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16. Abstract

Over the last few years the Texas Department of Transportation has expressed concern about mineralogical segregation (variation) of coarse aggregates used in bituminous mixes; problems are associated with variation in the quality of aggregates taken from a quarry/gravel pit. The primary objective of this project was to examine the effects of poor quality coarse limestone aggregate on hotmix asphalt performance and to determine how much of the poor quality limestone can be used before adversely affecting performance. A Type C aggregate composed of a high quality limestone from one quarry was blended with soft and absorptive limestone aggregates from two other quarries in different proportions using a PG 64-22 asphalt binder. The individual aggregates were run through Los Angles abrasion, Micro-Deval, magnesium sulfate soundness, specific gravity, and absorption tests. Molded bituminous samples were tested with the Hamburg wheel tracker, dynamic modulus, and the overlay tester. In order to obtain less than 10 percent marginal Texas coarse limestone aggregate, the Micro-Deval loss should not exceed 20 percent, and the magnesium sulfate soundness percent loss should not exceed 15. The introduction of marginal coarse limestone aggregate will lower the reflection cracking life of the bituminous mix, so a maximum of 10 percent marginal (soft and absorptive) coarse limestone aggregate is recommended.

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TESTS TO IDENTIFY POOR QUALITY COARSE LIMESTONE AGGREGATES AND ACCEPTABLE LIMITS FOR SUCH AGGREGATES IN BITUMINOUS MIXES

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DISCLAIMER

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There is no invention or discovery conceived or first actually reduced to practice in the course of or under this contract, including any art, method, process, machine, manufacture, design, or composition of matter, or any new useful improvement thereof, or any variety of plant, which is or may be patentable under the patent laws of the United States of America or any foreign country.

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CHAPTER 1
FIELD EVALUATION OF QUARRIES/GRAVEL PITS

INTRODUCTION

Over the last few years, the Texas Department of Transportation (TxDOT) has expressed concern about mineralogical segregation (variation) of aggregates used in bituminous mixes. Problems are associated with variation in the quality of aggregates taken from a quarry/gravel pit. There are more than 200 aggregate sources in Texas. The aggregates are as variable as the geology of Texas with all major rock types (igneous, metamorphic, and sedimentary) being represented. Many quarries/gravel pits provide uniform, high-quality aggregates from one week to the next. However, some quarries/gravel pits that are inconsistent in the production of high quality aggregates on a day-to-day basis.

With a greater demand for aggregate in hotmix asphalt concrete (HMAC), high-quality natural resources are quickly vanishing. Poor quality aggregates are sometimes blended with high quality aggregates. TxDOT is concerned about how increases in the quantity of poor quality coarse aggregate affect hotmix asphalt concrete pavement quality and life. Current TxDOT specifications allow a coarse aggregate stockpile to have a five-cycle magnesium sulfate soundness (MSS) loss as high as 30 percent and still be acceptable. Hotmix asphalt concrete produced one day may have a MSS loss of 30 percent coarse aggregate and the next day may only have a MSS loss of 5 percent coarse aggregate. The quality and performance of the hotmix asphalt concrete will be different for each day.

The literature is extensive regarding the qualities to look for in a good performing aggregate (Fookes, 1980; Shakoor et al., 1982; Williamson, 1984; Fookes and Hawkins, 1988a; Fookes et al., 1988b; Smith and Collis, 1993; Mckirahan et al., 2004). For example, Smith and Collis (1993) list six qualities required for an aggregate to be used as a surface course:

- toughness,
- hardness,
- resistance to polishing,

- resistance to stripping,
- resistance to weathering effects in pavement, and
- ability to contribute to strength and stiffness.

The problem is not identification of poor quality aggregates, but to determination of the boundary between acceptable and unacceptable aggregates in terms of performance and costs.

Previous studies have not been able to resolve this problem because different regions of the world have diverse climates, construction practices, financial resources, and aggregates of varying qualities. So each region needs to determine what is an acceptable aggregate product.

Phase I of this research focused on identifying what constitutes a poor quality coarse aggregate in Texas rocks and what measures could be taken at the quarry and hotmix plants to identify and decrease the amount of poor quality coarse aggregate before it goes into the hotmix asphalt concrete.

Based upon findings from Phase I of this research project, the following properties have been identified as important for coarse aggregate:

- porosity or absorption,
- cleanliness and deleterious materials,
- toughness and abrasion resistance, and
- durability and soundness.

These properties are all related to the mineralogy, texture, and chemistry of the coarse aggregate.

As part of this investigation, researchers conducted an evaluation of 13 quarries representing both good and poor performing aggregates throughout Texas (Figure 1, Table 1). Five of these quarries were selected for detailed examination based on significant variation detected by TxDOT's Aggregate Quality Monitoring Program (AQMP) testing. Three of the quarries are Cretaceous limestones, and the other two are Quaternary basalt flows.

The data presented in Chapter 1 are a continuation of research conducted in Phase I and contain detailed explanations of how to quantitatively identify poor quality aggregate collected in the field and analyze it in the laboratory. This chapter details how much of each size aggregate should be collected from a quarry to obtain results that are statistically significant with respect to identifying how much poor quality aggregate is being produced.

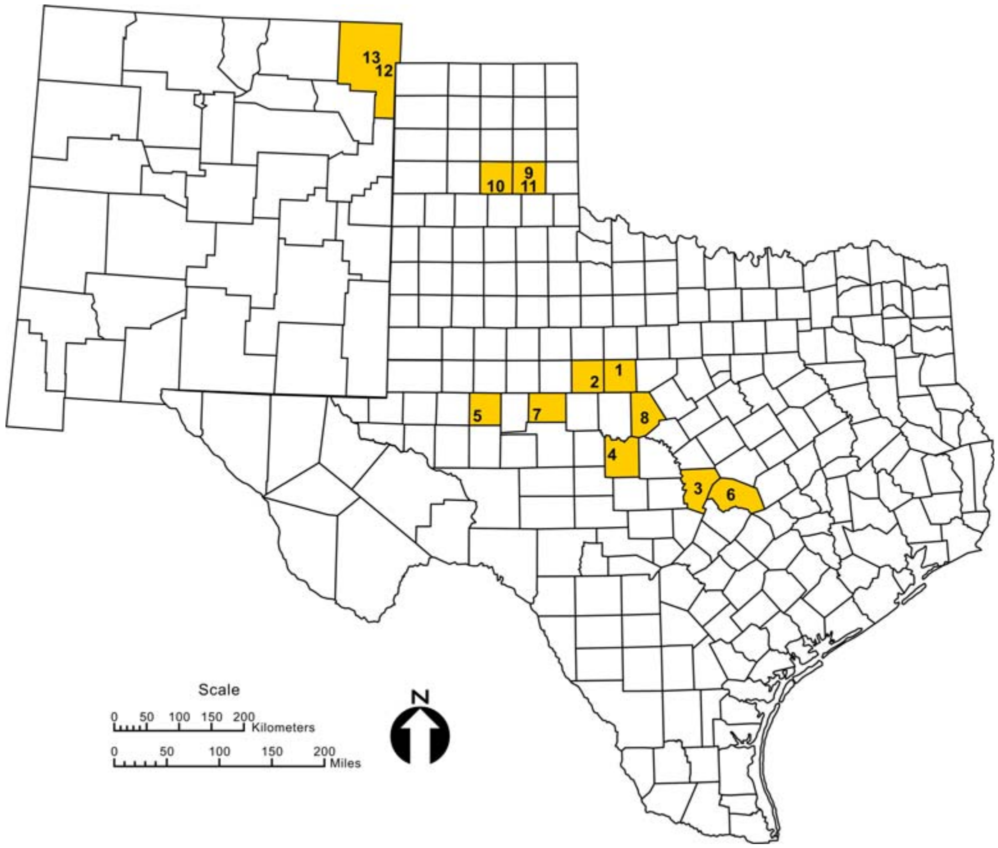


Figure 1. Map Showing Locations of Quarries Evaluated in This Project.

Table 1. List of Quarries Evaluated in the Field Study.

Producer	Quarry	Rock Type	Formation	Location on Map
Vulcan	Baird	Limestone	Jagger Bend	1
Vulcan	Black	Limestone	Edwards, Comanche Peak, Walnut	2
Hanson	Burnet	Dolomite	Ellenberger Group	3
CSA	Turner	Limestone	Fort Terrett	4
Price	Clements	Limestone	Fort Terrett	5
Texas Crushed Stone	Feld	Limestone	Edwards	6
CSA	Limestone #3	Limestone	Segovia	7
Vulcan	Limestone #1	Limestone	Adams Branch	8
Gilvin-Terrell	Fletcher	Conglomerate	Ogallala	9
Advanced Pavement	Stocket	Conglomerate	Ogallala	10
J. Lee Milligan	Roach	Conglomerate	Ogallala	11
J. Lee Milligan	Behne	Basalt	Clayton Basalt	12
J. Lee Milligan	Smith	Basalt	Clayton Basalt	13

METHODS

Once the quarries were selected for detailed evaluation, the researchers identified the locations on topographic maps at a 1:24,000 scale using latitude and longitude coordinates obtained from a Garmin GPSMAP 76S Global Positioning System (GPS). GPS was used to locate the five quarries and pinpoint their locations on the Geologic Atlas of Texas. Following the site location, the working face of each quarry was measured and described as outlined in Compton (1985). Samples were selected from specific locations and marked on a stratigraphic/lithologic column to return to the lab for more in-depth study. Portions of each sample returned to the lab were submitted to a private laboratory where blue-dyed, epoxy impregnated, 35 μm thin-sections were prepared. A total of 65 thin-sections were made so a detailed petrographic investigation could be performed on all of the units. The thin-sections were examined on a Zeiss petrographic microscope as outlined in American Society of Testing and Materials (ASTM) C-294 and ASTM C-295 for evaluation of concrete aggregates.

RESULTS

Field Descriptions

Following is a detailed description of observations made at the five quarries examined in depth. The first quarry is operated by Vulcan Materials Company and is located in the Abilene District. It is named the Baird Pit. The rock they are quarrying consists of the Jagger Bend Formation deposited in the Permian Period. The rock is composed of thin, well-cemented limestones intercalated with fissile shale and poorly indurated sandstone lenses (Figure 2). The 10-foot high working face will be important when considering economical options for decreasing the amount of poor quality aggregate in this quarry. Much of the material mined in the quarry is composed of lower quality shale and sandstone lenses as depicted in Figure 3. The stratigraphic column shown in Figure 4 represents the aggregates observed on the working face at the time the researchers visited the quarry. Figure 4 illustrates how the top and base of the working face contain good quality limestone aggregate, but the middle 6 feet of the section consists of discontinuous limestone, sandstone, and shale beds. It is the 6 feet in the middle that contains all of the rock that yields poor quality aggregate.

Figure 2. Ten-Foot Working Face at the Baird Quarry Illustrating Resistant Limestone Intercalated with Fissile Shale and Sandstone Lenses.

Figure 3. Close-Up of Fissile Shale and Sandstone Lenses.

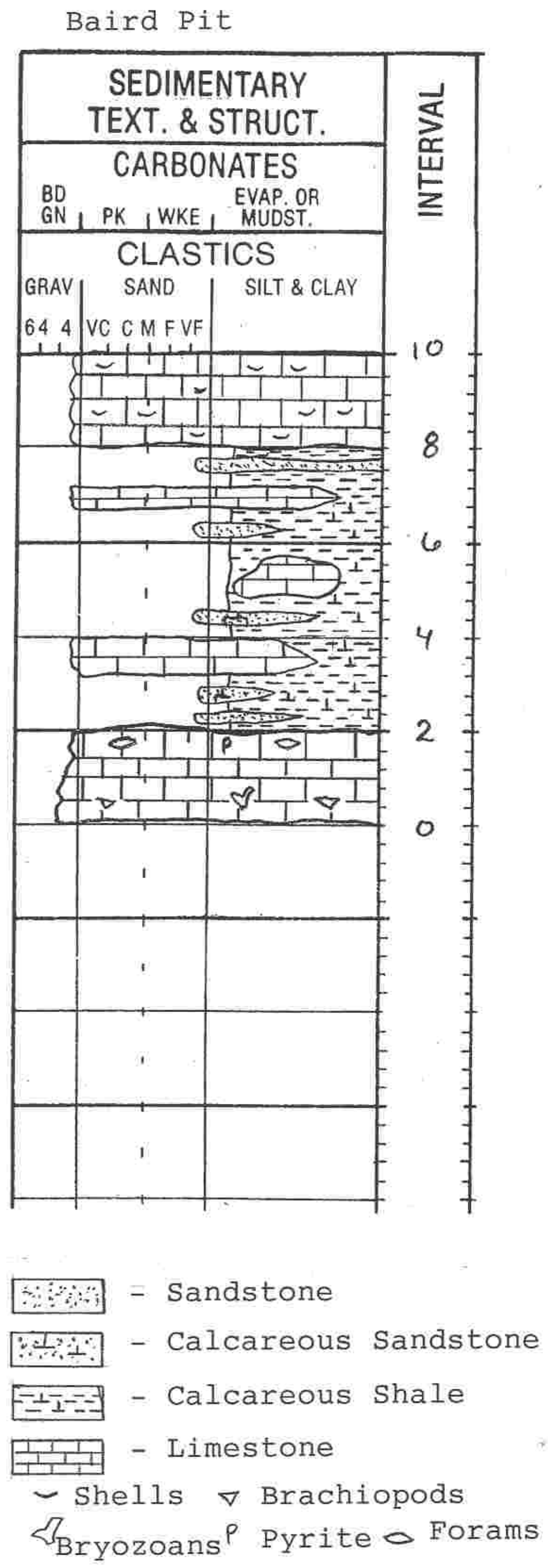


Figure 4. Stratigraphic Column of the Working Face at the Baird Pit.

The second quarry the researchers investigated was the Black Pit. It is in the Abilene District as well, but it consists of limestone deposited in the Cretaceous Period, which is younger than the Baird aggregates by approximately 150 million years. This difference in age is a good indicator of limestone quality. The younger rock typically is more poorly cemented and softer, resulting in less durable aggregate. Figure 5 shows four distinctive units in the working face of the Black Pit. Two of the less durable units are represented in Figure 6. Note the large pores (vugs) in the left-hand image that are the result of water-dissolving fossil fragments. The right-hand image contains thin, tan-colored seams of clay minerals that can cause durability problems. The argillaceous limestone observed in the stratigraphic column in Figure 7 is a poor quality aggregate.

Figure 5. Working Face of the Black Pit Showing Four Different Units That Vary in Quality as an Aggregate.

Figure 6. Image on Left Shows Vugs in the Limestone, and Image on the Right Shows Stylolites That Contain Clay Minerals.

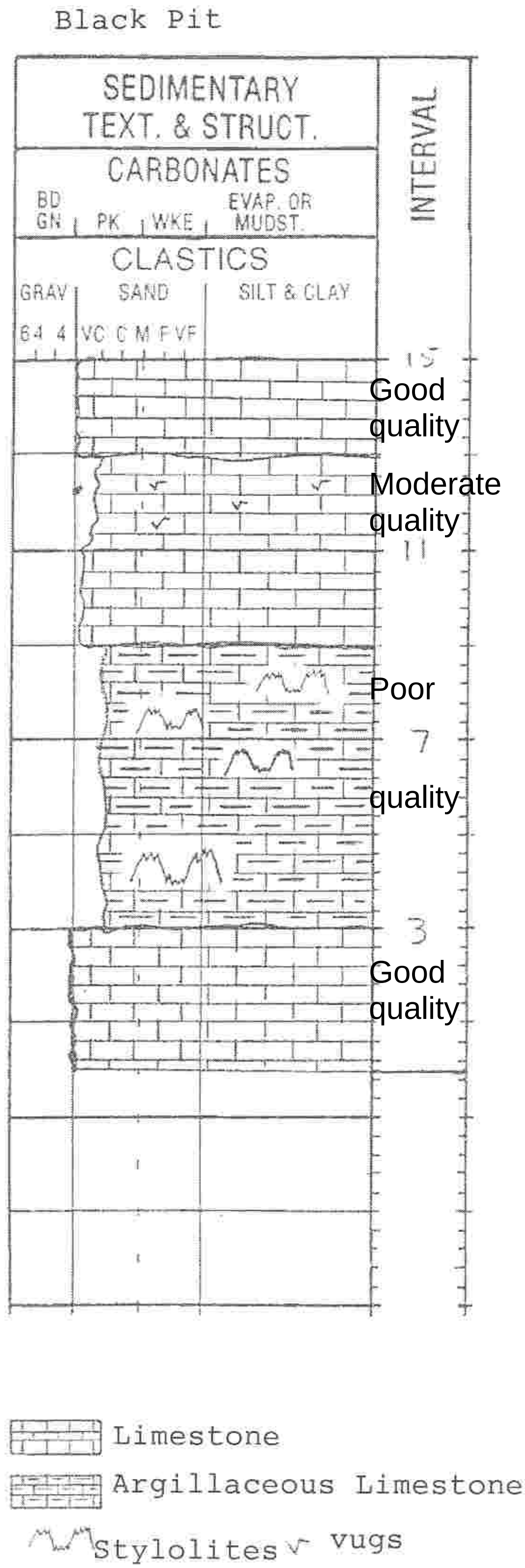


Figure 7. Stratigraphic Column for the Working Face at the Black Pit.

The researchers performed a detailed investigation of the Clements Pit in the San Angelo District (Figure 8). The quarry is in the Fort Terrett Formation, which was deposited in the Cretaceous Period. This quarry is quite extensive with aggregate being produced from several benches. One bench was investigated where the state stockpile was being generated. The working face was about 15 feet high and was composed of several thin, laterally continuous limestone beds intercalated (sandwiched between) with thin sand/silt and shale stringers (Figures 8, 9, and 10). Bioturbation (burrows) was abundant in good quality aggregate (Figure 9), and there was very little poor quality rock in this particular section of the quarry.

Figure 8. Working Face at the Clements Pit Showing Thin, Laterally Extensive Limestone Beds.

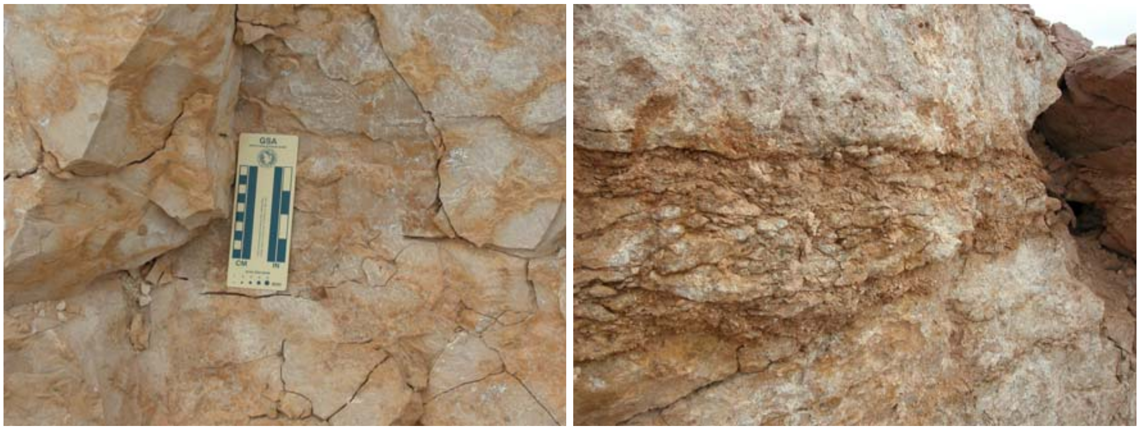
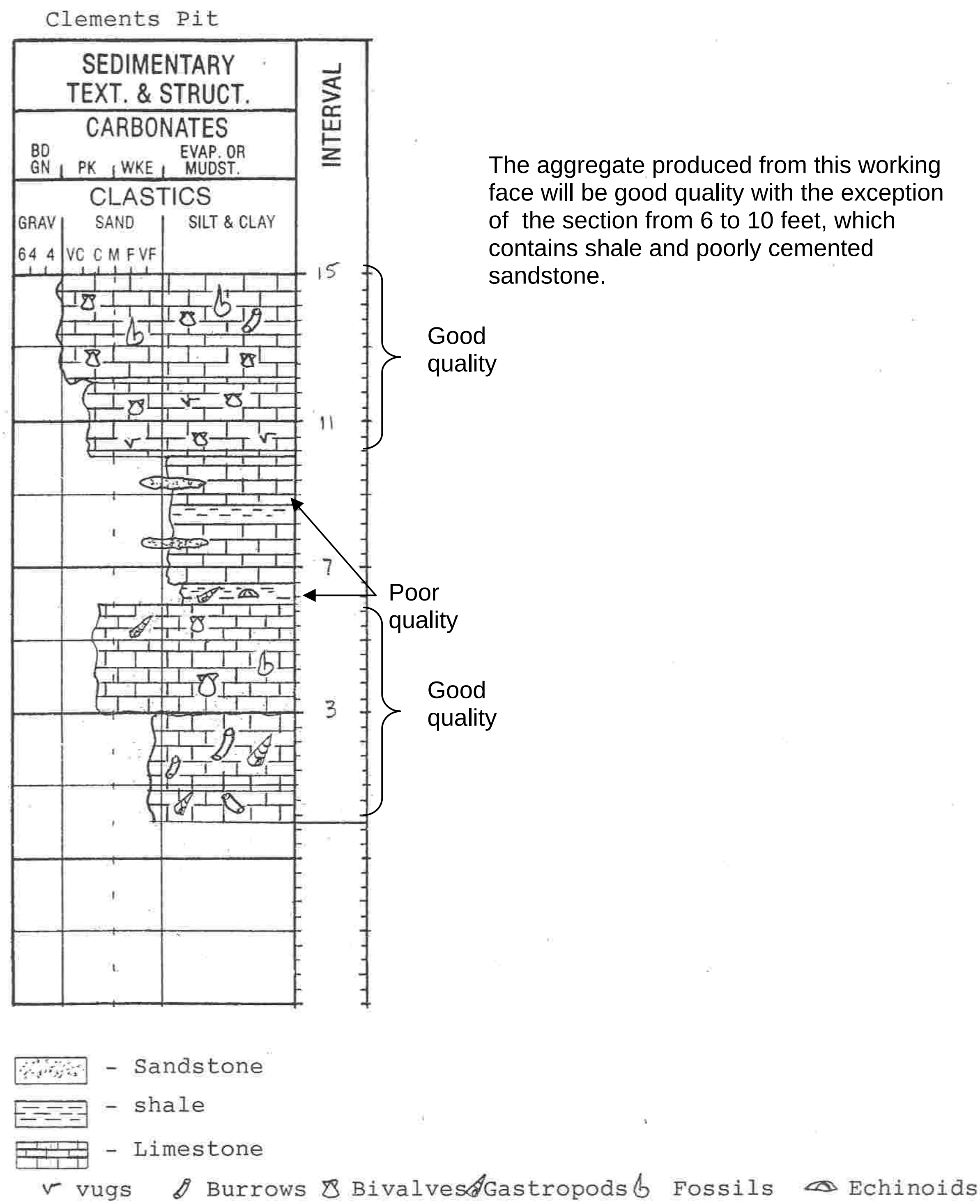


Figure 9. The Left-Hand Image Shows Extensive Burrowing near the Base of the Working Face, and the Right-Hand Image Shows Less Resistant Rock Which Makes a Poor Quality Aggregate.



The aggregate produced from this working face will be good quality with the exception of the section from 6 to 10 feet, which contains shale and poorly cemented sandstone.

Figure 10. Stratigraphic Column for the Working Face at the Clements Pit.

Two basalt quarries in New Mexico were studied as well. They are both in the Clayton Basalt that formed in the Quaternary Period, which is geologically very young, having formed from an erupting volcano in the last 1.5 million years.

The first quarry is called the Behne Pit, and the working face is about 30 feet thick. It is more weathered (red color in Figure 11, and Figure 12) along fractures and near the top of the quarry where the rock is exposed to the elements (i.e., rain, wind, etc.). The working face appears to be a single lava flow due to the vertical vents where hot gases escaped from the flow (Figure 12), vesicles (air bubbles) near the top (Figure 13), and variation in grain size of the phenocrysts (large mineral grains).

Figure 11. Thirty-Foot High Working Face at the Behne Pit.

Figure 12. The Left-Hand Image Shows a Vent in the Quarry Wall, and the Right-Hand Image Shows Weathering Products Developed along Fracture Surfaces.

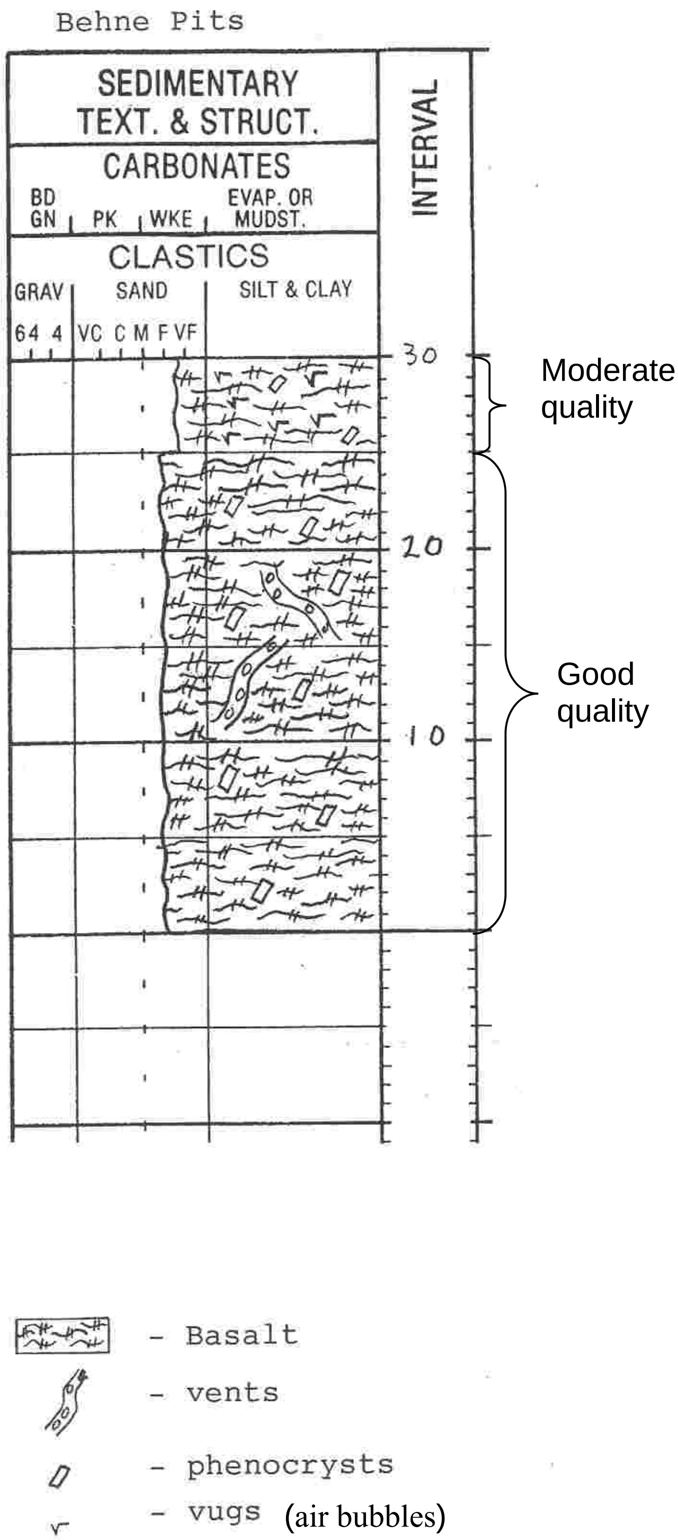


Figure 13. Lithologic Column of the Working Face from the Behne Pit.

The last quarry to be examined in detail is the Smith Pit, which also contains rock from the Clayton Basalt. The rock in the Smith Pit is very similar to the Behne Pit. The only differences observed in the working face are abundant red clay balls filling vesicles (air bubbles) near the top of the Smith Pit (Figure 14) and a lack of vertical vents (Figure 15).

This rock should provide a good source of aggregate if the weathered material represented in Figure 14 is excluded from the stockpile. There are numerous red clay balls filling the voids near the top of this quarry face. The clay balls are alteration products of the basalt and indicate that this material is unstable and should be removed from the top of the quarry prior to crushing.

