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Investigation of Relationships Between AIMS Shape Properties and VST Friction Values

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16. Abstract

A thorough analysis was conducted for AIMS shape properties measured for virgin aggregates, aggregates polished in the Micro-Deval (MD) for 105 and 210 minutes, and VST friction samples. Excellent repeatability of AIMS angularity and texture measurements was observed. Investigating the relationships between AIMS-MD angularity and texture, a strong relationship was found between VST friction values and AIMS AMD-105 angularity and a combined angularity and texture of AIMS measurements also for AMD-105. This indicates that VST friction values are a function of both texture and angularity. Furthermore, the strong correlation between AIMS AMD-105 texture and the surface texture of VST friction samples indicated that MD is a viable option for replacing VST as a polishing mechanism and that current VST procedure might not be long enough to achieve terminal texture. Further analysis indicated that AIMS AMD-105 shape properties could potentially replace AMD-210 for selecting and ranking aggregates for friction properties. However, the recommendation is to keep testing at both polishing intervals. Finally, clustering analysis was conducted to obtain threshold for classifying aggregate angularity and texture into acceptable and non-acceptable zones (i.e., defining the criteria for qualifying aggregates for friction purposes). In this study, two types of clustering were used: two-step cluster analysis and the K-means cluster analysis. The final outcome of this analysis was that an aggregate source with texture AMD-105 > 140 and angularity AMD-105 > 1240 is recommended for friction purposes.

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EXECUTIVE SUMMARY

The objective of this project was to conduct a thorough analysis of the second-generation Aggregate Imaging System (AIMS-II) and Micro-Deval (MD) shape properties and variable speed test (VST) friction data collected in project R27-129 and by personnel in the Bureau of Materials and Physical Research (BMPR) of the Illinois Department of Transportation (IDOT).

In coordination with IDOT personnel, the database obtained in R27-129 was updated with aggregate sources tested during 2013 and 2014. Additional VST friction testing was performed by BMPR in the first half of 2014. These data were added to the original VST and AIMS testing results; a total of 88 aggregate samples had both AIMS and VST friction data available.

Preliminary analysis of 13 samples from R27-129 and thorough analyses of the 88 samples from this project clearly indicated a strong relationship between VST friction data and AIMS angularity for AMD-105 samples; furthermore, the relationship is enhanced when a combined AIMS angularity and texture is correlated to VST friction data. This clearly indicated that VST friction data are dependent on both aggregate texture and angularity; it also indicated that the current VST friction procedure might not be long enough to achieve terminal polishing.

This was further investigated by scanning VST friction sample surfaces with AIMS to obtain texture measurements. The texture measurements had a strong correlation with AIMS texture for AMD-105, which also indicated that MD is a viable polishing procedure that is capable of achieving a similar or higher level of polishing compared with VST.

In addition, the data collected were used to study AIMS angularity and texture repeatability and the relationship between AMD-105 and AMD-210 for both properties. The analysis found an excellent repeatability with linear regression R-squared values of 0.94 for angularity and 0.98 for texture correlating replicate samples; additionally, the AMD-105 and AMD-210 correlation was higher for texture than angularity, which is attributed to the fact that changes in angularity are dependent on both abrasion and breakage. This analysis indicated that the AMD-105 could potentially replace AMD-210 for selecting and ranking aggregates for friction properties. However, the recommendation is to keep testing at both polishing intervals.

Finally, clustering analysis was conducted to obtain a threshold for classifying aggregate angularity and texture into acceptable and non-acceptable zones (i.e., defining the criteria for qualifying aggregates for friction purposes). In this study, two types of clustering were used: two-step cluster analysis and K-means cluster analysis. The final outcome of this analysis was that an aggregate source with texture AMD-105 > 140 and angularity AMD-105 > 1240 is recommended for friction purposes.

CONTENTS

CHAPTER 1 INTRODUCTION

1.1 BACKGROUND AND RELEVANT LITERATURE

Properties of aggregates impact several aspects of asphalt pavement performance. The performance parameters affected by aggregate properties are permanent deformation, fatigue cracking, frictional resistance, thermal cracking, and raveling (Kandhal and Parker 1998). The main aggregate properties that are linked to asphalt pavement performance are gradation and size, particle shape and surface texture, porosity, cleanliness, toughness and abrasion resistance, durability and soundness, expansive characteristics, polish and frictional characteristics, and mineralogy and petrography (Kandhal and Parker 1998).

Additionally, the shape properties of aggregate particles significantly affect the performance of the unbound/bound layers of highway/airfield pavements, as well as railroad ballast, under dynamic traffic loading in terms of shear strength, modulus, and permanent deformation characteristics (Kandhal and Parker 1998; Masad et al. 2007; Tutumluer and Pan 2008; Indraratna and Salim 2005). The influence of aggregate shape characteristics on asphalt pavement performance was highlighted in a research study conducted under National Cooperative Highway Research Program NCHRP 4-30A (Masad et al. 2007). The study revealed that shape, angularity, and texture were all significant characteristics for predicting pavement performance.

In another study (McGahan 2005), comprehensive statistical analyses were conducted to investigate relationships between aggregate shape characteristics and asphalt mix mechanical properties. The study showed that aggregate shape characteristics impact the mechanical properties of asphalt mixes.

Frictional resistance, known as skid resistance, is considered one of the most important performance parameters of asphalt pavement. The importance of pavement frictional resistance stems from its impact on travel safety; thus, a minimum acceptable safe limit must be maintained (Bloem 1971). Skid resistance of asphalt pavements depends primarily on the microtexture and macrotexture of the surface (Dahir 1979). Microtexture depends primarily on aggregate shape characteristics, while macrotexture is a function of the mix properties, compaction method, and aggregate gradation (Kandhal and Parker 1998; Crouch et al. 1995; Luce et al. 2007; Forster 1989). Skid resistance of asphalt pavement surfaces is presumably adequate right after pavement construction and after the pavement is opened to traffic; aggregates that resist polishing and wear are therefore desired (Bloem 1971). Aggregate polishing resistance is often tested to evaluate aggregate materials before they are used in hot-mix asphalt (HMA) surface courses.

Another important aggregate property that influences several HMA performance parameters is aggregate resistance to abrasion and breakage, better known as degradation. Abrasion is defined as the loss of aggregate angularity, while breakage refers to the fracturing of particles. Before the pavement is put into service, aggregates are exposed to degradation during production, transportation, and construction (mixing and compaction). Several types of forces such as attrition, impact, and grinding are imposed on the aggregate particles at different stages. This includes production at the quarry/plant (Page et al. 1997), transportation to job site, and compaction during construction. These factors, along with in-service dynamic traffic loading and environmental effects, cause aggregate degradation.

Aggregate degradation affects gradation; thus, the mix produced in the field differs from the mix designed in the laboratory (Wu, Parker, and Kandhal 1998). Initially, contact forces provide the energy required for the relocation/rearrangement of particles, and therefore aggregate particles are subjected to contact forces when adjusting to their new locations, which may eventually cause breakage and wear at the points of contact (Moavenzadeh and Goetz 1963). Mineralogical and petrographic properties as well as initial gradations are crucial factors that control the magnitude and trend of aggregate degradation.

Several studies investigated the characterization of aggregate degradation and its effect on the bearing capacity of unbound/bound layers in terms of the change in size distribution or decrease in the coarse to fine fraction ratio (Pintner, Vinson, and Johnson 1987; Gatchalian et al. 2006; Lynn et al. 2007). Only a few research studies examined the effect of aggregate degradation on altering shape characteristics of the aggregates. Aggregate degradation can cause particles to lose their angularity and surface texture or become more rounded and spherical. This results in changing the void ratio or packing properties, ultimately influencing the performance.

The lack or research in this area may possibly be attributed to the absence of a unified standard procedure for rapid and quantitative measurement of the shape properties of aggregate particles. New generations of asphalt mixes, such as stone matrix asphalt (SMA), transfer stresses within the aggregate structure, thus producing high stresses at the stone-to-stone contact points that might cause aggregate fracture and, consequently, affect the performance of the mix (Gatchalian 2005).

The methods used for measuring aggregate shape characteristics are classified into two categories: direct and indirect (Kandhal, Motter, and Khatri 1991; Janoo 1998; Chowdhury et al. 2001). In direct methods, particle shape characteristics are measured, described, or quantified through direct measurement of individual aggregate particles, whereas the indirect methods measure particle shape characteristics as a bulk property of aggregate particles.

Direct methods range from simple, visual methods to mechanical devices and sophisticated advanced imaging systems. Several imaging systems are currently available for measuring aggregate shape characteristics (Barksdale et al. 1992; Kuo et al. 1996; Masad et al. 1999a, 1999b; Brzezicki and Kasperkiewicz 1999; Weingart and Prowell 1999; Maertz and Zhou 2001; Tutumluer, Rao, and Stefanski 2000; Li et al. 1993; Wilson and Klotz 1996; Yeggoni, Button, and Zollinger 1994; Masad, Button, and Papagiannakis 2000, Masad et al. 2001; Kuo and Freeman 2000; Rao, Tutumluer, and Kim 2002; Hryciw and Raschke 1996; Wang and Lai 1998; Masad and Button 2000; Masad et al. 2001).

With the introduction of the software and hardware components of advanced machine vision technology, it has become possible to measure the shape properties of aggregates in a quantitative and objective manner. A variety of imaging-based aggregate morphological indices have been developed and linked to material strength and deformation properties (Al-Rousan et al. 2007; Wang et al. 2012). Although none of these methods has yet been recommended as a standard testing procedure, extensive research has been performed of aggregate productions (Mahmoud et al. 2010; Pan and Tutumluer 2010). According to the NCHRP 4-30 study (Masad et al. 2007), flat and elongated ratio (FER), angularity index (AI), and surface texture index (STI) measured with the Aggregate Imaging System (AIMS) and the University of Illinois Aggregate Image Analyzer (UIAIA) are recognized as the most validated indices to represent the aggregate shape properties and their linkage to field performance.

During the past decade, researchers have started using imaging-based measurement of aggregate shape properties along with laboratory degradation resistance testing methods to quantify the magnitude and trend of aggregate degradation. UIAIA has been combined with the Los Angeles abrasion and impact test (ASTM C535) to measure the effect of abrasion and impact forces on shape properties during the degradation process (Boler, Wnek, and Tutumluer 2012).

Recently, several studies evaluated the use of the Micro-Deval test along with imaging systems to measure the effect of the test on aggregate shape characteristics (Mahmoud 2005; Luce 2006; Lane et al. 2011). Mahmoud and Masad (2007) used AIMS along with the Micro-Deval test to measure aggregate polishing, abrasion, and breakage. Aggregate polishing was characterized at several Micro-Deval polishing times by measuring the texture index, while abrasion and breakage were characterized by angularity and weight loss measurements. The study illustrated the capability of Micro-Deval along with AIMS texture measurements to polish aggregates and to measure aggregate polishing characteristics: initial texture, rate of polishing, and terminal texture were successfully estimated.

More recent studies have shown the ability of imaging techniques to evaluate the level of degradation on site by measuring the shape properties of the aggregate samples collected from asphalt plants or from in-service, unbound aggregate layers (Singh, Zaman, and Commuri 2013; Moaveni et al. 2013).

1.2 OBJECTIVE OF THE STUDY

A recently completed research study (project R27-129) sponsored by the Illinois Department of Transportation (IDOT) through the Illinois Center for Transportation (ICT) focused on implementation of the second-generation Aggregate Imaging Measurement System (AIMS-II; Figure 1.1) in measuring aggregate shape properties. An aggregate polishing procedure coupling AIMS-II for measuring aggregate shape properties and the Micro-Deval (MD) as a polishing procedure was developed in R27-129, and the polishing trends and ranking compared favorably with IDOT historical friction data; however, it was not feasible within the time and budget limitations of R27-129 project to obtain variable speed test (VST) friction data to directly compare it with the newly developed polishing procedure results. Additionally, a database was generated for all aggregates tested in R27-129; the database included aggregate shape properties (texture and angularity) measured before and after MD polishing.

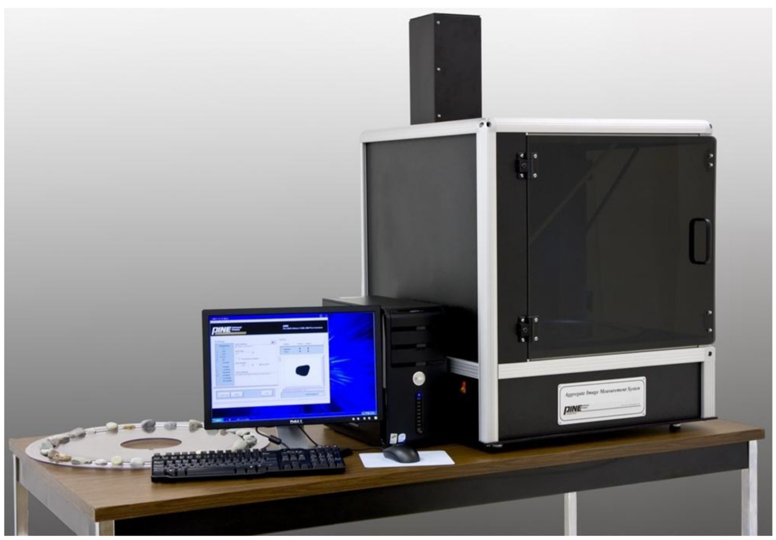


Figure 1.1 Second-generation Aggregate Imaging Measurement System (AIMS-II).

The objective of the current project was to conduct a thorough analysis of AIMS-II and MD shape properties and VST friction data collected in R27-129 and by BMPR personnel. The major outcomes of this project are recommendations on the use of AIMS-II data and modified specifications for IDOT’s aggregate polishing procedure.

For simplicity, AIMS-II will be referred to as AIMS in this report.

1.3 RESEARCH APPROACH

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

1.3.1 Task 1—Compile AIMS and VST Data

The research team worked with IDOT personnel to compile all AIMS and VST data collected by the principal investigator in R27-129 and by BMPR during 2013–2014. During the first half of the 2014 calendar year, BMPR personnel collected VST friction data for aggregate sources/samples tested in R27-129. These data were added to the R27-129 project database.

1.3.2 Task 2—Preliminary Analysis

The research team performed preliminary analysis on the collected AIMS and VST data. The objective of this analysis was to explore relationships between AIMS shape properties and VST friction data. The analysis focused on aggregate shape properties before M-DI polishing and after 105, and 210 minutes of polishing (terminal polishing), aggregate gradation change after MD polishing, and how these properties related to VST data.

1.3.3 Task 3—Preliminary Analysis Presentation to TRP

The research team met with the TRP and discussed the results of Tasks 1 and 2. Based on the preliminary analysis and discussions with the TRP, the research team performed clustering analysis of aggregate shape properties before Micro-Deval (BMD), after Micro-Deval 105 minutes degradation (AMD-105), and after Micro-Deval 210 minutes degradation (AMD-210) to establish recommendations for future use of AIMS data and modified specifications for IDOT aggregate polishing procedure.

1.3.4 Task 4—Recommendations and Modified Specification

Recommendations and suggested specifications are outlined in this report.

1.3.5 Task 5—Prepare and Revise the Final Report

This final report explains the methodology, findings, and conclusions of this study.

CHAPTER 2 EXPERIMENTAL PROGRAM

2.1 MATERIALS AND EQUIPMENT

The aggregate materials used in this study were selected from a wide range of mineralogical properties and various quarries in different geographical regions in the state of Illinois and neighboring states. All aggregate materials were washed, oven dried, and sieved to obtain particle sizes passing the 1/2 in. (12.5 mm) sieve and retained on the 3/8 in. (9.5 mm) sieve. Table 2.1 lists the types and designations of all aggregate materials tested. Testing equipment used in this research were MD, AIMS, VST, and the British Pendulum Tester.

