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16. Abstract <p>Skid resistance on wet pavements is influenced by friction at the tire-pavement interface as well as overall hot mix asphalt (HMA) performance. It is important to control aggregate, asphalt, and mix properties to achieve desirable frictional properties on HMA during its service life. Thus, it is important to identify and control these properties through an effective testing and monitoring program.</p> <p>There is also a need for upgrading current testing criteria and aggregate classification systems in view of new techniques that can be used either as replacements and/or supplements to current tests.</p> <p>This project, a part of the Texas Department of Transportation (TxDOT) current research program to evaluate inadequacies of current tests to skid performance, focuses on tests evaluating aggregate shape and distribution parameters. In this project, a wet weather test selection criteria was developed to evaluate the effectiveness of current and new testing techniques to monitor aggregate shape, texture, and distribution characteristics.</p> <p>Extensive tests conducted on 40 aggregates selected from the TxDOT Quality Material Catalog covered various parts of the U.S.A. Fine aggregate tests, including the Uncompacted Void Content, the Compacted Aggregate Resistance, the Methylene Blue, and the Particle Size Analysis, were performed to evaluate angularity, texture, and distribution characteristics within fine aggregates. Flat and elongated tests on coarse aggregates used both conventional and automated techniques to analyze shape and size distribution characteristics. A statistical analysis was performed to select tests that would enable monitoring of aggregate shape and distribution properties enhancing skid performance. The evaluation criteria were based upon a sensitivity and correlation analysis to evaluate consistency, reproducibility, and ability of tests to effectively discern aggregates with good and marginal performance.</p>			
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**DEVELOPMENT OF STATISTICAL WET WEATHER MODEL TO
EVALUATE FRICTIONAL PROPERTIES AT THE PAVEMENT-TIRE
INTERFACE ON HOT-MIX ASPHALT CONCRETE**

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CHAPTER I

INTRODUCTION

Safety of highway pavements is a primary concern for Departments of Transportation (DOTs) as well as to the motoring public. Frictional levels necessary for safe driving depend on a number of factors including roadway geometrics, vehicle speeds, and skid resistance of the roadway. Skid resistance of hot mix asphalt (HMA) is primarily influenced by aggregate properties at the surface (1). However, the aggregate matrix and overall mix properties are also extremely important as they ensure resistance to pavement distresses including permanent deformation and fatigue cracking that indirectly influence skid resistance (2).

Research evaluating aggregate and binder properties influencing HMA performance in terms of permanent deformation, fatigue, and frictional properties have justified a need for binder and aggregate quality control to achieve desired field performance. Extensive laboratory and field-testing of aggregates, binder, and HMA is essential to improve long-term skid performance (1).

The Soils and Aggregates Branch of the Construction Division of the Texas Department of Transportation (TxDOT) monitors aggregate quality in HMA design. The TxDOT Aggregate Quality Monitoring Program (AQMP) helps to ensure quality aggregates are used in HMA pavements. The current AQMP program prequalifies aggregates based on their performance in the Polish Value (PV), 5-cycle Magnesium Sulfate Soundness (MSS), and Los Angeles Abrasion (LAA) tests.

A study conducted at the National Center for Asphalt Technology (NCAT) indicated that many empirically developed aggregate tests were currently being used for evaluating and characterizing aggregates. Some aggregate tests had either very poor or no correlation with actual field performance of HMA (1). Current testing protocol for prequalification of aggregates in the AQMP includes some empirical tests and does adequately take into account fine aggregate properties critical to stability, durability, and frictional performance. Therefore, there is a need to upgrade the existing AQMP program in order to improve long-term skid performance.

PURPOSE

Many highway pavements are experiencing a rapid deterioration in their skid resistance properties that can be attributed to several factors including increased traffic volumes, adverse weather conditions, inadequate aggregate materials, and poor construction quality and maintenance practices (3). The aggregate selection process should effectively take into account aggregate properties pertinent to skid performance of HMA. Macro-texture and micro-texture aggregate properties together influence HMA stability, durability, and frictional performance (4). It is important to identify and evaluate individual aggregate properties as well as overall matrix characteristics critical to skid performance of HMA. This calls for an aggregate selection process to effectively screen aggregates taking into account the overall frictional demand of the pavement.

Current TxDOT AQMP testing protocol for prequalification of aggregates is limited in terms of evaluating various aggregate properties critical to long-term HMA skid performance. In addition, the applicability of some tests for monitoring aggregate quality is being questioned due to poor correlation of laboratory test results with field performance. Therefore, there is a need to upgrade the current aggregate screening process and the aggregate classification system in view of new techniques that may be used either as replacements and/or supplements to the current index tests. The new criteria should adequately account for both coarse and fine aggregate properties and should be superior to the conventional process in terms of:

- sensitivity of tests to aggregate properties for discriminating different aggregate materials,
- reproducibility of test results,
- ability to relate to actual field performance, and
- time and cost associated with testing.

Index tests with unacceptably low sensitivity to aggregate properties need to be eliminated with a view of developing an evaluation system that would enable testing and monitoring of aggregates from different sources and environmental conditions. Test results from newly developed techniques need to be analyzed through correlation with tests evaluating similar aggregate properties. In addition, current sampling and testing of aggregates with respect to the frequency and duration of tests also need to be evaluated,

taking into account variability in aggregate quality from the same source sampled over different time periods.

The overall process review to enable selection of tests and a quality-monitoring process will include the following key tasks:

- identification of HMA performance parameters that affect skid resistance,
- identification of aggregate properties that influence skid properties,
- review and improvement of the existing AQMP based on identification of index tests as indicators of aggregate performance, and
- review and development of a proposed Surface Aggregate Classification System (SACS) to ensure good frictional performance of HMA over the design life of the pavement.

OBJECTIVES

Several research efforts have been carried out over the years to improve frictional properties between the HMA surface and the tire interface. These studies have focused on laboratory testing of aggregates and HMA as well as field-testing of HMA skid resistance to ensure good skid properties of HMA pavements over the design life (3, 4). The main objective of this research was to develop a Wet Weather Test Criteria that will aid in defining tests for monitoring aggregate properties that affect matrix characteristics, which significantly influence skid performance on wet pavements.

This research primarily focused on the role of fine aggregates on the frictional performance of HMA. The following objectives include:

- Identify frictional performance parameters of HMA mix affected by aggregate properties.
- Develop hypothesis for each test as a wet weather performance indicator.
- Test and evaluate aggregate properties through both conventional and new recommended techniques.
- Determine sensitivity of tests to aggregates varying in source and environmental characteristics while evaluating similar properties.

- Develop correlations between tests with a goal of eliminating cumbersome and time consuming tests.
- Select tests that are sensitive, reproducible, and consistent in monitoring aggregate properties.

CHAPTER II

LITERATURE REVIEW

BACKGROUND

Aggregates constitute about 94 percent by weight of an HMA. Aggregate properties influence HMA performance in terms of stability, durability, and overall frictional resistance (1). Skid performance of a HMA pavement is affected by both coarse and fine aggregate properties. Thus, evaluation of aggregate properties influencing HMA performance is extremely important. Several variables, including aggregate mineralogy, shape, size, texture, gradation, toughness and durability, traffic characteristics, and environmental conditions, affect aggregate performance in HMA (5). Some aggregate tests currently being used for evaluating and characterizing aggregates in HMA may not relate well to their actual field performance (1). Therefore, there is a need to identify and select aggregate tests that would relate laboratory results to expected field performance.

In 1987, the Strategic Highway Research Program (SHRP) was launched to develop new guidelines on asphalt materials. A performance-based specification for asphalt binders, aggregates, and asphalt mixture design was developed to ensure good correlation between laboratory tests and field performance. The Superior Performing Asphalt Pavements Specification or "Superpave" accounts for temperature and environmental factors on binder, aggregate, and asphalt mixture that are critical to HMA performance. The mix design procedure includes guidelines on material selection and volumetric proportioning to ensure long-term performance of HMA (2). Superpave identifies aggregate "consensus" and "source" properties as critical to the overall performance of HMA pavements. Therefore, these properties need to be carefully monitored while evaluating aggregate quality and performance.

Consensus properties represent aggregate characteristics that play a key role in the performance of an HMA pavement. Criteria for the consensus properties are based on the anticipated traffic level and aggregate position within the pavement structure. Aggregates near the pavement surface are subjected to high traffic levels and require stringent consensus properties. Critical values for these properties have been recommended based on performance history and field experience. Though the criterion for consensus properties is proposed for an

aggregate blend, many consensus aggregate requirements are applied to individual aggregates to identify undesirable elements. The consensus properties include (2):

- coarse aggregate angularity,
- fine aggregate angularity,
- flat and elongated particles, and
- clay content in fine aggregate.

Agencies consider aggregate source properties for qualifying local aggregates. Aggregate mineralogy and physical chemistry influence source properties. Critical values for these properties have not been established as these are source specific. Source properties include (3):

- toughness,
- soundness, and
- deleterious material.

Superpave also specifies a 0.45 power gradation chart to enhance the performance of the aggregate blend in HMA in terms of improved resistance to susceptible potential distresses including permanent deformation and fatigue cracking. The 0.45 power chart represents the maximum density gradation that would enable aggregate particles to fit together in the densest possible arrangement (2). The aim of this chart is aimed to improve volumetric properties of a compacted mix including air voids, voids in mineral aggregate (VMA), and voids filled with asphalt (VFA) (2). Volumetric properties are affected by the characteristics and proportion of coarse and fine aggregates in the blend.

FRICTIONAL PROPERTIES

Aggregate properties, including shape, surface texture, and polish resistance determined with precision in the laboratory, can effectively be used to predict frictional performance of bituminous pavements (6). Studies conducted to evaluate and predict field skid resistance of HMA using laboratory test results and skid performance history has indicated that good frictional resistance on HMA pavements could be achieved through proper material selection, design, and construction procedures (3).

Frictional performance of an HMA pavement is affected by aggregate properties with respect to tire-pavement interaction as well as HMA pavement performance. Adhesion and hysteresis are the two main components in stopping a moving vehicle as the tire rubber interacts

with the pavement surface (6). Macro-texture and micro-texture properties of aggregates influence adhesion and hysteresis components in an HMA pavement. Micro-texture properties provide the adhesion component through the effective tire-aggregate contact. The hysteresis component controlled by macro-texture properties is a function of the energy losses within the tire rubber as the deformed tire mass slides over and around the protruded pavement surface (7). Macro-texture properties are controlled by coarse aggregate size, shape, and gradation. Construction techniques along with environmental factors also influence macro-texture properties. Micro-texture properties are source dependent and can be controlled through effective material selection (4). Frictional demands of a roadway can be met through surface treatments such as seal coats or open-graded friction courses, and roadway characteristics including pavement surface drainage, cross slope, and surface treatments (8). To attain a desired level of pavement friction, it is necessary to maintain a balance between the macro-and micro-texture properties and evaluate how these parameters relate to overall pavement friction (6).

To effectively address frictional demands of pavements, TxDOT has developed and implemented the Texas Wet Weather Accident Reduction Program (WWARP) that addresses friction issues on pavements through its three phases: accident analysis, aggregate selection, and skid testing (8). Accident analysis is the first phase and includes identification, evaluation, and improvement needed for all wet weather accident locations. Aggregate selection involves classification of aggregates into one of four categories-A, B, C, or D-based on a combination of frictional needs of the HMA pavement and durability properties of aggregates. Frictional and durability indicator tests, including PV, MSS, Acid Insoluble Residue (AIR), and Micro-Deval (MD), are used for classifying aggregates. Table 1 lists guidelines used for determining friction demand. The aggregate classification is listed and updated in a Rated Source Quality Catalog provided by the Soils and Aggregates Branch of the Materials Section of the Construction Division. Skid testing on HMA sections is performed in the third phase, and the skid data is stored as a part of the Pavement Management Information System (8).

Table 1. Guidelines for Determining Friction Demand on a HMA Pavement (8).

Attribute	Low	Moderate	High
Rainfall (inch/year)	≤ 20	$> 20 \leq 40$	> 40
Traffic (ADT)	≤ 5000	$> 5000 \leq 15,000$	$> 15,000$
Speed (mph)	≤ 35	$> 35 \leq 60$	> 60
Trucks (%)	≤ 8	$> 8 \leq 15$	> 15
Vertical Grade (%)	≤ 2	$> 2 \leq 5$	> 5
Horizontal Curve	≤ 3	$> 3 \leq 7$	> 7
Driveways (per mile)	≤ 5	$> 5 \leq 10$	> 10
Intersecting Roadways (ADT)	≤ 500	$> 500 \leq 750$	> 750
Cross Slope (inches/foot)	3/8-	- 3/8	\leq
Surface Design Life (years)	≤ 3	$> 3 \leq 7$	> 7
Macro-Texture	Coarse	Medium	Fine

Based on overall surface friction demand, aggregate gradation is chosen from the surface aggregate classification system. Engineering judgment has to be applied in order to select an aggregate classification for a particular roadway. Table 2 illustrates the aggregate classification chosen based on overall friction demand.

Table 2. Aggregate Classification System Based on Overall Friction Demand (8).

Attribute	Overall Friction Demand		
	Low	Moderate	High
Surface Aggregate Classification	C	B	A

Frictional Performance Parameters of HMA

As vehicles move over a pavement, wearing of the surface layer due to polish and abrasive action of the wheels occurs, reducing frictional resistance at the asphalt tire-pavement interface. In addition, due to high wheel loads and pressures, two primary stresses developed in the HMA pavement (2):

- vertical compressive stress within the HMA layer, and
- horizontal tensile stress at the bottom of the HMA layer.

An HMA pavement is desired to be both structurally and functionally efficient. A weak HMA pavement subjected to heavy traffic load and repetitions may experience the following three types of distresses that may reduce skid resistance:

- permanent deformation,
- fatigue cracking, and
- loss of frictional resistance.

Permanent Deformation

Permanent deformation is characterized by a surface cross section that is not in its design position. It can be attributed to the accumulation of small unrecoverable deformation caused by increased wheel loads and high-pressure truck tires (2). It is usually found along the wheel path in the top 75 mm to 100 mm of the pavement (1). Premature rutting of a pavement is usually associated with two principal causes: deformation of HMA layer, and a weak subgrade or base due to repeated stress.

Premature deformation or rutting of the HMA layer occurs due to inadequate shear resistance of the HMA. Shear strength of the HMA is primarily dependent upon the internal friction within the HMA. Load repetition over a pavement causes aggregates to slide or shear with respect to each other, resulting in failure along the shear plane. Cubical and rough-textured aggregate in a mix improves shear properties, as they provide a high degree of internal friction through better particle-to-particle contact. In addition, a stiffer asphalt grade improves stiffness of the HMA layer, reducing its susceptibility to rut at higher temperatures (2). It is important to control rutting in HMA pavements as water may accumulate in the depressions along the wheel path during and after rainfall causing hydroplaning problems for fast-moving vehicles, thereby reducing safety.

Stripping

Stripping of the HMA layer due to moisture intrusion and subsequent deterioration can lead to rutting. Stripping is primarily related to binder properties and physio-chemical properties of the mineral aggregates. Dust coatings on aggregate surfaces can change adhesion chemistry resulting in the formation of a weak bond between the aggregate and asphalt binder. Such a mix

is highly susceptible to attrition in presence of moisture in the mix and oxidation of the binder (1).

Fatigue Cracking

Repeated heavy traffic over a pavement with a weak underlying layer results in high deflections that lead to increased horizontal tensile stresses at the bottom of the HMA layer causing fatigue cracking. Initially, longitudinal cracks are observed along the traffic wheel path; however, with increased load and traffic repetitions, these cracks increase and join together resulting in the formation of a network of transverse cracks interconnected to longitudinal cracks, often referred to as alligator cracking (2).

Several factors including binder and aggregate properties play an important role in improving tensile strength at the base of the HMA layer. Stiffer HMA mixtures have greater fatigue life in thick pavements, whereas flexible HMA mixtures have greater fatigue life in thin pavements (1). A dense aggregate blend in thick HMA pavements increases stiffness, whereas an open gradation is desired for thin HMA pavements for lowering mix stiffness. Filler material or P200 material also affects stiffness properties (2). It is important to control fatigue problems in HMA as water may percolate inside the pavement through these cracks and cause erosion of the underlying material. Also, pore pressure in the pavement due to stresses induced by traffic can lead to failure of the binder-aggregate bond leading to potholes that cause safety problems on wet pavements.

Frictional Properties

Frictional properties on the pavement surface are influenced by both individual aggregate properties as well as overall blend characteristics. Therefore, it is important to control aggregate properties including gradation, coarse and fine aggregate shape, angularity, surface texture, and mineralogy for long-term skid performance (4). Table 3 summarizes HMA performance parameters that influence frictional properties.

Table 3. HMA Frictional Performance Parameters.

Parameter	Distress	Description	Failure Mechanism
Permanent Deformation	Rutting	Longitudinal surface depression in wheel path Caused by consolidation and/or lateral movement of material due to load	Inadequate shear strength of mix Problems with initial density of the mix Poor durability of mix resulting in change of mixes properties with time
Fatigue	Fatigue Cracking Raveling and Popouts	Appear as longitudinal hairline cracks along the wheel path Cracks interconnect resulting in Alligator cracking Wearing away of pavement surface	Lack of stiffness of the mix Excessive bending strains in HMA Dislodging of aggregates in a mix Loss of asphalt binder
Frictional Resistance	Polished Aggregate Bleeding	Surface binder worn away resulting in exposed aggregate Loss of surface texture due to excessive asphalt	Abrasion of aggregate due to traffic Excessive bituminous binder Inadequate filler material

AGGREGATE PROPERTIES

Aggregate selection is important to ensure long-term pavement performance as well as resistance to pavement distresses, including permanent deformation, raveling or popouts, fatigue cracking, and bleeding, that influence skid performance of a pavement. Effective aggregate quality control monitored through random sampling and aggregate testing of stockpiles at regular intervals ensures proper aggregate selection. Long-term skid performance of an HMA mix can be improved by controlling size and gradation, shape and surface texture, durability and soundness,

polish, and deleterious materials in fine aggregates (1). Skid performance of an HMA pavement is primarily controlled by aggregate type and quality used in the mix (9). Coarse aggregate characteristics affect macro-texture properties whereas fine aggregates influence micro-texture properties (3).

Aggregate Properties Influencing Skid Performance

Aggregate properties, as well as overall blend characteristics, are key in controlling volumetric properties and providing resistance to induced stresses due to heavy traffic loads and repetitions (2).

Table 4 illustrates aggregate properties that affect skid performance parameters.

Table 4. Aggregate Properties Influencing Skid Performance.

HMA Performance Parameter	Aggregate Property
Permanent Deformation Stripping	Fine aggregate particle shape, angularity, and surface texture Coarse aggregate particle shape, angularity, and surface texture Deleterious fines and organic material Properties of P200 material
Fatigue Cracking	Coarse aggregate particle shape, angularity, and surface texture Fine aggregate particle shape, angularity, and surface texture Properties of P200 material
Frictional Properties	Aggregate Gradation (blend) Properties of P200 material Coarse aggregate particle shape, angularity, and surface texture

Gradation and Size

Aggregate gradation affects shear strength and permeability of an HMA mix and can be characterized into three categories (1):

- dense gradation,
- open gradation, and
- stone matrix asphalt.

A dense aggregate blend is desirable for a durable and stable HMA pavement as it provides resistance to degradation during construction and traffic, improved resistance to distress, and improved resistance to stripping or moisture damage. However, such a gradation lies very close to the maximum density line and is susceptible to variations in asphalt binder content within the mix (1). It is important to control volumetric properties and the asphalt binder content in the mix (2). High asphalt content with low VMA may result in bleeding or rutting of the pavement whereas high VMA along with low binder content in the mix may cause raveling or fatigue cracking.

An open graded or gap graded mix, such as an open-graded friction course (OGFC) and stone matrix asphalt (SMA), is desirable for surface frictional properties of an HMA pavement. Such a gradation provides better stone-to-stone contact of coarse aggregates resulting in improved macro-texture properties, which minimize hydroplaning problems on wet pavements (1). Extensive research conducted over the years evaluates the performance of an HMA mix using different aggregate gradation. Table 5 lists some of the studies performed and the results obtained from the study analysis.

Table 5. Review of Literature Examining the Effect of Aggregate Gradation on HMA Properties.

Research Study	HMA Property	Gradation	Material Used		Evaluation Technique	Study results
			Coarse Aggregate	Fine Aggregate		
Campan and Smith	Stability	Dense	Rounded river gravel, crushed quartzite, crushed gravel, and limestone	Platte river rounded sand	Ohama Testing Laboratory Bearing Index	Stability increased from 30 to 100 percent using crushed aggregates in lieu of natural rounded aggregates
Herrin and Goetz	Stability with respect to compressive strength, angle of friction and cohesion	Dense and Open	Crushed gravel varied from 0, 55, 70 and 100 percent	Round natural sand, and crushed limestone passing No.4 sieve(4.75 mm)	Triaxial Test	Stability increase observed when angular fine aggregate used along with round natural sand
Lefebvre	Stability	Dense	Crushed gravel (cubical aggregate) and crushed trap rock	Fine dense sand	Marshall Stability Test	Fine aggregate properties including angularity and surface texture critical in HMA performance

Particle Shape and Surface Texture

Aggregate particle shape and surface texture is important for maintaining high stability and frictional performance of HMA. Cubical and angular aggregate particles with rough surface texture are desired as they provide increased internal friction between particles improving stability and rut resistance of the mix. Rough aggregate surface texture results in a strong bond between the aggregate surface and asphalt binder, improving durability and shear properties (2). This helps in improved resistance of the mix to permanent deformation, fatigue cracking, and stripping. Extensive studies conducted evaluating the effect of aggregate shape and surface texture along with the aggregate gradation on performance parameters of the mix. Tables 6, 7, and 8 represent a review of studies conducted for evaluating the role of aggregate shape parameters on HMA performance.

From the literature review the following can be inferred on the influence of particle shape, angularity, and surface texture pertaining to the performance of HMA (1):

- Coarse aggregate particle shape and surface texture are critical in open-graded HMA mixtures as compared to dense-graded mixtures.
- Fine aggregate particle shape and surface texture have more influence on the physical properties of dense-graded mixtures as compared to open-graded mixtures.
- Higher stability and resistance to distresses, including permanent deformation and fatigue cracking, can be achieved through an aggregate blend with angular aggregate with rough surface texture.
- Excessive flat and elongated particles in an aggregate matrix is undesirable as it results in the breakdown of the aggregate matrix, especially in open-graded mixtures during production and construction.

Table 6. Review of Literature Examining the Effect of Aggregate Shape Parameters on HMA Properties (Ref. 11-13).

