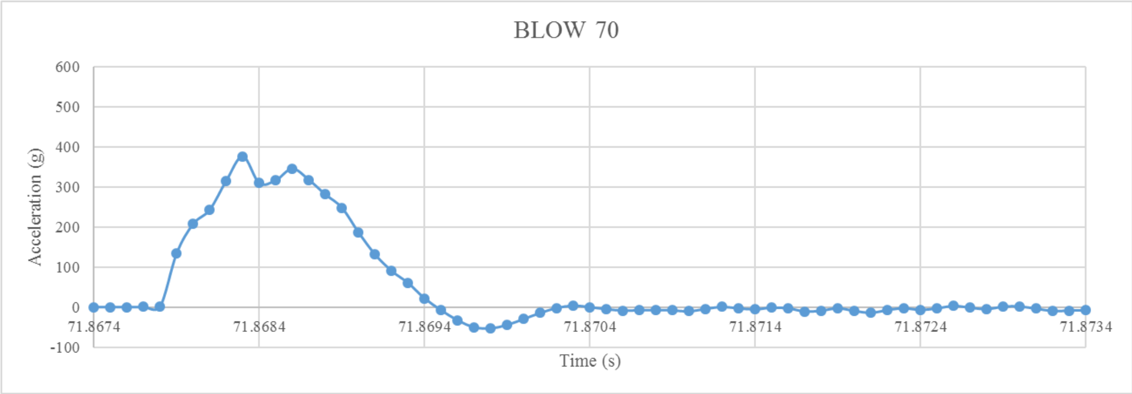

BLOW 150
Acceleration (g)
Time (s)
600
500
400
300
200
100
0
-100
76.6328
76.6338
76.6348
76.6358
76.6368
76.6378
76.6388

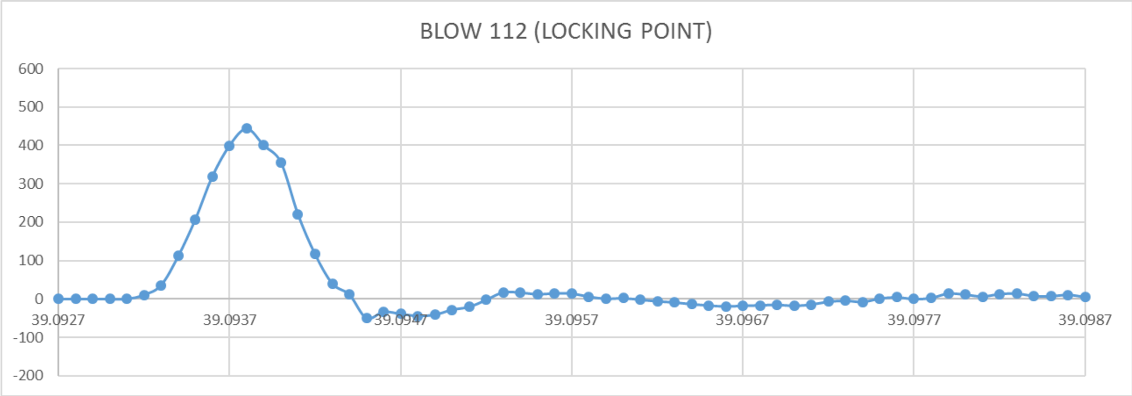
A-6 Mixture 4 Sample 1

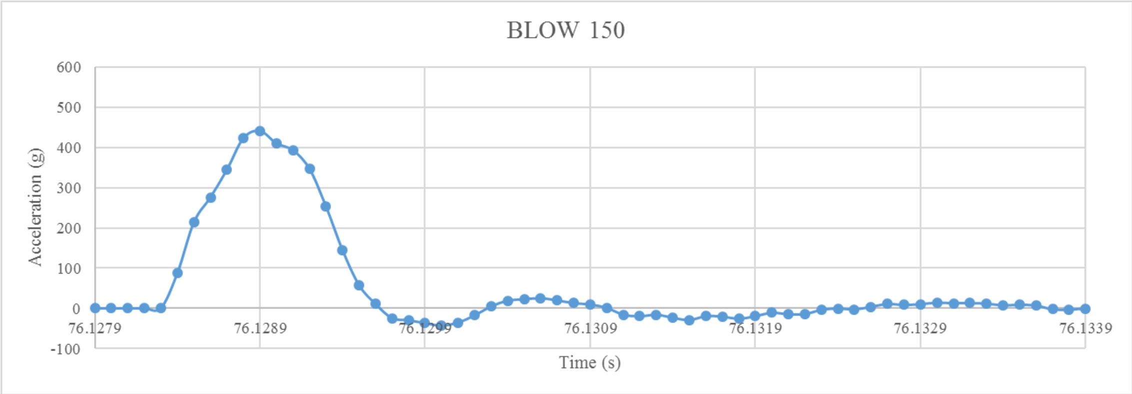




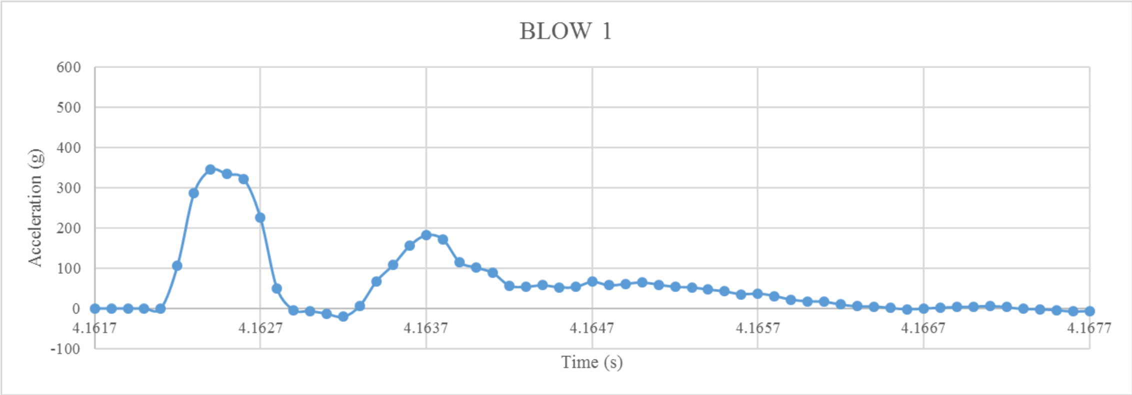


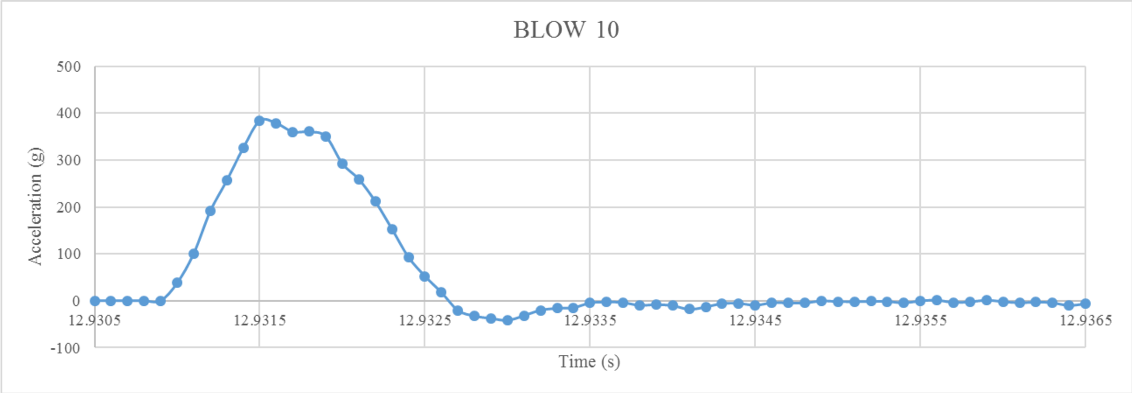

BLOW 70
Acceleration (g)
600
500
400
300
200
100
0
-100
71.8674
71.8684
71.8694
71.8704
71.8714
71.8724
71.8734
Time (s)

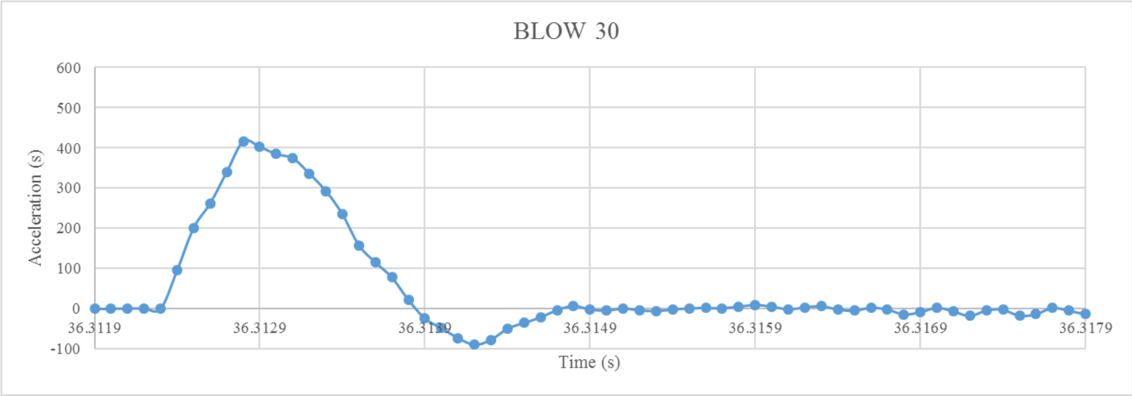

BLOW 112 (LOCKING POINT)
600
500
400
300
200
100
0
-100
-200
39.0927
39.0937
39.0947
39.0957
39.0967
39.0977
39.0987

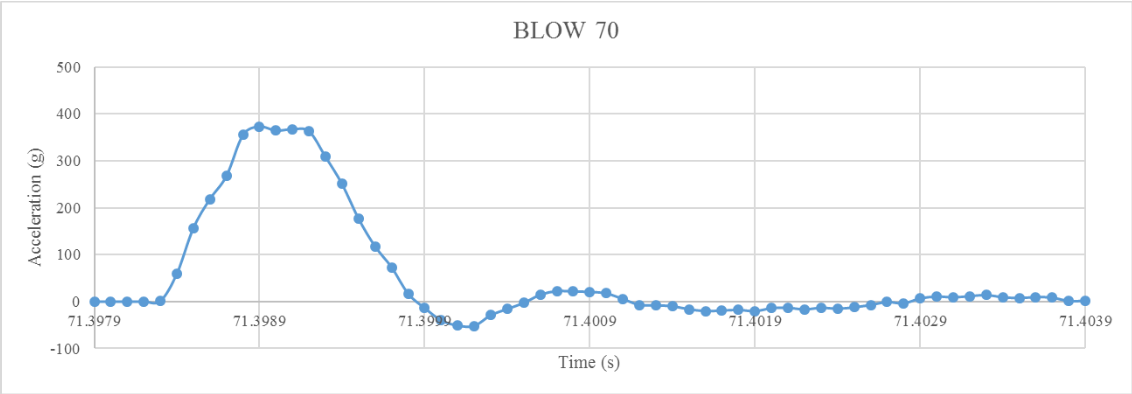

BLOW 150
Acceleration (g)
600
500
400
300
200
100
0
-100
76.1279
76.1289
76.1299
76.1309
76.1319
76.1329
76.1339
Time (s)