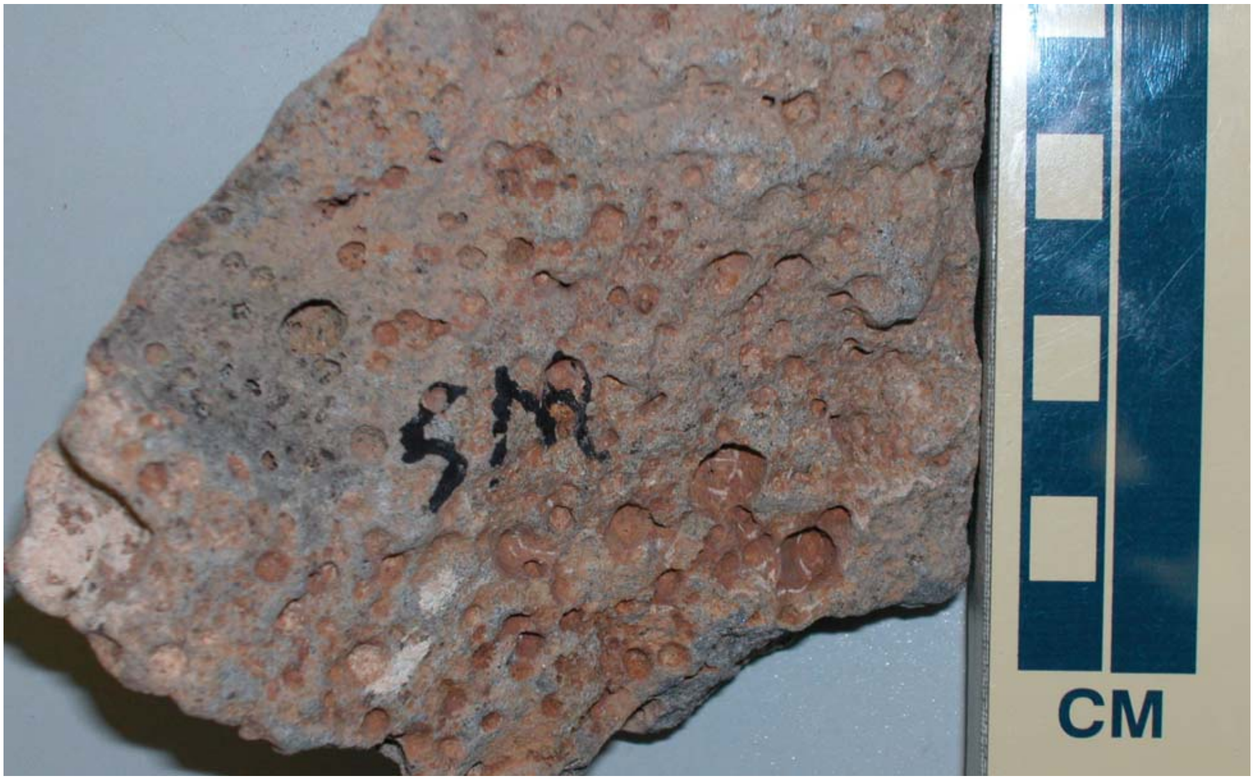


Figure 14. Vesicular Basalt from the Top of the Smith Pit with Red Clay Filling Vesicles (Air Bubbles).

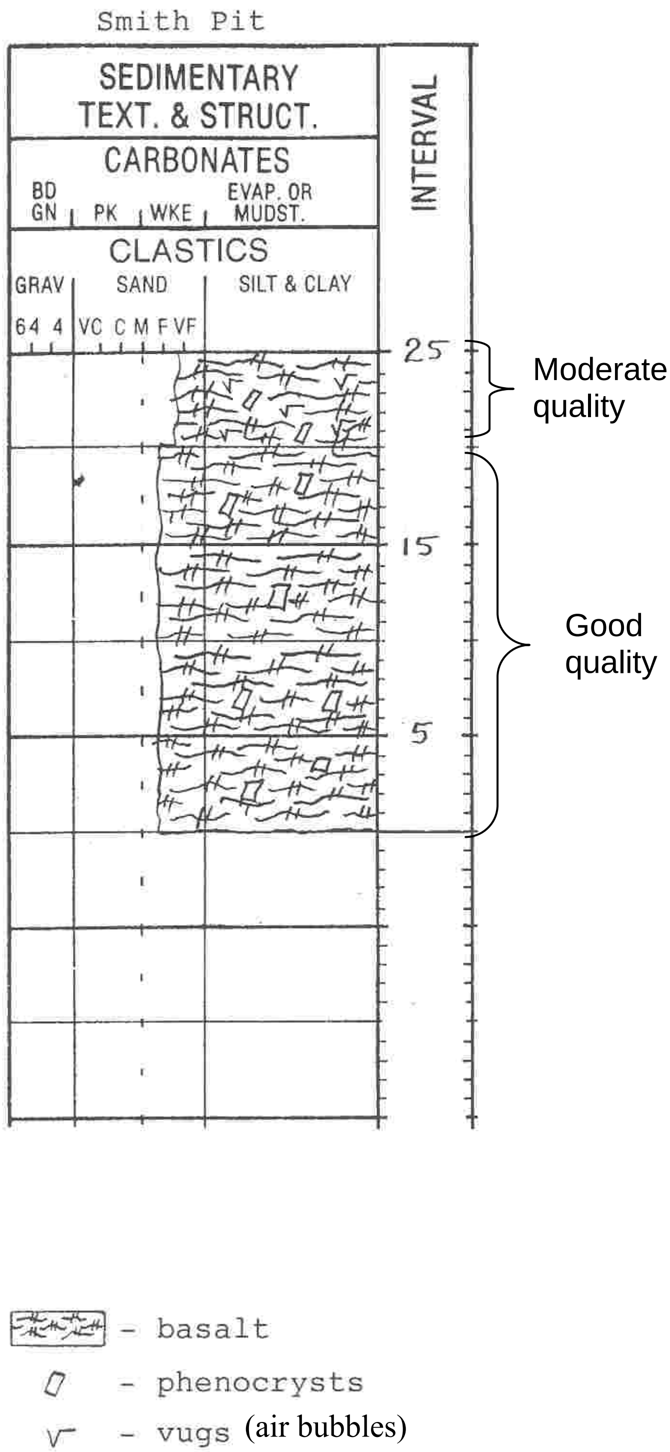


Figure 15. Lithologic Column from the Working Face of the Smith Pit.

Thin-Section Analyses

For the detailed quarry investigation, a total of 32 thin-sections were analyzed using both stereoscopic and petrographic microscopes. The rock types ranged from sedimentary sandstones and limestones for the Baird, Black, and Clements Pits to extrusive igneous basalts for the Behne and Smith Pits.

Aggregate quality for the sedimentary rocks can generally be correlated with the degree and type of cementation (e.g., quartz vs. calcite vs. clay cement) and the pore types and sizes (e.g., large isolated vs. small interconnected pores).

The basalt samples from the Behne and Smith Pits are all very similar based on the petrographic analysis, but the Smith Pit contains abundant clay balls in the upper 10 feet of the quarry that increase the percentage of less durable rock.

DISCUSSION

Field Description and Thin-Section Analyses

Based upon the field evaluation and detailed analysis of thin-sections from the five quarries discussed in detail, the limestone quarries all consist of rocks formed in a shallow-water marine environment.

The stratigraphic column and thin-section analysis of the Baird Pit show a cyclic sedimentation pattern controlled by changes in relative sea level. The carbonate aggregates are deposited on a broad, shallow shelf, and the sandstones are supplied when a terrigenous source is made available by changes in relative sea level or by storms lowering the wave base, allowing for rapid sedimentation of terrigenous rocks.

The Black Pit is composed of hard, nonporous packstones to argillaceous packstones with Rudist bivalves being the most common fossil. The argillaceous limestone contains abundant stylolites, which may make a poor aggregate based on work by Mckirahan et al. (2004) and results from this project presented in Chapter 2.

The stratigraphic column of the Clements Pit reveals a classic shoaling upward sequence, typical of Cretaceous limestones, where the rock contains less mud as one proceeds upsection, indicating a fall in sea level or an increase in energy.

From the lithologic column and thin-section analyses, it appears that the Behne Pit is a single lava flow originating in the Quaternary. The aggregates in this quarry appear to be very fresh with small weathering rinds present around some of the olivine phenocrysts.

The aggregates in the Smith Pit are very similar to the Behne Pit, but they appear to be more weathered near the top of the quarry (i.e., ground surface). Clay balls fill vesicles or vugs near the top of this quarry (Figure 14).

Aggregate Sampling and Quantification at the Quarry

As stated in Report 0-4523-1, TxDOT's current method of sampling from a stockpile (Tex-221-F) is inadequate for obtaining a representative sample in the large stockpiles encountered at the quarries examined in this investigation.

If there is little variation in a sample and there is no bias in collecting the sample, then a small sample will be representative of the population. If the variation is large, then more and larger samples will be required (Smith and Collis, 1993).

The best method is to sample from the conveyor belt as outlined by Shergold (1963). Crushed rock aggregate should be sampled while in motion with a minimum of eight increments over a period of one day with the weight depending on the size of the material (Table 2). The entire cross-section of the conveyor belt should be sampled, including the fines adhering to the belt. The increments are then mixed to form a composite and reduced by riffling (Shergold, 1963).

Table 2. Minimum Weights for Sampling as Defined by Shergold (1963).

Max size present in substantial proportion (85% passing) mm	Minimum weight of each increment (kg)	Minimum number of increments	Minimum weight dispatched (kg)
64 (2 ½ inch)	50	16	100
50 (2 inch)	50	16	100
38 (1 ½ inch)	50	8	50
25 (1 inch)	50	8	50
19 (3/4 inch)	25	8	25
13 (1/2 inch)	25	8	25
10 (3/8 inch)	13	8	13
6.5 and less (1/4 inch)	13	8	13

To obtain a representative sample by riffling, there are different recommendations concerning the amount of aggregate needed to get a good quantitative analysis of constituents. ASTM C-295 recommends 45 kg for all aggregate sizes; however, the British (BS 812: Part 104) have a more reasonable recommendation. They have developed a nomograph to determine the minimum sample size to achieve ±10 percent relative error. Table 3 illustrates how sample size changes based on the percentage of a constituent one is interested in measuring. For example, if one were interested in achieving ±10 percent relative error for a 3/8-inch aggregate that contained 2 percent of a poor quality rock, then 10,000 g of material would have to be analyzed.

Table 3. Minimum Test Portion Sizes for Quantitative Analysis.

Max. particle Size in mm (English)	Min. Mass to Test Constituent at 20% (g)	Min. Mass to Test Constituent at 2% (g)
20 (3/4 inch)	6000	60,000
10 (3/8 inch)	1000	10,000
5 or less (No. 4)	100	1000

Following the sample reduction by riffling, to get a good indication of the percentages of different rock types at a quarry, the researchers recommend a technique used by James Bates (TxDOT – retired) where 3000 g is weighed out, a washed sieve analysis is performed, and the sample is placed in a box that has been partitioned off by sieve size (Figure 16). A digital photo is taken of the sample for documentation purposes. Following the digital photo, the aggregate pieces from the 5/8 inch, 3/8 inch, and #4 sieve partitions are further subdivided into like groups based on outward physical appearance (i.e., color, roundness, sphericity, relative density, and absorption). Aggregates with similar physical characteristics are placed on a sample mat, and a digital photo is taken (Figure 17). The percent of each constituent can be calculated based on the number of pieces in each grouping. There should be at least 150 particles in each of these size ranges to obtain a representative sample (Mielenz, 1994; Langer and Knepper, 1998).

Figure 16. Aggregate Fractionation Used by James Bates and Recommended by the Researchers.

Figure 17. Aggregates Grouped According to Similar Physical Characteristics.

CONCLUSIONS AND RECOMMENDATIONS

Based on results of the detailed quarry analyses, the three limestone quarries consist of aggregates deposited in shallow seas that will result in rocks that are laterally continuous. All of the limestone quarries contain varying proportions of rock that makes a good aggregate. Two things that appear to affect limestone aggregate quality in the limestone quarries are clay minerals mixed in the limestone (Figures 3 and 6) and the amount of interconnected pores. Report 0-4523-1 outlines various steps that can be taken at the quarry to increase the quality of the aggregate.

The two basalt quarries raised some different issues as far as aggregate quality is concerned. The quality of the basalt seems to be tied to the amount of degradation or weathering of the basalt. As observed in Figure 14, clay is filling vesicles in rock that has been exposed to weathering, but the clay-filled vesicles disappear at depth where the rock has not been exposed to the elements. The clay contributes to the breakdown of the aggregate in use.

Testing Frequency to Identify Mineralogical Segregation

The only way to guarantee aggregate quality in quarries with variable/marginal aggregate is to sample according to the following scheme for each job the aggregate is to be used on and every time new aggregate is to be added to an existing TxDOT approved stockpile.

In order to obtain a representative sample to evaluate mineralogical segregation in an aggregate source, one can have up to 10 percent very poor aggregate in a hotmix asphalt concrete mix without adversely affecting performance, as illustrated in Chapter 3. This will determine how much sample needs to be taken from the quarry for detailed analysis. The British (BS 812: Part 104: Draft) recommend the following amounts of aggregate be delivered to the laboratory so it can be split into smaller fractions for detailed mineralogical analysis: 50 kg of aggregate in the 20 mm (3/4 inch) size range, 25 kg of 10 mm (3/8 inch), and 10 kg of aggregate in the 5 mm (#4) or smaller size range.

For example, if one wanted to evaluate a 3/8 inch aggregate from a crushed rock quarry, then he would need to obtain 25 kg of aggregate from the quarry as described in Report 0-4523-1. The sample should then be split into smaller fractions for detailed laboratory analysis by either quartering or riffling. In order to obtain a statistically significant lithologic analysis at an accuracy of ±10 percent for a poor quality 3/8 inch aggregate present at 10 percent in a quarry, then one would need to analyze 1100 g of sample. For the same accuracy in a 3/4 inch sample, 10,000 g would need to be analyzed.

CHAPTER 2
MINERALOGICAL EVALUATION

INTRODUCTION

Mineralogy of an aggregate can play a key role in the performance of a pavement. Examples of performance problems include alkali aggregate reaction (AAR) in Portland cement concrete pavements where alkalies in the cement react with certain siliceous and carbonate aggregates to form a gel that expands when wet (St. John et al., 1998; Fookes, 1980). In hotmix asphalt concrete, certain aggregates are more susceptible to stripping due primarily to the surface energy of the aggregate and the bond generated with the asphalt.

Many previous studies have focused on testing engineering properties (i.e., strength) without considering the influence that mineralogy and chemistry have on an aggregate (Kandhal and Parker, 1998). Ramsay et al. (1974) stated that bulk composition is an important factor in determining the strength of a rock; e.g., aggregates with significant carbonate minerals are weaker than aggregates with silicate minerals, whether sedimentary, igneous, or metamorphic. Other studies have focused on aggregate interactions with cement paste (Fookes, 1980). Roy et al. (1955) investigated durability of limestone aggregates and determined that clay reduces the durability of limestone aggregates. Shakoor et al. (1982) determined that clay minerals and pores smaller than 0.1 μm in diameter cause problems with freeze-thaw resistance of carbonate aggregates in Indiana. Clay minerals dispersed evenly throughout the aggregate increase water absorption, and the small pores in the aggregate make the skeletal framework of the rock weak. This combination increases the hydraulic pressures and reduces the tensile strength, causing damage to the aggregate (Shakoor et al., 1982).

Because of the clay mineral influence on aggregate durability, Iowa and Kansas use X-ray fluorescence (XRF) to identify the Al_2O_3 content in carbonate aggregates. If the Al_2O_3 content is too high, then the aggregate is deemed poor quality. Researchers have focused on insoluble residue, rock texture, and bulk composition of aggregates, but they have not evaluated the effect minute changes in mineralogy play on rock durability.

In Chapter 1, the field evaluation of 13 quarries around the state was discussed with respect to variations in aggregate quality due to mineralogical and/or textural changes. The researchers selected aggregates from three of these quarries based upon past field performance to be used in a detailed mineralogical study. Researchers selected limestone #1 for its exceptionally uniform quality and performance in AQMP testing. Limestone #2 aggregate was selected because of inconsistent quality and performance. Limestone #3 aggregate performed so poorly that the quarry was closed by the operators, but the researchers obtained permission and collected aggregate from an abandoned stockpile at the quarry. The researchers also evaluated samples from other quarries where TxDOT had obtained inconsistent results.

The objective of this research task was to correlate mineralogical variations with aggregate performance in bituminous mixes. Researchers wanted to test the hypothesis that Al_2O_3 content measured by XRF is a good gauge of aggregate durability so that Al_2O_3 content may be used as a quick test for aggregate durability.

METHODS

Ed Morgan (TxDOT geologist) delivered samples from 13 quarries (some overlap with field quarry investigation) across Texas to the researchers for detailed mineralogical analysis (Table 4). Two to three samples taken at different times were submitted from each quarry. Sample selection was based on large variations in the Micro-Deval and magnesium sulfate soundness test from one sampling time to the next sampling time.

Aggregates from the following six quarries were selected for detailed mineralogical investigation: Yearwood, Clements, Waco Pit #365, Squaw Creek, Black, and Kyle. Each sample was subdivided into groups exhibiting similar mineralogical and textural characteristics such as roundness, matrix, cement type, and porosity (Figures 17 and 18). Seventy-seven thin-sections were prepared of each distinctive aggregate identified by TxDOT geologists. Seventy-three samples for XRF analysis were collected simultaneously to ensure uniformity between the thin-section and XRF samples (Appendix A). Two to three aggregate pieces were submitted to private laboratories for thin-section preparation and XRF elemental analyses, respectively.

Table 4. Samples Obtained from TxDOT for Mineralogical Investigation.

Producer/Sample Location	M-D	Mg-(bit)	Mg (ST)	Mg (con)	Na-(con)
1) Centex (Yearwood)	33.1	37	32		
	20.4	15	12		
2) Dolese (Ardmore)	11.1			5	2
	14.7			14	7
3) Dolese (Cyril)	26.6	26	20		
	27.8	39	34		
4) Price (Clements)	25.2	26	26		
	19.6	15	16		
5) Killeen (Gibbs)	22.8			15	2
	18.1			7	1
6) Martin Marietta (Chambers)	24.5	30			
	23.8	21			
7) Mine Services (Waco Pit 365)	19.0	31	29		
	13.7	11	9		
	16.5	23	20		
8) Squaw Creek LP (Squaw Creek)	35.1	11			
	44.0	18			
9) Cemex (New Braunfels)	16.8	8			
	19.4	19			
10) Vulcan (Black)	N/A				
	19.0				
11) Vulcan (Helotes)	17.8			7	1
	22.0			13	7
12) Vulcan (Tehuacana)	18.5	9	3		
	23.8	14	14		
13) Yarrington Rd Mtrls (Kyle)	13.4			5	1
	26.7			21	20

*(bit) means bituminous mixes, (ST) means surface treatment, and (con) means concrete, M-D means Micro-Deval.

Figure 18. Partitioning of Aggregates Based on Textural Variations.

The methods used for the detailed analysis of the two quarries were somewhat different than those used for analysis of the TxDOT supplied aggregates because more sample is needed than was available with the TxDOT supplied samples. Samples were first sieved to fractionate different aggregate sizes. Researchers submitted the coarser sizes (>#10 sieve) to a private laboratory for thin-section preparation. The material passing the #200 sieve was subjected to various wet chemical treatments outlined in Dixon and White (1999). Following the chemical pretreatments, samples were separated into sand, silt, coarse, and fine clay fractions with a #230 sieve and an IEC high-speed centrifuge. After size fractionation, the samples were readied for X-ray diffraction (XRD) analysis on a Rigaku X-ray diffractometer. Sand and silt-sized samples were mounted in a random powder mount as described in Moore and Reynolds (1997) and analyzed from 2.1 to 65° two-theta at a scan speed of 1°/minute and a step of 0.02°. The coarse and fine clay fractions were saturated with magnesium and potassium and evaporated onto glass (Mg) or Vycor (K) slides to create an oriented clay mount. The potassium-saturated clay sample was analyzed at room temperature, 300ºC, and 550ºC, and the Mg-saturated sample was analyzed at room temperature and after exposure to ethylene glycol for 24 hours. The clay fractions were analyzed from 2.1 to 32° two-theta at a scan speed of 1°/minute and a step of 0.05°.

RESULTS

X-Ray Diffraction of HMAC Samples

Two samples (limestone #2 and limestone #1) used in the hotmix asphalt concrete (HMAC) portion of this research were extensively characterized using specialized mineralogical techniques. The limestone #3 pit sample was not analyzed because the stockpile had been exposed to the environment for a couple of years and much of the deleterious material had been removed by rain and wind. The minus 200 sieve fraction was subjected to various chemical pretreatments to remove cementing agents and allow for more clear size fractionation. As part of the pretreatments, samples are treated with a 1N sodium acetate solution buffered to a pH of 5.0 with acetic acid. This solution dissolve calcite (the principal mineral in limestone) without damaging the non-carbonate minerals in the sample. The material remaining after treatment is called the percent insoluble and can be used to determine the amount of calcite and other minerals in the sample. Table 5 shows that the limestone #2 pit has about one-third the insoluble residue as the limestone #1 material, but the fine clay fraction is substantially higher than the limestone #1 pit.

Table 5. Size Fractionation for the Minus 200 Sieve Fraction.

Sample	**Limestone #2 Pit**		**Limestone #1 Pit**	
Type	**Dolomitic Limestone**		**Sandy Limestone**	
% Insoluble	9.74		29.42	
Size Fraction	% of Total	% of Insoluble	% of Total	% of Insoluble
Sand*	0.14	1.41	17.16	58.33
Silt*	2.58	26.46	8.82	29.99
Coarse Clay*	0.85	8.69	2.22	7.55
Fine Clay*	6.31	64.85	1.22	4.14

* Sand 2000 - 50 μm; Silt 50 - 2 μm; Coarse clay 2 - 0.2 μm; Fine Clay <0.2 μm.

The following figures are XRD patterns of the two samples selected for detailed mineralogical analyses. Figures 19, 20, and 21 are from the limestone #2 pit and represent the silt, coarse, and fine clay fractions, respectively. The silt fraction is dominated by quartz with a small amount of kaolinite (K), mica (M), either smectite (S) or chlorite (C), and feldspar (F) (Figure 19). The coarse clay fraction of the limestone #2 pit sample consists of quartz (Q), kaolinite (K), mica (M), goethite (G), and minor amounts of a mica/smectite (M/S) interstratified mineral (Figure 20). The fine clay (Figure 21) is dominated by smectite (S), with lesser amounts of kaolinite (K), mica (M), and goethite (G). The broad smectite peaks indicate a poorly crystallized mineral.

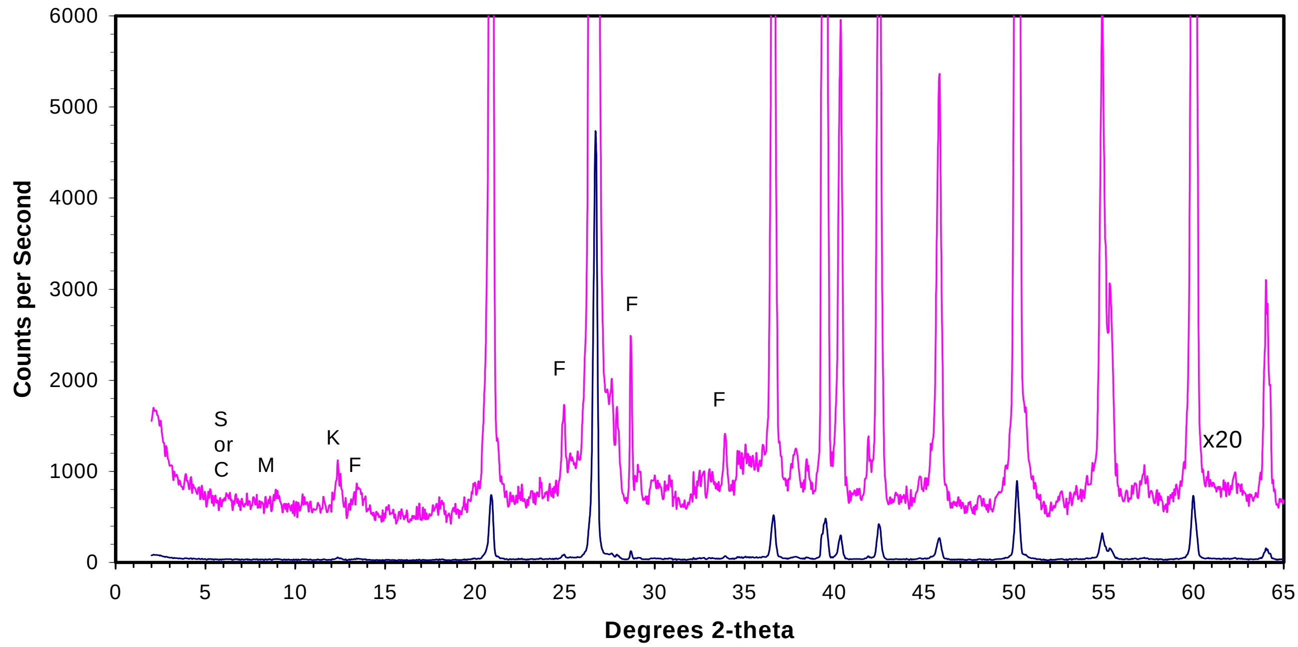


Figure 19. XRD of the Silt Fraction of the Limestone #2 Pit Shows Quartz as the Dominant Mineral.

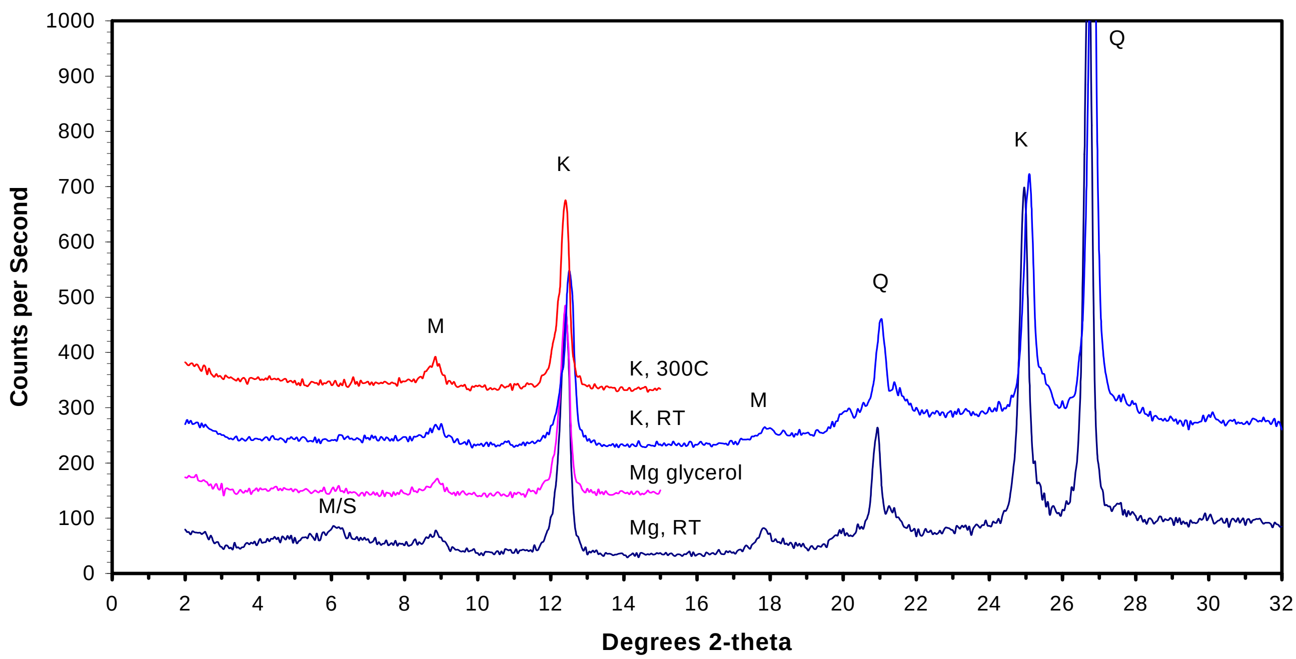


Figure 20. XRD Patterns of the Coarse Clay Fraction from the Limestone #2 Pit.