Research Study	HMA Property	Aggregate Property	Evaluation Technique	Study results
Barksdale, Pollard, Siegel, and Moeler	Rutting and Fatigue Cracking	Aggregate shape and surface texture for Georgia aggregate	Pouring test based on packing volume concept Image analysis techniques	Micro-and macro- texture properties from pouring test statistically related to rutting behavior of selected HMA mix
Jimenez	Stability	Aggregate shape and surface texture for natural and crushed sand	Shape Texture Index (STI) for shape properties Marshall and Hveem stability	Direct relationship observed between shape texture index and stability Creep tests indicated higher mix stiffness and less susceptibility to change with time for mixtures with high STI values
First Phase				
Li and Kett	Stability	Aggregate angularity for both coarse and fine aggregate	British Method for particle angularity Marshall and Hveem Stability	High correlation observed between coarse and fine aggregate angularity, and stability
Second Phase				
		Shape characteristics Flat and Elongated particles (F&E)	Dimension Ratio (DR)	Classification based on Dimension Ratio (DR) Rhombic (DR between one and two) Slightly flat (DR between two and three) Flat (DR of five and over) Stability not affected until DR less than 3:1 Maximum permissible F&E DR three to one should not exceed 40 percent

Table 7. Review of Literature Examining the Effect of Aggregate Shape Parameters on HMA Properties (Ref. 14-17).

Research Study	HMA Property	Aggregate Property	Evaluation Technique	Study results
Stephens and Sinha	Stability	Aggregate shape Flat and Elongated (F&E) for trap rock	Dimension Index (DR) Kneading Compaction	Classification based on Dimension Equi-dimensioned (same dimensions) Flat (two large and one small) Rod (two small and one large) Higher voids in mix with 30 percent or more F&E particles Aggregate blend with 50 percent regular, 25 percent flat and 25 percent rod aggregates provide most stable mix for asphalt content higher than 6 percent
Gandhi	Stability	Aggregate shape and surface texture for natural sand, crushed limestone, and synthetic lightweight	Triaxial Test using static and dynamic loading conditions	Direct relationship observed between aggregate shape and texture and stability of HMA specimens
Kandhal, Motter, and Khatri	Stability	Coarse and fine aggregate angularity and surface texture	NAA Flow Test (FAA) (ASTM C-1252) Aggregate Shape and Texture Index (ASTM 3398)	High correlation between FAA and ASTM D3398 Fine aggregate shape and texture more important than coarse aggregate for permanent deformation
Kalcheff and Tunnicliff	Stability	Fine aggregate shape and angularity for a natural sand and three manufactured sand	National Crushed Stone Association Shape Index Marshall Test Repeated Load Triaxial Test Static and Repeated load Indirect tensile splitting strength	Manufactured sand having higher angularity HMA mix with manufactured sand had higher stability and resistance to permanent deformation

**Table 8. Review of Literature Examining the Effect of Aggregate Shape Parameters on HMA Properties
(Ref. 18-20.1).**

Research Study	HMA Property	Aggregate Property	Evaluation Technique	Study Results
Griffith and Kallas	Stability	Fine aggregate shape and angularity for natural sand from Maryland and crushed New York trap rock	Marshall and Hveem stability	Improved strength and stiffness using angular and rough fine aggregate
Meier and Elnicky	Shear Resistance	Fine aggregate shape and surface texture	National Aggregate Association Aggregate Particle Shape and Texture (ASTM 3398) Void Ratio by Western Technologies Direct Shear Test Florida Bearing Ratio Surface Rugosity by Packing Volume Hveem Stability	Hveem stability of HMA mix linearly related to fine aggregate angularity shape and texture
Chowdhury	Rutting	Aggregate shape and surface texture for limestone, gravel and igneous aggregate	Compacted Aggregate Resistance NAA Flow Test (FAA), Direct Shear Test (DST) Aggregate Shape and Texture Index Hough Transform Image Analysis	Good correlation between CAR and DST Good correlation between NAA and Hough Transform image analysis No linear correlation between FAA and SHRP-LTPP rutting database
Butcher	Permanent Deformation	Coarse and fine aggregate, angularity, and surface texture	Unroded Particle Index I_{ua}	Increase in resistance to permanent deformation with increase in I_{ua}

Cleanliness and Deleterious Materials

Aggregates in an HMA should be clean and free from deleterious material that may cause premature failure of a pavement. Cleanliness refers to dust coatings or excessive filler material often found on aggregate surface. Deleterious material is related to weak, reactive, or unsound material that may be present in fine aggregate (1). Excessive dust or clay coatings on coarse and/or fine aggregate results in poor adhesion between the aggregate surface and asphalt binder in HMA. A weak contact is established between the binder and the aggregate surface as the binder coats the dust particles present on the aggregate surface. Water percolating in such a mix results in stripping problems. Excessive fines may also cause the asphalt binder to stiffen and make the HMA susceptible to fatigue cracking (1). Moisture susceptibility of a neat asphalt-aggregate system is both asphalt-and aggregate-source dependent. Siliceous aggregates are highly susceptible to moisture irrespective of the binder used. In contrast, aggregates with calcium, magnesium, and iron contents provide higher resistance to stripping (21).

Other deleterious material, including clay lumps, friable particles, shale, and metal oxides, are also detrimental to HMA. Clay lumps in finished HMA can break-down from repeated freezing and thawing or wetting and drying and cause stripping, raveling, and loss of durability. Concentration of clay particles may not be representative of the mineral fraction, especially if aggregate filler is obtained from a source other than the fine aggregate such as manufactured sand (22). Sand equivalent (SE) test, developed by Hveem and recommended by Superpave, is used by most agencies for determining the amount of clay in fine aggregates (2). Recent studies recommend the use of the Methylene Blue (MB) test to determine deleterious fines and organic material in fine aggregate (1). The MB test indicates and quantifies harmful clay from the smectite group together with organic matters and iron hydroxide based on their absorption capacity. It assesses the absorbent filler material and its concentration in the fine aggregate fraction (22). The Methylene Blue Value (MBV) determined from this test is directly proportional to the product of the clay content and the specific surface of the clay material (1). This test controls the acidity of the mineral filler assuming that particles with positively charged surfaces are deleterious with respect to adhesion in the presence of water (23). In France, both the SE and MB tests are being used for quantifying deleterious material in fine aggregate. The MB test has been found to have good repeatability and reproducibility based on French specifications (24).

NCHRP 4-19 study assesses the performance of current laboratory aggregate testing protocol with respect to both aggregate quality and their performance in HMA (1). Correlations between aggregate test results and mixture performance analyze aggregate properties that influence mixture properties and performance. The study identified the following aggregate properties as related to pavement performance. These properties included:

- coarse aggregate particle shape, angularity, and surface texture;
- fine aggregate particle shape, angularity, and surface texture;
- plastic fines in fine aggregate;
- toughness and abrasion resistance;
- durability and soundness; and
- characteristics of particles finer than No. 200 (0.075mm) sieve.

Table 9 and Table 10 represent aggregate and mix properties evaluated and results obtained from this study.

Researchers recommended the use of Micro-Deval (MD) and Methylene Blue (MB) tests for evaluating abrasion resistance of coarse aggregates and for determining the amount and nature of the deleterious fines in fine aggregates (1). The MD test is more repeatable and reproducible than the MSS test and is faster in terms of testing time (25).

Table 9. Review of Literature Examining Aggregate Properties Affecting HMA Performance (1).

Material Used		Aggregate Property	Evaluation Technique		Study Results
Coarse Aggregate	Fine Aggregate		Coarse Aggregate	Fine Aggregate	Coarse Aggregate
Round Natural Gravel Crushed Gravel Sandstone Limestone Dolomite Granite Siltstone Blast Furnace Slag	Round Natural Sand Surounded Natural Sand Sandstone Limestone Dolomite Granite Quartzite Blast Furnace Slag Manufactured Sand	Aggregate Angularity Surface Texture	Index of Aggregate Shape and Texture Image Analysis Flat or/and Elongated Particles (2:1,3:1, 5:1) Flakiness Index Elongation Index Percent Fractured Particles Uncompacted Voids (Funnel Tech) Uncompacted Voids (Shovel Tech)	Index of Aggregate Particle Shape and Texture Image Analysis Uncompacted Void Content	Good Correlation F or E (2:1) and F&E (3:1) High Correlation F or E (2:1) and Flakiness Index Good Correlation F and E (3:1) and Flakiness Index High Correlation F or E (5:1) and Elongation Index Fine Aggregate High Correlation UV and Index Good Correlation UV and Image Good Correlation Index and Image
Granite Sandstone Limestone Steel Slag Limerock		Resistance to Abrasion Resistance to freeze-thaw and durability	Micro-Deval Los Angeles Abrasion Aggregate Crushing and Impact Value Superpave Compactor Sodium Sulfate Soundness (SSS) Magnesium Sulfate Soundness (MSS) Canadian Freeze-Thaw (Procedure A, B, and C)		High Correlation LAA and AIV High Correlation LAA and ACV Good Correlation ACV and SGC High Correlation MSS and SSS Good Correlation SSS and CF-T(A) Good Correlation MSS and CF-T(A)
	Round Natural Sand Limestone Dolomite Granite Blast Furnace Slag Limerock	Deleterious Fines Size Distribution Shape and Angularity of Filler Material		Filler (P200) Rigden Voids German Filler Methylene Blue Particle Size Analysis (D10, D30 D60)	High Correlation between D10 and FM High Correlation between D10 and FM Good Correlation between MB and German Filler

Table 10. Review of Literature Examining Aggregate Characteristics Affecting HMA Performance (1).

Aggregate Property	Evaluation Technique		HMA Property	Evaluation technique	Results
	Coarse Aggregate	Fine Aggregate			Coarse Aggregate
Aggregate Angularity Surface Texture	Index of Aggregate Shape and Texture Image Analysis Flat and/or Elongated Particles (2:1,3:1, 5:1) Flakiness Index Elongation Index Percent Fractured Uncompacted Voids (Funnel Tech) Uncompacted Voids (Shovel Tech)	Index of Aggregate Particle Shape and Texture Image Analysis Uncompacted Void Content	Permanent Deformation Fatigue Cracking	Georgia Load Wheel Test Superpave Mix Design (Level I and Level II) Simple Shear and Frequency Sweep at Constant Height Superpave Mix Design (Level I and Level II) Frequency Sweep and Simple Shear at Constant Height Indirect Tensile Strength	High Correlation between UV, For E 2:1 and EI vs. PD
					Fine Aggregate
					High Correlation between UV, Index and Image Analysis vs. PD
					Coarse Aggregate
					High Correlation between UV and F&E (5:1) vs. Fatigue Cracking
					Fine Aggregate
					No strong correlation between fine aggregate angularity vs. FC
Resistance to Abrasion Resistance to freeze- thaw and durability	Micro-Deval Los Angeles Abrasion Aggregate Crushing and Impact Value Superpave Compactor Sodium Sulfate Soundness Magnesium Sulfate Soundness Canadian Freeze-Thaw (Procedure A, B, and C)		Popouts, raveling and potholing		Micro-Deval and Magnesium Sulfate Soundness recommended for evaluating durability of HMA
Deleterious Fines Size Distribution Shape and Angularity of Filler Material		Filler (P200) Rigden Voids German Filler Methylene Blue Particle Size	Moisture Susceptibility	Hamburg Wheel Tracking Device Resistance of Compacted Bituminous Mixture to Moisture Induced Damage	High Correlation D60, D30, D10, and Fineness Modulus vs. Permanent Deformation Good correlation between MB, D10 vs.Fatigue Cracking

AUTOMATED TECHNIQUES FOR AGGREGATE EVALUATION

Automated techniques are versatile tools for characterizing shape parameters of aggregates. Several new automated techniques have been developed and are being used for determining aggregate shape, angularity, and surface texture that influence the rutting potential of HMA (26). Image analysis techniques are now being applied for determining aggregate shape parameters. Digital processing techniques are used for digitizing aggregate images, and mathematical techniques are applied to these digital forms for quantifying aggregate shape parameters (27).

Current testing techniques to evaluate coarse and fine aggregate properties are distinct and do not relate well with each other. Thus, it may not be feasible to quantify the overall effect of aggregate angularity on pavement performance through these tests. Limitations of current testing protocols can cause inconsistency in predicting the extent to which these measured properties effect the overall pavement performance (27). Recent studies have also indicated that current Superpave criterion for fine aggregate angularity may not be able to discern aggregates with poor and high performance levels (26). This can be attributed to the packing properties of aggregate, which are a function of aggregate angularity, gradation, and surface texture (27).

Aggregate shape can be expressed in terms of three independent terms: form, angularity, and surface texture. The form parameter reflects variations in proportions of a particle. Aggregate angularity represents variations at corners, and surface texture describes the surface irregularity. Image analysis techniques are capable of directly measuring aggregate shape attributes and distinguish between form, angularity, and texture for both coarse and fine aggregates. A large number of aggregates can be evaluated quickly and accurately in either two or three dimensions. This technique can evaluate compacted asphalt mixtures with respect to both aggregate and mix properties (27).

Several image analysis techniques, including the Hough Transform Method, the Washington State Method, and the VDG-40 Videograder, are being used to evaluate aggregate form and angularity. In addition, automated techniques are now available for determining grain size distribution of the aggregates. Some of these include: the Particle Size Analyzer, the Video Imaging System, the Particle Size Distribution Analyzer, and the Micrometrics Optisizer PSDA 5400 (28).

In a study, the Texas Transportation Institute (TTI) evaluated and compared fine aggregate angularity (FAA) test procedures with potential image analysis techniques for quantifying fine aggregate angularity and distinguishing good and poor performing aggregates used in HMA. Twenty-three aggregates from different parts of the U.S. were tested for FAA using ASTM C-1252, Method A. These aggregates were also evaluated using three image analysis techniques: the Hough Transform Method, the Washington State Method, and the VDG-40 Videograder. Table 11 describes image analysis techniques and parameters used for evaluating aggregate properties (26). Correlations between FAA and the image analysis tests were developed and analyzed. Table 12 illustrates results from the correlation analysis.

Table. 11. Image Analysis Techniques and Parameters Used for Evaluating Aggregate Properties (26).

Technique	Category	Aggregate Size Distribution	Parameter	Results	Remarks
Hough Transform	Large	(-) 4.75 mm - (+) 1.18 mm	K-Index	(0.43-0.65)	Higher K values indicate angularity and rougher surface texture
		(-) 1.18 mm - (+) 0.30 mm	K-Index	(0.43-0.65)	Higher K values indicate angularity and rougher surface texture
Washington State University	Small	(-) 1.18 mm - (+) 0.60 mm	SP	(0.97 - 4.48)	Higher SP indicates higher angularity
			Fractal Length (FL)	(0.02 - 0.22)	Higher FL represents higher angularity
			Form Factor (FF)	0.15 - 0.82	FF < 1 indicates angularity Lower FF indicate higher surface irregularity
VDG-40 Videograder	Large	(-) 19.00 mm - (+) 1.18 mm	Flatness Ratio (FR)	0.6 - 1.285	Higher FR indicate higher surface irregularity
			Slenderness Ratio (SR)	1.390 - 1.645	Higher SR indicates higher particle angularity

Table 12. Results of Correlation Analysis Between Superpave FAA Test and Image Analysis Techniques (26).

Superpave Test	Image Analysis Technique	Parameter	R ²	Remarks
FAA Analysis	Hough Transform	K-Index	0.76	Good Correlation
FAA Analysis	Washington State Method	SP	0.72	Good Correlation
		Fractal Length	0.57	Fair Correlation
		Form Factor	0.5	Fair Correlation
FAA Analysis	VDG-40 Videograder	Flatness Ratio	-	No Correlation
		Slenderness Ratio	0.46	Fair Correlation

Fractal length was observed to increase with increasing FAA values. In contrast, the form factor decreased with increasing FAA values. Correlations were developed between image analysis parameters from the three techniques. Table 13 shows the results from the correlation analysis (26).

Table 13. Results of Correlation Analysis from Hough Transform, Washington State Method, and VDG-40 Videograder (26).

Image Analysis Technique	Parameter	Image Analysis Technique	Parameter	R ²	Remarks
Hough Transform	K-Index	Washington State Method	SP	0.71	Good Correlation
			Fractal Length	0.62	Good Correlation
			Form Factor	0.48	Fair Correlation
Hough Transform	K-Index	VDG-40 Videograder	Slenderness Ratio	0.49	Fair Correlation
			Flatness Ratio	-	No Correlation

The following conclusions were made based on the analysis of the test results (26):

- Good correlation between FAA and the K-index from the Hough Transform Method.
- Image analysis techniques were successful in distinguishing poor and good performing aggregates.
- Image analysis techniques are promising for directly quantifying fine aggregate form, angularity, and surface texture.

In another study conducted at the Center for Transportation Research (CTR), researchers evaluated fine aggregate gradation using five automated aggregate analyzers and compared results obtained from automated techniques with those from standard testing (28). Five automated testing methods available commercially were used for the analysis. Table 14 lists the testing techniques and the particle range sizes evaluated during the study. Fifteen test samples were evaluated using each technique, and results were compared for grain size distribution. All test samples were processed twice through each of the five test machines. The results were plotted as a cumulative distribution of the percent retained versus the logarithm of equivalent size. Variations in results were observed for the same test sample using different techniques. This was attributed to different image capturing techniques and processing algorithms for each technique. Matrix-scan based devices were able to analyze only about 10 percent to 20 percent of the particles in the test sample. The remaining falling particles were missed during the intervals between the acquisitions of successive images. In contrast, line scan cameras were able to analyze almost all falling particles due to shorter delay between data acquisitions of successive images. Thus, it was concluded that line scan devices provide more consistent results with standard sieving results as compared to the matrix-scan devices (28).

From the literature review, it is observed that automated techniques can be used in the upgraded AQMP as replacements and/or supplements to current tests for evaluating aggregate properties and monitoring quality control.

Table 14. Review of Literature Examining Fine Aggregate Properties Using Automated Techniques (28).

Device Name	Technology	Particle Size Range Tested	Approximately Time to Test (1 Kg Sample)
VDG- 40 Videograder	2D digital imaging: line scan CCD camera continuously scans entire sample	No. 16 mesh to 1.5 inches (1.18 to 38.1 mm)	1 to 6 minutes
Computer Particle Analyzer (CPA)	2D digital imaging: line scan CCD camera continuously scans entire sample	NO. 200 mesh to 1.5 inches (0.75 to 38.1 mm)	1 to 3.5 minutes
Optisizer PSDA 5400	2D digital imaging: line scan CCD camera captures a fraction of total sample	No. 200 mesh to 1.5 inches (0.75 to 38.1 mm)	40 seconds to 5.5 minutes
Video Imaging System (VIS)	2D digital imaging: matrix CCD camera captures a fraction of total sample	No. 16 mesh to 1.5 inches (1.18 to 38.1 mm)	15 to 30 seconds
Particle Size Distribution Analyzer (PSDA)	2D digital imaging: progressive CCD camera captures a fraction of total sample	No. 200 mesh to 1.5 inches (0.75 to 38.1 mm)	5 seconds to 2.5 minutes

CHAPTER III

EXPERIMENTAL PROGRAM

This project examines the role of aggregate particle shape, angularity, surface texture, and size distribution of fine material pertaining to skid performance parameters of an HMA pavement. The ultimate goal of this research project is to select and recommend tests that would enable modifications to current testing protocol to improve skid properties on HMA pavements.

PLAN OF STUDY

To achieve this goal the following key tasks need to be accomplished:

- identification of aggregate properties related to skid performance and determine tests for monitoring these properties, and
- extensive testing and evaluation of aggregates for accessing properties that affect performance.

In order to achieve the above-mentioned tasks, a comprehensive laboratory testing and evaluation program was developed and implemented.

Aggregate Properties and Tests Related to Skid Performance

Table 15 summarizes the laboratory tests evaluating aggregate shape and distribution properties that influence skid performance of HMA.

TABLE. 15. Laboratory Tests for Evaluation of Aggregate Properties.

Laboratory Test	Aggregate Property	Related HMA Property	Remarks
Uncompacted Void Content of Fine Aggregate	fine aggregate angularity	permanent Deformation fatigue cracking, and skid properties	aggregate angularity influences shear properties and aggregate orientation that effects rut potential and macro- texture properties
Compacted Aggregate Resistance Test	fine aggregate angularity and surface texture	permanent deformation skid properties surface micro-texture	aggregate shape and texture control orientation affecting shear resistance and rut potential
Methylene Blue Test on P200 Material	deleterious material including clay, organic matter, and iron oxide	stripping permanent deformation durability	deleterious material influence moisture susceptibility fatigue, and rut properties
Particle Size Analysis of P200	diameter and proportion of filler material in fine aggregate	Striping Bleeding Permanent Deformation Fatigue cracking	properties of filler material influence moisture, stiffness and adhesion properties of a HMA mix
Flat and Elongated Particles	coarse aggregate shape and angularity	permanent deformation durability skid properties	flat and elongated particles reduce shear potential of the mix causing rutting and durability

Laboratory Testing

The laboratory testing program focused on aggregate tests to evaluate aggregate properties affecting stability, durability, and general wet weather performance. The testing methodology adopted for this project included some current tests being used by state DOTs for monitoring aggregate quality and performance as well as automated tests that have exhibited good correlation between aggregate properties and their field performance. Forty aggregates from various sources, including limestone, gravel, and igneous aggregates, were selected from TxDOT's Quality Material Catalogue. Aggregate shape parameters, size distribution within fine aggregate, and deleterious fines were first evaluated using standard American Society of Testing

and Materials (ASTM) testing protocols. Later, an automated testing technique was incorporated to determine coarse aggregate shape parameters.

The work plan was divided into the following steps:

- Material selection and acquisition - This phase included the identification and classification of aggregate based on their type and source.
- Aggregate characterization - This phase included testing aggregates using conventional as well as automated testing in order to evaluate their shape parameters, size distribution, and deleterious material.
- Aggregate evaluation – This phase was based on the finds of the two previous phases.

The above methodology was used to assess tests in terms of their ability to discern aggregates with poor and good performance levels with respect to their shape, size, and distribution characteristics. Correlations among tests were analyzed for evaluating consistency with which various tests could monitor similar aggregate properties. Based on the analysis, aggregate tests were selected that could effectively monitor variations in properties and produce consistent results. Correlations between results from current and automated testing techniques were analyzed with a goal of suggesting replacements for conventional tests with automated techniques for monitoring aggregate properties.

Material Selection and Acquisition

A suite of 40 bituminous aggregate sources representing approximately 70 percent of all HMA aggregate sources used in Texas were selected including a range of limestone, gravel, and igneous rock sources covering various mineralogical sources and environmental regions. This was done in order to analyze variability among aggregate properties to source and environmental factors and to evaluate sensitivity of tests to these aggregate properties. Aggregates were listed based on their type and source properties. Appendix A presents various aggregates in terms of their source and general description.

Aggregate Testing

Aggregate consensus properties pertaining to aggregate shape, angularity, surface texture, and size distribution were evaluated during the course of this project.

Uncompacted Void Content of Fine Aggregate (UVC) (ASTM C-1252) (29)

ASTM C-1252 also referred to as the National Aggregate Association Flow Test, is an indirect method for measuring fine aggregate angularity (FAA). The test determines percent air voids present in loosely compacted fine aggregate (passing 2.36 mm sieve) when a sample of fine aggregate is allowed to flow into a small-calibrated cylinder through a standard funnel. The diameter of the funnel orifice is approximately 12.5 mm (0.5 inch), and its tip is located 114 mm (4.5 inch) above the top of the cylinder. This test relates uncompacted void content to the number of fractured faces in an aggregate (20).