A-7 Mixture 4 Sample 2

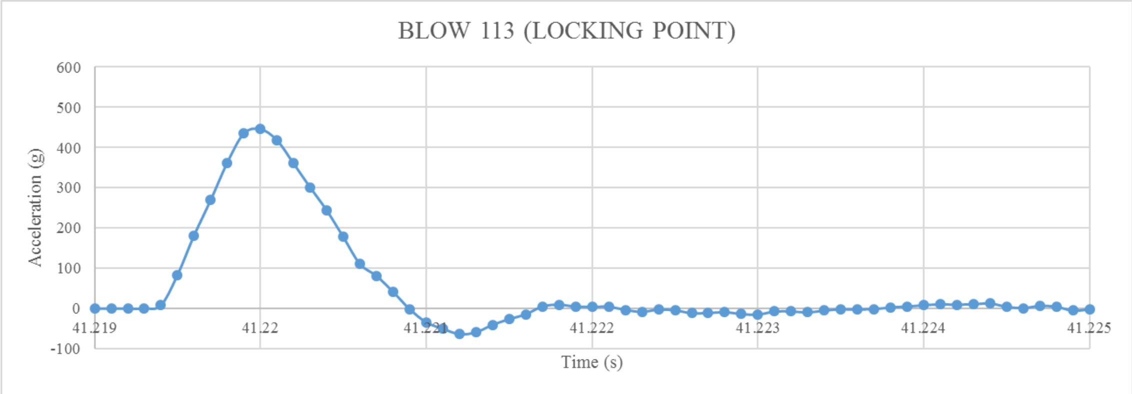




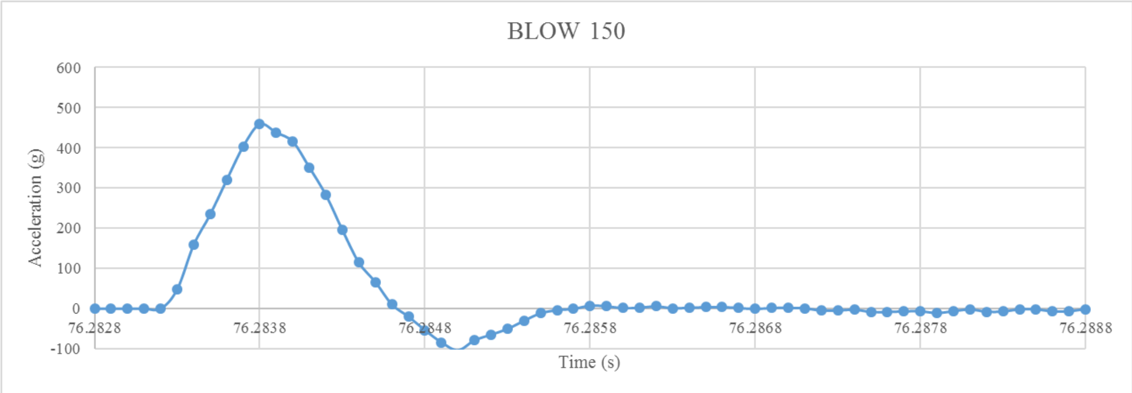




BLOW 70
Acceleration (g)
Time (s)
500
400
300
200
100
0
-100
71.3979
71.3989
71.3999
71.4009
71.4019
71.4029
71.4039

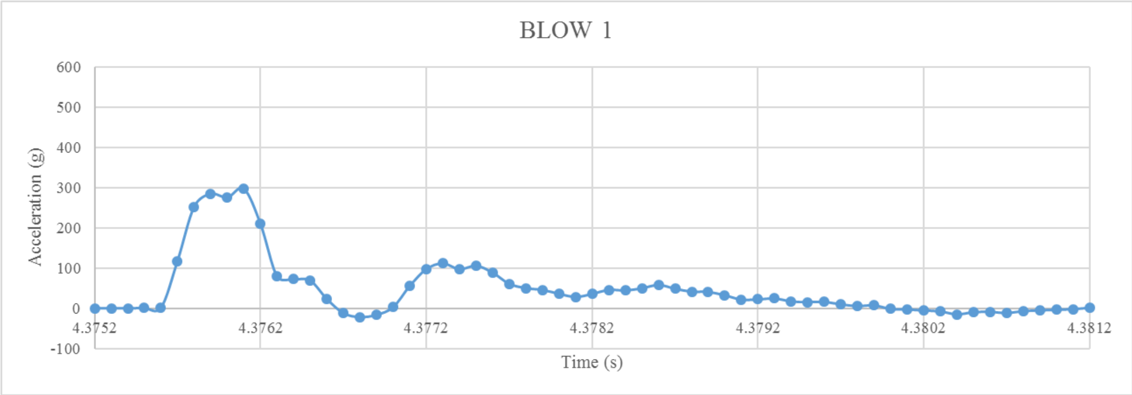


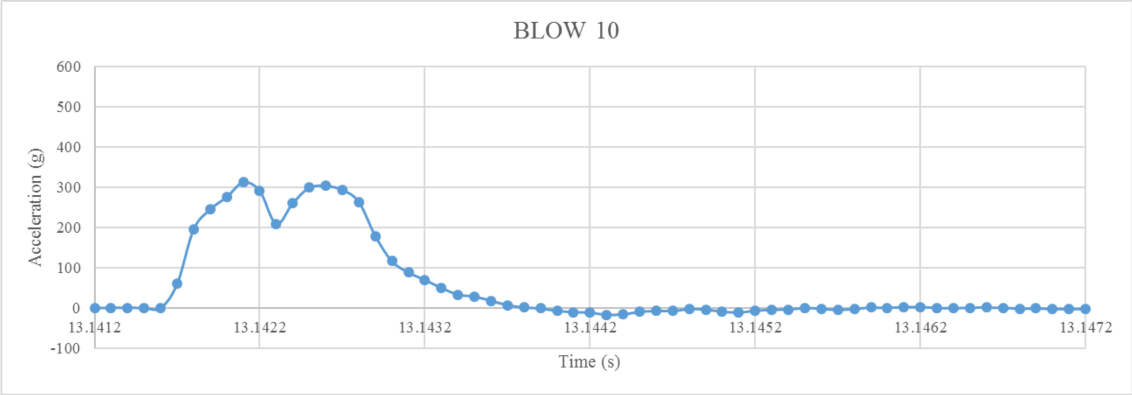
BLOW 113 (LOCKING POINT)
Acceleration (g)
Time (s)
600
500
400
300
200
100
0
-100
41.219
41.22
41.221
41.222
41.223
41.224
41.225

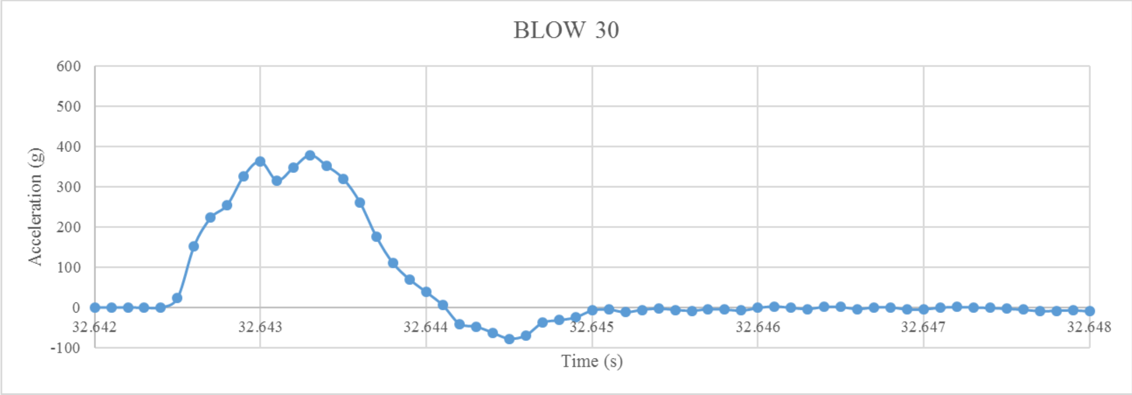


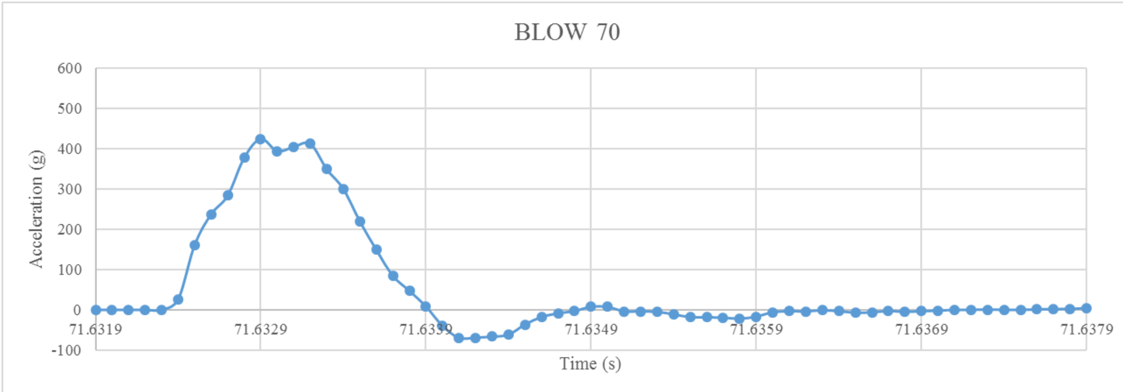
BLOW 150
Acceleration (g)
Time (s)
600
500
400
300
200
100
0
-100
76.2828
76.2838
76.2848
76.2858
76.2868
76.2878
76.2888

