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MODIFIED MICRO-DEVAL PROCEDURE FOR POLISHING OF FINE ASPHALT MIX AGGREGATES

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A report of the findings of

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Modified Micro-Deval Procedure for Polishing of Fine Asphalt Mix Aggregates

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16. Abstract
A procedure combining Micro-Deval and 2nd generation Aggregate Imaging Measurement System (AIMS-II) test procedures was developed to characterize aggregate polishing characteristics, and in turn, provide a means for qualifying aggregate sources for friction purposes. This study focused on the minimum number of aggregate particles, aggregate sizes, and the number of revolutions in the Micro-Deval test. Only two aggregate sources were included in this study. Thus, further analyses are needed for wider range of aggregate sources/mineralogical properties in order to establish the minimum required aggregate shape properties for friction.

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EXECUTIVE SUMMARY

The main objectives of this project were to: 1) Develop a modified Micro-Deval procedure that is based on an aggregate size range of 3/8 in. (9.5mm) to #8 (2.36mm), which can achieve terminal polishing; and 2) Identify the minimum number of aggregate particles needed for testing with the Micro-Deval and characterization of its shape properties using the 2nd generation Aggregate Imaging Measurement System (AIMS-II).

The procedure developed in this study requires two separate samples for each aggregate source. The first sample is for aggregate particles passing the 3/8 in. sieve and retained on the #4 sieve, while the second sample is of aggregate particles passing the #4 sieve and retained on the #8 sieve. Each sample is then scanned in AIMS-II to obtain initial aggregate shape properties, polished in Micro-Deval for 13,500 revolutions, and then scanned again in AIMS-II to obtain terminal polishing aggregate shape properties. Polishing of the aggregate requires soaking the aggregate for 60 minutes in 0.75 L of water, followed by tumbling in the Micro-Deval with 1250 grams of steel balls.

In addition to the modified procedure, an asymptotic analysis of the data collected during this study was conducted to determine the target number of particles for AIMS-II imaging. The analysis revealed that a target of 250 particles should be used to obtain shape properties for the aggregate sizes selected in this study.

The main recommendation of this report is to implement the modified procedure developed in this study, and test aggregate sources covering the state of Illinois and neighboring states. Such sources should also cover a wide variety of aggregate mineralogical properties such as: limestone, dolomite, gravel, etc.

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CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

Recently completed research studies, sponsored by the Illinois Department of Transportation (IDOT) through the Illinois Center for Transportation (ICT), focused on the implementation of the 2nd generation Aggregate Imaging Measurement System (AIMS-II, see Figure 1.1) in measuring aggregate shape properties (Mahmoud and Ortiz, 2014 & Mahmoud and Perales, 2015). An aggregate polishing procedure, coupling AIMS-II for measuring aggregate shape properties and the Micro-Deval (MD) as a polishing procedure, was developed by Mahmoud and Ortiz (2014). The polishing trends and ranking from that study compared favorably with IDOT's historical friction data. Additionally, a database was generated for all aggregates tested in that study; the database included aggregate shape properties (texture and angularity) measured before and after polishing in the MD. In a follow up study (Mahmoud and Perales, 2015), further analyses were conducted and Variable Speed Test (VST) friction values were included to provide a direct comparison to polishing in the MD. Finally, a system for qualifying aggregates for friction purposes was introduced based on aggregate angularity and surface texture (Figure 1.2).

Figure 1.1. Second generation Aggregate Imaging Measurement System (AIMS-II).

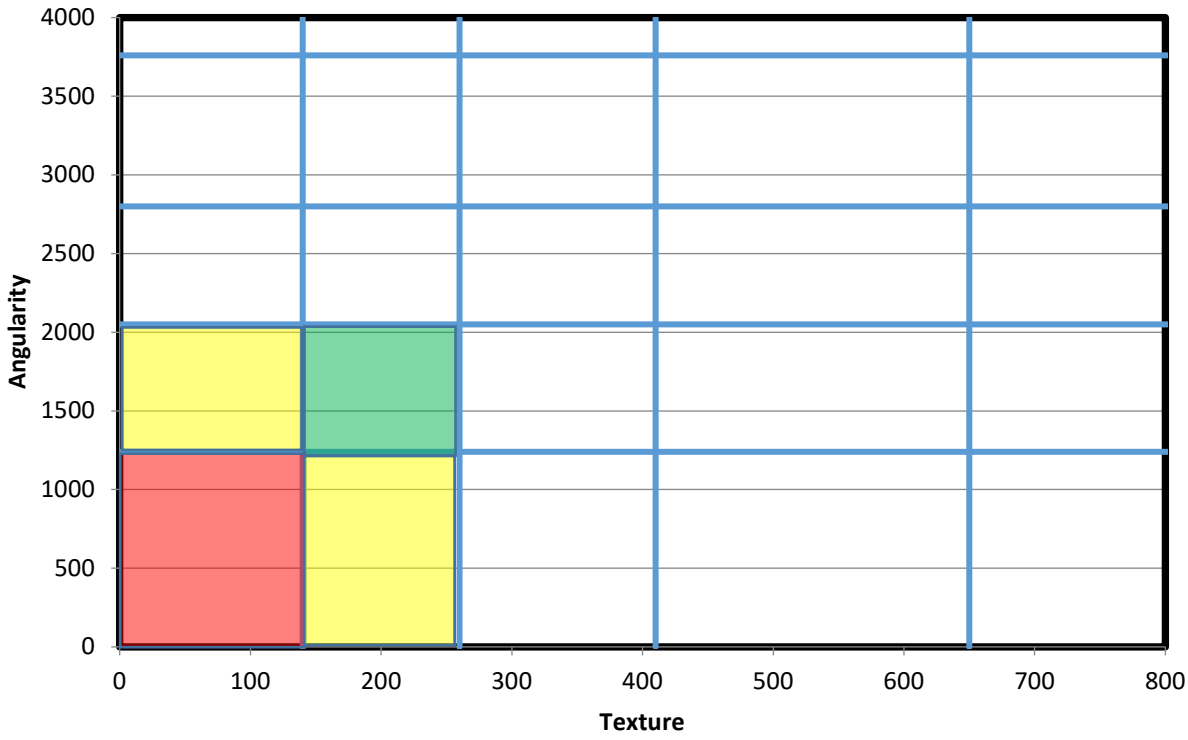

Figure 1.2. R27-SP27 Texture vs. Angularity with Proposed Acceptable Zones.

The previous two projects focused on one aggregate size fraction (passing the 1/2 in. sieve and retained on the 3/8 in. sieve). However, with IDOT moving toward finer surface mixes, it is important to understand the terminal polishing for finer surface mix aggregates (3/8 in to #8).

1.2 OBJECTIVES

The main objectives of this project were to:

1. Develop a modified Micro-Deval procedure that is based on the aggregate size range of 3/8 in. to #8 that can achieve terminal polishing.

2. Identify the minimum number of particles that need to be scanned in AIMS-II to effectively capture aggregate shape properties.

1.3 RESEARCH APPROACH

1.3.1 Tasks

The objectives of this research study were accomplished by performing the following tasks:

1.3.1.1 Task 1 – Kickoff Meeting

A kickoff meeting was held, the Principal Investigator (PI) discussed the research approach and the details of the tasks in this project. In this meeting, the PI and the Technical Review Panel (TRP) decided on details regarding aggregate sources, the number of samples, and the aggregate sizes for the rest of the tasks.

1.3.1.2 Task 2 – Modified Micro-Deval Procedure

The PI worked with IDOT personnel to develop a modified Micro-Deval procedure to include aggregate sizes passing the 3/8 in. sieve and retained on the #8 sieve.

1.3.1.3 Task 3 – Minimum Number of Aggregate Particles

The PI analyzed aggregate shape properties obtained from AIMS-II scanning results for both polished and raw aggregates to obtain the minimum number of aggregate particles for the size fractions considered in this study. The analysis focused on the asymptotic approach.

1.3.1.4 Task 4 – Preliminary Analysis and Recommendation Presentation to TRP

The PI met with the TRP and discussed the results of Tasks 2 and 3. Based on the preliminary analysis and discussions with the TRP, the PI will provide recommendations for future use of AIMS-II data, and a modified aggregate polishing procedure in this final report.

1.3.1.5 Task 5 – Prepare and Revise the Final Report

The final report explains the study methodology, findings, and conclusions.

1.3.2 Materials and Testing Methods

Two aggregate sources were selected for this study Midway (source 1) and Pana (source 2). For each source, two sizes were investigated. The first size contained aggregate particles passing the 3/8 in. sieve and retained on the #4 sieve. The second size contained aggregate particles passing the #4 sieve and retained on the #8 sieve. For the sake of simplicity, the first size will be referred to as #4 size, and the second size will be referred to as #8 size for the remainder of this report.

AIMS-II was used to measure aggregate shape properties, and Micro-Deval was used as the polishing mechanism. The aggregate shape properties considered for this study included texture, angularity, and Coarse Aggregate Angularity and Texture (CAAT) Index. Details of AIMS-II shape properties and the equipment operations can be found in previous studies (Mahmoud and Ortiz 2014; Mahmoud and Perales 2015)

The following procedure was used to obtain the required aggregate polishing characteristics:

1. Aggregate Samples Preparation: as mentioned earlier in this section, two sizes were investigated for each aggregate source. Several samples were prepared for each of the two

sizes from the various sources. Multiple samples were prepared to allow for polishing at different intervals in the Micro-Deval as explained in Step-3 of this procedure.

2. Initial Scan: every sample was scanned in AIMS-II prior to polishing to obtain initial aggregate shape properties.

3. Polishing: aggregate samples were then polished in Micro-Deval at increasing numbers of revolutions (3,000, 4,500, 6,000, … etc.). The samples were soaked in 0.75 +/- 0.05 L of water for 60 minutes and placed in the Micro-Deval with 1250 +/- 5 grams of steel balls to induce polishing.

4. Post Polishing Scan: following the the Micro-Deval process, every polished sample was then scanned in AIMS-II to obtain final aggregate shape properties.

CHAPTER 2: RESULTS AND ANALYSES

2.1 MODIFIED MICRO-DEVAL PROCEDURE

The polishing procedure detailed in Chapter 1 was carried out for the aggregate sources and sizes selected for this study. The main objective of this task was to determine the minimum number of revolutions needed in the modified Micro-Deval procedure to achieve terminal polish. An exponential polishing curve (Equation 1) was fitted to the data:

$$AggProp(Rev) = a + be^{-c*Rev} \qquad (1)$$

where:

AggProp: aggregate shape property such as Angularity, Texture, or CAAT;

Rev: Micro-Deval Revolutions in thousands;

a: regression coefficient representing terminal value;

b: regression coefficient (a+b: representing initial value); and

c: regression coefficient representing polishing rate.

Several research studies utilized this equation to describe aggregate polishing curves (Mahmoud and Ortiz, 2014; Mahmoud and Perales, 2015; Kassem et. Al, 2014; & Masad e.al, 2007). Figure 2.1 illustrates the change in angularity as a function of the number of revolutions in the Micro-Deval for Source 1 – Size #4. The "x" markers on each plot represent the AIMS-II test results. The solid line represents the exponential polishing curve fitted to the data points. The data shows a clear drop in angularity after the first 3,000 cycles. After 3,000 cycles, the angularity value appears to remain approximately constant as the number of the revolutions increase. This trend was noticed for Source 1 – Size #4 texture and CAAT values, as can be seen in Figures 2.2 and 2.3, respectively. The same evaluation was completed on a second aggregate size from the same source. Figures 2.4 through 2.6 illustrate the changes in angularity, texture, and CAAT, respectively, as a function of the number of revolutions in the Micro-Deval for Source 1 – Size #8. The trends were very similar to the Size #4 of the same aggregate source.

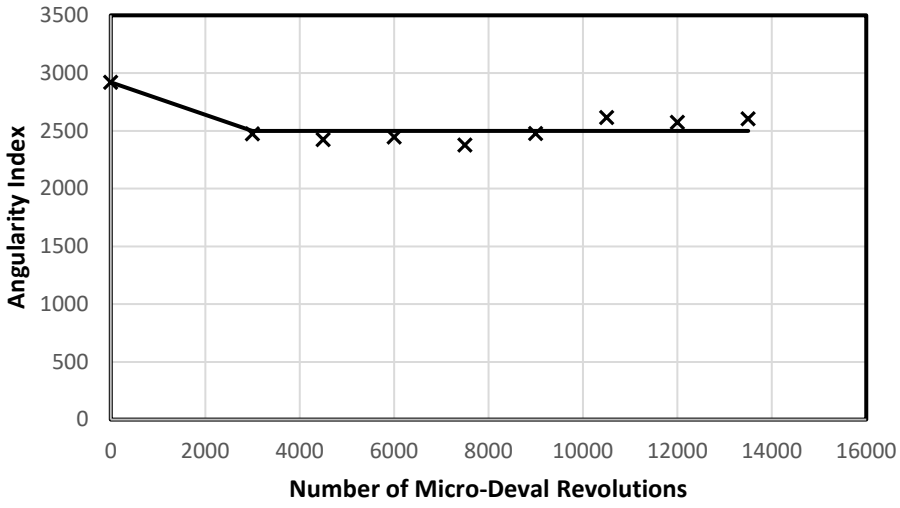

Figure 2.1. Angularity Index as a Function of Micro-Deval Revolutions (Source 1 - Size #4).

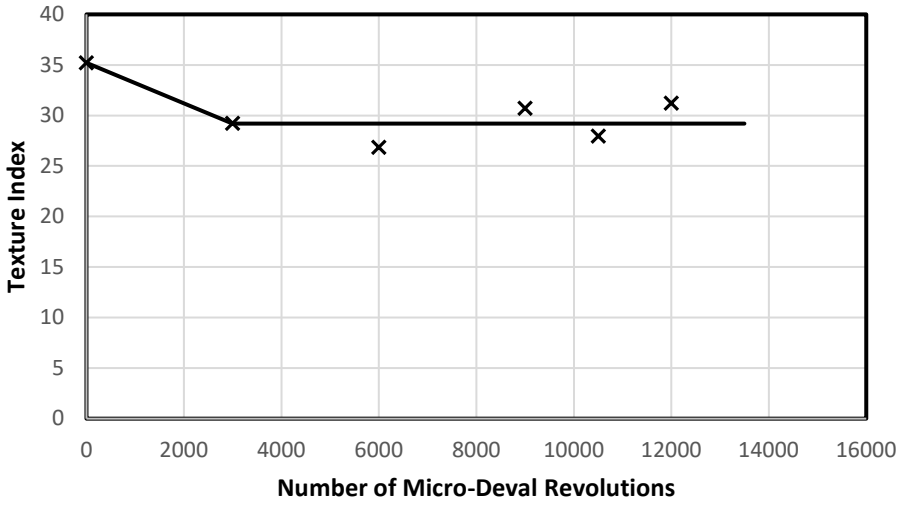

Figure 2.2. Texture Index as a Function of Micro-Deval Revolutions (Source 1 - Size #4).

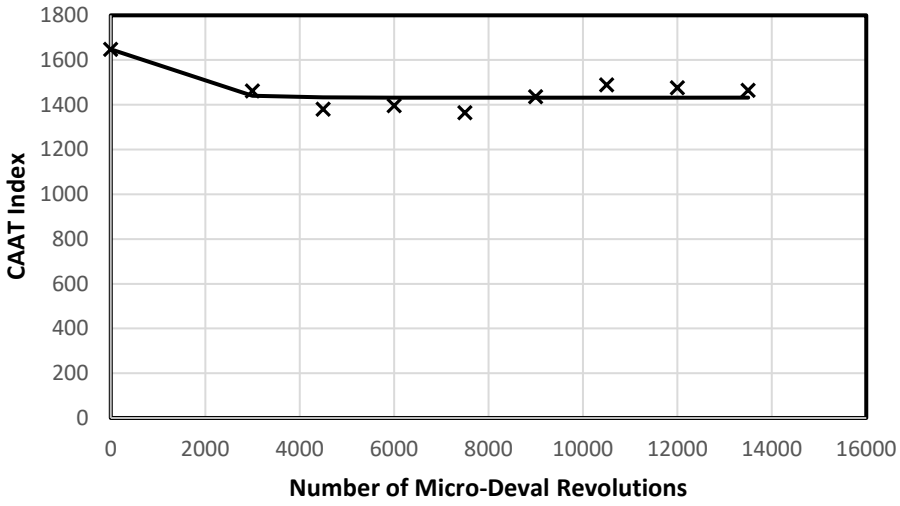

Figure 2.3. CAAT Index as a Function of Micro-Deval Revolutions (Source 1 - Size #4).

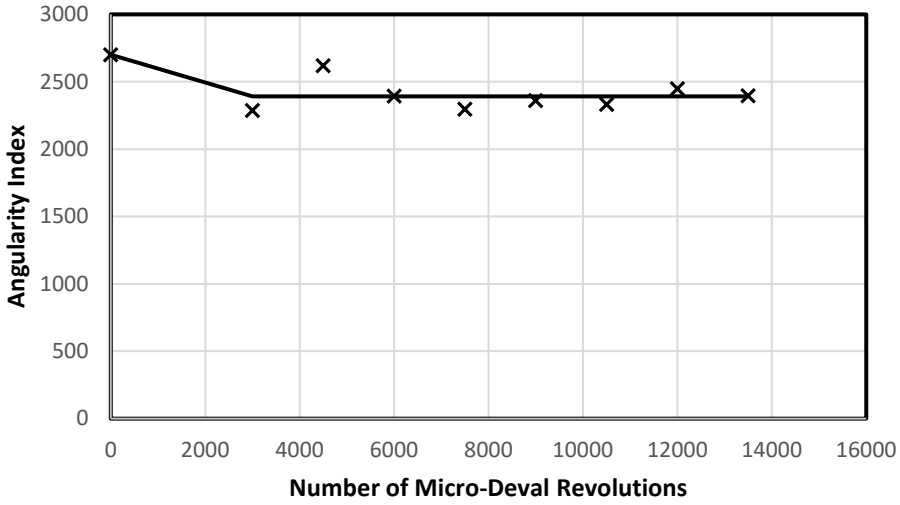

Figure 2.4. Angularity Index as a Function of Micro-Deval Revolutions (Source 1 - Size #8).

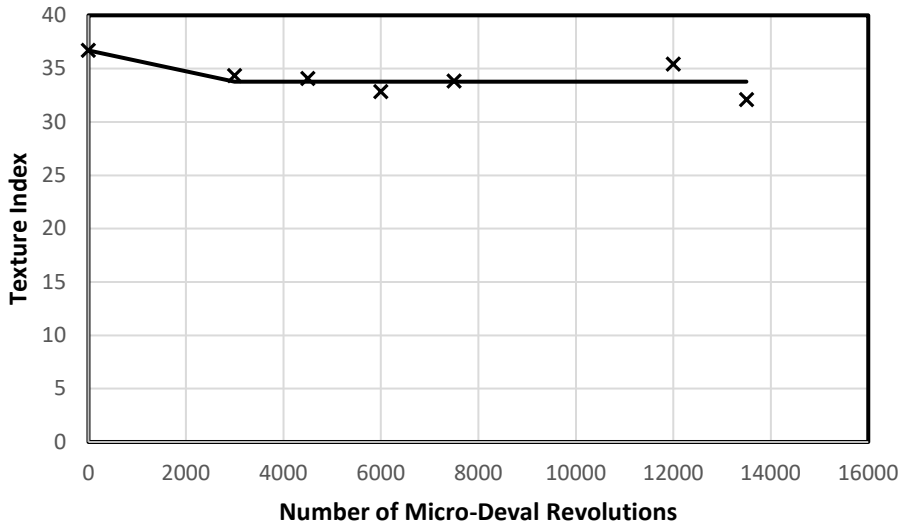

Figure 2.5. Texture Index as a Function of Micro-Deval Revolutions (Source 1 - Size #8).

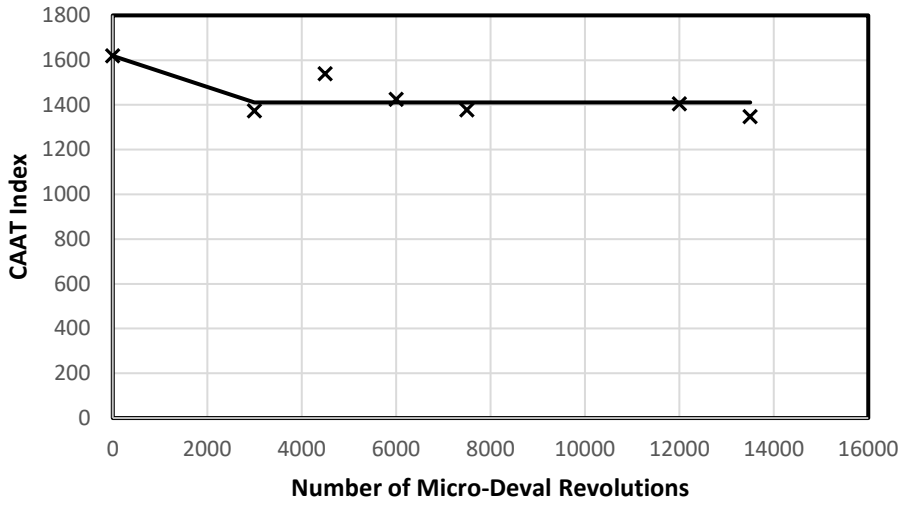

Figure 2.6. CAAT Index as a Function of Micro-Deval Revolutions (Source 1 - Size #8).

The polishing curves for Source 1 showed an immediate drop in measured aggregate properties and reached terminal polishing with less than 5,000 revolutions in the Micro-Deval. However, Source 2 exhibited more sensitivity to polishing in the Micro-Deval. This can be clearly seen in Figures 2.7 through 2.12. Figure 2.7 illustrates the change in angularity as a function of the number of revolutions in the Micro-Deval for Source 2 – Size #4. The data shows a continuous drop in angularity with an increasing number of revolutions. However, the angularity reduction rate decreased around 8,000 revolutions and seemed to reach a plateau afterward. A similar trend was noticed for Source 2 – Size #4 texture and CAAT values, as can be seen in Figures 2.8 and 2.9, respectively. On the other hand, Figures 2.10 through 2.12 illustrate the change in angularity, texture, and CAAT as a function of the

number of revolutions in the Micro-Deval for Source 2 – Size #8. The trends were very similar to Size #4 of the same aggregate source.