Air voids present in loosely compacted or uncompacted aggregates are calculated as the difference between the volume of the calibrated cylinder and the absolute volume of the fine aggregate collected in the cylinder. The volume of the cylinder is calibrated and is approximately 100 ml. Absolute volume of the collected fine aggregate is calculated using the dry bulk specific gravity of the fine aggregate. The dry bulk specific gravity of samples is calculated using ASTM C-128. The uncompacted void content of fine aggregate is calculated from the following formula:

$$U = \frac{V - (F / G_b)}{V} \times 100$$

where:

U = uncompacted void content in fine aggregate, percent;

V = volume of a calibrated cylinder, ml;

F = mass of fine aggregate in the cylinder; and

G_b = dry bulk specific gravity of fine aggregate.

ASTM C-1252 describes three test procedures for determining FAA based on specific fine aggregate gradations:

- Method A using a defined specific gradation,
- Method B using three separate aggregate fractions, and
- Method C testing on an “as-received” aggregate gradation passing through the 4.75 mm (No. 4) sieve.

Table 16 illustrates the gradation used in Method A.

Table 16. FAA Test Method: A Fine Aggregate Gradation (29).

Individual Size Fraction	Mass, g
2.36 mm (No. 8) to 1.18 mm (No. 16)	44
1.18 mm (No. 16) to 0.60 mm (No. 30)	57
0.60 mm (No. 30) to 0.30 mm (No. 50)	72
0.30 mm (No. 30) to 0.150 mm (No. 100)	17
Total	190 g

Superpave Fine Aggregate Angularity Criteria

Superpave specifies minimum values for FAA based on traffic level and position within the pavement for gradation used in Test Method A. Table 17 illustrates Superpave criteria for FAA.

Table 17. Superpave Fine Aggregate Angularity Criteria (2).

Traffic	Depth from Surface	
Million ESALs	< 100 mm	> 100 mm
<0.3	-	-
< 1	40	-
< 3	40	40
< 10	45	40
< 30	45	40
< 100	45	40
> 100	45	45
Note: The criteria are presented as a minimum percentage air voids in the loosely compacted fine aggregate.		

Superpave criterion is based on the assumption that a higher void content indicates more fractured faces in an aggregate. However, this is not always true. Some aggregates with 100

percent fractured faces have not been able to meet UVC criteria for high traffic conditions (20). UVC of fine aggregates often ranges between 43 and 46 (26). Cubical particles often exhibit similar characteristics as rounded aggregates by forming a dense configuration in a loose uncompacted sample, resulting in lower UVC values. Also, some round aggregates with flaky or flat and elongated particles may also exhibit high UVC values as the edges of these particles prevent the aggregates from reaching a dense gradation (20). Some aggregates with good performance history have not been able to meet Superpave UVC criteria for high traffic conditions. Thus, the overall validity of the test in terms of the Superpave criteria is being questioned (26).

Compacted Aggregate Resistance (CAR) Test (20)

This test is an indirect method for evaluating fine aggregate angularity and texture. It measures shear resistance of compacted fine aggregates passing the 2.36 mm sieve in an “as received” condition (20). The test evaluates the stability of combined fine aggregate materials used in a paving mixture. A high stability fine aggregate blend is observed to have a uniform distribution of fines within the sample.

Aggregate samples oven dried to a constant weight passing the No. 8 sieve are used for the test. A 1200 g sample of aggregate is mixed with 1.75 percent water by weight and then placed in a 102 mm (4 inch) diameter Marshall HMA mold. It is then compacted using 50 blows from a Marshall Hammer to prepare a sample approximately 63.5 mm (2.5 inch) high. The sample is subjected to an unconfined compressive load at a rate of 50.8 mm/min (2 inch/minute) transmitted through a 37.5 mm (1.5 inch) diameter flat faced steel cylinder on the plane surface of the compacted sample through the Marshall HMA test machine. A plotter plots a graph of sample stability versus flow that is used for interpretation of the stability of the fine aggregate sample. This test is a performance-based test for measuring fine aggregate angularity and is similar to the California Bearing Ratio test (AASHTO T-193) (20).

Methylene Blue (MB) Test on P200 Material (1)

This French test method recommended by the International Slurry Seal Association (ISSA) is used to quantify the amount of harmful clays of the smectite (montmorillonite) group, organic matter, and iron oxides present in filler aggregate material (passing 75 μm). In this

titration test, aqueous solution (methylene blue) is added to the aggregate suspension until the absorption of the dye ceases. A Methylene Blue Value (MBV) is calculated based on the amount of MB dye required to completely cover the surface of the clay fraction of the sample with a monomolecular layer of MB dye. MBV is a direct measure of the amount of potentially harmful fine material (including clay and organic material) present in an aggregate (1).

Aggregate passing the 75 μm sieve is used for the test. A 10 grams sample is dispersed in 30 grams of distilled water in a beaker, and the suspension is stirred continuously using a mechanical mixer. Methylene Blue solution at 0.5N concentration is used for titration such that 1 ml of solution contains 5 milligrams of MB. This solution is added step-wise in 0.5 aliquotes from the burette into the continually stirred fine aggregate suspension. After each addition of the solution and stirring for 1 min, a small drop of aggregate suspension is removed from the glass rod and placed on a filter paper. The end point is reached when a light blue coloration or "halo" is observed in this ring of clear water. Successive additions of MB are made until the end point is reached. The MBV of the fine aggregate is reported as milligrams of MB per gram of specific fine aggregate fraction. The MBV is proportional to the product of clay content times the specific surface area of clay (1).

A general performance scale of the MBV to its anticipated pavement performance is shown in Table 18 (1).

Table 18. Performance Scales for Methylene Blue Values (1).

Methylene Blue Value (mg/g)	Expected Performance
5-6	Excellent
10-12	Marginally Acceptable
16-18	Problems or Failure
20+	Failure

Particle Size Analysis of Soils (Hydrometer Analysis for P200 Material)
(ASTM D 422-63) (30)

ASTM D-422-63 test method is used for quantitatively determining fine aggregate distribution. This test effectively determines the diameter and proportion of filler material that may act as an extender or a stiffener in a mix depending upon its size and proportion of fine aggregate. In the latter case, excessive fines may result in stiffening of mix causing fatigue problems. An HMA with excessive binder may result due to limited filler material, with smaller diameter particles leading to bleeding and stripping problems (1).

Distribution of particle sizes larger than the 75 μm is determined by sieving. Aggregate diameter and corresponding proportion of filler material is determined through a sedimentation process using a hydrometer. Fine aggregate passing the No. 10 sieve is used for hydrometer analysis (30).

A 100 gram sample of fine material passing the No. 10 sieve (2.00 mm sieve) is taken and mixed with 125 ml of sodium hexametaphosphate solution having 4 percent concentration (40g/L). The sample is soaked in the solution for 16 hours. The suspension is then agitated using standard stirring apparatus. The soil water slurry is transferred immediately after dispersion into a glass sedimentation cylinder, and distilled water is added until the total volume reaches 1000 ml. A rubber stopper is placed at the open end of the cylinder and the slurry agitated by turning the cylinder upside down by hand for a period of 1 minute. At the end of the 1 minute period hydrometer readings are taken using standard hydrometer 152 H at intervals 2, 5, 15, 30, 60, 250, and 1440 min from the beginning of the sedimentation period. The hydrometer readings are corrected for meniscus and zero reading, and after each reading, the temperature of the suspension is measured using a thermometer. After the final hydrometer reading, the suspension is transferred onto a No. 200 sieve and washed with tap water until the water is clear. The material retained on the No. 200 sieve is oven dried at 230 ± 9 °F (110 ± 5 °C). A sieve analysis is performed on this portion retained using the No. 10, No. 50, and No. 200 sieves. Using hydrometer and temperature readings along with the bulk specific gravity of the aggregate sample, the diameter and corresponding proportion of finer material is calculated (30).

Flat and Elongated Particles in Coarse Aggregates (ASTM D 4791-99) (31)

ASTM D 4791-99 test method determines percent flat and elongated particles within aggregate samples retained on the No. 4 sieve (4.75 mm) or higher sieves. The test quantifies aggregate particles with a ratio of length to thickness greater than a specified value (31). A proportional caliper device with different sets of openings (2:1, 3:1, and 5:1) is used for measuring aggregate size ratios. Percent flat and elongated particles can be determined either using an aggregate mass or a particle count method.

Superpave specifies this aggregate property as a consensus property and has specified guidelines for the maximum percent of flat and elongated particles (5:1 ratio) acceptable based on traffic conditions. Table 19 illustrates Superpave criteria for maximum flat and elongated particles.

Table 19. Superpave Flat and Elongated Criteria (2).

Traffic	Maximum Percent
Million ESALs	< 100 mm
<0.3	-
< 1	-
< 3	10
< 10	10
< 30	10
< 100	10
> 100	10

Flat and elongated particles tend to break up during construction and under traffic and weaken the aggregate blend, making it susceptible to shear failure, resulting in permanent deformation of the mix. Restricting the percentage of flat and elongated particles in HMA ensures a high degree of internal friction in the aggregate blend, resulting in high shear strength and resistance to rutting (1).

A particle count method measures the amount of flat and elongated particles for a 5:1 ratio to check coarse aggregate shape parameters based on Superpave specifications. The larger

oriented to measure its thickness could pass completely through the smaller opening of the caliper, it was said to be flat and elongated. The number of flat and elongated particles was counted for each aggregate, and percent flat and elongated particles was calculated (31).

AUTOMATED TESTING

Automated testing and analysis techniques are versatile tools for characterizing shape parameters of aggregates. Several new automated techniques have been developed and are being used for determining aggregate shape, angularity, surface texture, and size distribution of fines that influence HMA performance parameters (27).

Superpave tests for measuring the coarse aggregate shape properties are laborious and also have limitations in their ability to test a representative sample of aggregate (27). Moreover, Superpave criteria for flat and elongated coarse aggregate is based only on a 5:1 size ratio and does not represent the various ratios found within aggregate samples (32). Thus, it may not be possible to quantify the overall effect of aggregate shape and angularity on pavement performance through this test.

Multiple Ratio Analysis (MRA) Digital Caliper

This device developed by Martin Marietta Aggregates can effectively measure multiple size ratios found within an aggregate sample. Determining various aggregate ratios within an aggregate sample is critical, as it would enable proper blending of angular and cubical particles to ensure that the resulting combined gradation passes close to the maximum density line.

The MRA Digital Caliper can evaluate multiple aggregate size ratios at the same time and restricts flat and elongated aggregate particle in an aggregate blend (32). The experimental setup consists of a digital caliper interfaced with an Excel spreadsheet. The largest and smallest dimension of an aggregate particle is measured by orienting it in the caliper. This data is entered into the spreadsheet by pressing a foot switch.

The spreadsheet then calculates the ratio and informs the operator which one of the five ratios ($< 2:1$, $2:1$ to $3:1$, $3:1$ to $4:1$, $4:1$ to $5:1$, and $> 5:1$) the particle falls within. Dimension ratios are color coded on the Excel spreadsheet to prevent any errors during evaluation. Once the aggregate sample has been separated into the five ratios, the number of aggregates in each

fraction can be determined and weighed. A weighted average for the total sample is then calculated to determine the proportion of different aggregate sizes in the sample (32).

AGGREGATE EVALUATION

Results from the laboratory-testing program were analyzed to accomplish the following objectives:

- Determine aggregate tests that are sensitive to aggregate properties and would ensure aggregate quality control and performance with respect to:
 - ability to evaluate variability in results with precision,
 - testing and report time,
 - cost, and
 - reproducibility of results.
- Recommend tests that would ensure proper aggregate selection and help maintain quality control and extended skid performance.

ANALYSIS METHODOLOGY

To accomplish the above-mentioned tasks the following methodology was followed:

- Evaluate variability between aggregates from various sources assuming aggregates from different sources yield different results.
- Analyze sensitivity of tests to aggregate properties between, as well as within, aggregates groups. Sensitivity analysis should help determine precision of tests to discriminate aggregates with varying performance levels while measuring similar properties.
- Develop correlation between index tests evaluating similar properties with a goal of eliminating cumbersome and time-consuming tests.
- Develop correlation between automated tests and conventional testing methods to identify tests exhibiting similar results while evaluating similar properties.
- Select tests that can be used as wet weather performance indicators based on sensitivity to aggregate properties and consistency in test results.
- Recommend tests to the AQMP for evaluating aggregate properties, monitoring aggregate quality, and improving HMA performance.

Figure 1 illustrates the flow diagram for the analysis methodology used.

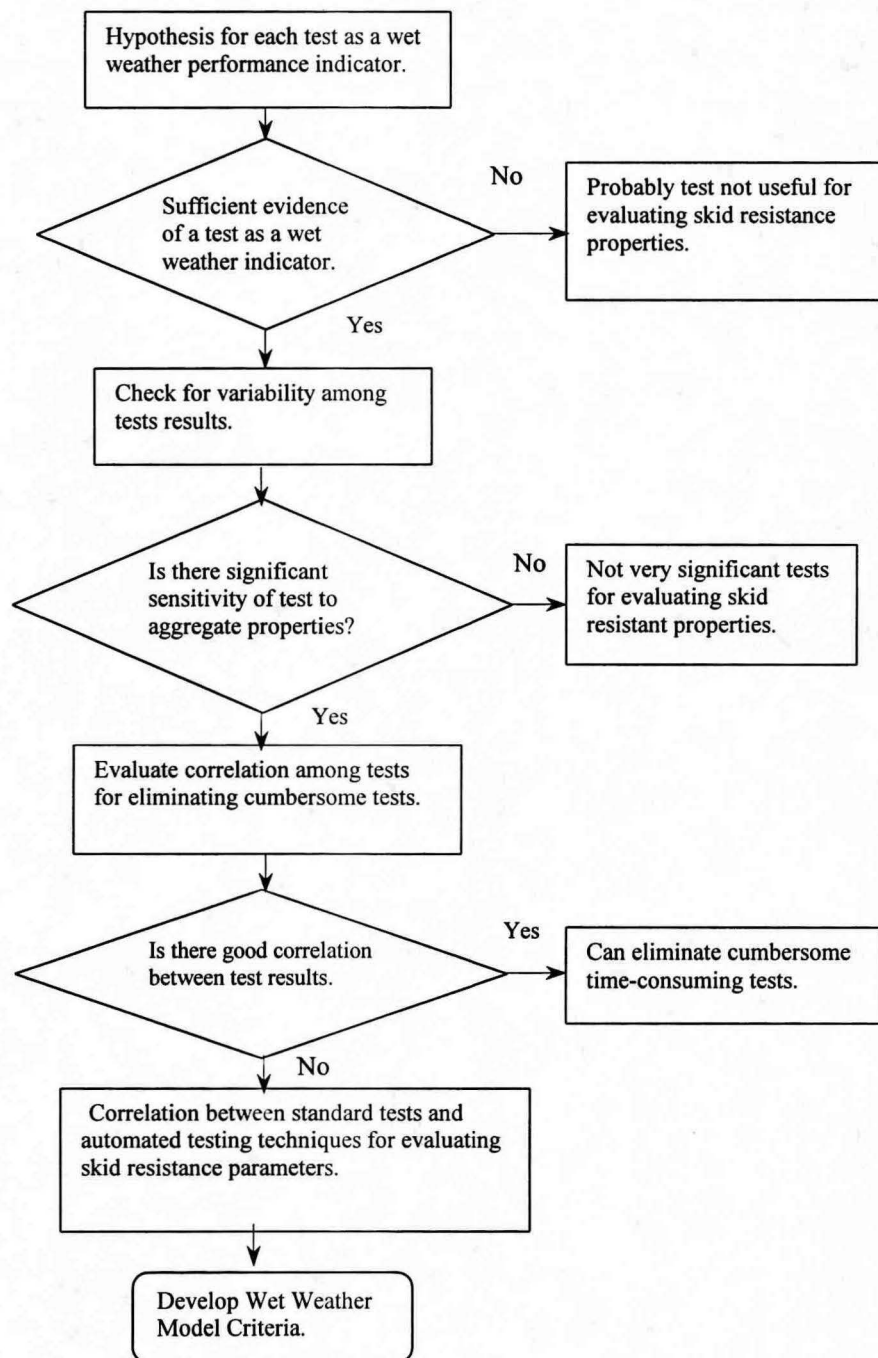


Figure 1. Flow Diagram Representing Analysis Methodology.

CHAPTER IV

RESULTS AND DISCUSSION

LABORATORY TEST RESULTS

Six aggregate determined the variability in aggregate properties and sensitivity of aggregate tests to evaluate shape, angularity, and distribution properties for a suite of 40 aggregates covering a wide range of sources and aggregate types. Correlations between aggregate tests were analyzed to determine whether tests evaluating similar properties gave consistent results and whether tests which were cumbersome, laborious, and time-consuming could be eliminated.

Uncompacted Void Content of Fine Aggregate (UVC) (ASTM C 1252)

The UVC test was used for quantifying voids present in uncompacted fine aggregate samples passing the 2.36 mm sieve. The aggregate results were checked for Superpave FAA specifications based on a high traffic volume condition. UVC values ranged from 39.5 to 50.5 for various aggregates. Two replicates were tested for each aggregate sample, and the average UVC value was reported. ASTM C-1252 specification limits maximum variability in test results of two replicates for an aggregate sample to 0.37 percent. Most sample results were observed to be within limits; however, a few samples did show higher variation in results. Dry bulk specific gravity for samples were calculated using ASTM C-128.

Tables 20, 21, and 22 show UVC results for limestone, gravel, and igneous aggregates, respectively.

Table 20. UVC Test Results for Limestone Aggregates.

S. No.	Material Type	Producer	FAA	FAA	FAA
			Test 1	Test 2	(Average)
1	Gr. Limestone	Colorado Material	50.37	50.63	50.50
2	Gr. 4 Limestone	Jobe Concrete Product	45.36	45.68	45.52
3	Limestone	Johnny Thompson	49.75	49.94	49.85
4	Crushed Limestone	Luhr Bros.	43.89	43.63	43.76
5	Type D, Crushed Limestone	Marrock Chambers	42.66	42.6	42.63
6	Crushed Limestone	Martin Marietta	49.41	49.66	49.53
7	3/8 Crushed Stone	Lattimore Material	42.47	42.4	42.44
8	340 (3/8 inch) Crushed Stone	Dolese Bros, Ardamore	45.93	46.4	46.16
9	Flex Base, Type A	Dean World/Dow Pit	45.18	45.42	45.30
10	340 (3/8 inch)	Dolese Bros. Richard Spur	48.79	48.37	48.58
11	Type D, Asphalt Concrete	Vulcan Material, Huebner Road	43.89	43.52	43.71
12	Type D Asphalt Concrete	Sunbelt Material	46.39	46.61	46.50
13	Type D, Crushed Limestone	Young Contractors	45.14	44.82	44.98
14	Limestone	Vulcan Material, Brownwood	45.24	44.9	45.07
15	Type D 3/8 inch Crushed Stone	Stringtown Material	44.73	44.55	44.64
16	Crushed Limestone	Dolese Bros., Cooperton	42.63	42.43	42.53
17	Type D, Limestone	Dean Word, Marble Falls	45.42	45.54	45.48
18	Type D Crushed Limestone	Vulcan Material, Kelly	43.16	42.99	43.08
19	Type D, Limestone	Vulcan Material, Helotes	46.37	46.64	46.50
20	TXI Manufactured Sand	Texas Industries	45.92	45.8	45.86
21	Type D, Limestone	Pioneer Construction	45.79	45.84	45.81
22	Gr. 4 Aggregate	Price Construction	47.46	47.25	47.36
23	Gr. 4 Limestone	Ingrom, Bridgeport	48.32	48.14	48.23

Table 21. UVC Test Results for Gravel Aggregates.

S. No.	Material Type	Producer	FAA	FAA	FAA
			Test 1	Test 2	(Average)
1	Siliceous Gravel	Trinity Material	49.86	49.84	49.85
2	Gravel	Texas Sand & Gravel	39.53	39.39	39.46
3	Type D	Fordyce Material	42.14	42.07	42.11
4	Type D	Hanson Delight	42.42	42.95	42.68
5	Gr.4 aggregate,	Capitol Sand & Gravel	48.26	48.05	48.16
6	Type D Aggregate	County Knippa	46.02	45.86	45.94
7	Type D Asphalt Concrete	Valley Caliche	47.88	47.73	47.81
8	Gr. 4 Aggregate	Wright Bros	44.9	44.65	44.77
9	Type D	Johnson Pit	40.28	40.55	40.42
10	Type D	Capitol Aggregate	45.01	44.94	44.97
11	Type D Asphalt Concrete	Trinity Material, Cresslenn	45.66	45.33	45.49

Table 22. UVC Test Results for Igneous Aggregates.

S. No.	Material Type	Producer	FAA	FAA	FAA
			Test 1	Test 2	(Average)
1	3/8 inch Aggregate	Jobe Concrete , Vado	44.15	43.95	44.05
2	340 (1/2inch)	Western Rock	43.89	43.75	43.82
3	Crushed Granite	Meridian Aggregates	49.98	50.07	50.02
4	Crushed Granite	Jobe Concrete	40.17	40.39	40.28
5	Type D Granite Material	-	39.96	40.46	40.21
6	Gr. 4 Trap Rock	Vulcan Material, Knippa	46.18	45.85	46.01

Figures 11, 12, and 13 in Appendix B graphically represent UVC test results for limestone, gravel, and igneous aggregates, respectively.

Results indicated that many aggregates from different sources could not meet the Superpave specification for high traffic conditions. Limestone aggregates exhibited consistently higher UVC values compared to gravel and igneous aggregates. Variation in UVC results within igneous and gravel aggregates were observed to be higher than limestone aggregates.

The UVC test is extremely sensitive to dry bulk specific gravity results, with a variation in sample results of 0.05 resulting in differences in UVC values up to one percent (20). ASTM C-1252 recommends testing bulk specific gravity for a specific gradation of test sample only if bulk specific gravity values on two replicates determined on minus 4.75 mm (No. 4) material in an "as received" condition vary by more than 0.05. Thus, using bulk specific gravity values of minus 4.75 mm (No. 4) material in an "as received" gradation may cause inaccuracy of results in the UVC test (20).

Compacted Aggregate Resistance (CAR) Test

CAR tests were performed on fine aggregates in an "as received" condition passing the No. 2.36 mm sieve. Tests were carried out at a moisture content of 1.75 percent of the total aggregate sample weight. Aggregate samples were tested using a conventional Marshall machine with a load of 5,000 lb at a rate of vertical deformation of 50.8 mm/min (2.0 inches per minute). Stability values for some aggregates exceeded the limits of the machine. In such cases, stability value at a flow of 4 inches was reported. For all other aggregates, the highest stability value achieved prior to a flow of 4 inches was reported. For each aggregate, triplicate CAR tests were conducted, and the average of the three stability results was reported as the CAR stability.