Table 2.1 Aggregate Material Type and Number of Samples

Aggregate Type	Number of Samples
Dolomite	44
Limestone	39
Lower Gravel	10
Lower Crushed Gravel	3
Upper Gravel	13
Upper Crushed Gravel	8
ACBF Slag	2
Steel Slag	4
Sandstone	4
Granite/Diabase/Quartzite	3
Total Samples	130

2.2 TESTING PROCEDURES

Aggregate resistance to degradation was measured based on the following procedure:

- Two aggregate samples were obtained from the selected source: each sample was 750 g passing the 1/2 in. sieve and retained on the 3/8 in. sieve.
- The aggregate particles were scanned with AIMS to obtain initial aggregate shape properties BMD.
- The Micro-Deval drum was filled with 750 g of aggregate materials.
- The drum was charged with 5000 g of 9.5 mm diameter steel balls and 2 L of water.
- The aggregate sample was subjected to a target degradation time:
    - Sample 1: 105 minutes
    - Sample 2: 210 minutes
- The sample was washed on top of the No. 16 sieve size and the steel balls were removed.
- The aggregate shape measurements associated with each degradation time for the portion retained on the 3/8 in. sieve were recorded and labeled as AMD-105 and AMD-210.

In addition to AIMS-MD testing, BMPR personnel prepared and polished VST friction testing samples. After polishing, the samples were tested with the British Pendulum Tester to obtain their friction properties. Finally, a subset of the VST friction samples was scanned with AIMS for texture measurements.

CHAPTER 3 RESULTS AND ANALYSES

3.1 PRELIMINARY ANALYSIS

Initially, a limited number of VST samples was available for preliminary analysis of the relationship between VST friction data and AIMS-MD results. Table 3.1 lists the VST friction values before and after polishing, along with the sample number, which corresponds to AIMS sample numbers from the in R27-129 database. VST initial friction values (before polishing) were compared with AIMS angularity, texture, and coarse aggregate angularity texture (CAAT) before polishing in the MD, as illustrated in Figures 3.1, 3.2, and 3.3, respectively. The results show the general relationship between AIMS shape properties and VST.

Table 3.1 VST R27-129 Data

	VST	
Sample #	**Initial**	**Final**
030	48.7	35.4
029	57.5	39.4
039	55.0	38.6
070	56.3	39.4
016	55.1	36.4
072	58.7	45.8
031	58.7	45.8
062	56.2	46.8
032	56.2	46.8
043	68.4	49.3
027	68.4	49.3
023	73.3	56.3
063	65.0	47.7

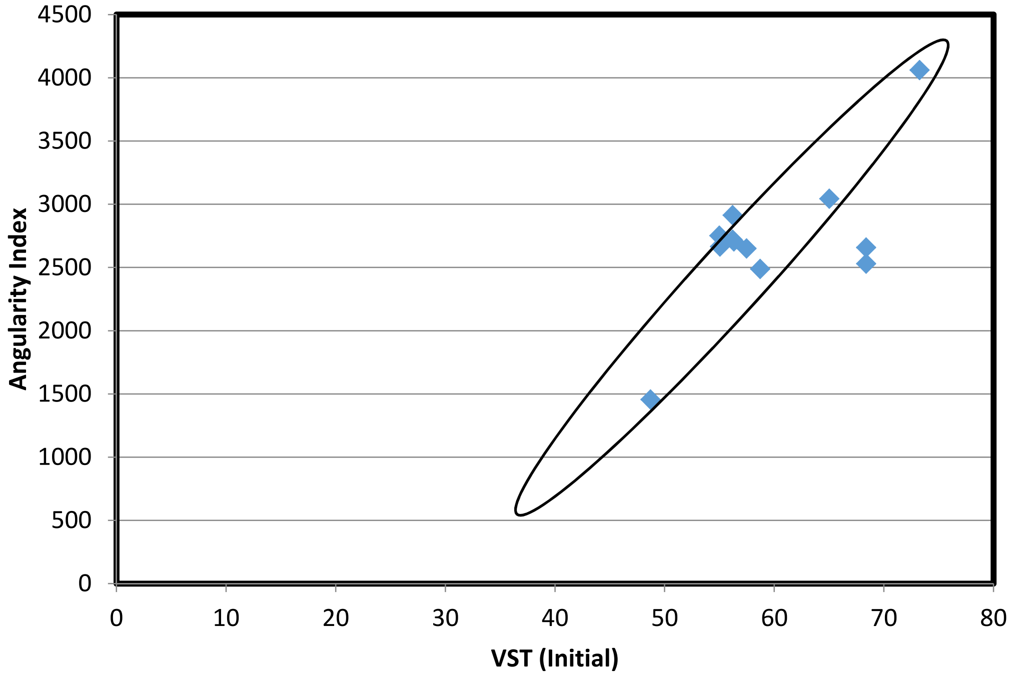


Figure 3.1 Relationship between angularity (BMD) and initial VST.

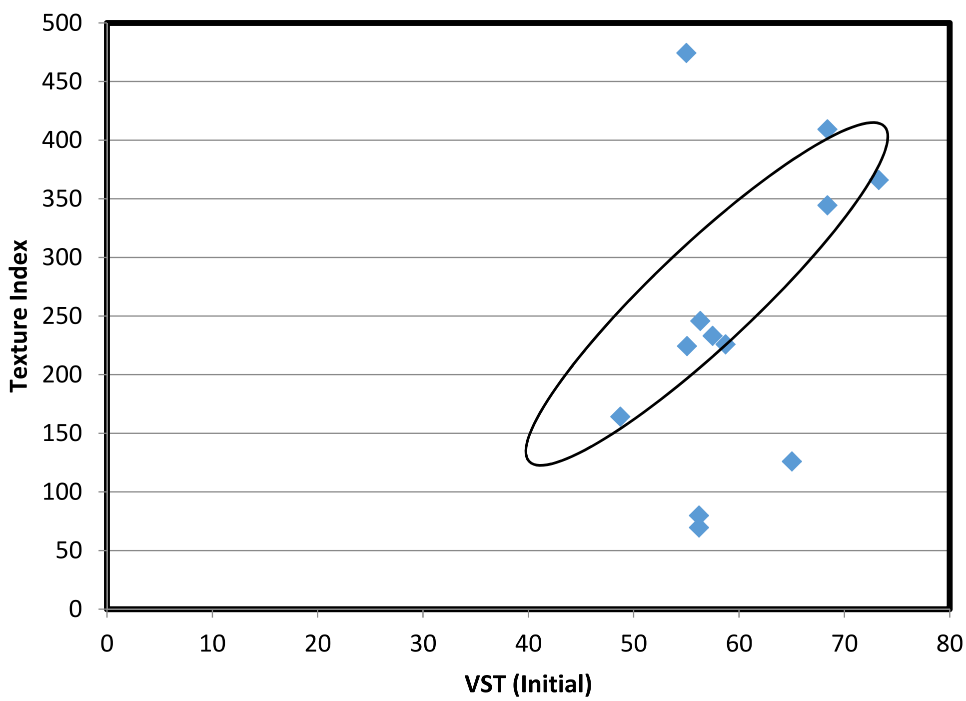


Figure 3.2 Relationship between texture (BMD) and initial VST.

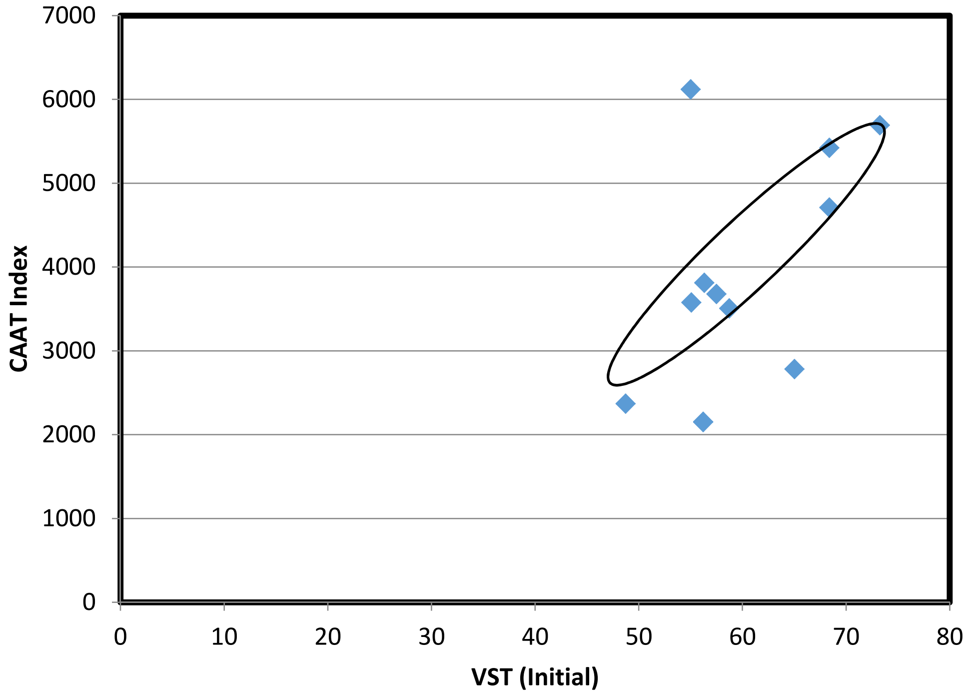


Figure 3.3 Relationship between CAAT (BMD) and initial VST.

Additionally, the relationships between AIMS shape properties after polishing in the MD at 105 minutes and 210 minutes and VST were investigated, Figure 3.4(a–e) illustrates those relationships. As shown in the figures, a very strong relationship exists between angularity AMD-105 minutes and VST final.

In general, AIMS shape properties after 105 minutes of MD polishing showed a stronger relationship with VST final, which could be explained by one of two hypothesis: (1) VST polishing time is not sufficient to reach terminal texture, or (2) MD-210 minutes is producing more breakage, which affects the angularity results. Further analysis of AMD-105 and AMD-210 results will be discussed later in this chapter.

Finally, the research team examined the relationship between VST friction results and a combination of AIMS angularity and texture values because both angularity and texture are expected to contribute to VST friction values. A regression analysis was conducted to establish a simple linear relationship between VST and AIMS angularity and texture. BMD angularity and texture as a function of Initial VST is shown in Figure 3.5, while AMD-105 angularity and texture as function of final VST is shown in Figure 3.6. As shown in those two figures, the results were very promising, and, on the basis of this preliminary analysis, further samples were tested to establish relationships between AIMS and VST friction values.

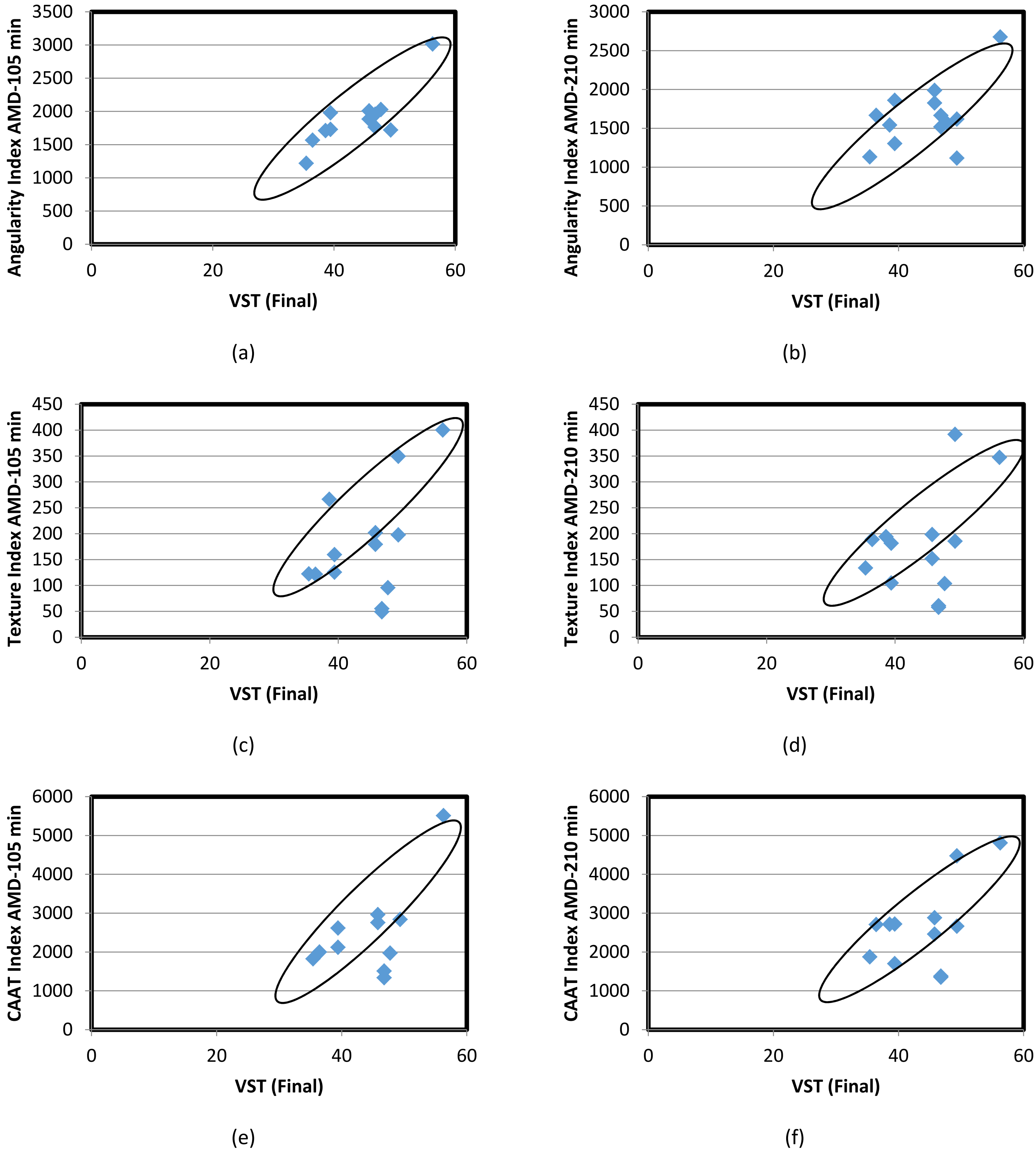


Figure 3.4 Relationships between final VST and AIMS shape properties: (a) angularity AMD-105 minutes, (b) angularity AMD-210 minutes, (c) texture AMD-105 minutes, (d) texture AMD-210 minutes, (e) CAAT AMD-105 minutes, and (f) CAAT AMD-210 minutes.

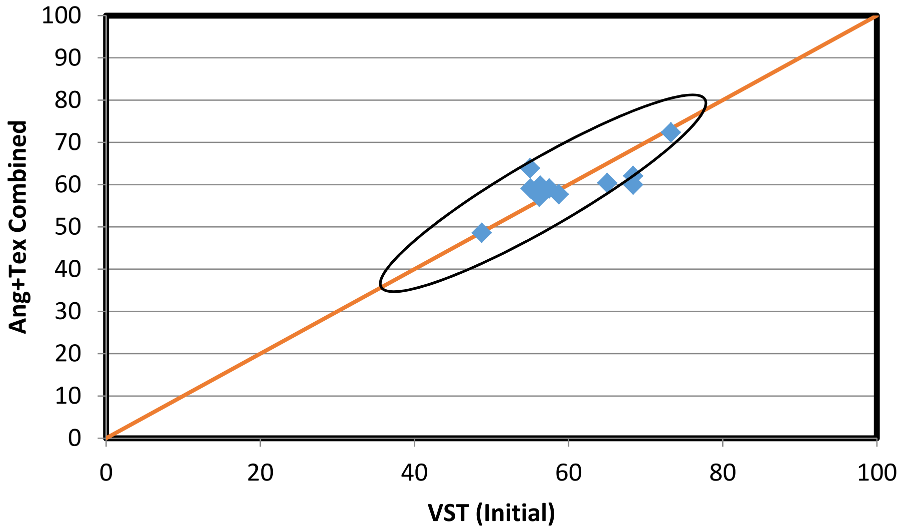


Figure 3.5 Relationships between initial VST and angularity and texture combined.