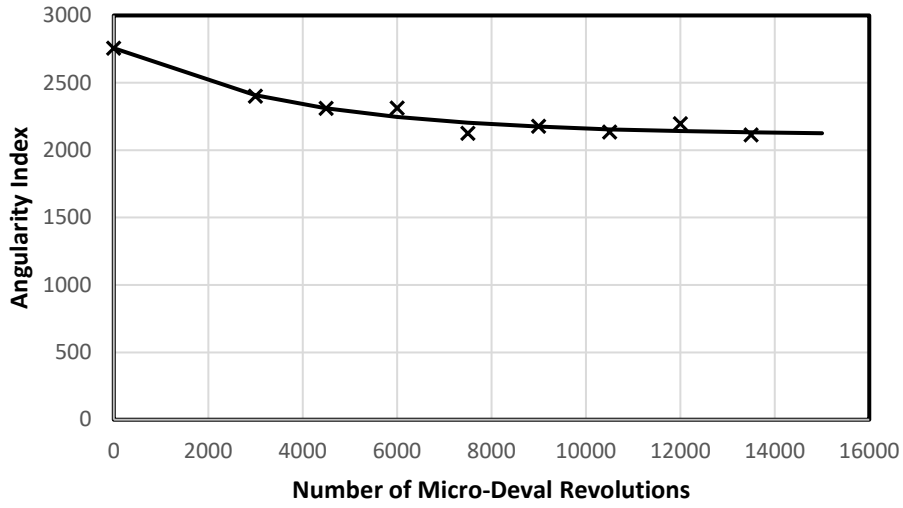

Figure 2.7. Angularity Index as a Function of Micro-Deval Revolutions (Source 2 - Size #4).

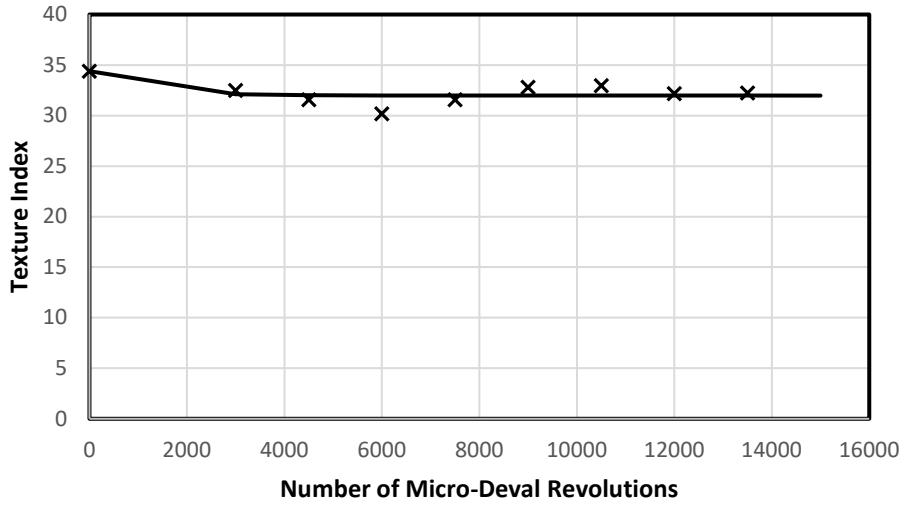

Figure 2.8. Texture Index as a Function of Micro-Deval Revolutions (Source 2 - Size #4).

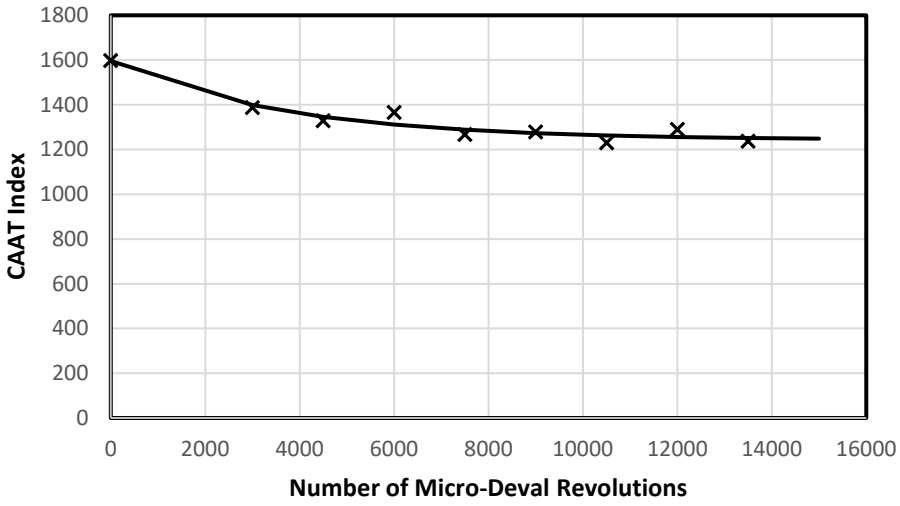

Figure 2.9. CAAT Index as a Function of Micro-Deval Revolutions (Source 2 - Size #4).

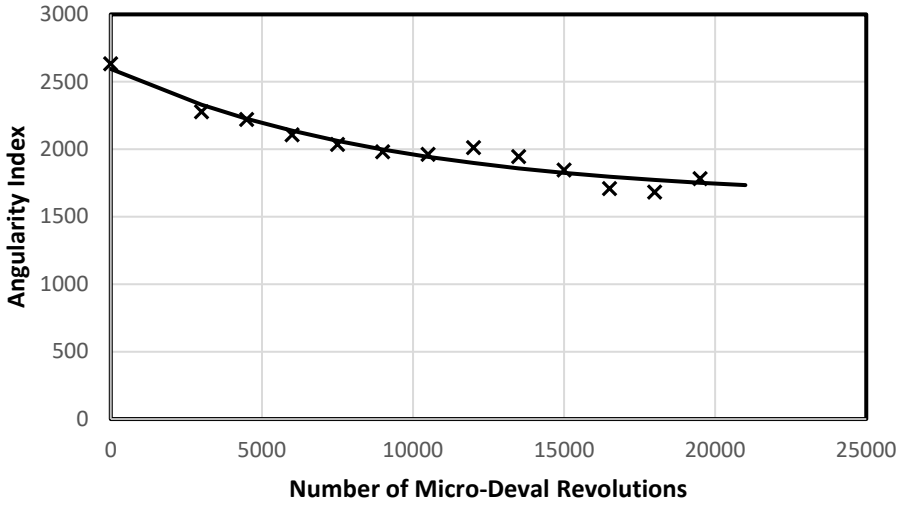

Figure 2.10. Angularity Index as a Function of Micro-Deval Revolutions (Source 2 - Size #8).

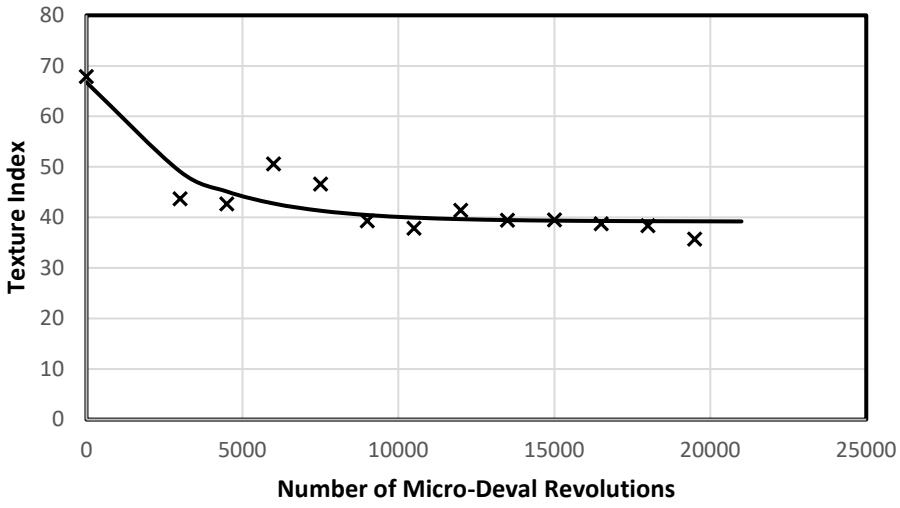

Figure 2.11. Texture Index as a Function of Micro-Deval Revolutions (Source 2 - Size #8).

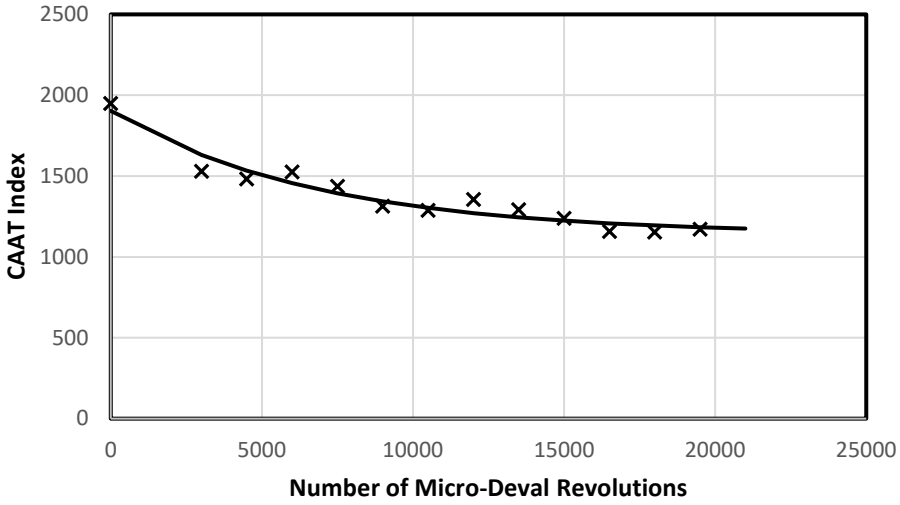

Figure 2.12. CAAT Index as a Function of Micro-Deval Revolutions (Source 2 - Size #8).

The least squares method was used to obtain parameters a, b, and c of Equation 1 that best fit the data points as shown in Figures 2.1 thorough 2.12. The fitting parameters are summarized in Table 2.1.

Table 2.1. Polishing Function Fitting Results

		a	b	c	R^2
Source 1 - #4	**Angularity**	2499.25	420.77	3.58	0.74
	Texture	29.19	6.01	4.69	0.69
	CAAT	1432.09	215.94	1.07	0.73
Source 1 - #8	**Angularity**	2391.60	309.10	5.83	0.52
	Texture	33.78	2.93	4.69	0.52
	CAAT	1410.87	208.01	4.86	0.61
Source 2 - #4	**Angularity**	2113.10	643.85	0.26	0.96
	Texture	31.98	2.41	0.95	0.48
	CAAT	1242.79	352.89	0.27	0.94
Source 2 - #8	**Angularity**	1634.14	961.32	0.11	0.94
	Texture	39.21	27.53	0.34	0.83
	CAAT	1140.69	762.43	0.15	0.93

Based on the visual inspection of Figures 2.1 through 2.12, the research team decided to investigate the efficacy of the current procedure to reach terminal polishing at 13,500 revolutions. A t-test statistical analysis was conducted to compare aggregate shape properties between consecutive Micro-Deval polishing revolution intervals. A 95% Confidence Interval (CI) was calculated for the difference in the shape property mean between consecutive Micro-Deval revolutions intervals. The CIs are obtained using the following equation:

$$Z_0 = \overline{X_1} - \overline{X_1} - Z_{\frac{\alpha}{2}}\sqrt{\frac{\sigma_1^2}{n_1} + \frac{\sigma_2^2}{n_2}} \leq \mu_1 - \mu_2 \leq Z_0 = \overline{X_1} - \overline{X_1} + Z_{\frac{\alpha}{2}}\sqrt{\frac{\sigma_1^2}{n_1} + \frac{\sigma_2^2}{n_2}} \quad (2)$$

where $Z_{\alpha/2}$ is the upper $\alpha/2$ percentage point of the standard normal distribution ($\alpha = 0.05$ for this study). Table 2.2 lists the CIs for the angularity results, while Tables 2.3 and 2.4 list the CIs for the texture and CAAT results, respectively. A CI containing zero shows that the averages are not different, which indicates that terminal polishing is achieved at that number of revolutions. Assessing terminal polishing at 13,500 revolutions, eleven out of twelve CIs contained zero, which reinforced the visual observation from Figures 2.1 through 2.12.

Table 2.2. Statistical Inference on the Angularity Means

Sample	Micro-Deval Revolutions	CI Lower Limit	CI Upper Limit
Source 1 - #4	**3000**	-529.926	-282.786
	4500	-175.43	79.24999
	6000	-101.715	146.638
	7500	-189.198	48.41544
	9000	-22.1291	222.337
	10500	13.49738	262.5005
	12000	-167.16	86.30898
	13500	-96.4208	154.9718
Source 1 - #8	**3000**	-517.802	-288.237
	4500	219.8787	443.6271
	6000	-341.395	-109.106
	7500	-208.343	14.91009
	9000	-43.8523	172.7402
	10500	-140.121	81.29314
	12000	2.30266	229.7573
	13500	-170.083	67.3848
Source 2 - #4	**3000**	-446.07	-217.584
	4500	-208.058	25.77346
	6000	-116.186	121.0331
	7500	-303.438	-72.8657
	9000	-57.0216	162.2084
	10500	-156.516	71.84258
	12000	-56.8389	178.4584
	13500	-199.91	37.37861
Source 2 - #8	**3000**	-471.18	-241.657
	4500	-168.138	57.03934
	6000	-232.761	3.175882
	7500	-184.461	42.62262
	9000	-167.538	59.61746
	10500	-132.386	94.55281
	12000	-58.082	157.0507
	13500	-175.858	45.34275

Table 2.3. Statistical Inference on the Texture Means

Sample	Micro-Deval Revolutions	CI Lower Limit	CI Upper Limit
Source 1 - #4	**3000**	-10.5216	4.29894
	4500	-4.27404	24.00624
	6000	-25.822	1.317737
	7500	-1.59596	28.77702
	9000	-25.0165	5.555059
	10500	-6.34022	0.86073
	12000	-4.03582	10.56826
	13500	-4.50531	10.41235
Source 1 - #8	**3000**	-3.45082	2.835481
	4500	-4.29025	3.782736
	6000	-5.04963	2.576308
	7500	-3.59058	5.564673
	9000	30.60549	40.83231
	10500	-7.34069	1.676267
	12000	-38.3814	-24.2263
	13500	-13.6129	6.972728
Source 2 - #4	**3000**	-6.60356	2.206815
	4500	-5.04169	3.174708
	6000	-5.19051	2.418576
	7500	-1.28024	4.041655
	9000	-1.92551	4.446998
	10500	-4.06429	4.362816
	12000	-5.00241	3.444038
	13500	-3.46303	3.562993
Source 2 - #8	**3000**	-1.39814	4.852607
	4500	-4.30684	2.378847
	6000	4.497096	11.23837
	7500	-7.20714	-0.71454
	9000	-10.5067	-4.05923
	10500	-4.80701	1.92761
	12000	0.286307	6.739651
	13500	-4.75181	0.878517

Table 2.4. Statistical Inference on the CAAT Means

Sample	Micro-Deval Revolutions	CI Lower Limit	CI Upper Limit
Source 1 - #4	**3000**	-259.914	-38.0107
	4500	-201.33	39.75259
	6000	-84.56	114.8455
	7500	-135.416	74.48222
	9000	-39.7728	180.5947
	10500	-48.7385	154.4027
	12000	-101.506	75.92153
	13500	-99.2102	78.23386
Source 1 - #8	**3000**	-308.06	-181.766
	4500	103.8944	228.1525
	6000	-178.77	-51.1048
	7500	-107.628	13.47542
	9000	429.4145	559.8822
	10500	-117.506	27.56874
	12000	-500.939	-344.125
	13500	-150.178	36.45039
Source 2 - #4	**3000**	-256.378	-126.521
	4500	-122.068	6.295251
	6000	-33.7201	105.749
	7500	-169.353	-26.7565
	9000	-58.082	80.14285
	10500	-119.803	24.38754
	12000	-12.9598	132.1025
	13500	-123.255	18.57486
Source 2 - #8	**3000**	-227.719	-95.4568
	4500	-115.16	17.12503
	6000	-23.4244	110.5468
	7500	-153.247	-22.1147
	9000	-189.343	-58.4758
	10500	-89.0377	39.47819
	12000	6.377879	129.165
	13500	-125.979	-3.21782

2.2 MINIMUM NUMBER OF PARTICLES

To investigate the minimum number of aggregate particles required for scanning with AIMS, an asymptotic analysis was conducted. In this analysis, the changes in shape properties were tracked as functions of the number of particles scanned. Figures 2.13 through 2.20 illustrate examples for angularity and texture analyses (similar plots for all aggregates scanned in this study are listed in Appendix A). It is evident that the average of both angularity and texture reach an approximately

constant value at around 200 particles for the sources considered in this study. Based on this, it is recommended that 250 particles should be scanned with AIMS-II.

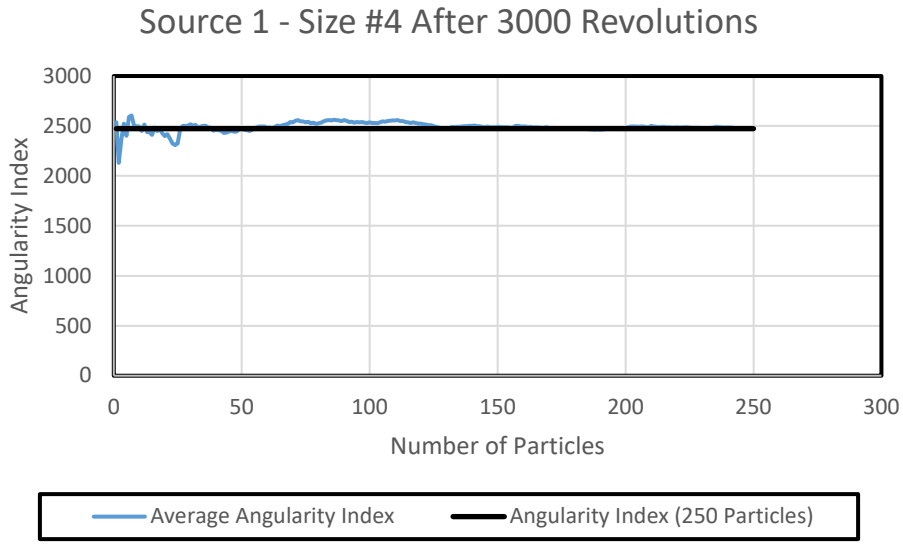

Figure 2.13. Asymptotic Analysis: Source 1 – Size #4 Angularity after 3,000 Micro-Deval Revolutions.

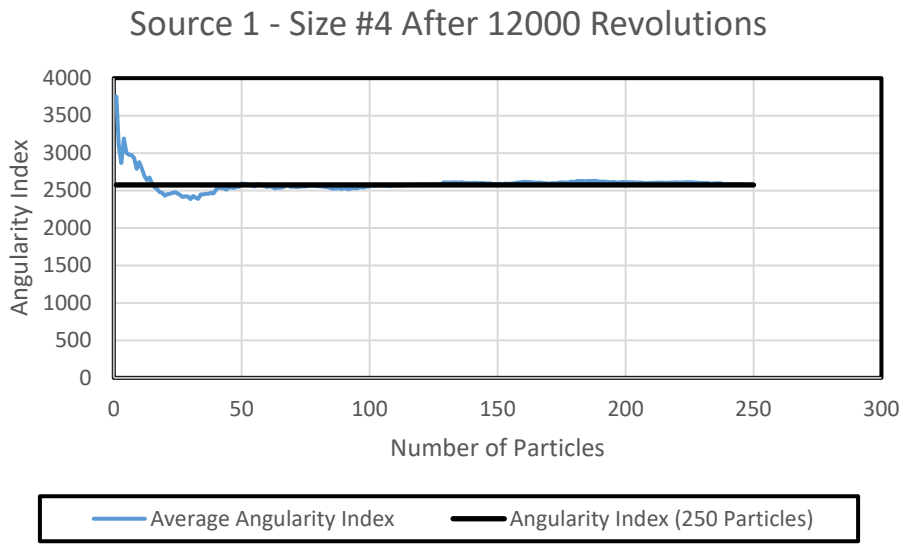

Figure 2.14 Asymptotic Analysis: Source 1 – Size #4 Angularity after 12,000 Micro-Deval Revolutions

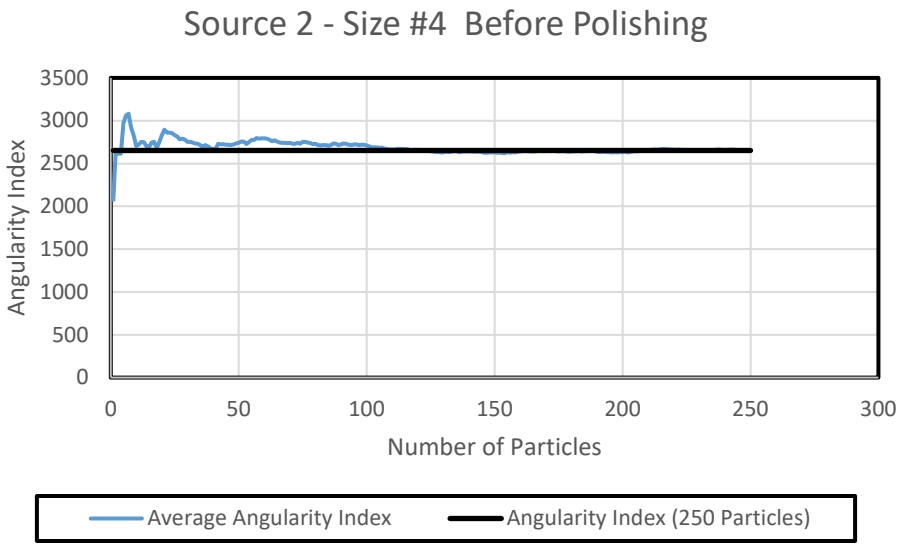

Figure 2.15. Asymptotic Analysis: Source 2 – Size #4 Angularity Before Polishing in Micro-Deval.

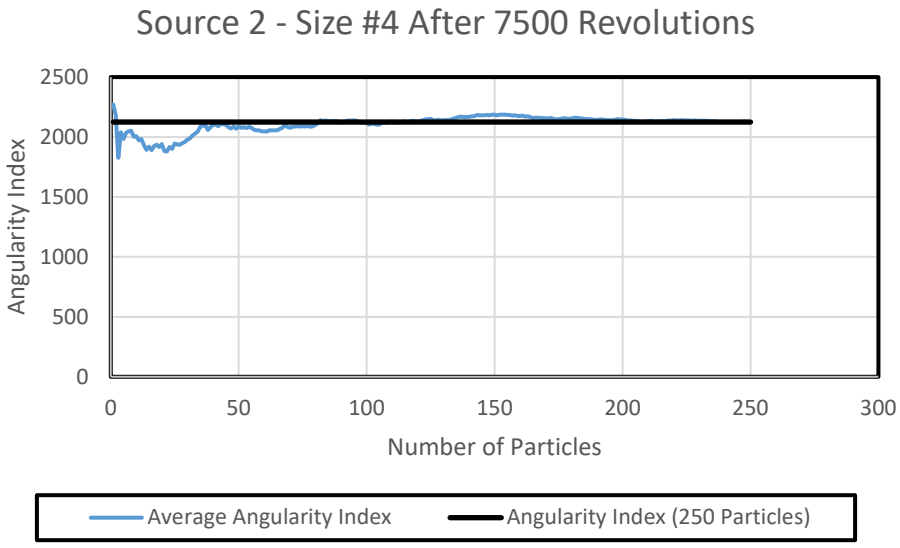

Figure 2.16. Asymptotic Analysis: Source 2 – Size #4 Angularity after 7,500 Micro-Deval Revolutions.