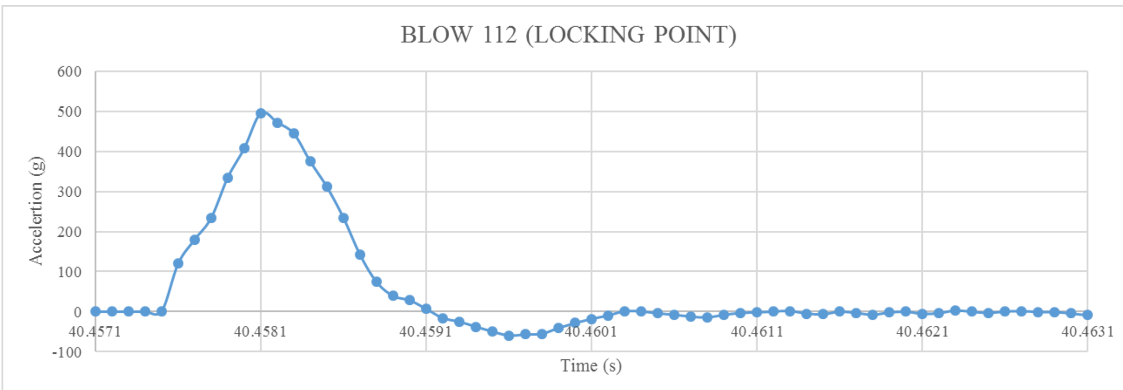
A-8 Mixture 5 Sample 1

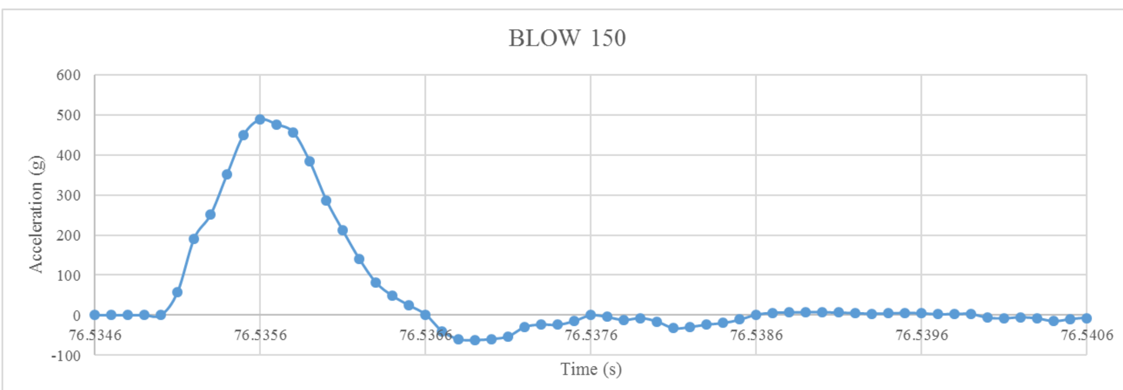




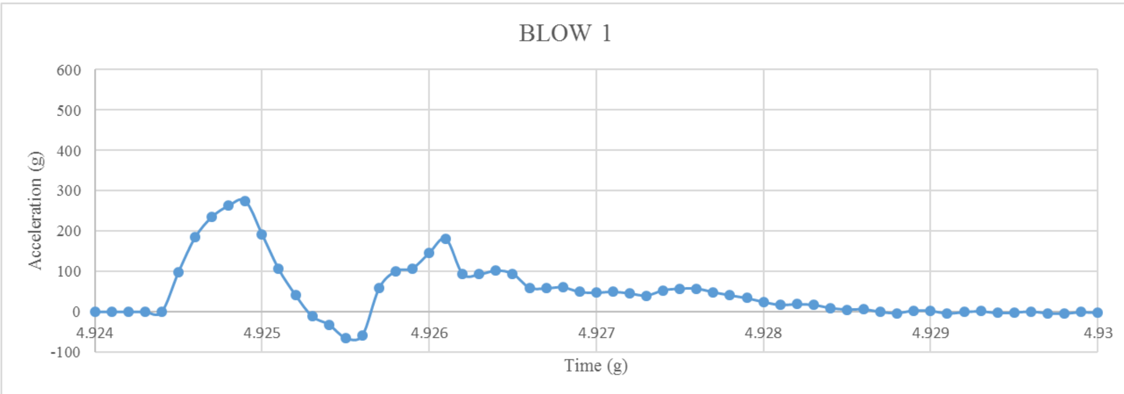


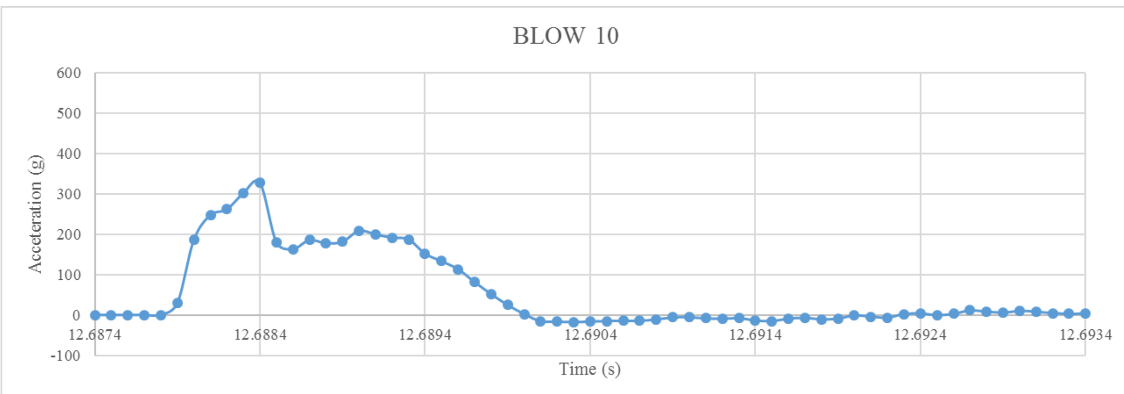

BLOW 70
600
500
400
300
200
100
0
-100
Acceleration (g)
71.6319
71.6329
71.6339
71.6349
71.6359
71.6369
71.6379
Time (s)

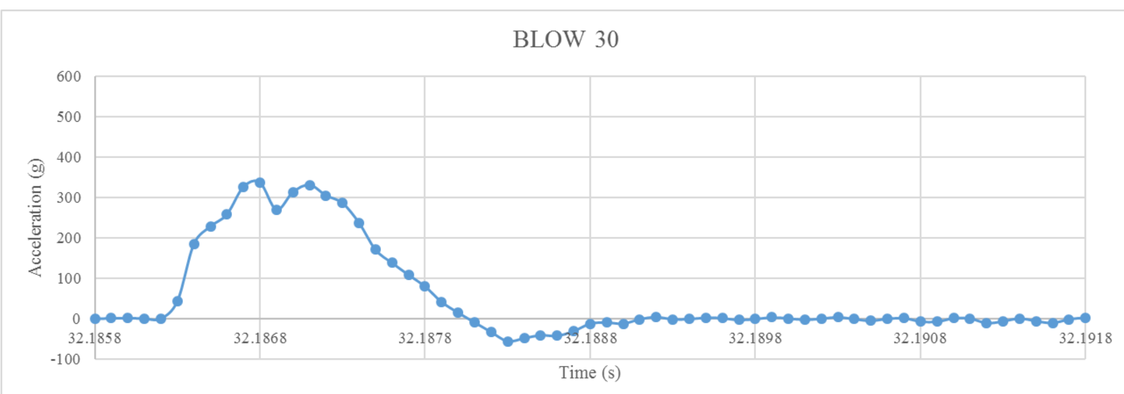

BLOW 112 (LOCKING POINT)
600
500
400
300
200
100
0
-100
Accelertion (g)
40.4571
40.4581
40.4591
40.4601
40.4611
40.4621
40.4631
Time (s)

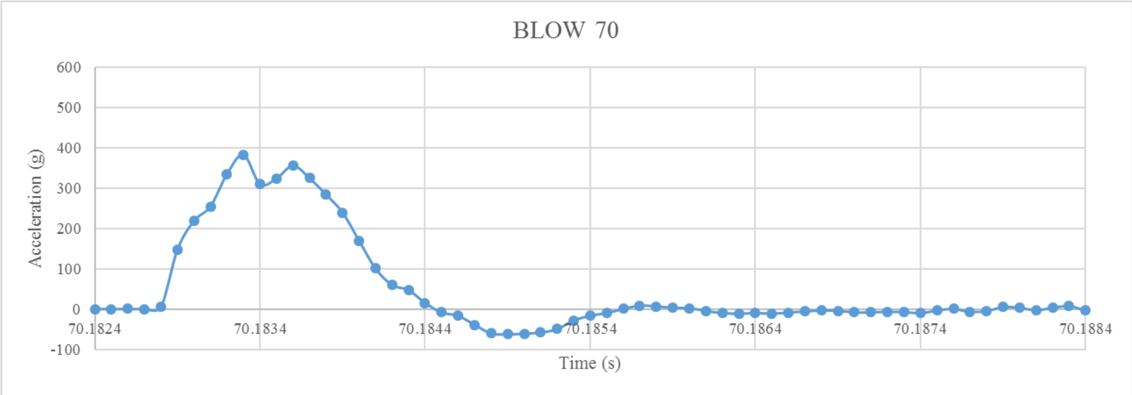

BLOW 150
600
500
400
300
200
100
0
-100
Acceleration (g)
76.5346
76.5356
76.5366
76.5376
76.5386
76.5396
76.5406
Time (s)

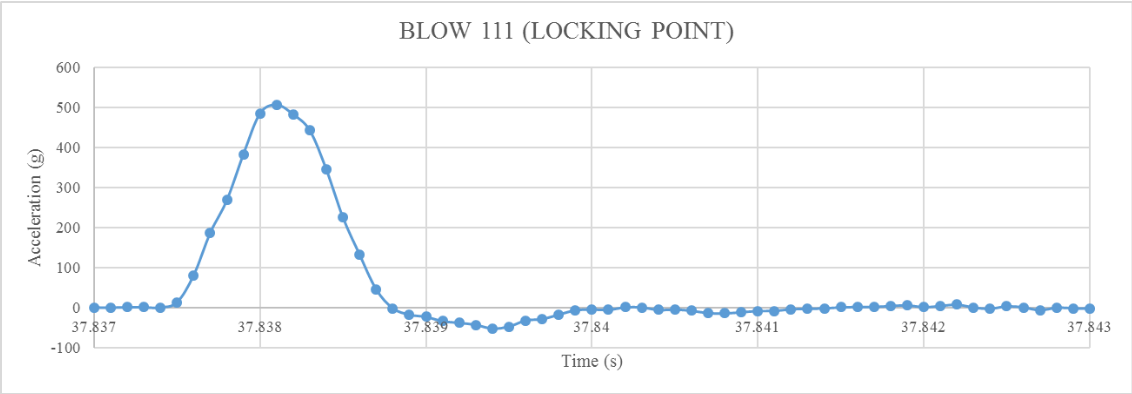
A-9 Mixture 5 Sample 2

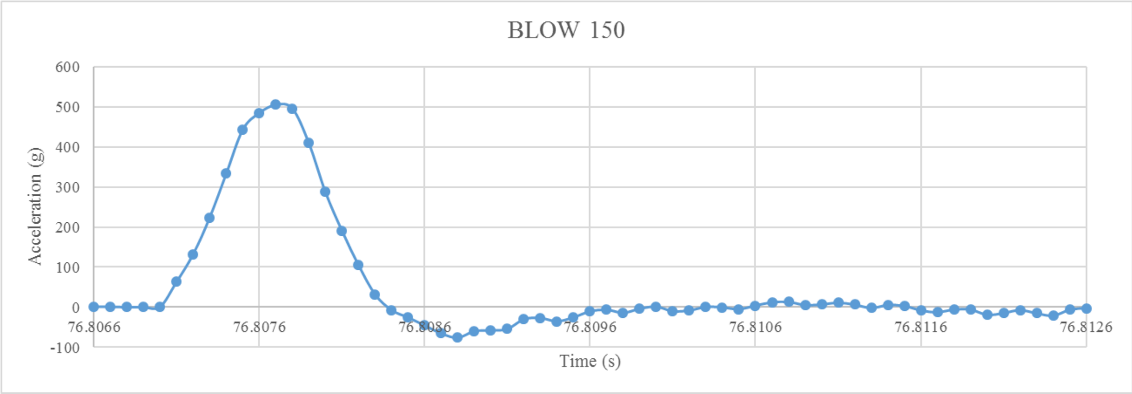




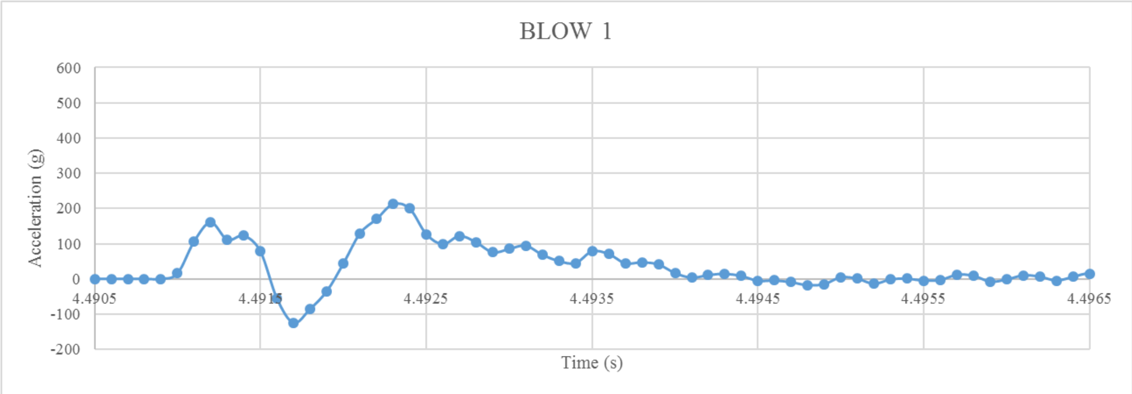


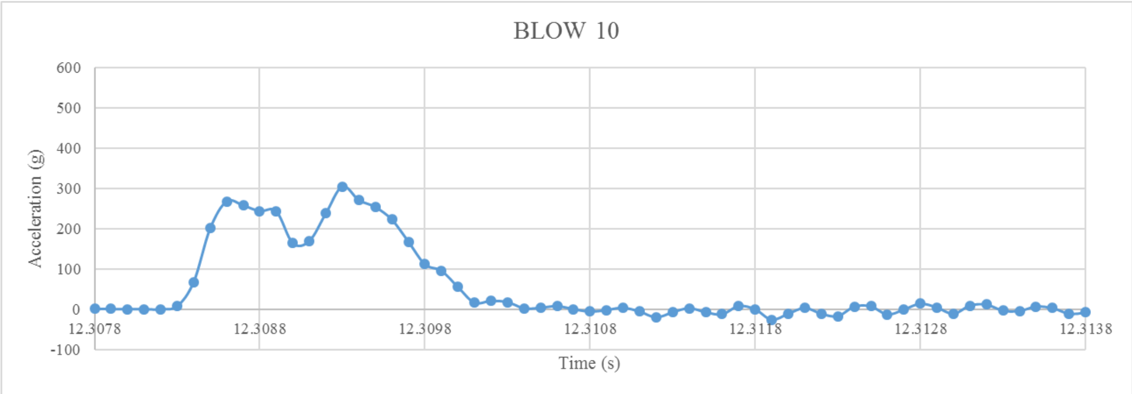

BLOW 70
Acceleration (g)
600
500
400
300
200
100
0
-100
70.1824
70.1834
70.1844
70.1854
70.1864
70.1874
70.1884
Time (s)