Tables 23, 24, and 25 show the results for tests on limestone, gravel, and igneous aggregates.

Table 23. CAR Test Results for Limestone Aggregates.

S. No.	Material Type	Producer	CAR Test 1	CAR Test 2	CAR Test 3	CAR (Average)
1	Gr. Limestone	Colorado Material	4150.0	4325.0	4550.0	4341.7
2	Gr. 4 Limestone	Jobe Conc Products	3850.0	4300.0	3450.0	3866.7
3	Limestone	Johnny Thompson	2700.0	2250.0	1900.0	2283.3
4	Crushed Limestone	Luhr Bros.	4300.0	2950.0	2475.0	3241.7
5	Type D, Crushed Limestone	Marrock Chambers	4250.0	4050.0	3750.0	4016.7
6	Crushed Limestone	Martin Marietta	4100.0	4400.0	4300.0	4266.7
7	3/8 Crushed Stone	Lattimore Material	4100.0	2800.0	4150.0	3683.3
8	340 (3/8 inch)	Dolese Bros., Ardamore	5000.0	5000.0	5000.0	5000.0
9	Flex Base, Type A	Flex Base, Dean Word	5000.0	5000.0	5000.0	5000.0
10	340 (3/8 inch)	Dolese Bros., Richard Spur	5000.0	5000.0	5000.0	5000.0
11	Type D, Asphalt Concrete	Vulcan Material, Huebner Road	5000.0	5000.0	5000.0	5000.0
12	Type D Asphalt Concrete	Sunbelt Material	5000.0	5000.0	5000.0	5000.0
13	Type D, Crushed Limestone	Young Contractors	5000.0	5000.0	5000.0	5000.0
14	Limestone	Vulcan Material, Brownwood	5000.0	5000.0	5000.0	5000.0
15	Type D 3/8 inch Crushed Stone	Stringtown Material	4400.0	4150.0	4400.0	4316.7
16	Crushed Limestone	Dolese Bros, Cooperton	4650.0	5000.0	5000.0	4883.3
17	Type D	Dean Word, Marble Falls	5000.0	5000.0	5000.0	5000.0
18	Type D Crushed Limestone	Vulcan Material, Kelly	5000.0	5000.0	5000.0	5000.0
19	Type D	Vulcan Material, Helotes	5000.0	5000.0	5000.0	5000.0
20	TXI Manufactured Sand	Texas Industries	2100.0	2250.0	2150.0	2166.7
21	Type D	Pioneer Construction	5000.0	5000.0	5000.0	5000.0
22	Gr. 4 Aggregate	Price Construction	5000.0	5000.0	5000.0	5000.0
23	Gr. 4 Limestone	Ingrom, Bridgeport	5000.0	5000.0	5000.0	5000.0

Table 24. CAR Test Results for Gravel Aggregates.

S. No.	Material Type	Producer	CAR Test 1	CAR Test 2	CAR Test 3	CAR (Average)
1	Siliceous Gravel	Trinity Material, Waco	5000.0	5000.0	5000.0	5000.0
2	Gravel	Texas Sand & Gravel, Amarillo	2950.0	2075.0	2800.0	2608.3
3	Type D, Fordyce	Fordyce Material	1650.0	3125.0	3250.0	2675.0
4	Type D	Hanson Delight,	500.0	750.0	800.0	683.3
5	Gr. 4 Aggregate	Capitol Sand & Gravel	1850.0	1800.0	1950.0	1866.7
6	Type D Aggregate	Southwestern Aggregates	5000.0	5000.0	5000.0	5000.0
7	Type D Asphalt Concrete	Valley Caliche, Beck pit	5000.0	5000.0	5000.0	5000.0
8	Gr. 4 Aggregate	Wright Bros.	3250.0	3525.0	2700.0	3158.3
9	Type D	Johnson Pit	3550.0	3350.0	3800.0	3566.7
10	Type D	Capitol Aggregate	5000.0	3625.0	4950.0	4525.0
11	Type D Asphalt Concrete	Trinity Material, Cresslenn	5000.0	4800.0	5000.0	4933.3

Table 25. CAR Test Results for Igneous Aggregates.

S. No.	Material Type	Producer	CAR Test 1	CAR Test 2	CAR Test 3	CAR (Average)
1	3/8 Aggregate	Jobe Concrete, Vado	4650.0	4100.0	5000.0	4583.3
2	340 (1/2inch),	Western Rock	5000.0	3800.0	4550.0	4450.0
3	Crushed Granite	Meridian Aggregates	4700.0	3200.0	4650.0	4183.3
4	Crushed Granite	Jobe Concrete, Knippa	4100.0	3000.0	3100.0	3400.0
5	Type D Granite	-	5000.0	4900.0	5000.0	4966.7
6	Gr. 4 Trap Rock	Vulcan Material	4900.0	4550.0	5000.0	4816.7

Figures 14, 15, and 16 in Appendix B graphically represent the CAR test results for limestone, gravel, and igneous aggregates, respectively.

CAR values for 40 aggregates ranged from 683.8 lb to 5000 lb and indicated variability in test results depending on aggregate shape parameters, size distribution, and source properties. Limestone aggregates generally exhibited higher stability values, which can be attributed to angularity and uniform gradation within the fine aggregate fraction. Igneous aggregates also attained higher stability values due to their angular form and rough surface texture.

Methylene Blue (MB) Test on P200 Material

The MB test was performed on material passing the No. 200 or 0.075 μ m sieve for quantifying the amount of deleterious material including the smectite clay group and other organic matter present in the filler material (1). The MBV was calculated for aggregate samples, indicating absorption of the dye that is directly related to the surface area of the clay fraction present in the filler material. For each aggregate, triplicate MB tests were conducted, and the average value was reported as the MBV.

Tables 26, 27, and 28 show MBV results for limestone, gravel, and igneous aggregates, respectively.

Table 26. MBV Test Results for Limestone Aggregates.

S. No.	Material Type	Producer	MBV Test 1	MBV Test 2	MBV Test 3	MBV (Average)
1	Gr. Limestone	Colorado Material	6.25	6.5	6.5	6.4
2	Gr. 4 Limestone	Jobe Concrete	6	6	6.25	6.1
3	Limestone	Johnny Thompson	7.75	8.25	8.25	8.1
4	Crushed Limestone	Luhr Bros.	8	8	8	8.0
5	Type D, Crushed Limestone	Marrock Chambers	6.75	7.25	7.25	7.1
6	Crushed Limestone	Martin Marietta	16.75	17.5	17	17.1
7	3/8 Crushed Stone	Lattimore Material	3.5	3.5	3.5	3.5
8	340 (3/8 inch)	Dolese Bros., Ardmore	3.5	3	3	3.2
9	Flex Base, Type A	Flex Base, Dean Word	7.5	7.25	7.25	7.3
10	340 (3/8")	Dolese Bros., Richard Spur	5.75	5.5	5.5	5.6
11	Type D, Asphalt Concrete	Vulcan Material, Huebner Road	5.5	5.25	5.25	5.3
12	Type D Asphalt Concrete	Sunbelt Material	1.75	1.75	1.5	1.7
13	Type D, Crushed Limestone	Young Contractors	5	4.75	4.75	4.8
14	Limestone	Vulcan Material, Brownwood	2.25	2.25	2	2.2
15	Type D, 3/8 inch Crushed Stone	Stringtown Material	6	6.25	6.25	6.2
16	Crushed Limestone	Dolese Bros., Cooperton	1	1	1.25	1.1
17	Type D	Dean Word, Marble Falls	16	16.25	16.25	16.2
18	Type D, Crushed Limestone	Vulcan Material, Kelly	3.5	3.25	3	3.3
19	Type D	Vulcan Material, Helotes	1	0.75	1	0.9
20	TXI Manufactured sand	Texas Industries	3	2.75	3	2.9
21	Type D	Pioneer Construction	2.5	2.5	2.25	2.4
22	Gr4 Aggregate	Price Construction	3.5	3.75	3.75	3.7
23	Gr. 4 Limestone	Ingrom, Bridgeport	3.25	3.5	3.75	3.5

Table 27. MBV Test Results for Gravel Aggregates.

S. No.	Material Type	Producer	MBV Test 1	MBV Test 2	MBV Test 3	MBV (Average)
1	Siliceous Gravel, TM	Trinity Material, Waco	3	3.25	3.25	3.2
2	Gravel	Texas Sand & Gravel, Amarillo	18	18.5	18.25	18.3
3	Type D, Fordyce	Fordyce Material	3.75	3.75	3.75	3.8
4	Type D	Hanson Delight	2.75	2.5	2.5	2.6
5	Gr. 4 Aggregate	Capitol Sand & Gravel	6	5.75	5.5	5.8
6	Type D, Aggregate	Southwestern Aggregates	3	2.5	2.5	2.7
7	Type D, Asphalt Concrete	Valley Caliche, Beck Pit	16	16	15.5	15.8
8	Gr. 4 Aggregate	Wright Bros.	3	3.25	3	3.1
9	Type D	Johnson Pit	11.5	11	10.5	11.0
10	Type D	Capitol Aggregate	7	7.25	7.25	7.2
11	Type D, Asphalt Concrete	Trinity Material, Cresslenn	10	9.75	9.75	9.8

Table 28. MBV Test Results for Igneous Aggregates.

S. No.	Material Type	Producer	MBV	MBV	MBV	MBV
			Test 1	Test 2	Test 3	(Average)
1	3/8 Aggregate	Jobe Concrete, Vado	3.5	3.75	3.75	3.7
2	340 (1/2inch)	Western Rock	6.5	6.75	6.75	6.7
3	Crushed Granite	Meridian Aggregates	8.75	8.25	8.25	8.4
4	Crushed Granite	Jobe Concrete, Knippa	7.5	7.75	7.75	7.7
5	Type D, Granite		1.5	1.5	1.5	1.5
6	Gr. 4 Trap Rock	Vulcan Material	8.5	8.5	8.5	8.5

Figures 17, 18, and 19 in Appendix B graphically represent MB test results for limestone, gravel, and igneous aggregates, respectively.

The MBV for most aggregates was within good performance levels as recommended in *NCHRP-4-19*. This could be attributed to selection of quality aggregate material having lower concentration of clay fraction. However, a few aggregates exhibited higher MBVs indicating the presence of clay or other organic deleterious material.

Particle Size Analysis of Soils (Hydrometer Analysis on P200) (ASTM D 422-63)

The Hydrometer Test was performed on fine aggregates passing the No. 10 sieve to determine and evaluate particle size and distribution of P200 material within fine aggregates. Filler material may cause the mix to stiffen or extend depending on size and distribution of particles within fine aggregate. A sedimentation process was used for determining aggregate diameter and the corresponding proportion of material within the filler aggregate using a 152 H hydrometer. Percent filler material passing the 0.005 mm and 0.001 mm diameter size were calculated and reported.

Tables 29, 30, and 31 show Hydrometer test results for limestone, gravel, and igneous aggregates for percent material smaller than 0.005 mm and 0.001mm sizes.

Table 29. Hydrometer Test Results for Limestone Aggregates.

S. No.	Material Type	Producer	% Passing 0.005mm	% Passing 0.001mm
1	Gr. Limestone	Colorado Material	23.5	9.0
2	Gr. 4 Limestone	Jobe Concrete	6.6	4.9
3	Limestone	Johnny Thompson	32.6	14.2
4	Crushed Limestone	Luhr Bros	26.7	12.0
5	Type D, Crushed Limestone	Marrock Chambers	6.5	4.2
6	Crushed Limestone	Martin Marietta	22.6	11.7
7	3/8 Crushed Stone	Lattimore Material	18.7	6.4
8	340 (3/8inch)	Dolese Bros., Ardamore	14.5	7.4
9	Flex Base, Type A	Flex Base, Dean Word	18.3	7.5
10	340 (3/8inch)	Dolese Bros., Richard Spur	10.3	7.6
11	Type D, Asphalt Concrete	Vulcan Material, Huebner Road	15.6	10.2
12	Type D, Asphalt Concrete	Sunbelt Material	16.4	10.1
13	Type D, Crushed Limestone	Young Contractors	14.8	11.3
14	Limestone	Vulcan Material, Brownwood	22.2	14.1
15	Type D, 3/8inch Crushed Stone	Stringtown Material	6.8	5.7
16	Crushed Limestone	Dolese Bros., Cooperton	11.0	7.4
17	Type D	Dean Word, Marble Falls	18.4	10.6
18	Type D, Crushed Limestone	Vulcan Material, Kelly	6.8	5.0
19	Type D	Vulcan Material, Helotes	12.8	5.6
20	TXI Manufactured Sand	Texas Industries	6.4	4.5
21	Type D	Pioneer Construction	11.7	7.3
22	Gr. 4 Aggregate	Price Construction	26.8	10.9
23	Gr. 4 Limestone	Ingrom, Bridgeport	12.4	7.5

Table 30. Hydrometer Test Results for Gravel Aggregates.

S. No.	Material Type	Producer	% Passing 0.005 mm	% Passing 0.001 mm
1	Siliceous Gravel, TM	Trinity Material, Waco	6.1	4.2
2	Gravel	Texas Sand & Gravel, Amarillo	10.8	6.2
3	Type D, Fordyce	Fordyce Material	13.2	9.1
4	Type D	Hanson Delight	3.0	2.5
5	Gr. 4 Aggregate,	Capitol Sand & Gravel	2.2	1.1
6	Type D, Aggregate	Southwestern Aggregates	8.1	6.0
7	Type D, Asphalt Concrete	Valley Caliche, Beck pit	16.4	10.0
8	Gr. 4 Aggregate	Wright Bros.	4.0	3.9
9	Type D	Johnson Pit	11.7	7.2
10	Type D	Capitol Aggregate, Hoban.	4.2	3.5
11	Type D, Asphalt Concrete	Trinity Material, Cresslenn	5.4	4.0

Table 31. Hydrometer Test Results for Igneous Aggregates.

S. No.	Material Type	Producer	% Passing 0.005 mm	% Passing 0.001 mm
1	3/8 Aggregate	Jobe Concrete, Vado	19.7	10.6
2	340 (1/2inch)	Western Rock	11.5	5.8
3	Crushed Granite	Meridian Aggregates	5.6	0.8
4	Crushed Granite	Jobe Concrete, Knippa	10.1	5.9
5	Type D, Granite Material	-	6.7	4.3
6	Gr. 4 Trap Rock	Vulcan Material	6.4	5.2

Figures 20, 21, and 22 in Appendix B graphically represent Hydrometer test results for material smaller than the 0.005 mm in diameter for limestone, gravel, and igneous aggregates. Figures 23, 24, and 25 in Appendix B represent Hydrometer test results for material smaller than the 0.001 mm in diameter for limestone, gravel, and igneous aggregates, respectively.

Percent material passing the 0.005 mm and 0.001 mm sizes were observed to be higher for limestone aggregates as compared to gravel and igneous aggregates. Moreover, variability in percent finer material passing the 0.005 mm and 0.001 mm sizes was also observed to be higher for limestone aggregates compared with the other two groups.

Flat and Elongated Test on Coarse Aggregate (ASTM D 4791-99)

The flat and elongated test was used for evaluating coarse aggregate shape and size parameters. Percentage flat and elongated (F&E) particles retained on the No. 4 sieve (4.75 mm) were determined for each aggregate sample using a particle count method. Approximately 100 particles were selected for each size fraction and were tested for a (5:1 ratio) on the caliper. Test results were checked for Superpave criteria limiting maximum allowable flat and elongated particles based on expected traffic conditions. Tables 32, 33, and 34 show F&E results for limestone, gravel, and igneous aggregates, respectively.

Table 32. Flat and Elongated Test Results for Limestone Aggregates.

S. No.	Material Type	Producer	% Flat and Elongated (5:1)	
			Retained 3/8 inch	Retained 4.75 mm
1	Gr. Limestone	Colorado Material	1.9	4.8
2	Gr. 4 Limestone	Jobe Concrete	3.0	18.1
3	Limestone	Johnny Thompson	0.1	2.7
4	Crushed Limestone	Luhr Bros.	0.3	2.8
5	Type D, Crushed Limestone	Marrock Chambers	3.5	12.5
6	Crushed Limestone	Martin Marietta	5.8	6.4
7	3/8 Crushed Stone	Lattimore Material	0.8	3.1
8	340 (3/8 inch)	Dolese Bros., Ardamore	0.1	9.5
9	Flex Base, Type A	Flex Base, Dean Word	6.7	8.5
10	340 (3/8 inch)	Dolese Bros., Richard Spur	0.1	28.2
11	Type D, Asphalt Concrete	Vulcan Material, Huebner Road	0.1	0.1
12	Type D, Asphalt Concrete	Sunbelt Material	3.7	20.9
13	Type D, Crushed Limestone	Young Contractors	3.5	3.7
14	Limestone	Vulcan Material, Brownwood	0.1	3.8
15	Type D, 3/8 inch Crushed Stone	Stringtown Material	11.7	18.2
16	Crushed Limestone	Dolese Bros., Cooperton	0.1	12.7
17	Type D	Dean Word, Marble Falls	6.7	13.6
18	Type D, Crushed Limestone	Vulcan Material, Kelly	0.1	0.1
19	Type D	Vulcan Material, Helotes	1.5	2.8
20	TXI Manufactured Sand	Texas Industries	0.1	0.1
21	Type D	Pioneer Construction	3.4	5.3
22	Gr. 4 Aggregate	Price Construction	0.1	1.5
23	Gr. 4 Limestone	Ingrom, Bridgeport	4.9	17.1

Table 33. Flat and Elongated Test Results for Gravel Aggregates.

S. No.	Material Type	Producer	% Flat and Elongated (5:1)	
			Retained 3/8 inch	Retained 4.75 mm
1	Siliceous Gravel	Trinity Material, Waco	2.5	3.3
2	Gravel	Texas Sand & Gravel, Amarillo	1.9	5.1
3	Type D, Fordyce	Fordyce Material	0.2	1.1
4	Type D	Hanson Delight, Delight	0.1	0.1
5	Gr. 4 Aggregate,	Capitol Sand & Gravel	0.1	1.1
6	Type D, Aggregate	Southwestern Aggregates	0.1	1.6
7	Type D, Asphalt Concrete	Valley Caliche, Beck pit	2.9	6.4
8	Gr. 4 Aggregate	Wright Bros.	0.1	4.2
9	Type D	Johnson Pit	1.7	2.9
10	Type D	Capitol Aggregate, Hoban.	0.9	0.1
11	Type D, Asphalt Concrete	Trinity Material, Cresslenn	9.4	7.0

Table 34. Flat and Elongated Test Results for Igneous Aggregates.

S. No.	Material Type	Producer	% Flat and Elongated (5:1)	
			Retained 3/8 inch	Retained 4.75 mm
1	3/8 Aggregate	Jobe Concrete, Vado	4.6	3.0
2	340 (1/2 inch)	Western Rock	6.0	15.0
3	Crushed Granite	Meridian Aggregates	1.2	7.9
4	Crushed Granite	Jobe Concrete, Knippa	1.1	18.0
5	Type D, Granite	-	0.9	6.8
6	Gr. 4, Trap Rock	Vulcan Material	5.8	12.0

Figure 26, 27, and 28 in Appendix B graphically represent F&E test results retained on the 3/8 inch sieve for limestone, gravel, and igneous aggregates, respectively. Figure 29, 30, and 31 in Appendix B represent F&E test results retained on 4.75 mm sieve for limestone, gravel, and igneous aggregates, respectively.

Most aggregates retained on 3/8 inch sieve were found to be within Superpave maximum allowable range of 10 percent. However, many aggregates retained on 4.75 mm sieve, especially igneous and limestone, exhibited higher percentage flat and elongated particles indicating susceptibility to failure under heavy traffic conditions.

Flat and Elongated Test on Coarse Aggregate Using MRA Caliper

Coarse aggregates retained on the 4.75 mm sieve or higher were tested for shape and size parameters using the MRA Digital Caliper. Aggregates were classified into different categories (< 2:1, 2:1-3:1, 3:1-4:1, 4:1-5:1, and > 5:1) based upon measurement of their maximum and minimum dimensions. Percent flat and elongated aggregates were checked for Superpave criteria limiting F& E particles based on traffic conditions.

Tables 35, 36, and 37 show F&E results retained on the 3/8 inch sieve for limestone, gravel, and igneous aggregates, respectively.

Table 35. Automated Flat and Elongated Test Results for Limestone Aggregates Retained on 3/8 Inches Sieve.

S. No.	Material Type	Producer	% Not Flat and Elongated				% Flat and Elongated
			<2:1	2:1-3:1	3:1-4:1	4:1-5:1	
1	Gr. Limestone	Colorado Material	34.7	48.4	12.1	3.2	1.6
2	Gr. 4 Limestone	Jobe Concrete	28.3	43.4	9.0	15.1	4.0
3	Limestone	Johnny Thompson	0	0	0	0	0
4	Crushed Limestone	Luhr Bros	57	40	2	1	0
5	Type D, Crushed Limestone	Marrock Chambers	43.9	32.7	16.8	2.8	3.7
6	Crushed Limestone	Martin Marietta	40.4	51	6.7	1.9	0
7	3/8 Crushed Stone	Lattimore Material	49.4	38.8	7.3	2.8	1.6
8	340 (3/8 inches)	Dolese Bros. Ardamore	55.6	38.9	5.5	0	0
9	Flex Base, Type A	Flex Base, Dean Word	27.4	45.1	19.4	2.6	0
10	340 (3/8 inches)	Dolese Bros., Richard Spur	0	0	0	0	0
11	Type D, Asphalt Concrete	Vulcan Material, Huebner Road	74.8	25.2	0	0	0
12	Type D, Asphalt Concrete	Sunbelt Material	35.8	46.8	3.6	11.0	2.7
13	Type D, Crushed Limestone	Young Contractors	57.5	32.7	6.1	1.7	1.7
14	Limestone	Vulcan Material, Brownwood	65.7	34.3	0	0	0
15	Type D, 3/8 inches Crushed Stone	Stringtown Material	31.5	36.9	11.7	12.6	7.2
16	Crushed Limestone	Dolese Bros., Cooperton	55.5	34.5	3.6	0.90	5.4
17	Type D	Dean Word, Marble Falls	44	45.7	5.1	3.4	1.7
18	Type D, Crushed Limestone	Vulcan Material, Kelly	0	0	0	0	0
19	Type D	Vulcan Material, Helotes	57.3	35	5.1	1.7	0.8
20	TXI Manufactured Sand	Texas Industries	0	0	0	0	0
21	Type D	Pioneer Construction	44.3	40.6	12.2	2.8	0
22	Gr. 4 Aggregate	Price Construction	76.4	19.7	3.9	0	0
23	Gr. 4 Limestone	Ingrom, Bridgeport	46.6	35.9	12.6	4.8	0

Table 36. Automated Flat and Elongated Test Results for Gravel Aggregates Retained on 3/8 Inches Sieve.