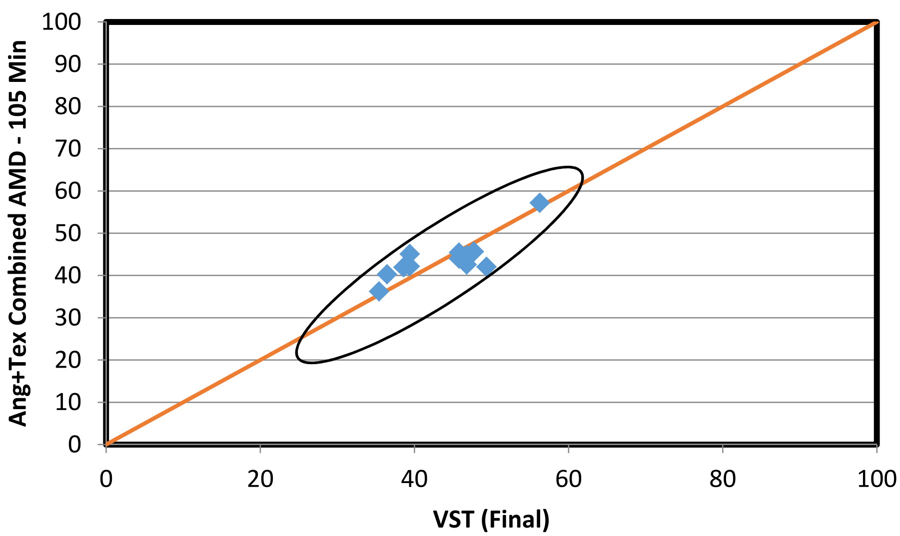


Figure 3.6 Relationships between final VST and angularity and texture combined (AMD-105).

3.2 AIMS VS. VST ANALYSIS

On the basis of the preliminary analysis results, BMPR tested more aggregate samples to establish specifications for AIMS results. In total, 200 samples were tested in AIMS and/or VST, 88 samples were tested in both systems, and every sample had two BMD samples scanned. In addition, 18 VST samples were scanned by AIMS for texture measurements. The analyses included in this section are as follows:

- AIMS angularity and texture repeatability (two BMD samples)
- AIMS and VST data analysis
- VST texture and AIMS texture analysis
- AIMS AMD-105 and AMD-210 comparisons

3.2.1 AIMS Repeatability

The objective of this analysis was to study AIMS repeatability by comparing BMD samples scanned. For each aggregate source, two samples were scanned with AIMS separately. Figures 3.7 and 3.8 illustrate the relationship between the two samples for angularity and texture, respectively. The figures clearly indicate an excellent relationship that is aligned with the equality line. Regression analysis results are summarized in Table 3.2; the relationships are very close to equality with excellent correlation as indicated by the high R-squared values. This analysis provides further evidence of the repeatability of the AIMS system and that it is not sample dependent.

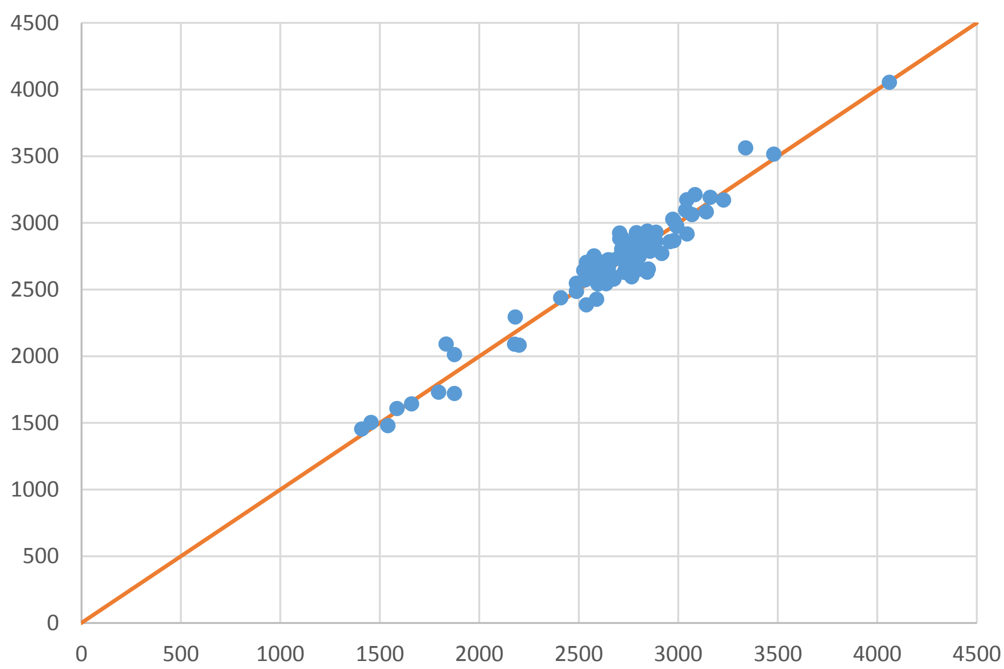


Figure 3.7 AIMS repeatability (angularity).

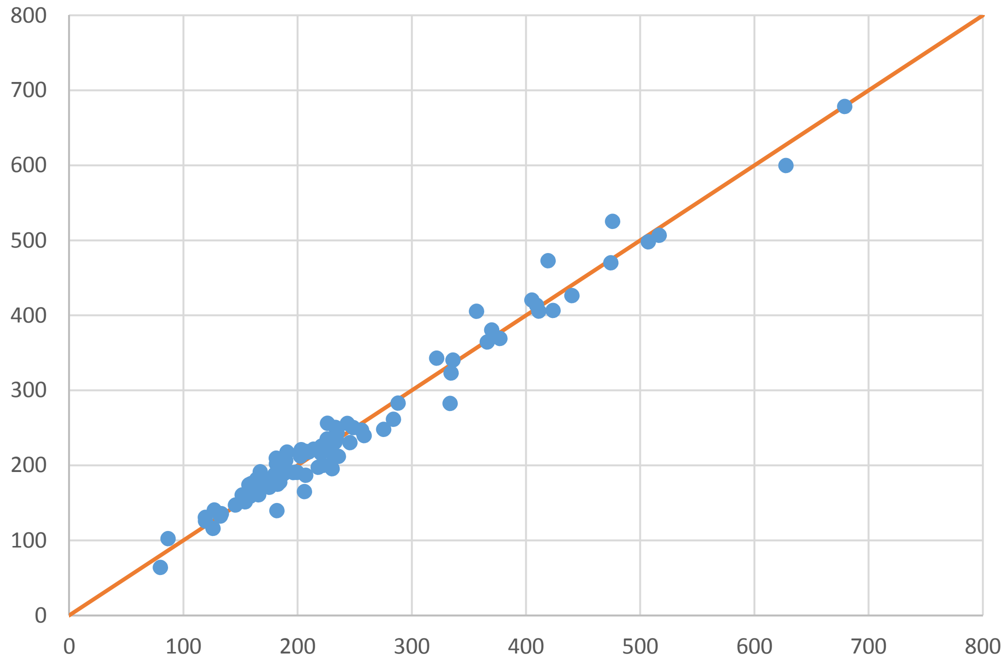


Figure 3.8 AIMS repeatability (texture).

Table 3.2 AIMS Repeatability Regression Results

Shape Property	Linear Equation	R-squared
Angularity	Y = 0.99 X + 33.72	0.94
Texture	Y = 0.99 X + 3.41	0.98

3.2.2 AIMS and VST Data

As previously mentioned, 88 aggregate samples were tested in both AIMS (BMD, AMD-105, and AMD-210) and the VST friction system. A direct comparison between AIMS shape properties (angularity, texture, and angularity and texture combined) is provided in Figure 3.9 a-f. As illustrated in the preliminary analysis, AIMS measurements at AMD-105 minutes showed a more defined relationship with VST friction values than at AMD-210 minutes. Additionally, the best relationship was found for the combination of angularity and texture. However, it is important to note, that the objective of this research was not to find a method that correlates with VST friction values; rather, the objective is to develop more accurate and repeatable methods for measuring aggregate polishing characteristics.

The general agreements in the trends between the two methods is very encouraging. However, there is a clear effect of angularity on the VST friction values, which indicates that it is primarily measuring the macrotexture of the aggregates.

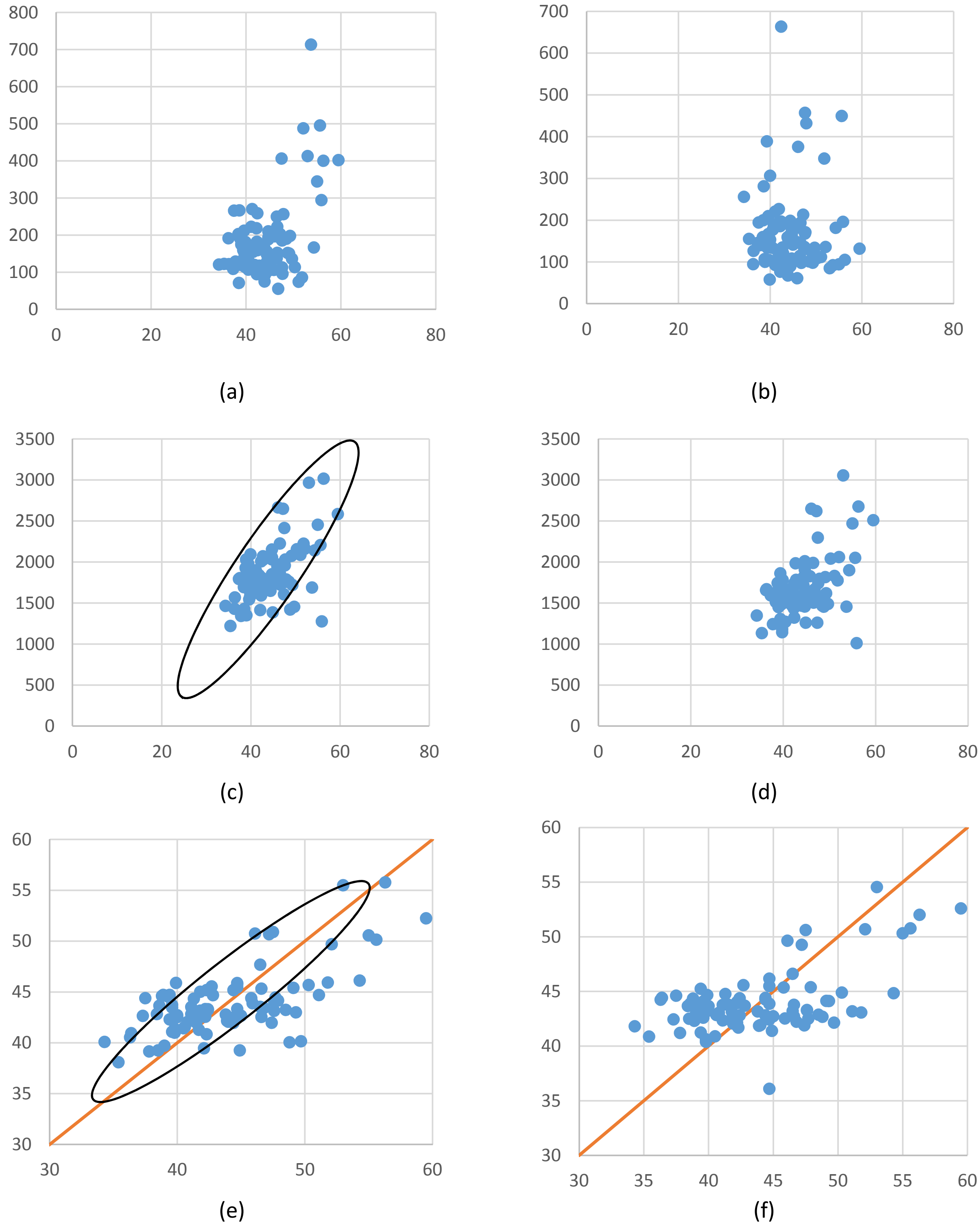


Figure 3.9 Relationships between final VST and AIMS shape properties:
(a) texture AMD-105 minutes, (b) texture AMD-210 minutes, (c) angularity AMD-105 minutes,
(d) angularity AMD-210 minutes, (e) angularity and texture combined AMD-105 minutes,
and (f) angularity and texture combined AMD-210 minutes.

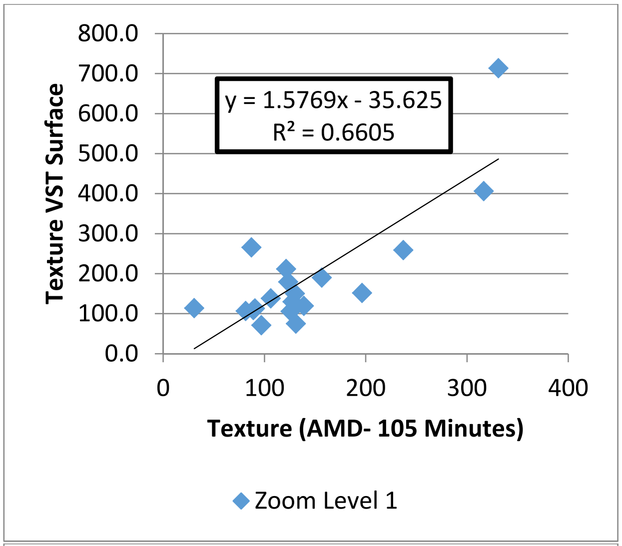
On the basis of these findings and results in the literature, it is anticipated that the strong correlation of angularity with VST friction values rather than texture with VST friction values is due to the use of the British Pendulum and not the polishing mechanism itself. The following are some highlights from the literature about the British Pendulum test:

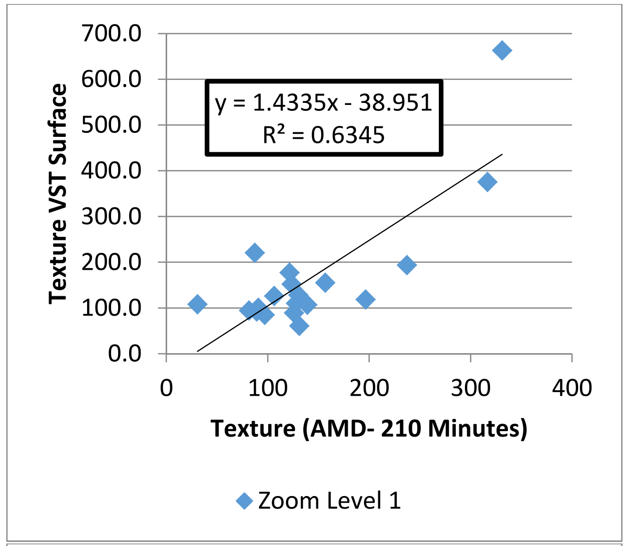
- Aggregate arrangement: Heterogeneous aggregates such as gravel contain some sandy particles that will provide more friction than other particles. Up to a polish value (PV) of 10 decrease was obtained when sandy particles were grouped rather than dispersed (Won and Fu 1996).
- Slider load: A PV change of 4 was reported as a result of changes in slider load within ASTM limits (Won and Fu 1996).
- Number of swings: The slider itself polishes aggregates each time, and the polished value changes with number of swings (Won and Fu 1996).
- Changing the pendulum pad changes the results, even if the two pads used in the study meet the specification (Smith and Fager 1991).
- Data from Kandhal et al. (1993) indicate that it is difficult to distinguish between aggregates using this test (small range).

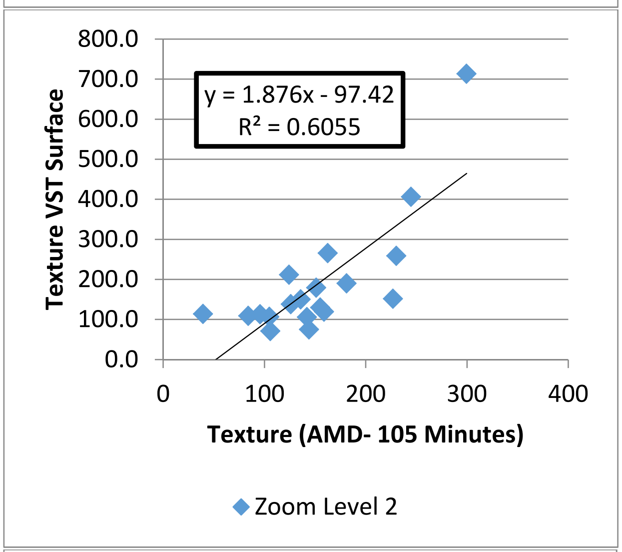
The relationship between AIMS and VST was further investigated by studying the relationship between AIMS texture measurements on AMD-105 and AMD-210 with AIMS texture measurements of the VST sample surface itself.