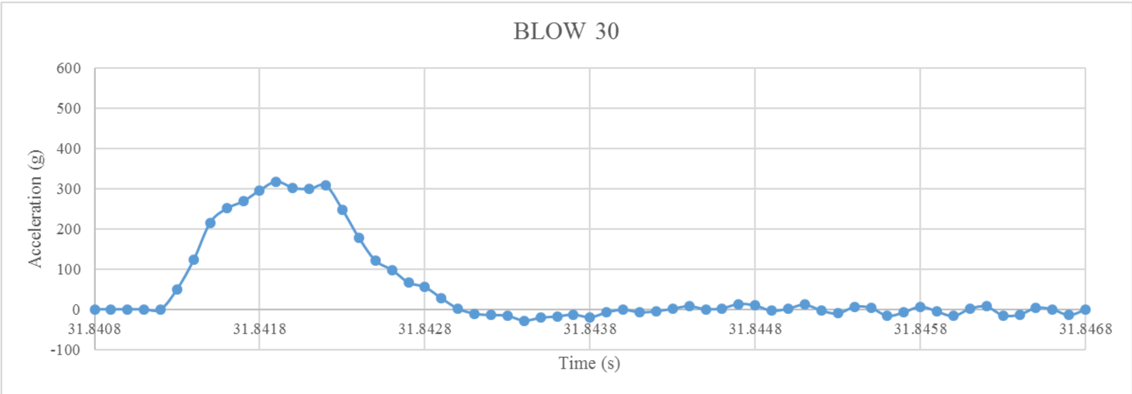

BLOW 111 (LOCKING POINT)
Acceleration (g)
600
500
400
300
200
100
0
-100
37.837
37.838
37.839
37.84
37.841
37.842
37.843
Time (s)

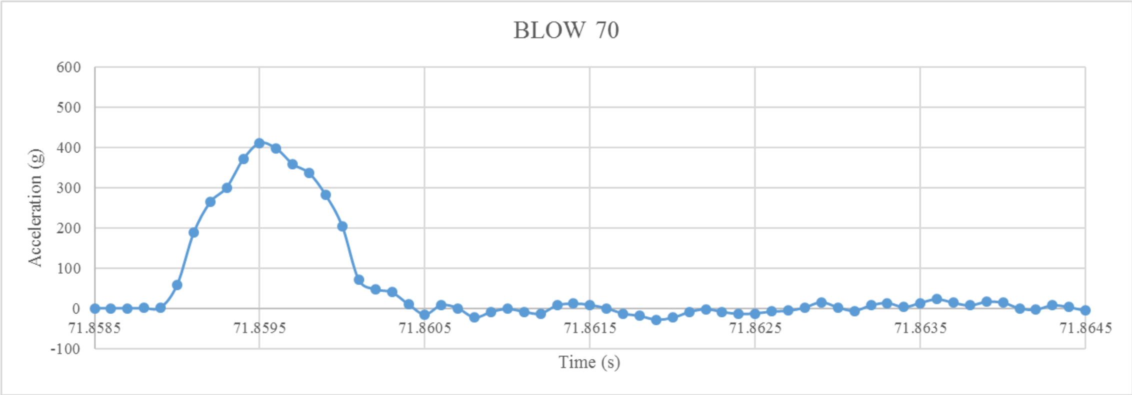

BLOW 150
Acceleration (g)
600
500
400
300
200
100
0
-100
76.8066
76.8076
76.8086
76.8096
76.8106
76.8116
76.8126
Time (s)

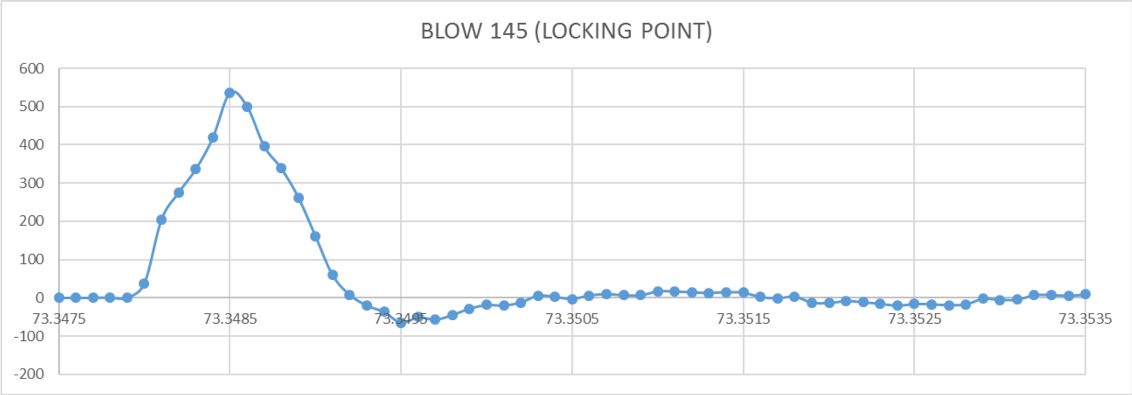
A-10 Mixture 6 Sample 1

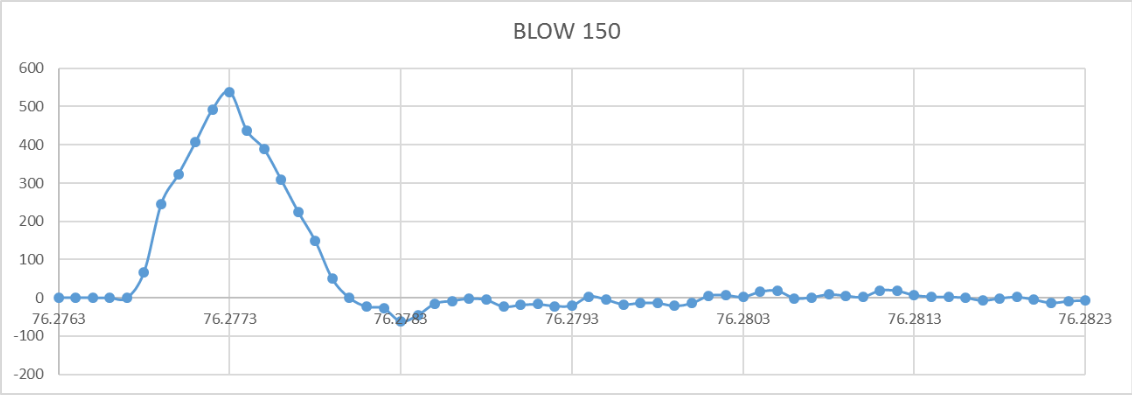




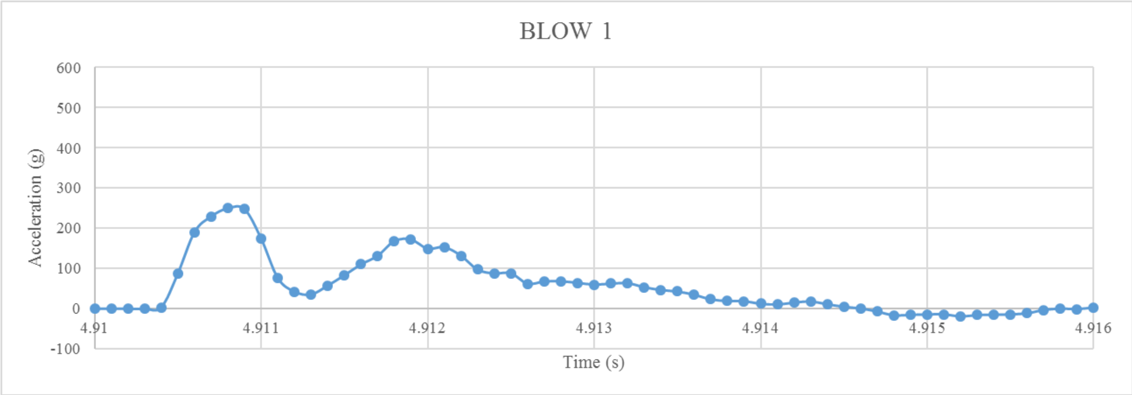


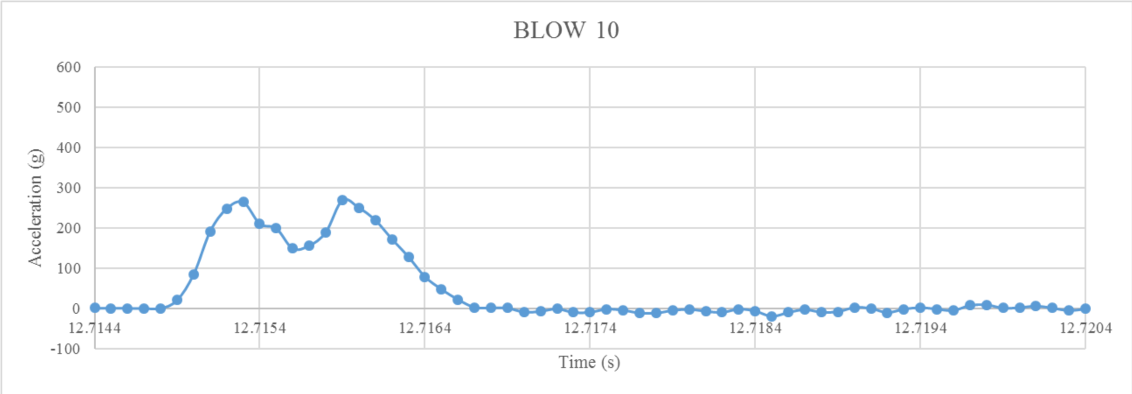

BLOW 70
Acceleration (g)
Time (s)
600
500
400
300
200
100
0
-100
71.8585
71.8595
71.8605
71.8615
71.8625
71.8635
71.8645