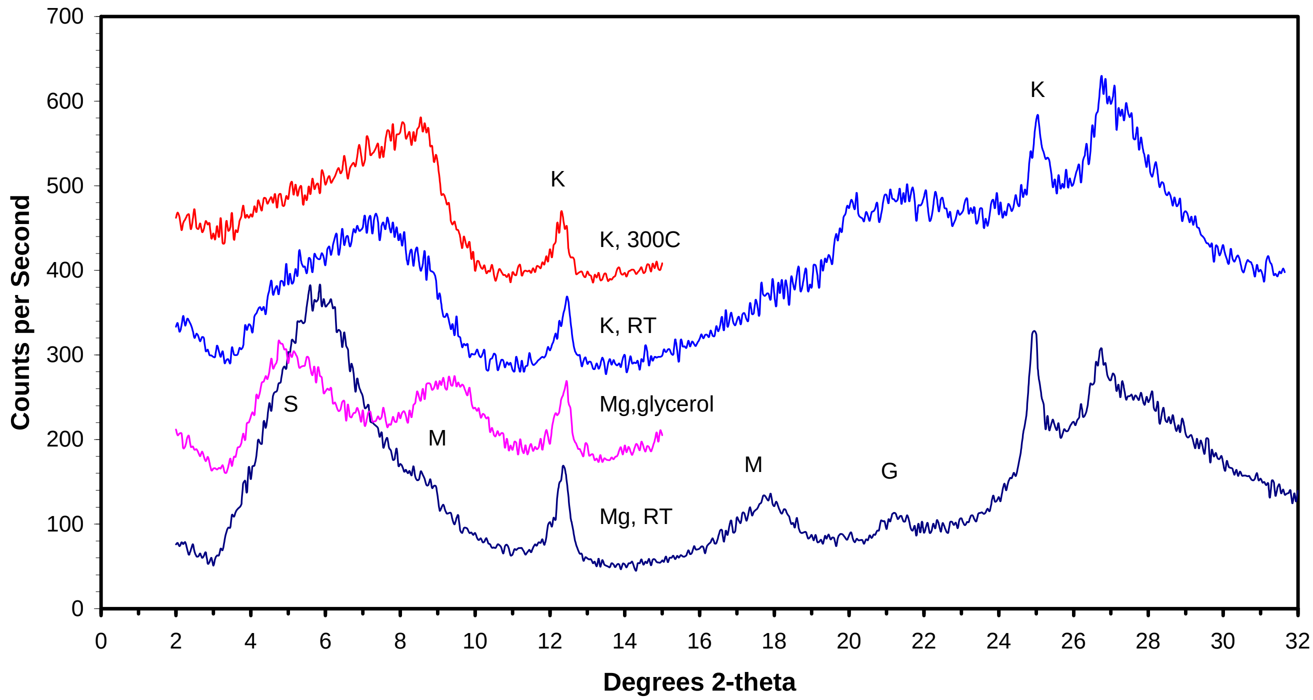


Figure 21. XRD Patterns of the Fine Clay Fraction from the Limestone #2 Pit Showing a Predominance of Smectite (S).

The mineralogy of the limestone #1 pit sample is similar to the mineralogy of the limestone #2 pit. Figure 22 illustrates the importance of performing the size fractionation to determine the mineralogy of a sample. This sample is dominated by calcite (Ca) with a minor amount of quartz (Q). This XRD pattern is of the –200 fraction from the limestone #1 pit before it was subjected to any chemical pretreatments (to remove calcite) or size fractionation. Note the absence of clay mineral peaks in the region of 5º to 20º two-theta. The calcite (Ca) masks all of the clay minerals present in lower concentrations.

Figure 23 is the result of chemical pretreatments to remove the calcite and sieving coupled with centrifugation to separate the sand, silt, and coarse and fine clay fractions. The coarse clay fraction (Figure 23) from the limestone #1 pit consists primarily of quartz (Q) and mica (M). Kaolinite (K), chlorite (C), and smectite (S) are present in lower concentrations. Note the sharp and narrow peaks on this pattern are indicative of larger and better crystallized minerals.

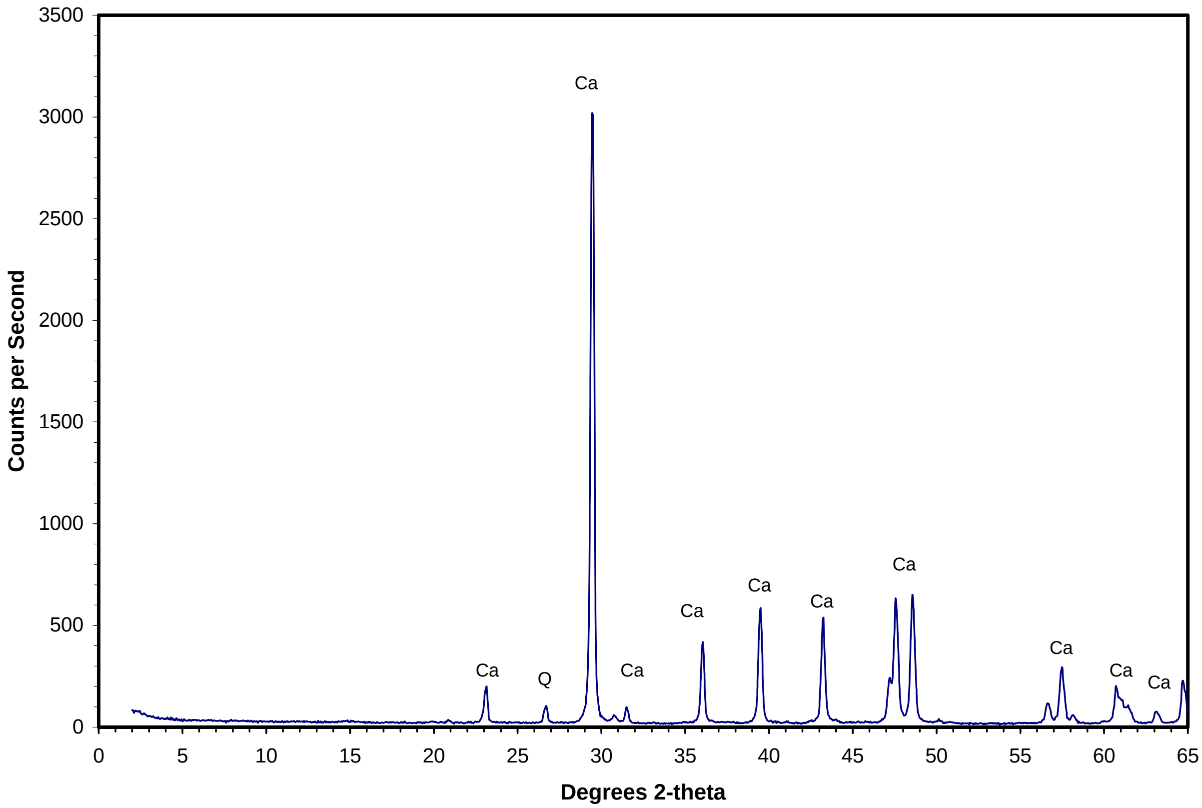


Figure 22. XRD Pattern of the Minus 200 Fraction from the Limestone #1 Pit.

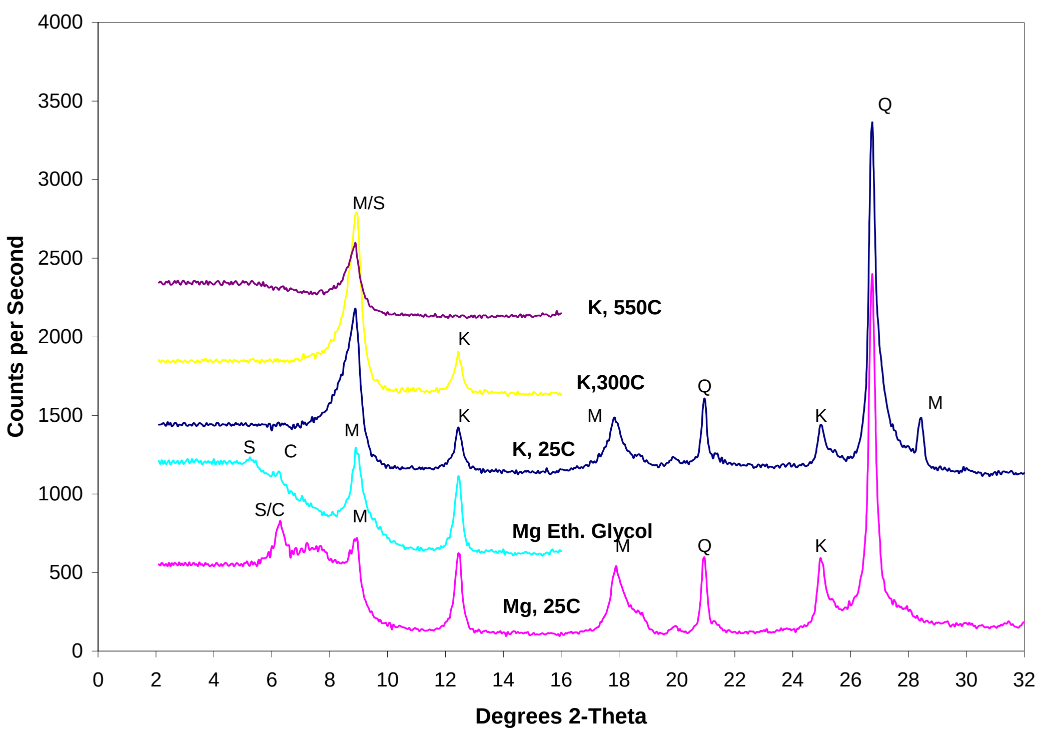


Figure 23. XRD Patterns of the Coarse Clay Fraction from the Limestone #1 Pit.

Figure 24 is from the fine clay fraction of the limestone #1 pit. The individual peaks are generally broader, indicating smaller and more poorly crystallized minerals. This sample is dominated by smectite (S), with lower concentrations of mica (M) and kaolinite (K).

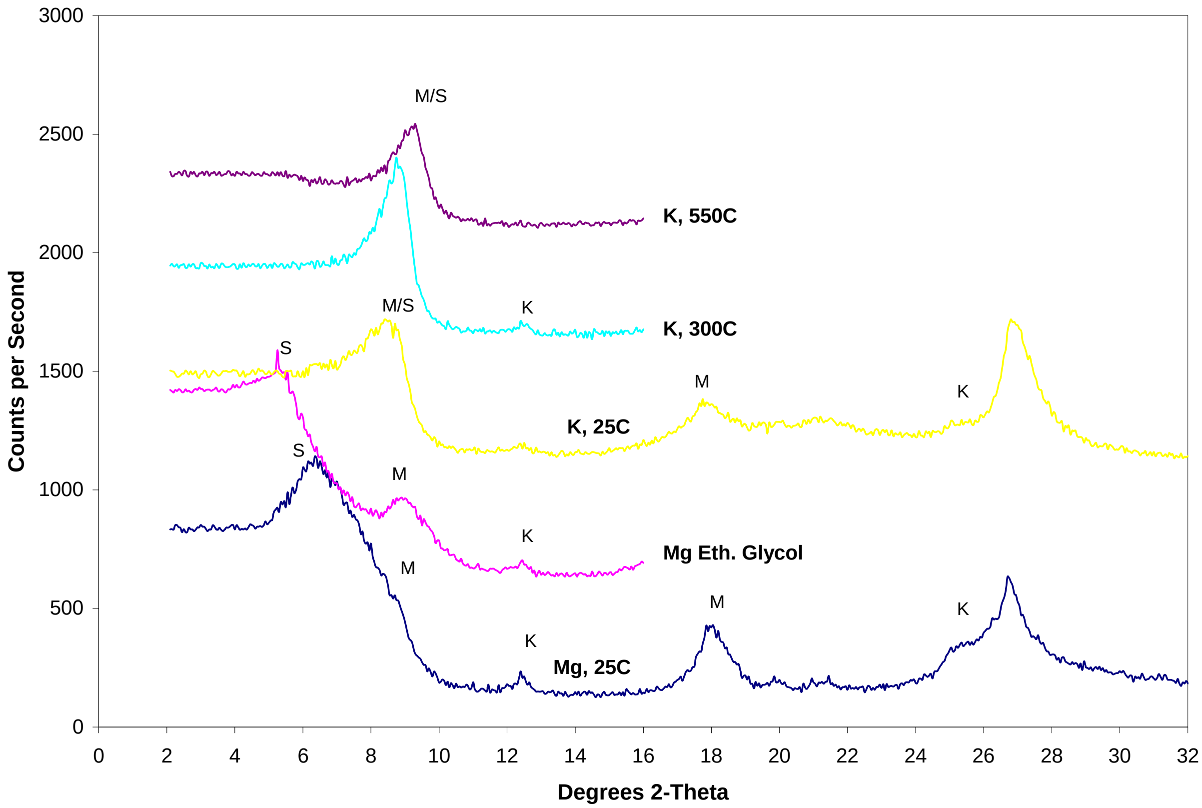


Figure 24. XRD Patterns of the Fine Clay Fraction from the Limestone #1 Pit.

XRF of Texas Department of Transportation Samples

Many departments of transportation commonly use Al_2O_3 content or insoluble residue as an indication of the clay content of an aggregate source based upon observations made in several research studies (Shakoor et al., 1982). As part of this research effort, there was enough data from three quarries to compare Al_2O_3 content with two traditional aggregate quality tests: the Micro-Deval (M-D) and magnesium sulfate soundness (Mg). These data are presented in Table 6 (all XRF data are in Appendix B). From the limited data, there is no clear correlation between aggregate quality as measured by these two tests and the aluminum oxide content.

Table 6. Correlation of Aggregate Tests with Aluminum Oxide Content.

Producer/Location	M-D	Mg-(bit)	Mg (ST)	Mg (con)	Al_2O_3 (%)
Centex/Yearwood	33.1	37	32		1.68
	20.4	15	12		0.24
Mine Services/ Waco Pit 365	19.0	31	29		0.58
	13.7	11	9		0.50
	16.5	23	20		0.59
Yarrington Road Materials/Kyle	13.4			5	0.56
	26.7			21	0.50

DISCUSSION

There have been many studies on factors affecting the quality of limestone aggregates (Shakoor et al., 1982; Fookes and Hawkins, 1988a; and Mckirahan et al., 2004). They all agree that weathering is detrimental to aggregate quality. Weathering generally increases pore volume and increases the percentage of clay minerals in the rock (Railsback, 1993). Shakoor et al. (1982) determined that poor performing Indiana limestones are highly argillaceous and have insoluble residues ranging from 20 to 45 percent consisting of low-plasticity silts and medium-plasticity silty clays. Shakoor et al. (1982) state that clay evenly distributed throughout the rock seems to be most problematic. Limestones with a large pore volume and small pore diameters (less than 0.1 µm) are also considered nondurable (Shakoor et al., 1982; Winslow, 1994).

Mckirahan et al. (2004) report that textural variations in Kansas limestones do not affect durability, but the abundance, distribution, and mineralogy of clays seem to be the most important factors affecting durability. Based upon observations from this research project and other work performed by the researchers, the authors have to agree with Mckirahan et al. (2004) about the importance of clay mineral type in affecting durability. The dominant clay mineral groups as outlined in Dixon and Weed (1989) are kaolinite, illite, smectite, chlorite, and vermiculite. Smectite and vermiculite are the only ones that expand and contract upon wetting and drying and would be the most detrimental.

CONCLUSIONS AND RECOMMENDATIONS

The authors do not have enough evidence to support the conclusion that Al_2O_3 content is a good indicator of aggregate durability. Based on the data obtained in this investigation, the researchers speculate that clay mineralogy may be the most important factor controlling aggregate durability. The authors further speculate that smectite is the most detrimental clay mineral.

From the data on the two limestone aggregates used in the HMAC portion of this project, one would have to conclude that there is a certain threshold of clay that causes detrimental effects on aggregate quality because both aggregates contained very similar clay mineralogies, but the lower quality aggregate contained a higher percentage of smectite.

CHAPTER 3

PERFORMANCE EVALUATION OF HMAC MIXTURES WITH DIFFERENT LIMESTONE AGGREGATES

INTRODUCTION

The qualities of a good aggregate used in hotmix asphalt concrete have long been recognized. Smith and Collis (1993) identified six properties of aggregates that affect their suitability as a pavement surfacing material. Kandhal and Parker (1998) performed a thorough investigation of hotmix asphalt concrete performance issues and current test methods used to identify poor quality coarse and fine aggregates. They identified the following HMAC performance parameters as being affected by the aggregate quality:

- permanent deformation (directly from traffic loading and indirectly from stripping);
- raveling, popouts, or potholing;
- fatigue cracking; and
- frictional resistance.

Studies in the past have focused on identifying what makes an aggregate not perform well and how the aggregate affects pavement performance. The question is not what constitutes a poor quality aggregate, but how much of a poor quality aggregate can be added to hotmix asphalt concrete and maintain the quality of the pavement layer.

The project monitoring committee informed the researchers that most of the coarse aggregate problems in hotmix asphalt concrete applications in Texas were limestones. The research team identified three limestone aggregate sources (one good, one marginal, and one poor quality aggregate) of varying quality for the hotmix asphalt-aggregate testing phase. Aggregate was collected from three pits labeled: limestone #1, limestone #2, and limestone #3 (Table 7). Both coarse and fine aggregate from the limestone #1 pit were collected. Only coarse aggregate was obtained from the other two pits.

There are two primary objectives to this task. First, the researchers wanted to examine the effects of poor quality coarse limestone aggregate on the performance of HMAC. Secondly, researchers determined how much poor quality coarse limestone aggregate can be used and still get acceptable mixture performance.

Table 7. Aggregates Included in HMA Mixture Testing.

Quarry Name	Code	Mineralogy	District
Limestone #1	LS1	Limestone	Brownwood
Limestone #2	LS2	Limestone	Austin
Limestone #3	LS3	Limestone	San Angelo

Aggregate from these three sources and their blends were tested using the following laboratory tests:

- Los Angeles (LA) abrasion,
- Micro-Deval,
- sulfate soundness,
- specific gravity and absorption,
- decantation, and
- aggregate image analysis.

With the exception of the Micro-Deval and sulfate soundness tests, a brief description of the above aggregate tests and their results are presented below. The Micro-Deval and sulfate soundness tests will be discussed in Chapter 4.

LA Abrasion Test

The Los Angeles abrasion test is the most widely used test for evaluating the resistance of coarse aggregate to degradation by abrasion and impact (Kandhal and Parker, 1998). This test measures the percent fines generated by impact and abrasion forces. In this test procedure, coarse aggregate of a defined gradation is placed in a steel drum along with a specified number of steel balls of a certain size. The drum is rotated for 500 revolutions. The shelf within the drum lifts and drops the aggregate and steel balls during each revolution. Some research studies have indicated that this test, at best, relates to the aggregate performance during construction (handling, mixing, and compaction) instead of its performance in-service.

In this research project, the researchers followed TxDOT procedure Tex-410-A, "Abrasion of Coarse Aggregate Using the Los Angeles Machine" to conduct this test. Table 8 lists the results of the three original aggregates. As expected, limestone #1 performed best and limestone #3 performed worst. But limestone #2 showed a large difference between sample 1 and sample 2.

Table 8. LA Abrasion Test Results with Original Aggregate.

Aggregate	LA Abrasion Value (%)		
	Sample 1	Sample 2	Average
Limestone #1	26.15	25.82	26.0
Limestone #2	35.34	31.83	33.6
Limestone #3	44.73	44.94	44.8

Limestone #1 aggregate was blended with the other two sources at different ratios and tested with the LA abrasion test to examine whether blending had any effect on test results. Table 9 shows the test results with aggregate blends. The theoretical value was calculated from the weighted average of the test results shown in Table 8. The test results of limestone #3-limestone #1 blends are similar to their respective theoretical values, whereas the limestone #1-limestone #2 blends show large differences. The differences indicate two things: 1) that limestone #2 may exhibit better performance than limestone #3 but is less consistent, or 2) the LA abrasion test has large variability. This explanation is supported by the fact that the 100 percent limestone #2 aggregate showed a large variation between the two samples.

Table 9. LA Abrasion Test Results with Aggregate Blend.

Aggregate Name	Description	LA Abrasion Value	
		Theoretical Value	Actual Test Value
80-20 Limestone #3	80% Limestone #1 aggregate and 20% Limestone #3 aggregate	29.76	27.7
80-20 Limestone #2	80% Limestone #1 aggregate and 20% Limestone #2 aggregate	27.5	22.6
50-50 Limestone #3	50% Limestone #1 aggregate and 50% Limestone #3 aggregate	35.4	33.0
50-50 Limestone #2	50% Limestone #1 aggregate and 50% Limestone #2 aggregate	29.8	23.5

Specific Gravity and Absorption Test

Determination of specific gravity of aggregate used in the HMAC mixture is required for mixture design. In addition to the specific gravity measurement, water absorption is also measured without any additional time. The researchers followed Tex-201-F to measure specific gravity and water absorption of each aggregate. Table 10 shows the results of this test. Specific gravity and water absorption were measured separately for each size of coarse aggregate from a given source. The research team tested additional aggregate sizes from the limestone #3 pit. The limestone #3 aggregate was obtained from a base course stockpile and contained a large variation in sizes (2 inch downward). The limestone #1 yielded the lowest water absorption with little difference for the different size fractions. The limestone #2 aggregate had a higher absorption value that increased as the particle size decreased. The limestone #3 aggregate demonstrated the highest absorption values, which increased with smaller particles. These results reveal that both marginal aggregates are porous. Higher water absorption and, hence, porosity of aggregate leads to higher absorption of asphalt when used in HMAC mixtures.

Table 10. Specific Gravity and Absorption Test Results.

Aggregate	Specific Gravity (gm/cc)			Water Absorption (%)
	Oven Dried	Saturated Surface Dry	Apparent	
Limestone #1 ½ inch	2.684	2.703	2.736	0.70
Limestone #1 ¾ inch	2.673	2.690	2.719	0.64
Limestone #2 ½ inch	2.376	2.463	2.602	3.66
Limestone #2 ¾ inch	2.394	2.459	2.562	2.74
Limestone #3 ½ inch	2.210	2.344	2.550	6.03
Limestone #3 ¾ inch	2.239	2.352	2.524	5.03
Limestone #3 1 inch	2.219	2.332	2.502	5.09
Limestone #3 1½ inch	2.237	2.339	2.489	4.52

Decantation Test

Aggregates from the three sources were tested following Tex-217-F, "Determining Deleterious Material and Decantation Test for Coarse Aggregates, Part II." Determination of deleterious materials was not pursued because that procedure is deemed very subjective. The objective of this test was to determine the fine dust, clay-like particles, and/or silt present as coatings on the coarse aggregate.

In the decantation test, a representative amount of oven-dried coarse aggregate is soaked in water for 24 hours and then washed over a #200 sieve. The aggregate is again oven dried and weighed. The loss in the soaking and washing is expressed as a percentage and is termed the decantation value. Higher decantation values indicate more dust and clay-like particles present in the coarse aggregate. Table 11 presents the decantation test results. The limestone #2 aggregate yielded the highest decantation loss, suggesting that it had more fine dust and/or clay-like particles. The limestone #1 aggregate yielded the lowest decantation value, but it had been washed in the plant. All three aggregates meet the TxDOT specification. The limestone #3 aggregate was expected to show a higher decantation loss. However, it was exposed to rain and weathering for several years. The authors suggest that the fine dust and/or clay-like particles may have been washed out.

Table 11. Decantation Test Results.

Aggregate	Decantation Loss (%)
Limestone #1	0.23
Limestone #2	1.11
Limestone #3	0.35

Aggregate Imaging System (AIMS)

Image analysis of aggregate to characterize its angularity, shape, and texture is a promising and versatile technology (Chowdhury, et al. 2001; Fernlund, 2005). Several new automated techniques have been developed and are being used for measuring shape and surface parameters. Dr. Eyad Masad developed AIMS to characterize aggregate parameters. Details of the main components and design of the prototype aggregate imaging system are reported elsewhere (Masad, 2003). AIMS was developed for capturing images and analyzing the shape of a wide range of aggregate types and sizes that cover those used in hotmix asphalt concrete mixes, hydraulic cement concrete, and unbound aggregate layers of pavements. AIMS uses a simple setup that consists of one camera and two different types of lighting schemes to capture images of aggregates at different resolutions, from which aggregate shape and surface texture are measured using image analysis software. Figure 25 shows the AIMS equipment setup.

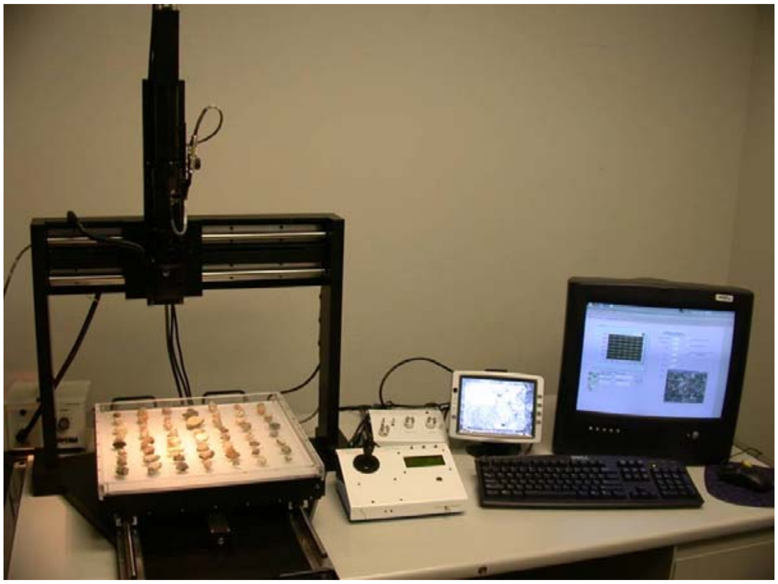


Figure 25. Aggregate Image Analysis System Equipment Setup.

The three limestone aggregates evaluated in the other aggregate tests were tested with the AIMS technology. Researchers evaluated three different size fractions (3/8 inch, 1/4 inch, and #4 sieve sizes). Figures 26 through 28 depict different parameters measured with this equipment. Figure 26 shows that the surface texture for all three size fractions from the limestone #1 pit have a rougher texture than the limestone #2 or limestone #3 pit fractions. It can be argued that the coarser fractions (3/8 inch and 1/4 inch) from the limestone #3 pit show the smoothest texture of the two marginal aggregates. These results agree well with the expected outcome based on the performance of the aggregates in the other tests. The best performing aggregate (limestone #1) exhibits the roughest surface texture, and the most poorly performing aggregate (limestone #3) exhibits the smoothest surface texture.

The same size fractions for the three limestone aggregates were used to calculate the flatness and elongation. The flatness is plotted along the x-axis, and the elongation is plotted along the y-axis of Figure 27. A perfectly cubic aggregate would plot in the upper right corner of the graph. There is no distinction in the flatness to elongation graph for the three different limestone aggregates. This outcome is to be expected since all aggregates analyzed are of the same mineralogy and were properly crushed.

Figure 28 is a measure of the angularity for the three limestone aggregates. The researchers were surprised about the outcome of these measurements. The observations made on aggregate at the quarries and with samples returned to the laboratory for analysis indicated that the lower quality limestone aggregates were more rounded than the higher quality and harder limestone aggregates (Harris and Chowdhury, 2004). However, if one believes the data presented in Figure 28, then there is not a correlation between aggregate quality and angularity. The researchers are somewhat skeptical of these results.