S. No.	Material Type	Producer	% Not Flat and Elongated				% Flat and Elongated
			< 2:1	2:1-3:1	3:1-4:1	4:1-5:1	
1	Siliceous Gravel	Trinity Material, Waco	32.1	37.5	16.9	8.9	4.4
2	Gravel	Texas Sand & Gravel, Amarillo	63.6	25.5	5.4	5.4	0
3	Type D, Fordyce	Fordyce Material	67	30.1	1.9	0.9	0
4	Type D	Hanson Delight	77	19	4	0	0
5	Gr. 4 Aggregate	Capitol Sand & Gravel	0	0	0	0	0
6	Type D, Aggregate	Southwestern Aggregates	0	0	0	0	0
7	Type D, Asphalt Concrete	Valley Caliche, Beck pit	50.4	39	7.3	3.2	0
8	Gr. 4 Aggregate	Wright Bros.	67.6	29.4	2.9	0	0
9	Type D	Johnson Pit	66	29.2	2.8	1.8	0
10	Type D	Capitol Aggregate, Hoban.	70.8	25	1.6	2.5	0
11	Type D, Asphalt Concrete	Trinity Material, Cresslenn	48.1	17	15.0	9.4	10.3

Table 37. Automated Flat and Elongated Test Results for Igneous Aggregates Retained on 3/8 Inches Sieve.

S. No.	Material Type	Producer	% Not Flat and Elongated				% Flat and Elongated > 5:1
			< 2:1	2:1-3:1	3:1-4:1	4:1-5:1	
1	3/8 Aggregate	Jobe Concrete, Vado	50.5	28.7	11.8	4.9	3.9
2	340 (1/2 inch),	Western Rock	33	39.3	11.6	9.8	6.2
3	Crushed Granite	Meridian Aggregates	56.5	31.5	6.4	2.7	2.7
4	Crushed Granite,	Jobe Concrete, Knippa	60.3	39.7	0	0	0
5	Type D, Granite	-	49	29.8	17.3	2.8	0.9
6	Gr. 4 Trap Rock	Vulcan Material	29.4	43.1	13.7	12.7	0.9

Figures 32, 33 and 34 in Appendix B graphically represent automated F&E test results retained on the 3/8 inches sieve for limestone, gravel, and igneous aggregates, respectively.

Most aggregates were found to be within the Superpave criteria. Limestone aggregates exhibited higher percentages of F&E aggregates compared to gravel and igneous aggregates. Since the digital caliper quantifies aggregates into multiple ratios, percent F&E particles for the three groups were observed to be slightly less as compared to the results from ASTM D 4791.

Table 38, 39, and 40 show F&E results retained on the 4.75 mm sieve for limestone, gravel, and igneous aggregates, respectively.

Table 38. Automated Flat and Elongated Test Results for Limestone Aggregates Retained on 4.75 mm Sieve.

S. No.	Material Type	Producer	% Not Flat and Elongated				% Flat and Elongated
			< 2:1	2:1-3:1	3:1-4:1	4:1-5:1	
1	Gr. Limestone	Colorado Material	23.3	39.0	27.6	5.6	4.0
2	Gr.4 Limestone	Jobe Concrete	22.2	26.4	14.7	13.7	23.5
3	Limestone	Johnny Thompson	0	28.3	12.3	2.6	3.5
4	Crushed Limestone	Luhr Bros.	47	38.9	19.4	0.8	0.8
5	Type D, Crushed Limestone	Marrock Chambers	29.9	33.3	21.6	10	8.3
6	Crushed Limestone	Martin Marietta	40.3	28.5	20	9.5	1.9
7	3/8 Crushed Stone	Lattimore Material	25.2	27.5	16.6	6.6	11.6
8	340 (3/8 inch)	Dolese Bros., Ardamore	138.9	37.8	14.1	11.0	17.3
9	Flex Base, Type A	Flex Base, Dean Word	26.5	32.2	23.7	9.3	9.3
10	340 (3/8 inch)	Dolese Bros., Richard Spur	0	35.6	8.9	8.9	13.8
11	Type D, Asphalt Concrete	Vulcan Material, Huebner Rd	52.4	47.2	9.4	0.8	0
12	Type D, Asphalt Concrete	Sunbelt Material	22.9	24.7	20.9	9.5	20.9
13	Type D, Crushed Limestone	Young Contractors	62.8	38.8	9.0	2.7	0
14	Limestone	Vulcan Material, Brownwood	41.1	48.0	6.8	3.9	0
15	Type D 3/8 inch Crushed Stone	Stringtown Material	25.2	33.0	15.5	15.5	10.0
16	Crushed Limestone	Dolese Bros., Cooperton	24.5	33.6	17.2	10.9	13.6
17	Type D	Dean Word, Marble Falls	43.9	33.0	14.8	4.9	4.9
18	Type D, Crushed Limestone	Vulcan Material, Kelly	0	0	0	0	0
19	Type D	Vulcan Material, Helotes	41.8	35.5	10.5	3.8	2.8
20	TXI Manufactured Sand	Texas Industries	0	0	0	0	0
21	Type D	Pioneer Construction	43.4	42.6	12.2	4.0	3.2
22	Gr. 4 Aggregate	Price Construction	46.4	33.6	7.9	0	0
23	Gr. 4 Limestone	Ingrom, Bridgeport	20.3	28.8	27.8	17.3	5.7

Table 39. Automated Flat and Elongated Test Results for Gravel Aggregates Retained on 4.75 mm Sieve.

S. No.	Material Type	Producer	%Not Flat and Elongated				% Flat and Elongated
			< 2:1	2:1-3:1	3:1-4:1	4:1-5:1	
1	Siliceous Gravel, TM	Trinity Material, Waco	32.7	38.1	17.2	9.0	5.4
2	Gravel	Texas Sand & Gravel, Amarillo	55.5	22.2	4.7	4.7	3.1
3	Type D, Fordyce	Fordyce Material	57.0	25.6	1.6	0.8	0.8
4	Type D	Hanson Delight, Delight	62.6	15.4	3.2	0	0
5	Gr. 4 Aggregate,	Capitol Sand & Gravel	0	0	0	0	3.7
6	Type D, Aggregate	Southwestern Aggregates	0	0	0	0	0
7	Type D, Asphalt Concrete	Valley Caliche, Beck pit	53.4	41.3	7.7	3.4	6.0
8	Gr. 4 Aggregate	Wright Bros.	72.4	31.5	3.1	0	2.3
9	Type D	Johnson Pit	64.2	28.4	2.7	1.8	1.8
10	Type D	Capitol Aggregate, Hoban.	82.5	29.1	1.9	2.9	0
11	Type D, Asphalt Concrete	Trinity Material, Cresslenn	50.5	17.8	15.8	9.9	6.9

Table 40. Automated Flat and Elongated Test Results for Igneous Aggregates Retained on 4.75 mm Sieve.

S. No.	Material Type	Producer	% Not Flat and Elongated				% Flat and Elongated > 5:1
			< 2:1	2:1-3:1	3:1-4:1	4:1-5:1	
1	3/8 Aggregate	Jobe Concrete, Vado	29.7	38.0	17.3	9.9	4.9
2	340 (1/2 inch)	Western Rock	18.4	41.6	20	11.2	8.8
3	Crushed Granite	Meridian Aggregates	39.3	32.2	14.1	7.8	6.2
4	Crushed Granite	Jobe Concrete, Knippa	51.6	42.5	5	0.8	0
5	Type D, Granite Material		22.4	38.7	18.1	18.1	2.4
6	Gr. 4 Trap Rock	Vulcan Material	12.7	20	22.7	28.1	16.3

Figures 35, 36, and 37 in Appendix B graphically represent automated F&E test results retained on the 4.75 mm sieve for limestone, gravel, and igneous aggregates, respectively.

Results indicated higher percentages of F&E aggregates retained on the 4.75 mm sieve as compared to those retained on the 3/8 inches sieve for all aggregate groups. Limestone and igneous aggregates exhibited higher percentages of F&E aggregates compared to gravel aggregates.

STATISTICAL ANALYSIS

Results from the above experiments were analyzed using SPSS software to accomplish the following objectives:

- Evaluate variability in test results for aggregates from various sources assuming aggregates from different source and environmental regions yield different results
- Evaluate the sensitivity of the test to aggregates both between and within groups to evaluate whether tests can effectively monitor change in aggregate properties for different aggregates.
- Develop correlation between tests evaluating similar properties with a goal of eliminating cumbersome and time-consuming tests.
- Develop correlation between automated tests and standard testing methods to analyze precision of test to monitor aggregate properties.

Analysis for Variability in Test Results

The objective of this analysis was to determine variability in test results for different tests assuming aggregates from different sources and environmental regions yield different results.

For the purpose of analysis, the aggregates were classified into three categories:

- limestone (group 1),
- gravel (group 2), and
- igneous (group 3).

A two-step process was followed for achieving this goal:

- analysis of variability in test results for all aggregates groups, and
- analysis of variability in test results within the same aggregate group.

A one-way ANOVA test checked for variability in test results at a 95-percentile confidence interval. In addition, a Bonferroni analysis determined groups with significant variability.

Sensitivity of Test to Aggregate Properties

The objective of this analysis was to analyze whether aggregate tests could effectively discriminate aggregates with marginal and good performance while evaluating similar characteristics. This test was performed for the UVC test, the CAR test, and MB tests as replicate results were available for each sample.

A Student-Newman-Keuls test analyzed the level of sensitivity of aggregate tests to monitor change in aggregate properties with respect to replicates tested for each aggregate sample.

Uncompacted Void Content of Fine Aggregate

Table 41 shows the descriptive statistics for the UVC test.

Table 41. Descriptive Statistics for UVC Test.

Group	Aggregate Count	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
1	23	45.88	2.294	.478	44.895	46.879	42.4	50.5
2	11	44.67	3.141	.947	42.562	46.783	39.5	49.5
3	6	44.16	3.660	1.494	40.320	48.001	40.3	50.0
Total	40	45.29	2.780	.440	44.405	46.183	39.5	50.5

Table 42 shows Levene statistic test result for homogeneity of variance for the UVC test.

Table 42. Test of Homogeneity of Variance for UVC Test.

H₀: Equal variance in test results for all groups

H₁: Significant variance in test results for all groups

Levene Statistic	df1	df2	Sig.
.893	2	37	.418

Testing at a $\alpha = 0.05$ significance level, H₀ is accepted and there is no significant variability in UVC test results for all groups.

Table 43 shows the ANOVA test results for variation in test results between all aggregate groups for the UVC test.

Table 43. Test for Variation Between Groups for UVC Test.

H₀: No significant variation in test results between groups

H₁: Significant variation in test results between groups

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	20.049	2	10.025	1.318	.280
Within Groups	281.422	37	7.606		
Total	301.471	39			

Testing at a $\alpha = 0.05$ significance level, H₀ is accepted and there is no significant variability in UVC test results between the three groups.

Figure 2 graphically represents variability in UVC test results between aggregate groups.

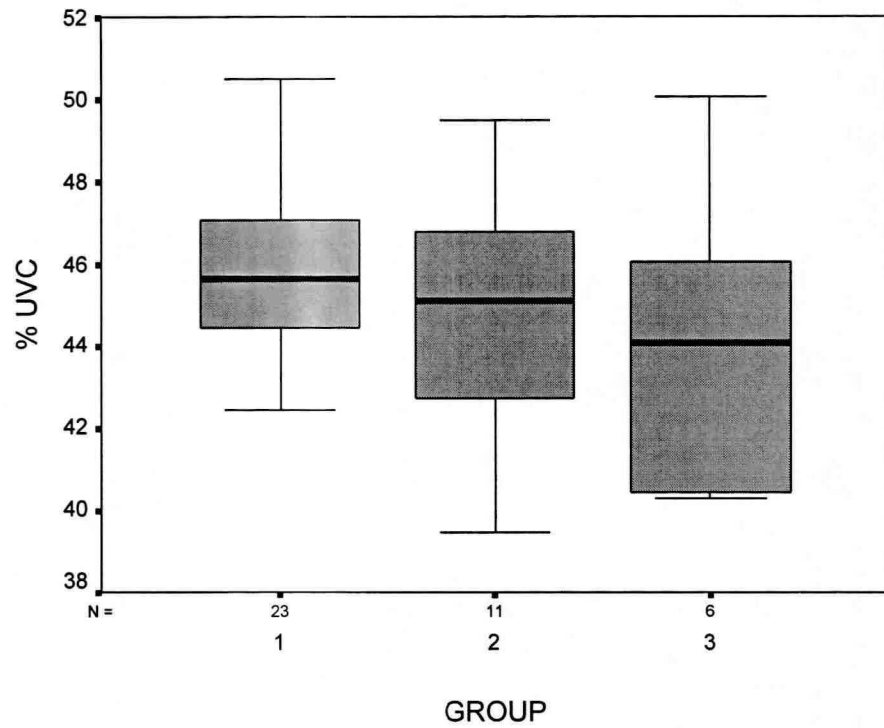


Figure 2. Variability in UVC Test Results Between Aggregate Groups.

Tables 44, 45, and 46 show sensitivity analysis results for limestone, gravel, and igneous aggregates, respectively.

Table 44. Sensitivity of UVC Test Among Limestone Aggregates.

H_0 : Test not sensitive among aggregates from same group

H_1 : Test sensitive among aggregates from same group

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	241.094	22	10.959	339.040	.000
Within Groups	.743	23	3.232E-02		
Total	241.837	45			

Student-Newman-Keuls

	N	Subset for alpha = .05												
GROUP		1	2	3	4	5	6	7	8	9	10	11	12	13
7	2	42.438												
16	2	42.530												
5	2	42.629												
18	2		43.077											
11	2			43.705										
4	2			43.759										
15	2				44.641									
13	2				44.978	44.978								
14	2				45.067	45.067	45.067							
9	2					45.302	45.302							
17	2						45.477	45.477						
2	2						45.518	45.518						
21	2							45.812	45.812					
20	2							45.861	45.861					
8	2								46.161	46.161				
12	2									46.501				
19	2									46.504				
22	2										47.358			
23	2											48.228		
10	2											48.579		
6	2												49.533	
3	2												49.846	
1	2													50.499
Sig.		.547	1.000	.766	.066	.192	.085	.172	.150	.159	1.000	.063	.095	1.000

Testing at $\alpha = 0.05$ significance level, H_0 is rejected and UVC test is sensitive to aggregates among limestone group.

Table 45. Sensitivity of UVC Test Among Gravel Aggregates.

H_0 : Test not sensitive among aggregates from same group

H_1 : Test sensitive among aggregates from same group

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	213.898	10	21.390	730.708	.000
Within Groups	.322	11	2.927E-02		
Total	214.220	21			

Student-Newman-Keuls

	N	Subset for alpha = .05								
GROUP		1	2	3	4	5	6	7	8	9
2	2	39.461								
9	2		40.415							
3	2			42.109						
4	2				42.685					
8	2					44.774				
10	2					44.975				
11	2						45.494			
6	2							45.939		
7	2								47.807	
5	2								48.155	
1	2									49.850
Sig.		1.000	1.000	1.000	1.000	.266	1.000	1.000	.066	1.000

Testing at $\alpha = 0.05$ significance level, H_0 is rejected and UVC test is sensitive to aggregates among gravel group.

Table 46. Sensitivity of UVC Test Among Igneous Aggregates.H₀: Test not sensitive among aggregates from same groupH₁: Test sensitive among aggregates from same group**ANOVA**

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	137.143	5	27.429	692.934	.000
Within Groups	.237	6	3.958E-02		
Total	137.381	11			

Student-Newman-Keuls

	N	Subset for alpha = .05			
GROUP		1	2	3	4
5	2	40.210			
4	2	40.280			
2	2		43.820		
1	2		44.050		
6	2			46.015	
3	2				50.025
Sig.		.737	.292	1.000	1.000

Means for groups in homogeneous subsets are displayed.

Uses Harmonic Mean Sample Size = 2.000.

Testing at $\alpha = 0.05$ significance level, H₀ is rejected and UVC test is sensitive to aggregates among igneous group.**Compacted Aggregate Resistance Test**

Table 47 shows the descriptive statistics for the CAR test.

Table 47. Descriptive Statistics for CAR Test.

Group	Aggregate Count	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
1	23	4590.94	723.75	150.91	4277.96	4903.91	2283.3	5000.0
2	11	3510.60	1462.60	440.99	2528.01	4493.19	683.3	5000.0
3	6	4400.00	561.74	229.33	3810.48	4989.51	3400.0	4966.7
Total	40	4265.20	1053.77	166.61	3928.19	4602.22	683.3	5000.0

Table 48 shows Levene statistic test result for homogeneity of variance for the CAR test.

Table 48. Test of Homogeneity of Variance for CAR Test.H₀: Equal variance in test results for all groupsH₁: Significant variance in test results for all groups

Levene Statistic	df1	df2	Sig.
6.314	2	37	.004

Testing at a $\alpha = 0.05$ significance level, H₀ is rejected and there is significant variability in CAR test results for all groups.

Table 49 shows the ANOVA test results for variation in test results between all aggregate groups for the CAR test.

Table 49. Test for Variation Between Groups for CAR Test.

H₀: No significant variation in test results between groups

H₁: Significant variation in test results between groups

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	8813039.382	2	4406519.69	4.727	.015
Within Groups	34494028.327	37	932271.036		
Total	43307067.708	39			

Testing at a $\alpha=0.05$ significance level, H₀ is rejected and there is significant variability in CAR test results for all groups.

Since the ANOVA table shows significant variation in test results between the three aggregate groups, pair-wise comparison of the group means were conducted using Bonferroni analysis.

Table 50 shows Bonferroni test results for analysis of variation within groups for the CAR test.

Table 50. Analysis of Variation Within Groups for CAR Test.

Multiple Comparisons

Bonferroni Test

		Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
(I) GROUP	(J) GROUP				Lower Bound	Upper Bound
1	2	1080.336	353.957	.013*	192.706	1967.966
	3	190.942	442.620	1.000	-919.031	1300.915
2	1	-1080.336	353.957	.013*	-1967.966	-192.706
	3	-889.394	490.031	.233	-2118.263	339.475
3	1	-190.942	442.620	1.000	-1300.915	919.031
	2	889.394	490.031	.233	-339.475	2118.263

* The mean difference is significant at the 0.05 level.

Testing at a $\alpha = 0.05$ significance level, there is significant variability in CAR test results for limestone and gravel aggregates. However, no significant variation is observed between limestone and igneous or between gravel and igneous aggregates.

Figure 3 graphically represents variability in CAR test results between aggregate groups.

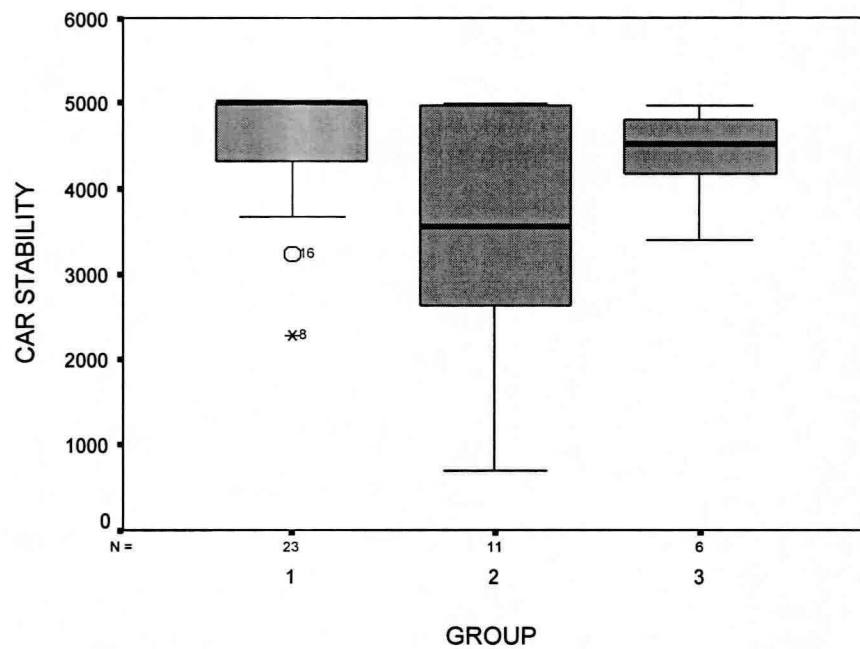


Figure 3. Variability in CAR Test Results Between Aggregate Groups.

Tables 51, 52, and 53 show sensitivity analysis results for limestone, gravel, and igneous aggregates, respectively.

Table 51. Sensitivity of CAR Test Among Limestone Aggregates.

H_0 : Test not sensitive among aggregates from same group

H_1 : Test sensitive among aggregates from same group

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	49991612.319	22	2272346.014	25.895	.000
Within Groups	4036666.667	46	87753.623		
Total	54028278.986	68			

Student-Newman-Keuls

	N	Subset for alpha = .05			
GROUP		1	2	3	4
20	3	2166.667			
3	3	2283.333			
4	3		3241.667		
7	3		3683.333	3683.333	
2	3			3866.667	
5	3			4016.667	
6	3			4266.667	4266.667
15	3			4316.667	4316.667
1	3			4341.667	4341.667
16	3				4883.333
8	3				5000.000
9	3				5000.000
10	3				5000.000
11	3				5000.000
12	3				5000.000
13	3				5000.000
14	3				5000.000
17	3				5000.000
18	3				5000.000
19	3				5000.000
21	3				5000.000
22	3				5000.000
23	3				5000.000
Sig.		.632	.074	.090	.212

Testing at $\alpha = 0.05$ significance level, H_0 is rejected and CAR test is sensitive to aggregates among limestone group.

Table 52. Sensitivity of CAR Test Among Gravel Aggregates.

H_0 : Test not sensitive among aggregates from same group

H_1 : Test sensitive among aggregates from same group

ANOVA

CAR	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	66087196.970	10	6608719.697	38.438	.000
Within Groups	3782500.000	22	171931.818		
Total	69869696.970	32			

Student-Newman-Keuls

	N	Subset for alpha = .05				
GROUP		1	2	3	4	5
4	3	683.333				
5	3		1866.667			
2	3		2608.333	2608.333		
3	3		2675.000	2675.000		
8	3			3158.333	3158.333	
9	3				3566.667	
10	3					4525.000
11	3					4933.333
1	3					5000.000
6	3					5000.000
7	3					5000.000
Sig.		1.000	.065	.257	.241	.632

Testing at $\alpha = 0.05$ significance level, H_0 is rejected and CAR test is sensitive to aggregates among gravel group.

Table 53. Sensitivity of CAR Test Among Igneous Aggregates.

H_0 : Test not sensitive among aggregates from same group

H_1 : Test sensitive among aggregates from same group

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	4733333.333	5	946666.667	3.286	.042
Within Groups	3456666.667	12	288055.556		
Total	8190000.000	17			

Student-Newman-Keuls

	N	Subset for alpha = .05	
GROUP		1	2
4	3	3400.000	
3	3	4183.333	4183.333
2	3	4450.000	4450.000
1	3	4583.333	4583.333
6	3		4816.667
5	3		4966.667
Sig.		.079	.423

Testing at $\alpha = 0.05$ significance level, H_0 is rejected and CAR test is sensitive to aggregates among igneous group.