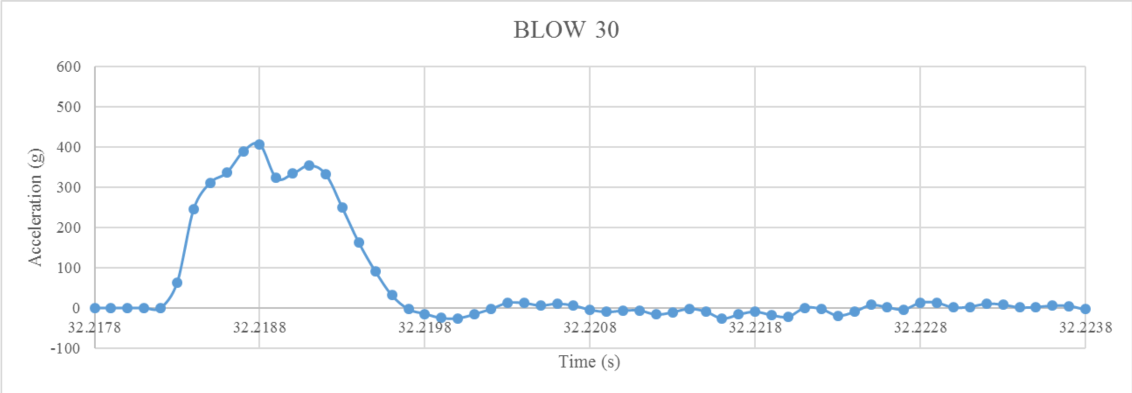

BLOW 145 (LOCKING POINT)
600
500
400
300
200
100
0
-100
-200
73.3475
73.3485
73.3495
73.3505
73.3515
73.3525
73.3535

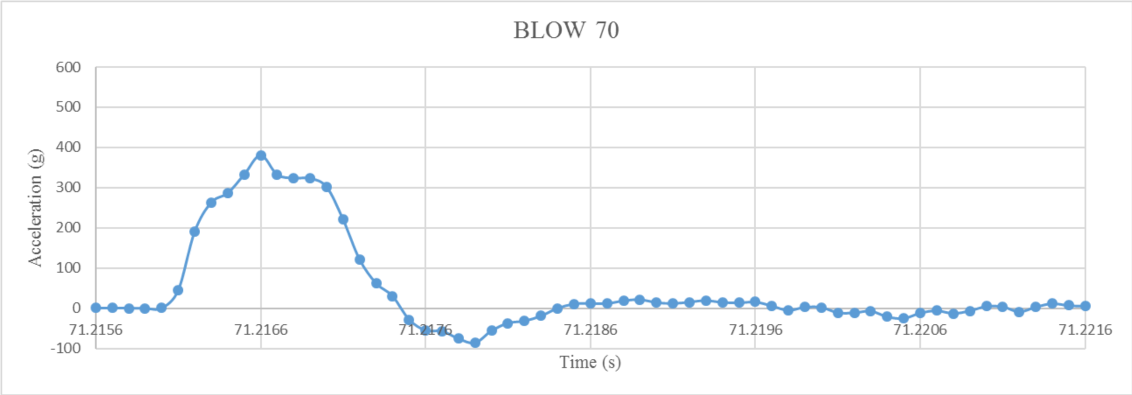

BLOW 150
600
500
400
300
200
100
0
-100
-200
76.2763
76.2773
76.2783
76.2793
76.2803
76.2813
76.2823

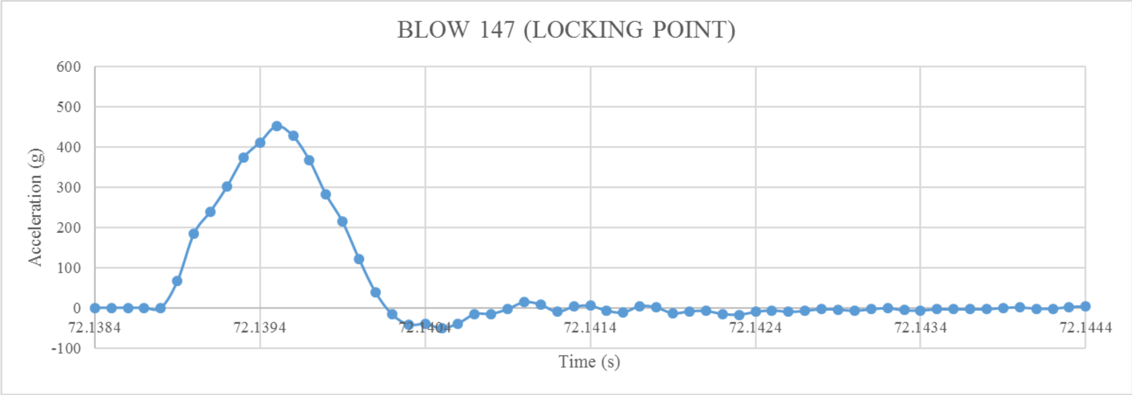
A-11 Mixture 6 Sample 2

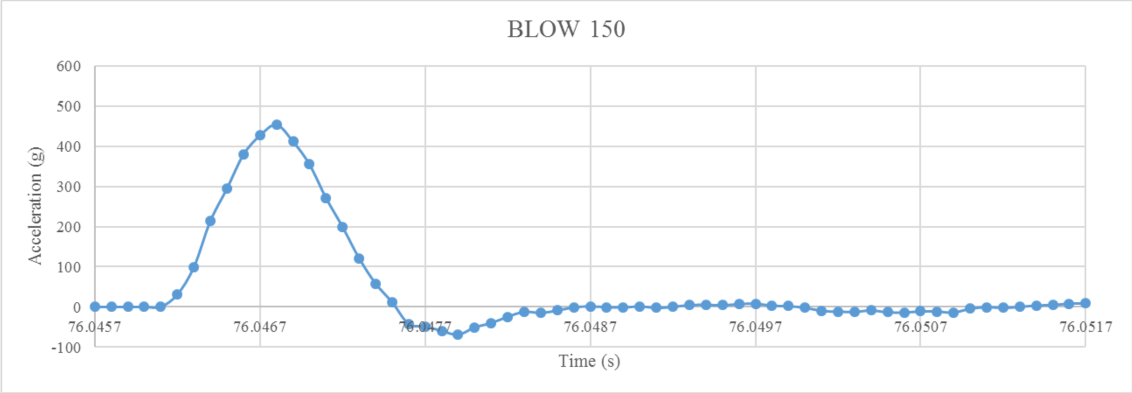




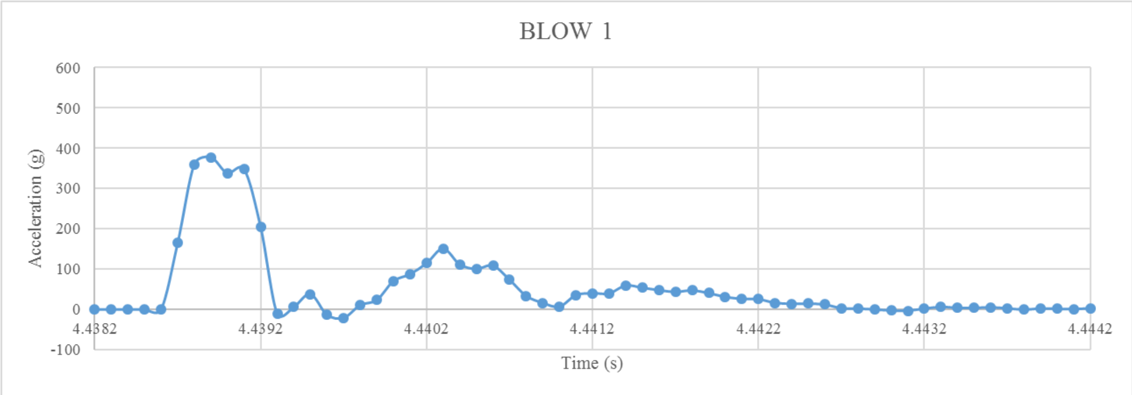


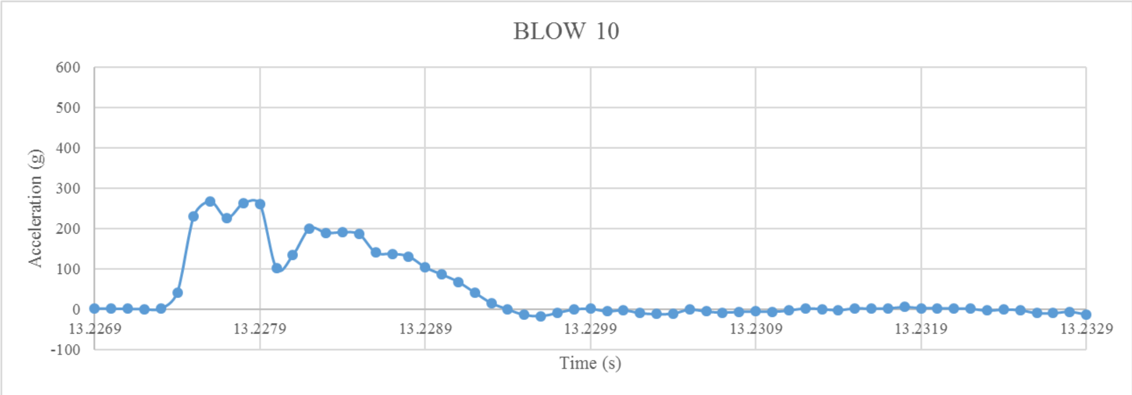

BLOW 70
600
500
400
300
200
100
0
-100
Acceleration (g)
71.2156
71.2166
71.2176
71.2186
71.2196
71.2206
71.2216
Time (s)

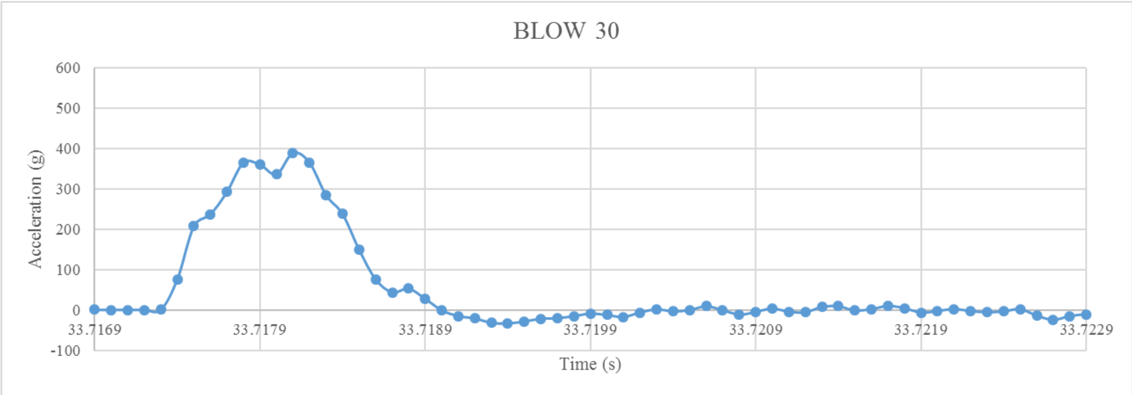

BLOW 147 (LOCKING POINT)
600
500
400
300
200
100
0
-100
Acceleration (g)
72.1384
72.1394
72.1404
72.1414
72.1424
72.1434
72.1444
Time (s)

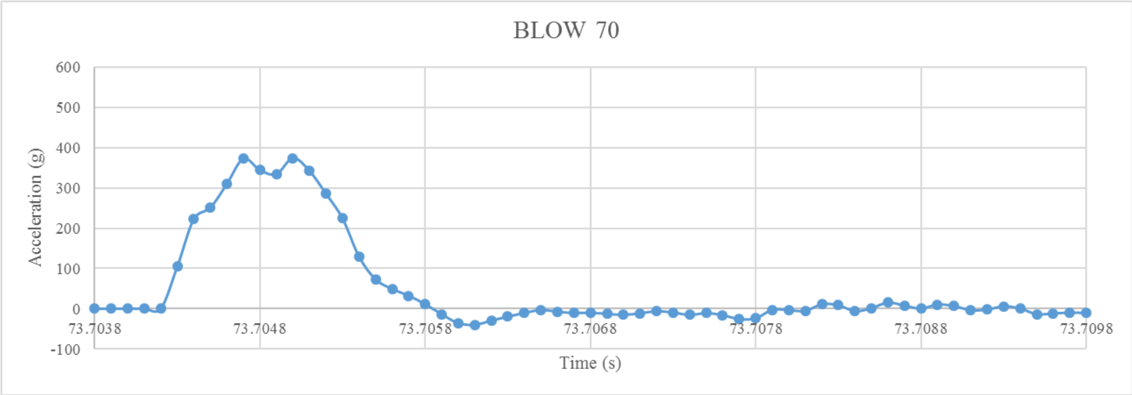

BLOW 150
600
500
400
300
200
100
0
-100
Acceleration (g)
76.0457
76.0467
76.0477
76.0487
76.0497
76.0507
76.0517
Time (s)

A-12 Mixture 7 Sample 1

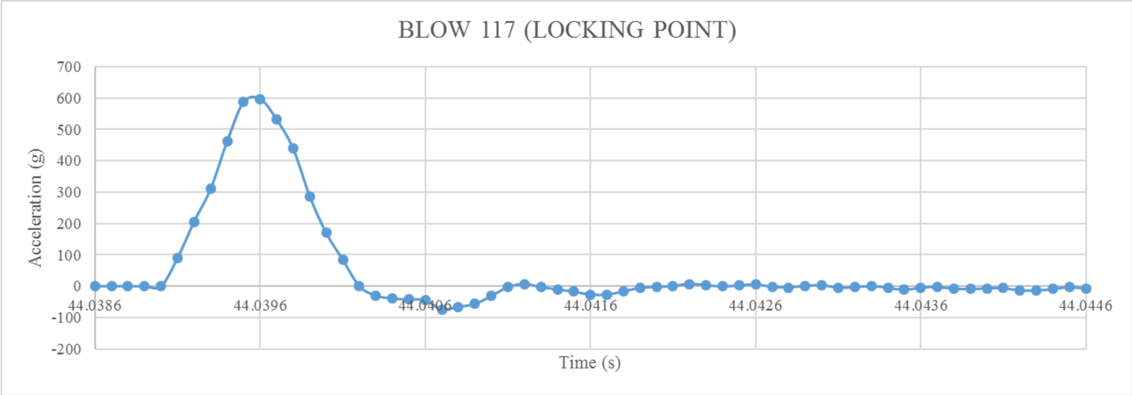




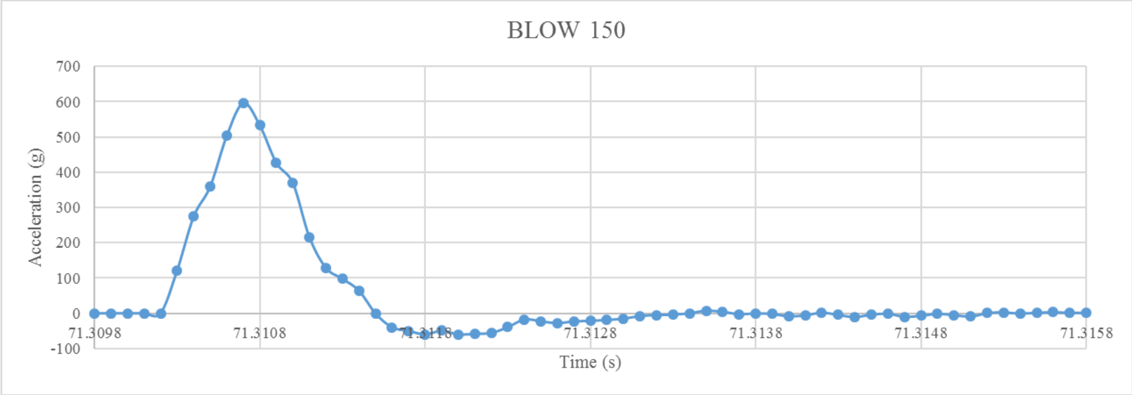




BLOW 70
Acceleration (g)
600
500
400
300
200
100
0
-100
73.7038
73.7048
73.7058
73.7068
73.7078
73.7088
73.7098
Time (s)