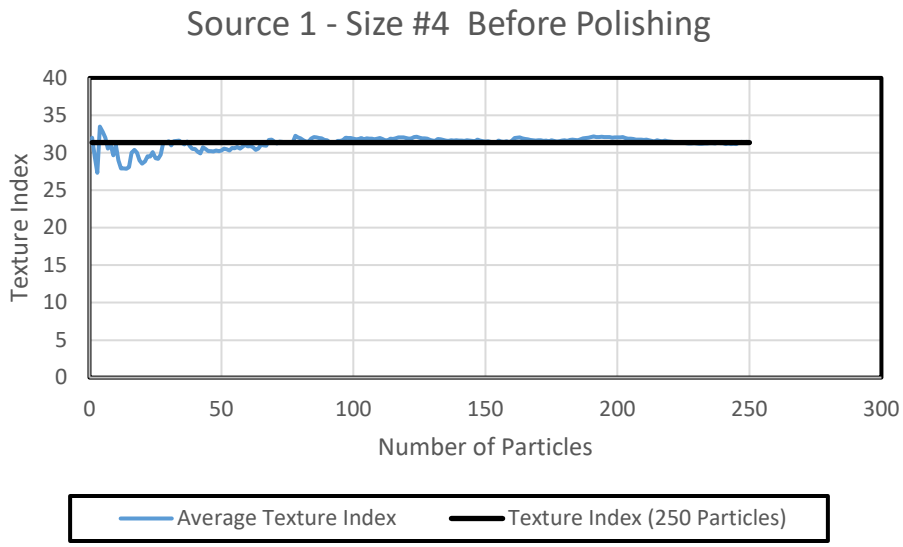

Figure 2.17. Asymptotic Analysis: Source 1 – Size #4 Texture Before Polishing in Micro-Deval.

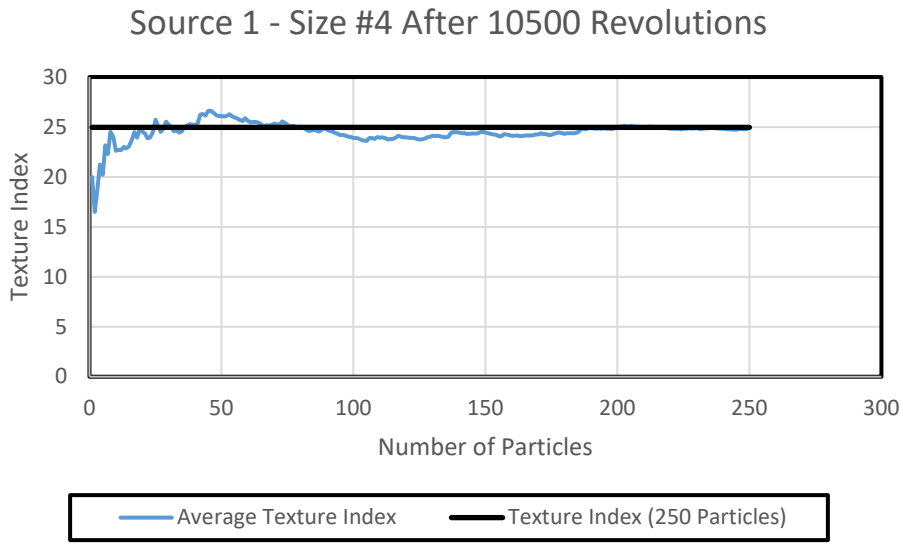

Figure 2.18. Asymptotic Analysis: Source 1 – Size #4 Texture after 10,500 Micro-Deval Revolutions.

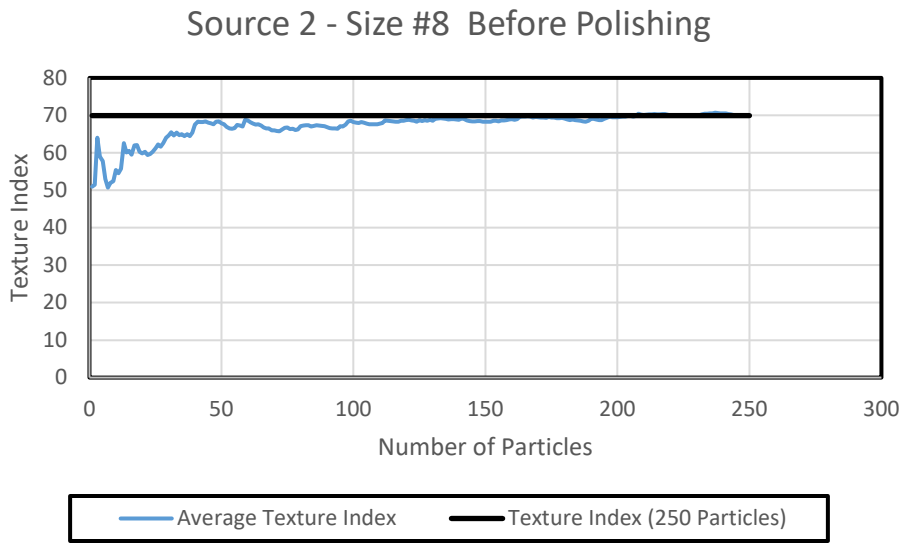

Figure 2.19. Asymptotic Analysis: Source 2 – Size #8 Texture Before Polishing in Micro-Deval.

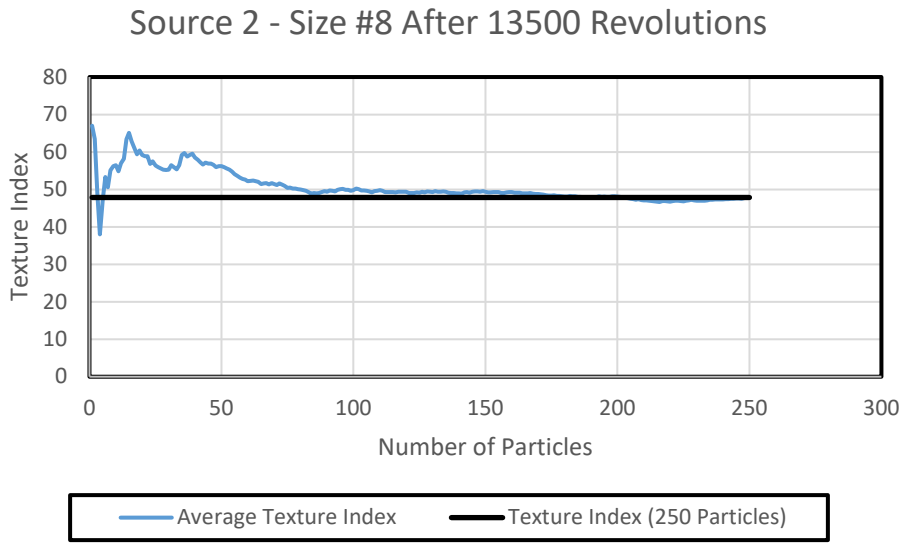

Figure 2.20. Asymptotic Analysis: Source 2 – Size #8 Texture after 13,500 Micro-Deval Revolutions.

CHAPTER 3: SUMMARY AND IMPLEMENTATION RECOMMENDATIONS

3.1 SUMMARY

A modified Micro-Deval procedure for the assessment of aggregate polishing was developed. Specifically, the procedure focused on aggregate sizes passing the 3/8 in. sieve and retained on #8 sieve. This procedure can be summarized in the following steps:

1. Sample 1:
    a. Obtain 250 grams of aggregate particles passing a 3/8 in. sieve and retained on a #4 sieve.
    b. Scan the aggregate sample prior to polishing in the Micro-Deval, to obtain initial Angularity, Texture, and CAAT values.
    c. Place the sample into a Micro-Deval container.
    d. Add 0.75 +/- 0.05 L of water to the sample in the container and soak for 60 minutes.
    e. Add 1,250 +/- 5 grams of stainless steel ballsto the aggregate sample and water mix.
    f. Place the container into a Micro-Deval apparatus and apply 13,500 revolutions.
    g. Wash and sieve the sample over a #4 sieve.
    h. Scan the polished aggregate sample to obtain terminal Angularity, Texture, and CAAT values.
    i. [Optional] repeat steps A through G for a second sample and modify the number of revolutions to 5,000 in part f.
2. Sample 2:
    a. Obtain 250 grams of aggregate particles passing a #4 sieve and retained on a #8 sieve.
    b. Scan the aggregate sample prior to polishing in the Micro-Deval, to obtain initial Angularity, Texture, and CAAT values.
    c. Place the sample into a Micro-Deval container.
    d. Add 0.75 +/- 0.05 L of water to the sample in the container and soak for 60 minutes.
    e. Add 1,250 +/- 5 grams of stainless steel balls to the aggregate sample and water mix.

f. Place the container into a Micro-Deval apparatus and apply 13,500 revolutions.

g. Wash and sieve the sample over a #8 sieve.

h. Scan the polished aggregate sample to obtain terminal Angularity, Texture, and CAAT values.

i. [Optional] repeat steps A through G for a second sample and modify the number of revolutions to 5000 in part f.

In addition to the modified procedure, an asymptotic analysis revealed that a target of 250 particles should be used to obtain shape properties in AIMS-II for the aggregate sizes selected in this study.

3.2 IMPLEMENTATION RECOMMENDATION

It is important to establish the correct aggregate shape properties requirement for asphalt pavement surface friction. In order to do so, a full factorial study should be initiated to focus on the following:

1. Cover as many sources from around the state and from neighboring states as possible. Sources should cover a wide variety of aggregate mineralogical properties such as: limestone, dolomite, gravel, etc.

2. Similar to this study, two sizes should be considered: passing the 3/8 in. sieve and retained on the #4; and passing the #4 sieve and retained on the #8.

3. Each aggregate sample should be scanned in AIMS-II prior to polishing, and after 13,500 Micro-Deval polishing revolutions.

4. It's also recommended to obtain aggregate shape properties in AIMS-II after 5,000 Micro-Deval polishing revolutions. This intermediate polishing point will help in understanding the polishing rate and aggregate source, rather than just initial and terminal values.

5. Use a cluster analysis and other statistical methods to establish limits for acceptable aggregate shape properties to provide required friction in asphalt surface mixes. A comparison to historical friction data and previous ICT projects will be critical to accomplishing this task.

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Kassem, E., Awed, A., Masad, E., and D. Little. 2014. "Development of Predictive Model for Skid Loss of Asphalt Pavements". *Journal of Transportation Research Board* 2372:83-96.

Mahmoud, E. and E. Ortiz. 2014. *Implementation of AIMS in Measuring Aggregate Resistance to Polishing, Abrasion, and Breakage.* Report No. FHWA-ICT-14-014. Illinois Center for Transportation, Rantoul, IL: Illinois Department of Transportation. 52 pp.

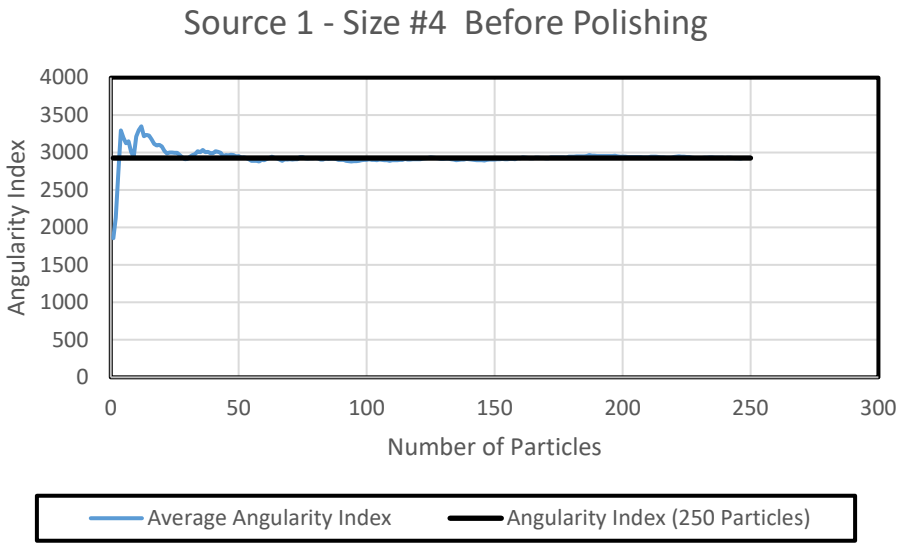
Mahmoud, E. and G. Perales. 2015. *Investigation of Relationships between AIMS Shape Properties and VST Friction Values.* Report No. FHWA-ICT-15-006. Illinois Center for Transportation, Rantoul, IL: Illinois Department of Transportation. 37 pp.

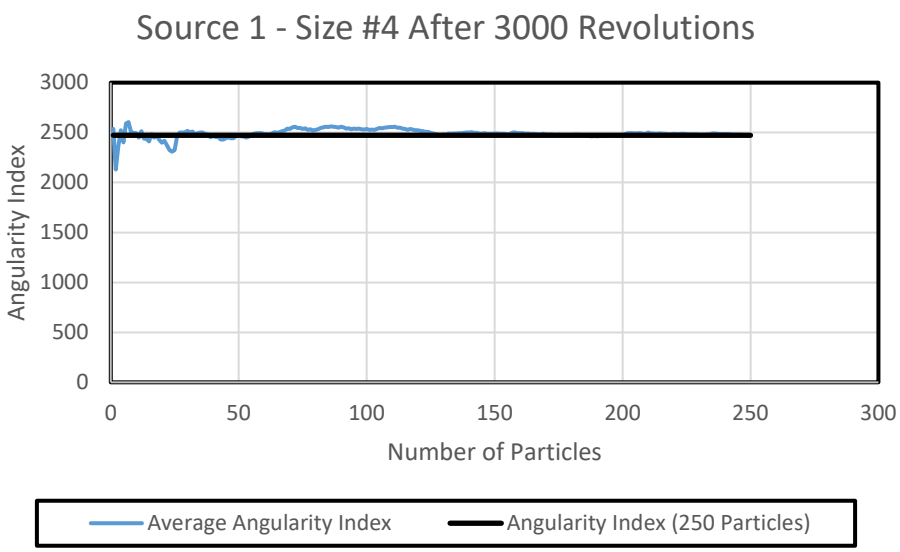
Masad, E., Luce. A., Mahmoud, E. and A. Chowdhury. 2007. *Relationship of Aggregate Texture to Asphalt Pavement Skid Resistance Using Image Analysis of Aggregate Shape*. Final Report for Highway IDEA Project 114.NCHRP. 24 pp.

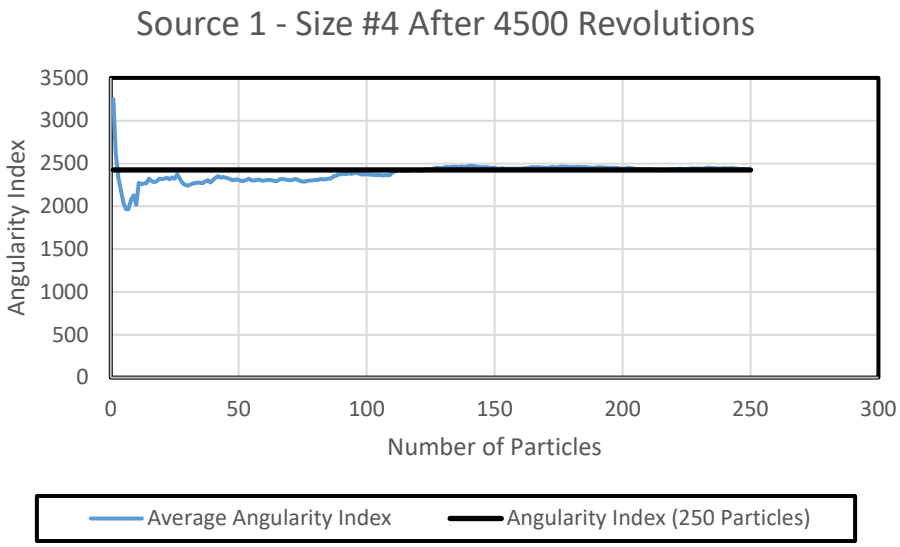
APPENDIX A: ASYMPTOTIC ANALYSIS RESULTS

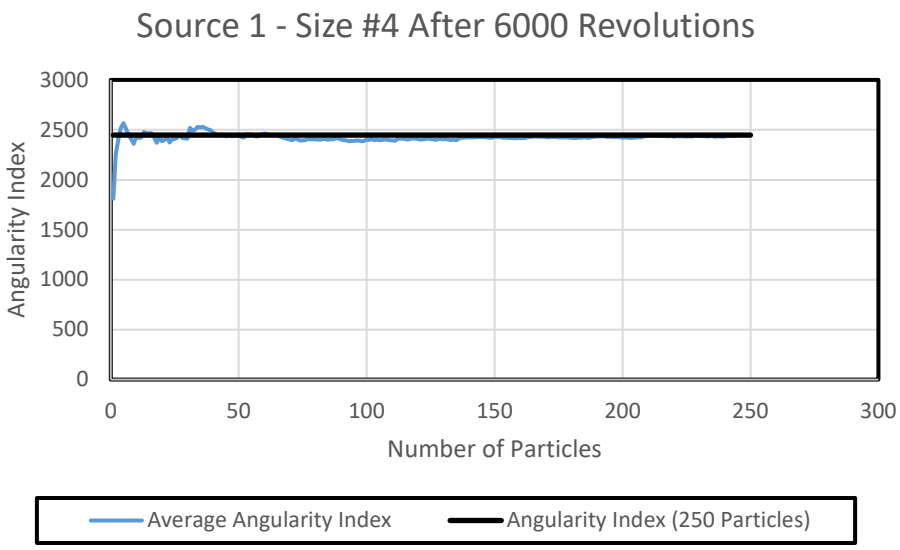
A.1 ANGULARITY

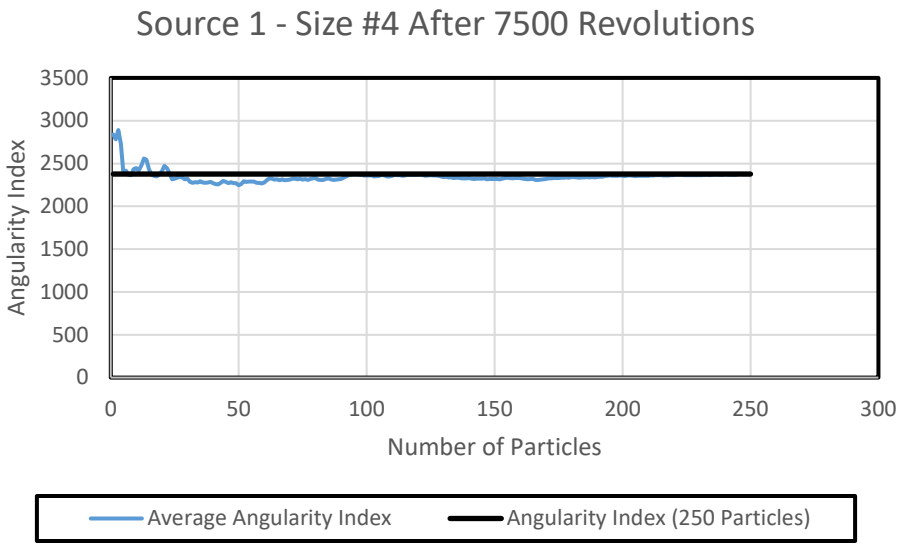
Source 1 – Size #4

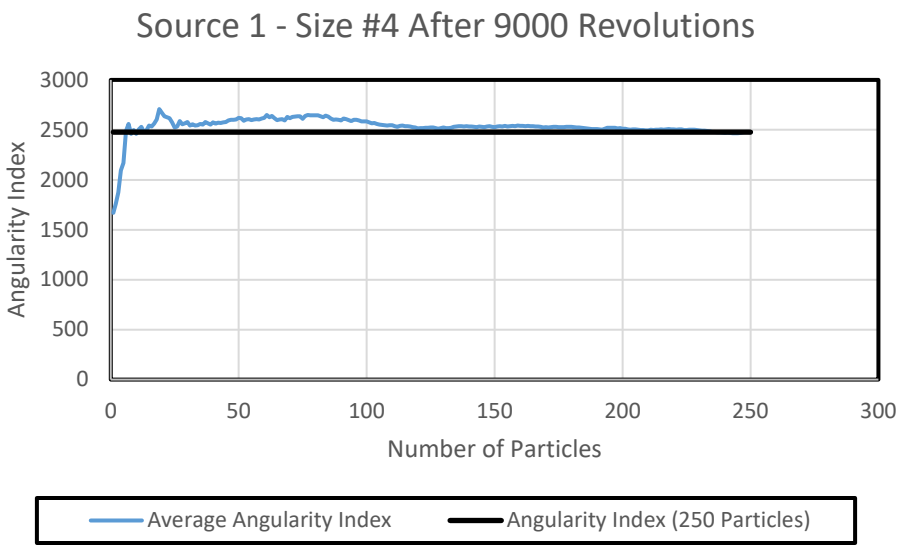


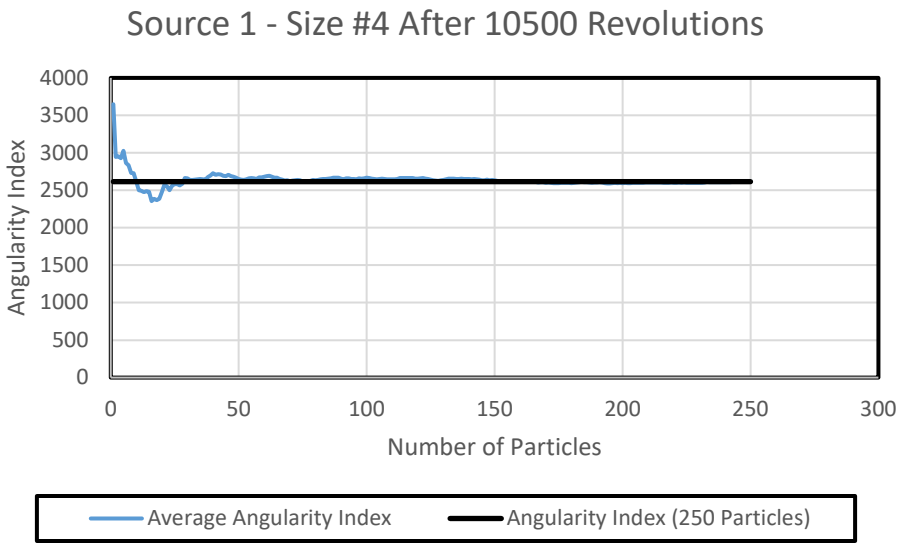



Source 1 - Size #4 After 4500 Revolutions
Angularity Index
3500
3000
2500
2000
1500
1000
500
0
0
50
100
150
200
250
300
Number of Particles
Average Angularity Index
Angularity Index (250 Particles)


Source 1 - Size #4 After 6000 Revolutions
Angularity Index
3000
2500
2000
1500
1000
500
0
0
50
100
150
200
250
300
Number of Particles
Average Angularity Index
Angularity Index (250 Particles)


Source 1 - Size #4 After 7500 Revolutions
Angularity Index
3500
3000
2500
2000
1500
1000
500
0
0
50
100
150
200
250
300
Number of Particles
Average Angularity Index
Angularity Index (250 Particles)