Methylene Blue Test on P200 Material

Table 54 shows the descriptive statistics for the MB test.

Table 54. Descriptive Statistics for MB Test.

Group	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
1	23	5.496	4.119	.859	3.715	7.277	.9	17.1
2	11	7.553	5.529	1.667	3.838	11.268	2.6	18.3
3	6	6.069	2.863	1.169	3.065	9.074	1.5	8.5
Total	40	6.148	4.389	.694	4.744	7.552	.9	18.3

Table 55 shows Levene statistic test result for homogeneity of variance for the MB test.

Table 55. Test of Homogeneity of Variance for MB Test.

H_0 : Equal variance in test results for all groups

H_1 : Significant variance in test results for all groups

Levene Statistic	df1	df2	Sig.
1.702	2	37	.196

Testing at a $\alpha = 0.05$ significance level, H_0 is accepted and there is no significant variability in MB test results for all groups.

Table 56 shows the ANOVA test results for variation in test results between all aggregate groups for the MB test.

Table 56. Test for Variation Between Groups for MB Test.

H_0 : No significant variation in test results between groups

H_1 : Significant variation in test results between groups

ANOVA

	Sum of Squares	Df	Mean Square	F	Sig.
Between Groups	31.518	2	15.759	.810	.453
Within Groups	719.919	37	19.457		
Total	751.437	39			

Testing at a $\alpha = 0.05$ significance level, H_0 is accepted and there is no significant variability in MB test results between the three groups.

Figure 4 graphically represents variability in MB test results between aggregate groups.

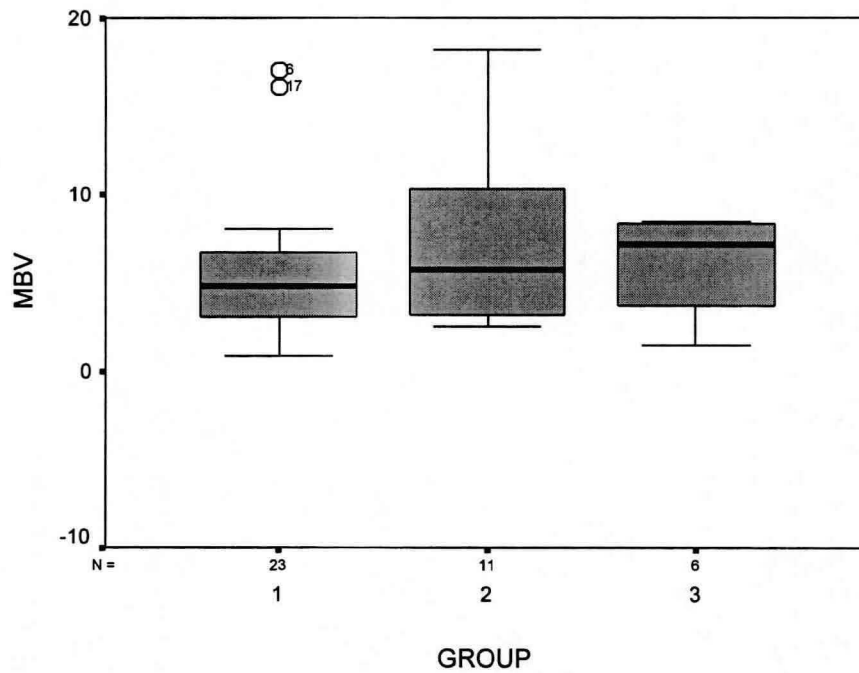


Figure 4. Variability in MB Test Results Between Aggregate Groups.

Tables 57, 58, and 59 show sensitivity analysis results for limestone, gravel, and igneous aggregates, respectively.

Table 57. Sensitivity of MB Test Among Limestone Aggregates.

H_0 : Test not sensitive among aggregates from same group

H_1 : Test sensitive among aggregates from same group

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	1119.645	22	50.893	1404.645	.000
Within Groups	1.667	46	3.623E-02		
Total	1121.312	68			

Student-Newman-Keuls

	N	Subset for alpha = .05												
GROUP		1	2	3	4	5	6	7	8	9	10	11	12	13
19	3	.917												
16	3	1.083												
12	3		1.667											
14	3			2.167										
21	3			2.417										
20	3				2.917									
8	3				3.167	3.167								
18	3				3.250	3.250								
7	3					3.500	3.500							
23	3					3.500	3.500							
22	3						3.667							
13	3							4.833						
11	3								5.333					
10	3								5.583					
2	3									6.083				
15	3									6.167				
1	3									6.417				
5	3										7.083			
9	3										7.333			
4	3											8.000		
3	3											8.083		
17	3												16.167	
6	3													17.083
Sig.		.289	1.000	.115	.092	.154	.536	1.000	.115	.092	.115	.594	1.000	1.000

Testing at $\alpha = 0.05$ significance level, H_0 is rejected and MB test is sensitive to aggregates among limestone group.

Table 58. Sensitivity of MB Test Among Gravel Aggregates.

H_0 : Test not sensitive among aggregates from same group

H_1 : Test sensitive among aggregates from same group

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	917.178	10	91.718	1562.161	.000
Within Groups	1.292	22	5.871E-02		
Total	918.470	32			

Student-Newman-Keuls

	N	Subset for alpha = .05								
GROUP		1	2	3	4	5	6	7	8	9
4	3	2.583								
6	3	2.667								
8	3		3.083							
1	3		3.167							
3	3			3.750						
5	3				5.750					
10	3					7.167				
11	3						9.833			
9	3							11.000		
7	3								15.833	
2	3									18.250
Sig.		.678	.678	1.000	1.000	1.000	1.000	1.000	1.000	1.000

Testing at $\alpha = 0.05$ significance level, H_0 is rejected and MB test is sensitive to aggregates among gravel group.

Table 59. Sensitivity of MB Test Among Igneous Aggregates.H₀: Test not sensitive among aggregates from same groupH₁: Test sensitive among aggregates from same group

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	122.934	5	24.587	1011.571	.000
Within Groups	.292	12	2.431E-02		
Total	123.226	17			

Student-Newman-Keuls

	N	Subset for alpha = .05				
GROUP		1	2	3	4	5
5	3	1.500				
1	3		3.667			
2	3			6.667		
4	3				7.667	
3	3					8.417
6	3					8.500
Sig.		1.000	1.000	1.000	1.000	.525

Testing at $\alpha = 0.05$ significance level, H₀ is rejected and MB test is sensitive to aggregates among igneous group.

Particle Size Analysis of Soils

Particle Size Distribution at 0.005 mm Diameter Size

Table 60 shows the descriptive statistics for the Hydrometer test results at 0.005 mm diameter size.

Table 60. Descriptive Statistics for Hydrometer Test at 0.005 mm Diameter.

Group	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
1	23	15.7565	7.4013	1.5433	12.5559	18.9571	6.40	32.60
2	11	7.7364	4.6672	1.4072	4.6009	10.8718	2.20	16.40
3	6	10.0000	5.2832	2.1568	4.4556	15.5444	5.60	19.70
Total	40	12.6875	7.3243	1.1581	10.3451	15.0299	2.20	32.60

Table 61 shows Levene statistic test result for homogeneity of variance for the Hydrometer test results at 0.005 mm diameter size.

Table 61. Test of Homogeneity of Variance for Percent Passing 0.005 mm Diameter Size.

H₀: Equal variance in test results for all groups

H₁: Significant variance in test results for all groups

Levene Statistic	df1	df2	Sig.
1.643	2	37	.207

Testing at a $\alpha = 0.05$ significance level, H₀ is accepted and there is no significant variability in Hydrometer test results for all groups at 0.005 mm diameter size.

Table 62 shows the ANOVA test results for variation in test results between all aggregate groups.

Table 62. Test of Variation Between Groups for Percent Passing 0.005 mm Diameter Size.

H₀: No significant variation in test results between groups

H₁: Significant variation in test results between groups

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	529.622	2	264.811	6.271	.005
Within Groups	1562.542	37	42.231		
Total	2092.164	39			

Testing at a $\alpha = 0.05$ significance level, H₀ is rejected and there is significant variability for the Hydrometer test results at 0.005 mm diameter size.

Since the ANOVA table shows significant variation in test results between the three aggregate groups, pair-wise comparisons of group means were conducted using Bonferroni analysis.

Table 63 shows Bonferroni test results for analysis of variation within groups for the Hydrometer test results at 0.005 mm diameter size.

Table 63. Analysis of Variation Within Groups for Percent Passing 0.005 mm Diameter Size.

Multiple Comparisons
Bonferroni

		Mean Difference (I-J)	Std. Error	Sig.	90% Confidence Interval	
(I) GROUP	(J) GROUP				Lower Bound	Upper Bound
1	2	8.0202	2.3823	.005*	2.7541	13.2862
	3	5.7565	2.9790	.183	-.8286	12.3417
2	1	-8.0202	2.3823	.005*	-13.2862	-2.7541
	3	-2.2636	3.2981	1.000	-9.5542	5.0269
3	1	-5.7565	2.9790	.183	-12.3417	.8286
	2	2.2636	3.2981	1.000	-5.0269	9.5542

* The mean difference is significant at the 0.005 level.

Testing at a $\alpha = 0.005$ significance level, there is significant variability in limestone and gravel aggregates. However, no significant variation is observed between limestone and igneous or between gravel and igneous aggregates.

Figure 5 graphically represents variability for the Hydrometer test results at 0.005 mm diameter size between aggregate groups.

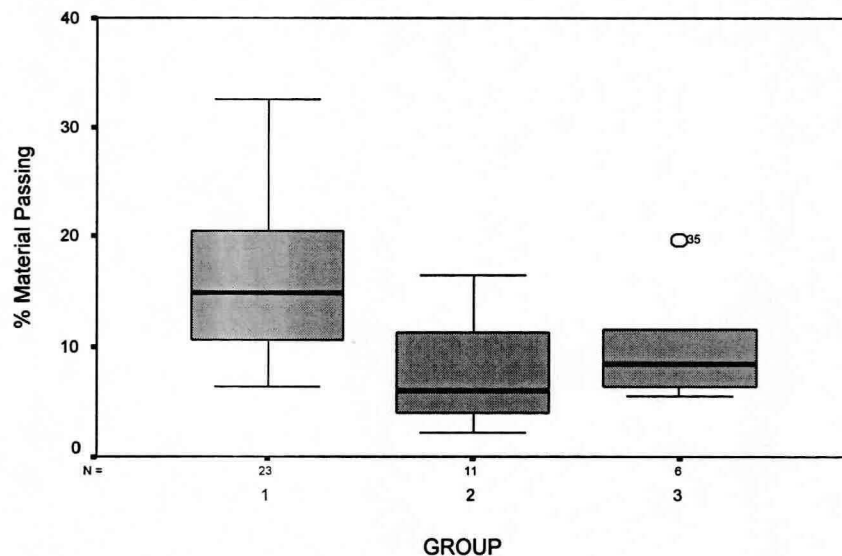


Figure 5. Variability in Hydrometer Test Results Between Aggregate Groups for Percent Passing 0.005 mm Diameter Size.

Particle Size Distribution at 0.001 mm Diameter Size

Table 64 shows the descriptive statistics for the Hydrometer test results at 0.001 mm diameter size.

Table 64. Descriptive Statistics for Hydrometer Test at 0.001 mm Diameter.

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
1	23	8.4826	2.9930	.6241	7.1884	9.7769	4.20	14.20
2	11	5.2455	2.7384	.8257	3.4058	7.0851	1.10	10.00
3	6	5.4333	3.1576	1.2891	2.1196	8.7471	.80	10.60
Total	40	7.1350	3.2829	.5191	6.0851	8.1849	.80	14.20

Table 65 shows Levene statistic test result for homogeneity of variance for the Hydrometer test results at 0.001 mm diameter size.

Table 65. Test of Homogeneity of Variance for Percent Passing 0.001 mm Diameter Size.

H₀: Equal variance in test results for all groups

H₁: Significant variance in test results for all groups

Levene Statistic	df1	df2	Sig.
.342	2	37	.713

Testing at a $\alpha = 0.05$ significance level, H₀ is accepted and there is no significant variability in Hydrometer test results at 0.001 mm diameter size for all groups.

Table 66 shows the ANOVA test results for variation in test results between all aggregate groups.

Table 66. Test of Variation Between Groups for Percent Passing 0.001 mm Diameter Size.

H₀: No significant variation in test results between groups

H₁: Significant variation in test results between groups

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	98.417	2	49.209	5.656	.007
Within Groups	321.914	37	8.700		
Total	420.331	39			

Testing at a $\alpha = 0.05$ significance level, H₀ is rejected and there is significant variability for the Hydrometer test results at 0.001 mm diameter size.

Since the ANOVA table shows significant variation in test results between the three aggregate groups, pair-wise comparisons of group means were conducted using Bonferroni analysis.

Table 67 shows Bonferroni test results for analysis of variation within groups for the Hydrometer test results at 0.001 mm diameter size.

Table 67. Analysis of Variation Within Groups for Percent Passing 0.001 mm Diameter Size.

Multiple Comparisons
Bonferroni

		Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
(I) GROUP	(J) GROUP				Lower Bound	Upper Bound
1	2	3.2372	1.0813	.015*	.5255	5.9488
	3	3.0493	1.3522	.090	-.3416	6.4401
2	1	-3.2372	1.0813	.015*	-5.9488	-.5255
	3	-.1879	1.4970	1.000	-3.9420	3.5662
3	1	-3.0493	1.3522	.090	-6.4401	.3416
	2	.1879	1.4970	1.000	-3.5662	3.9420

The mean difference is significant at the 0.05 level.

Testing at a $\alpha = 0.05$ significance level, there is significant variability in limestone and gravel aggregates.

However, no significant variation is observed between limestone and igneous or between gravel and igneous aggregates.

Figure 6 graphically represents variability for the Hydrometer test results at 0.001 mm diameter size between aggregate groups.

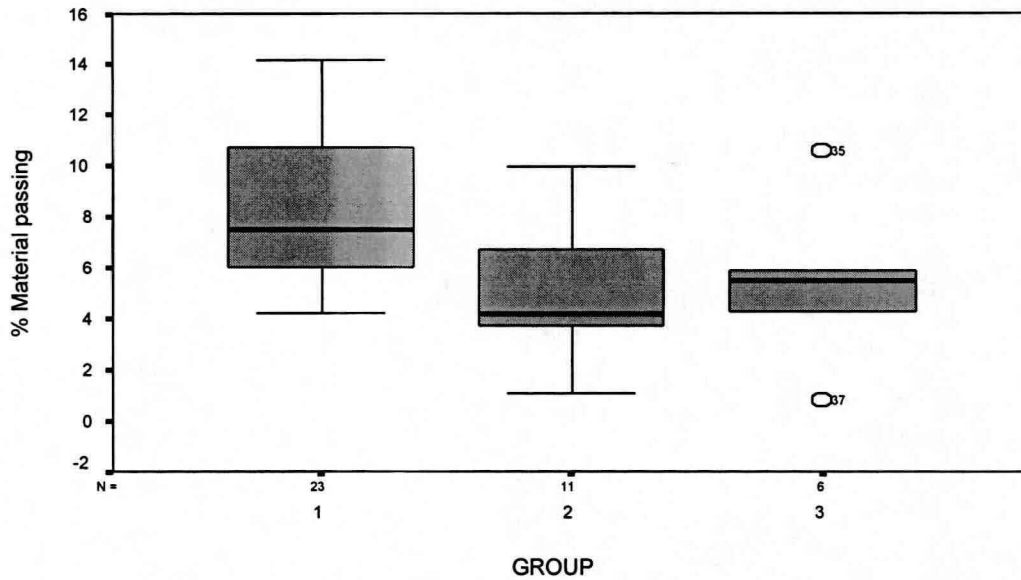


Figure 6. Variability in Hydrometer Test Results Between Aggregate Groups for Percent Passing 0.001 mm Diameter Size.

Flat and Elongated Test on Coarse Aggregate

Aggregates Retained on 3/8 Inch Sieve

Table 68 shows the descriptive statistics for F&E test for material retained on 3/8" sieve.

Table 68. Descriptive Statistics for Flat and Elongated Test (3/8 Inch Sieve Retained).

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
1	23	2.535	3.030	.632	1.225	3.845	0	11.7
2	11	1.809	2.728	.822	-2.347E-02	3.642	0	9.4
3	6	3.267	2.459	1.004	.686	5.847	0	6.0
Total	40	2.445	2.843	.450	1.536	3.354	0	11.7

Table 69 shows Levene statistic test result for homogeneity of variance for the F&E test and material retained on 3/8 inch sieve.

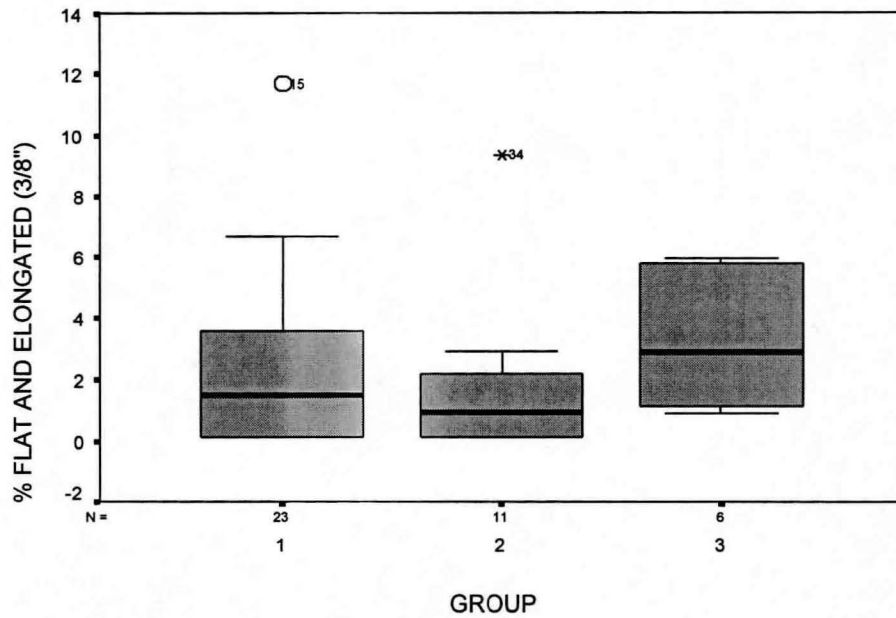


Figure 7. Variability Between Aggregate Groups for Percent Flat and Elongated Particles Retained on 3/8 Inch Sieve Using ASTM D 4791.

Aggregates Retained on 4.75 mm Sieve

Table 71 shows the descriptive statistics for F&E test for material retained on 4.75 mm sieve.

Table 71. Descriptive Statistics for Flat and Elongated Test (4.75 mm Sieve Retained).

Group	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
1	23	8.5435	7.7594	1.6180	5.1880	11.8989	.10	28.20
2	11	2.9909	2.4394	.7355	1.3521	4.6298	.10	7.00
3	6	10.4500	5.5756	2.2762	4.5988	16.3012	3.00	18.00
Total	40	7.3025	6.8667	1.0857	5.1064	9.4986	.10	28.20

Table 72 shows Levene statistic test result for homogeneity of variance for the F&E test and material retained on 4.75 mm sieve.

Table 72. Test of Homogeneity of Variance for Percent Flat and Elongated Particles Retained on 4.75 mm Sieve.

H₀: Equal variance in test results for all groups

H₁: Significant variance in test results for all groups

Levene Statistic	df1	df2	Sig.
6.429	2	37	.004

Testing at a $\alpha = 0.05$ significance level, H₀ is rejected and there is significant variability in F&E results for material retained on 4.75 mm sieve for all groups.

Table 73 shows the ANOVA test results for variation in test results between all aggregate groups.

Table 73. Test of Variation Between Groups for Percent Flat and Elongated Particles Retained on 4.75 mm Sieve.

H₀: No significant variation in test results between groups

H₁: Significant variation in test results between groups

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	299.349	2	149.675	3.597	.037
Within Groups	1539.541	37	41.609		
Total	1838.890	39			

Testing at a $\alpha = 0.05$ significance level, H₀ is rejected and there is significant variability for material retained on 4.75 mm sieve size.

Since the ANOVA table shows significant variation in test results between the three aggregate groups, pair-wise comparisons of group means were conducted using Bonferroni analysis.

Table 74 shows Bonferroni test results for analysis of variation within groups for the F&E test and material retained on 4.75 mm sieve.

Table 74. Analysis of Variation Within Groups for Percent Flat and Elongated Particles Retained on 4.75 mm Sieve.

Multiple Comparisons
Bonferroni

		Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
(I) GROUP	(J) GROUP				Lower Bound	Upper Bound
1	2	5.5526	2.3647	.073	-.3774	11.4826
	3	-1.9065	2.9570	1.000	-9.3219	5.5089
2	1	-5.5526	2.3647	.073	-11.4826	.3774
	3	-7.4591	3.2738	.086	-15.6688	.7506
3	1	1.9065	2.9570	1.000	-5.5089	9.3219
	2	7.4591	3.2738	.086	-.7506	15.6688

Testing at a $\alpha = 0.05$ significance level, there is no significant variability between the three groups.

Figure 8 graphically represents variability for the F&E test results for material retained on 4.75 mm sieve.

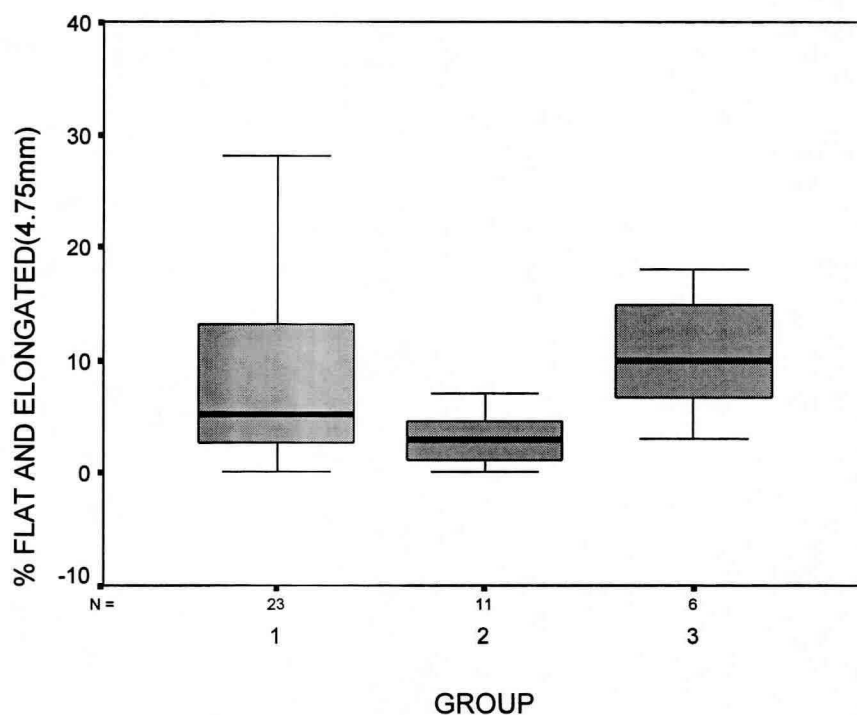


Figure 8. Variability Between Aggregate Groups for Percent Flat and Elongated Particles Retained on 4.75 mm Sieve Using ASTM D 4791.