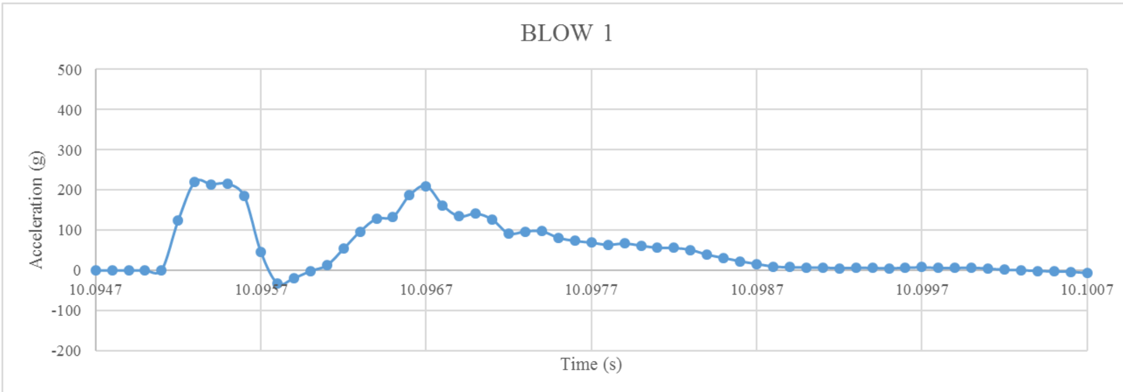


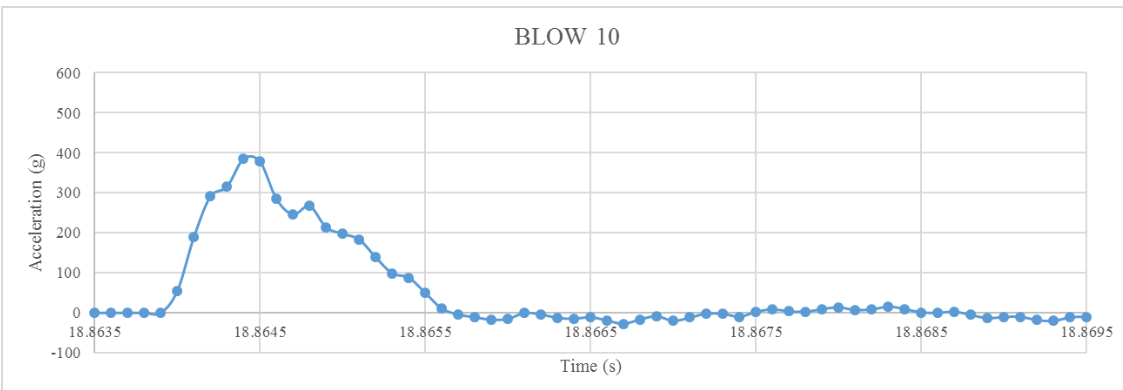
BLOW 117 (LOCKING POINT)
Acceleration (g)
700
600
500
400
300
200
100
0
-100
-200
44.0386
44.0396
44.0406
44.0416
44.0426
44.0436
44.0446
Time (s)

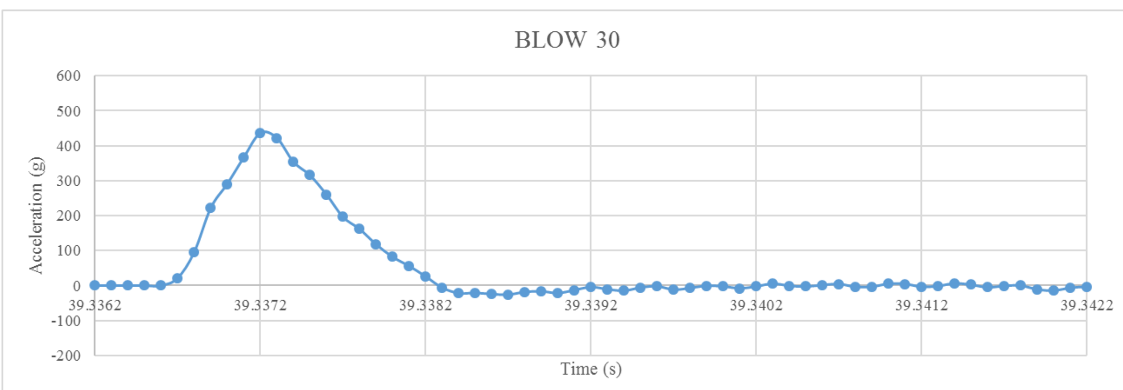


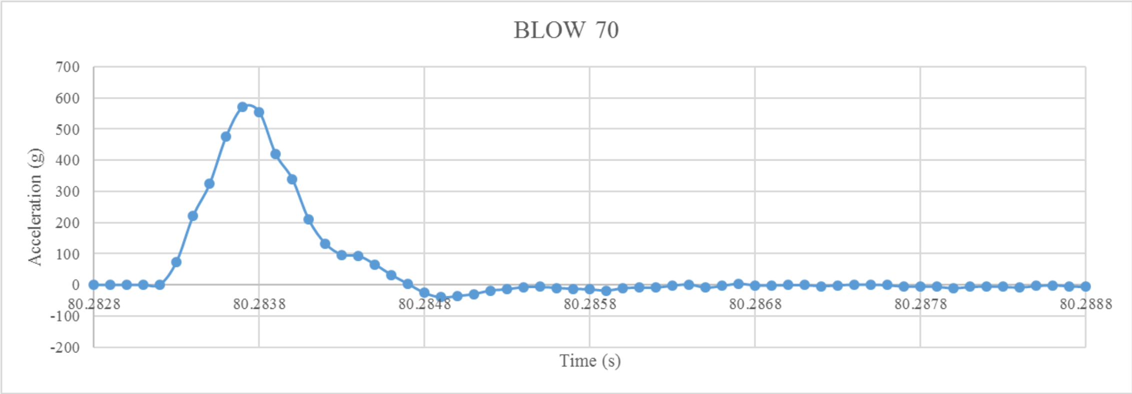
BLOW 150
Acceleration (g)
700
600
500
400
300
200
100
0
-100
71.3098
71.3108
71.3118
71.3128
71.3138
71.3148
71.3158
Time (s)

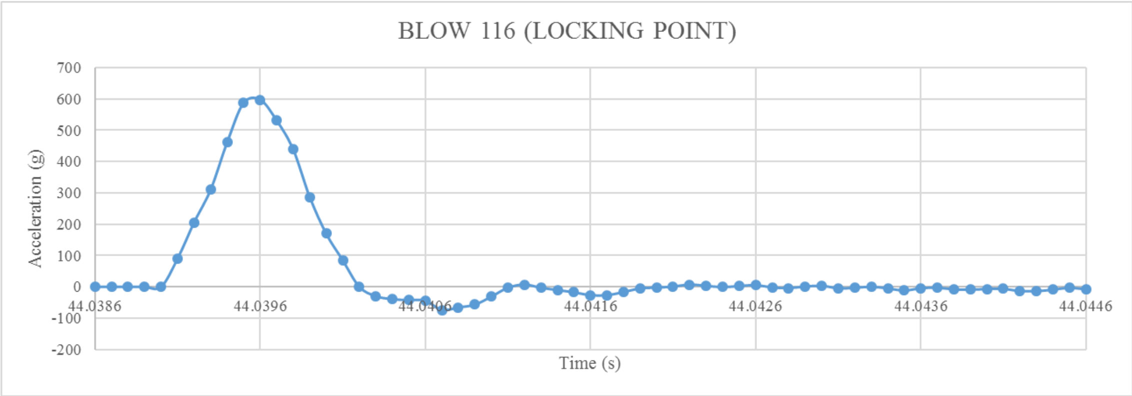
A-13 Mixture 7 Sample 2

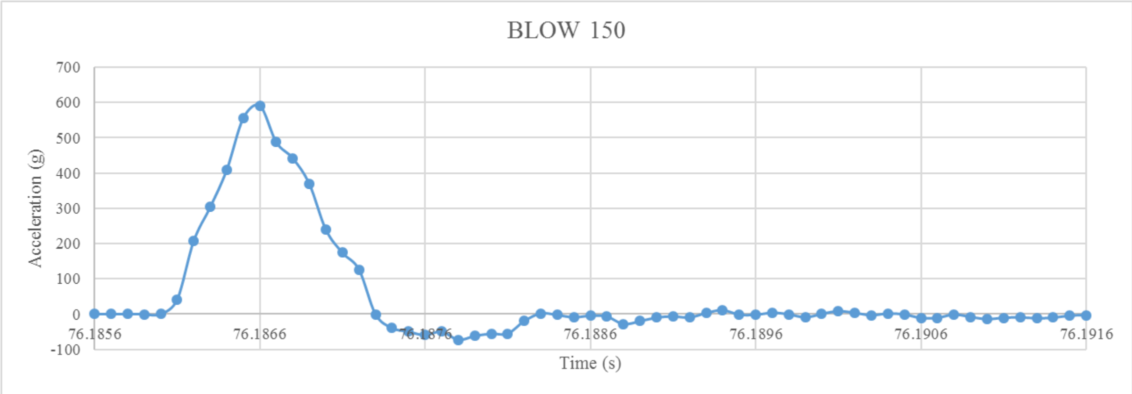




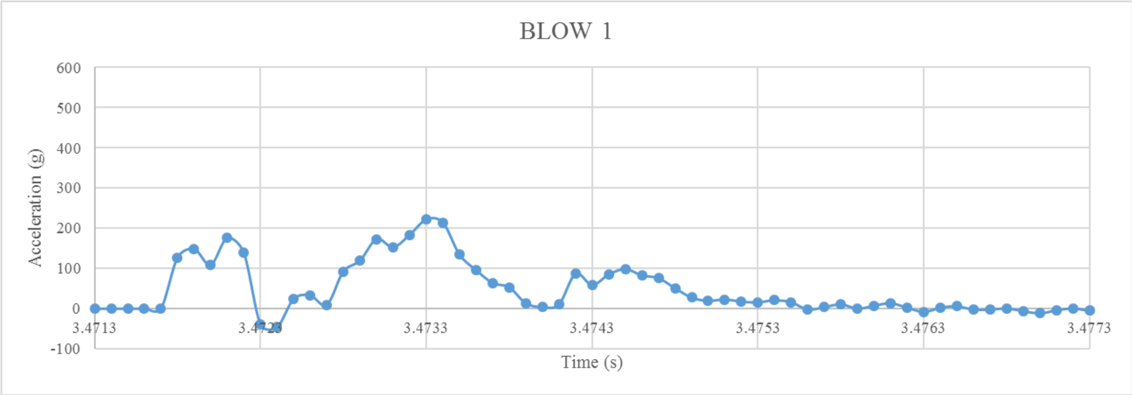


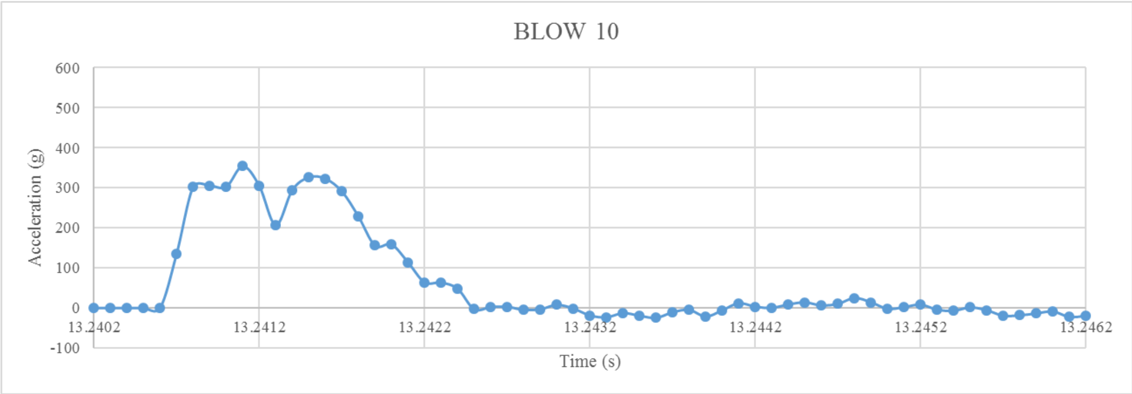

BLOW 70
Acceleration (g)
700
600
500
400
300
200
100
0
-100
-200
80.2828
80.2838
80.2848
80.2858
80.2868
80.2878
80.2888
Time (s)