Source 1 - Size #4 After 9000 Revolutions
Angularity Index
3000
2500
2000
1500
1000
500
0
0
50
100
150
200
250
300
Number of Particles
Average Angularity Index
Angularity Index (250 Particles)


Source 1 - Size #4 After 10500 Revolutions
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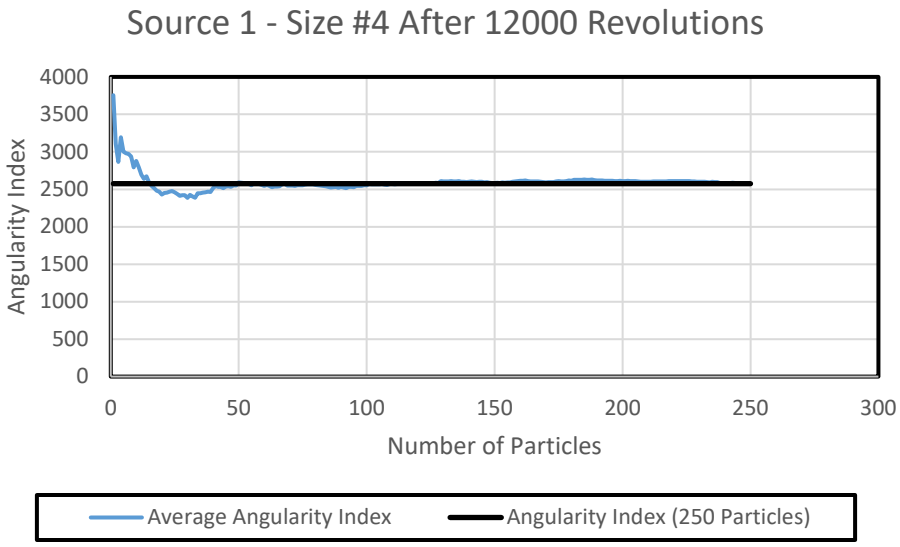
3500
3000
2500
2000
1500
1000
500
0
0
50
100
150
200
250
300
Number of Particles
Average Angularity Index
Angularity Index (250 Particles)


Source 1 - Size #4 After 12000 Revolutions
Angularity Index
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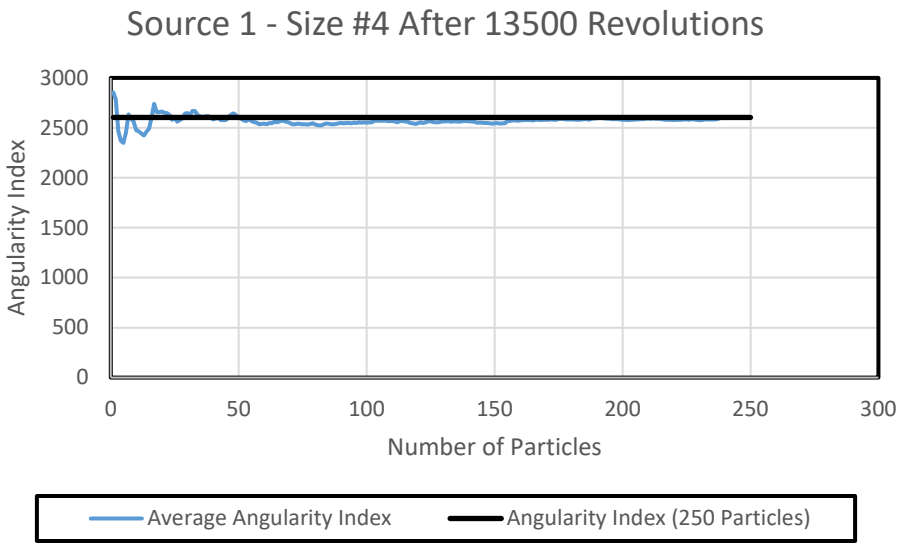
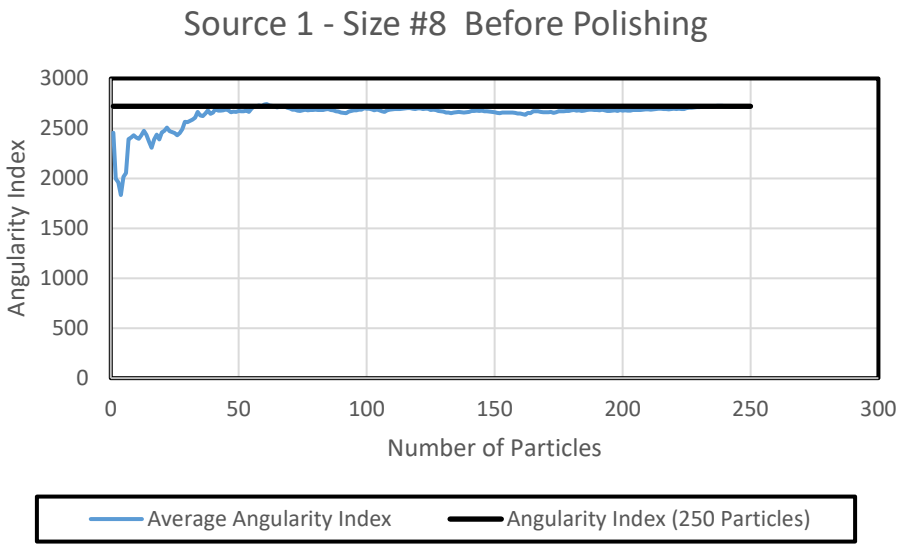
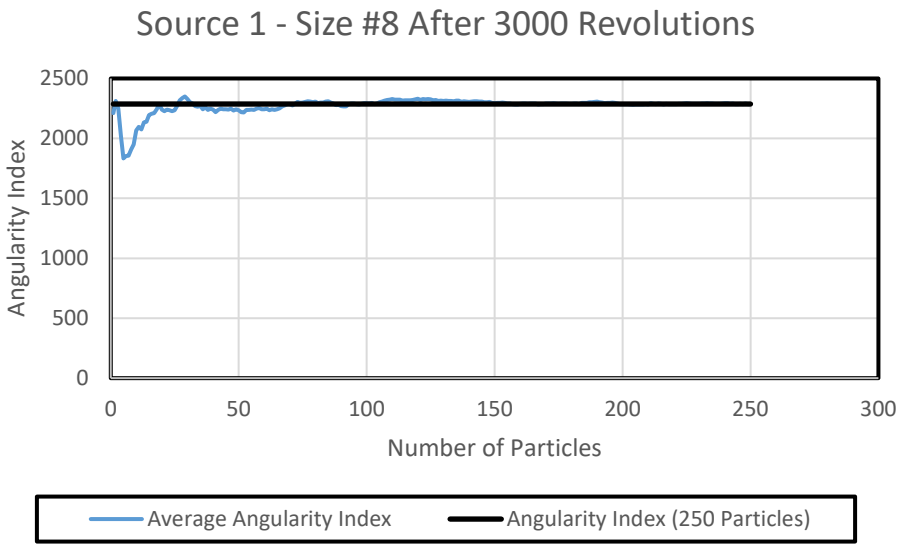
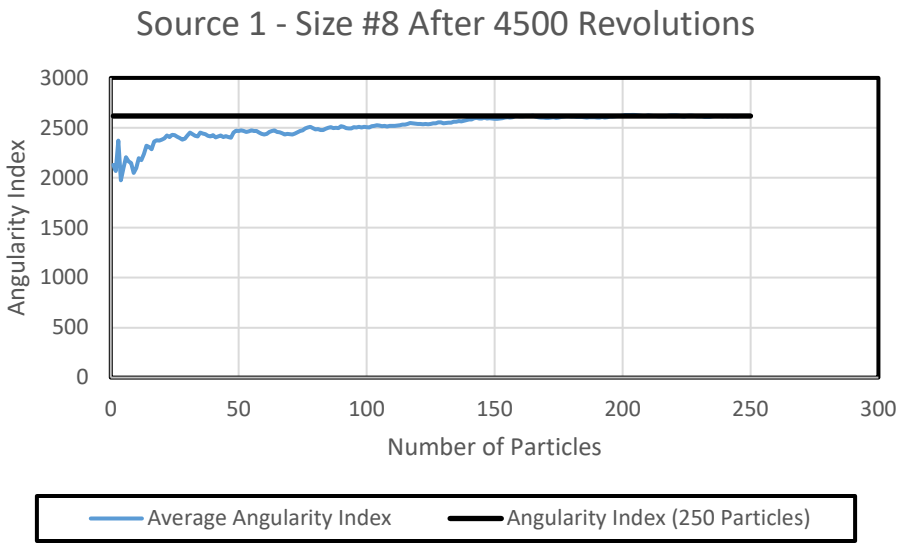
3500
3000
2500
2000
1500
1000
500
0
0
50
100
150
200
250
300
Number of Particles
Average Angularity Index
Angularity Index (250 Particles)


Source 1 - Size #4 After 13500 Revolutions
Angularity Index
3000
2500
2000
1500
1000
500
0
0
50
100
150
200
250
300
Number of Particles
Average Angularity Index
Angularity Index (250 Particles)

Source 1 – Size #8 (Angularity)



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1500
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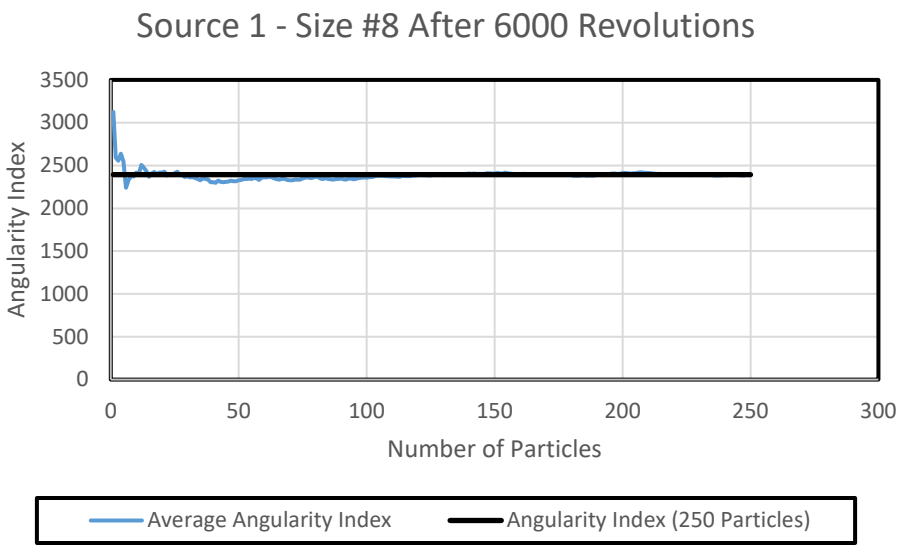
500
0
0
50
100
150
200
250
300
Number of Particles
Average Angularity Index
Angularity Index (250 Particles)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Angularity Index
3500
3000
2500
2000
1500
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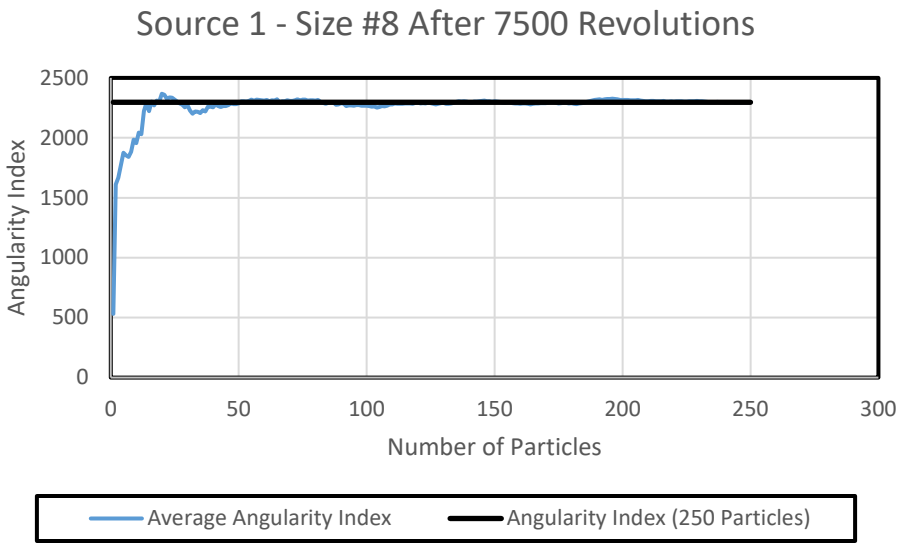
500
0
0
50
100
150
200
250
300
Number of Particles
Average Angularity Index
Angularity Index (250 Particles)


Source 1 - Size #8 After 7500 Revolutions
Angularity Index
2500
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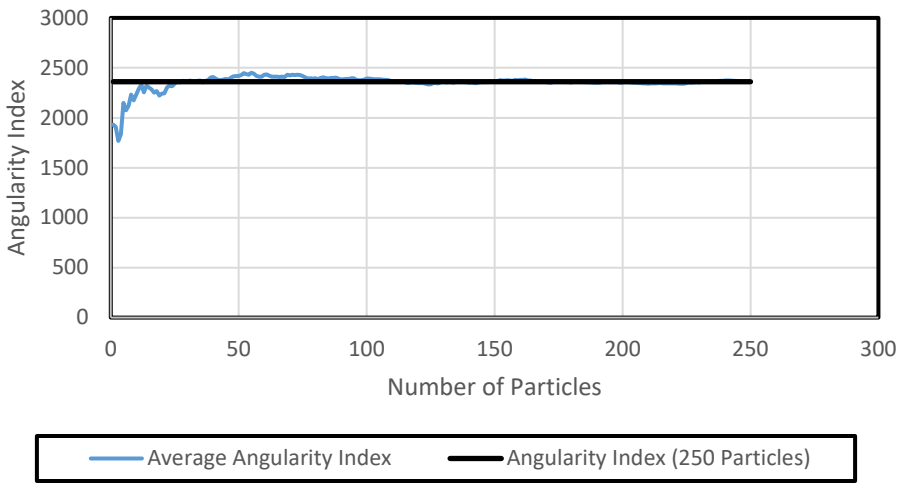
500
0
0
50
100
150
200
250
300
Number of Particles
Average Angularity Index
Angularity Index (250 Particles)


Source 1 - Size #8 After 9000 Revolutions
Angularity Index
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2500
2000
1500
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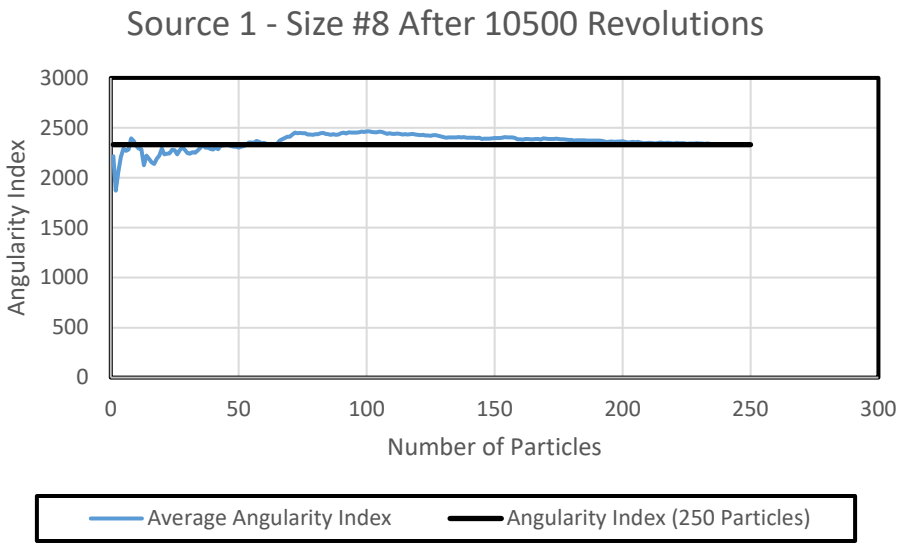
500
0
0
50
100
150
200
250
300
Number of Particles
Average Angularity Index
Angularity Index (250 Particles)


Source 1 - Size #8 After 10500 Revolutions
Angularity Index
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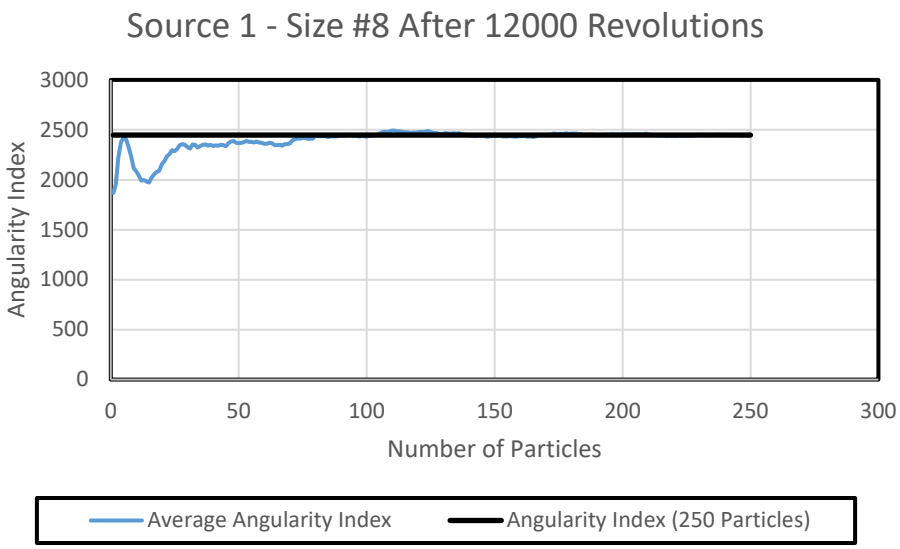
2000
1500
1000
500
0
0
50
100
150
200
250
300
Number of Particles
Average Angularity Index
Angularity Index (250 Particles)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Angularity Index
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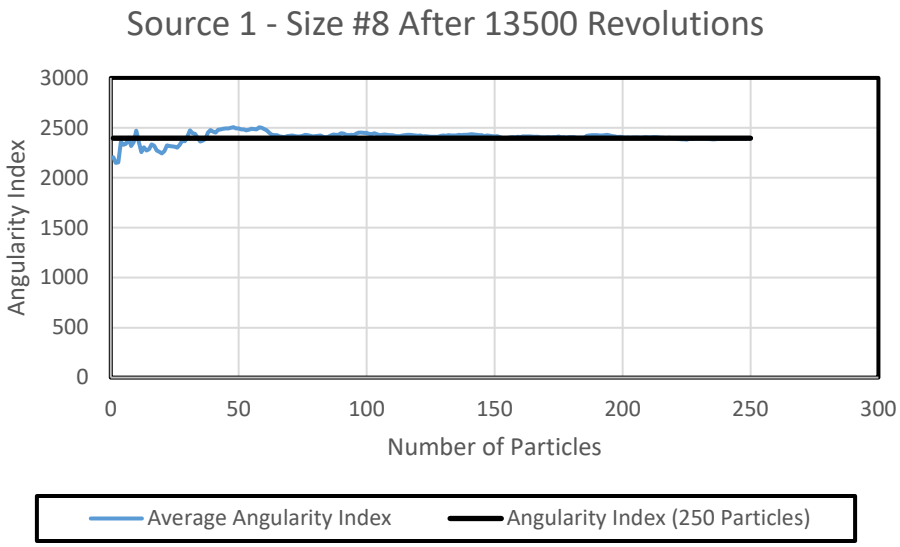
2500
2000
1500
1000
500
0
0
50
100
150
200
250
300
Number of Particles
Average Angularity Index
Angularity Index (250 Particles)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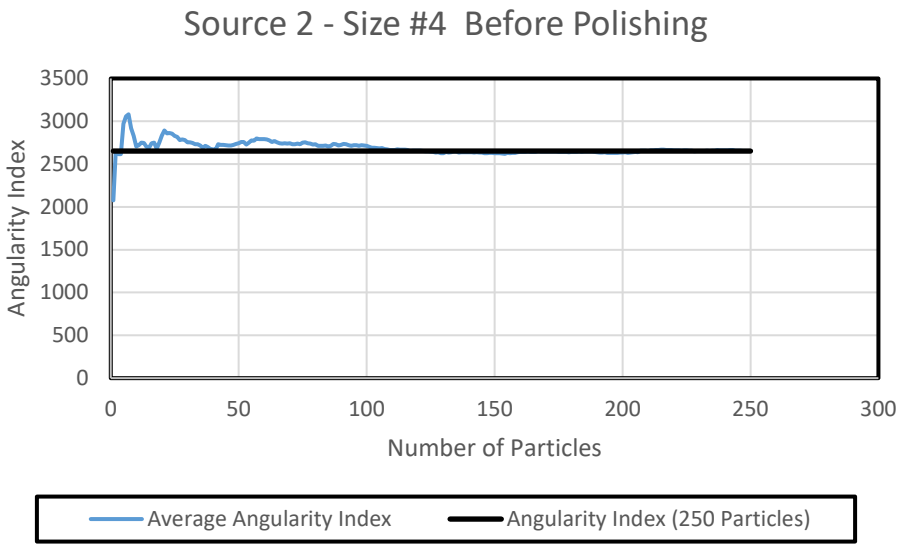
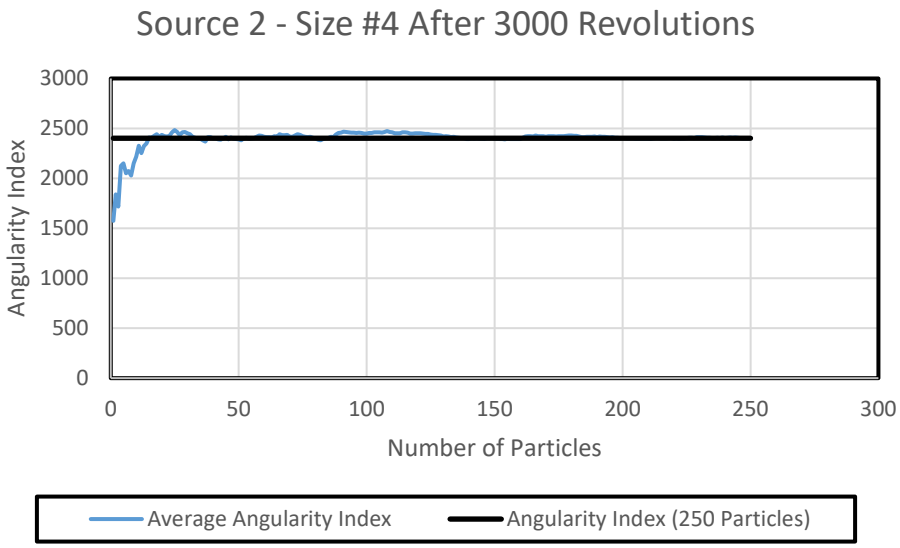
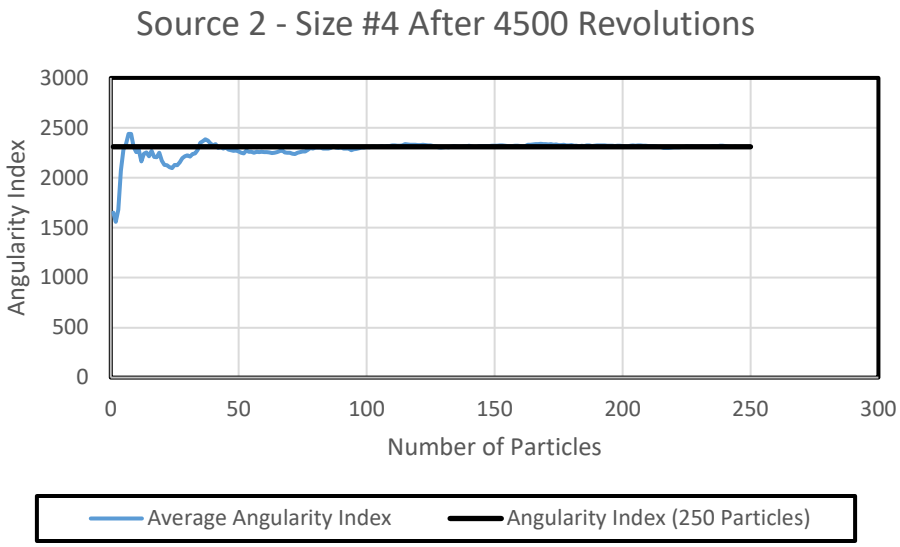
2500
2000
1500
1000
500
0
0
50
100
150
200
250
300
Number of Particles
Average Angularity Index
Angularity Index (250 Particles)