Flat and Elongated Test on Coarse Aggregate Using MRA Caliper

Aggregates Retained on 3/8 Inch Sieve

Table 75 shows the descriptive statistics for automated F&E test and material retained on 3/8 inch sieve.

TABLE. 75. Descriptive Statistics for Automated Flat and Elongated Test (3/8 Inch Sieve Retained).

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
1	23	1.3409	2.0282	.4229	.4638	2.2179	0.00	7.21
2	11	1.3492	3.2802	.9890	-.8544	3.5529	0.00	10.38
3	6	2.4884	2.3323	.9521	4.077E-02	4.9359	0.00	6.25
Total	40	1.5153	2.4389	.3856	.7353	2.2953	0.00	10.38

Table 76 shows Levene statistic test result for homogeneity of variance for the automated F&E test and material retained on 3/8 inch sieve.

Table 76. Test of Homogeneity of Variance for Percent Flat and Elongated Particles Retained on 3/8 Inch Sieve .

H₀: Equal variance in test results for all groups

H₁: Significant variance in test results for all groups

Levene Statistic	df1	df2	Sig.
.614	2	37	.547

Testing at a $\alpha = 0.05$ significance level, H₀ is accepted and there is no significant variability in F&E results for material retained on 3/8 inch sieve for all groups.

Table 77 shows the ANOVA test results for variation in test results between all aggregate groups.

Table 77. Test of Variation Between Groups for Percent Flat and Elongated Particles Retained on 3/8 Inch Sieve.

H_0 : No significant variation in test results between groups

H_1 : Significant variation in test results between groups

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	6.684	2	3.342	.549	.582
Within Groups	225.289	37	6.089		
Total	231.973	39			

Testing at a $\alpha = 0.05$ significance level, H_0 is accepted and there is no significant variability for material retained on 3/8 inch sieve size.

Figure 9 graphically represents variability between aggregate groups for the automated F&E test results for material retained on 3/8 inch sieve.

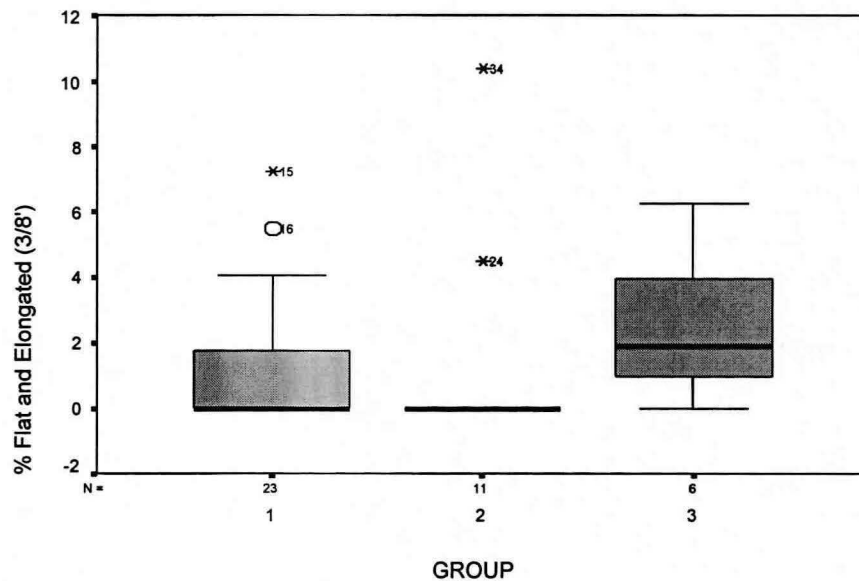


Figure 9. Variability Between Aggregate Groups for Percent Flat and Elongated Particles Retained on 3/8 Inch Sieve Using MRA Digital Caliper.

Aggregates Retained on 4.75 mm Sieve

Table 78 shows the descriptive statistics for automated F&E test for material retained on 4.75 mm sieve.

Table 78. Descriptive Statistics for Automated Flat and Elongated Test (4.75 mm Sieve Retained).

Group	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
1	23	6.781	7.128	1.486	3.699	9.864	0.0	23.5
2	11	2.763	2.533	.764	1.061	4.465	0.0	6.9
3	6	6.474	5.725	2.337	.467	12.482	0.0	16.4
Total	40	5.630	6.142	.971	3.666	7.594	0.0	23.5

Table 79 shows Levene statistic test result for homogeneity of variance for the F&E test for material retained on 4.75 mm sieve.

Table 79. Test of Homogeneity of Variance for Percent Flat and Elongated Particles Retained on 4.75 mm Sieve.

H₀: Equal variance in test results for all groups

H₁: Significant variance in test results for all groups

Levene Statistic	df1	df2	Sig.
4.999	2	37	.012

Testing at a $\alpha = 0.05$ significance level, H₀ is rejected and there is significant variability in F&E results for material retained on 4.75 mm sieve for all groups.

Table 80 shows the ANOVA test results for variation in test results between all aggregate groups.

Table 80. Test of Variation Between Groups for Percent Flat and Elongated Particles (4.75 mm Sieve Retained).

H₀: No significant variation in test results between groups

H₁: Significant variation in test results between groups

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	125.176	2	62.588	1.721	.193
Within Groups	1345.881	37	36.375		
Total	1471.057	39			

Testing at a $\alpha = 0.05$ significance level, H₀ is accepted and there is no significant variability in F&E results for material retained on 4.75 mm sieve for all groups.

Figure 10 graphically represents variability between aggregate groups for the automated F&E test results for material retained on 4.75 mm sieve.

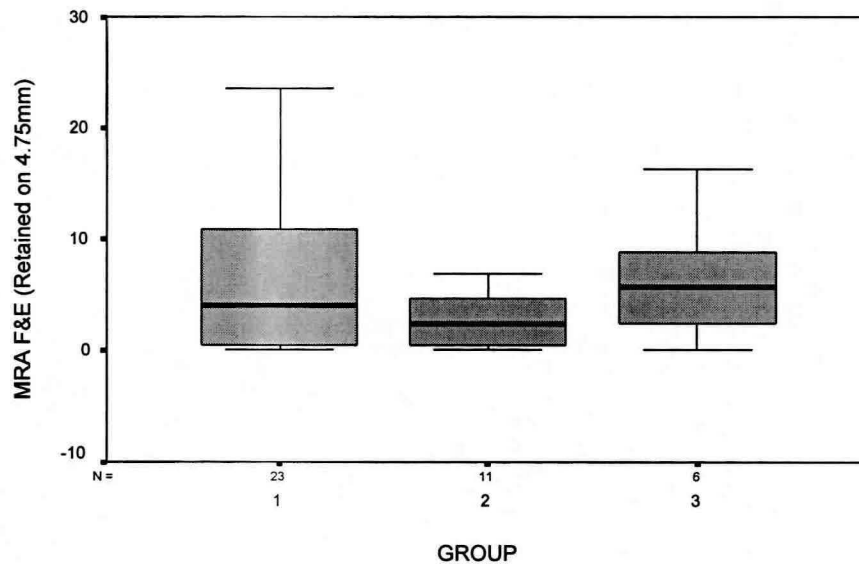


Figure 10. Variability Between Aggregate Groups for Percent Flat and Elongated Particles Retained on 4.75 mm Sieve Using MRA Digital Caliper.

Correlation Between Tests Evaluating Aggregate Properties

Correlations between test results were analyzed to determine how closely and discretely different tests predicted similar measured properties. Correlations between FAA and CAR, MBV and Hydrometer, and CAR and Hydrometer were particularly of interest as they were assumed to evaluate similar aggregate characteristics. Both correlations among all aggregate groups, as well as within groups, were analyzed.

Correlation Between Test Results for All Aggregate Groups

Table 81 illustrates correlation between fine aggregate tests for all three groups.

Table 81. Correlation Between Fine Aggregate Tests (All Groups).

Test		MBV	HYD (0.005mm)	HYD (0.001 mm)	UVC	CAR	Remarks
MBV	Pearson Correlation	1.000	.173	.159	-.041	.046	A weak linear relationship between MBV and Hydrometer (0.005 mm) and Hydrometer (0.001 mm)
	Sig. (2-tailed)		.286	.327	.803	.776	No significant correlation between MBV and any other test
HYD 0.005 mm	Pearson Correlation	.173	1.000	.894*	.165	.302	A linear relationship between Hydrometer (0.005 mm) and CAR
	Sig. (2-tailed)	.286		.000	.310	.058	Correlation between Hydrometer (0.005 mm), and Hydrometer (0.001 mm), and CAR
HYD 0.001	Pearson Correlation	.159	.894*	1.000	.067	.346	A linear relationship between Hydrometer (0.001 mm) and CAR
	Sig. (2-tailed)	.327	.000		.681	.029	Significant correlation between Hydrometer (0.001 and CAR
UVC	Pearson Correlation	-.041	.165	.067	1.000	.261	A weak linear relationship between UVC and CAR.
	Sig. (2-tailed)	.803	.310	.681		.104	No significant correlation between UVC and any other test
CAR	Pearson Correlation	.046	.302	.346	.261	1.000	A linear relationship between Hydrometer (0.001 mm) and CAR
	Sig. (2-tailed)	.776	.058	.029	.104		Strong Correlation between CAR and Hydrometer (0.001 mm)

*Significant linear relationship correlation at 0.05 level

Table 82 illustrates correlation between ASTM D 4791 test results for F&E particles retained on 3/8 inch and 4.75 mm sieves for all three groups.

Table 82. Correlation Between Flat and Elongated Test Results ASTM D 4791 (All Groups).

		Flat and Elongated (3/8 inch)	Flat and Elongated (4.75 mm)	Remarks
Flat and Elongated (3/8 inch)	Pearson Correlation	1.000	.412**	Linear relationship between flat and elongated retained on 3/8 inch and No. 4 sieve
	Sig. (2-tailed)		.008	Significant correlation between flat and elongated retained on 3/8 inch and No. 4 sieve
Flat and Elongated (4.75 mm)	Pearson Correlation	.412**	1.000	Linear relationship between flat and elongated retained on 3/8 inch and No. 4 sieve
	Sig. (2-tailed)	.008		Significant correlation between flat and elongated retained on 3/8 inch and No. 4 sieve

** Correlation is significant at the 0.01 level (2-tailed).

Table 83 illustrates correlation between Digital MRA Caliper and ASTM D 4791 test results for F&E particles retained on 3/8 inch and 4.75 mm sieves for all three groups.

Table 83. Correlation Between Flat and Elongated Test Results Using MRA Caliper (All Groups).

		MRA F&E(Retained on 3/8 inch)	MRA F&E (Retained on 4.75 mm)	Remarks
MRA F&E(Retained on 3/8 inch)	Pearson Correlation	1.000	.400**	Linear relationship between flat and elongated retained on 3/8 inch and No. 4 sieve
	Sig. (2-tailed)		.011	Significant correlation between flat and elongated retained on 3/8 inch and No. 4 sieve
MRA F&E (Retained on 4.75mm)	Pearson Correlation	.400	1.000	Linear relationship between flat and elongated retained on 3/8 inch and No. 4 sieve
	Sig. (2-tailed)	.011		Significant correlation between flat and elongated retained on 3/8 inch and No. 4 sieve

** Correlation is significant at the 0.01 level (2-tailed).

Table 84 illustrates correlation between Digital MRA Caliper and ASTM D 4791 test results for F&E particles retained on 3/8 inch sieve for all three groups.

Table 84. Correlation Between MRA Caliper and ASTM D 4791 Flat and Elongated Test (All Groups Retained on 3/8 Inch Sieve).

		Flat and Elongated (3/8 inch)	MRA F&E (Retained on 3/8 inch)	Remarks
Flat and Elongated (3/8 inch)	Pearson Correlation	1.000	.628**	Strong linear relationship between flat and elongated test results from ASTM and MRA
	Sig. (2-tailed)	.	.000	Significant correlation between flat and elongated test results from ASTM and MRA
MRA F&E(Retained on 3/8 inch)	Pearson Correlation	.628**	1.000	Strong linear relationship between flat and elongated test results from ASTM and MRA
	Sig. (2-tailed)	.000	.	Significant correlation between flat and elongated test results from ASTM and MRA

** Correlation is significant at the 0.01 level (2-tailed).

Table 85 illustrates correlation between Digital MRA Caliper and ASTM D 4791 test results for F&E particles retained on 4.75 mm sieve for all three groups.

Table 85. Correlation Between MRA Caliper and ASTM D 4791 Flat and Elongated Test (All Groups Retained on 4.75 mm Sieve).

		Flat and Elongated (4.75 mm)	MRA F&E (Retained on 4.75 mm)	Remarks
Flat and Elongated (4.75 mm)	Pearson Correlation	1.000	.692**	Strong linear relationship between flat and elongated test results from ASTM and MRA digital caliper
	Sig. (2-tailed)		.000	Significant correlation between flat and elongated test results from ASTM and MRA digital caliper
MRA F&E (Retained on 4.75 mm)	Pearson Correlation	.692**	1.000	Strong linear relationship between flat and elongated test results from ASTM and MRA digital caliper
	Sig. (2-tailed)	.000		Significant correlation between flat and elongated test results from ASTM and MRA digital caliper

** Correlation is significant at the 0.01 level (2-tailed).

Correlation Between Test Results for Limestone Aggregates

Table 86 illustrates correlation between fine aggregate tests for limestone aggregates.

Table 86. Correlation Between Fine Aggregate Tests for Limestone Group.

		MBV	HYD (0.005mm)	HYD (0.001mm)	UVC	CAR	Remarks
MBV	Pearson Correlation	1.000	.321	.325	.142	.232	A weak linear relationship between MBV and hydrometer (0.005 mm) and hydrometer (0.001mm), and CAR
	Sig. (2-tailed)		.135	.130	.518	.287	No significant correlation between MBV and any other test
HYD (0.005 mm)	Pearson Correlation	.321	1.000	.846**	.255	.063	Strong linear correlation between Hydrometer (0.005 mm) and Hydrometer (0.001 mm) and a weak linear relationship between MBV and Hydrometer (0.005 mm)
	Sig. (2-tailed)	.135		.000	.240	.774	Significant correlation between Hydrometer (0.005mm) and Hydrometer (0.001 mm)
HYD (0.001 mm)	Pearson Correlation	.325	.846	1.000	.182	.139	A weak relationship between hydrometer (0.005 mm) and CAR
	Sig. (2-tailed)	.130	.000		.405	.527	Significant correlation between Hydrometer (0.001mm) and Hydrometer (0.005 mm)
UVC	Pearson Correlation	.142	.255	.182	1.000	-.006	A weak linear relationship between UVC and Hydrometer (0.005 mm)
	Sig. (2-tailed)	.518	.240	.405		.980	No significant correlation between UVC and any other test
CAR	Pearson Correlation	.232	.063	.139	-.006	1.000	A weak linear relationship between MBV and CAR
	Sig. (2-tailed)	.287	.774	.527	.980		No significant correlation between CAR and any other test

** Correlation is significant at the 0.01 level (2-tailed).

Table 87 illustrates correlation between ASTM D 4791 test results for F&E particles retained on 3/8 inch and 4.75 mm sieves for limestone aggregates.

Table 87. Correlation Between Flat and Elongated Test for Limestone Group (ASTM D 4791).

		Flat and Elongated (3/8 inch)	Flat and Elongated (4.75 mm)	Remarks
Flat and Elongated (3/8 inch)	Pearson Correlation	1.000	.411*	Linear relationship between flat and elongated retained on 3/8 inch and No. 4 sieve
	Sig. (2-tailed)		.051	Significant correlation between flat and elongated retained on 3/8 inch and No. 4 sieve
Flat and Elongated (4.75 mm)	Pearson Correlation	.411	1.000	Linear correlation between flat and elongated retained on 3/8" and No.4 sieve
	Sig. (2-tailed)	.051		Significant correlation between flat and elongated retained on 3/8 inch and No. 4 sieve

* Correlation is significant at the 0.05 level (2-tailed).

Correlation Between Test Results for Gravel Aggregates

Table 88 illustrates correlation between fine aggregate tests for gravel aggregates.

TABLE. 88. Correlation Between Fine Aggregate Tests for Gravel Group.

		MBV	HYD (0.005 mm)	HYD (0.001 mm)	UVC	CAR	Remarks
MBV	Pearson Correlation	1.000	.578	.446	-.345	.171	A linear relationship between MBV, Hydrometer (0.005 mm) and Hydrometer (0.001 mm). A negative linear relationship between UVC and MBV
	Sig. (2-tailed)		.063	.169	.298	.615	Significant correlation between MBV and Hydrometer (0.005 mm)
HYD (0.005 mm)	Pearson Correlation	.578	1.000	.978**	-.256	.325	Linear relationship between Hydrometer (0.005 mm) and Hydrometer (0.001 mm) and MBV
	Sig. (2-tailed)	.063		.000	.448	.329	Significant correlation between Hydrometer (0.005 mm) and Hydrometer (0.001) and MBV
HYD (0.001 mm)	Pearson Correlation	.446	.978**	1.000	-.246	.372	Linear relationship between Hydrometer (0.001 mm), MBV and CAR. A negative linear relationship between UVC and Hydrometer (0.001 mm)
	Sig. (2-tailed)	.169	.000		.465	.261	Significant correlation between Hydrometer (0.001 mm) and Hydrometer (0.005 mm)
UVC	Pearson Correlation	-.345	-.256	-.246	1.000	.436	A weak negative linear relation between UVC and Hydrometer (0.005 mm), and MBV
	Sig. (2-tailed)	.298	.448	.465		.180	No significant correlation between UVC and any other test
CAR	Pearson Correlation	.171	.325	.372	.436	1.000	A weak linear relation between UVC and CAR
	Sig. (2-tailed)	.615	.329	.261	.180		No significant correlation between CAR and any other test

** Correlation is significant at the 0.01 level (2-tailed).

Table 89 illustrates correlation between ASTM D 4791 test results for F&E particles retained on 3/8 inch and 4.75 mm sieves for gravel aggregates.

Table 89. Correlation Between Flat and Elongated Test for Gravel Group (ASTM D 4791).

		Flat and Elongated (3/8 inch)	Flat and Elongated (4.75 mm)	Remarks
Flat and Elongated (3/8 inch)	Pearson Correlation	1.000	.430	Linear relationship between flat and elongated retained on 3/8 inch and No. 4 sieve
	Sig. (2-tailed)		.085	No significant correlation between flat and elongated retained on 3/8 inch and No. 4 sieve
Flat and Elongated (4.75 mm)	Pearson Correlation	.430	1.000	Linear relationship between flat and elongated retained on 3/8 inch and No. 4 sieve
	Sig. (2-tailed)	.085		No significant correlation between flat and elongated retained on 3/8 inch and No. 4 sieve

*Correlation is significant at the 0.05 level (2-tailed).

Correlation Between Test Results for Igneous Aggregates

Table 90 illustrates correlation between fine aggregate tests for igneous aggregates.

Table 90. Correlation Between Fine Aggregate Tests for Igneous Group.

		MBV	HYD (0.005 mm)	HYD (0.001 mm)	UVC	CAR	Remarks
MBV	Pearson Correlation	1.000	-.347	-.392	.555	-.509	A negative linear relationship between MBV Hydrometer (0.005 mm) and Hydrometer (0.001 mm) and CAR
	Sig. (2-tailed)		.500	.442	.253	.302	No significant correlation between MBV and any other test
HYD (0.005 mm)	Pearson Correlation	-.347	1.000	.907*	-.217	-.045	Strong linear relationship between Hydrometer (0.005 mm) and Hydrometer (0.001 mm) and MBV. A negative linear relationship between hydrometer (0.005 mm) and MBV
	Sig. (2-tailed)	.500		.012	.680	.933	Significant correlation between Hydrometer (0.005 mm) and Hydrometer (0.001 mm)
HYD (0.001 mm)	Pearson Correlation	-.392	.907*	1.000	-.438	.086	Linear relationship between Hydrometer (0.001 mm), MBV and CAR. A negative linear relationship between UVC and Hydrometer (0.001 mm)
	Sig. (2-tailed)	.442	.012		.384	.871	Significant correlation between Hydrometer (0.001 mm) and Hydrometer (0.005 mm)
UVC	Pearson Correlation	.555	-.217	-.438	1.000	.124	A linear relationship between UVC and MBV and a weak negative linear relation between UVC and hydrometer (0.005 mm), and MBV
	Sig. (2-tailed)	.253	.680	.384		.815	No significant correlation between UVC and any other test
CAR	Pearson Correlation	-.509	-.045	.086	.124	1.000	A negative linear relation between UVC and CAR
	Sig. (2-tailed)	.302	.933	.871	.815		No significant correlation between CAR and any other test

* Correlation is significant at the 0.05 level (2-tailed).

Table 91 illustrates correlation between ASTM D 4791 test results for F&E particles retained on 3/8 inch and 4.75 mm sieves for igneous aggregates.

Table 91. Correlation Between Flat and Elongated Test Results for Igneous Group (ASTM D 4791).

		Flat and Elongated (3/8 inch)	Flat and Elongated (4.75 mm)	Remarks
Flat and Elongated (3/8 inch)	Pearson Correlation	1.000	.058	No linear correlation between flat and elongated retained on 3/8 inch and No. 4 sieve
	Sig. (2-tailed)		.913	No significant correlation between flat and elongated retained on 3/8 inch and No. 4 sieve
Flat and Elongated (4.75 mm)	Pearson Correlation	.058	1.000	No linear correlation between flat and elongated retained on 3/8 inch and No. 4 sieve
	Sig. (2-tailed)	.913		No significant correlation between flat and elongated retained on 3/8 inch and No. 4 sieve

Analysis of Variance for Two-Way Classification Fixed Effects Model

In order to evaluate the effect of testing technique, aggregate type, and their interaction on overall test results, a two-way analysis of variance test was performed. This analysis was used for determining the sensitivity of test method and aggregate source on results.

Table 92 illustrates results for the analysis of variance for a two-way classification model.

Table 92. Fixed Effects Model.

Source		Type III Sum of Squares	Df	Mean Square	F	Sig.
Intercept	Hypothesis	107285935.460	1	107285935.460	133.063	.006
	Error	1712251.168	2.124	806276.659		
TEST	Hypothesis	411918921.416	4	102979730.354	130.496	.000
	Error	6712120.701	8.506	789143.011		
GROUP	Hypothesis	1794174.146	2	897087.073	1.022	.402
	Error	7019544.842	8	877443.105		
TEST * GROUP	Hypothesis	7019544.842	8	877443.105	4.706	.000
	Error	34496914.123	185	186469.806		

Testing at $\alpha = 0.05$ significance level, a significant effect of the test technique and interaction of test and group on overall results are observed. However, the effect of different aggregate groups is not observed to be significant on the overall results.