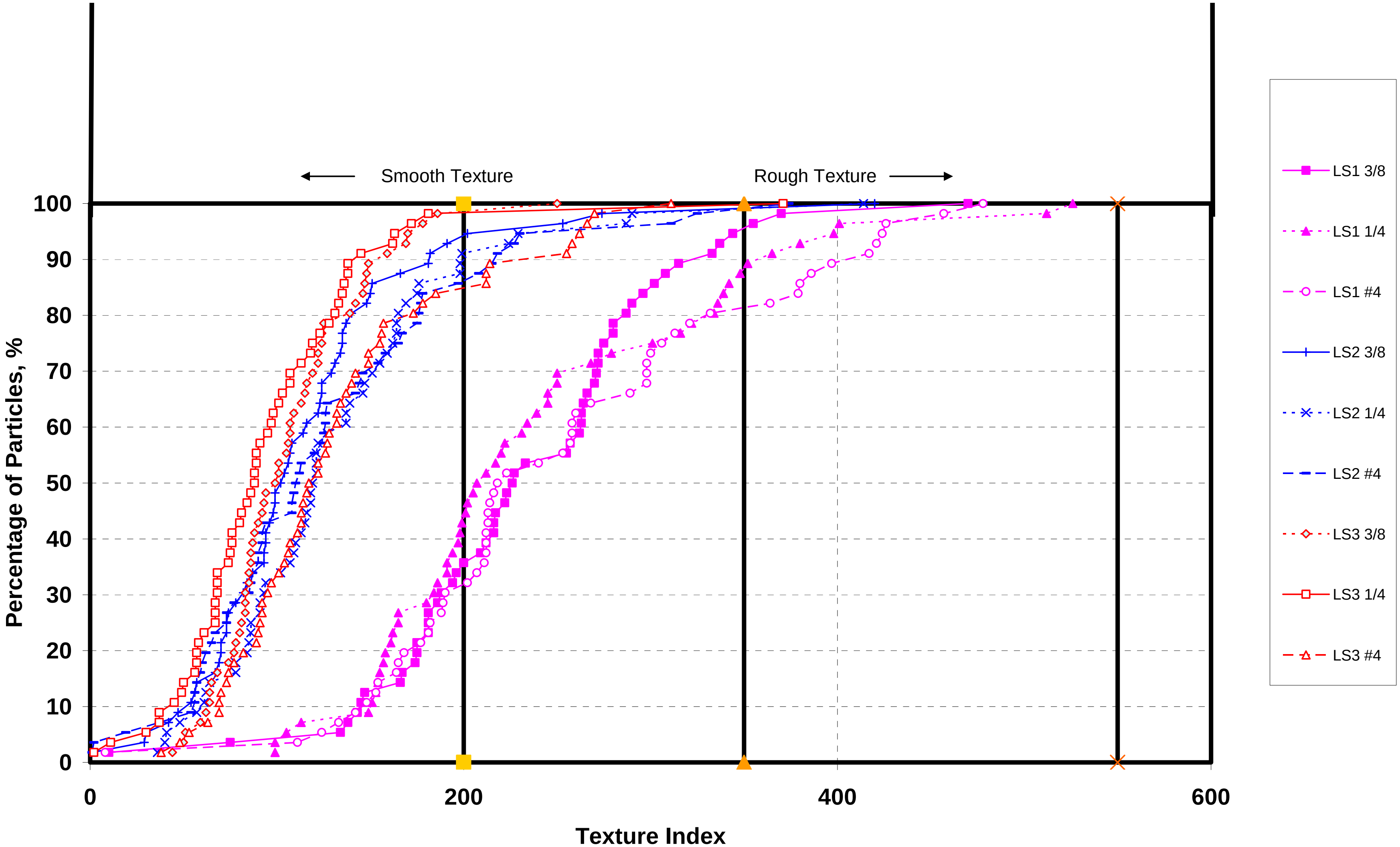


Figure 26. Texture Index Measured with AIMS.

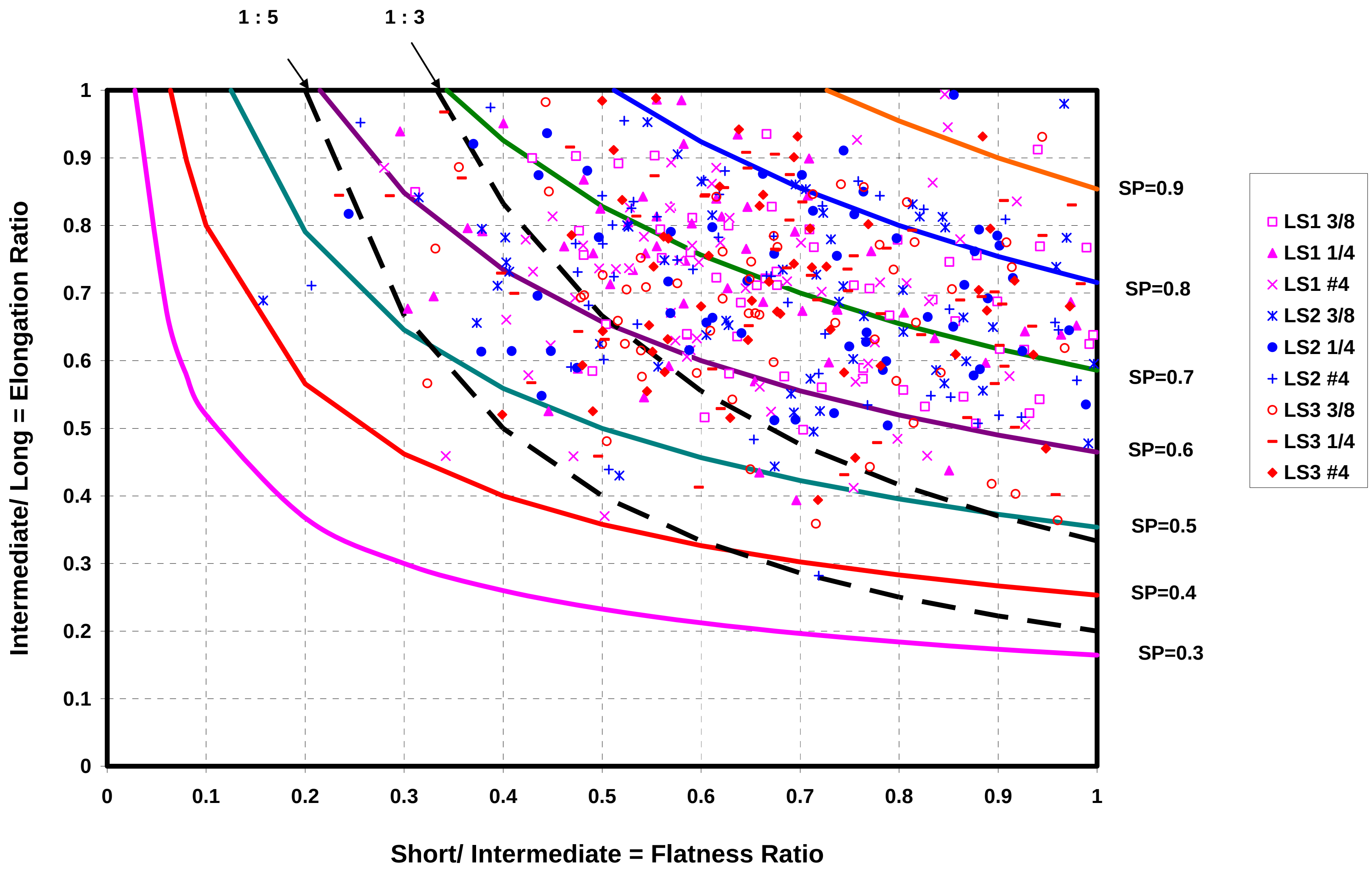


Figure 27. Shape Index Measured with AIMS.

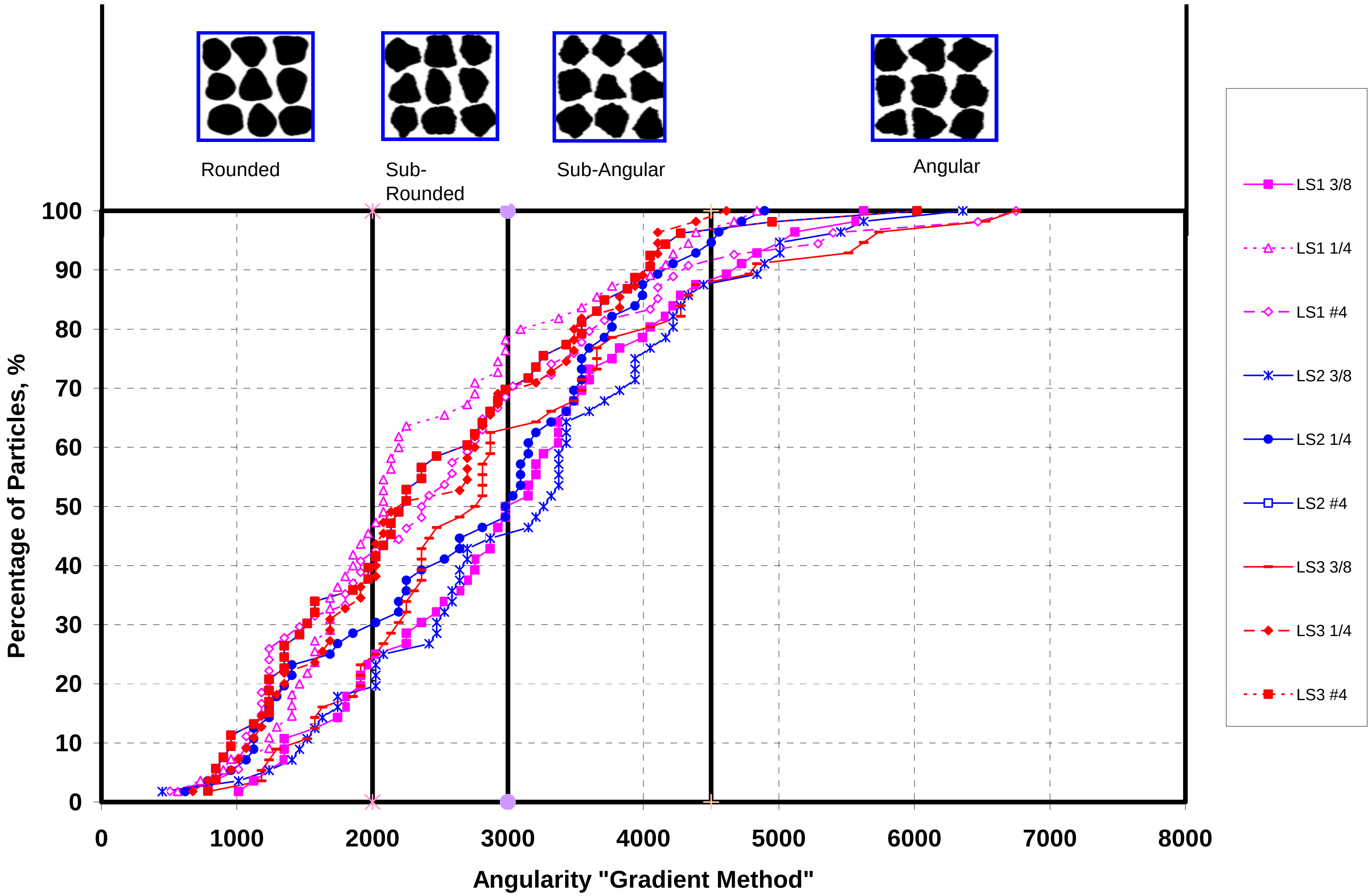


Figure 28. Angularity Index Measured with AIMS.

PERFORMANCE EVALUATION OF HMAC MIXTURE

This part of the research provided the information on how mineralogical segregation of coarse aggregate affects the properties of HMAC mixtures. As mentioned earlier, coarse and fine aggregates were collected from the limestone #1 pit and coarse aggregate from two other sources (limestone #2 pit and limestone #3 pit). Limestone #1 limestone, manufactured by Vulcan materials, was selected as the best performing aggregate. Researchers at the Texas Transportation Institute (TTI) have been using limestone #1 limestone as standard laboratory aggregate for a long time. Aggregate test results described earlier confirm the quality of aggregates expected by the research team.

The idea was to combine the poor quality coarse aggregate in different proportions with the good quality coarse aggregate in the HMAC mix to examine the performance of such mixes by a series of laboratory tests. In order to keep the mixture variables to a minimum, the fine aggregate of each mixture blend was from the limestone #1 pit. In this research, particles passing the #10 sieve (2.0 mm) were considered as fine aggregate. Table 12 shows the composition of each blend.

Mixture Design

The researchers planned to evaluate the performance of the HMAC mixtures with different aggregates. Vulcan materials provided a Type C HMA mixture design that they used in the Brownwood District as a surface mixture. Type C is a common mixture used on Texas highways. This design used a PG 64-22 asphalt, which is the most prevalent asphalt used in Texas. The researchers tried to avoid hard asphalt so that the properties of the binder do not overshadow the performance of the aggregate.

Table 12 lists the three limestone coarse aggregates used in this phase of the research. The fine aggregate fraction of all mixes (blends) had 100 percent crushed limestone from the limestone #1 pit. The coarse aggregate of each size fraction (retained on the 5/8, 3/8, #4, and #10 sieves) was replaced with an appropriate percentage of poorer quality coarse aggregate from the limestone #2 pit or the limestone #3 pit. For example in LS2 20 percent blend, for any given sieve (larger than Sieve #10) 20 percent aggregate comes from limestone #2 pit and 80 percent comes from limestone #1 pit; where as 100 percent fine aggregate fraction come from limestone #1 pit. Figure 29 shows the aggregate gradation used in the Type C mixture.

Table 12. Limestone Aggregate Blends Used in HMAC Evaluation.

Mixture ID	Coarse Aggregate Fraction (percent by weight)			Fine Aggregate Fraction
	Limestone #1	Limestone #2	Limestone #3	
LS1 100%	100			100%
LS2 10%	90	10		100%
LS2 20%	80	20		100%
LS2 30%	70	30		100%
LS2 50%	50	50		100%
LS2 100%		100		100%
LS3 10%	90		10	100%
LS3 20%	80		20	100%
LS3 30%	70		30	100%
LS3 50%	50		50	100%
LS3 100%			100	100%

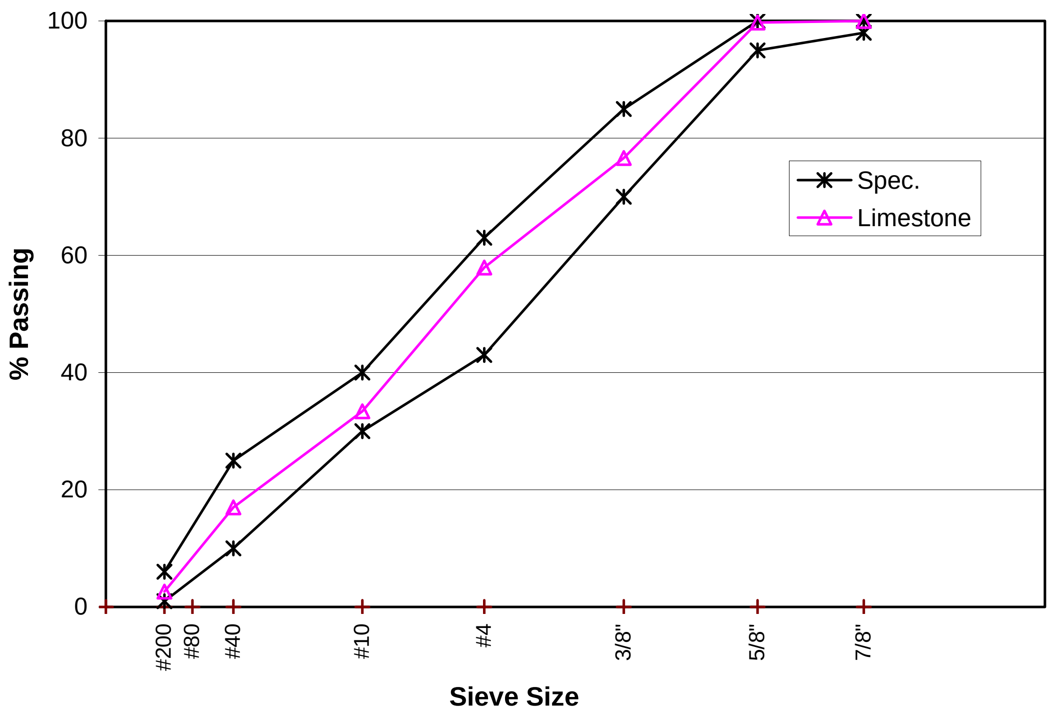


Figure 29. Gradation of Aggregate Used in HMA Mixture Evaluation.

The optimum asphalt content (OAC) of the original mixture design obtained from Vulcan materials was 4.3 percent. This asphalt content was fixed for each of the aggregate blends mentioned above. If each aggregate blend was designed separately, then the OACs may have been different. Even though the gradation of each blend is identical, the properties (hardness, texture, angularity, absorption, etc.) of the three sources were highly variable. The primary reason for only one asphalt content of 4.3 percent was to determine the effects of variable concentrations of lower quality aggregate on the hotmix asphalt concrete performance. If higher asphalt contents were used with the more absorptive, lower quality aggregates, then another variable would be introduced to try to interpret. There is common practice that once a mixture design is approved, contractors usually don't change the binder content regardless of mineralogical variability of aggregate from day to day quarry operation.

Mixture Testing

A total of 11 aggregate blends were selected to evaluate their mixture properties using the following laboratory tests:

- Hamburg wheel tracking test,
- Dynamic modulus test, and
- TTI's overlay test.

The following sections provide a description of the procedures and present results from each of the laboratory tests.

Hamburg Wheel Tracking Test

The Hamburg wheel tracking device (HWTD) is an accelerated wheel tester. Helmut-Wind, Inc., in Hamburg, Germany, originally developed this device (Aschenbrener, 1995). It has been used as a specification requirement for some of the most traveled roadways in Germany to evaluate rutting and stripping (Cooley et al., 2000). Use of this device in the United States began during the 1990s. Several agencies undertook research efforts to evaluate the performance of the

HWTD. The Colorado Department of Transportation, Federal Highway Administration (FHWA), National Center for Asphalt Technology, and TxDOT are among them.

Since the adoption of the original HWTD, significant changes have been made to this equipment. The basic idea is to operate a steel wheel on a submerged, compacted HMA slab or cylindrical specimen. The slab is usually compacted at 7 ± 1 percent air voids using a linear kneading compactor. The test is conducted under water at a constant temperature ranging from 77 to 158°F (25 to 70°C). Testing at 122°F (50°C) is the most common practice. The sample is loaded with a 1.85-inch (47 mm) wide steel wheel using a 158-lb force (705 N) and travels in a reciprocating motion. Usually, the test is conducted at 20,000 cycles or up to a specified amount of rut depth. Rut depth is measured at several locations including the center of the wheel travel path, where it usually reaches the maximum value.

The HWTD measures rut depth, creep slope, stripping inflection point, and stripping slope (Cooley et al., 2000). The creep slope is the inverse of the deformation rate within the linear range of the deformation curve after densification and prior to stripping (if stripping occurs). The stripping slope is the inverse of the deformation rate within the linear region of the deformation curve after the stripping takes place. The creep slope relates primarily to rutting from plastic flow, and the stripping slope indicates accumulation of rutting primarily from moisture damage (Izzo and Tahmoressi, 1998). The stripping inflection point is the number of wheel passes corresponding to the intersection of creep slope and stripping slope.

Tim Aschenbrener found an excellent correlation between the HWTD and pavements with known field performance. He mentioned that this device is sensitive to the quality of aggregate, asphalt cement stiffness, length of short-term aging, refining process or crude oil source of the hotmix asphalt cement, liquid and hydrated lime anti-stripping agent, and compaction temperature.

Izzo and Tahmoressi (1998) conducted a repeatability study of the HWTD. Seven different agencies took part in that study. They experimented with several different versions of the HWTD. They used both slab and Superpave gyratory compacted specimens. Some of their conclusions were that the device yielded repeatable results for mixtures produced with different aggregates and with test specimens fabricated using different compacting devices.

Hamburg Test Results

The Hamburg test with each aggregate blend was run using TxDOT test method Tex-242-F. Tests were conducted at 122°F with 7±1 percent specimen air voids. Tests were continued for 20,000 load cycles or until 0.5 inch rut depth, whichever occurred first. According to TxDOT specifications, mixtures designed with PG 64-22 asphalt should not have more than 0.5 inch (12.5 mm) rut depths at 10,000 cycles of wheel load. The asphalt content was maintained at 4.3 percent to try to measure the effects of lower quality aggregate on a mix design determined with good quality aggregate.

Figure 30 presents the Hamburg test results of these mixtures. The graph shows the number of load cycles for each mixture to reach 0.5 inch rut depth. The mixtures with 100 percent limestone #1 coarse aggregate and 10 percent limestone #2 are probably the only valid results in this test due to the absorptive nature of the lower quality coarse aggregate. If the blends with larger fractions of lower quality absorptive aggregate were compacted with same asphalt content and same compaction (design) effort they would have ended with below 96 percent density. But other mixtures did not demonstrate any clear pattern. Mixtures with 50% LS2, and 30% LS3 coarse aggregate were as good as 100% LS1.

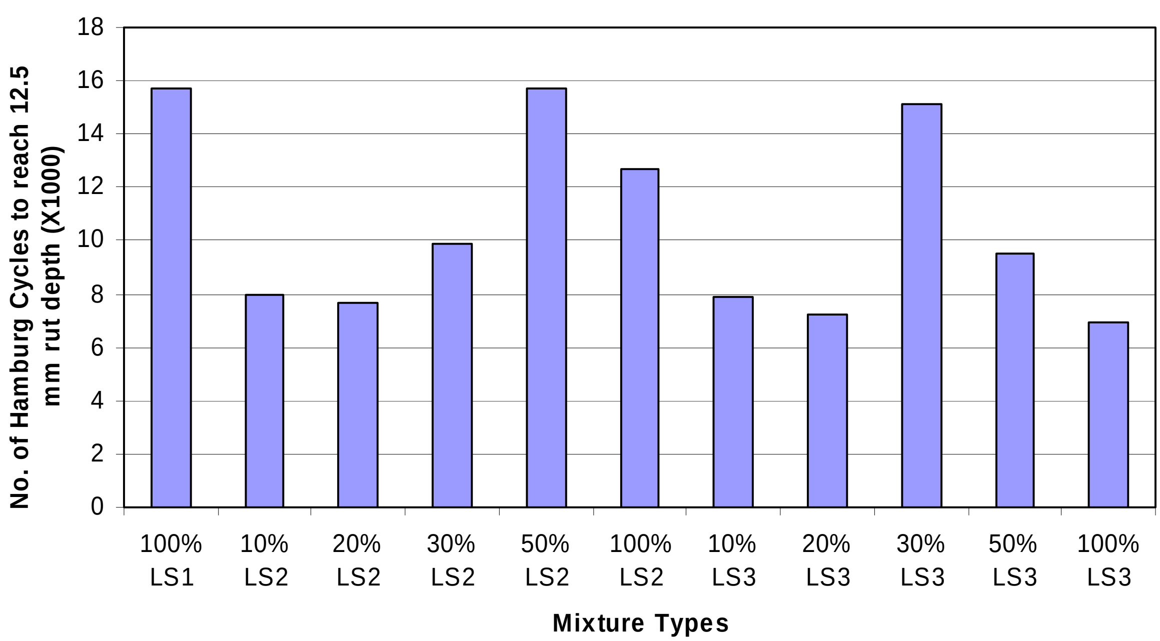


Figure 30. Hamburg Test Results.

Obviously, the Hamburg wheel tracking test could not be used to differentiate HMAC issues related to these limestone aggregate mixtures. Addition of more poor quality coarse aggregate did not always yield more rut susceptible mixes. In most cases, the mixtures experienced stripping. When mixtures experience stripping, Hamburg test results can be highly variable (Chowdhury et al., 2004). The researchers speculate that the poor quality coarse aggregate used in the mixture absorbed more asphalt, which made the mixture stiffer.

A good continuation of this research would be to adjust the asphalt content of the mix for the more absorptive aggregates to reach a density of 96 percent and check the performance in the Hamburg wheel tracking test. Perhaps a better correlation would exist with the absorptive aggregates and the Hamburg wheel tracking test results.

Dynamic Modulus Test

The dynamic modulus test is typically performed over a range of different temperatures by applying sinusoidal loading at different frequencies to an unconfined specimen. In this test, a sinusoidal axial compressive load is applied to a cylindrical specimen at a series of temperature and loading frequencies. The typical parameters derived from this test are complex modulus (E^*) and phase angle (ϕ). E^* is a function of the storage modulus (E') and loss modulus (E''). Typically, the magnitude of the complex modulus is represented as:

$$|E^*| = \frac{\sigma_0}{\varepsilon_0}$$

where,

σ_0 = axial stress and
ε_0 = axial strain.

The phase angle can be used to assess the storage and loss moduli.

In this task, tests were conducted in accordance with the American Association of State Highway and Transportation Officials (AASHTO) Designation: TP 62-03 Determining Dynamic Modulus of Hot-Mix Asphalt Concrete Mixture at 25, 10, 5, 1, 0.5, and 0.1 Hz; and 14, 40, 70, 100 and 130°F (Witczak et al., 2002). The stress level for measuring dynamic modulus was chosen to achieve the measured resilient strain within a range of 50 to 150 microstrain. The research team performed each test in order of lowest to highest temperature and highest to lowest frequency of loading at each temperature to minimize specimen damage. Figure 31 shows the test equipment.

The data generated were used to plot a master curve using the sigmoidal curve fitting function as Pellinen (2002) demonstrates. The sigmoidal function used is given below:

$$\log(|E^*|) = \delta + \frac{\alpha}{1 + e^{\beta - \gamma \log(\xi)}}$$

where,

|E*| = dynamic modulus,
ξ = reduced frequency,
δ = minimum modulus value,
α = span of modulus values,
β = shape parameter, and
γ = shape parameter.

Dynamic Modulus Test Results

Parameters from the dynamic modulus test used for evaluating the mixtures in this project are:

- E* sin ϕ at 10 Hz and 14°F to compare the cracking potential of the different mixes, which is based on previous work by Witczak et al. (2002);
- E*/sin ϕ at 1 Hz and 130°F to compare the rutting potential. The researchers selected these test parameters based on previous research (Witczak et al., 2002; Bhasin et al., 2003); and
- dynamic modulus master curve.

Figure 31. Dynamic Modulus Test Setup.

Figure 32 shows the cracking potential of different mixtures as estimated by plotting the E* sinϕ measured at 10 Hz and 14°F. Higher values indicate that a mixture is more susceptible to cracking (at lower temperature). Lower modulus values at colder temperatures are usually better for cracking resistance. The lower stiffness of mastic at cold temperatures is preferred. But a lower modulus value resulting from softer aggregate is not desirable. The mixture with 10 percent limestone #2 pit aggregate yields higher E* sinϕ than that of the 100 percent limestone #1 mixture and progressively decreases up to 50 percent limestone #2 pit aggregate. A possible explanation of this phenomenon could be that the addition of small (10 percent) amounts of poor quality coarse aggregate causes absorption of hotmix asphalt and, hence, higher mastic stiffness; but further addition of poor quality coarse aggregate (more soft aggregate) causes aggregate crushing at high stress and, thus, yields lower modulus values.

Figure 33 presents the rutting potential of mixtures at higher temperature (or slower loading) by plotting E*/sinϕ at 1 Hz and 130°F. Higher values of E*/sinϕ indicate a more rut-resistant mixture. The mixture with 100 percent limestone #1 limestone had the highest E*/sinϕ (i.e., more rut resistant). Rut resistance decreases with the increase of poor (soft) quality coarse

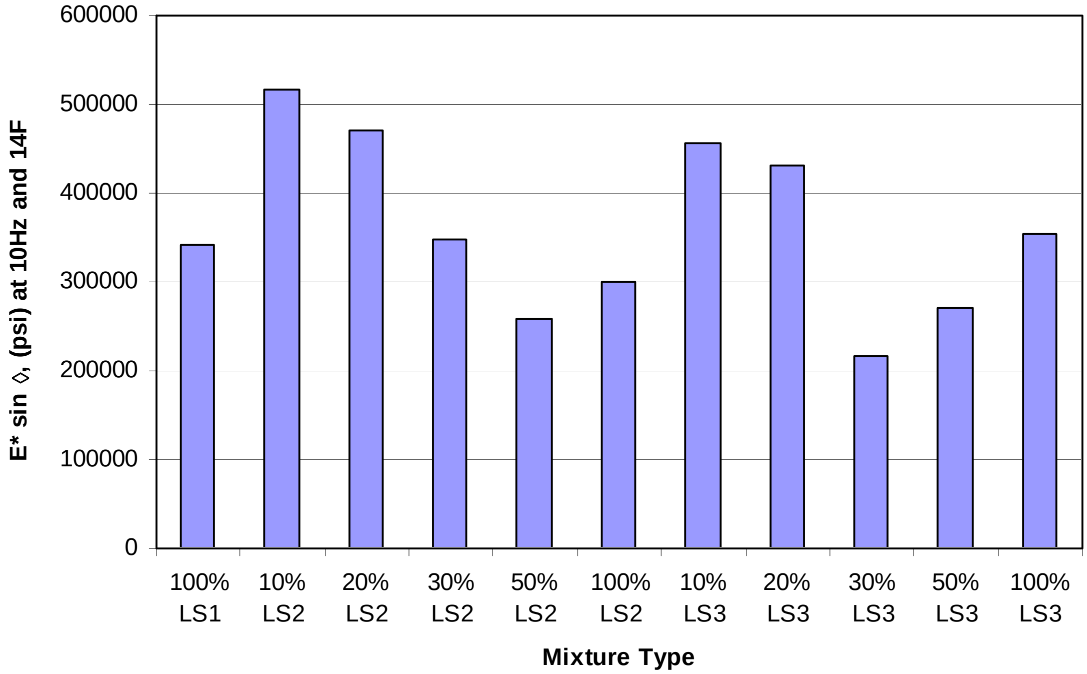


Figure 32. Cracking Potential of Different Mixtures Measured by Dynamic Modulus Test.