Source 2 – Size #4 (Angularity)



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1500
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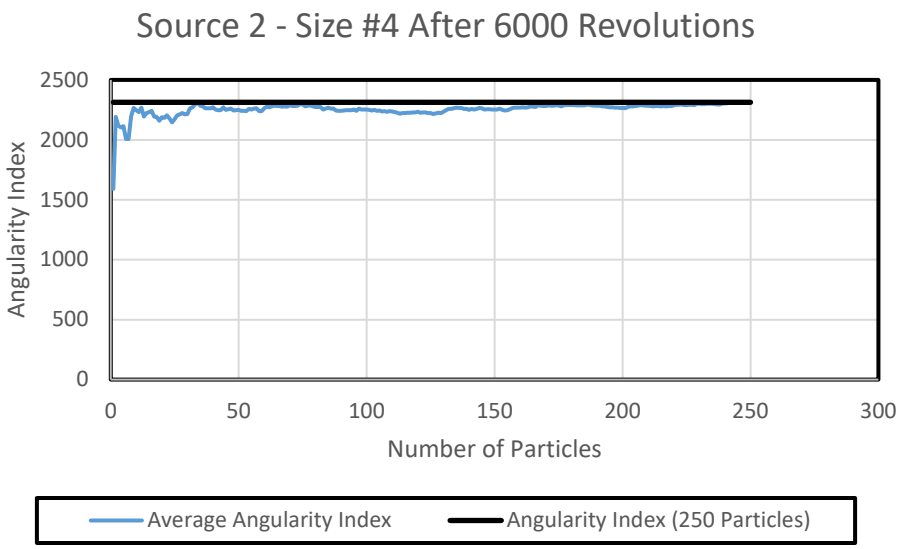
0
50
100
150
200
250
300
Number of Particles
Average Angularity Index
Angularity Index (250 Particles)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Angularity Index
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1500
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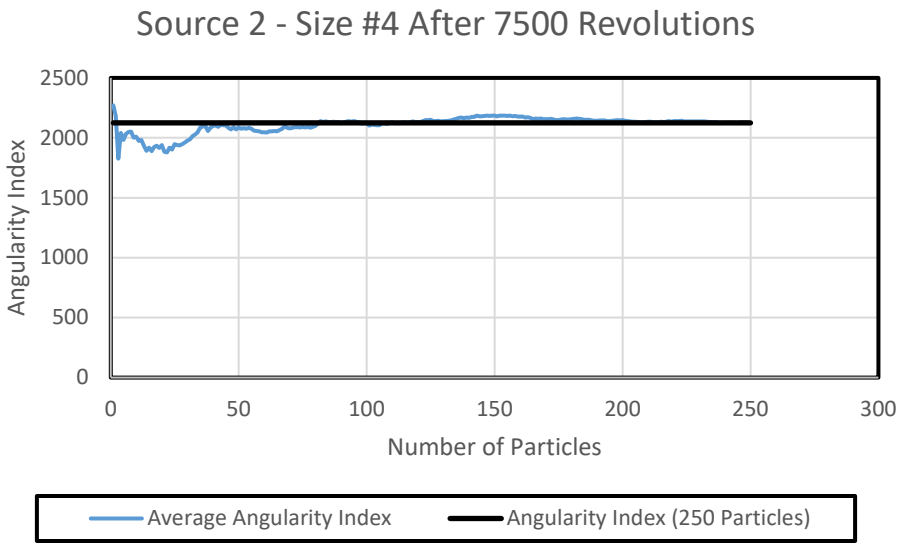
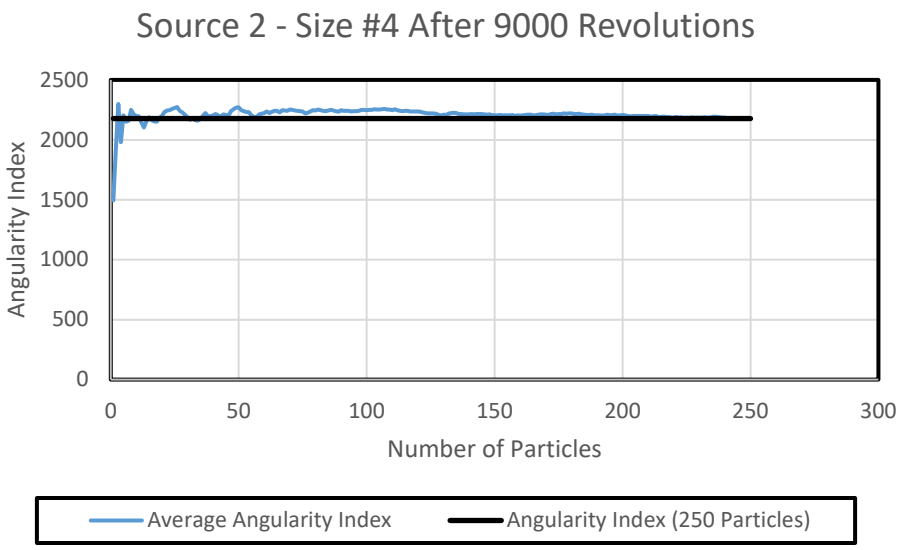
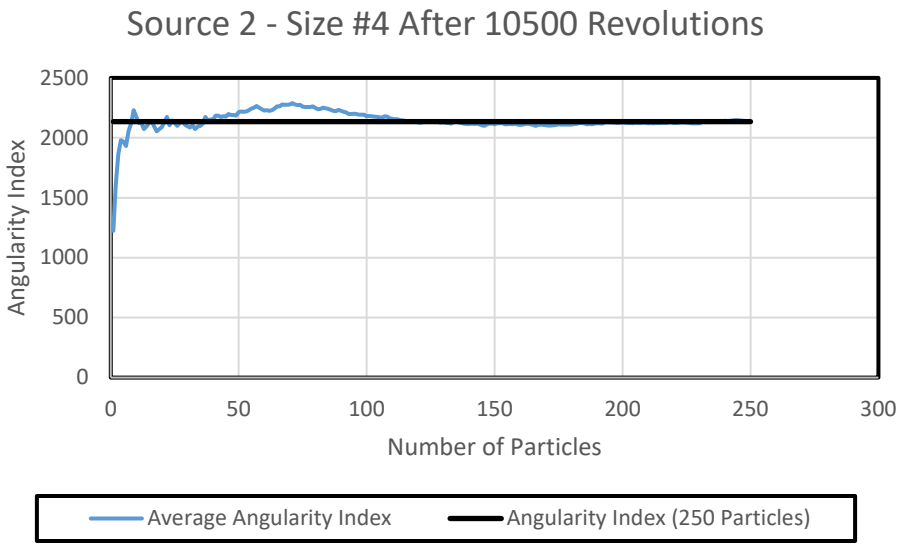
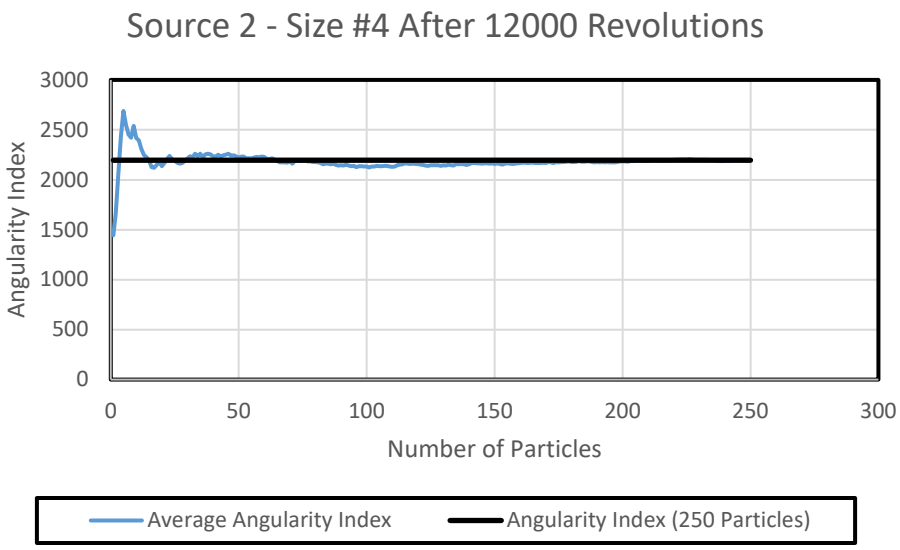
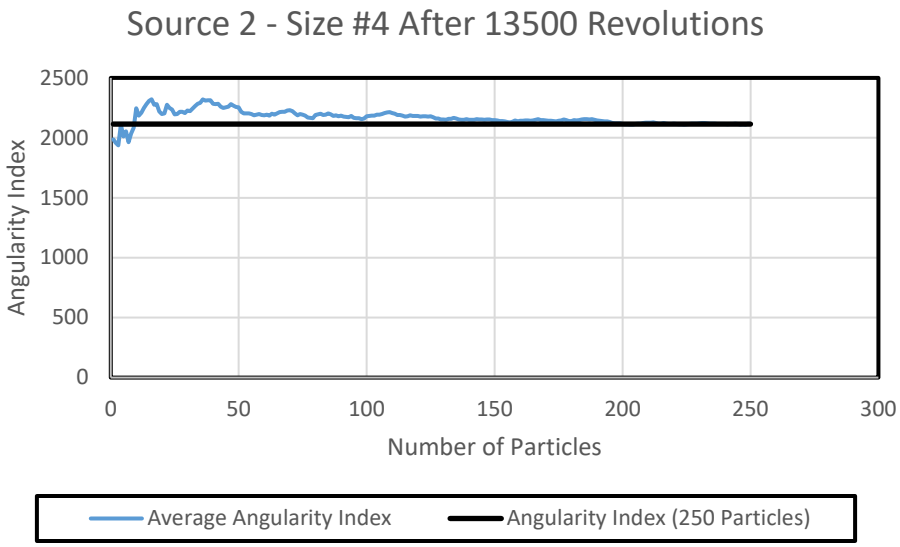
500
0
0
50
100
150
200
250
300
Number of Particles
Average Angularity Index
Angularity Index (250 Particles)


Source 2 - Size #4 After 7500 Revolutions
Angularity Index
2500
2000
1500
1000
500
0
0
50
100
150
200
250
300
Number of Particles
Average Angularity Index
Angularity Index (250 Particles)

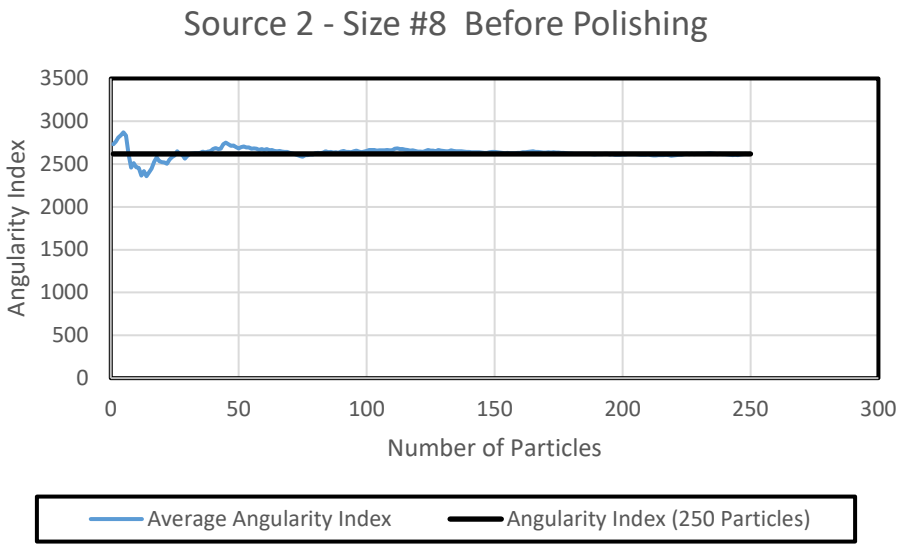

Source 2 - Size #4 After 9000 Revolutions
Angularity Index
2500
2000
1500
1000
500
0
0
50
100
150
200
250
300
Number of Particles
Average Angularity Index
Angularity Index (250 Particles)

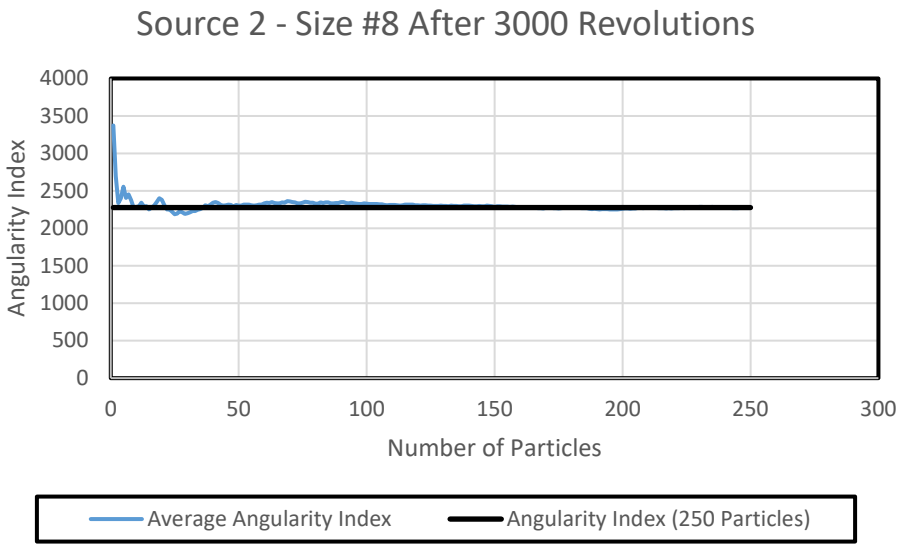

Source 2 - Size #4 After 10500 Revolutions
Angularity Index
2500
2000
1500
1000
500
0
0
50
100
150
200
250
300
Number of Particles
Average Angularity Index
Angularity Index (250 Particles)

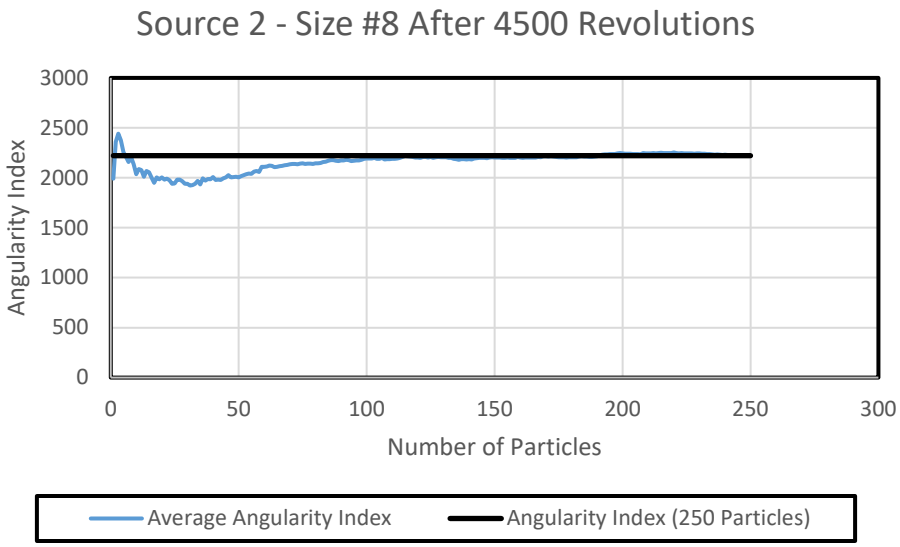

Source 2 - Size #4 After 12000 Revolutions
Angularity Index
3000
2500
2000
1500
1000
500
0
0
50
100
150
200
250
300
Number of Particles
Average Angularity Index
Angularity Index (250 Particles)

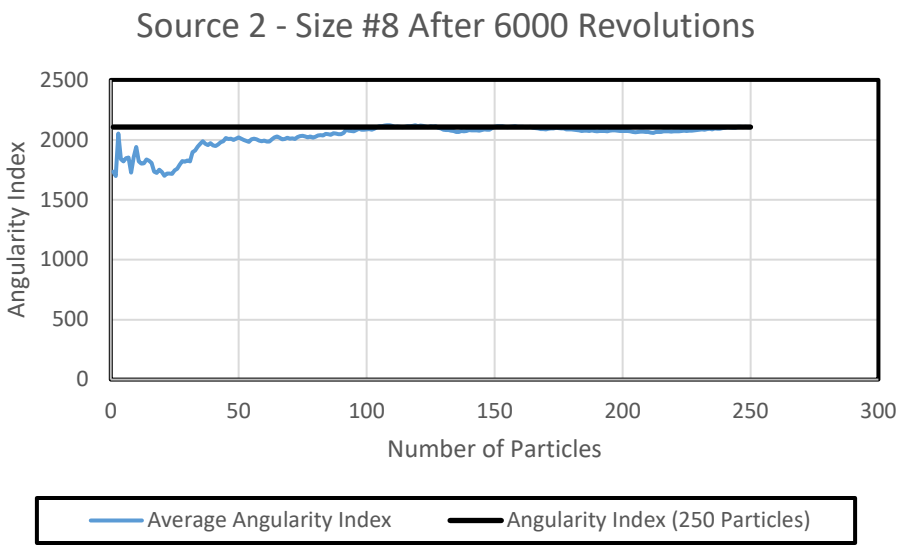

Source 2 - Size #4 After 13500 Revolutions
Angularity Index
2500
2000
1500
1000
500
0
0
50
100
150
200
250
300
Number of Particles
Average Angularity Index
Angularity Index (250 Particles)

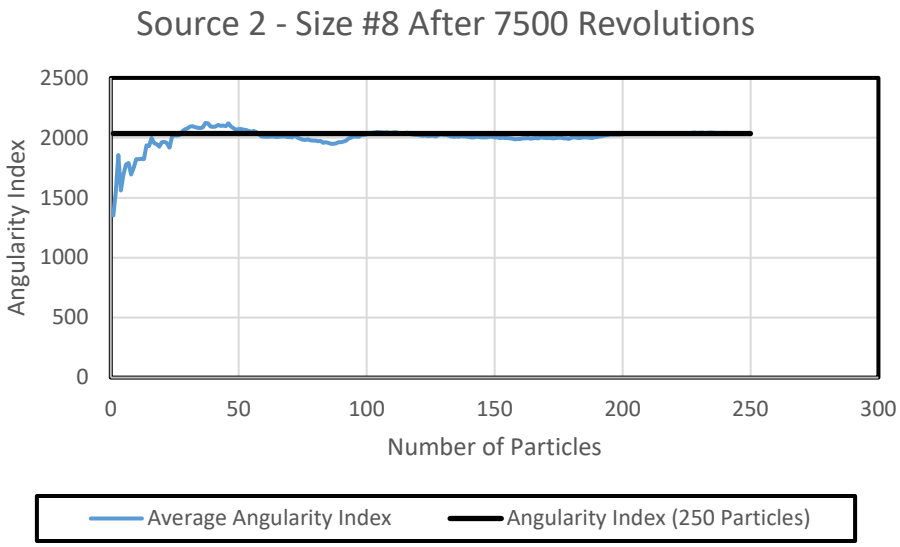
Source 2 – Size #8 (Angularity)

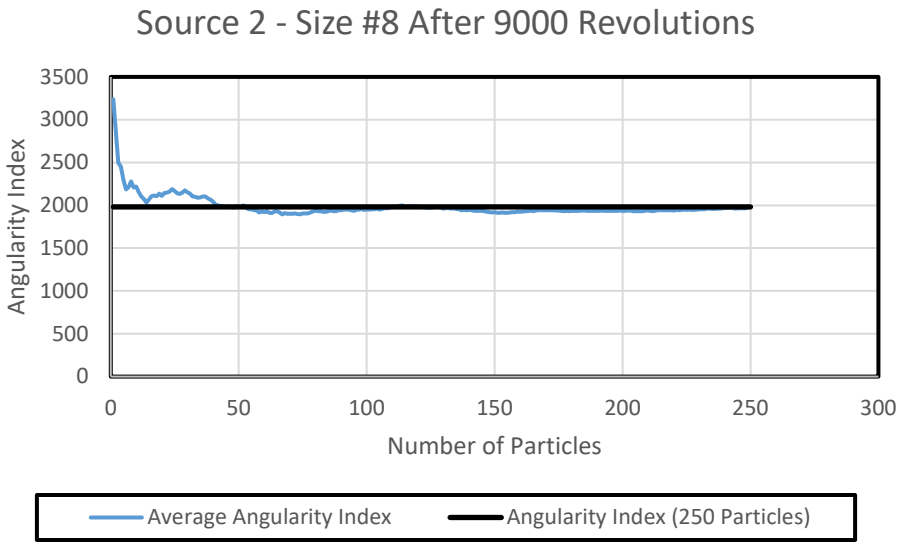


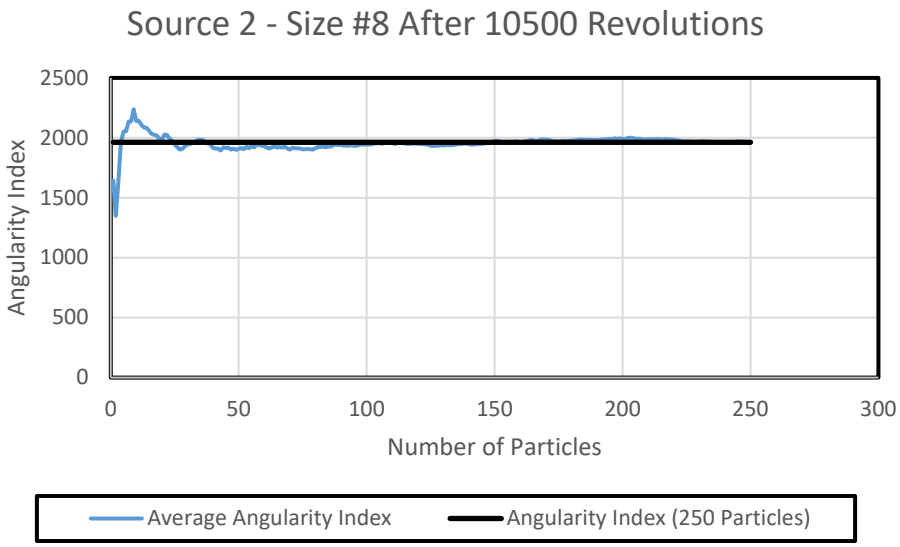


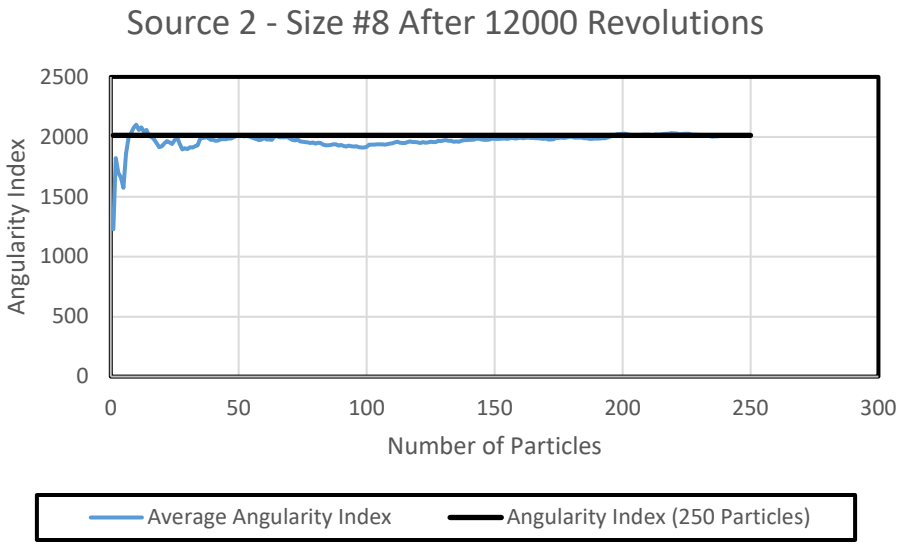

Source 2 - Size #8 After 4500 Revolutions
Angularity Index
3000
2500
2000
1500
1000
500
0
0
50
100
150
200
250
300
Number of Particles
Average Angularity Index
Angularity Index (250 Particles)