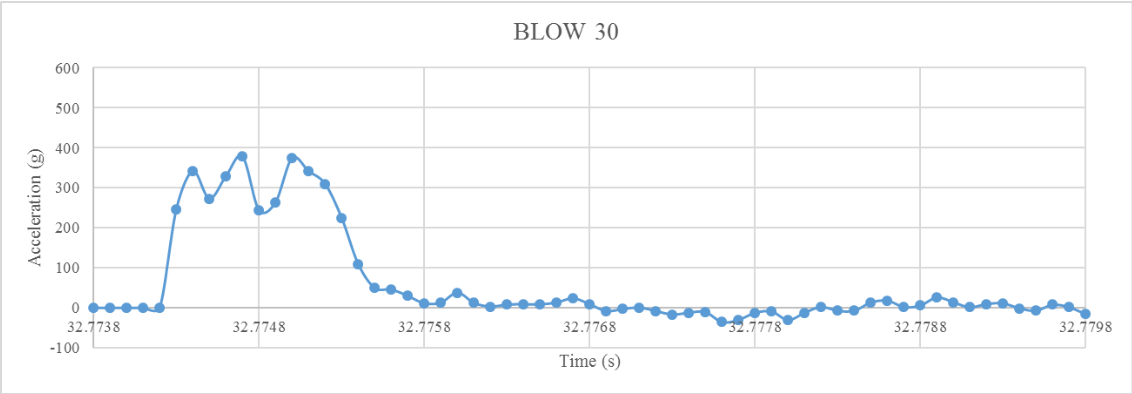

BLOW 116 (LOCKING POINT)
Acceleration (g)
700
600
500
400
300
200
100
0
-100
-200
44.0386
44.0396
44.0406
44.0416
44.0426
44.0436
44.0446
Time (s)

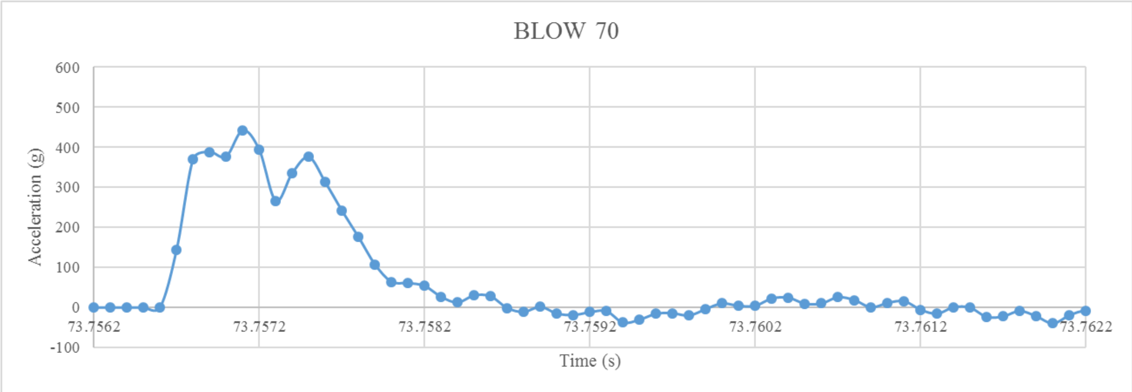

BLOW 150
Acceleration (g)
700
600
500
400
300
200
100
0
-100
76.1856
76.1866
76.1876
76.1886
76.1896
76.1906
76.1916
Time (s)

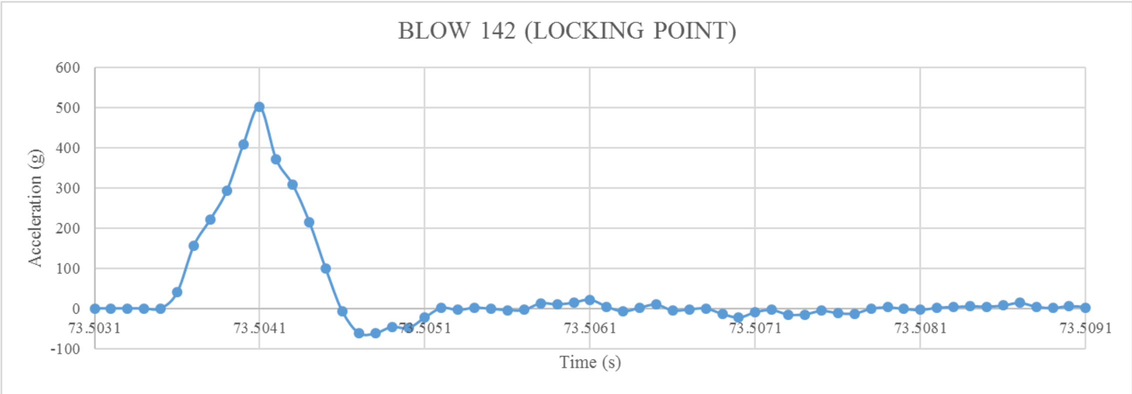
A-14 Mixture 8 Sample 1

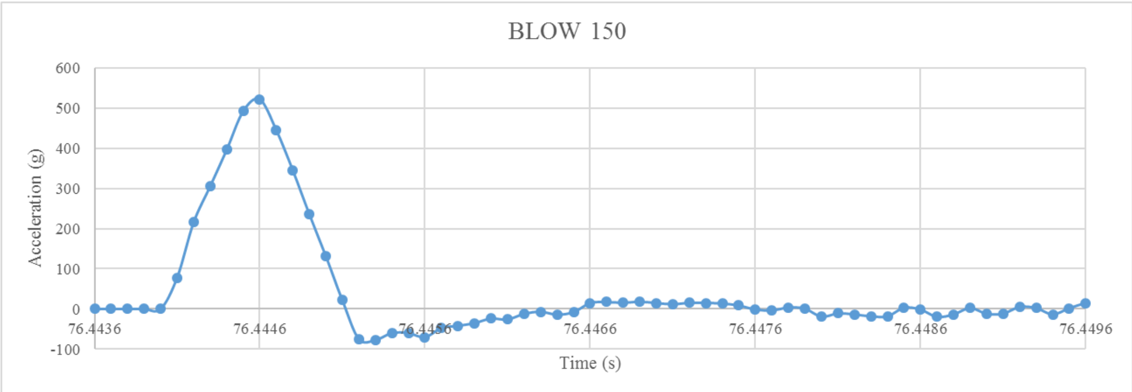




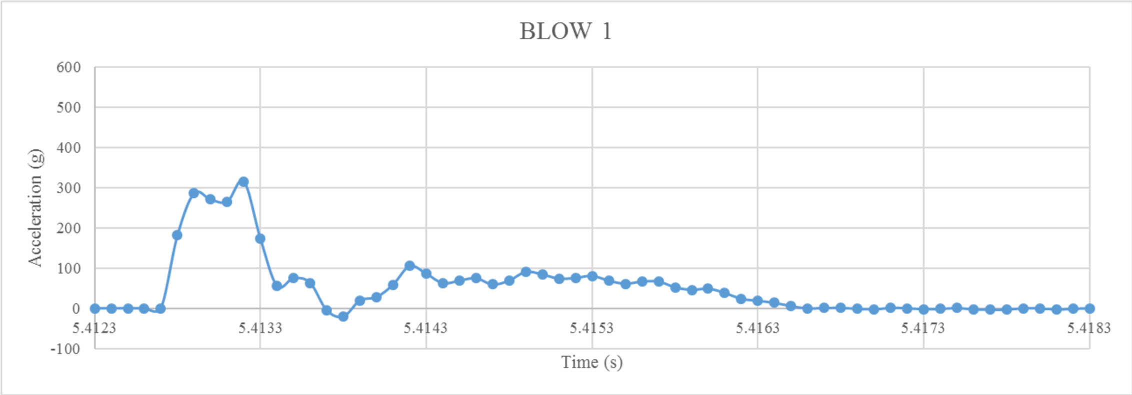


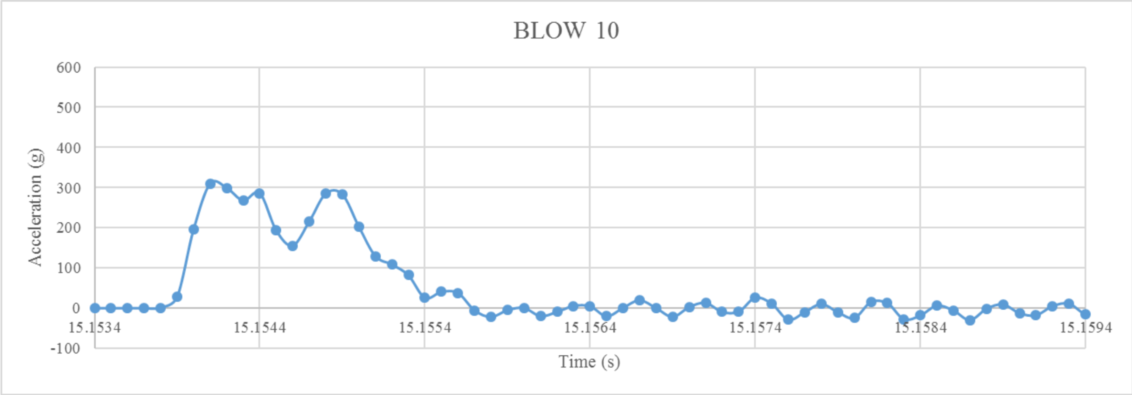

BLOW 70
600
500
400
300
200
100
0
-100
Acceleration (g)
73.7562
73.7572
73.7582
73.7592
73.7602
73.7612
73.7622
Time (s)

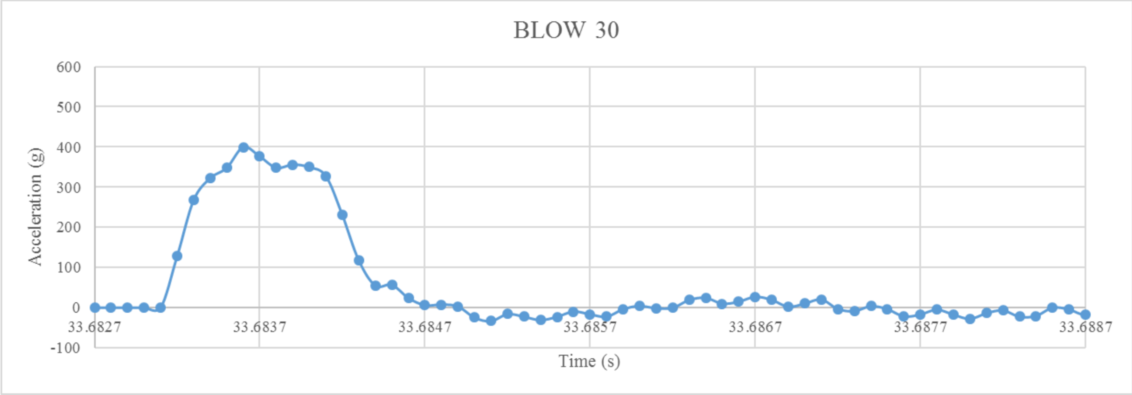

BLOW 142 (LOCKING POINT)
600
500
400
300
200
100
0
-100
Acceleration (g)
73.5031
73.5041
73.5051
73.5061
73.5071
73.5081
73.5091
Time (s)