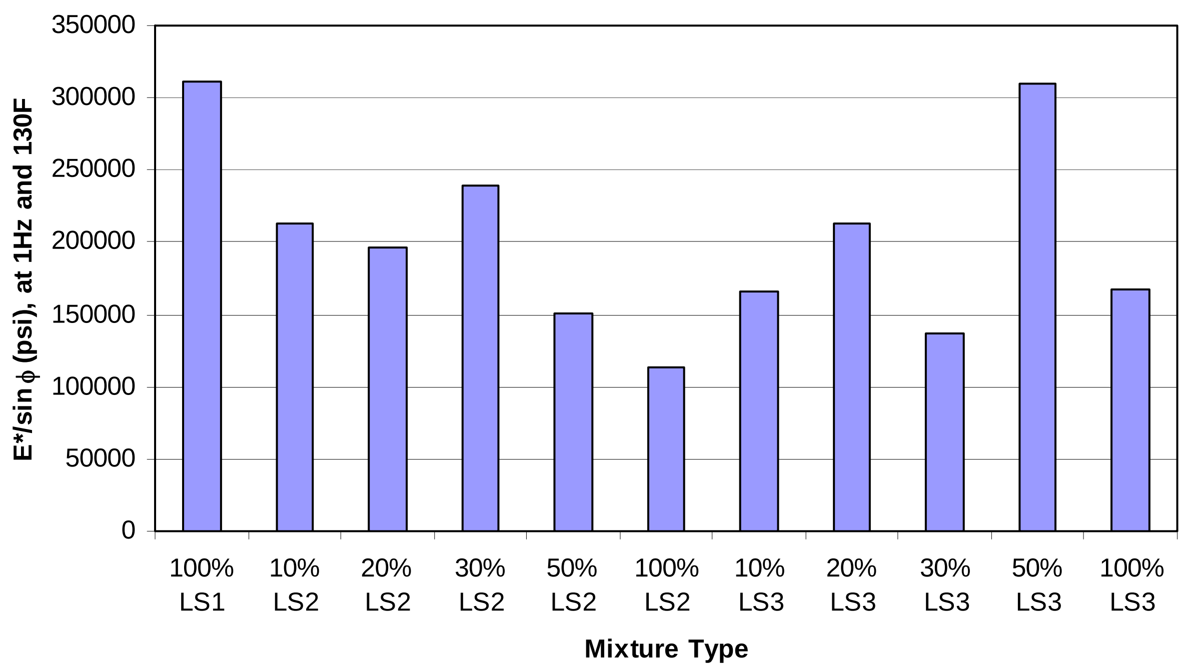


Figure 33. Rutting Potential of Different Mixtures Measured by Dynamic Modulus Test.

aggregates in the mixture. The mixture with 50 percent limestone #3 shows an unusually high value of E*/sinϕ. This is probably an outlier.

Figures 34 and 35 present the dynamic modulus master curves of limestone #2 pit aggregate blends with limestone #1 aggregate and limestone #3 pit aggregate blends with limestone #1 aggregate, respectively. These master curves were generated using the sigmoidal function (Pellinen, 2002) described earlier. This model typically represents a curve that is flat at very high and very low values of log(t), and typically represents the behavior of a viscoelastic material. The four variables involved in the model, i.e., δ, α, γ, and β, along with the shift factors for the other three temperature ranges, are derived simultaneously using a nonlinear regression analysis supported by the solver function in the Microsoft Excel spreadsheet. The reference temperature assumed in this case was 68°F (20°C). This temperature was selected arbitrarily. With the raw data available, a master curve can be created at different base temperatures. The dynamic modulus values for other temperatures were shifted to this value for plotting the master curve.

Unlike E*/sinϕ and E* sinϕ, E* (complex modulus) obtained from the dynamic modulus test value does not consider the effect of phase angle. Generally, the right-hand side of the master curve indicates the rutting resistance of the mix, and the left side of the curve indicates the cracking potential. Ideally, higher on right side and lower on left side is better. These graphs show that the 100 percent limestone #1 aggregate mixture demonstrates the best performance for rutting at higher temperature (higher log reduced frequency), but the others show distinctively poorer performance. For cracking response (lower log reduced frequency), all of the mixtures are not much different from each other. Dynamic modulus tests did not reveal any consistent pattern for the performance of mixes with different aggregate blends. Even though the dynamic modulus test is highly recommended test for pavement design, it may have a limiting capability of identifying poor quality aggregate in HMAC.

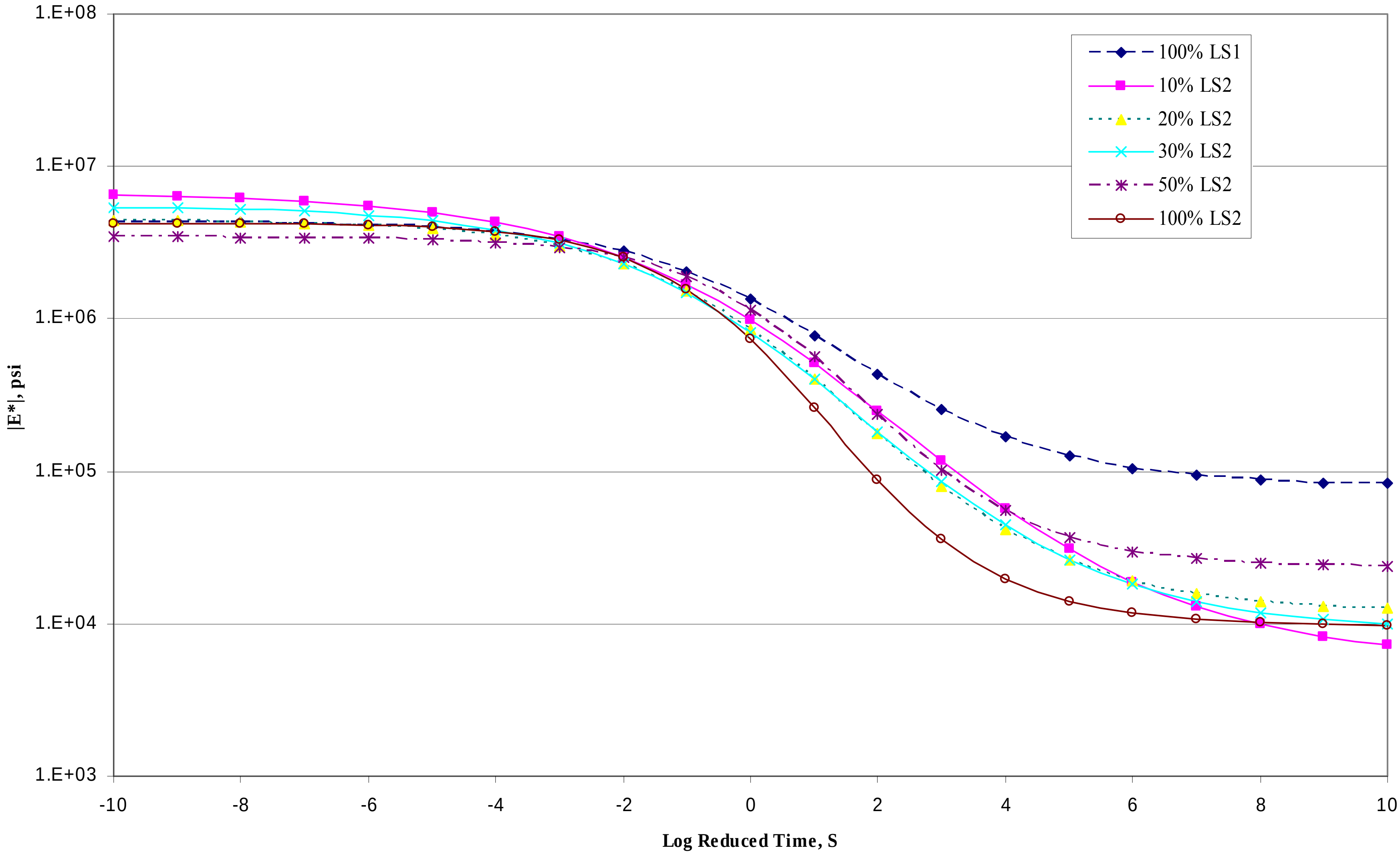


Figure 34. Dynamic Modulus Master Curve for Limestone #1 and Limestone #2 Blend Mixtures.

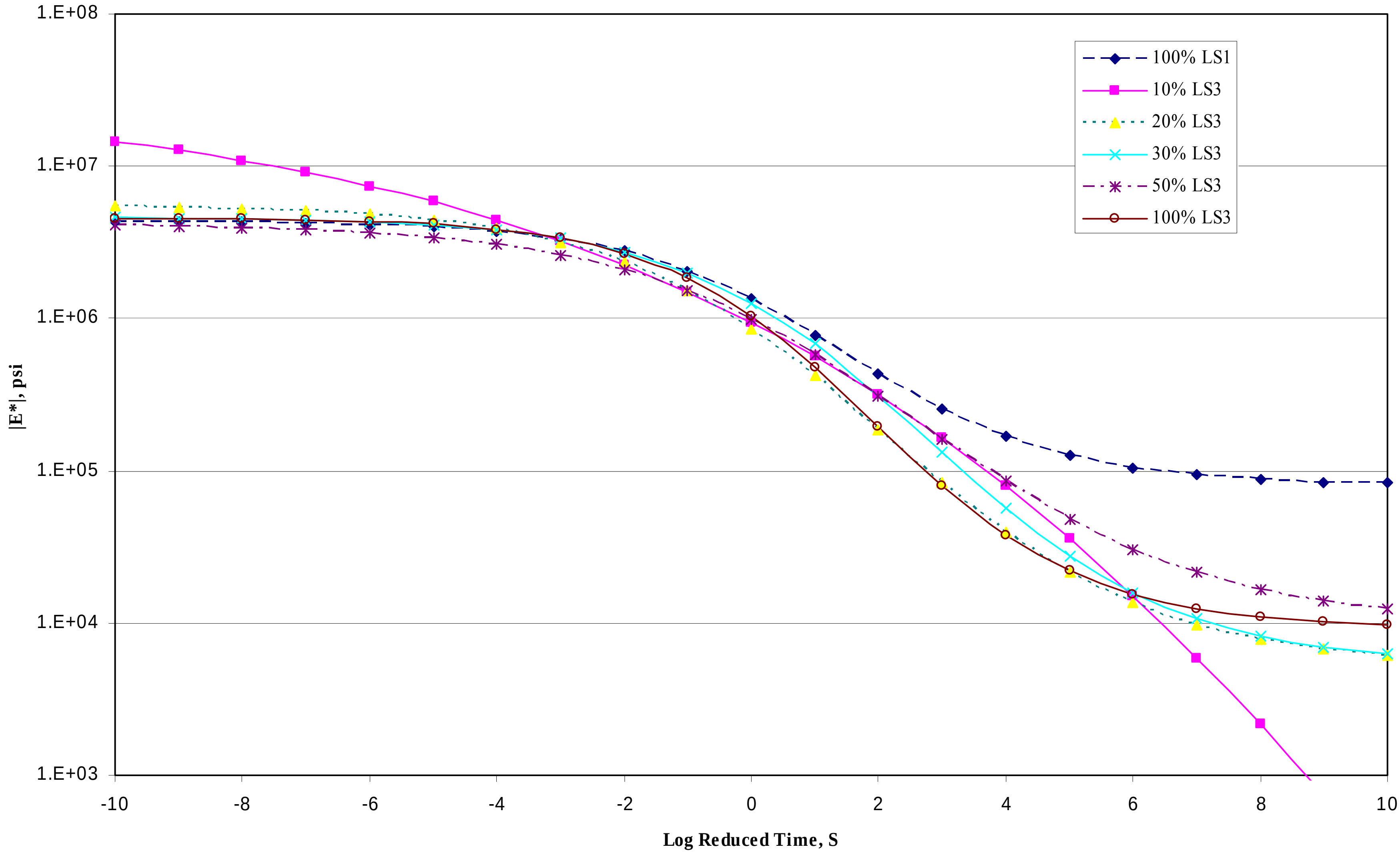


Figure 35. Dynamic Modulus Master Curve for Limestone #1 and Limestone #3 Blend Mixtures.

Overlay Test

Germann and Lytton (1979) designed the TTI overlay testers to simulate the opening and closing of joints or cracks, which are the main driving force inducing reflection crack initiation and propagation. Later, this overlay tester was further modified and developed. Two types of overlay testers have been successfully used at TTI to evaluate the effectiveness of geosynthetic materials on retarding reflection cracking. These applications indicate that the overlay tester has the potential to characterize the reflection cracking resistance of hotmix asphalt concrete mixtures.

The overlay tester data include the time, displacement, and load corresponding to a certain number of loading cycles. In addition, the crack length can be manually measured. Two types of information can be gained from the overlay tester: one is the reflection cracking life of a hotmix asphalt concrete mixture under certain test conditions; the other is fracture parameters of a hotmix asphalt concrete mixture.

Figure 36 depicts the key parts of the apparatus. This overlay tester consists of two steel plates; one is fixed, and the other moves horizontally to simulate the opening and closing of joints or cracks in the old pavements beneath an overlay. The load is applied in a cyclic, triangular waveform with constant magnitude. The overlay test is run at room temperature (77ºF) in a controlled displacement mode at a loading rate of one cycle per 10 seconds with a maximum displacement of 0.025 inch until failure occurs. This amount of horizontal movement is approximately equal to the displacement experienced by Portland cement concrete (PCC) pavements undergoing 30ºF temperature changes in pavement temperature with a 15 feet joint or crack spacing (Zhou and Scullion, 2003).

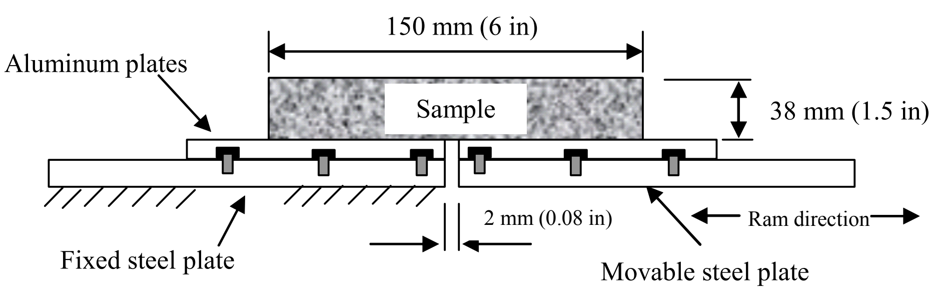


Figure 36. Schematic Diagram of TTI Overlay Tester System.

Three prismatic specimens (6 inch × 3 inch × 1.5 inch) cut from superpave gyratory compactor (SGC) compacted 6-inch samples were tested with the TTI overlay tester at 77°F. The test followed the protocol suggested by Zhou and Scullion (2003). The number of gyrations of the SGC were varied to achieve 7±1 percent air voids to reduce the influence of density on test results.

Overlay Test Results

Initially, the research team prepared specimens with 4.3 percent asphalt content (original design asphalt content) and started testing specimens. Most mixtures with poor quality coarse aggregate failed too early to conduct any analysis (Figure 37). Researchers speculated that the poor quality coarse aggregate absorbed too much asphalt, which made the specimens too brittle, resulting in premature failure. Not all the mixtures were tested at this relatively low binder content. Following the initial results, the researchers decided to prepare specimens by increasing the asphalt content and only placing bad aggregate particles in the new mixtures. Arbitrarily, 5 percent asphalt content was selected for preparation of new sets of specimens with the idea that there would be enough asphalt left after absorption to bind the aggregate together. Each sieve fraction of the limestone #2 and limestone #3 pit aggregates was manually separated into good and poor aggregate piles. Only the poor aggregate piles were recombined with the limestone #1 aggregate in proportions of 0, 10, 20, 30, 50, and 100 percent to ensure a more uniform distribution of poor quality aggregate in the samples. Figure 38 presents these results.

There is an increase in the average number of cycles to failure even for the limestone #1 aggregate between 4.3 and 5.0 percent asphalt content, which reveals possible problems with traditional mix designs when dealing with reflection cracking and aggregate absorption. The 10 percent and 30 percent limestone #2 mixes performed better than the 100 percent limestone #1 mix with 5.0 percent asphalt. One would expect these mixes to not perform as well as the 100 percent limestone #1 mix. One explanation is that the weak aggregate lined up, creating a zone of weakness. However, since three samples of each mixture were run, a more plausible explanation could be that 5.0 percent asphalt is too high for limestone #1, but 4.3 percent asphalt is too low for limestone #1. The addition of absorptive aggregates in the 5 percent asphalt mix reduced the effective asphalt content creating a better mix with regard to reflection cracking.

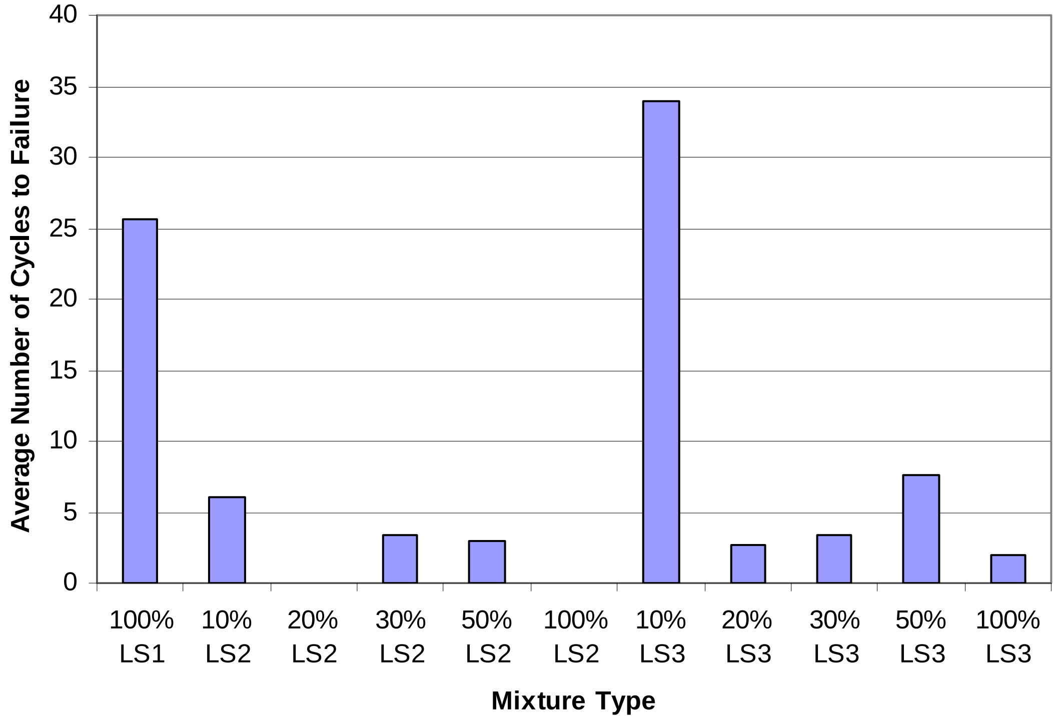


Figure 37. Overlay Test Results for Mixtures with 4.3 Percent Asphalt Content.

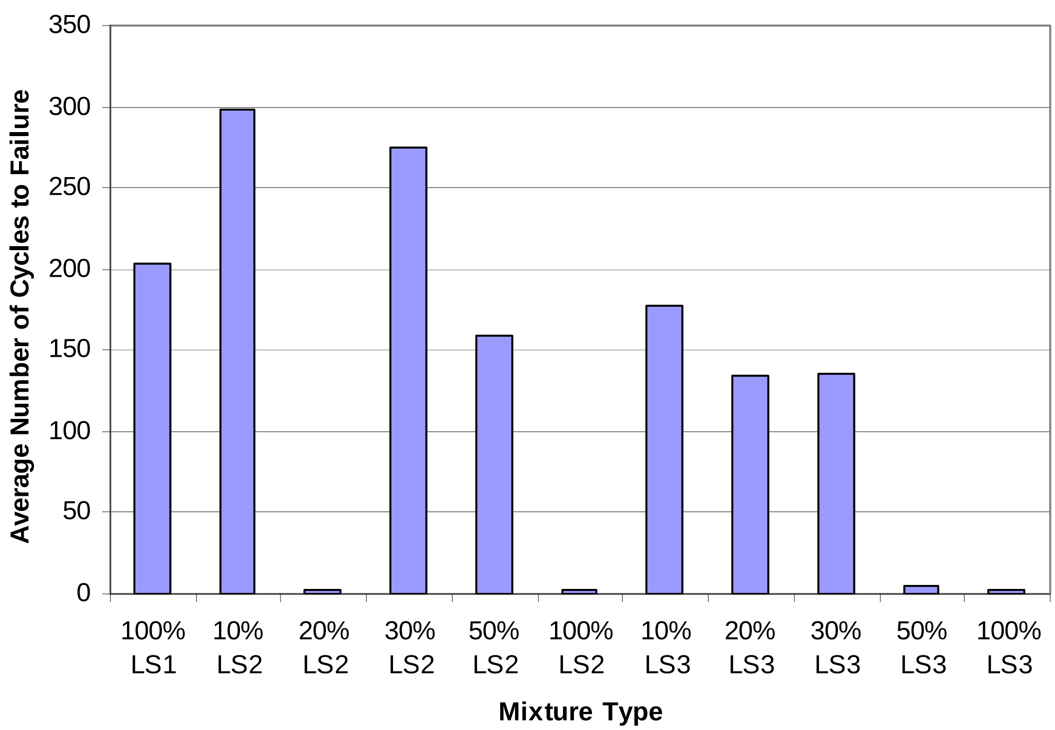


Figure 38. Overlay Test Results for Mixtures with 5 Percent Asphalt Content.

INTERPRETATION

The rutting results were somewhat surprising, but one aspect that was noted in the laboratory samples is that the marginal materials are absorptive to asphalt. In studies conducted by Zhou and Scullion (2005), similar phenomena were also noted. In those studies, researchers concluded that some aggregates selectively absorb the light oil fraction from the binder. The remaining binder in the mix is, therefore, stiffer than with the non-absorptive aggregates. This phenomenon at least partially explains the rutting results. However, the researchers do not have a good explanation for the erratic results; more research is needed to elucidate the factors affecting rut resistance when soft and adsorptive aggregates are used.

The fatigue cracking results are even more surprising; if the mix is indeed getting stiffer with the asphalt absorption, then this should have a negative impact on fatigue cracking potential. The authors note that no classical fatigue tests were run on these samples, and this property was inferred from parameters in the dynamic modulus test. This parameter did not show any consistent trends with higher percentages of marginal material.

The overlay tester measures the number of cycles for a crack to propagate through a standard 1.5-inch high sample. This test simulates the stresses introduced in a hotmix asphalt concrete overlay placed over a joint in a concrete pavement. In the test, three replicate samples were run for each aggregate combination, and the results were presented in Figures 37 and 38 earlier in this report. If one were to ignore the overlay test results for limestone #2 at 5 percent asphalt content, then a plot could be generated where the number of cycles to failure for the 100 percent limestone #1 aggregate is assumed to be the 100 percent reflection cracking life. As different percentages of marginal aggregate are introduced, the reduction in reflection cracking is calculated as the percentage of the reflection cracking life. The results graphed in Figure 39 show a dramatic decrease in reflection cracking life with minimal concentrations of low quality coarse aggregate; note a trend line was fitted through the data points given earlier in Figures 37 and 38.

The mixes made at the 4.3 percent binder level used the 64-22 binder, which is fairly common in surfacing used in Texas. The 4.3 percent binder level is also typical of the asphalt content typically used. The impact of the introduction of the marginal aggregates was very dramatic with this mix (Table D1 lists specific gravity data for these mixes). With the replacement of 20 percent limestone #1 with 20 percent limestone #2 pit (LS #2) material, the measured reflection cracking life reduced by more than 80 percent; with the limestone #3 pit material, the reduction was more than 50 percent.

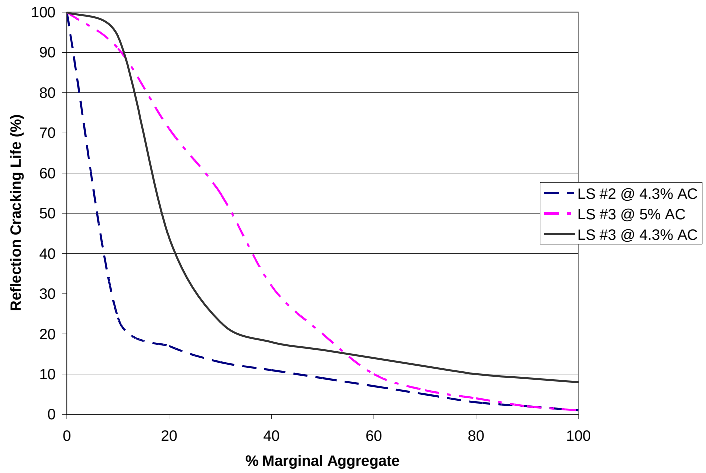


Figure 39. Graphical Summary of Overlay Tester Results.

In order to set limits on what level of marginal materials has a serious impact on the performance of the mix, it is important to include the repeatability of the overlay test. In repeatability studies conducted by Zhou (personal communication), it was concluded that using triplicate samples of the average number of cycles to failure will be within 10 percent of the mean for that mix. Therefore, for this report, researchers decided to conclude that a 20 percent reduction in reflection cracking life would be significant. From Figure 38, the 20 percent reduction in reflection cracking life was found by interpolation to be when less than 5 percent limestone #2 pit material was introduced or when 15 percent limestone #3 pit material was introduced. Taking an average of these two numbers, the authors propose that the introduction of more than 10 percent marginal coarse limestone aggregates into a hotmix layer could have a significant impact on the reflection cracking life of that mix. It is with some reservations that we conclude a maximum level of 10 percent marginal coarse limestone aggregate may result in decreased reflection cracking life.

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations are based upon controlled laboratory testing of one good quality limestone coarse aggregate blended with different proportions of two poor quality limestone coarse aggregates from Texas. The authors believe that the following recommendations can be applied to Texas limestone aggregates but must caution against applying the recommendations across the board for all Texas aggregates:

- Use of the AIMS imaging device revealed that surface texture could be used to separate the good from poor quality limestone coarse aggregate used in this project.
- The AIMS imaging device surprisingly did not show any pronounced variation in angularity among the three different limestone aggregates.
- The introduction of marginal coarse limestone aggregates into the mix had little clear impact on the rutting potential of the mix as measured by the Hamburg test or inferred from the dynamic modulus test.
- The introduction of marginal coarse limestone aggregates on the fatigue life inferred from the dynamic modulus was not clear. No consistent trends were observed in the data.
- The introduction of marginal coarse limestone aggregates may impact the reflection cracking resistance. Weak trends were observed where the higher the percentage of marginal material, the lower the reflection cracking life.
- More research definitely needs to be performed with the overlay tester to investigate the anomalous results with the marginal coarse limestone aggregates.