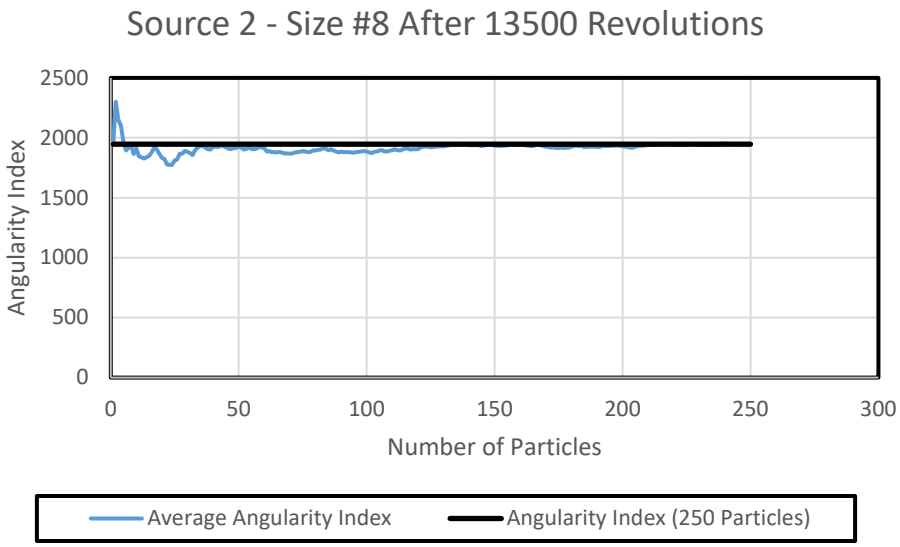

Source 2 - Size #8 After 6000 Revolutions
Angularity Index
2500
2000
1500
1000
500
0
0
50
100
150
200
250
300
Number of Particles
Average Angularity Index
Angularity Index (250 Particles)


Source 2 - Size #8 After 7500 Revolutions
Angularity Index
2500
2000
1500
1000
500
0
0
50
100
150
200
250
300
Number of Particles
Average Angularity Index
Angularity Index (250 Particles)


Source 2 - Size #8 After 9000 Revolutions
Angularity Index
3500
3000
2500
2000
1500
1000
500
0
0
50
100
150
200
250
300
Number of Particles
Average Angularity Index
Angularity Index (250 Particles)

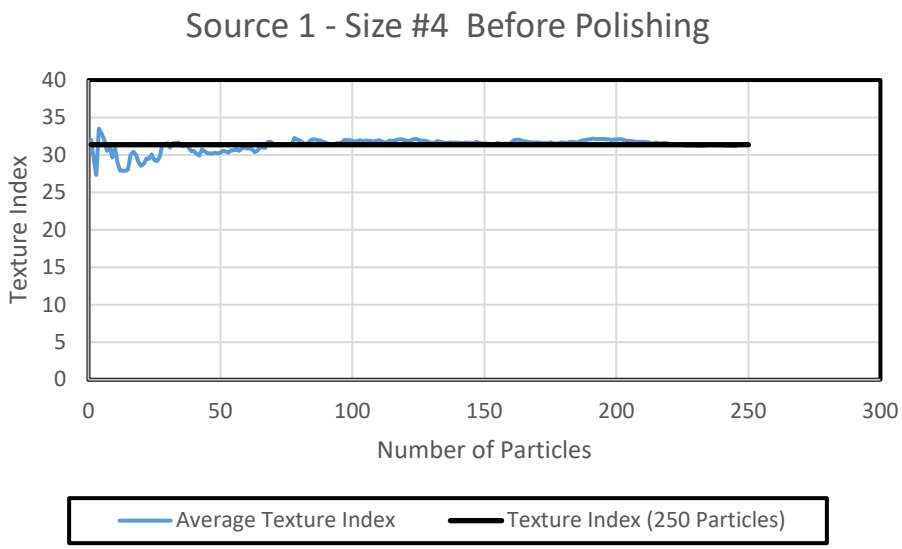

Source 2 - Size #8 After 10500 Revolutions
Angularity Index
2500
2000
1500
1000
500
0
0
50
100
150
200
250
300
Number of Particles
Average Angularity Index
Angularity Index (250 Particles)

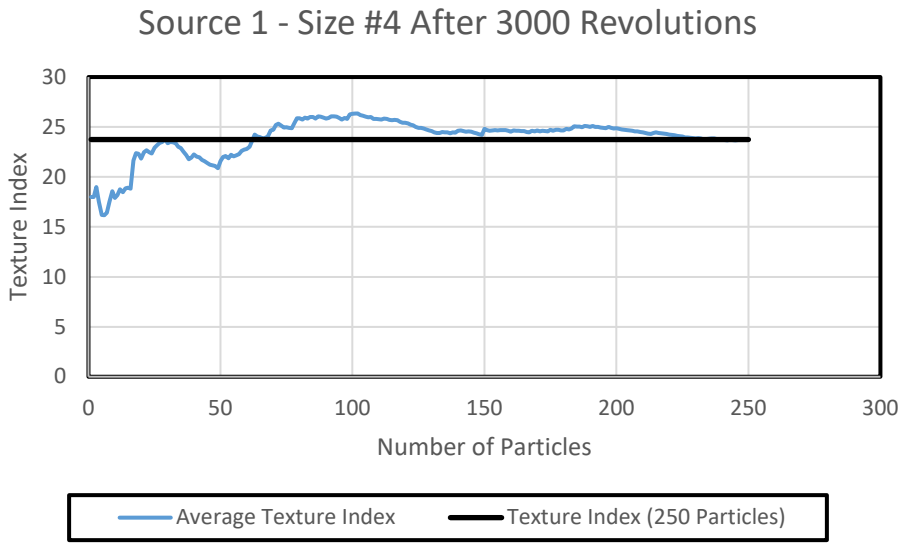

Source 2 - Size #8 After 12000 Revolutions
Angularity Index
2500
2000
1500
1000
500
0
0
50
100
150
200
250
300
Number of Particles
Average Angularity Index
Angularity Index (250 Particles)

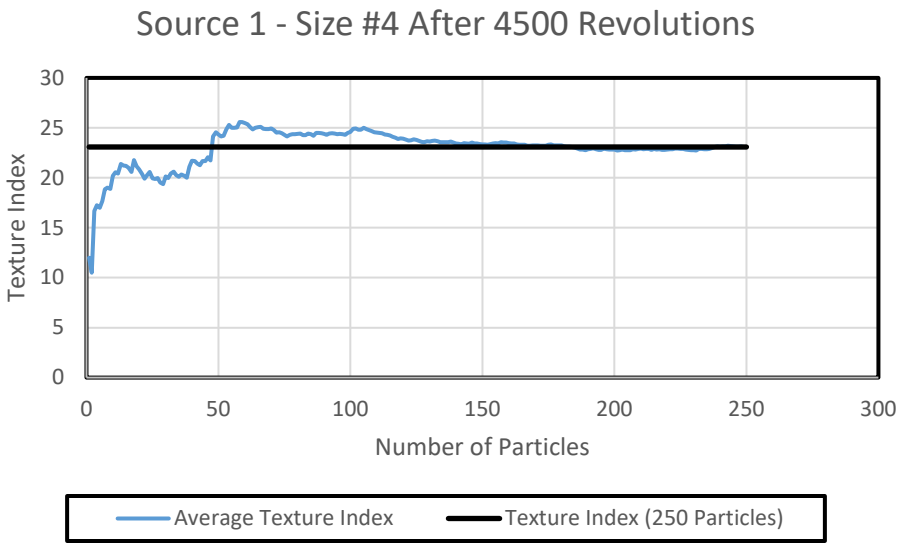

Source 2 - Size #8 After 13500 Revolutions
Angularity Index
2500
2000
1500
1000
500
0
0
50
100
150
200
250
300
Number of Particles
Average Angularity Index
Angularity Index (250 Particles)

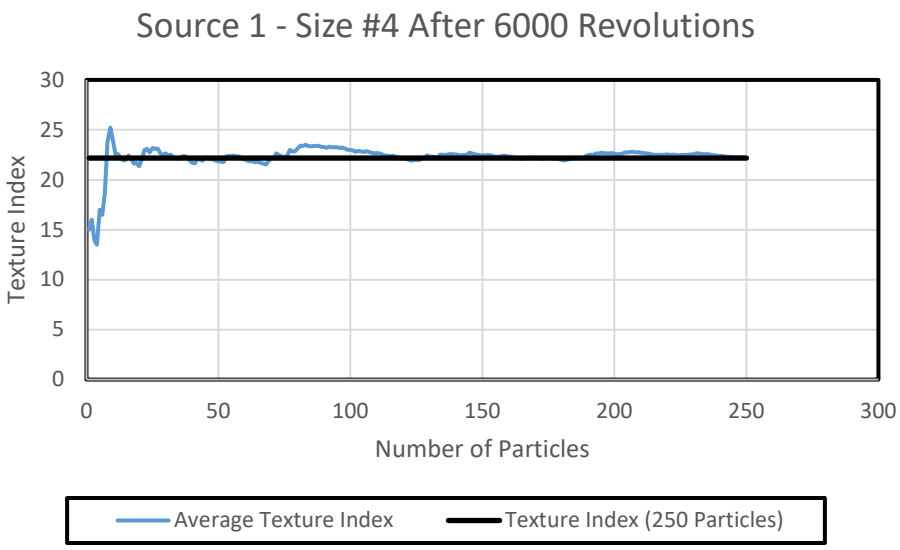
A.2 TEXTURE

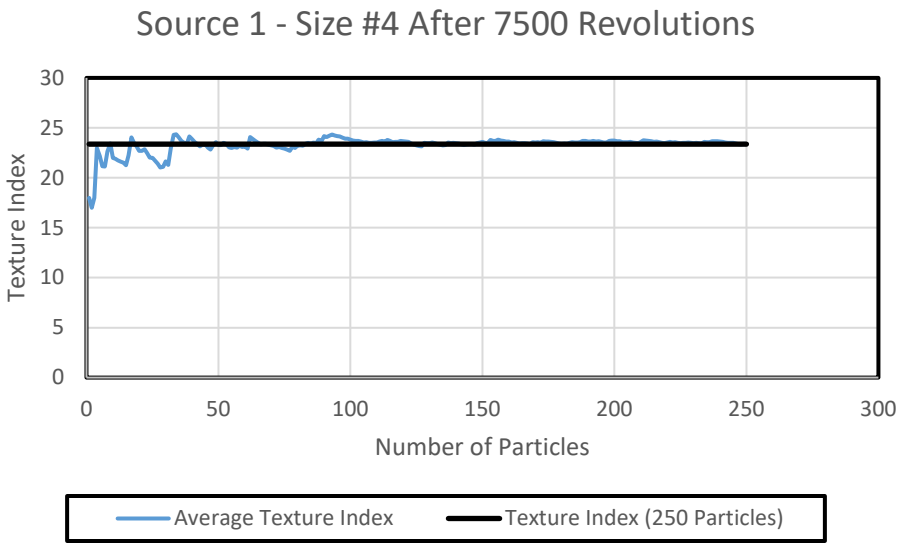
Source 1 – Size #4

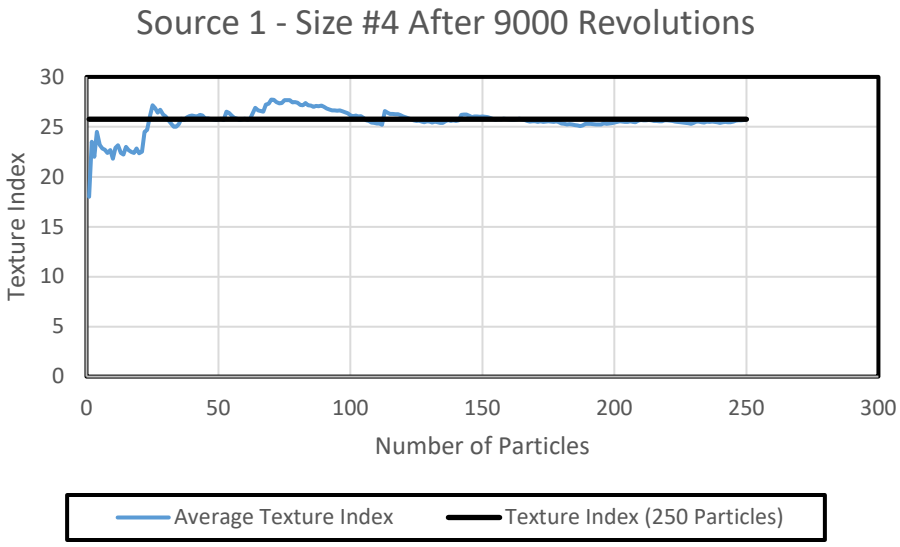


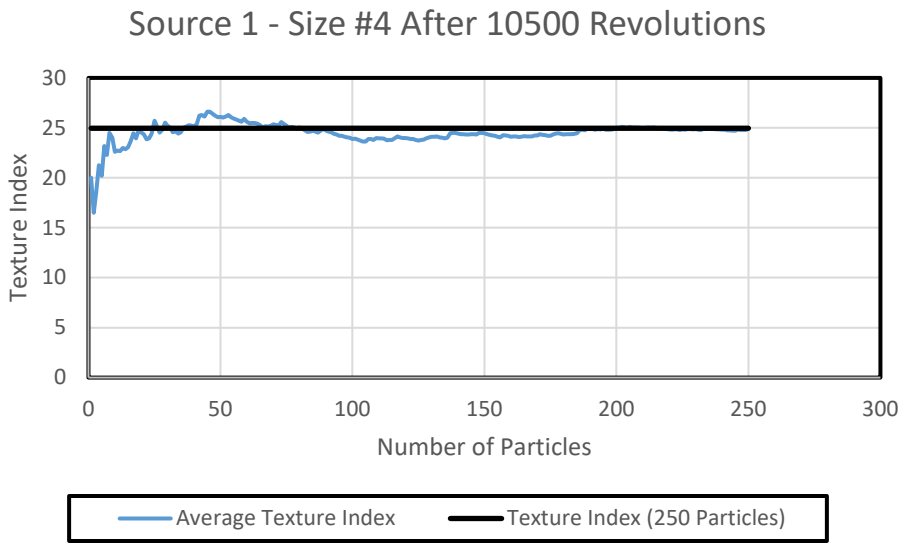


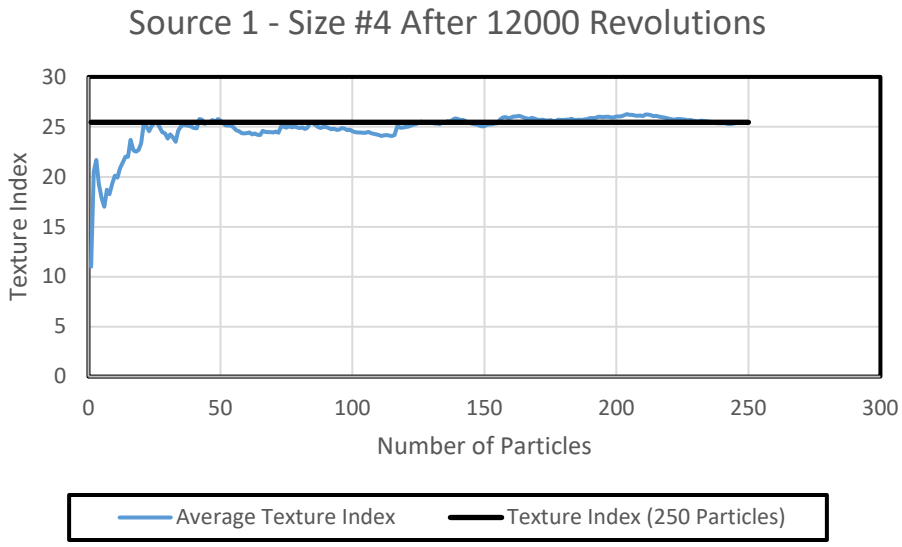

Source 1 - Size #4 After 4500 Revolutions
Texture Index
30
25
20
15
10
5
0
0
50
100
150
200
250
300
Number of Particles
Average Texture Index
Texture Index (250 Particles)

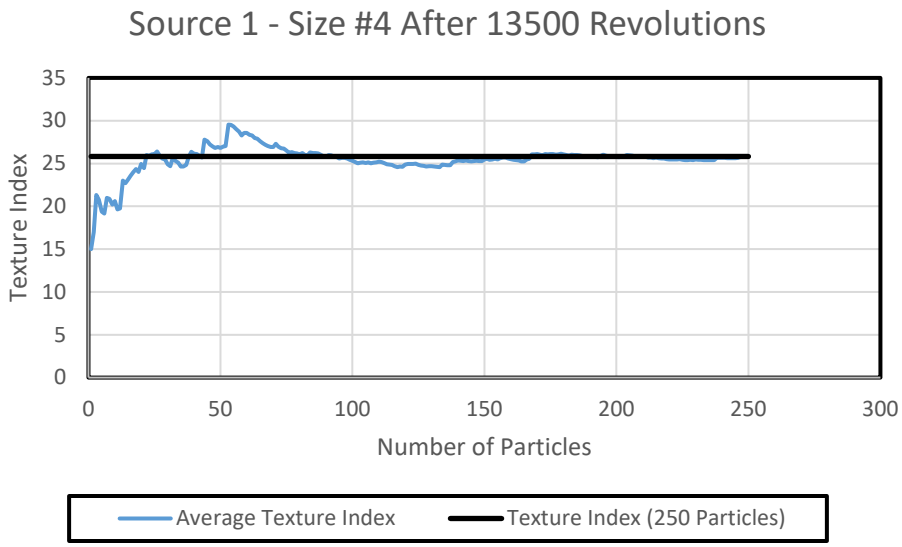

Source 1 - Size #4 After 6000 Revolutions
Texture Index
30
25
20
15
10
5
0
0
50
100
150
200
250
300
Number of Particles
Average Texture Index
Texture Index (250 Particles)


Source 1 - Size #4 After 7500 Revolutions
Texture Index
30
25
20
15
10
5
0
0
50
100
150
200
250
300
Number of Particles
Average Texture Index
Texture Index (250 Particles)

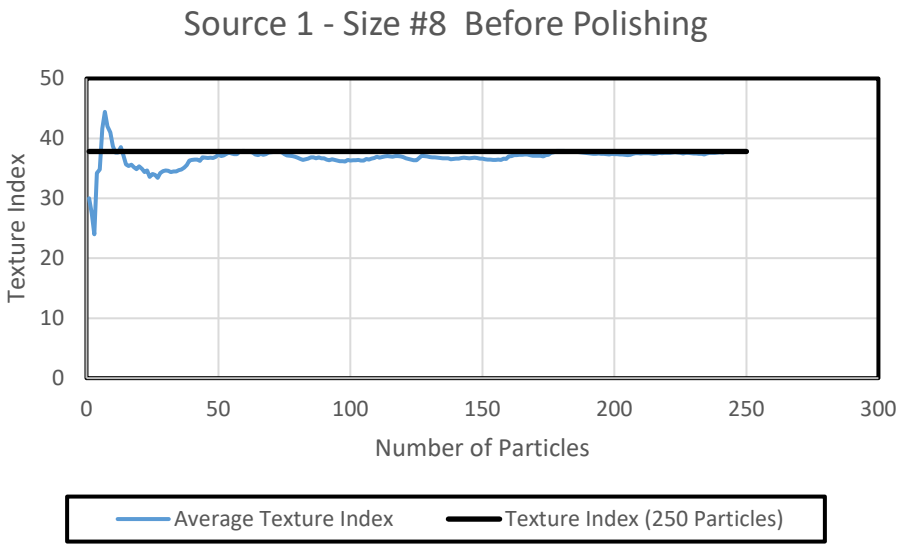

Source 1 - Size #4 After 9000 Revolutions
Texture Index
30
25
20
15
10
5
0
0
50
100
150
200
250
300
Number of Particles
Average Texture Index
Texture Index (250 Particles)