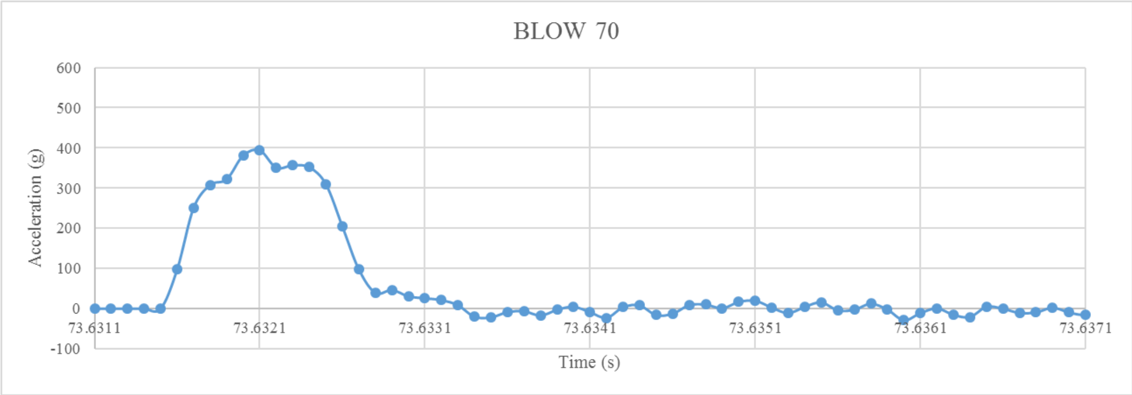

BLOW 150
600
500
400
300
200
100
0
-100
Acceleration (g)
76.4436
76.4446
76.4456
76.4466
76.4476
76.4486
76.4496
Time (s)

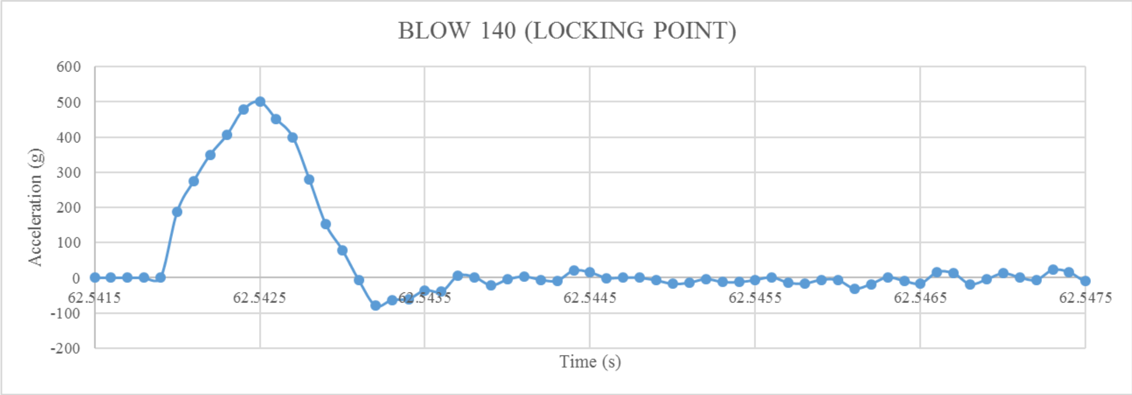
A-15 Mixture 8 Sample 2

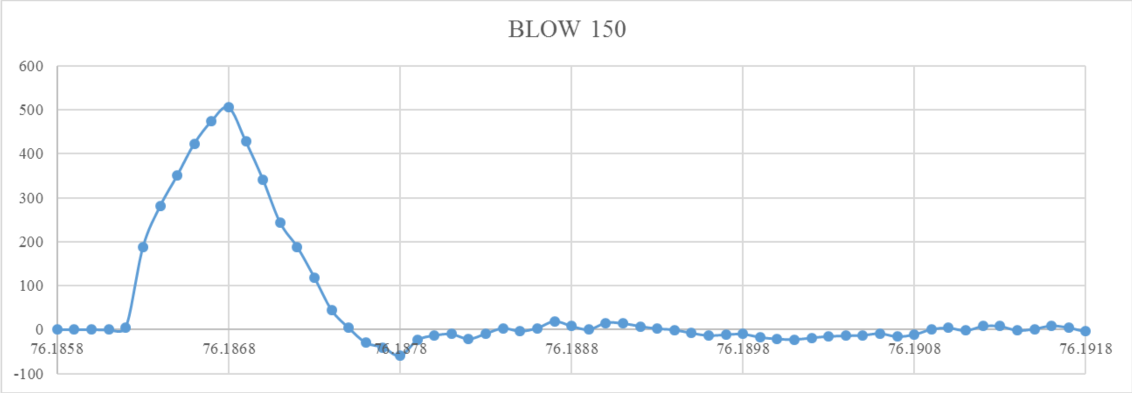







BLOW 70
Acceleration (g)
Time (s)
600
500
400
300
200
100
0
-100
73.6311
73.6321
73.6331
73.6341
73.6351
73.6361
73.6371


BLOW 140 (LOCKING POINT)
Acceleration (g)
Time (s)
600
500
400
300
200
100
0
-100
-200
62.5415
62.5425
62.5435
62.5445
62.5455
62.5465
62.5475


BLOW 150
600
500
400
300
200
100
0
-100
76.1858
76.1868
76.1878
76.1888
76.1898
76.1908
76.1918

A-16 Gradation Mixture 1

Sieve	Percents Used							% passing	LSL TDOT	USL TDOT
	D-Rock	Soft Limestone	Natural Sand	Baghouse Fines						
	50.0	24.0	25.0	1.0						
2"										
1.5"										
1.25"										
1"										
3/4"										
5/8"	100	100	100	100				**100**	0	100
1/2"	100	100	100	100				**100**	95	100
3/8"	81	100	100	100				**91**	80	93
No.4	25	91	99	100				**60**	54	76
No.8	5	58	86	100				**39**	35	57
No.30	4	25	51	100				**22**	17	29
No.50	3	18	26	100				**13**	10	18
No.100	2.0	13.5	9.6	100.0				**7.6**	3	10
No.200	1.0	10.0	3.3	100.0				**4.7**	0.0	6.5

A-17 Gradation Mixture 2

Sieve	Percents Used							% passing	LSL TDOT	USL TDOT
	Limestone #7	Slag	Hard Limestone	#10	Natural Sand	RAP				
	35.0	10.0	20.0	10.0	15.0	10.0				
2"										
1.5"										
1.25"										
1"										
3/4"										
5/8"	100	100	100	100	100	100		**100**	0	100
1/2"	98	100	100	100	100	100		**99**	95	100
3/8"	75	82	100	100	100	97		**89**	80	93
No.4	25	46	97	78	99	76		**63**	54	76
No.8	8	28	67	48	88	58		**43**	35	57
No.30	3	12	32	24	47	34		**21**	17	29
No.50	2	7	19	17	22	24		**13**	10	18
No.100	2.0	5.0	9.5	14.5	8.9	19.0		**7.8**	3	10
No.200	1.0	3.5	6.0	11.9	4.0	13.8		**5.1**	0.0	6.5

A-18 Gradation Mixture 3

Sieve	Percents Used							% passing	LSL TDOT	USL TDOT
	#57	#7	#10	RAP						
	35.0	20.0	25.0	20.0						
2"										
1.5"										
1.25"	100	100.0	100	100				**100**	100	100
1"										
3/4"	80	100.0	100	100				**93**	81	93
5/8"										
1/2"										
3/8"	27	59	100	95				**65**	57	73
No.4	5	8	91	78				**42**	40	56
No.8	3	2	58	63				**29**	28	43
No.30	2	1	23	31				**13**	13	25
No.50	1	1	15	22				**9**	9	19
No.100	0.8	0.6	12.7	16.5				**6.9**	6	10
No.200	0.6	0.4	11.4	12.8				**5.7**	2.5	6.5

A-19 Gradation Mixture 4

Sieve	Percents Used							% passing	LSL TDOT	USL TDOT
	D-Rock	#10	Natural Sand							
	50.0	25.0	25.0							
2"										
1.5"										
1.25"										
1"										
3/4"										
5/8"	100	100	100					**100**	0	100
1/2"	90	100	100					**95**	95	100
3/8"	66	100	100					**83**	80	93
No.4	22	93	98					**59**	54	76
No.8	14	60	84					**43**	35	57
No.30	11	25	51					**25**	17	29
No.50	8	17	25					**15**	10	18
No.100	5.2	13.3	8.9					**8.2**	3	10
No.200	3.1	11.1	4.0					**5.3**	0.0	6.5

A-20 Gradation Mixture 5

Sieve	Percents Used							% passing	LSL TDOT	USL TDOT
	BM-2 Rock	#7	Natural Sand	RAS	RAP					
	30.0	25.0	20.0	3.0	22.0					
2"										
1.5"										
1.25"	100	100	100	100	100			**100**	100	100
1"										
3/4"	78	100	100	100	100			**93**	81	93
5/8"										
1/2"										
3/8"	33	70	100	100	92			**71**	57	73
No.4	7	14	98	98	74			**44**	40	56
No.8	6	6	92	95	56			**37**	28	43
No.30	5	5	61	55	30			**23**	13	25
No.50	4	4	12	45	22			**11**	9	19
No.100	2.5	2.5	3.0	31.0	18.0			**6.9**	6	10
No.200	1.5	1.5	1.0	19.0	14.0			**4.7**	2.5	6.5

A-21 Gradation Mixture 6

Sieve	Percents Used							% passing	LSL TDOT	USL TDOT
	D-Rock	#10	Natural Sand							
	50.0	25.0	25.0							
2"										
1.5"										
1.25"										
1"										
3/4"										
5/8"	100	100	100					**100**	0	100
1/2"	98	100	100					**99**	95	100
3/8"	85	100	100					**93**	80	93
No.4	40	97	98					**69**	54	76
No.8	18	72	84					**48**	35	57
No.30	9	38	60					**29**	17	29
No.50	7	30	18					**16**	10	18
No.100	4.0	20.0	2.0					**7.5**	3	10
No.200	3.0	15.0	1.0					**5.5**	0.0	6.5

A-22 Gradation Mixture 7

Sieve	Percents Used							% passing	LSL TDOT	USL TDOT
	BM-2 Rock	#7	Natural Sand	#10	RAP 1/2"	RAP 5/16"				
	20.0	20.0	14.0	11.0	17.0	18.0				
2"										
1.5"										
1.25"	100	100	100	100	100	100		**100**	100	100
1"										
3/4"	85	79	100	100	100	100		**93**	81	93
5/8"										
1/2"										
3/8"	55	19	100	100	85	100		**72**	57	73
No.4	30	4	97	91	40	90		**53**	40	56
No.8	17	3	87	45	33	67		**39**	28	43
No.30	8	3	64	19	15	41		**23**	13	25
No.50	7	2	11	15	10	24		**11**	9	19
No.100	4.4	2.2	1.4	13.7	7.5	17.2		**7.4**	6	10
No.200	3.9	1.9	1.0	11.3	5.8	13.4		**6.0**	2.5	6.5

A-23 Gradation Mixture 8

Sieve	Percents Used							% passing	LSL TDOT	USL TDOT
	D-Rock	Natural Sand	#10	RAP 1/2"	RAP 5/16"					
	50.0	18.0	17.0	5.0	10.0					
2"										
1.5"										
1.25"										
1"										
3/4"										
5/8"	100	100	100	100	100			**100**	0	100
1/2"	91	100	100	97	100			**95**	95	100
3/8"	76	100	100	92	99			**87**	80	93
No.4	42	97	96	63	82			**66**	54	76
No.8	24	81	73	50	63			**48**	35	57
No.30	10	49	39	28	40			**26**	17	29
No.50	6	14	28	15	23			**13**	10	18
No.100	4.0	1.1	21.0	7.2	15.0			**7.6**	3	10
No.200	3.0	0.5	15.0	6.2	11.0			**5.6**	0.0	6.5

VITA

Pawel Andrzej Polaczyk was born in Warsaw, Poland, to the parents of Daniel and Marianna Polaczyk and he has one younger brother Lukasz. He is married to Ana Margarita Hernandez de Polaczyk. After High School graduation, he attended Warsaw University of Technology (College of Civil Engineering). In 2004 he obtained a Bachelor of Science degree in Civil Engineering with concentration in Transportation. He worked in road design and construction field in Poland and Guatemala for almost 10 years. Currently he attends Civil Engineering Graduate (Master) Program with concentration in Geotechnology and Materials Engineering at The University of Tennessee, Knoxville and works as Graduate Research Assistant under supervision of Dr. Baoshan Huang.