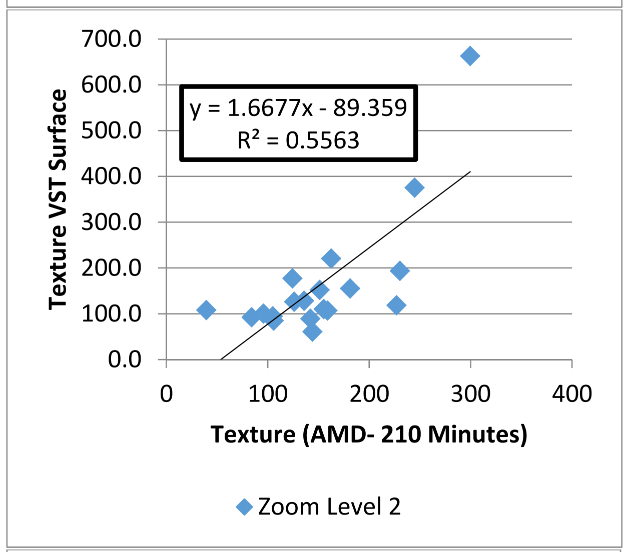
AIMS allows for measuring texture on surface of cylindrical mixes, such asphalt, concrete, field cores, or VST friction test samples. AIMS measures the texture at five zoom levels. AIMS texture AMD-105 and AMD-210 were compared with the VST surface texture measurements as shown in Figure 3.10, which clearly indicates that AIMS AMD-105 and AMD-210 textures for zoom levels 3 and 4 has an excellent correlation with VST surface texture (R-squared > 0.90). This is a clear indication that the MD test is a viable polishing technique and could be used as a replacement for VST.

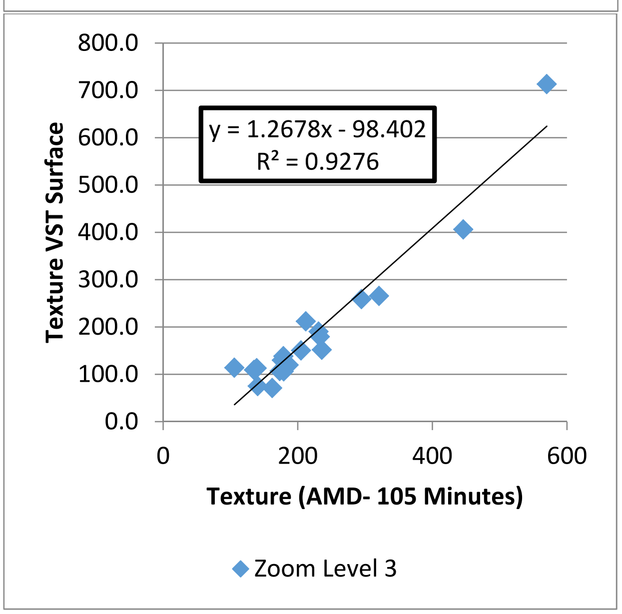
Consistent with previous findings in this report, the correlation between AMD-105 texture with VST texture was better than the correlation between AMD-210 texture with VST texture, which again supports the hypothesis that the current VST friction test procedure might not be long enough to produce terminal texture. Histogram distributions of AIMS texture and VST friction values from this study are presented in Appendix A and Appendix B, respectively.

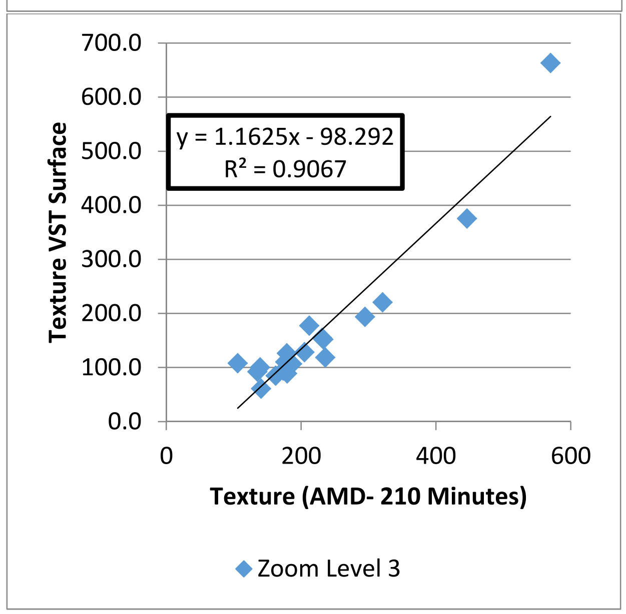

y = 1.5769x - 35.625
R² = 0.6605
Texture VST Surface
Texture (AMD- 105 Minutes)
Zoom Level 1


y = 1.4335x - 38.951
R² = 0.6345
Texture VST Surface
Texture (AMD- 210 Minutes)
Zoom Level 1


y = 1.876x - 97.42
R² = 0.6055
Texture VST Surface
Texture (AMD- 105 Minutes)
Zoom Level 2


y = 1.6677x - 89.359
R² = 0.5563
Texture VST Surface
Texture (AMD- 210 Minutes)
Zoom Level 2


y = 1.2678x - 98.402
R² = 0.9276
Texture VST Surface
Texture (AMD- 105 Minutes)
Zoom Level 3


y = 1.1625x - 98.292
R² = 0.9067
Texture VST Surface
Texture (AMD- 210 Minutes)
Zoom Level 3

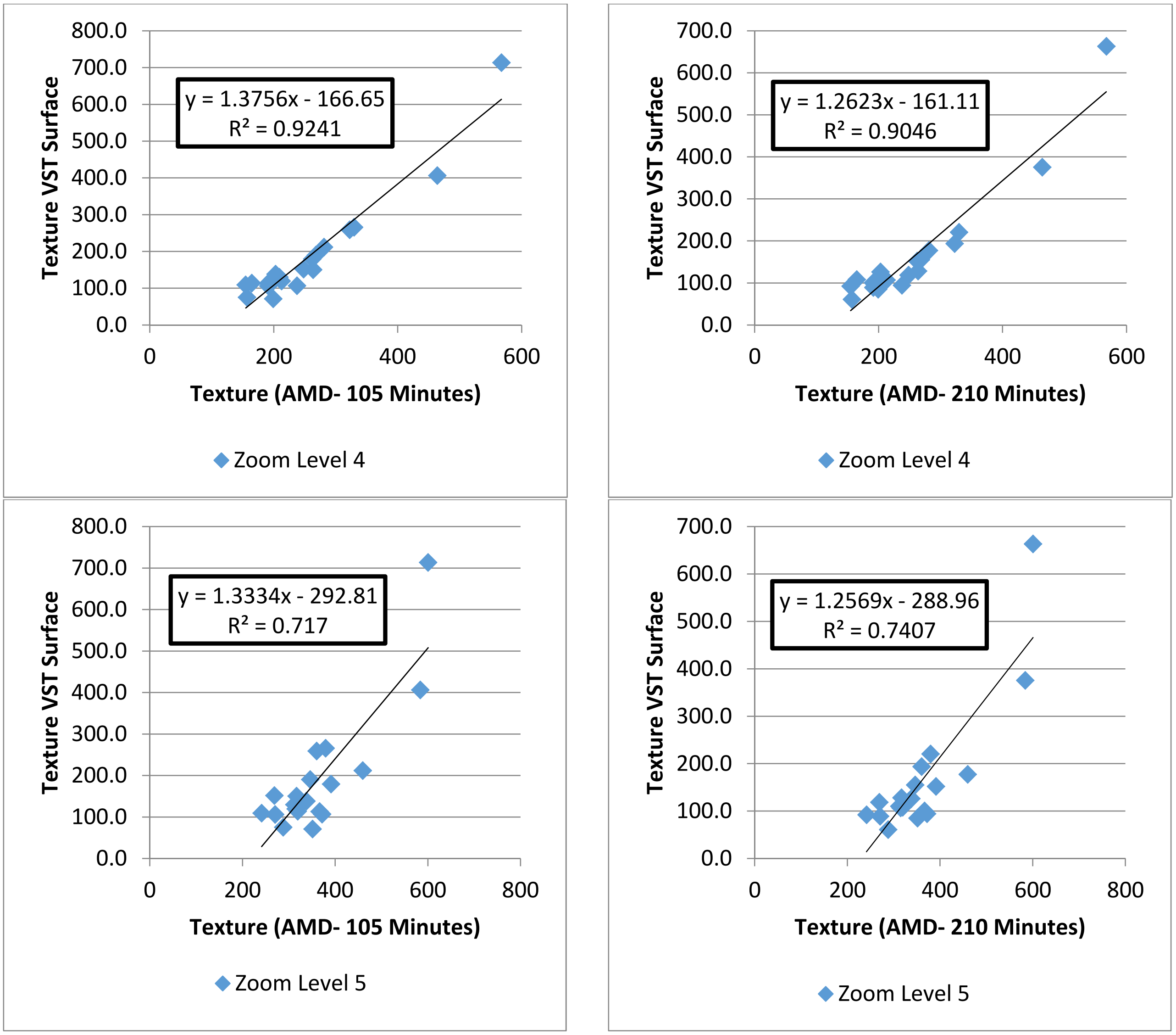


Figure 3.10 Relationships between final VST surface texture and AIMS AMD texture.

3.2.3 AIMS— AMD-105 and AMD-210 Comparison

As illustrated by the previous analyses, VST friction values and surface texture showed a better correlation with AIMS AMD-105 than with AMD-210. However, the polishing procedure recommended in R27-129 was to polish aggregates at both 105 and 210 minutes. To further investigate this issue, the relationship between AIMS shape properties at AMD-105 and AMD-210 minutes was investigated.

Simple linear regression was used to investigate these relationships. Figures 3.11 and 3.12 illustrate the results for angularity and texture, respectively. The figures clearly indicate an excellent relationship for texture results, which indicates that the ranking of aggregates will not change regardless of whether the texture is AMD-105 or AMD-210. However, the angularity relationship was less clear, which could be attributed to the fact that angularity measurements will be affected by both abrasion and breakage.

This analysis indicates that AMD-105 could potentially replace AMD-210 for selecting and ranking aggregates for friction properties. However, the recommendation is to keep testing at both polishing intervals, along with BMD to provide the minimum three points to define a polishing curve (which in turn could be used as part of a pavement skid-resistance prediction model).

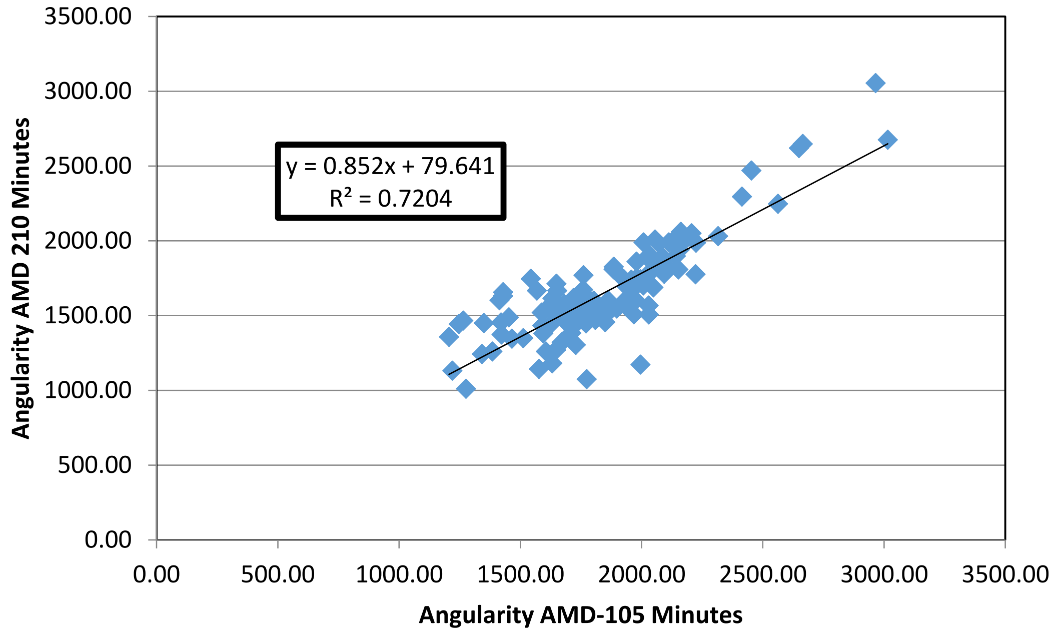


Figure 3.11 AIMS angularity AMD-105 vs. AMD-210.

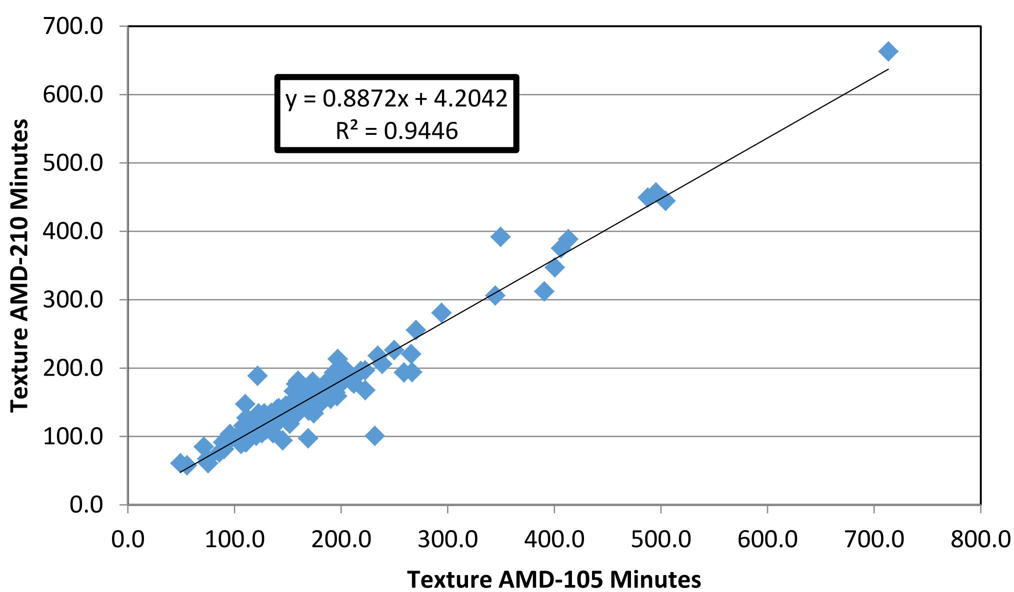


Figure 3.12 AIMS texture AMD-105 vs. AMD-210.

3.3 CLUSTERING ANALYSIS

As the previous analyses indicated, VST friction values are affected by both aggregate angularity and surface texture. A combined angularity and texture index correlated best with VST; however, the use of such an approach to qualify aggregates for friction purposes mighty be risky because a combined index could potentially qualify an aggregate with a very low texture or angularity. To avoid this issue, the research team analyzed the data in a two-dimensional manner rather than by using a linear approach (i.e., the best way to qualify an aggregate for friction purposes is to use both surface texture and angularity). To specify the limits for distinguishing different texture and angularity levels, a clustering analysis is required. In this study, two types of clustering were used: two-step cluster analysis and the K-means cluster analysis. IBM SPSS software was used to perform this analysis.

3.3.1 Two-Step and K-Means Cluster Analysis

Two-step cluster method is a tool designed to reveal natural groupings, also known as clusters, within a dataset. The two-step cluster procedure can automatically determine the optimal number of clusters by comparing the values of a model-choice criterion across different clustering solutions. The procedure then summarizes the records by constructing a cluster feature tree that summarizes the data.

The two-step cluster method is an analysis algorithm designed to handle very large data sets. It requires only one data pass. The first step is to pre-cluster the cases into many small sub-clusters. The second step is to cluster the sub-clusters resulting from the pre-cluster step into the desired number of clusters. This can also automatically select the number of clusters. The pre-cluster step uses a sequential clustering approach. The data records are scanned one by one and are used to determine whether the current record should be merged with the previously formed clusters or start a new cluster based on the distance criterion.