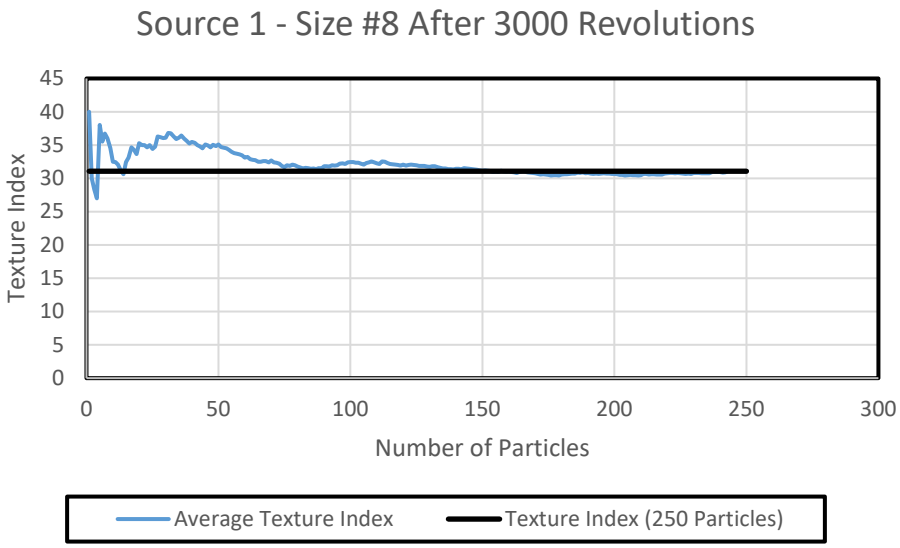

Source 1 - Size #4 After 10500 Revolutions
Texture Index
30
25
20
15
10
5
0
0
50
100
150
200
250
300
Number of Particles
Average Texture Index
Texture Index (250 Particles)

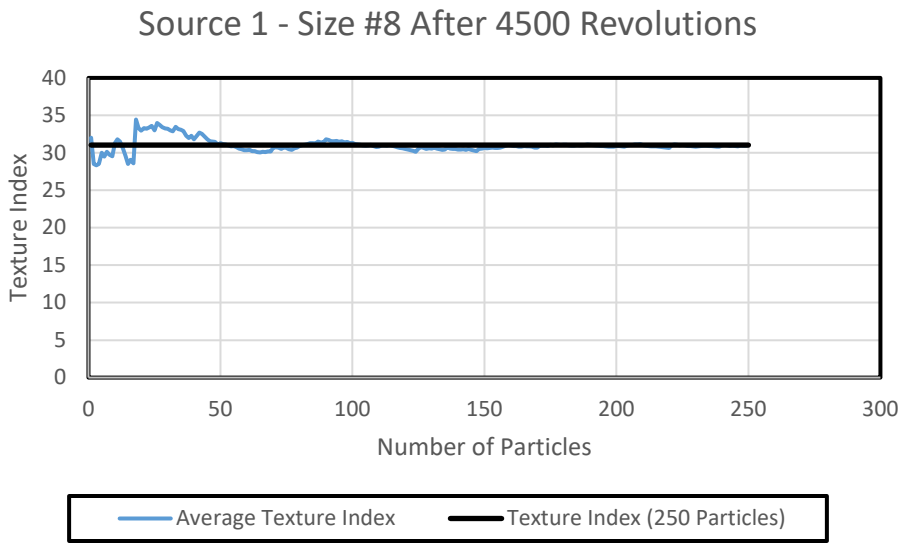

Source 1 - Size #4 After 12000 Revolutions
Texture Index
30
25
20
15
10
5
0
0
50
100
150
200
250
300
Number of Particles
Average Texture Index
Texture Index (250 Particles)

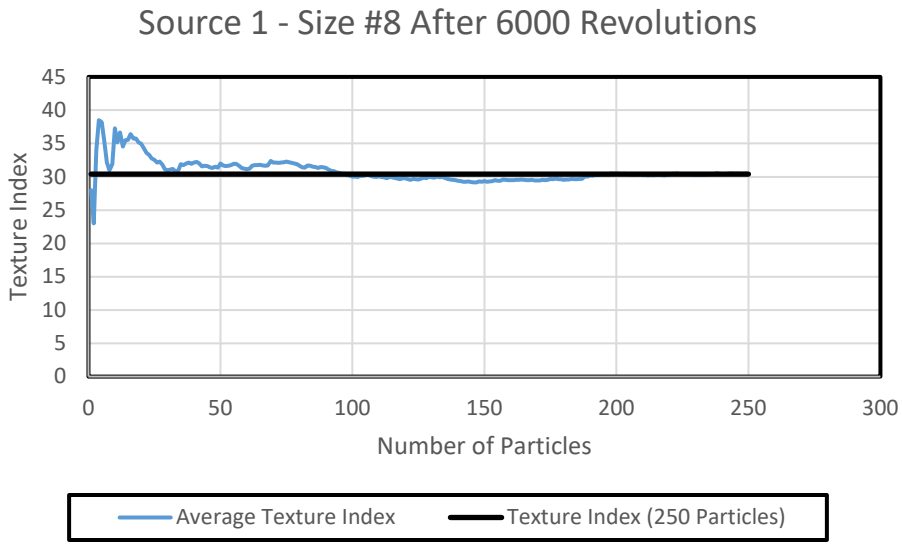

Source 1 - Size #4 After 13500 Revolutions
Texture Index
35
30
25
20
15
10
5
0
0
50
100
150
200
250
300
Number of Particles
Average Texture Index
Texture Index (250 Particles)

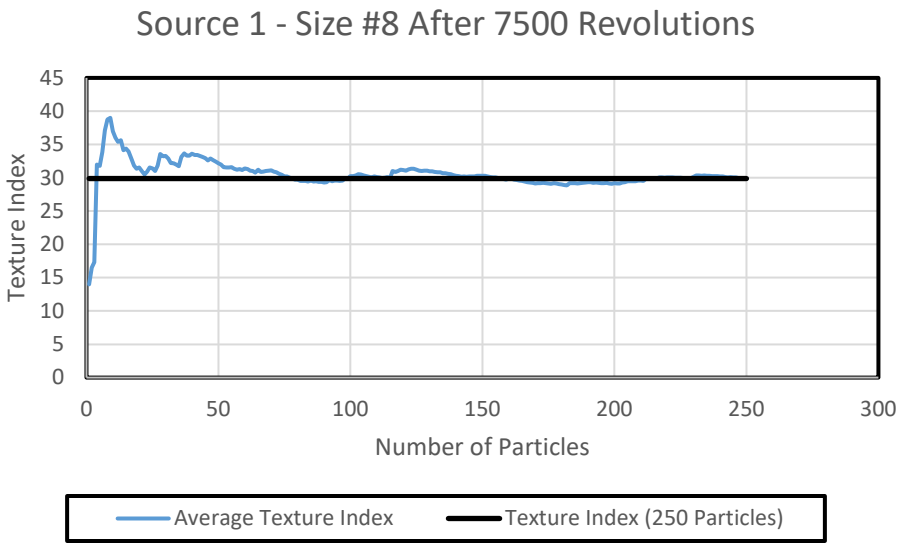
Source 1 – Size #8 (Texture)

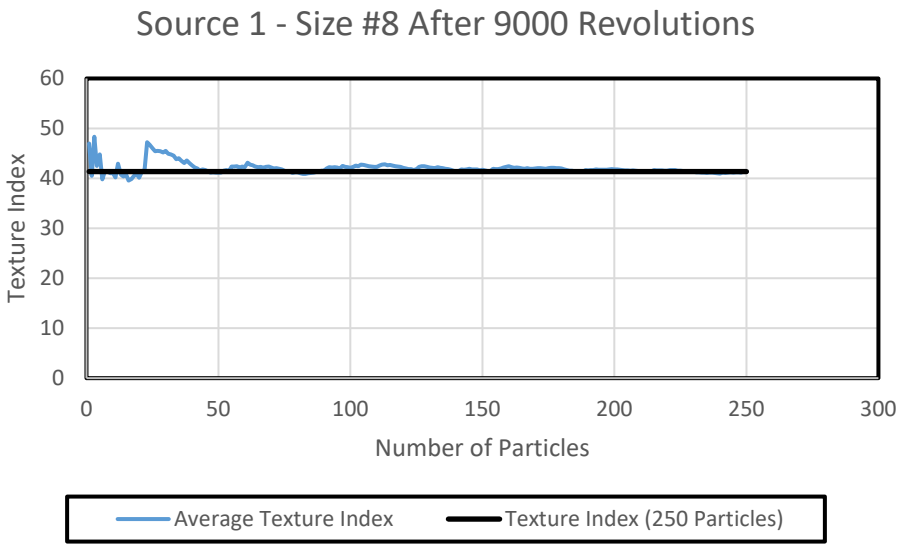


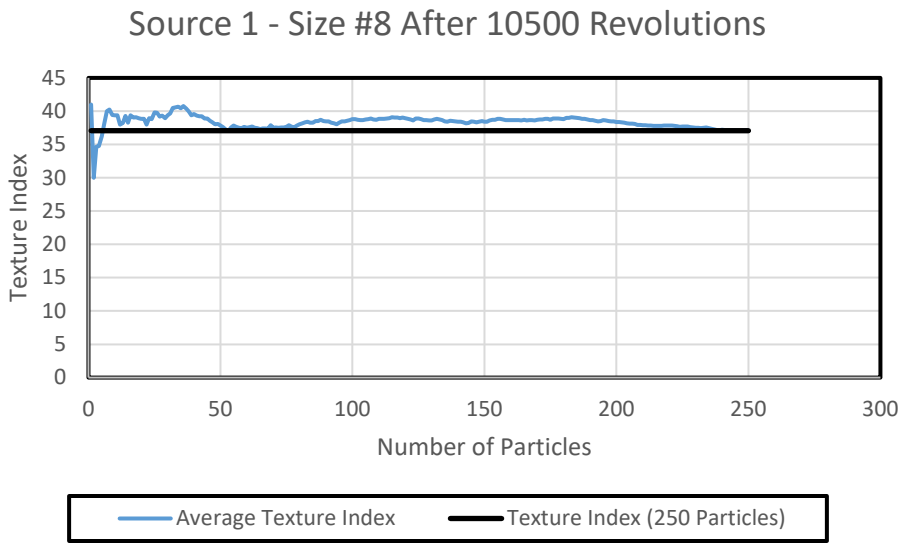


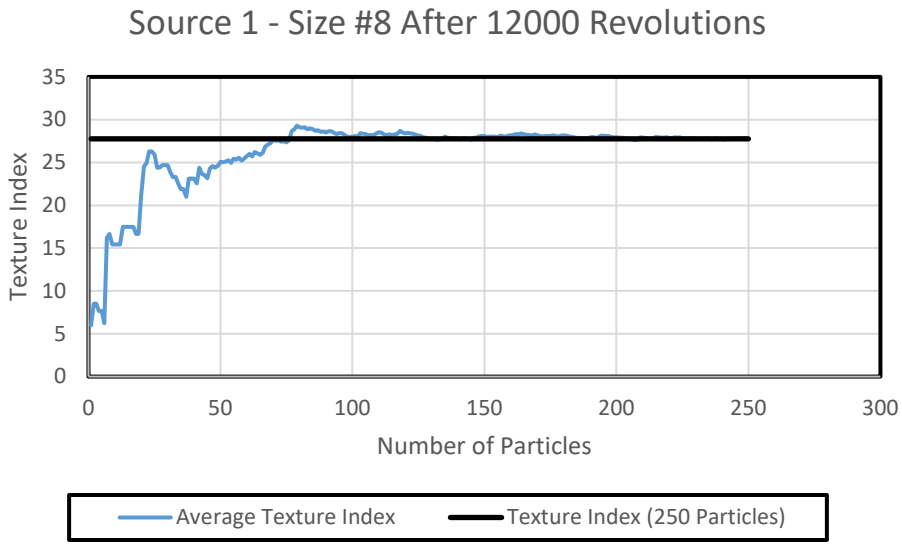

Source 1 - Size #8 After 4500 Revolutions
Texture Index
40
35
30
25
20
15
10
5
0
0
50
100
150
200
250
300
Number of Particles
Average Texture Index
Texture Index (250 Particles)

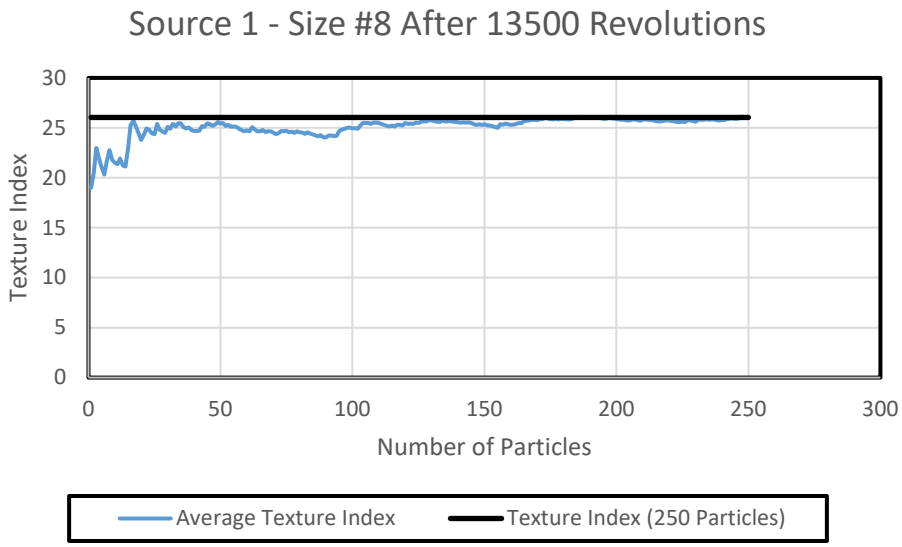

Source 1 - Size #8 After 6000 Revolutions
Texture Index
45
40
35
30
25
20
15
10
5
0
0
50
100
150
200
250
300
Number of Particles
Average Texture Index
Texture Index (250 Particles)


Source 1 - Size #8 After 7500 Revolutions
Texture Index
45
40
35
30
25
20
15
10
5
0
0
50
100
150
200
250
300
Number of Particles
Average Texture Index
Texture Index (250 Particles)

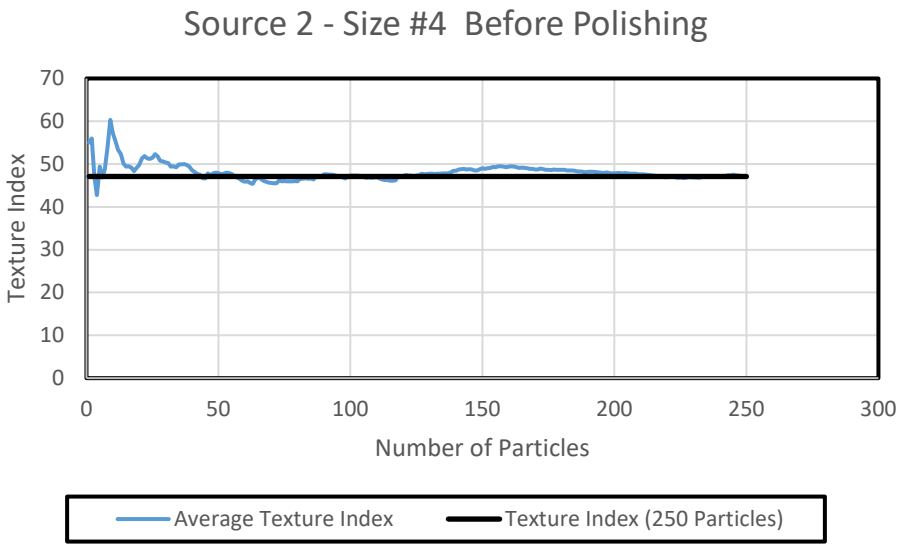

Source 1 - Size #8 After 9000 Revolutions
Texture Index
60
50
40
30
20
10
0
0
50
100
150
200
250
300
Number of Particles
Average Texture Index
Texture Index (250 Particles)

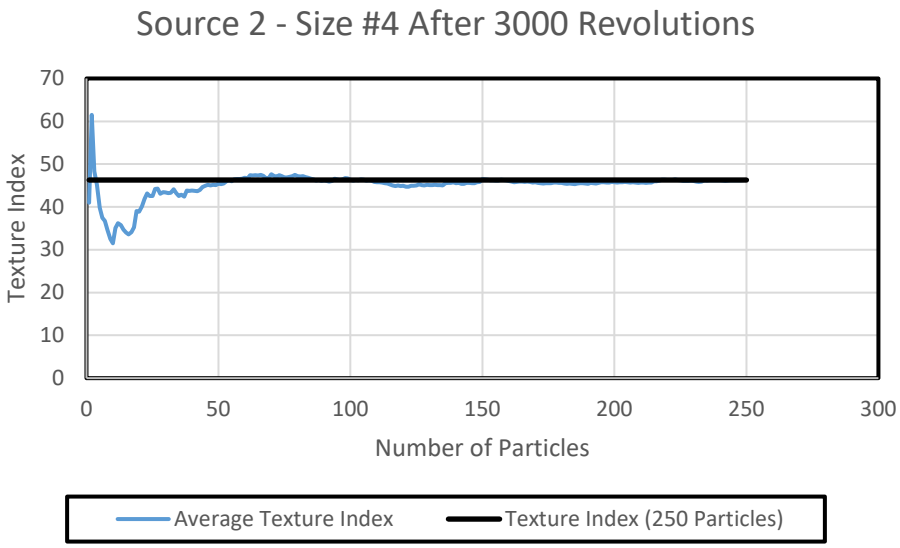

Source 1 - Size #8 After 10500 Revolutions
Texture Index
45
40
35
30
25
20
15
10
5
0
0
50
100
150
200
250
300
Number of Particles
Average Texture Index
Texture Index (250 Particles)

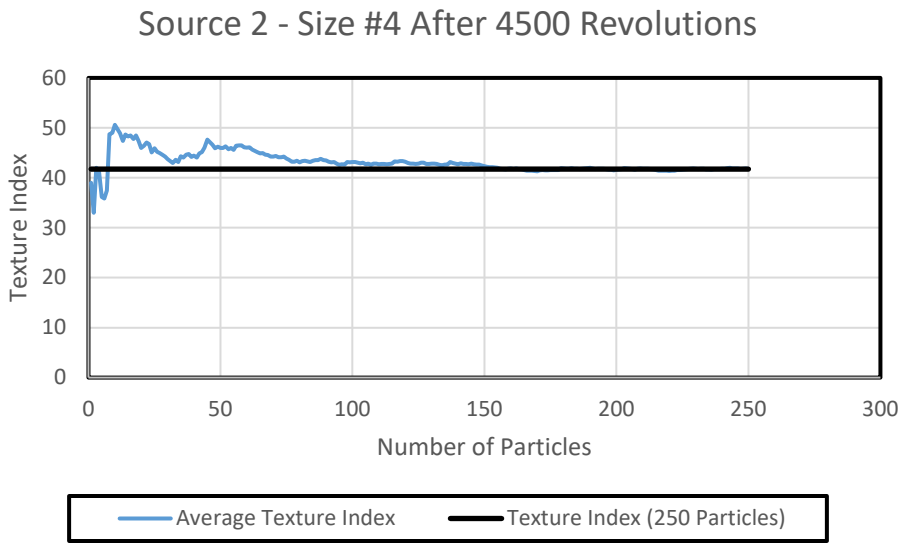

Source 1 - Size #8 After 12000 Revolutions
Texture Index
35
30
25
20
15
10
5
0
0
50
100
150
200
250
300
Number of Particles
Average Texture Index
Texture Index (250 Particles)

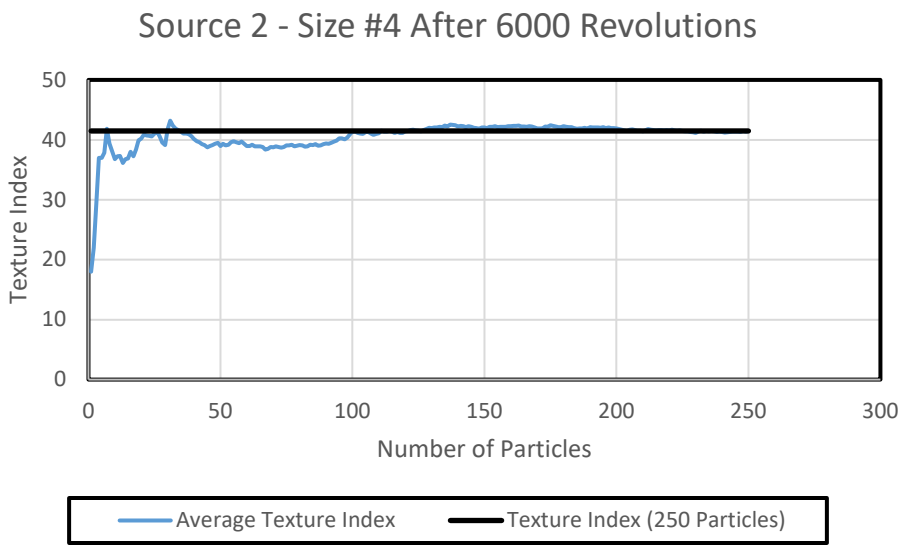

Source 1 - Size #8 After 13500 Revolutions
Texture Index
30
25
20
15
10
5
0
0
50
100
150
200
250
300
Number of Particles
Average Texture Index
Texture Index (250 Particles)

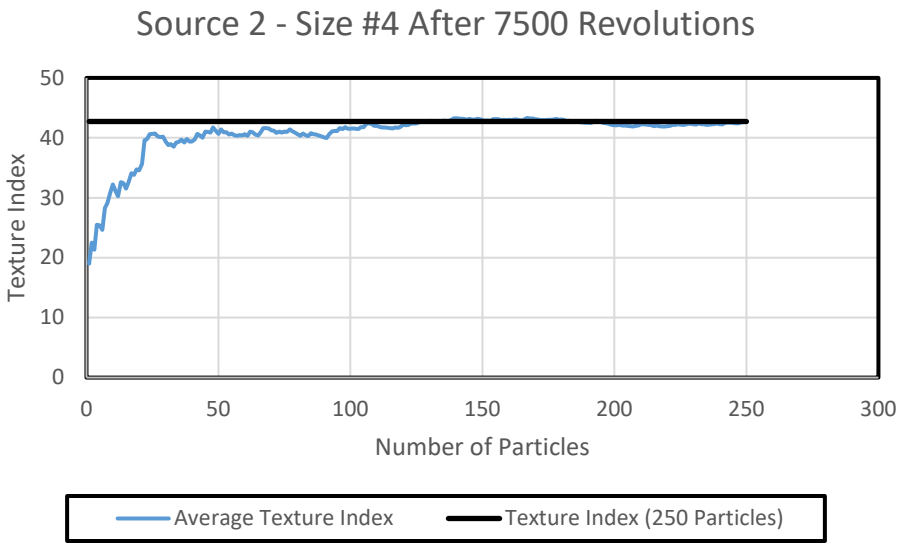
Source 2 – Size #4 (Texture)