CHAPTER 4

MICRO-DEVAL AND MAGNESIUM SULFATE SOUNDNESS TEST EVALUATION

INTRODUCTION

The magnesium sulfate soundness test currently used by TxDOT for evaluating aggregate durability is a procedure that requires a lot of time and is often difficult to obtain repeatable results, especially with carbonate rocks.

As stated in ASTM C-88, soundness is an aggregate's resistance to weathering in concrete or other applications. Forster (1994) describes sulfate soundness as a test where an aggregate sample is repeatedly immersed in a saturated solution of magnesium or sodium sulfate and placed in an oven to dry, where a salt precipitates in the permeable pore spaces. Expansive forces are exerted when the salt is rehydrated upon re-immersion in the saturated solution, simulating freezing water (Forster, 1994; Little et al., 2001).

A study performed at the University of Illinois on carbonate aggregates determined that decreased hardness, increased water absorption, increased dolomite in limestones, laminated limestones, and higher clay contents (alumina in excess of 0.9 percent) increase soundness loss (Harvey et al., 1974). Hudec and Rogers (1976) also determined that magnesium sulfate soundness loss increases with increasing water sorption, which correlated with increasing clay content for carbonate aggregates.

Forster (1994) contends that interpreters of soundness results must proceed with caution due to the low precision of the test method. He suggests that collaborative evidence from other tests or prior service records be used in conjunction with the soundness test.

The Micro-Deval test measures an aggregate's resistance to abrasion (Cooley and James, 2003). It consists of a steel drum where a graded sample and steel balls (9.5 mm) are placed with 2 L of water. After soaking for a minimum of 1 hour, the drum is rotated for a period of 105 minutes at 100 revolutions per minute. The aggregate is then washed, oven dried, and sieved with a 1.18 mm sieve. The percent passing the sieve is reported as the M-D loss.

There have been several studies evaluating the Micro-Deval and the magnesium sulfate soundness test (Senior and Rogers, 1991; Rogers, 1998; Kandhal and Parker, 1998; Cooley and James, 2003). The Canadians determined that the Micro-Deval test is a good test to replace the magnesium sulfate soundness test for fine aggregate (<4.75 mm) only (Rogers, 1998). One reason for the recommended change is that the Micro-Deval test has better multi-laboratory precision than other techniques (Rogers, 1998) and is a more rapid test.

The objective of this investigation is to compare Micro-Deval analyses of Texas' coarse limestone aggregate to magnesium sulfate soundness analyses to see if the Micro-Deval test can be used in place of the magnesium sulfate soundness test for detecting poor quality coarse aggregate in Texas. Secondly, the researchers wanted to evaluate the possible correlation between MSS and absorption in coarse limestone aggregates.

METHODS

To compare the Micro-Deval to the magnesium sulfate soundness test, the researchers used two techniques. First, TxDOT supplied the researchers with data from 10 quarries that had been collected over an extended period of time ranging from 3 to 5 years. Researchers plotted the Micro-Deval data in Microsoft Excel®, against the magnesium sulfate soundness data to identify possible correlations.

Second, the researchers gathered three limestone aggregates for blending. One of the limestone aggregates (limestone #1 pit) is considered a well-performing limestone aggregate in Texas. The other two limestone aggregates (limestone #2 pit and limestone #3 pit) have higher magnesium sulfate soundness loss and were blended with the aggregate with lower magnesium sulfate soundness loss in concentrations of 10, 20, 30, and 50 percent by weight to determine if the tests could distinguish between the different proportions of high quality and low quality aggregate. The Micro-Deval test was run according to Tex-461-A, and the magnesium sulfate soundness test followed Tex-411-A (TxDOT Manual System). The technician running both tests was trained by TxDOT personnel to ensure consistent results between laboratories.

RESULTS

M-D and MSS Samples over Time

Table 13 lists 10 quarries where TxDOT has collected Micro-Deval and magnesium sulfate soundness test data over the last 3 to 5 years. Generally, as the number of tests (M-D vs.

Table 13. Comparison of Analyses from M-D and MSS Data.

Quarry	Number of Samples	R^2	Time (years)
Beckman	19	0.51	3
Black	29	0.30	4
Limestone #1	8	0.49	4
Clements	42	0.27	4
Feld	32	0.64	3
FM 1604	7	0.07	4
Helotes	14	0.74	3.5
Tehuacana	11	0.83	5
Wood	8	0.45	4
4DG's	24	0.32	3.5

MSS) increases, there is a decrease in the correlation of the two test methods as observed in lower R^2 values.

Figure 40 shows the MSS percent loss on the y-axis and the M-D percent loss on the x-axis for all of the quarries. There is a one-to-one correlation between M-D and MSS test results as illustrated in Figure 41, but there is a large variation in the results. For a 95 percent confidence interval, the M-D result will be ±13.3 of the MSS result. For example, if the MSS percent loss is 31, then one can be 95 percent confident that the M-D percent loss will be between 18 and 44.

Micro-Deval and magnesium sulfate soundness test results for the Clements Pit are plotted in Figure 41. The scatter in the data is indicative of the difficulty in obtaining repeatable results due to the variability of the material from sample to sample. Additionally, Micro-Deval and magnesium sulfate soundness measure different aggregate properties. Micro-Deval and magnesium sulfate soundness test results for the other nine quarries are plotted in Appendix C.

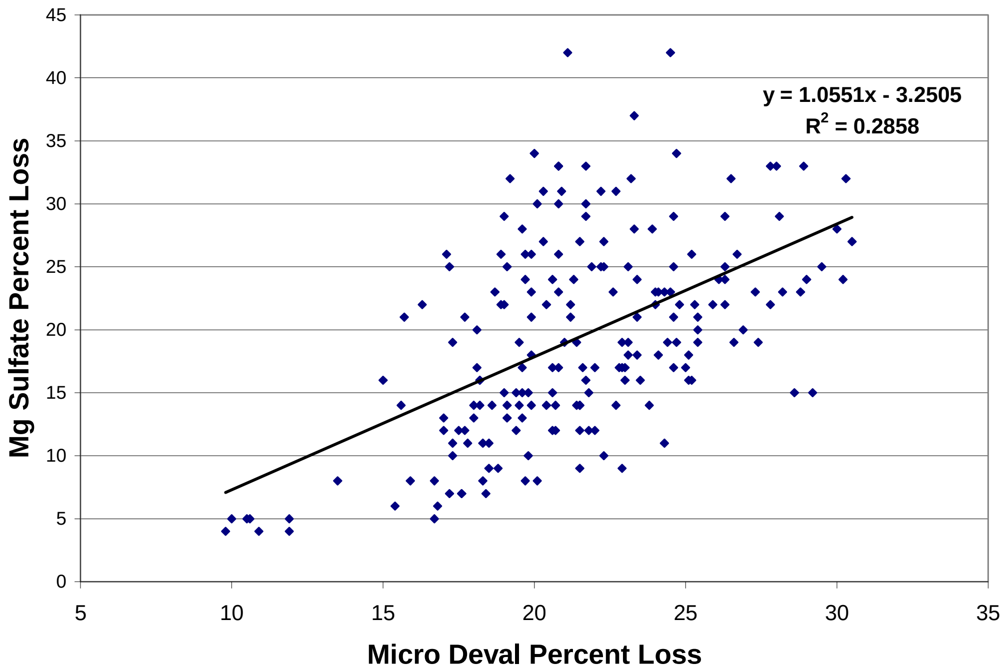


Figure 40. MSS vs. M-D Data for All of the Quarries.

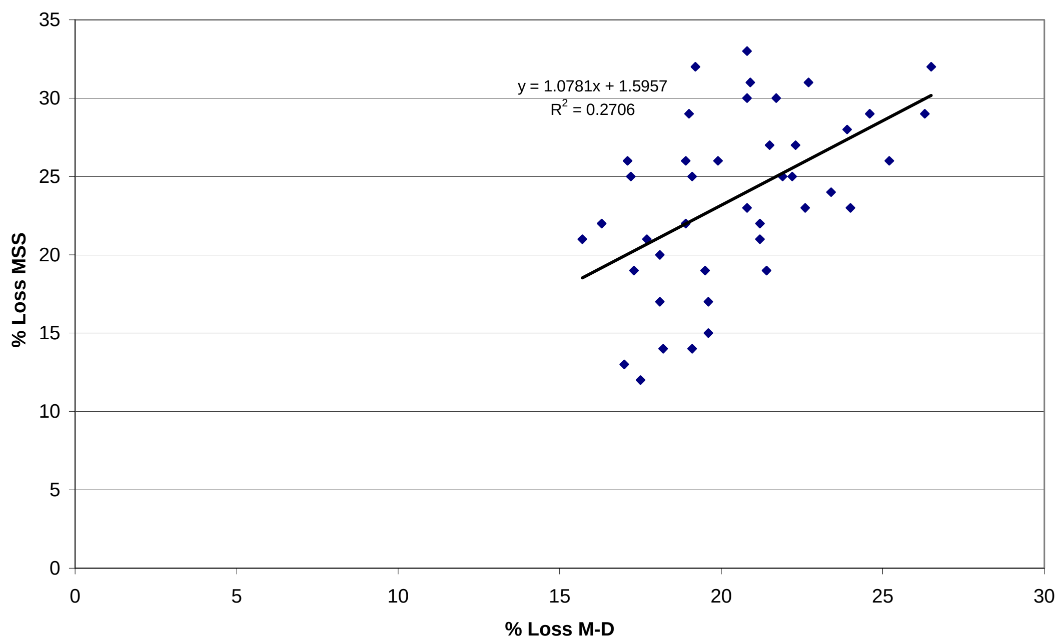


Figure 41. M-D and MSS Results for the Clements Pit.

M-D and MSS Samples Lab Evaluation

Initially, the Micro-Deval and magnesium sulfate soundness tests were conducted on limestone #1, limestone #2, and limestone #3 pit samples composed of 100 percent material from each pit. Table 14 presents these data. Each test was performed two times and an average was taken from the two results. As one can see, there is a larger variation in the results between samples 1 and 2 in the MSS data than in the M-D data.

Table 14. M-D and MSS Test Results for Three Limestone Quarries.

Aggregate Name	Micro-Deval Loss (%)			Sulfate Soundness Loss (%)		
	Sample 1	Sample 2	*Average*	Sample 1	Sample 2	*Average*
Limestone #1	13.23	13.31	*13.27*	5.71	5.08	*5.4*
Limestone #2	25.78	27.32	*26.55*	19.67	23.58	*21.6*
Limestone #3	59.59	56.75	*58.17*	48.53	52.69	*50.6*

In the controlled laboratory testing where the good aggregate (limestone #1) is mixed with varying proportions of lower quality aggregates (limestone #2 and limestone #3), there is a good correlation between actual test results and predicted results, which are calculated from the averages of the 100 percent individual aggregates listed in Table 14. Table 15 shows the actual results obtained from blending different amounts of each lower quality aggregate with the good quality aggregate versus the predicted values.

Table 15. M-D and MSS Test Results for Aggregate Blends.

Description	Micro-Deval Loss (%)		Sulfate Soundness Loss (%)	
	Predicted	Actual	Predicted	Actual
80% Limestone #1 20% Limestone #2	15.9	16.3	8.6	8.9
50% Limestone #1 50% Limestone #2	19.9	20.6	13.5	16.3
80% Limestone #1 20% Limestone #3	22.3	21.6	14.4	13.0
50% Limestone #1 50% Limestone #3	35.7	34.4	28.0	26.5

INTERPRETATION

Based on the results from limestone coarse aggregates in this project, the researchers have to agree with observations of other investigators about the good repeatability/ reproducibility of the M-D test (Rogers, 1998). The M-D results presented in Tables 14 and 15 show consistent and very predictable numbers for the three limestone aggregates. The MSS results are a little more variable, which is consistent with observations of other researchers (Forster, 1994).

In the course of this investigation, the absorption of the aggregate kept reappearing as a contributing factor in all of the test results. As the literature was reviewed, a number of other investigators made the same observation. Moreover, many of them concluded that increasing sulfate soundness correlated very well with increasing water absorption (Harvey et al., 1974; Hudec and Rogers, 1976; Forster, 1994; Phillips et al., 2000). This correlation should not be surprising since the sulfate soundness test relies on sodium or magnesium sulfate crystals forming in the pores of the rock, causing disintegration of the aggregate. Phillips et al. (2000) statistically determined that at a 95 percent confidence interval aggregates with less than 2.1 percent absorption show less than 30 percent MSS loss if the M-D loss is less than 25 percent. The researchers believe that this is a good start, but a correlation should be made looking at aggregates of different mineralogies.

CONCLUSIONS AND RECOMMENDATIONS

At this time, based upon the data, the researchers have to agree with results from other investigations and conclude that substituting the Micro-Deval for the magnesium sulfate soundness test on the coarse aggregate is not a good idea (Kandhal and Parker, 1998). The correlation between the two test methods is very weak at best. However, the Micro-Deval test appears to do a good job of identifying lower quality aggregate.

To develop acceptance guidelines using the Micro-Deval test, TxDOT may want to investigate different failure criteria for different aggregate types. For example, Lane et al. (2000) specified different M-D losses for different mineralogies: they recommend 5 percent for igneous and metamorphic gravel; 10 percent for traprock, diabase, and andesite; and 15 percent for dolomitic sandstone, granitic meta-arkose, and gneiss. Cooley and James (2003) noticed different M-D losses for different mineralogies in aggregates used in the southeastern United States. They observed that a granite considered a good performer had a mean percent loss of 6.8 percent, but a limestone was considered a good performer with a mean percent loss of 15.8 percent.

It has been well documented that soft, absorptive aggregates are less durable (Harvey et al., 1974; Hudec and Rogers, 1976) than a hard, nonporous aggregate of the same mineralogy. The authors propose to use the absorption test (Tex 201-F) in addition to the MSS test for coarse carbonate aggregates. It is less time consuming and correlates well with soundness test results, as demonstrated by other researchers. Perhaps at some point, a recommendation can be made to replace the sulfate soundness test with a simple absorption test.

The following conclusions are based on the extensive aggregate tests performed on the limestone #1, limestone #2, and limestone #3 aggregate blends:

- Based on the Micro-Deval results for the three limestones evaluated in Chapter 3, a conservative estimate to yield less than 10 percent poor quality coarse limestone aggregate, TxDOT may want to perform more testing on coarse limestone aggregates that have Micro-Deval percent losses exceeding 20.
- If the magnesium sulfate soundness percent loss exceeds 15 for coarse limestone aggregates, TxDOT may want to supplement soundness data with field performance records or other testing on the aggregate.

The authors recommend that the Micro-Deval, magnesium sulfate soundness, and the absorption tests be used to evaluate all Texas aggregates and then correlate the test results with field performance. Perhaps acceptance criteria could be developed based on the mineralogy and may actually reflect how the aggregate performs in the field.

CHAPTER 5
CONCLUSIONS AND RECOMMENDATIONS

The research conducted in this project was divided into two phases with the first phase concentrating on identifying poor quality aggregates in the field and the second phase focusing on how much of a bad coarse aggregate can be added to an HMAC pavement without causing premature failure of the pavement structure. Most of the results from Phase I are presented in Report 0-4523-1, but some of the results are presented in the first two chapters of this report. All of the research performed in Phase II is presented in the remainder of this report.

This chapter is devoted to conclusions and recommendations drawn from data presented in the first four chapters of this report. The conclusions and recommendations will not be presented in the same order in which they were discussed in the report, but they will be discussed in the order in which they address the four basic objectives listed below:

1) Examine the effects of poor quality aggregate on the performance of HMAC.
2) Determine how much poor quality coarse aggregate can be used and still get acceptable mixture performance.
3) What tests can be run to quantify the poor quality aggregate at levels low enough to get acceptable performance?
4) How frequently should the tests be run to achieve poor quality aggregate levels low enough to get acceptable performance?

EFFECTS OF POOR QUALITY COARSE LIMESTONE ON HMAC MIXES

One important aspect of Report 0-4523-1 was to determine the impact of different percentages of marginal coarse limestone aggregate on the significant engineering properties of hotmix asphalt concrete layers. Chapter 3 of this report described the work completed in this task in detail. In summary, limestone from the limestone #1 pit was assumed to be the good aggregate. The laboratory work involved introducing known percentages of marginal material into the aggregate blend and conducting materials characterization tests on hotmix asphalt concrete samples molded using these aggregate blends. A standard Type C gradation was used for this work, and one standard asphalt binder was included in the project. Tests were conducted using two “marginal” coarse aggregates: firstly, a crushed limestone (limestone #2 pit), and secondly a low quality crushed limestone labeled limestone #3 pit. The standard coarse aggregate tests indicated that their properties were significantly inferior to the limestone #1 material.

Samples were molded with the Superpave gyratory compactor with a blend of aggregates ranging from 100 percent good, 90 percent good/10 percent marginal, etc. Control samples were also manufactured with 100 percent marginal coarse aggregate material. The performance related tests conducted on these materials include:

- TxDOT Hamburg wheel tracker tests to measure rutting potential and moisture susceptibility;
- dynamic modulus test as recommended by the National Cooperative Highway Research Program (NCHRP) design guide; for each mix, a master curve of mix stiffness versus frequency of loading was generated, and the rutting and fatigue cracking estimates were made using NCHRP recommended procedures; and
- TTI’s overlay tester to measure the reflection cracking potential of each mixture.

The conclusions from the laboratory testing of the HMAC mixes using the coarse limestone aggregates were as follows:

- The introduction of marginal coarse limestone aggregates into the mix had little clear impact on the rutting potential of the mix as measured by the Hamburg test or inferred from the dynamic modulus test.
- The introduction of marginal coarse limestone aggregates on the fatigue life inferred from the dynamic modulus was not clear. No consistent trends were observed in the data.
- The introduction of marginal coarse limestone aggregates may impact the reflection cracking resistance. Weak trends were observed where the higher the percentage of marginal material, the lower the reflection cracking life.
- More research definitely needs to be performed with the overlay tester to investigate the anomalous results with the marginal coarse limestone aggregates.

The following conclusions are based on the AIMS imaging device, which was used on the three coarse limestone aggregates used in testing the HMAC mixes:

- Use of the AIMS imaging device revealed that surface texture could be used to separate the good from poor quality limestone coarse aggregate used in this project.
- The AIMS imaging device surprisingly did not show any pronounced variation in angularity among the three different limestone aggregates.

HOW MUCH POOR QUALITY AGGREGATE IS TOO MUCH?

In order to set limits on what level of marginal materials has a serious impact on the performance of the mix, it is important to include the repeatability of the overlay test. In repeatability studies conducted by Zhou (personal communication), it was concluded that using triplicate samples of the average number of cycles to failure will be within 10 percent of the mean for that mix. Therefore, for this report, researchers decided to conclude that a 20 percent reduction in reflection cracking life would be significant. From Figure 38, the 20 percent reduction in reflection cracking life was found by interpolation to be when less than 5 percent limestone #2 pit material was introduced or when 15 percent limestone #3 pit material was introduced. Taking an average of these two numbers, the authors propose that the introduction of more than 10 percent marginal coarse limestone aggregates into a hotmix layer could have a significant impact on the reflection cracking life of that mix. Based on the limited testing done in this research project, we conclude that a maximum level of 10 percent marginal coarse limestone aggregate may result in decreased reflection cracking life (i.e., more research is needed to validate this number).

QUANTIFICATION TESTS FOR POOR QUALITY AGGREGATE

Quarry Evaluations

The following conclusions are based on detailed quarry analyses:

- The three limestone quarries consist of rocks deposited in shallow seas, which will result in aggregates that are laterally continuous.
- All of the limestone quarries contain varying proportions of rock that makes a good aggregate.
- Two things that clearly affect limestone aggregate quality in the limestone quarries are clay minerals mixed in the limestone (Figures 3 and 6) and the amount of small interconnected pores. The methylene blue test may be able to identify deleterious clay minerals in the aggregate. The absorption test (Tex-201-F) may be a good test to evaluate the interconnected porosity.
- The quality of the basalt seems to be tied to the amount of degradation or weathering of the basalt. As observed in Figure 14, clay is filling vesicles in rock that has been exposed to weathering, but the clay-filled vesicles disappear at depth where the rock has not been exposed to the elements.
- Manually separate the rock types as explained in Report 0-4523-1 and determine the percentages of good to poor quality limestone aggregate using the amounts described in this report.
- In quarries where marginal aggregates are encountered, TxDOT has employed a technique where the coarser crushed rock is reprocessed into smaller aggregate gradations, and only rock derived from the coarser fraction is used on TxDOT jobs.

Mineralogical Properties Contributing to Aggregate Quality

The evidence the authors have does not support the conclusion that Al_2O_3 content is a good indicator of aggregate durability. Based on the data obtained in this investigation, the researchers speculate that clay mineralogy may be the most important factor controlling aggregate durability. The authors further speculate that smectite is the most detrimental clay mineral.

From the XRD data on the two limestone aggregates (limestone #1 pit and limestone #2 pit) used in the HMAC portion of this project, one would have to conclude:

- There is a certain threshold of clay that causes detrimental effects on aggregate quality because both aggregates contained very similar clay mineralogies, but the lower quality aggregate (limestone #2) contained a higher percentage of smectite.
- Smectite is the most detrimental clay mineral with respect to aggregate durability due to its affinity for moisture. As explained in Report 0-4523-1, the best way to remove clay from the aggregate is by washing the crushed rock at the quarry.

Micro-Deval and Magnesium Sulfate Soundness Testing

At this time, based upon the data, the researchers have to agree with results from other investigations and conclude that substituting the Micro-Deval for the magnesium sulfate soundness test on the coarse aggregate is not a good idea (Kandhal and Parker, 1998). The correlation between the two test methods is very weak at best. However, the Micro-Deval test appears to do a good job of identifying lower quality aggregate.

To develop acceptance guidelines using the Micro-Deval test, TxDOT may want to investigate different failure criteria for different aggregate types. For example, Lane et al. (2000) specified different M-D losses for different mineralogies: they recommend 5 percent for igneous and metamorphic gravel; 10 percent for traprock, diabase, and andesite; and 15 percent for dolomitic sandstone, granitic meta-arkose, and gneiss. Cooley and James (2003) noticed different M-D losses for different mineralogies in aggregates used in the southeastern United States. They observed that a granite considered a good performer had a mean percent loss of 6.8 percent, but a limestone was considered a good performer with a mean percent loss of 15.8 percent.

It has been well documented that soft, absorptive aggregates are less durable (Harvey et al., 1974; Hudec and Rogers, 1976) than a hard, nonporous aggregate of the same mineralogy. The authors propose to use the absorption test (Tex 201-F) in addition to the MSS test for coarse carbonate aggregates. It is less time consuming and correlates well with soundness test results, as demonstrated by other researchers. Perhaps at some point, a recommendation can be made to replace the sulfate soundness test with a simple absorption test.

The following conclusions are based on the extensive aggregate tests performed on the limestone #1, limestone #2, and limestone #3 aggregate blends:

- TxDOT should continue to use the Micro-Deval to screen for changes in aggregate consistency.
- Based on the Micro-Deval results for the three limestones evaluated in Chapter 3, a conservative estimate to obtain less than 10 percent poor quality coarse limestone aggregate, would be a Micro-Deval percent loss exceeding 20. TxDOT may want to perform more testing on coarse limestone aggregates that have Micro-Deval percent losses exceeding 20 (Table 14) to ensure a quality product.
- If the magnesium sulfate soundness percent loss exceeds 15 for coarse limestone aggregates, TxDOT may want to supplement soundness data with field performance records and/or other testing on the aggregate (Table 14).

TESTING FREQUENCY TO IDENTIFY MINERALOGICAL SEGREGATION

The only way to guarantee aggregate quality in quarries with variable/marginal aggregate is to sample according to the following scheme for each job the aggregate is to be used on and every time new aggregate is to be added to an existing TxDOT approved stockpile.

In order to obtain a representative sample to evaluate mineralogical segregation in an aggregate source, one can have up to 10 percent very poor limestone coarse aggregate in a hotmix asphalt concrete mix without adversely affecting performance, as illustrated in Chapter 3. This will determine how much sample needs to be taken from the quarry for detailed analysis (Table 16). For example, if one wanted to evaluate a 3/8 inch aggregate from a crushed rock quarry, then they would need to obtain 25 kg of aggregate from the quarry in a manner described in Report 0-4523-1. The sample should then be split into smaller fractions for detailed laboratory analysis by either quartering or riffling. In order to obtain a statistically significant lithologic analysis at an accuracy of ±10 percent for a poor quality 3/8 inch aggregate present at 10 percent in a quarry, then one would need to analyze 1100 g of sample. For the same accuracy in a ¾ inch sample, 11,000 g would need to be analyzed.

Table 16. Quantities of Aggregate Needed to Statistically Identify 10 Percent Poor Quality Aggregate at an Accuracy of ±10 Percent.

Maximum Aggregate Size in mm (inches)	Minimum Mass Delivered to the Laboratory in kg (lb)	Minimum Mass Needed For Lithologic Analysis in g (lb)
20 (0.79)	50 (110)	11,000 (24.23)
10 (0.4)	25 (55)	1100 (2.42)
5 (0.2)	10 (22)	110 (0.24)

*This table is based upon BS 812: Part 104: Draft.

RECOMMENDATIONS FOR FUTURE RESEARCH

A full mineralogical analysis of aggregates used in Texas should be performed using the techniques described in Chapter 2 of this report. Those results should be compared to standard aggregate tests to determine if smectite is indeed the main contributor to aggregate durability problems in Texas.

The authors recommend that the Micro-Deval, magnesium sulfate soundness, and the absorption tests be used to evaluate all Texas aggregates and then correlate the test results with field performance. Perhaps acceptance criteria could be developed based on the mineralogy and may actually reflect how the aggregate performs in the field.

An evaluation of the methylene blue test is recommended. It could potentially be used to determine the amount of poor quality clay minerals in an aggregate source.

PRODUCTS

Product 2 Mineralogical Segregation Tolerances for Bituminous mixes – Based upon the analysis of three coarse limestone aggregates of varying qualities, mixed in varying proportions, the researchers developed a tenuous relationship between fatigue cracking and coarse aggregate quality. Preliminary results suggest that up to 10 percent poor quality (absorptive and soft) coarse aggregate is acceptable.

	This only pertains to limestone coarse aggregate in hotmix asphalt concrete applications.
Product 3	Quantification Tests for Mineralogical Segregation – The researchers have identified five tests that can be used to quantitatively identify mineralogical segregation in quarries: 1) physically separating and counting aggregates, 2) Micro-Deval, 3) absorption, 4) magnesium sulfate soundness, and 5) overlay tester. Once again, these tests' limits will vary due to differences in mineralogy.
Product 4	Frequency of Tests for Mineralogical Segregation – The only way to guarantee aggregate quality in quarries with variable/marginal aggregate is to sample for each job (preferably from the conveyor belt) in the amounts described in Table 16.