The second step of the procedure takes sub-clusters resulting from the pre-cluster step as input and then groups them into the desired number of clusters. Because the number of sub-clusters is much smaller than the number of original records, traditional clustering methods can be used effectively. The output given by the two-step cluster analysis is the amount of clusters needed. After the number of clusters has been given to the user, the information may be used for the K-means cluster method.

The K-means cluster method identifies homogeneous groups of cases based on the selected characteristics using an algorithm that can handle a large numbers of clusters. One of two methods for classifying cases may be selected: either updating cluster centers iteratively or classifying only. The K-means cluster method then assigns the appropriate cluster to the data being processed. More details on cluster analysis can be found in most applied multivariate statistical texts (e.g., Johnson and Wichern 2002; Morrison 2005).

3.3.2 Clustering Analysis

Using the SPSS software, AIMS angularity and texture data were processed. The data were split into three categories for each shape property: BMD, AMD, and AMD and BMD combined. More than 76,000 values of angularity and texture were processed. Initial clustering results are shown in Tables 3.3 and 3.4 for angularity and texture, respectively. The clustering was done by enforcing three-cluster analysis (i.e., the number of the clusters was selected by the research team rather than by the two-step clustering analysis). This process was selected in an attempt to distinguish three clusters: low, medium, and high.

The 2D representation of the angularity–texture clusters is shown in Figure 3.13. The AMD-105 aggregate data points are plotted in that figure. One way to qualify aggregates for friction purposes is illustrated in Figure 3.14. In that figure, the green area represents aggregates with acceptable angularity and texture values, while the red area indicates aggregates with both low angularity and texture, which means they would not be recommended for friction applications. The yellow zones indicate an aggregate source with one of the two properties low and the other acceptable or high.

One of the main observations from these two figures is the fact that high percentages of aggregates are in the low texture zone. In fact, 71% of the aggregates fill in that zone (< 190). This indicates that a three-cluster analysis might not be suitable for the aggregate sources analyzed in this study.

Table 3.3 Angularity Clustering (Three Clusters)

Cluster	BMD Limits	AMD Limits	Combined Limits
Low	< 2100	< 1400	< 1770
Medium	2100–3250	1400–2400	1770–2970
High	> 3250	> 2400	> 2970

Table 3.4 Texture Clustering (Three Clusters)

Cluster	BMD Limits	AMD Limits	Combined Limits
Low	< 240	< 190	< 215
Medium	240–490	190–420	215–460
High	> 490	> 420	> 460

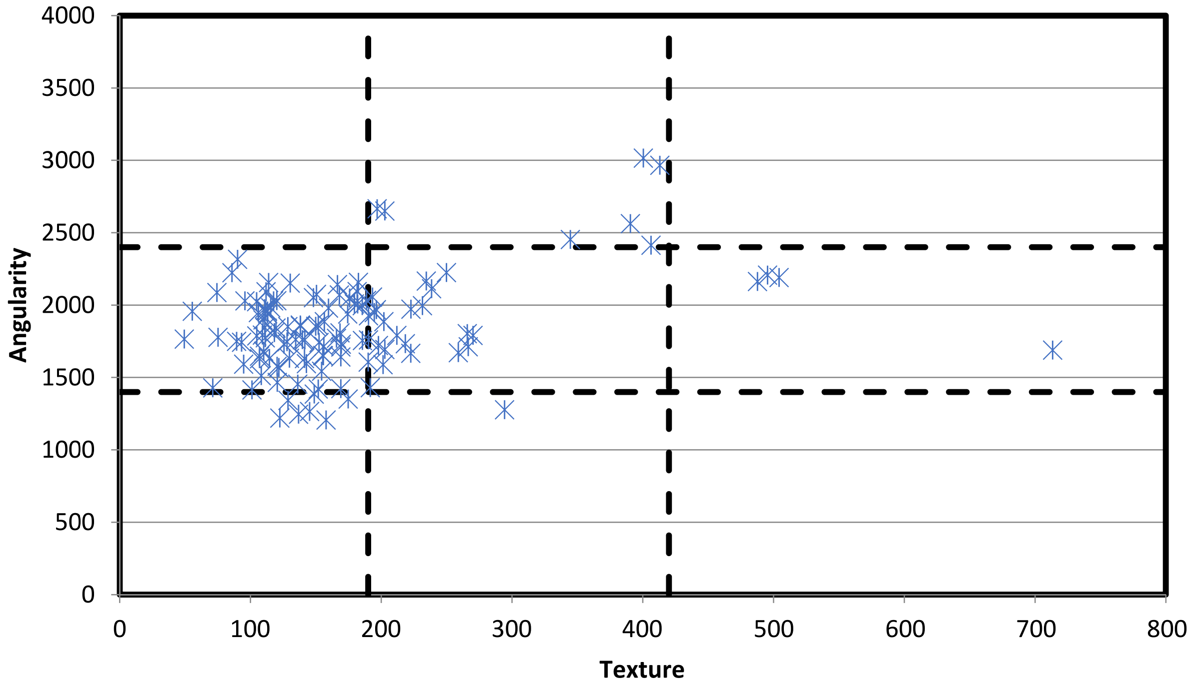


Figure 3.13 Texture vs. angularity (three-cluster analysis).

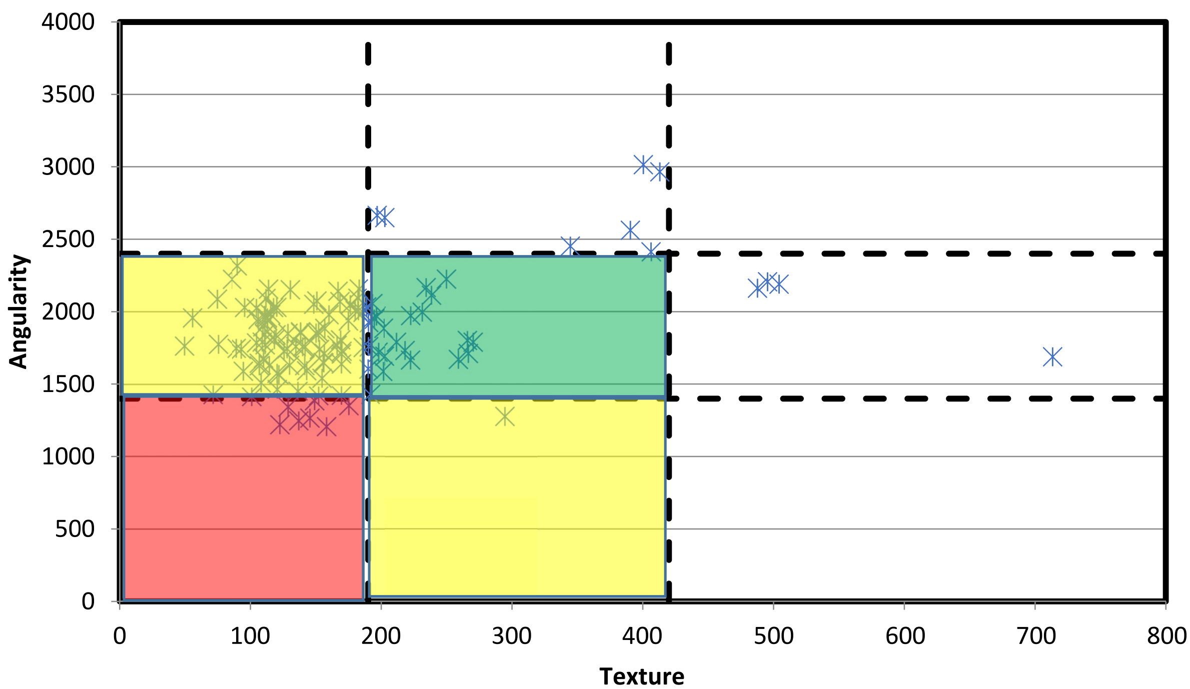


Figure 3.14 Texture vs. angularity (three-cluster analysis), with proposed acceptable zones.

A more reasonable clustering was the five-cluster analysis enabled by the two-step clustering analysis for the AMD–BMD combined aggregate samples. Table 3.5 shows the limits for each of the clusters. The 2D representation of the angularity–texture for the five-clusters is shown in Figures 3.15 and 3.16. On the basis of this clustering analysis, the research team recommends a minimum AMD-105 texture of 140 and AMD-105 angularity of 1240 for an aggregate to be qualified for friction purposes. The texture vs. angularity clustering analysis are provided in Appendix C for each aggregate type separately.

Table 3.5 Texture and Angularity Clustering (Five Clusters)

Cluster	Texture	Angularity
1	< 140	< 1240
2	140–260	1240–2050
3	260–410	2050–2800
4	410–650	2800–3750
5	> 650	> 3750

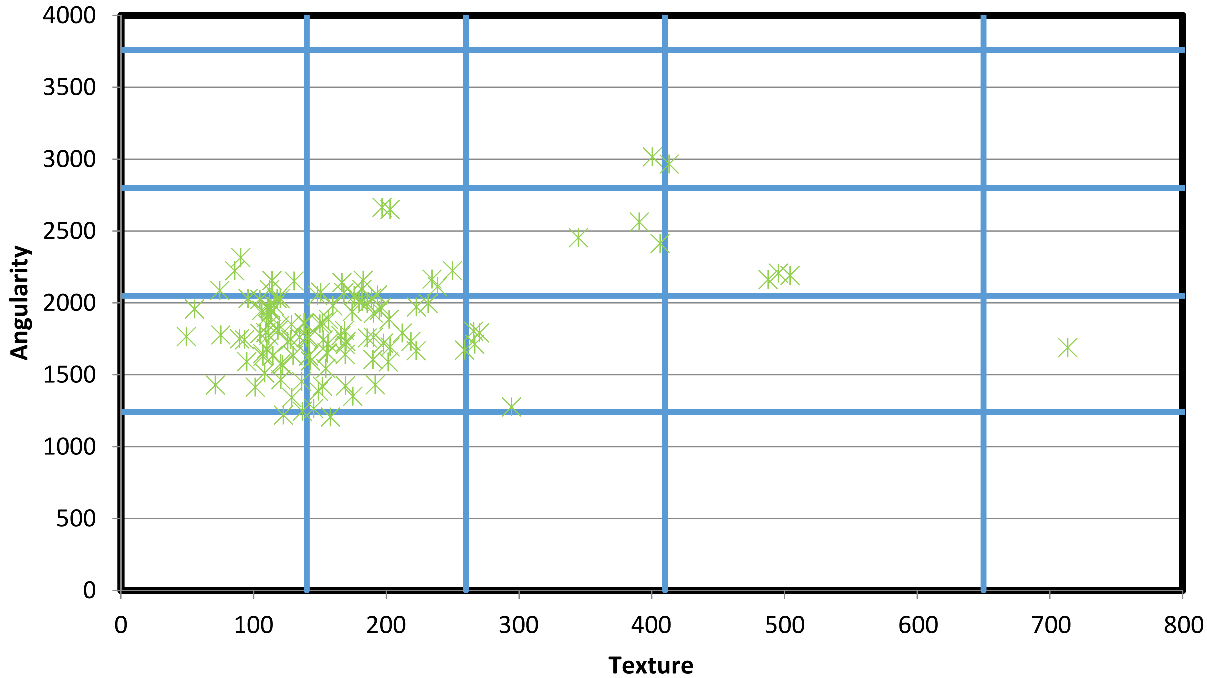


Figure 3.15 Texture vs. angularity (five-cluster analysis).

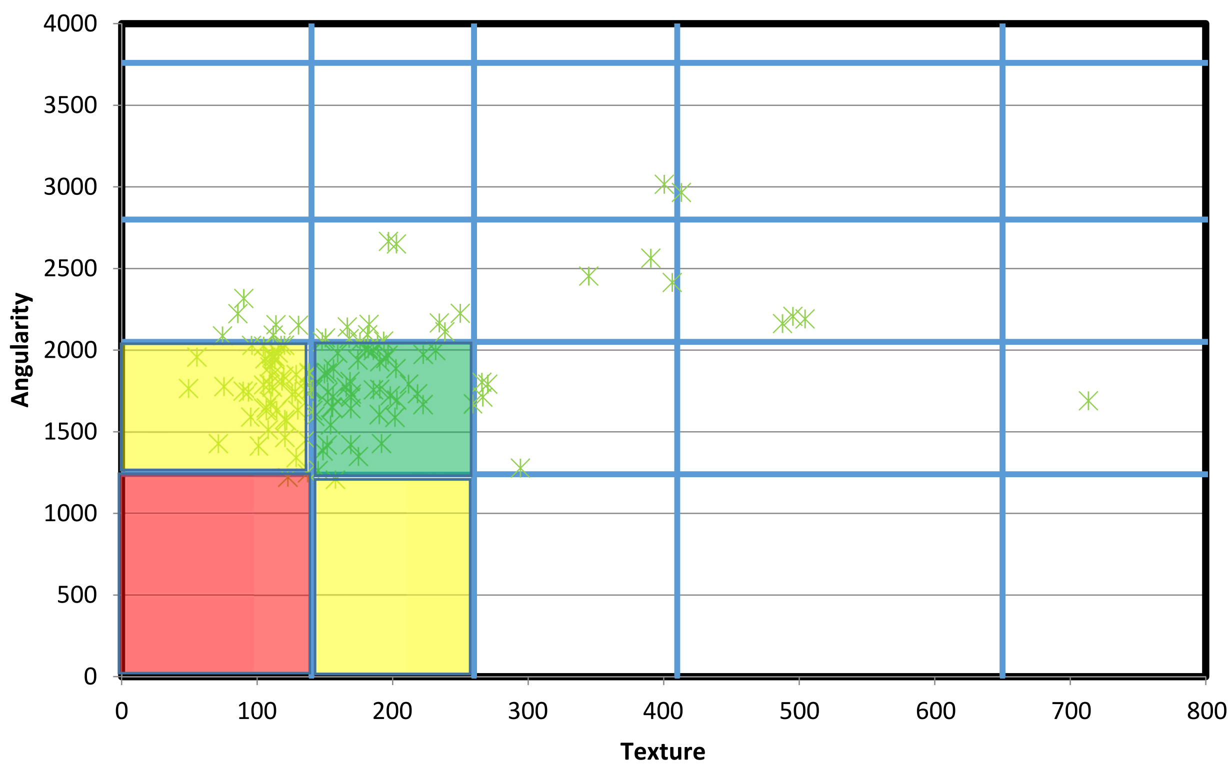


Figure 3.16 Texture vs. angularity (five-cluster analysis), with proposed acceptable zones.

CHAPTER 4 SUMMARY AND IMPLEMENTATION RECOMMENDATIONS

4.1 SUMMARY

The research team compiled all AIMS and VST data collected by the principal investigator in the R27-129 research project and by BMPR during 2013–2014. Preliminary analysis of 13 VST friction data samples, along with BMD, AMD-105, and AMD-210 for the same samples, indicated a strong relationship between AMD-105 angularity and VST friction values. In addition, combined angularity and texture for AMD-105 correlated very well with VST friction values.

On the basis of the preliminary analysis results, BMPR tested more aggregate samples to establish specifications for AIMS results. In total, 200 samples were tested in VST and/or AIMS, 88 samples were tested in both systems, and every sample had two BMD samples scanned. In addition, 18 VST samples were scanned by AIMS for texture measurements. The key findings of the analyses of these samples are as follows:

- AIMS angularity and texture repeatability was investigated. The results indicated an excellent repeatability, with a linear relationship very close to equality with high R-squared values (0.94 for angularity and 0.98 for texture).
- Analysis of 88 AIMS and VST samples reinforced the findings from the preliminary analysis, with strong correlations between AMD-105 angularity and VST friction values. The best relationship was for the combination of angularity and texture.
- VST texture and AIMS texture analysis indicated that VST surface texture has an excellent correlation with AIMS AMD-105 and AMD-210 textures for AIMS zoom levels 3 and 4 (R-squared > 0.90). This is a clear indication the Micro-Deval test is a viable polishing technique and could be used as a replacement for the VST. Consistent with previous findings in this report, VST texture correlated better with AMD-105 minutes, which again supports the hypothesis that the current VST friction test procedure might not be long enough to produce terminal texture.
- AMD-105 and AMD-210 comparisons clearly indicated an excellent relationship for texture results, which indicates that the ranking of aggregates will not change whether the texture is AMD-105 or AMD-210. However, the angularity relationship was less clear, which could be attributed to the fact that angularity measurements are affected by both abrasion and breakage. This analysis indicates that the AMD-105 could potentially replace AMD-210 for selecting and ranking aggregates for friction properties.
- The research team recommends testing at both polishing intervals (105 and 210 minutes). Along with BMD, that procedure will provide the minimum three points to define a polishing curve (which in turn could be used as part of a pavement skid-resistance prediction model).