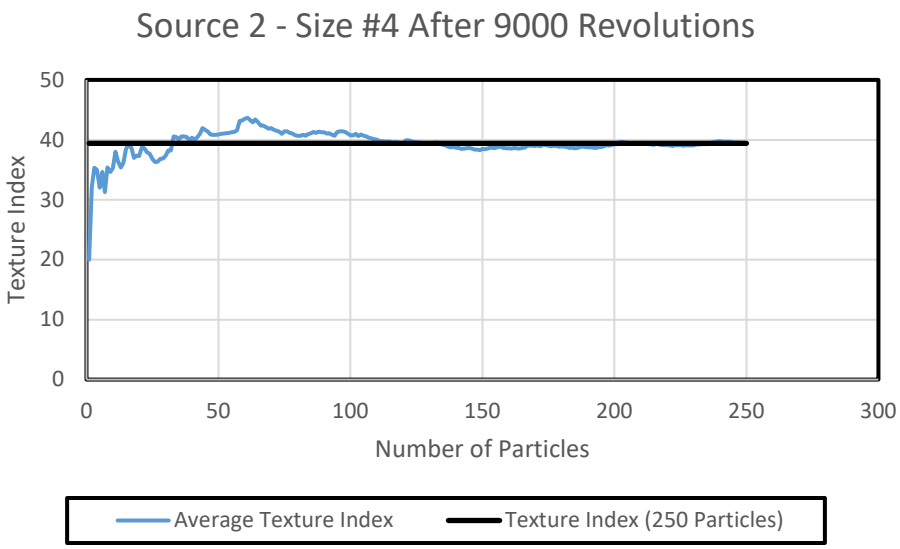


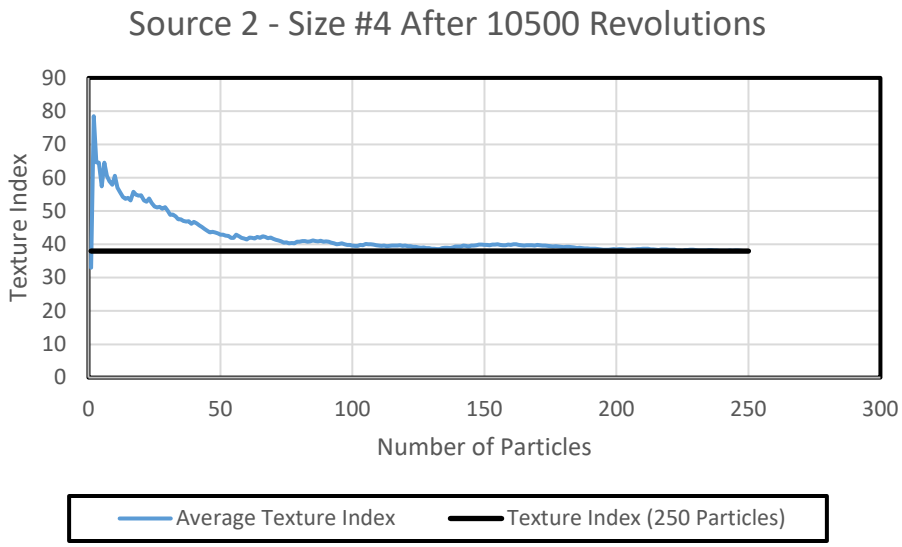


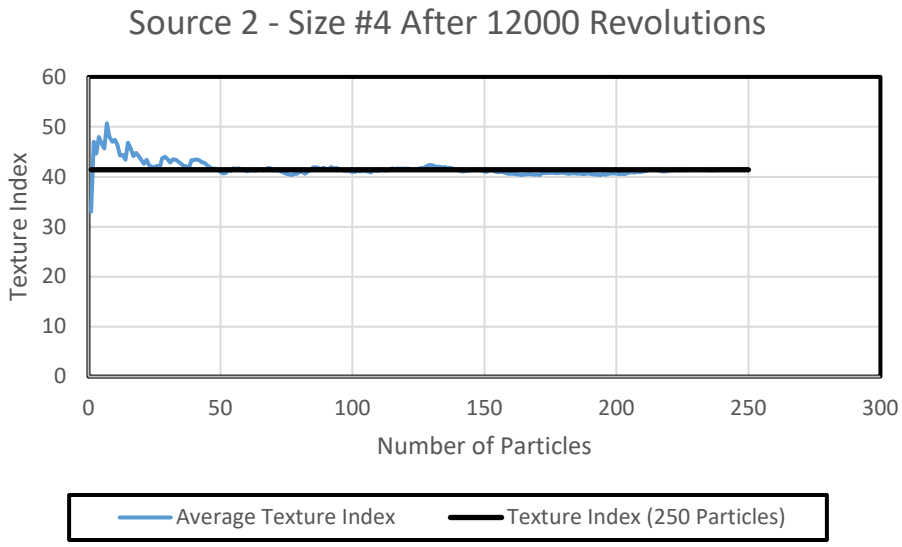

Source 2 - Size #4 After 4500 Revolutions
Texture Index
60
50
40
30
20
10
0
0
50
100
150
200
250
300
Number of Particles
Average Texture Index
Texture Index (250 Particles)

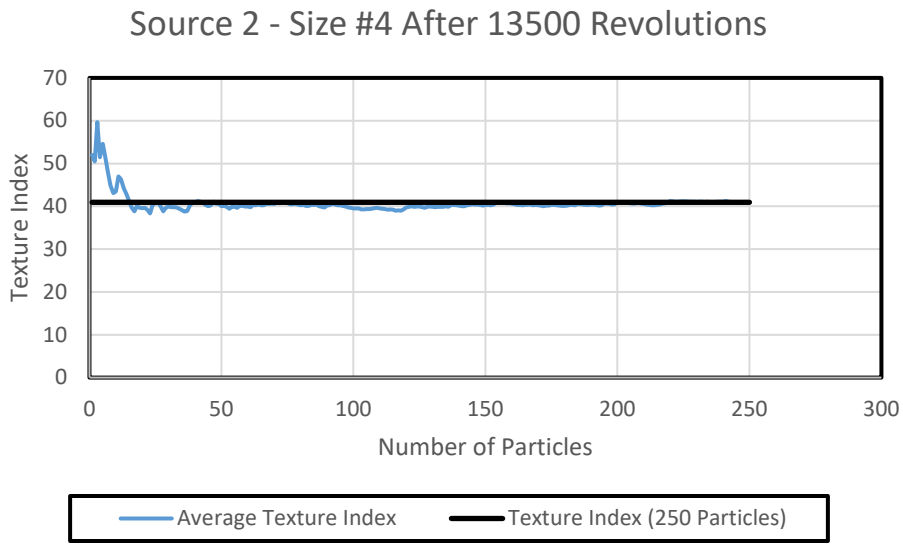

Source 2 - Size #4 After 6000 Revolutions
Texture Index
50
40
30
20
10
0
0
50
100
150
200
250
300
Number of Particles
Average Texture Index
Texture Index (250 Particles)


Source 2 - Size #4 After 7500 Revolutions
Texture Index
50
40
30
20
10
0
0
50
100
150
200
250
300
Number of Particles
Average Texture Index
Texture Index (250 Particles)

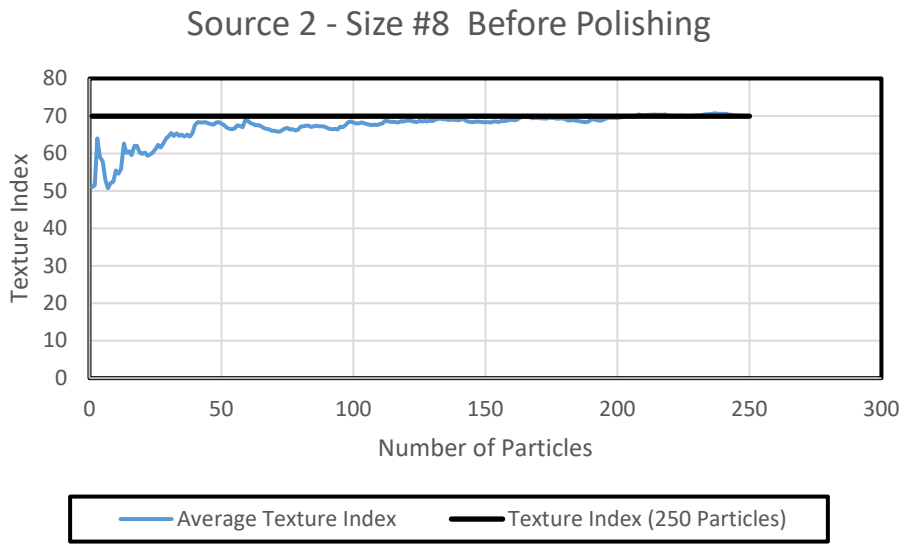

Source 2 - Size #4 After 9000 Revolutions
Texture Index
50
40
30
20
10
0
0
50
100
150
200
250
300
Number of Particles
Average Texture Index
Texture Index (250 Particles)

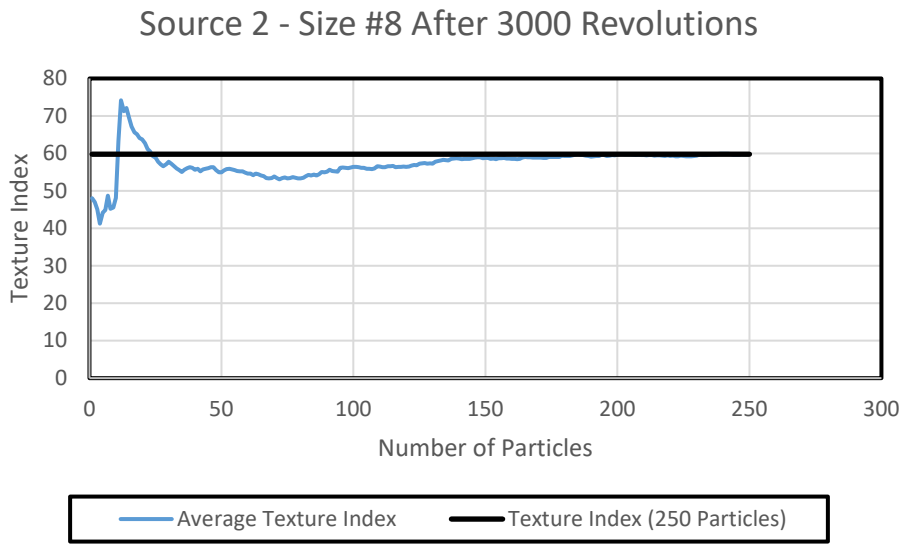

Source 2 - Size #4 After 10500 Revolutions
Texture Index
90
80
70
60
50
40
30
20
10
0
0
50
100
150
200
250
300
Number of Particles
Average Texture Index
Texture Index (250 Particles)

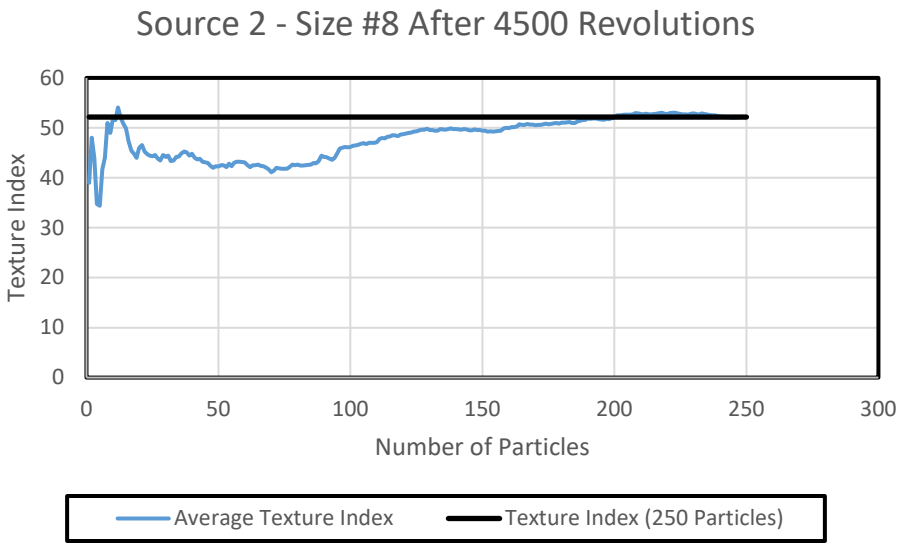

Source 2 - Size #4 After 12000 Revolutions
Texture Index
60
50
40
30
20
10
0
0
50
100
150
200
250
300
Number of Particles
Average Texture Index
Texture Index (250 Particles)

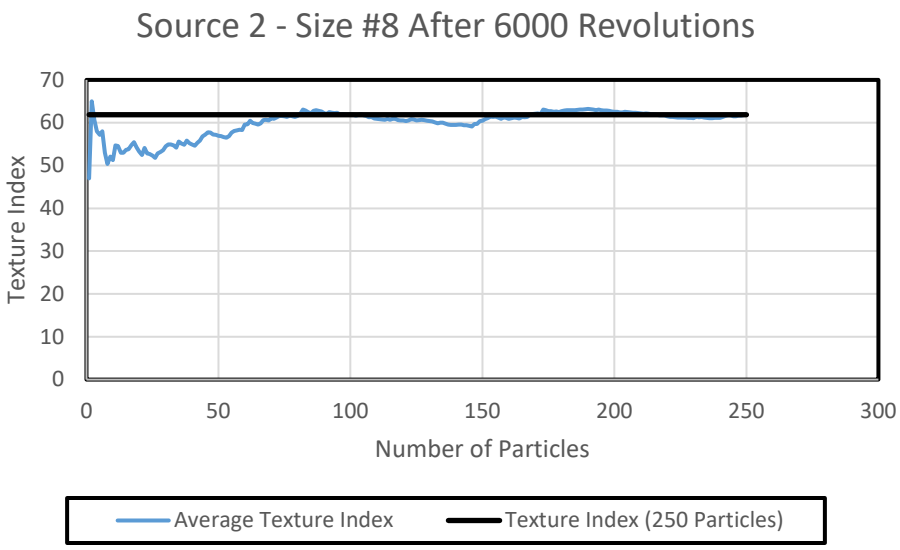

Source 2 - Size #4 After 13500 Revolutions
Texture Index
70
60
50
40
30
20
10
0
0
50
100
150
200
250
300
Number of Particles
Average Texture Index
Texture Index (250 Particles)

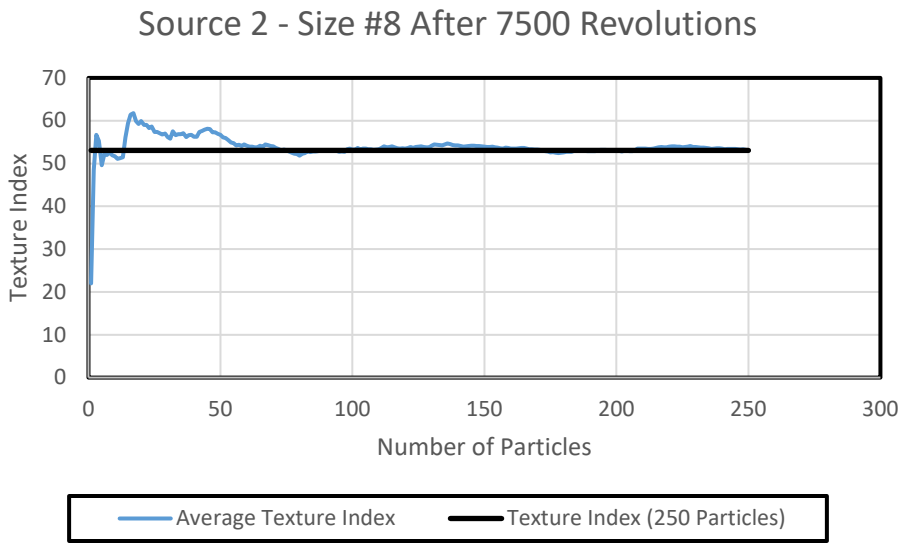
Source 2 – Size #8 (Texture)

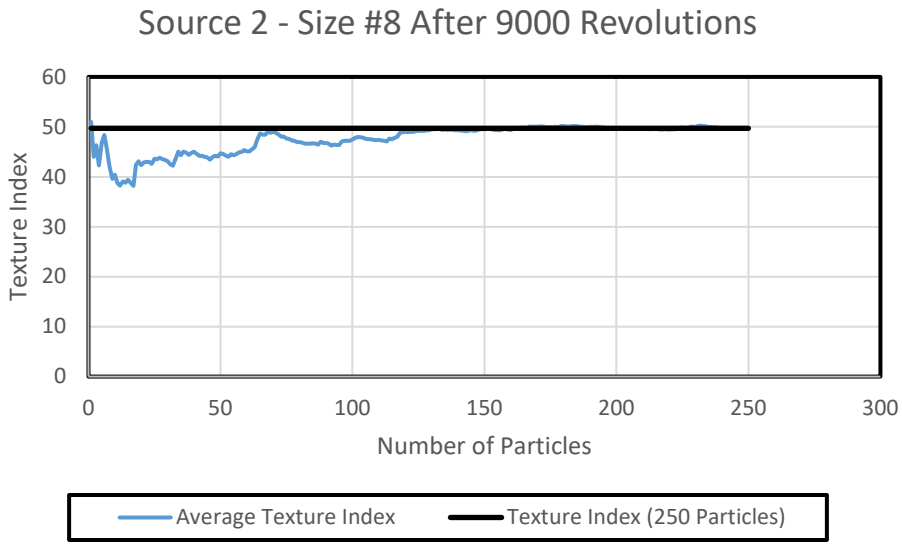


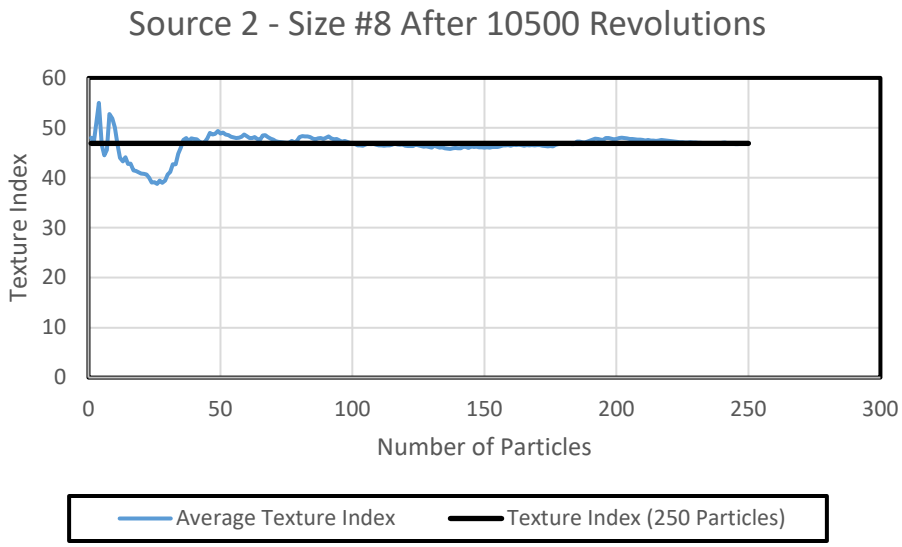


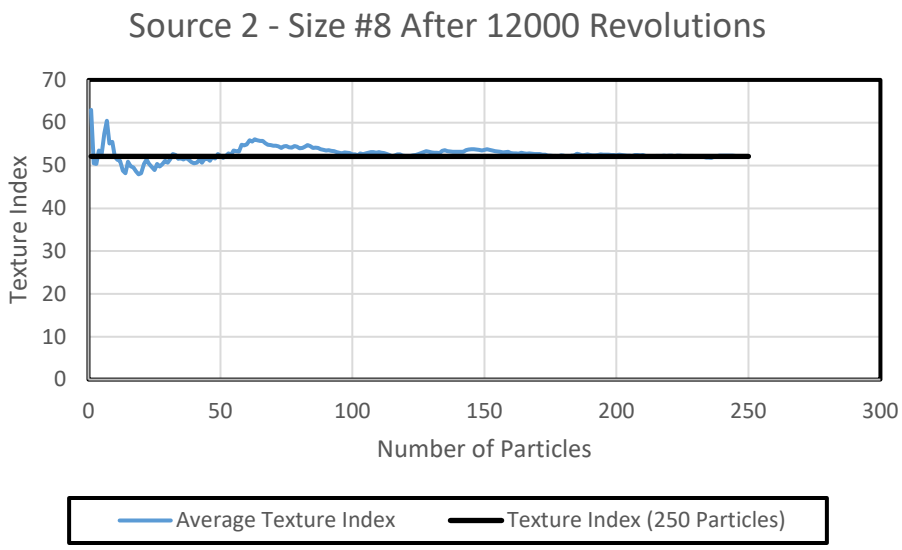

Source 2 - Size #8 After 4500 Revolutions
Texture Index
60
50
40
30
20
10
0
0
50
100
150
200
250
300
Number of Particles
Average Texture Index
Texture Index (250 Particles)

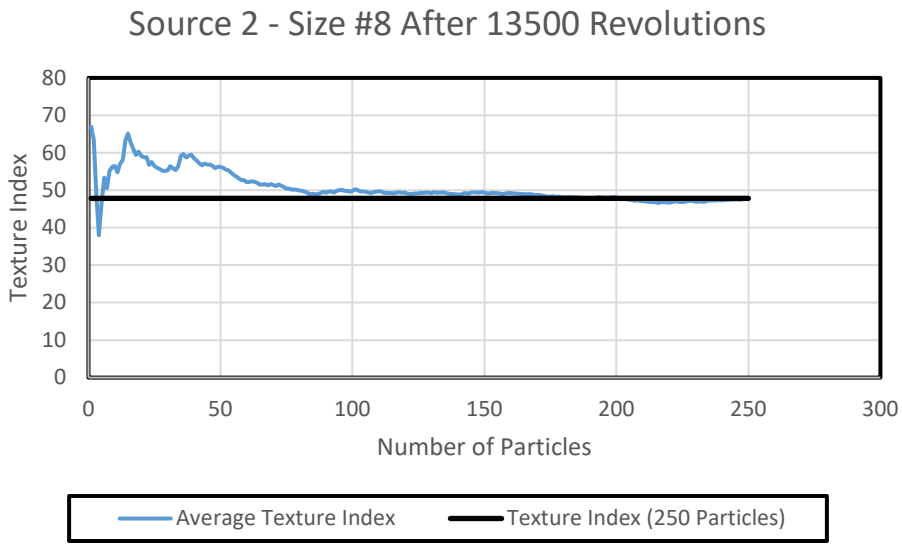

Source 2 - Size #8 After 6000 Revolutions
Texture Index
70
60
50
40
30
20
10
0
0
50
100
150
200
250
300
Number of Particles
Average Texture Index
Texture Index (250 Particles)


Source 2 - Size #8 After 7500 Revolutions
Texture Index
70
60
50
40
30
20
10
0
0
50
100
150
200
250
300
Number of Particles
Average Texture Index
Texture Index (250 Particles)


Source 2 - Size #8 After 9000 Revolutions
Texture Index
60
50
40
30
20
10
0
0
50
100
150
200
250
300
Number of Particles
Average Texture Index
Texture Index (250 Particles)


Source 2 - Size #8 After 10500 Revolutions
Texture Index
60
50
40
30
20
10
0
0
50
100
150
200
250
300
Number of Particles
Average Texture Index
Texture Index (250 Particles)


Source 2 - Size #8 After 12000 Revolutions
Texture Index
70
60
50
40
30
20
10
0
0
50
100
150
200
250
300
Number of Particles
Average Texture Index
Texture Index (250 Particles)


Source 2 - Size #8 After 13500 Revolutions
Texture Index
80
70
60
50
40
30
20
10
0
0
50
100
150
200
250
300
Number of Particles
Average Texture Index
Texture Index (250 Particles)

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