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APPENDIX A

THIN-SECTION AND X-RAY FLUORESCENCE SAMPLES

Thin-Section Label	Operator/Quarry	TxDOT Aggregate Type
YKI-1a *	Yarrington Rd. Mat'ls/Kyle	1a
YKI-1b *	Yarrington Rd. Mat'ls/Kyle	1b
YKI-1c *	Yarrington Rd. Mat'ls/Kyle	1c
YKI-3a *	Yarrington Rd. Mat'ls/Kyle	3a
YKI-3b *	Yarrington Rd. Mat'ls/Kyle	3b
YKI-3c *	Yarrington Rd. Mat'ls/Kyle	3c
YKII-1a *	Yarrington Rd. Mat'ls/Kyle	1a
YKII-1b *	Yarrington Rd. Mat'ls/Kyle	1b
YKII-1c *	Yarrington Rd. Mat'ls/Kyle	1c
YKII-3a *	Yarrington Rd. Mat'ls/Kyle	3a
YKII-3b *	Yarrington Rd. Mat'ls/Kyle	3b
YKII-3c *	Yarrington Rd. Mat'ls/Kyle	3c
CYI-1 *	Centex/Yearwood	1
CYI-2 *	Centex/Yearwood	2
CYI-3 *	Centex/Yearwood	3
CYI-4 *	Centex/Yearwood	4
CYI-5 *	Centex/Yearwood	5
CYI-6 *	Centex/Yearwood	6
CYI-7 *	Centex/Yearwood	7
CYII-1 *	Centex/Yearwood	1
CYII-2 *	Centex/Yearwood	2
CYII-3 *	Centex/Yearwood	3
CYII-4 *	Centex/Yearwood	4
CYII-5 *	Centex/Yearwood	5
CYII-6 *	Centex/Yearwood	6
CYII-7 *	Centex/Yearwood	7
PCI-1 *	Price/Clements	1
PCI-2 *	Price/Clements	2
PCI-3 *	Price/Clements	3
PCI-4 *	Price/Clements	4
PCI-5 *	Price/Clements	5
PCI-6	Price/Clements	6
PCII-1 *	Price/Clements	1
PCII-2 *	Price/Clements	2
PCII-3 *	Price/Clements	3
PCII-4	Price/Clements	4
PCII-5 *	Price/Clements	5
SSI-1	Squaw Creek LP/Squaw Creek	1
SSI-2 *	Squaw Creek LP/Squaw Creek	2
SSI-3 *	Squaw Creek LP/Squaw Creek	3
SSI-4 *	Squaw Creek LP/Squaw Creek	4
SSII-1	Squaw Creek LP/Squaw Creek	1
SSII-3 *	Squaw Creek LP/Squaw Creek	3
SSII-4 *	Squaw Creek LP/Squaw Creek	4

VBI-1a *	Vulcan/Black	1a
VBI-1b *	Vulcan/Black	1b
VBI-2 *	Vulcan/Black	2
VBI-3a *	Vulcan/Black	3a
VBI-3b *	Vulcan/Black	3b
VBI-4 *	Vulcan/Black	4
VBII-1a *	Vulcan/Black	1a
VBII-1b *	Vulcan/Black	1b
VBII-2 *	Vulcan/Black	2
VBII-3a *	Vulcan/Black	3a
VBII-3b *	Vulcan/Black	3b
VBII-4 *	Vulcan/Black	4
MWI-1 *	Mine Services/Waco Pit #365	1
MWI-2 *	Mine Services/Waco Pit #365	2
MWI-3 *	Mine Services/Waco Pit #365	3
MWI-4 *	Mine Services/Waco Pit #365	4
MWI-5 *	Mine Services/Waco Pit #365	5
MWI-6 *	Mine Services/Waco Pit #365	6
MWI-7 *	Mine Services/Waco Pit #365	7
MWII-1 *	Mine Services/Waco Pit #365	1
MWII-2 *	Mine Services/Waco Pit #365	2
MWII-3 *	Mine Services/Waco Pit #365	3
MWII-4 *	Mine Services/Waco Pit #365	4
MWII-5 *	Mine Services/Waco Pit #365	5
MWII-6 *	Mine Services/Waco Pit #365	6
MWII-7 *	Mine Services/Waco Pit #365	7
MWIII-1 *	Mine Services/Waco Pit #365	1
MWIII-2 *	Mine Services/Waco Pit #365	2
MWIII-3 *	Mine Services/Waco Pit #365	3
MWIII-4 *	Mine Services/Waco Pit #365	4
MWIII-5 *	Mine Services/Waco Pit #365	5
MWIII-6 *	Mine Services/Waco Pit #365	6
MWIII-7 *	Mine Services/Waco Pit #365	7

*Samples submitted for XRF analysis.

APPENDIX B

X-RAY FLUORESCENCE DATA

Sample Ident	SiO_2	Al_2O_3	CaO	MgO	Na_2O	K_2O	Fe_2O_3	MnO	TiO_2	P_2O_5	Cr_2O_3	LOI	Sum
Scheme Code	**XRF100**	**XRF100**	**XRF100**	**XRF100**	**XRF100**	**XRF100**	**XRF100**	**XRF100**	**XRF100**	**XRF100**	**XRF100**	**XRF100**	**XRF100**
Analysis Unit	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**
Detection Limit	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**
CYI-1	0.3	0.09	55.46	1	0.03	0.03	0.12	<0.01	<0.01	0.02	<0.01	42.95	**100**
CYI-2	0.41	0.1	51.26	3.82	0.03	0.1	0.18	<0.01	0.05	0.02	<0.01	43.25	**99.23**
CYI-3	0.8	0.22	48.99	5.92	0.04	0.06	0.22	<0.01	0.02	0.04	<0.01	43.55	**99.87**
CYI-4	1.01	0.33	53.09	2.03	0.04	0.04	0.32	<0.01	0.01	0.02	0.01	42.85	**99.75**
CYI-5	0.35	0.08	35.92	17.24	0.03	0.05	0.21	<0.01	<0.01	0.01	0.01	45.85	**99.78**
CYI-6	1.9	0.58	41.1	11.14	0.03	0.09	0.37	<0.01	0.02	0.02	0.01	44.45	**99.72**
CYI-7	1.42	0.37	53.13	1.41	0.04	0.04	0.27	<0.01	0.01	0.01	0.02	42.85	**99.58**
CYII-1	0.6	0.16	48.94	5.86	0.03	0.04	0.17	<0.01	<0.01	0.02	<0.01	43.85	**99.69**
CYII-2	0.83	0.17	52.5	3.17	0.04	0.05	0.17	<0.01	0.02	0.01	<0.01	43	**99.96**
CYII-3	1.16	0.33	50.19	4.94	0.03	0.07	0.25	<0.01	0.02	0.02	<0.01	43.2	**100.2**
CYII-4	4.26	0.82	50.51	2.16	0.04	0.13	0.45	<0.01	0.04	0.02	0.01	41.05	**99.5**
CYII-5	1.06	0.14	38.28	15	0.02	0.06	0.17	<0.01	<0.01	0.01	<0.01	45.3	**100.1**
CYII-6	1.52	0.31	45.45	9.37	0.03	0.06	0.25	<0.01	0.01	0.01	0.01	43.1	**100.1**
CYII-7	2.12	0.33	52.71	1.22	0.05	0.07	0.22	<0.01	0.01	0.01	0.02	42.31	**99.08**
MWI-1	1.57	0.56	54.02	0.5	0.03	0.1	1.14	0.09	0.03	0.13	<0.01	41.9	**100.1**
MWI-2	1.46	0.52	53.88	0.39	0.02	0.1	1.1	0.13	0.03	0.07	<0.01	41.95	**99.66**
MWI-3	2.25	0.64	53.78	0.42	0.03	0.11	0.76	0.08	0.03	0.06	<0.01	41.65	**99.81**
MWI-4	2.01	0.67	53.7	0.41	0.03	0.11	0.91	0.09	0.03	0.06	<0.01	41.9	**99.92**
MWI-5	1.71	0.63	54.45	0.4	0.03	0.09	0.44	0.07	0.02	0.05	<0.01	42.15	**100.1**
MWI-6	1.81	0.11	55.2	0.31	0.04	0.03	0.24	0.02	<0.01	0.02	0.01	42.35	**100.1**
MWI-7	1.88	0.64	53.82	0.38	0.03	0.1	0.93	0.13	0.02	0.07	<0.01	41.75	**99.75**
MWII-1	1.56	0.24	55.13	0.28	0.04	0.04	0.51	0.05	0.01	0.03	<0.01	42.2	**100.1**
MWII-2	2.04	0.75	53.69	0.3	0.03	0.12	1.15	0.17	0.04	0.06	<0.01	41.45	**99.8**
MWII-3	1.51	0.44	54.18	0.35	0.03	0.08	0.74	0.15	0.03	0.08	<0.01	42.05	**99.65**
MWII-4	1.72	0.62	54.14	0.35	0.03	0.08	0.8	0.14	0.02	0.06	<0.01	41.85	**99.82**
MWII-5	3.54	0.92	52.64	0.35	0.04	0.14	0.75	0.1	0.04	0.05	0.02	41	**99.57**
MWII-6	0.74	0.1	55.74	0.26	0.03	0.02	0.17	0.02	<0.01	0.02	<0.01	42.65	**99.76**
MWII-7	1.78	0.53	53.88	0.3	0.05	0.08	1.21	0.15	0.03	0.07	0.03	41.55	**99.67**
MWIII-1	8.35	0.6	50.8	0.4	0.04	0.13	0.78	0.1	0.02	0.06	0.02	38.55	**99.83**
MWIII-2	1.8	0.6	53.69	0.36	0.03	0.1	1.36	0.11	0.03	0.09	<0.01	41.55	**99.73**
MWIII-3	1.57	0.51	54.27	0.34	0.03	0.09	0.72	0.11	0.03	0.05	<0.01	42.1	**99.83**
MWIII-4	2.31	0.62	53.53	0.39	0.03	0.11	0.86	0.09	0.03	0.06	<0.01	41.7	**99.73**

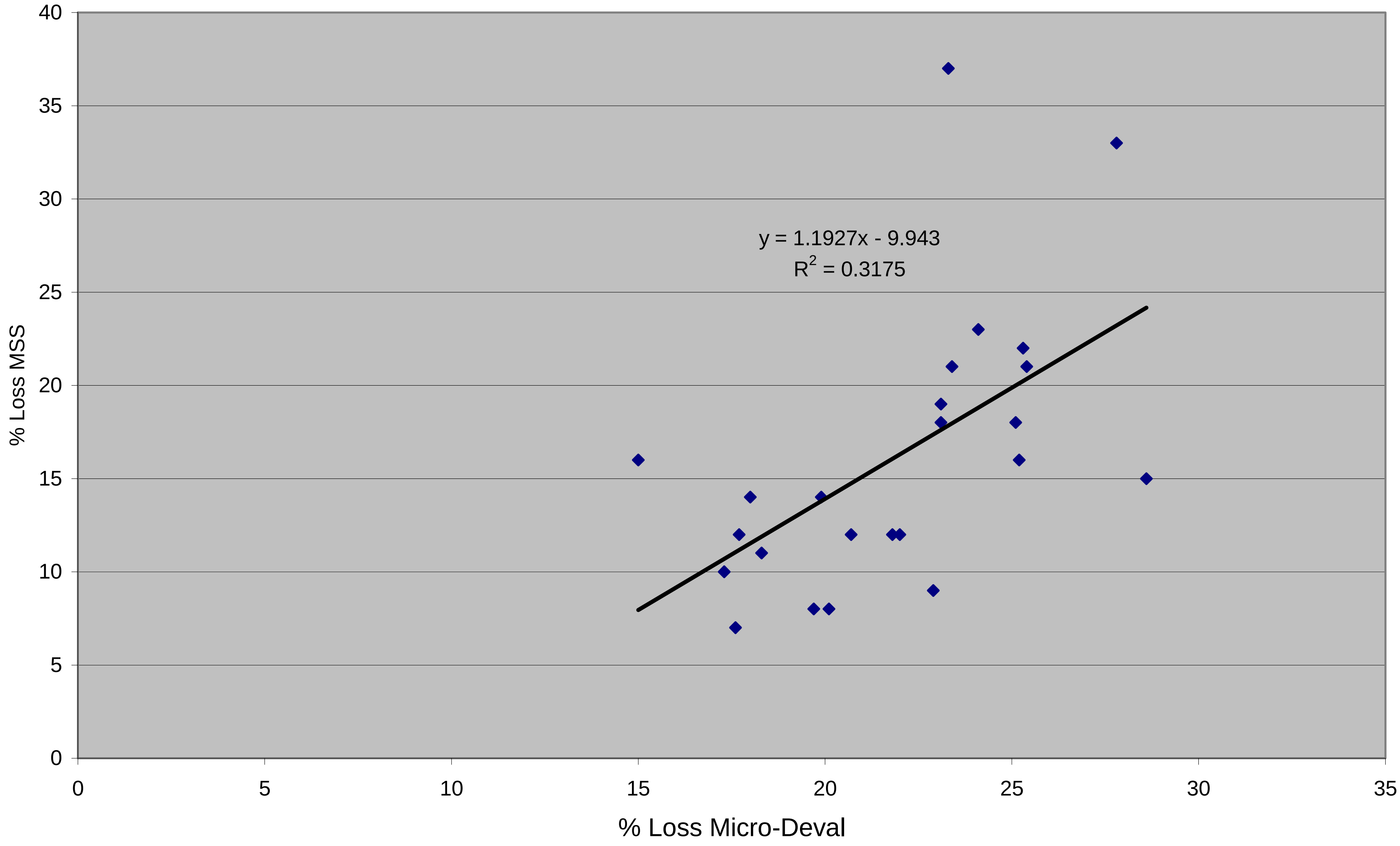
Sample Ident	SiO_2	Al_2O_3	CaO	MgO	Na_2O	K_2O	Fe_2O_3	MnO	TiO_2	P_2O_5	Cr_2O_3	LOI	Sum
Scheme Code	**XRF100**	**XRF100**	**XRF100**	**XRF100**	**XRF100**	**XRF100**	**XRF100**	**XRF100**	**XRF100**	**XRF100**	**XRF100**	**XRF100**	**XRF100**
Analysis Unit	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**
Detection Limit	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**
MWIII-5	2.64	0.6	53.83	0.37	0.04	0.09	0.55	0.07	0.02	0.05	0.02	41.5	**99.78**
MWIII-6	1.73	0.14	55.18	0.28	0.03	0.04	0.3	0.03	<0.01	0.02	<0.01	42.2	**99.96**
MWIII-7	2.86	0.92	52.85	0.4	0.03	0.16	0.84	0.14	0.04	0.08	<0.01	41.2	**99.52**
PCI-1	2.33	0.3	54.46	0.33	0.03	0.06	0.28	0.02	0.02	0.02	<0.01	42	**99.85**
PCI-2	1.94	0.42	54.39	0.34	0.03	0.04	0.55	0.02	0.02	0.02	<0.01	42.1	**99.88**
PCI-3	2.7	0.63	53.88	0.36	0.03	0.07	0.33	0.02	0.02	0.02	<0.01	41.9	**99.98**
PCI-4	2.87	0.66	53.36	0.43	0.03	0.08	0.8	0.04	0.02	0.03	<0.01	41.7	**100**
PCI-5	3.67	0.79	53.05	0.33	0.04	0.08	0.43	0.02	0.03	0.02	0.01	41.6	**100.1**
PCII-1	1.63	0.25	54.62	0.34	0.03	0.04	0.3	0.02	0.01	0.01	<0.01	41.6	**98.84**
PCII-2	3.32	0.46	53.51	0.31	0.02	0.08	0.76	0.02	0.02	0.02	<0.01	40.65	**99.19**
PCII-3	2.43	0.43	54.34	0.29	0.03	0.07	0.25	0.02	0.02	0.02	<0.01	41.05	**98.95**
PCII-5	2.85	0.68	53.86	0.33	0.03	0.09	0.31	0.02	0.03	0.02	<0.01	40.6	**98.83**
SSI-2	1.86	0.18	54.82	0.26	0.03	0.04	0.31	0.03	<0.01	0.04	0.01	41.2	**98.78**
SSI-3	5.24	0.38	52.68	0.38	0.03	0.13	0.32	0.03	0.03	0.08	<0.01	39.75	**99.07**
SSI-4	13.7	0.76	47.13	0.39	0.04	0.32	0.58	0.03	0.07	0.18	0.02	35.45	**98.67**
SSII-3	7.49	0.4	51.51	0.36	0.04	0.17	0.26	0.03	0.04	0.08	0.01	38.6	**98.97**
SSII-4	11.68	0.57	48.23	0.36	0.04	0.24	1.11	0.03	0.05	0.1	0.02	36.15	**98.56**
VBI-1A	1.48	0.16	55.15	0.37	0.03	0.05	0.1	0.01	0.02	0.01	<0.01	41.45	**98.84**
VBI-1B	1.96	0.44	54.44	0.47	0.03	0.07	0.19	0.01	0.02	0.02	<0.01	41.3	**98.96**
VBI-2	1.96	0.42	53.83	0.55	0.04	0.1	0.86	0.02	0.03	0.02	<0.01	41.1	**98.94**
VBI-3A	1.67	0.23	55.02	0.4	0.03	0.04	0.15	0.01	<0.01	0.01	<0.01	41.25	**98.85**
VBI-3B	1.76	0.37	54.73	0.47	0.03	0.08	0.47	0.02	0.03	0.02	<0.01	41.05	**99.04**
VBI-4	2.29	0.33	53.98	0.49	0.04	0.11	0.2	0.02	0.04	0.02	<0.01	42.4	**99.92**
VBII-1A	1.74	0.33	54.38	0.5	0.03	0.1	0.25	0.02	0.04	0.01	<0.01	42.35	**99.74**
VBII-1B	1.55	0.48	54.77	0.58	0.03	0.06	0.22	0.02	0.02	0.01	<0.01	41.4	**99.14**
VBII-2	1.93	0.38	53.93	0.53	0.03	0.09	0.64	0.02	0.03	0.02	<0.01	41	**98.61**
VBII-3A	1.38	0.29	54.79	0.45	0.03	0.06	0.23	0.01	0.02	0.01	<0.01	41.35	**98.63**
VBII-3B	2.63	0.68	53.55	0.57	0.04	0.12	0.37	0.01	0.04	0.02	0.01	40.95	**98.99**
VBII-4	2.64	0.36	54.6	0.48	0.03	0.06	0.21	0.01	0.02	0.02	<0.01	40.95	**99.39**
YKI-1A	1.84	0.38	54.58	0.48	0.03	0.08	0.36	0.01	0.02	0.02	<0.01	40.5	**98.3**
YKI-1B	4.28	0.47	53.01	0.36	0.04	0.2	0.51	0.02	0.04	0.03	<0.01	41.25	**100.2**
YKI-1C	1.61	0.24	54.87	0.25	0.04	0.05	0.17	<0.01	0.01	0.03	0.01	42.55	**99.84**

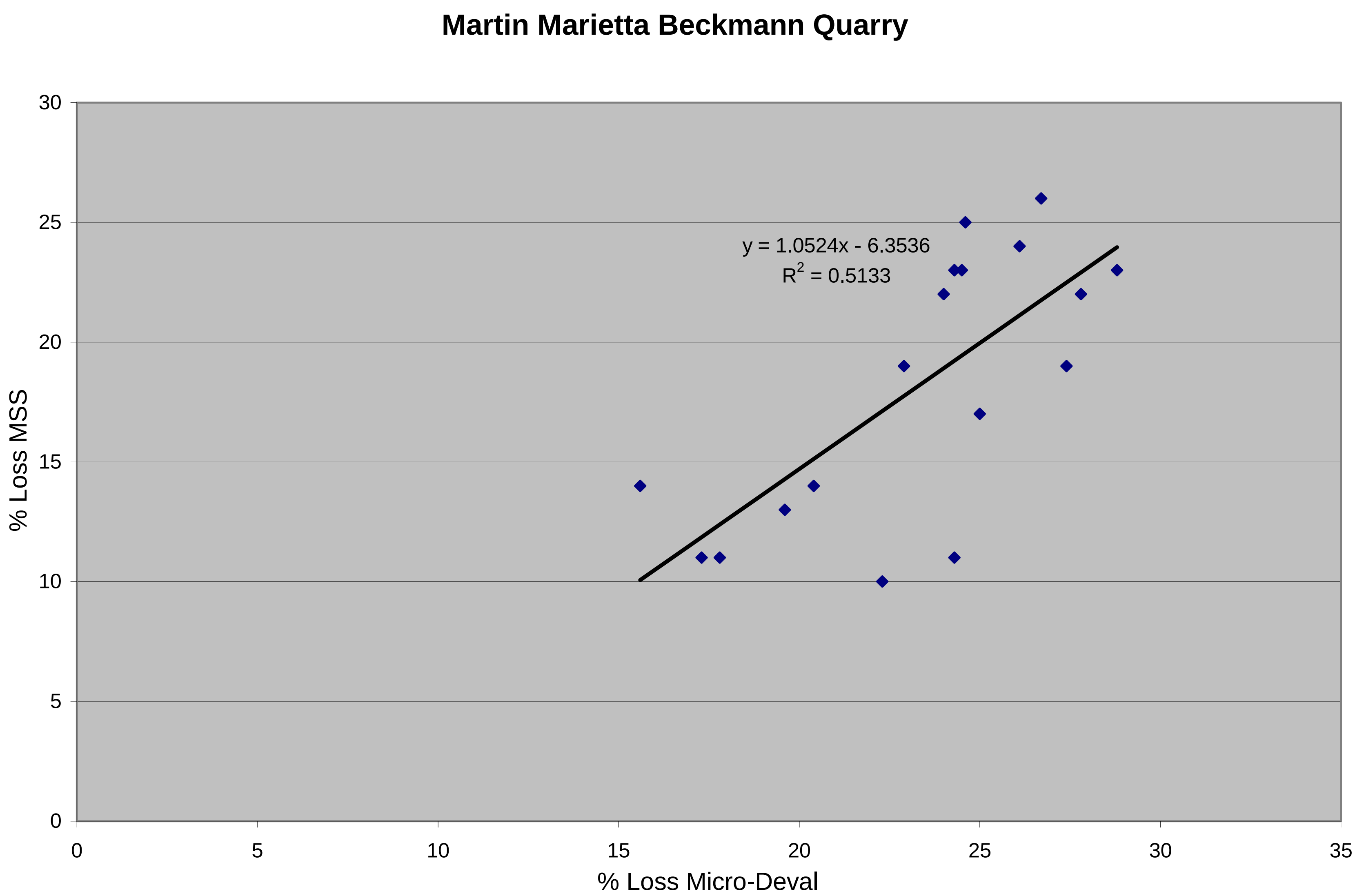
Sample Ident	SiO_2	Al_2O_3	CaO	MgO	Na_2O	K_2O	Fe_2O_3	MnO	TiO_2	P_2O_5	Cr_2O_3	LOI	Sum
Scheme Code	**XRF100**	**XRF100**	**XRF100**	**XRF100**	**XRF100**	**XRF100**	**XRF100**	**XRF100**	**XRF100**	**XRF100**	**XRF100**	**XRF100**	**XRF100**
Analysis Unit	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**	**%**
Detection Limit	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**
YKI-3A	2.86	0.55	53.88	0.44	0.03	0.11	0.68	0.04	0.03	0.04	<0.01	40.1	**98.75**
YKI-3B	3.88	0.78	53.04	0.36	0.03	0.17	0.6	0.02	0.04	0.15	<0.01	40	**99.06**
YKI-3C	2.46	0.5	54.01	0.36	0.03	0.1	0.38	0.01	0.02	0.03	<0.01	40.75	**98.66**
YKII-1A	2.06	0.32	54.26	0.36	0.03	0.07	0.3	<0.01	0.02	0.02	<0.01	40.9	**98.36**
YKII-1B	0.7	0.29	55.59	0.33	0.04	0.07	0.47	0.13	0.01	0.05	<0.01	42.55	**100.2**
YKII-1C	3.71	0.96	52.37	0.37	0.03	0.18	1.3	0.05	0.04	0.07	<0.01	40.85	**99.95**
YKII-3A	2.24	0.56	53.35	0.38	0.03	0.14	0.87	0.04	0.04	0.07	<0.01	42	**99.72**
YKII-3B	2.84	0.57	53.38	0.35	0.03	0.15	0.54	0.03	0.04	0.08	<0.01	41.8	**99.83**
YKII-3C	2.75	0.54	53.74	0.41	0.03	0.11	0.33	0.02	0.03	0.03	<0.01	40.7	**98.7**
DUP-CYI-1	0.3	0.09	55.37	1	0.03	0.03	0.12	<0.01	<0.01	0.02	<0.01	43.1	**100.1**
DUP-CYII-6	1.53	0.31	45.49	9.35	0.03	0.07	0.25	<0.01	0.01	0.01	0.01	43.05	**100.1**
DUP-MWII-4	1.72	0.62	54.09	0.35	0.03	0.08	0.8	0.14	0.02	0.06	0.01	41.7	**99.62**
DUP-PCI-2	1.94	0.41	54.23	0.34	0.03	0.04	0.55	0.02	0.02	0.02	<0.01	42	**99.61**
DUP-SSII-4	11.65	0.57	48.07	0.36	0.04	0.24	1.11	0.03	0.05	0.1	0.02	36.25	**98.47**
DUP-VBII-4	2.64	0.36	54.58	0.48	0.03	0.06	0.21	0.01	0.02	0.02	<0.01	40.95	**99.37**
DUP-YKII-3C	2.76	0.54	53.68	0.41	0.03	0.11	0.33	0.02	0.03	0.03	<0.01	40.75	**98.7**

APPENDIX C

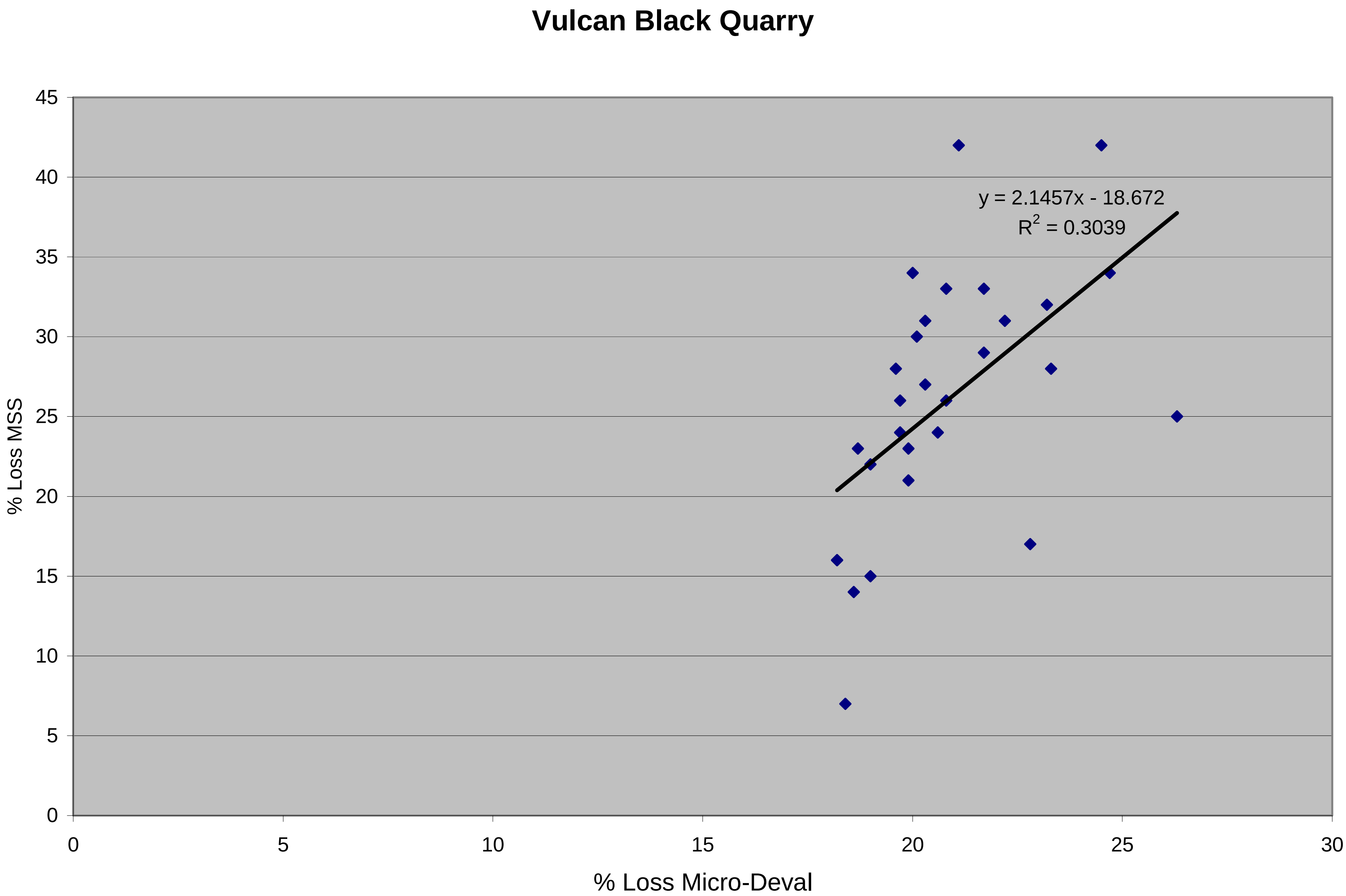
MICRO-DEVAL/MAGNESIUM SULFATE SOUNDNESS GRAPHS