To avoid specifications based on combined angularity and texture index, the research team performed clustering analysis to define minimum acceptable texture and angularity for polished aggregate to serve as guidelines for selecting aggregates for friction purposes. The results of the clustering analysis are as follows:

- Three-cluster analysis proved to be unrealistic because more than 70% of the aggregate samples fell in the low-texture cluster.

- Five-cluster analysis provided a more realistic and acceptable zoning for low texture and angularity. The threshold for the clusters and suggested guidelines are listed in the following section.

4.2 IMPLEMENTATION RECOMMENDATIONS

On the basis of the testing and results of this project, along with the results from project R27-129, the research team recommends implementation of the polishing procedure developed in R27-129 and that aggregate friction specifications be based on the clustering analysis used in this study.

4.2.1 Polishing Procedure

The following procedure is recommended to characterize coarse aggregate polishing:

1. Obtain two 750 g coarse aggregate samples passing the 1/2 in. sieve and retained on the 3/8 in. sieve.
2. Measure aggregate initial surface texture with AIMS (texture before polishing).
3. Subject one sample to polishing in Micro-Deval:
    a. Soak the aggregate sample in 2 L of water for a minimum of 60 minutes in Micro-Deval drum.
    b. Add a charge of 5000 g of 9.5 mm diameter steel balls.
    c. Subject the aggregate sample to polishing in the Micro-Deval for 105 minutes.
    d. Wash and sieve the aggregate sample retained on the No.16 sieve.
    e. Oven-dry the sample and obtain material retained on the 3/8 in. sieve.
    f. Measure aggregate surface texture with AIMS (texture at 105 minutes of polishing).
4. Repeat step 3 for the second aggregate sample to obtain aggregate surface texture at 210 minutes by changing the time in step 3c to 210 minutes.
5. If a four-point polishing curve is desired, repeat step 3 for a third sample to obtain the surface texture at 60 minutes by changing the time in step 3c to 60 minutes.

4.2.2 Aggregate Friction Specifications

The following specifications are recommended for qualifying aggregate for friction purposes:

1. Aggregate source with texture AMD-105 > 140 and angularity AMD-105 > 1240 are recommended for friction purposes.
2. Aggregate source with texture AMD-105 < 140 and angularity AMD-105 < 1240 are not recommended for friction purposes.
3. Aggregate source with either texture AMD-105 > 140 ***or*** angularity AMD-105 > 1240 requires further investigation and approval by BMPR prior to recommendation.

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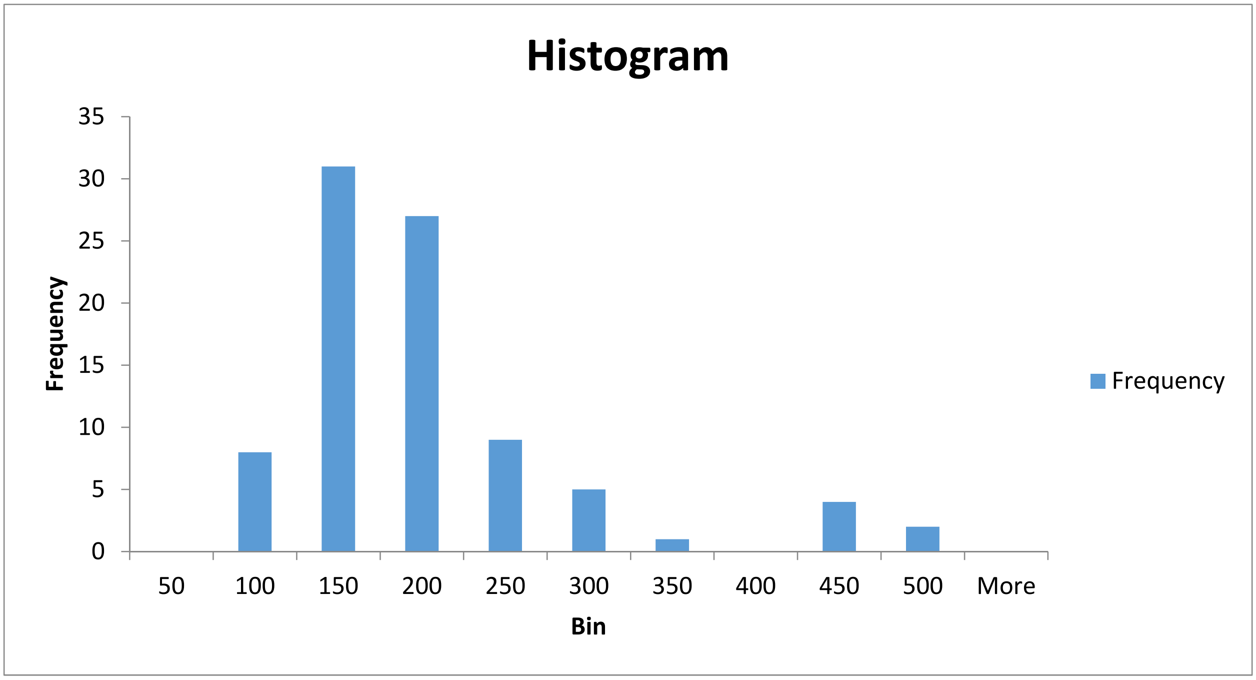
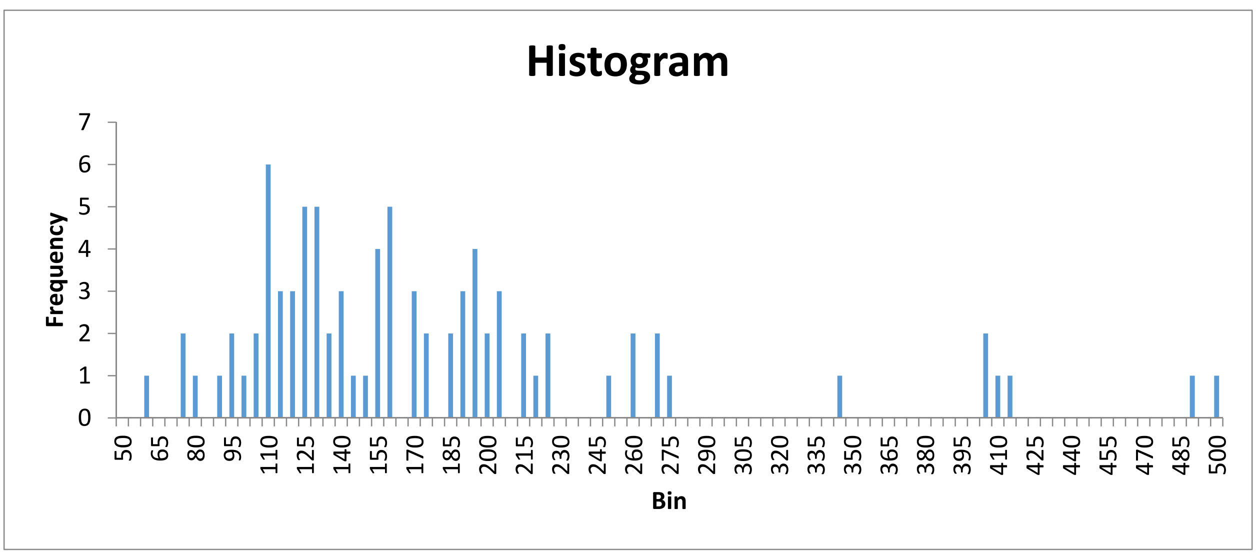
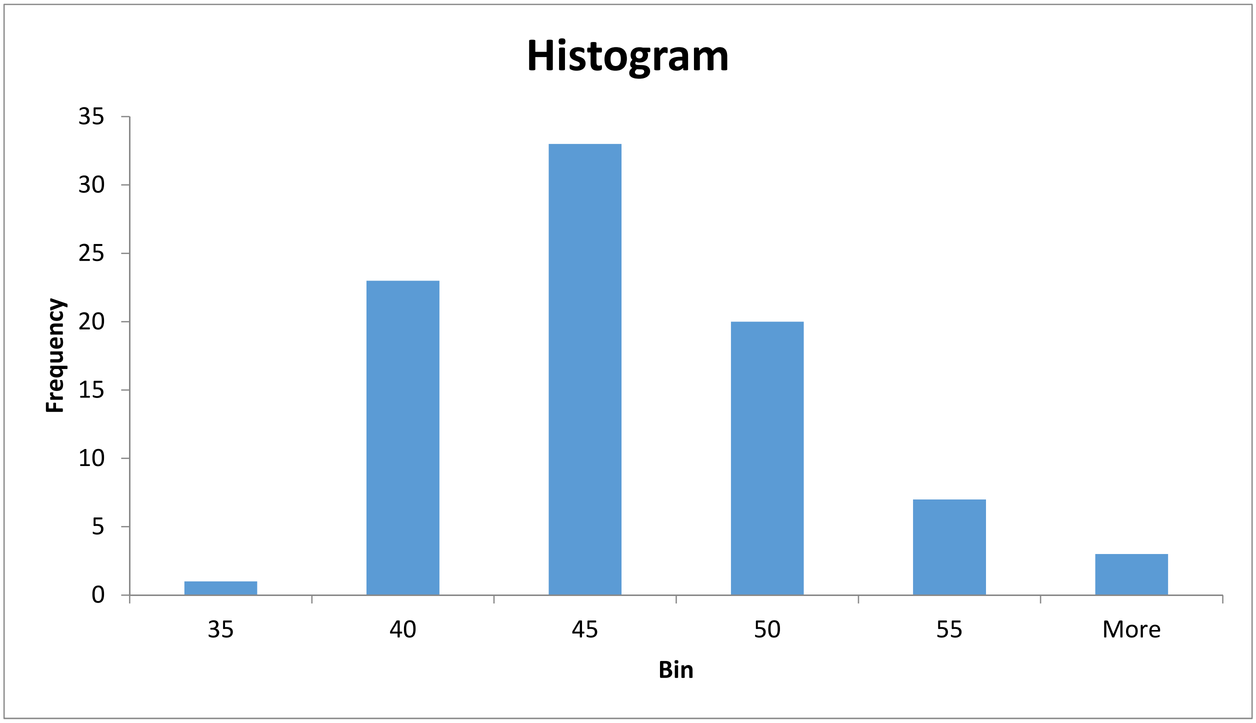
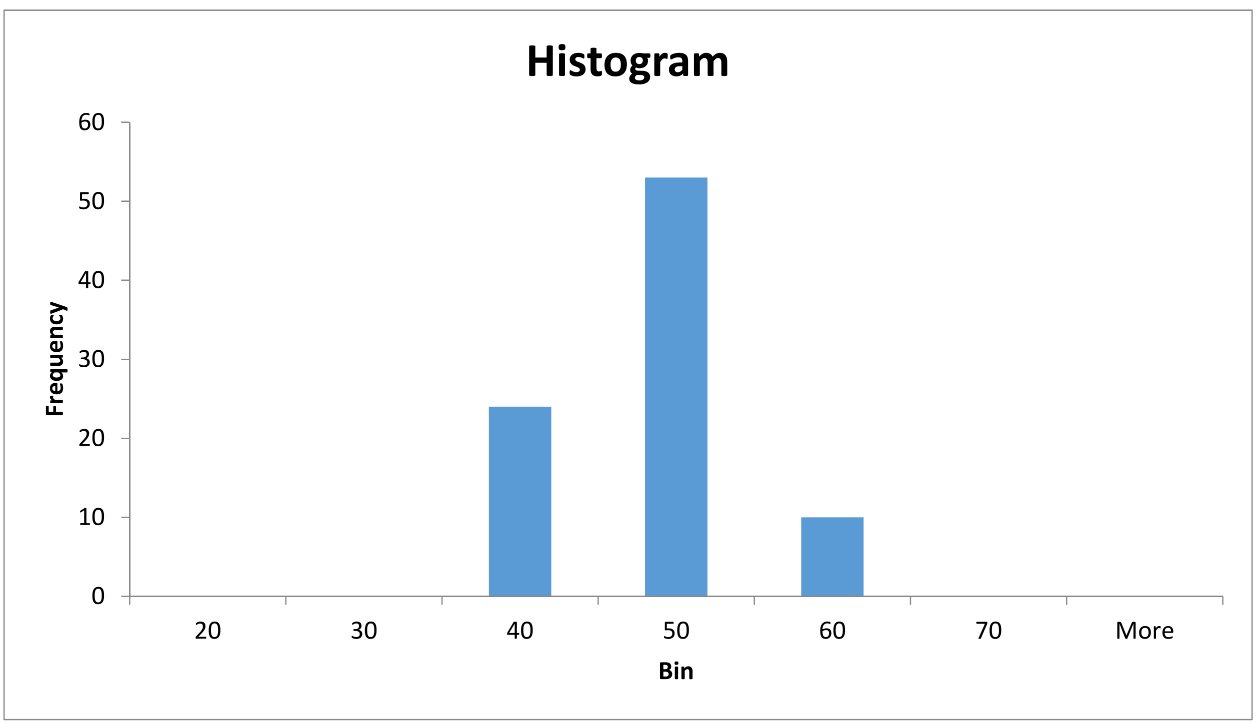
APPENDIX A AIMS TEXTURE HISTOGRAMS



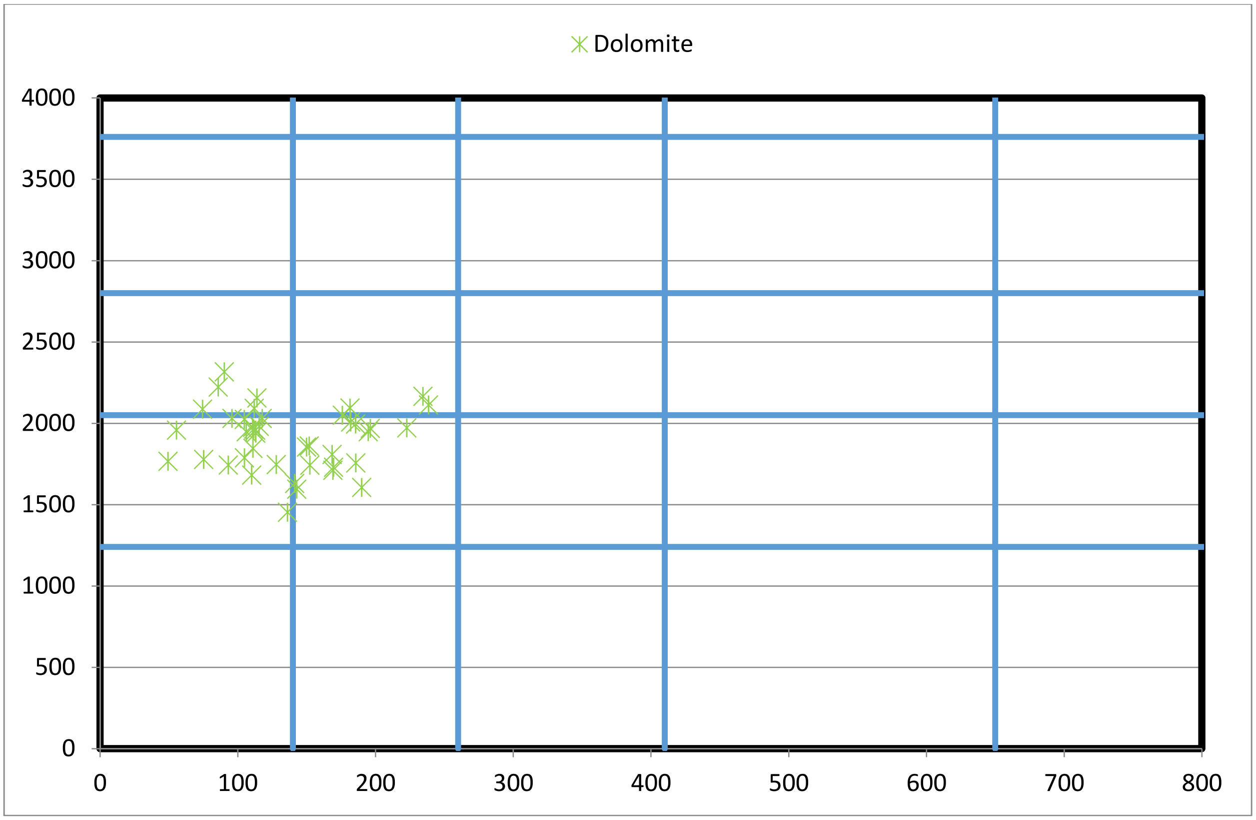


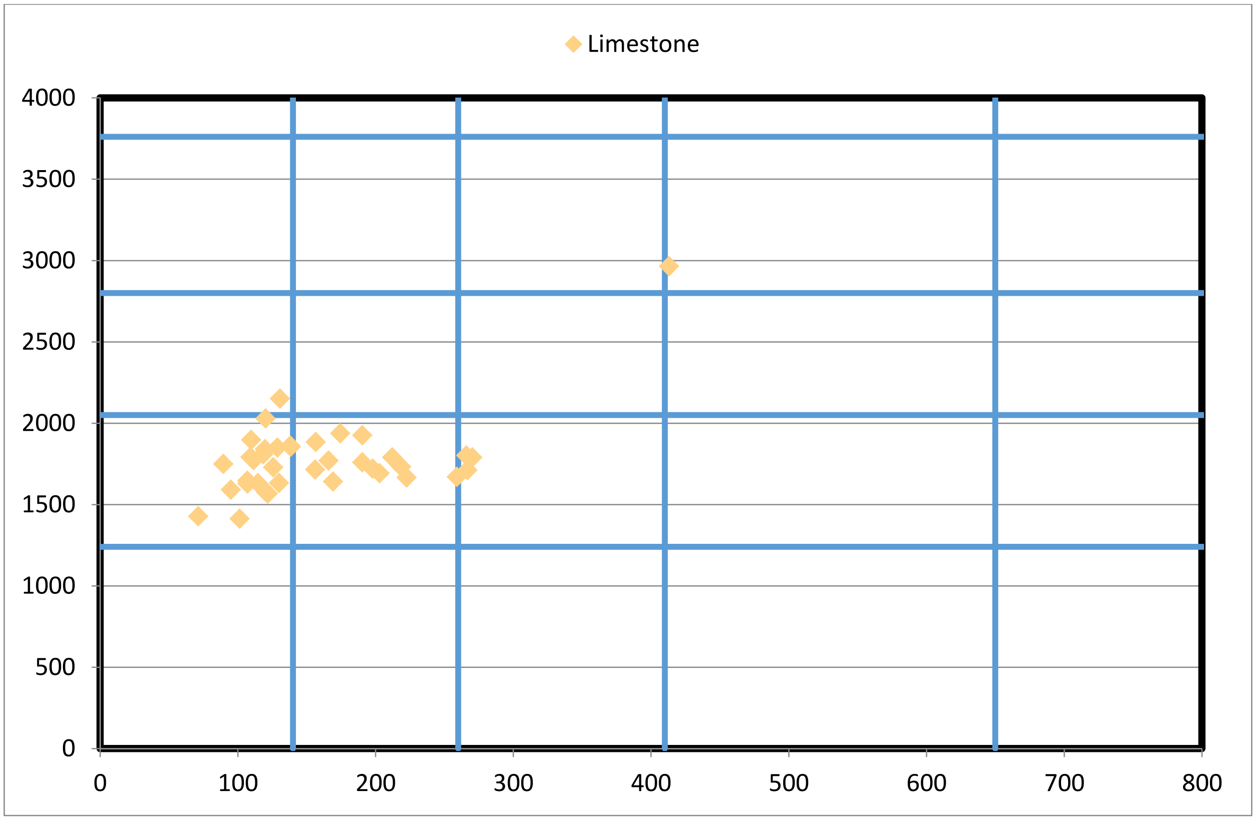
APPENDIX B VST FRICTION DATA HISTOGRAMS





APPENDIX C FIVE-CLUSTER ANALYSIS PER AGGREGATE TYPE




Limestone
4000
3500
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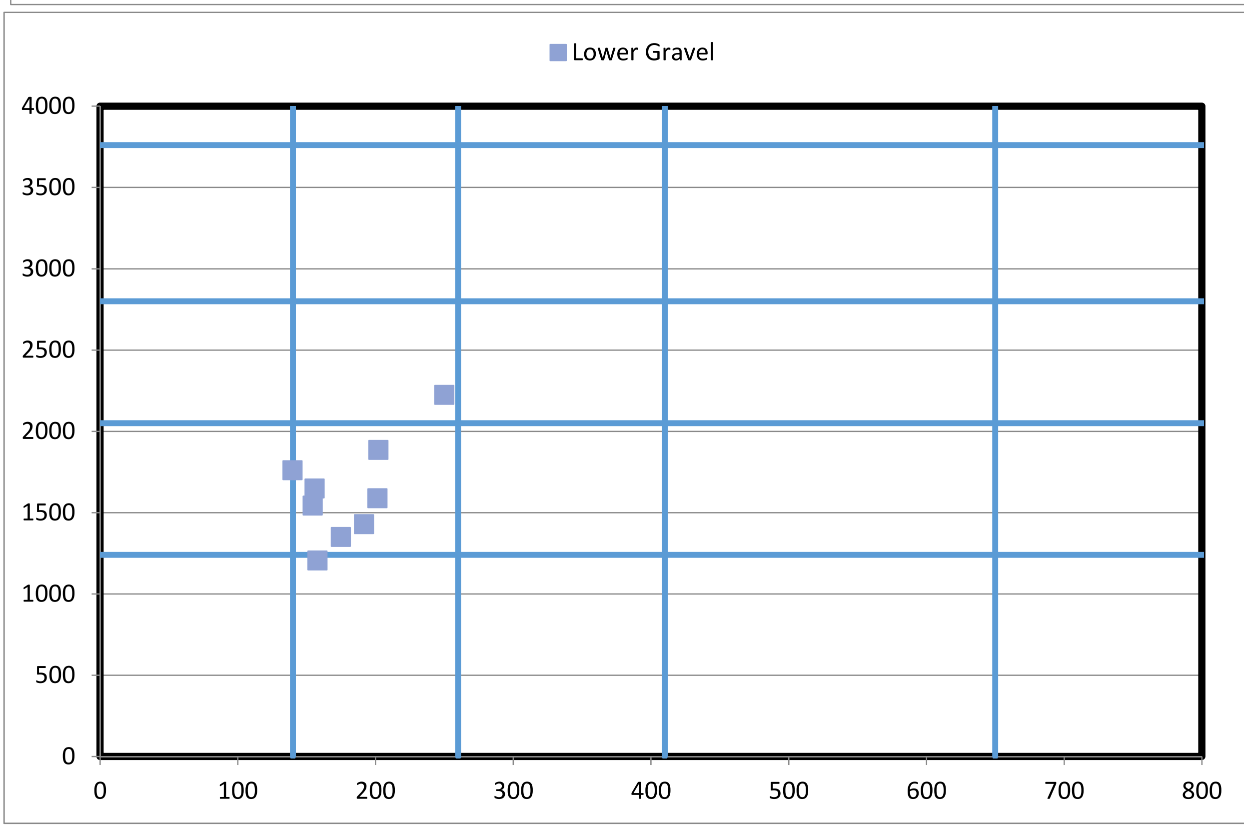
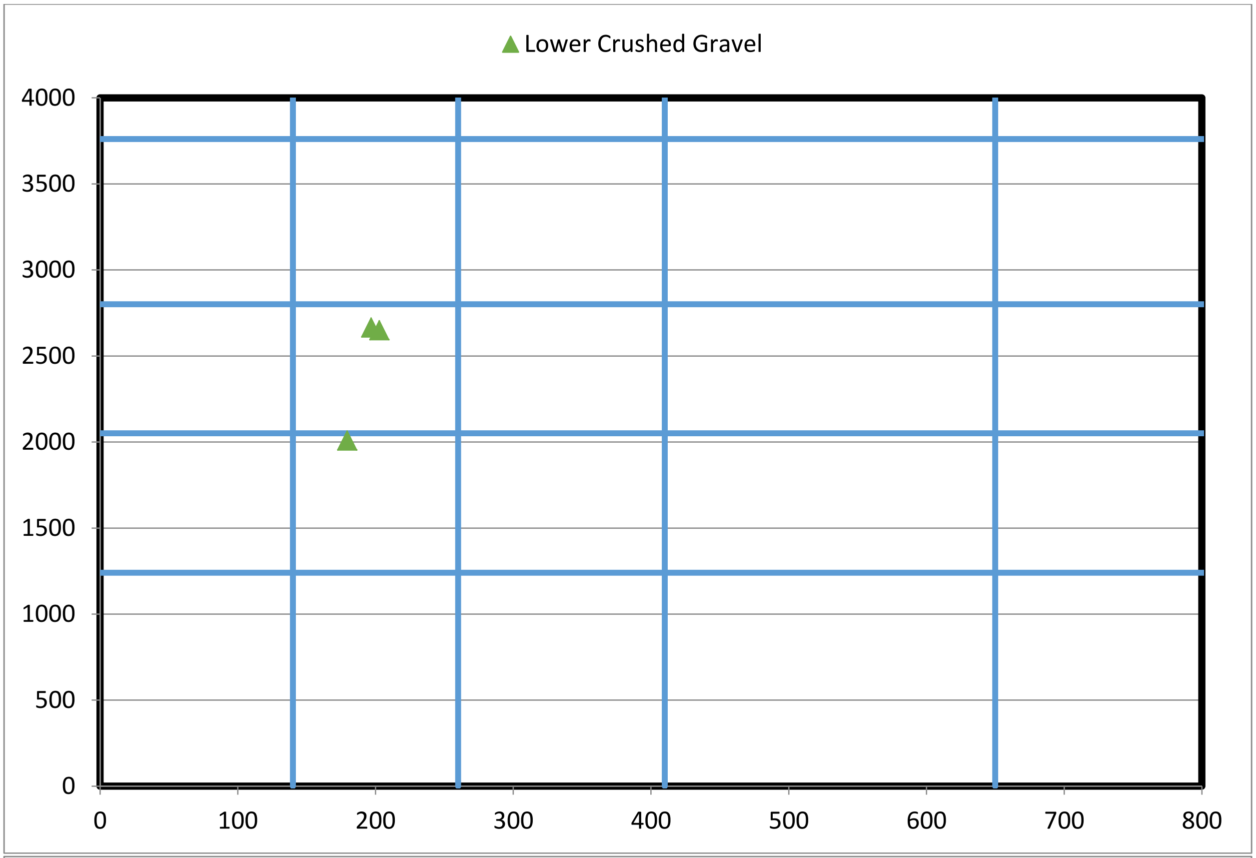
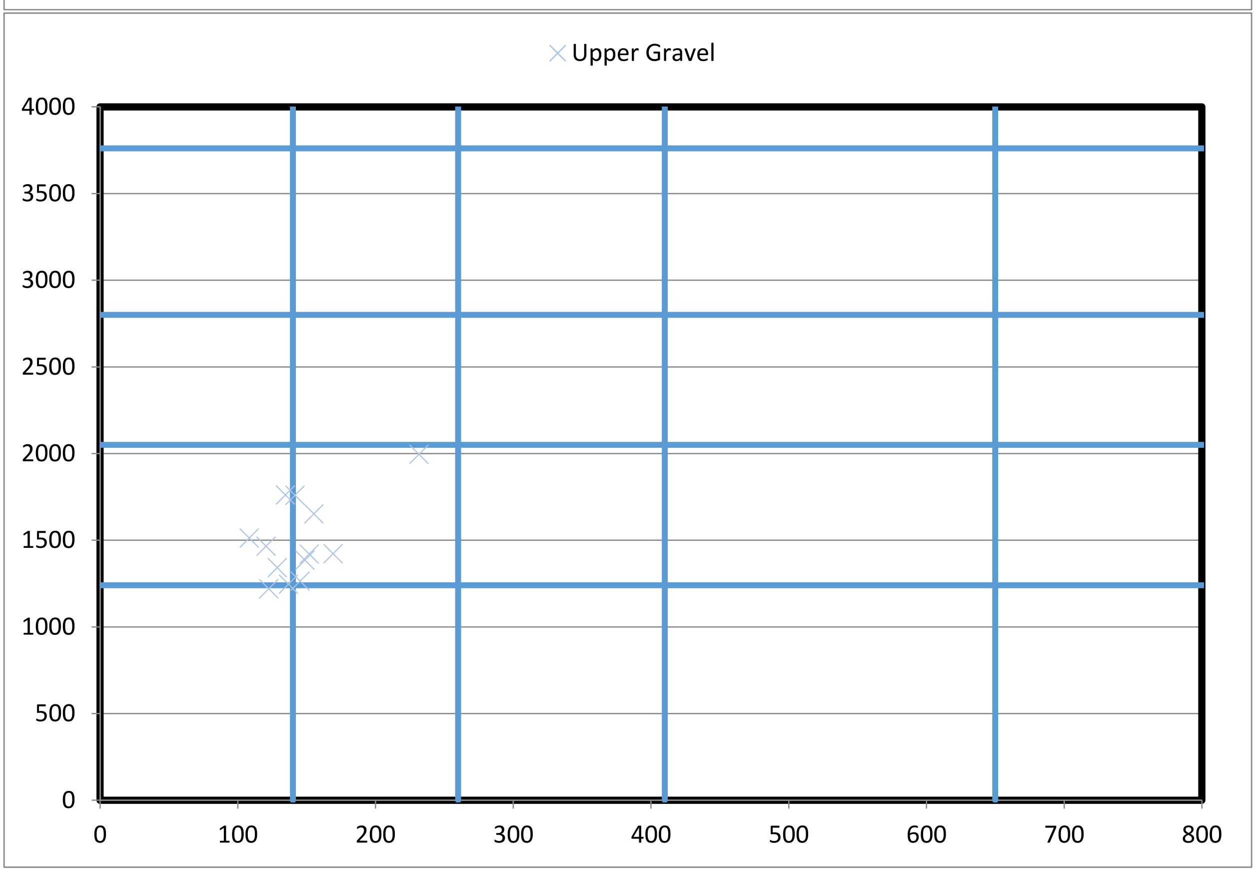
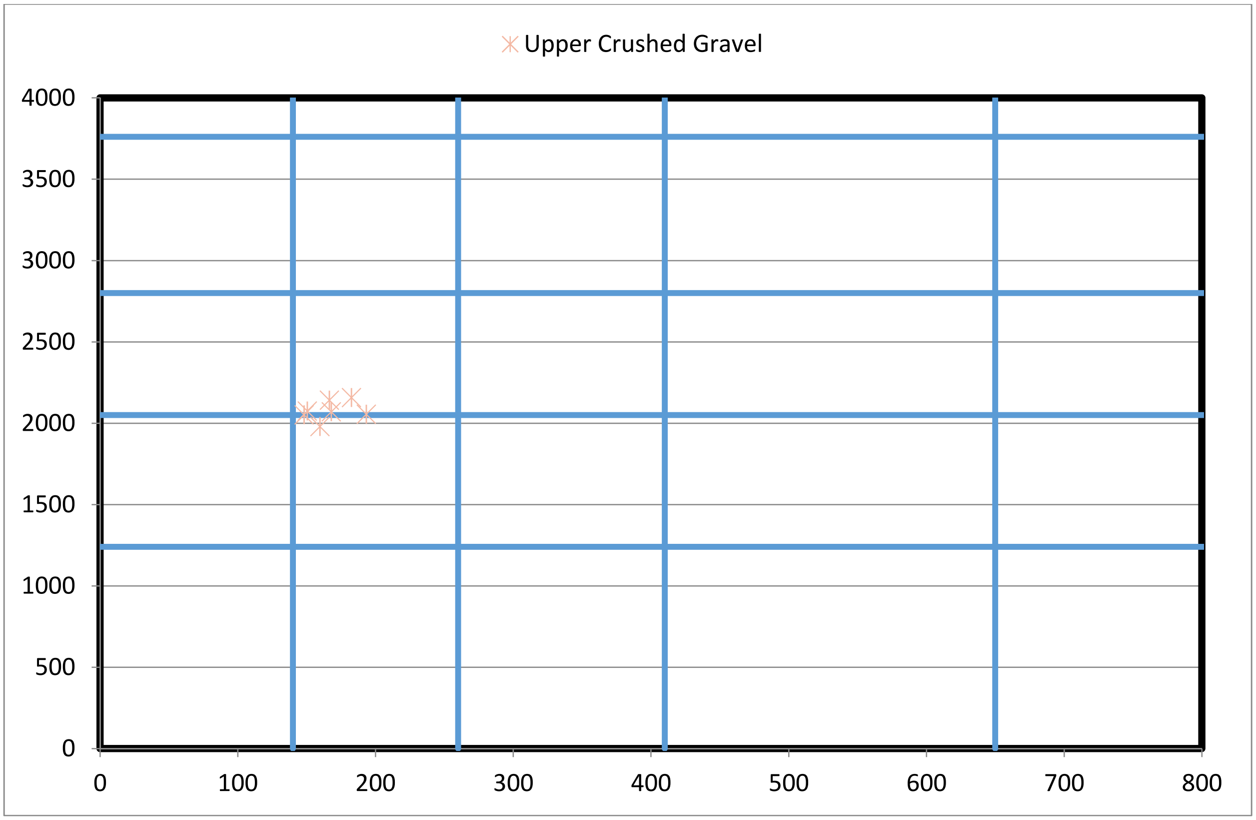
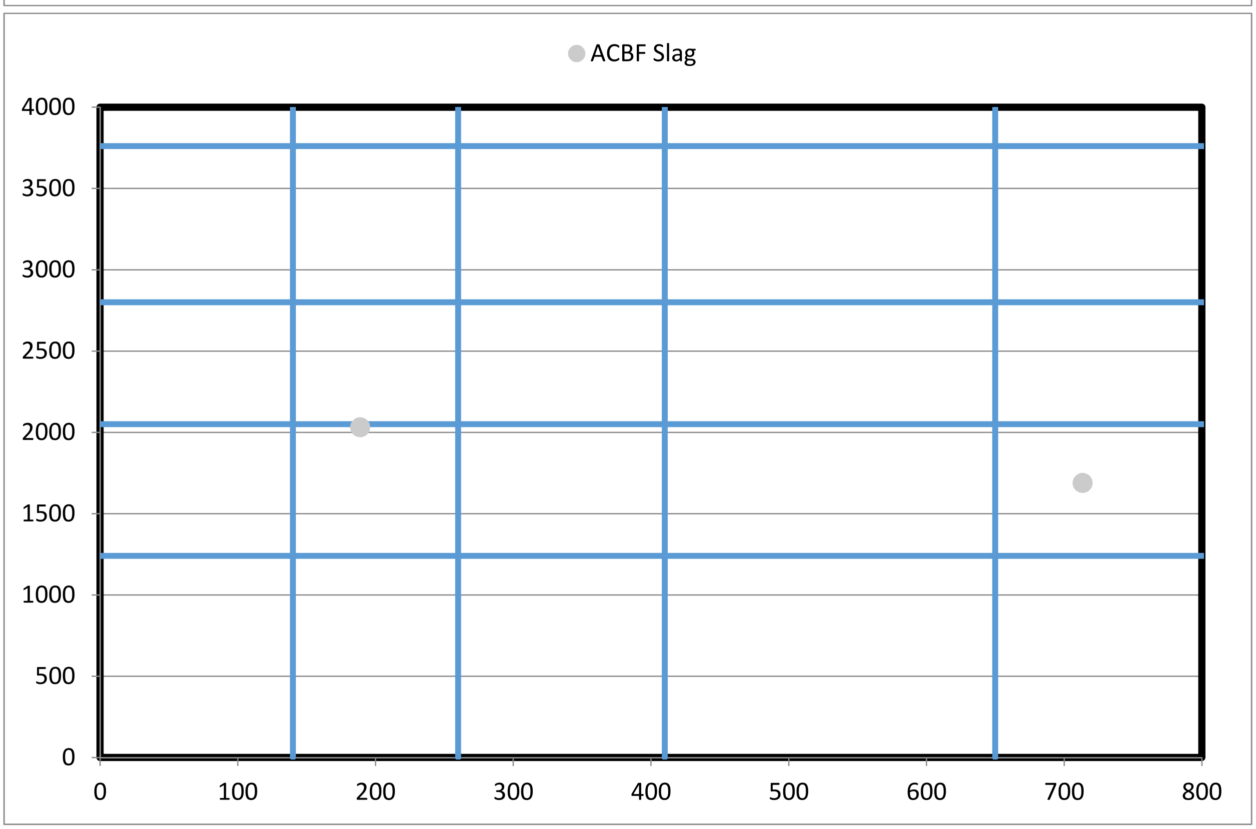
700
800