Amarillo Road Company 4DG's Quarry

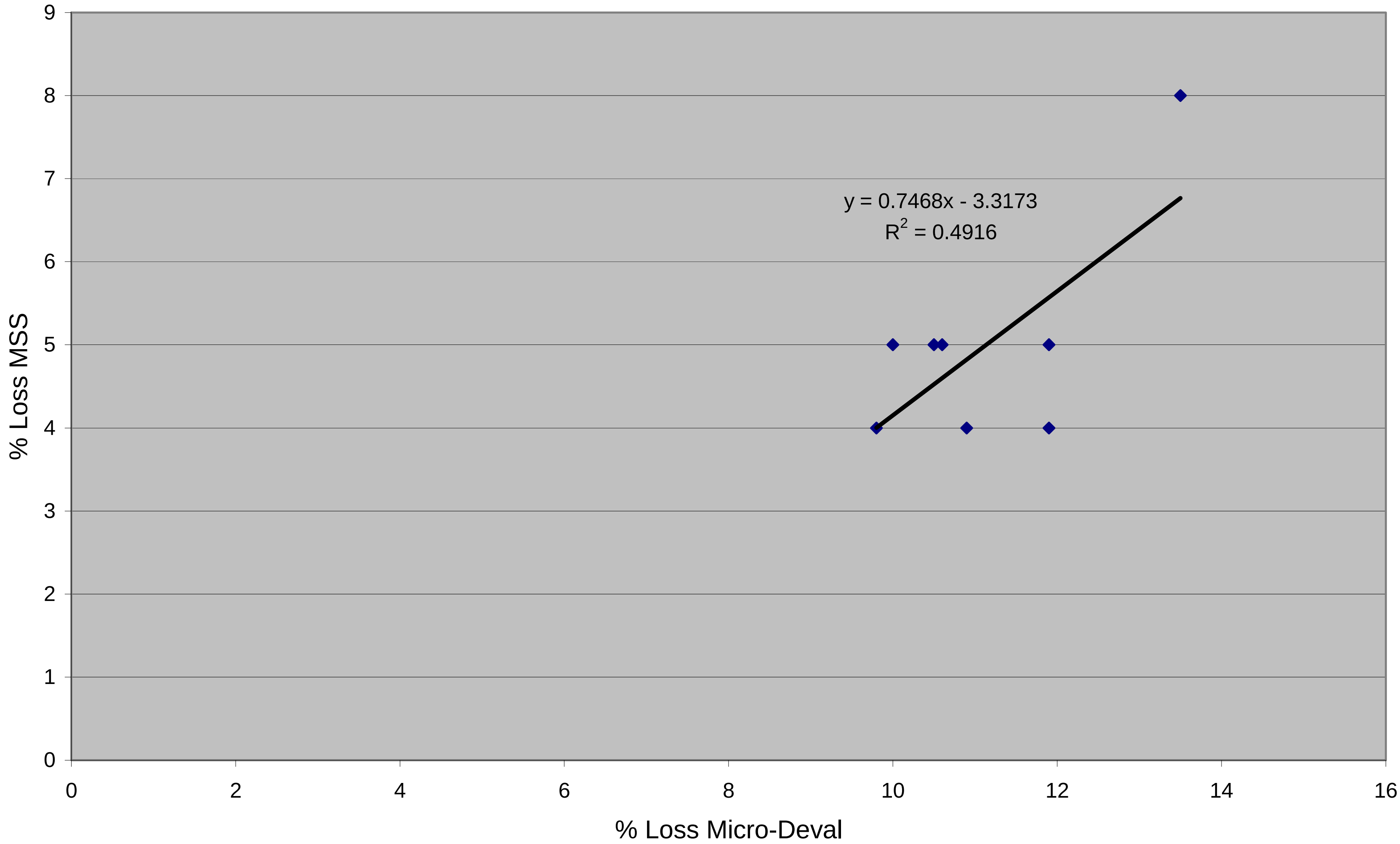




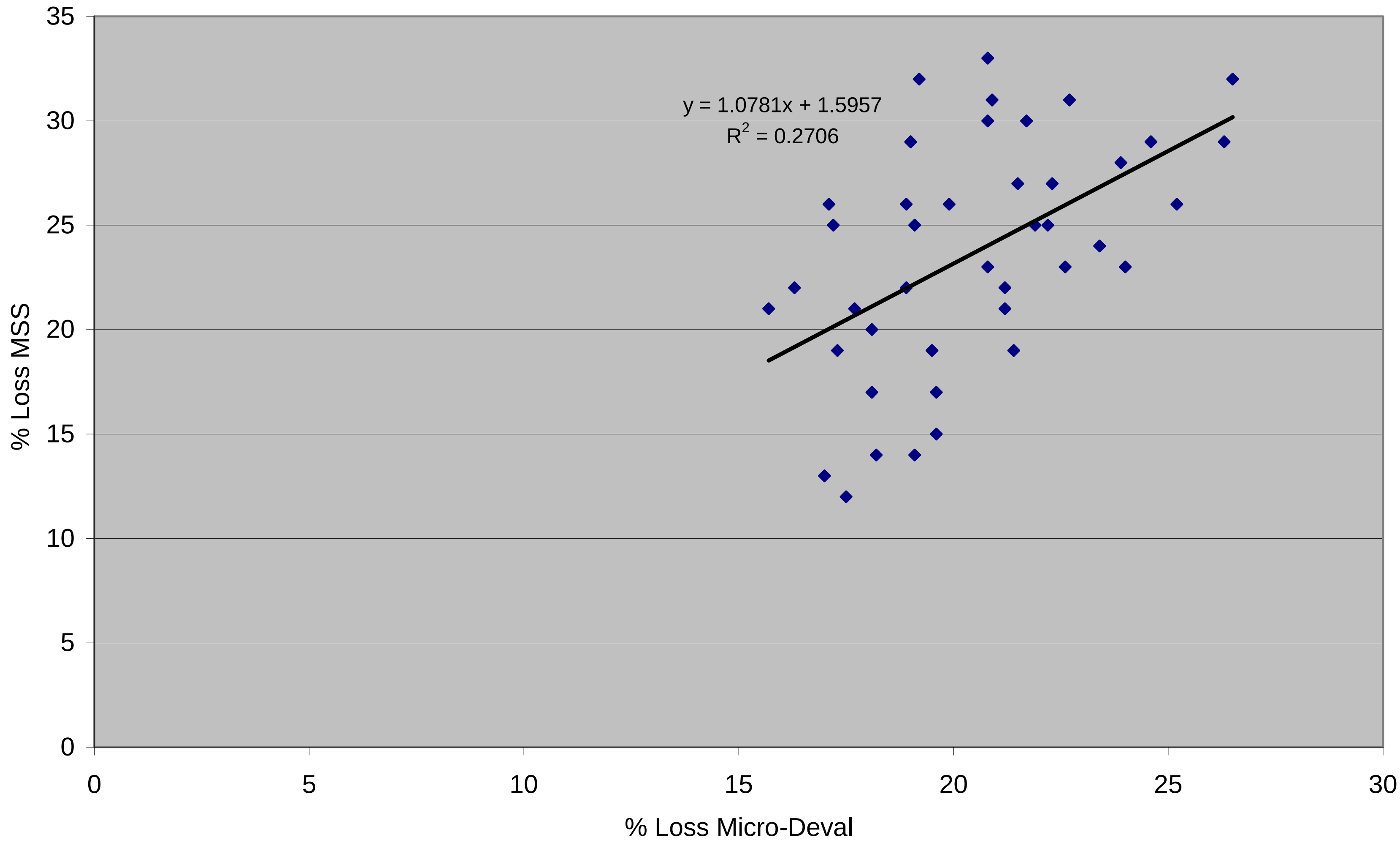
Martin Marietta Beckmann Quarry
y = 1.0524x - 6.3536
R2 = 0.5133
30
25
20
15
10
5
0
0
5
10
15
20
25
30
35
% Loss MSS
% Loss Micro-Deval

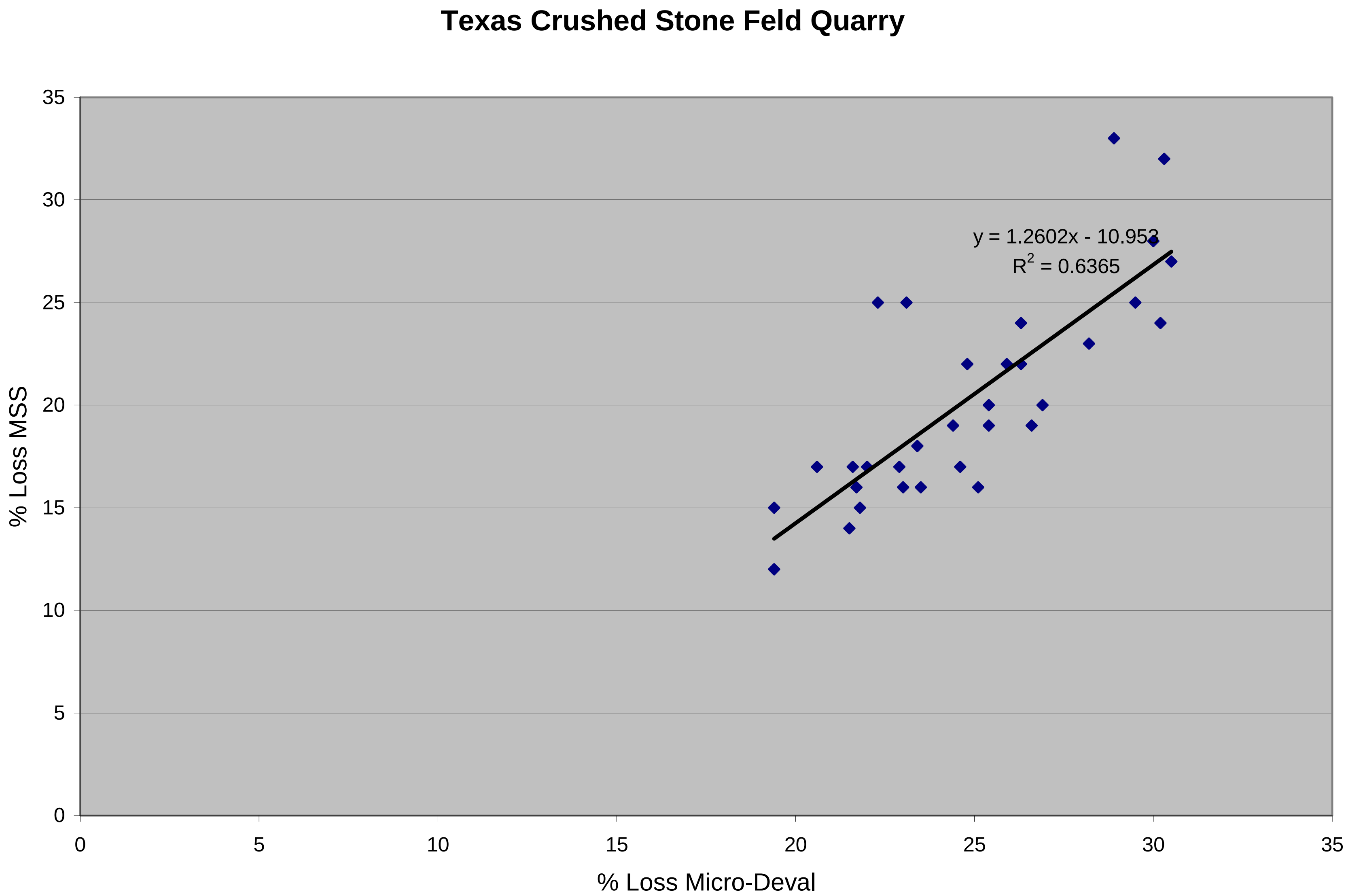

Vulcan Black Quarry
% Loss MSS
% Loss Micro-Deval
y = 2.1457x - 18.672
R^2 = 0.3039
0
5
10
15
20
25
30
35
40
45
0
5
10
15
20
25
30

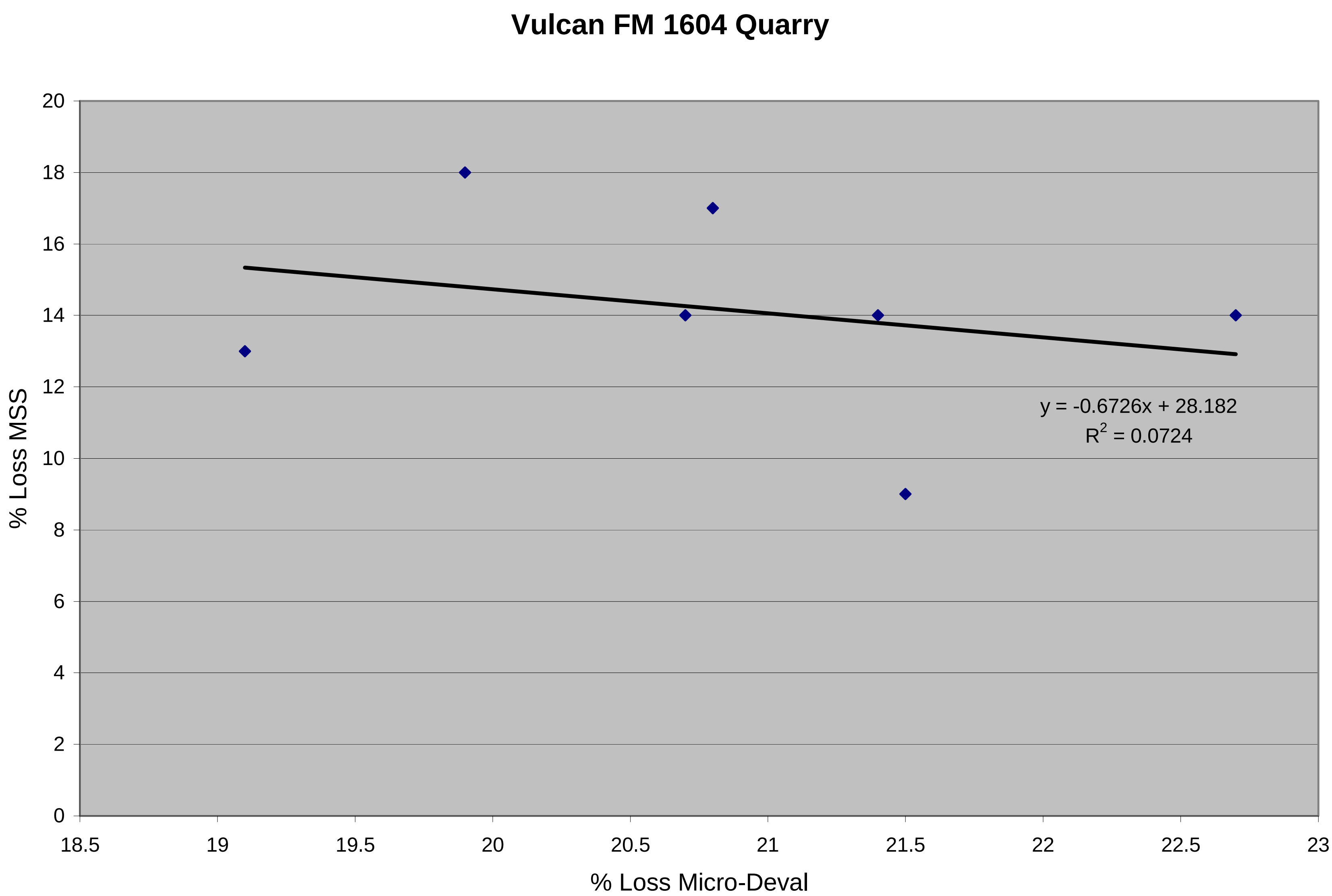
Vulcan Materials Brownwood Quarry



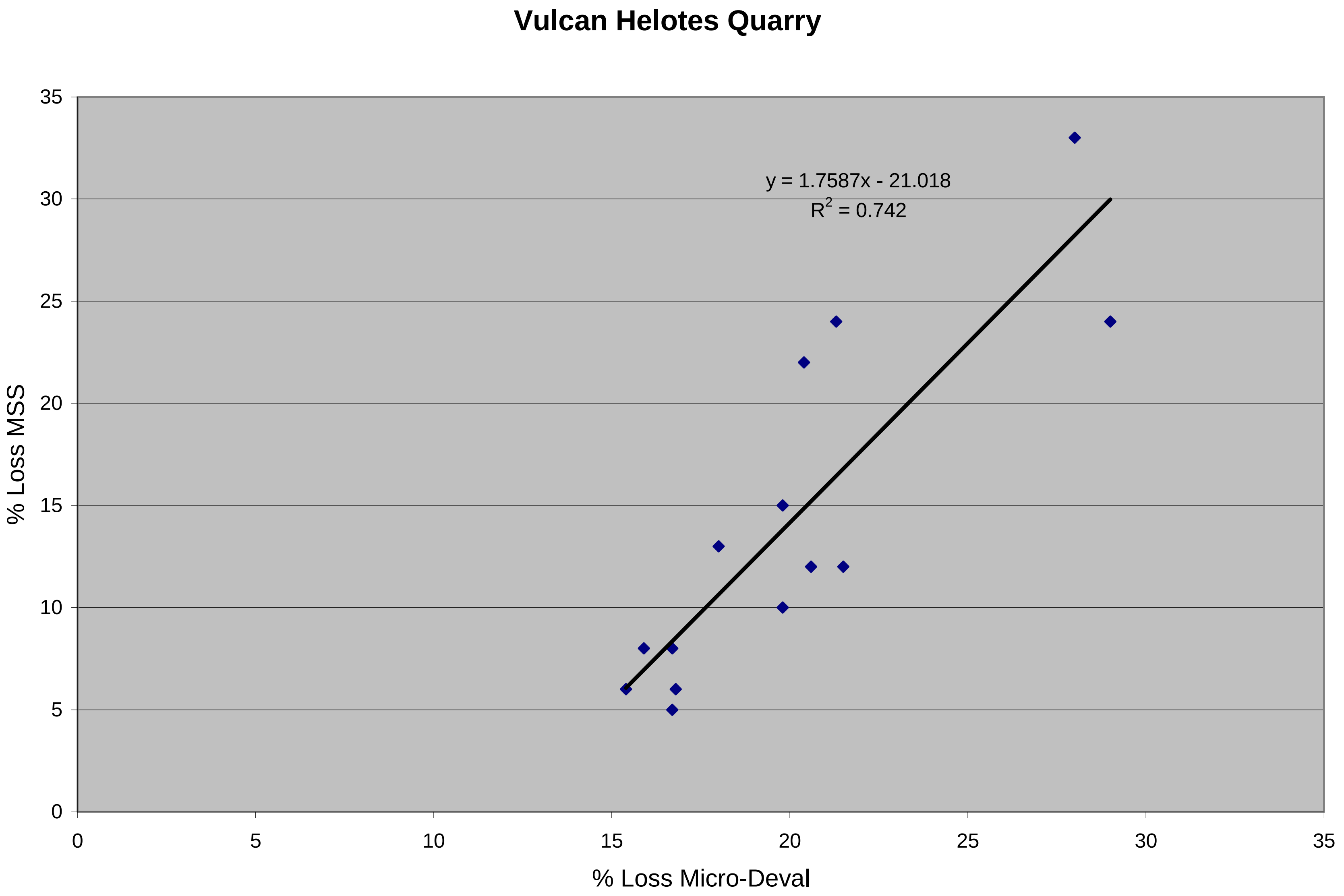
Price Clements Quarry



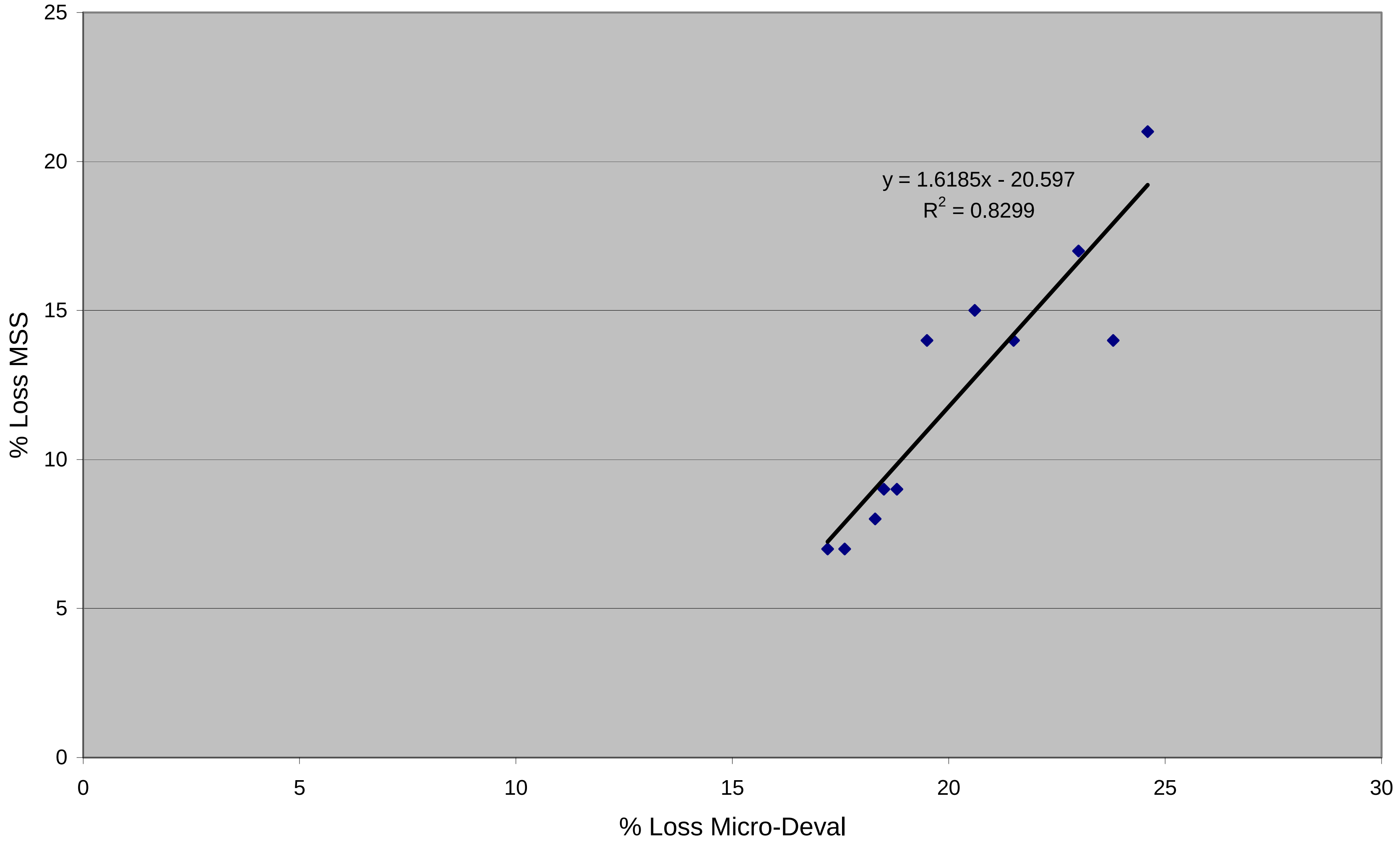

Texas Crushed Stone Feld Quarry
y = 1.2602x - 10.953
R^2 = 0.6365
% Loss MSS
% Loss Micro-Deval
0
5
10
15
20
25
30
35

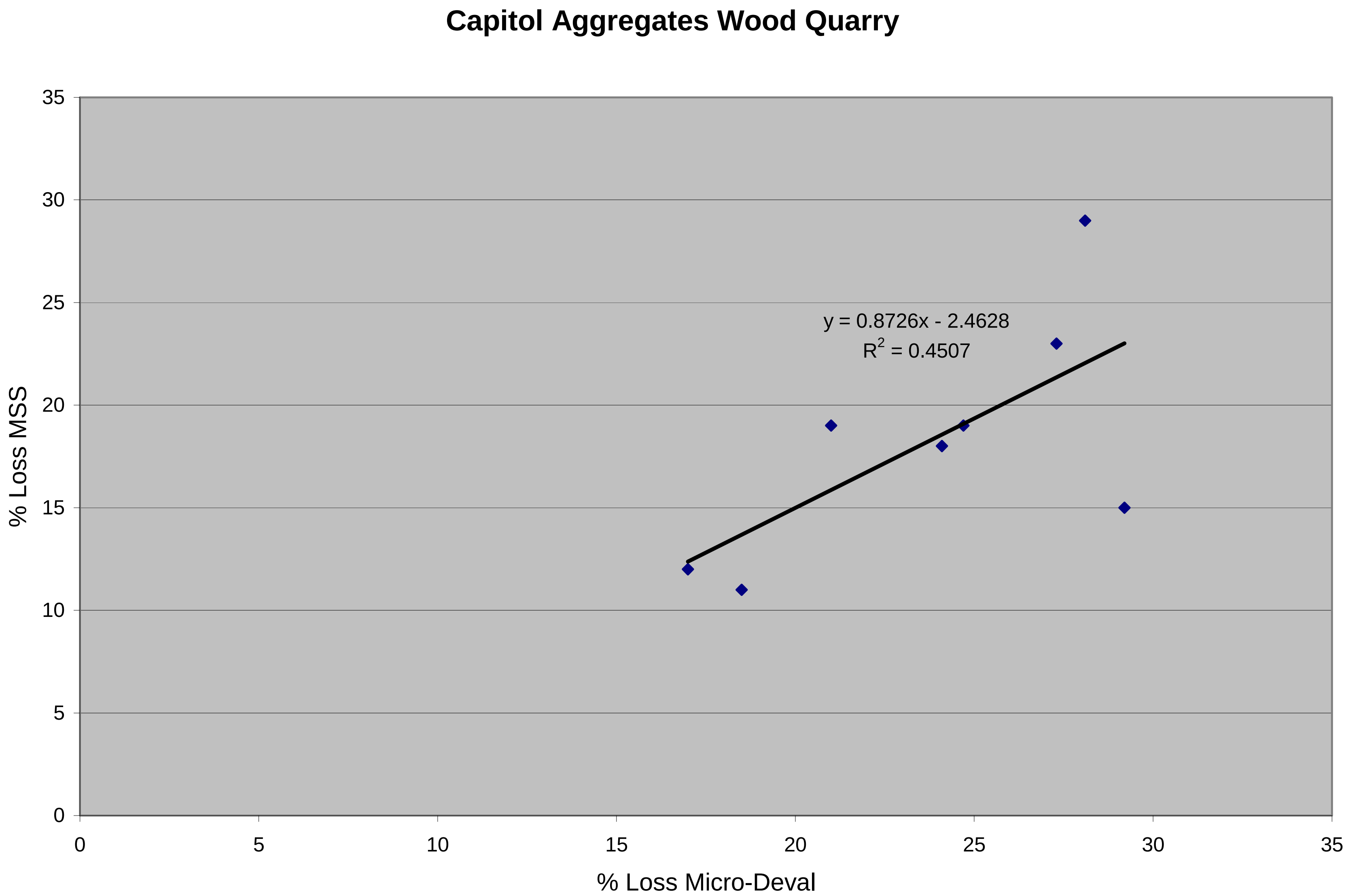


Vulcan FM 1604 Quarry
% Loss MSS
% Loss Micro-Deval
y = -0.6726x + 28.182
R2 = 0.0724
0
2
4
6
8
10
12
14
16
18
20
18.5
19
19.5
20
20.5
21
21.5
22
22.5
23


Vulcan Helotes Quarry
y = 1.7587x - 21.018
R^2 = 0.742
% Loss MSS
% Loss Micro-Deval
0
5
10
15
20
25
30
35

Vulcan Materials Tehuacana Quarry




Capitol Aggregates Wood Quarry
y = 0.8726x - 2.4628
R^2 = 0.4507
% Loss MSS
% Loss Micro-Deval
0
5
10
15
20
25
30
35

APPENDIX D

DENSITY OF AGGREGATE BLENDS AT 4.3 PERCENT ASPHALT CONTENT

Table D1. **Coarse Aggregate Bulk Specific Gravity of Different Blends and Respective Rice Specific Gravity**

Aggregate Blend	Bulk Specific Gravity of Coarse Aggregate Fraction	Rice Specific Gravity at 4.3 % Asphalt Content
100% Limestone #1	2.703	2.525
10% Limestone #2	2.679	2.508
20% Limestone #2	2.655	2.493
30% Limestone #2	2.631	2.485
50% Limestone #2	2.583	2.461
100% Limestone #2	2.463	2.413
10% Limestone #3	2.667	2.514
20% Limestone #3	2.631	2.481
30% Limestone #3	2.595	2.475
50% Limestone #3	2.523	2.456
100% Limestone #3	2.344	2.375