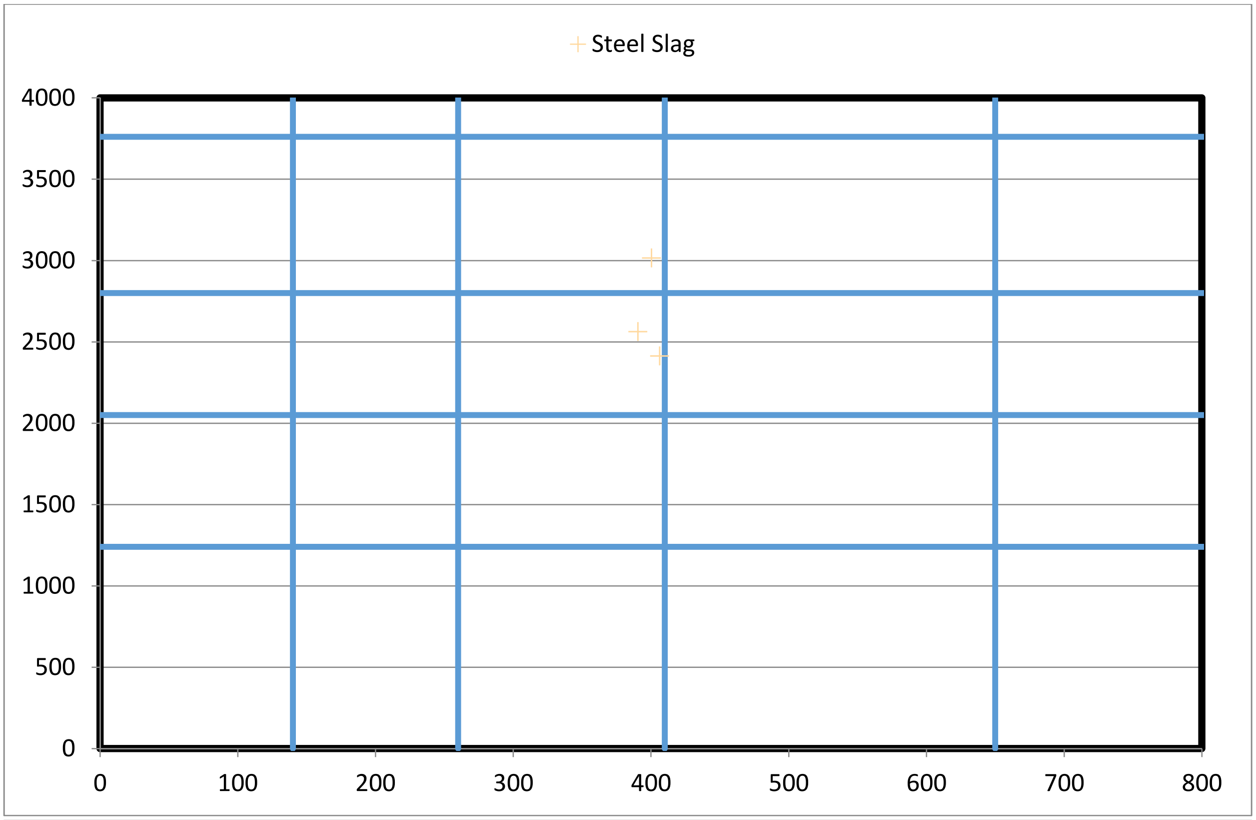

Lower Gravel
4000
3500
3000
2500
2000
1500
1000
500
0
0
100
200
300
400
500
600
700
800

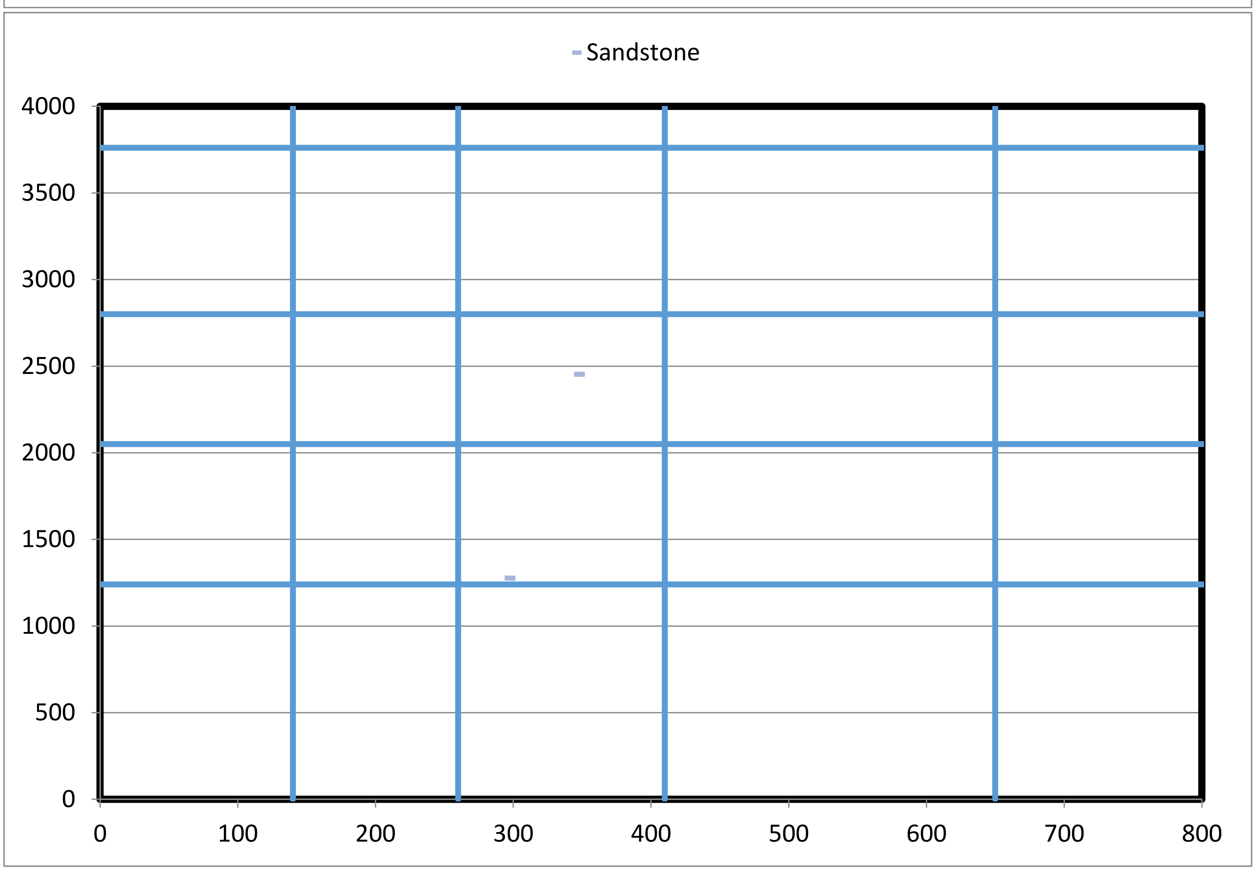

Lower Crushed Gravel
4000
3500
3000
2500
2000
1500
1000
500
0
0
100
200
300
400
500
600
700
800

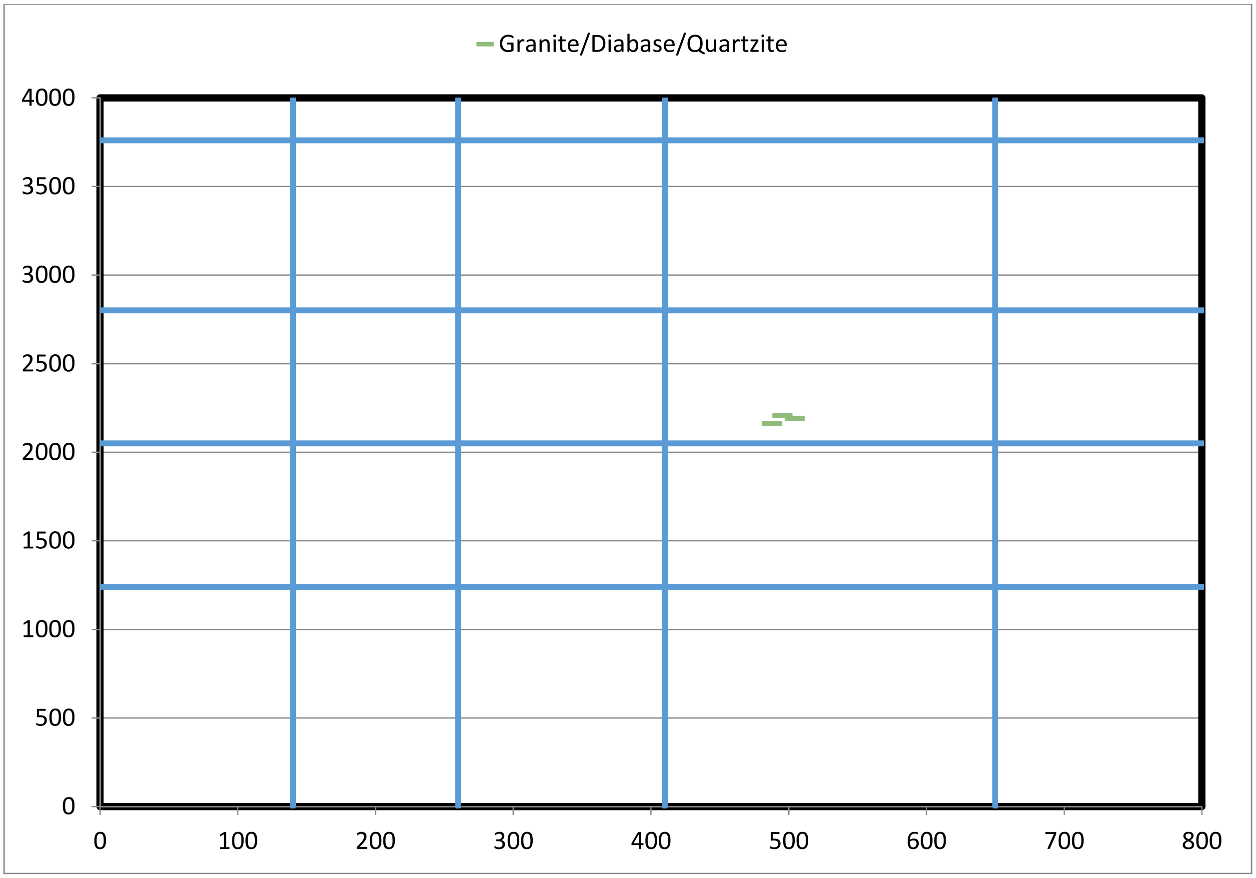

Upper Gravel
4000
3500
3000
2500
2000
1500
1000
500
0
0
100
200
300
400
500
600
700
800


Upper Crushed Gravel
4000
3500
3000
2500
2000
1500
1000
500
0
0
100
200
300
400
500
600
700
800


ACBF Slag
4000
3500
3000
2500
2000
1500
1000
500
0
0
100
200
300
400
500
600
700
800


Steel Slag
4000
3500
3000
2500
2000
1500
1000
500
0
0
100
200
300
400
500
600
700
800


Sandstone
4000
3500
3000
2500
2000
1500
1000
500
0
0
100
200
300
400
500
600
700
800


Granite/Diabase/Quartzite
4000
3500
3000
2500
2000
1500
1000
500
0
0
100
200
300
400
500
600
700
800