WET WEATHER TEST SELECTION CRITERIA

Based on the analysis of variability among the fine aggregate groups for various tests and the sensitivity of each test to monitor aggregate properties, a process was used for selecting tests that could monitor changes in aggregate properties effectively and with precision. Table 93 summarizes the selection process.

Fine Aggregate Tests

Sensitivity

Results from the Student-Newman-Keuls (S-N-K) analysis were used for evaluating the level of sensitivity of tests to aggregates from different sources and environmental regions. Sensitivity of UVC, CAR, and MB tests to aggregates were determined using replicate test results for each sample tested. The level of sensitivity of each test was evaluated between groups as well as within each aggregate group to determine whether the test could effectively discriminate aggregates with good and marginal performance levels.

Each test was classified as having a high, medium or low sensitivity test based on the number of subgroups listed from the S-N-K analysis. The following methodology showed the sensitivity classification:

- High – S-N-K analysis subgroups higher than the median value of all aggregate samples evaluated,
- Medium – S-N-K analysis subgroups within one negative standard deviation of the median value of all aggregate samples evaluated, and

- Low – S-N-K analysis subgroups lower than one negative standard deviation of the median value of all aggregate samples evaluated.

Table 93. Selection Process for Fine Aggregate Tests.

Index Test	Aggregate Property	Variability Between	Groups Varying	Sensitivity Between All Groups Results	Sensitivity within Group Results			Aggregate Selection
		All Group Results	Significantly		Limestone	Gravel	Igneous	
Uncompacted Void Content	Fine Aggregate Angularity	Low		Medium (18)*	Medium (13)*	High (9)*	High (4)*	YES
Compacted Aggregate Resistance	Fine Aggregate Angularity and Distribution	High	Limestone-Gravel	Low (7)*	Low (4)*	Low (5)*	Low (2)*	NO
Methylene Blue	Deleterious Material	Low		High (24)*	Medium (13)*	High (9)*	High (5)*	YES
Particle Size Analysis of Filler Material	Diameter and Proportion of Filler Material	High	Limestone-Gravel					YES

Note: ()* represents subgroups for aggregate test results from Student-Newman-Keuls Test.

Correlations

Correlations between test results determined how closely and discretely different tests predicted similar measured properties in order to eliminate aggregate tests that are cumbersome and laborious in terms of reproducibility and consistency of results.

Table 94 illustrates correlation between fine aggregate tests for all aggregate groups.

TABLE. 94. Correlation Matrix for Fine Aggregate Tests (All Groups).

		MBV	HYD 0.005	HYD 0.001	UVC	CAR
Correlation	MBV	1.000	.173	.159	-.041	.046
	HYD0.005	.173	1.000	.894	.165	.302
	HYD 0.001	.159	.894	1.000	.067	.346
	UVC	-.041	.165	.067	1.000	.261
	CAR	.046	.302	.346	.261	1.000
Sig. (1-tailed)	MBV		.143	.163	.402	.388
	HYD0.005	.143		.000	.155	.029
	HYD 0.001	.163	.000		.341	.014
	UVC	.402	.155	.341		.052
	CAR	.388	.029	.014	.052	

Testing at $\alpha = 0.05$ significance level, there was a significant correlation between the CAR and Hydrometer test. However no significant correlation was observed between the other tests.

Table 95 illustrates correlation between fine aggregate tests for limestone aggregates.

Table 95. Correlation Matrix for Fine Aggregate Tests (Limestone Aggregates).

		MBV	HYD0.005	HYD 0.001	UVC	CAR
Correlation	MBV	1.000	.321	.325	.142	.232
	HYD0.005	.321	1.000	.846	.255	.063
	HYD 0.001	.325	.846	1.000	.182	.139
	UVC	.142	.255	.182	1.000	-.006
	CAR	.232	.063	.139	-.006	1.000
Sig. (1-tailed)	MBV		.068	.065	.259	.143
	HYD0.005	.068		.000	.120	.387
	HYD 0.001	.065	.000		.203	.264
	UVC	.259	.120	.203		.490
	CAR	.143	.387	.264	.490	

Testing at $\alpha = 0.05$ significance level, there was no significant correlation observed between tests.

Table 96 illustrates correlation between fine aggregate tests for gravel aggregates.

Table 96. Correlation Matrix for Fine Aggregate Tests (Gravel Aggregates).

		MBV	HYD 0.005	HYD 0.001	UVC	CAR
Correlation	MBV	1.000	.584	.451	-.315	.237
	HYD 0.005	.584	1.000	.978	-.263	.196
	HYD 0.001	.451	.978	1.000	-.255	.225
	UVC	-.315	-.263	-.255	1.000	.454
	CAR	.237	.196	.225	.454	1.000
Sig. (1-tailed)	MBV		.030	.082	.173	.241
	HYD 0.005	.030		.000	.218	.282
	HYD 0.001	.082	.000		.225	.253
	UVC	.173	.218	.225		.080
	CAR	.241	.282	.253	.080	

Testing at $\alpha = 0.05$ significance level, there was a significant correlation between the MBV and Hydrometer test. A relationship was also observed between the CAR and the UVC test. However, no significant correlation was observed between other tests.

Table 97 illustrates correlation between fine aggregate tests for igneous aggregates.

Table 97. Correlation Matrix for Fine Aggregate Tests (Igneous Aggregates).

		MBV	HYD 0.005	HYD 0.001	UVC	CAR
Correlation	MBV	1.000	-.347	-.392	.555	-.509
	HYD 0.005	-.347	1.000	.907	-.217	-.045
	HYD 0.001	-.392	.907	1.000	-.438	.086
	UVC	.555	-.217	-.438	1.000	.124
	CAR	-.509	-.045	.086	.124	1.000
Sig. (1-tailed)	MBV		.250	.221	.127	.151
	HYD 0.005	.250		.006	.340	.466
	HYD 0.001	.221	.006		.192	.436
	UVC	.127	.340	.192		.408
	CAR	.151	.466	.436	.408	

Testing at $\alpha = 0.05$ significance level, there was no significant correlation observed between any tests.

Results from the correlation analysis indicate a relationship between proportion of filler material in fine aggregates and CAR stability of the fine aggregate matrix. Also, a correlation between the MB and the Hydrometer test was observed for gravel aggregates. Both tests indicated lower proportion of filler material in terms of clayey material in gravel aggregates. However, no significant correlations were observed between other fine aggregate tests both among aggregate groups as well as within groups.

Table 98 illustrates aggregate tests selected based on the sensitivity and correlation analysis.

Table 98. Selected Aggregate Tests for Evaluating and Monitoring Fine Aggregate Properties.

Index test	Aggregate Property
Uncompacted Void Content	Fine Aggregate Angularity
Methylene Blue	Deleterious Material
Particle Size Analysis of Filler Material	Diameter and Proportion of Filler Material

Coarse Aggregate Tests

Correlations

Table 99 illustrates correlation between MRA Digital Caliper and ASTM D 4791 Flat and Elongated Test for all aggregate groups.

Table 99. Correlation Matrix for MRA Digital Caliper and ASTM D 4791 Flat and Elongated Test (All Groups).

		Flat and Elongated (Retained on 3/8 inch)	Flat and Elongated (Retained on 4.75 mm)	MRA F&E (Retained on 3/8 inch)	MRA F&E (Retained on 4.75 mm)
Correlation	Flat and Elongated (3/8 inch)	1.000	.412	.628	.299
	Flat and Elongated (4.75 mm)	.412	1.000	.327	.692
	MRA F&E(Retained on 3/8 inch)	.628	.327	1.000	.400
	MRA F&E (Retained on 4.75 mm)	.299	.692	.400	1.000
Sig. (1-tailed)	Flat and Elongated (3/8 inch)		.004	.000	.030
	Flat and Elongated (4.75 mm)	.004		.020	.000
	MRA F&E (Retained on 3/8 inch)	.000	.020		.005
	MRA F&E (Retained on 4.75 mm)	.030	.000	.005	

Testing at $\alpha = 0.05$ significance level, there was a significant correlation between ASTM D 4791-99 and the Digital MRA Test for both aggregates retained on the 3/8 inch and 4.75 mm sieves.

Since the ASTM D 4791-99 method is laborious and time consuming, Digital MRA Caliper can be used as a replacement for evaluating flat and elongated particles in coarse aggregates.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

Laboratory experiments were performed to select fine and coarse aggregate tests for evaluation of shape, angularity, surface texture, size distribution, and deleterious fines in aggregates. The research focused on the following six major methods of measurement: the Uncompacted Void Content Test (ASTM C-1252, Method A), the Compacted Aggregate Resistance Test, the Methylene Blue Test, the Hydrometer Test (ASTM D 422-63), the Flat and Elongated Test on coarse aggregates (ASTM D 4791-99), and the Flat and Elongated test on coarse aggregates using the Multiple Ratio Analysis Digital Caliper. Tests were carried out on 40 aggregates from limestone, gravel, and igneous sources. Statistical analyses were performed on test data to evaluate:

- variability in tests results between aggregates groups as well as within aggregate groups, and
- analyze of the sensitivity of the testing technique on aggregates from a range of source and environmental properties.

Correlations between tests were established to evaluate whether some current tests could be supplemented and/or replaced with other tests evaluating similar properties that are less time consuming and more efficient in measuring aggregate properties in terms of consistency and reproducibility of results. Based on the findings of test results and data analysis, the following 13 conclusions and six recommendations include or conclude:

CONCLUSIONS

1. The UVC test did not exhibit variability in test results among aggregates from different groups assuming that different aggregate types yield different results. However, the test generally produces consistent and reproducible results for replicates and is highly sensitive to aggregate angularity both between and within groups. Thus, the UVC test

may consistently be able to discern aggregates in terms of sensitivity based on fine angularity, and surface texture can be used as an index test for determining fine aggregate angularity and texture.

2. Many aggregates among all groups tested were not able to meet the Superpave fine aggregate angularity specification for high traffic conditions. This is a concern for quantifying aggregates with poor and good performance levels. Past research has shown that some good performing aggregates may not have been able to meet the Superpave fine aggregate specifications. Thus, the UVC test results need to be quantified using some other techniques.
3. The CAR test was observed to identify variability among aggregates from different groups, especially limestone and gravel aggregates. However, this test does not discriminate among aggregates with higher stability values due to its limitation of measuring stability to a maximum specified range of 5000 lb. Thus, this test may not be able to effectively differentiate among aggregates with higher stability values.
4. The CAR test results for many aggregates were found to vary for three replicates tested. This may be attributed to the variation within fine aggregate distribution in an "as received" condition. The CAR test may produce consistent and reproducible results if tested using a specific gradation as in the UVC test.
5. The MB test did not effectively show variability among different aggregate groups. However, test results were generally found to be consistent and reproducible. This test is highly sensitive to aggregates both between and within aggregate groups, indicating an ability to effectively discern aggregates with respect to deleterious and organic material in fines. This test can be used as an index test for determining deleterious and organic material in fines.
6. The MBV for most aggregates tested were found to range within excellent and good performance levels as recommended by *NCHRP 4-19*. This could be attributed to the fact

that aggregates tested were quality material, thus indicating lower deleterious and organic material contents in the fine aggregate fraction.

7. The Hydrometer test was observed to effectively show variability among aggregates from different groups, especially limestone and gravel aggregates. Sensitivity of the test between all aggregates and within groups was not analyzed as only one sample for each aggregate was tested. The drawback of this method is the time associated with testing each sample.
8. No significant correlations were observed between the UVC and CAR tests among limestone, gravel, and igneous aggregates.
9. No significant correlation was observed between the CAR and MB tests among limestone, gravel, and igneous aggregates.
10. Significant correlation was observed between the Hydrometer and MB tests among gravel and limestone aggregate groups.
11. CAR stability was found to increase with increasing filler content for all aggregate groups indicating a relationship between the proportion and size of filler material and stability of fine aggregate matrix.
12. Significant correlations were observed between ASTM D 4791-99 and Digital MRA Caliper flat and elongated test methods for aggregates retained on a 3/8 inch sieve and a No. 4.75 mm sieve. Thus, the Digital MRA Caliper can be used as a replacement for ASTM D 4791-99 for evaluating coarse aggregate particle shape and form. This replacement test is fast and can evaluate multiple aggregate ratios at the same time.
13. It appears that the index tests currently used are not closely related as illustrated through the correlation analysis. Although correlations between some aggregate tests were observed, it currently appears that tests monitor independent properties. Thus, all these

tests may be needed to evaluate aggregate characteristics. In addition, results from tests need to be verified using other techniques, such as image analysis, or by laser techniques before selecting the testing protocol.

RECOMMENDATIONS

1. CAR test samples need to be tested at a much higher compression loading than currently specified in order to effectively differentiate between aggregates exhibiting high stability values.
2. The CAR test method should preferably be repeated with a similar gradation as used in the UVC test in order to effectively judge fine aggregate angularity and surface texture. This process may also result in improvements in quantifying fine aggregate shape and angularity that would enable effective screening of aggregates.
3. Since overall correlations between index tests are not very strong, there is a need for application of automated techniques, such as image analysis, for quantifying aggregate angularity and surface texture.
4. Image analysis results should be correlated with index tests to select tests that would enable effective screening and quality control of aggregates based on precision, consistency, and reproducibility of tests.
5. The Digital MRA Caliper can be used as a replacement for the current ASTM D 4791-99 test evaluating flat and elongated particles in coarse aggregate, as it is fast and can evaluate multiple aggregate ratios at the same time.
6. Automated techniques, such as those using lasers, can be used for determining particle size distribution within fine and filler aggregates. Results from these tests need to be correlated with current tests and other automated tests to determine precision, consistency, and reproducibility of test results.

REFERENCES

1. Kandhal, P.S., and Parker, F. *Aggregate Tests Related to Asphalt Concrete Performance in Pavements*. Research Report 405. National Cooperative Highway Research Program, National Research Council, Washington, D.C., 1998.
2. *Superpave Mix Design Guide*, Superpave Series SP-2. Asphalt Institute. Lexington, Kentucky, 1997.
3. Malak, A.U., Papaleontiou, C.G., Fowler, D.W., and Meyer, A.H. *Investigation of the Frictional Resistance of Seal Coat Pavement Surfaces*. Research Report FHWA/TX-89/490-1. Center for Transportation Research, Austin, Texas, June 1988.
4. Malak, A.U., Papaleontiou, C.G., Fowler, D.W., and Meyer, A.H. *A Comprehensive Methodology for Predicting Field Skid Resistance of Bituminous Aggregates Based on Laboratory Test Data as well as Their Past Skid Performance*. Research Report 0-1459. Texas Department of Transportation, Austin, Texas, September 1998.
5. Papaleontiou, C.G., Meyer A.H., and Fowler, D.W. *Evaluation of the 4-Cycle Magnesium Sulfate Test*. Technical Report-FHWA/TX-88/438-1F. Center for Transportation Research, Austin, Texas, November 1987.
6. Fu, C. N., and Little, D.N. Laboratory Testing to Predict Frictional Performance. *Proc., 9th Annual Symposium*, International Center for Aggregate Research, Austin, Texas, 22-25 April 2001.
7. Fu, C.N. Predicting Surface Friction -What Do We Want and What Do We Know? *Proc., 8th Annual Symposium*, International Center for Aggregate Research, Denver, Colorado, 12-14 April 2000.
8. Herrera, C.H., and Fults, K.W. Texas Department of Transportation Skid Reduction Program. *Proc., 8th Annual Symposium*, International Center for Aggregate Research, Denver, Colorado, 12-14 April 2000.
9. Jayawickrama, P.W. *Limitations on the Use of Aggregate Sulfate Soundness for the Prediction of Field Performance of HMAC on Seal Coat Pavement Surfaces*. Research Study 111/8D/91-1929. Texas Tech University, Lubbock, Texas, March 1992.

10. Herrin, M., and Goetz, W.H. Effect of Aggregate Shape on Stability of Bituminous Mixes. *Highway Research Board Bulletin*, Vol. 33, National Research Council, Washington, D.C., 1954, pp. 293-308.
11. Barksdale, R.D., Pollard, C.O., Siegel, T., and Moeller, S. *Evaluation of the Effects of Aggregate on Rutting and Fatigue of Asphalt*. Research Report FHWA-GA-92-8812. Georgia Department of Transportation, Atlanta, Georgia, 1992.
12. Jimenez, R.A. Flow Rate as an Index of Shape Texture of Sands. In *Transportation Research Record 1259*, TRB, National Research Council, Washington, D.C., 1990, pp. 120-132.
13. Li, M.C., and Kett, I. Influence of Coarse Aggregate Shape on the Strength of Asphalt Concrete Mixtures. In *Highway Research Record 178*, National Research Council, Washington, D.C., 1967, pp. 93-106.
14. Stephens, J.E., and Sinha, K.C. Effect of Aggregate Shape on Bituminous Mix Characteristics. *Journal of the Association of Asphalt Paving Technologists*, Vol. 47, 1978, pp. 434-456.
15. Gandhi, P.M. *A Study of the Effect of Aggregate Characteristics on the Behavior of Asphaltic Mixtures Under Both Static and Dynamic Loading Conditions*. Ph.D. Dissertation. Texas A&M University, College Station, Texas, May 1969.
16. Kandhal, P.S., Motter, J.B., and Khatri, M.A. Evaluation of Particle Shape and Texture: Manufactured Versus Natural Sands. In *Transportation Research Record 1301*, TRB, National Research Council, Washington, D.C., 1991, pp. 48-56.
17. Kalcheff, I.V., and Tunnicliff, D.G. Effect of Crushed Stone Size and Shape on Properties of Asphalt Concrete. *Journal of the Association of Asphalt Paving Technologists*, Vol. 51, 1982, pp. 453-483.
18. Griffith, J.M., and Kallas, B.F. Influence of Fine Aggregate on Asphalt Concrete Paving Mixtures. *Highway Research Record Bulletin*, Vol. 37, National Research Council, Washington, D.C., 1958, pp. 219-255.
19. Meier, W.R., and Elnicky, E.J. Laboratory Evaluation of Shape and Surface Texture of Fine Aggregate for Asphalt Concrete. In *Transportation Research Record 1250*, TRB, National Research Council, Washington, D.C., 1991, pp. 25-34.
20. Chowdhury, A. *Evaluation of Superpave Fine Aggregate Specification*. M.S. Thesis. Texas A&M University, College Station, Texas, May 1999.

21. Huang, S. C., Branthaver, J.F., and Robertson, R.E. Aggregate Effects on the Asphalt-Aggregate Interaction in the Presence of Water. *Proc., 8th Annual Symposium*, International Center for Aggregate Research, Denver, Colorado, 12-14 April 2000.
22. Dumitru, I., Paraschiv, V., Glass, C., and Barmac, G. Alternative or Complementary Methods for Assessment of Fine Aggregates. *Proc., 9th Annual Symposium*, International Center for Aggregate Research, Austin, Texas, 22-25 April 2001.
23. Anderson, D.A. Influence of Fines on Performance on Asphalt Concrete Mixtures. *Proc., 4th Annual Symposium*, International Center for Aggregate Research, Atlanta, Georgia, 15-17 April 1996.
24. Maldonado, A., Orsetti, S., and Tourenq, C. Standardization and Qualification of Fines in Aggregates in France. *Proc., 4th Annual Symposium*, International Center for Aggregate Research, Atlanta, Georgia, 15-17 April 1996.
25. Phillips, F., Jayawickrama, P.W., Hossain, M.S., and Thomas, M.L. *Comparative Analysis of Micro-Deval and Magnesium Sulfate Soundness Tests*. Final Report TX/99/1771-1R, Lubbock, Texas, October 2000.
26. Button, J.W., Chowdhury, A., and Kohale, V. *Comparative Evaluation of Different Fine Aggregate Angularity Tests*. ICAR Report 4011-1. Texas Transportation Institute, College Station, Texas, May 2000.
27. Masad, E. Review of Imaging Techniques for Characterizing the Shape of Aggregates Used in Asphalt Mixes. *Proc., 9th Annual Symposium*, International Center for Aggregate Research, Austin, Texas, 22-25 April 2001.
28. Hyounghyan, K., Haas, C.T., Rauch, A.F., and Browne, C. Comparison Tests of Automated Equipment for Analyzing Aggregate Gradation. *Proc., 9th Annual Symposium*, International Center for Aggregate Research, Austin, Texas, 22-25 April 2001.
29. American Society for Testing and Materials (ASTM), *Annual Book of ASTM Standards*, Vol. 04.02, ASTM, Philadelphia, Pennsylvania, 2000, pp.664-668.
30. American Society for Testing and Materials (ASTM), *Annual Book of ASTM Standards*, Vol. 04.03, ASTM, Philadelphia, Pennsylvania, 2000, pp.10-17.
31. American Society for Testing and Materials (ASTM), *Annual Book of ASTM Standards*, Vol. 04.08, ASTM, Philadelphia, Pennsylvania, 2000, pp 492-495.

32. Jahn, D.W. Evaluation of Aggregate Particle Shapes Through Multiple Ratio Analysis. *Proc., 8th Annual Symposium*, International Center for Aggregate Research, Denver, Colorado, 12 - 14 April 2000.

Table A1. Description of All Aggregates Evaluated.

Material Type	Sample	Material Type	Producer	Location
Limestone	1	Gr. 4 Limestone	Colorado Material	San Antonio, TX
	2	Gr 4. Limestone	Jobe Product	Elpaso, TX
	3	Limestone	Jonny Thompson, Inc.	Nunnley, OK
	4	Type D, Crushed Limestone	Luhr Brothers, Tower Rock	Tower Rock, MO
	5	Type D, Cr used Limestone	Marock Inc.	Chambers, TX
	6	Limestone	Martin Marietta	Bexar, TX
	7	3/8 inch Crushed Stone	Lattimore Material	Coleman, OK
	8	340 (3/8 inch)	Dolese Brothers	Admore, OK
	9	Type D	Dean Word, Dow Pit	Austin, TX
	10	340 (3/8 inch)	Dolese Brothers	Richard Spur, OK
	11	Type D, Asphalt Concrete	Vulcan Material	Huebner Rd, TX
	12	Type D, Asphalt Concrete	Sunbelt	San Antonio, TX
	13	Type D, Gravel Limestone	Young Contactors	Madox Pit, TX
	14	Limestone	Vulcan Material	Brownwood, TX
	15	Type D, 3/8 inch Crushed Stone	Amis material	Stringtown, OK
	16	Crushed Limestone	Dolese Brothers	Cooperton, OK
	17	Type A, Flex Base	Dean Word Co.	Dow Chem, Austin, TX
	18	Type D	Vulcan Material	Kelly, Fort Worth, TX
	19	Type D	Vulcan Material	Helotes, San Antonio, TX
	20	Manufactured Sand	Texas Industries	Bridgeport, TX
	21	Limestone	Pioneer Aggregates	Clinton, Austin, TX
	22	Limestone	Price Construction	Clement, San Angelo, TX
	23	Limestone	Inrose	Bridgeport, TX
Gravel	24	Siliceous Gravel - Type D	Trinity Materials	Waco, TX
	25	Type D	Texas Sand & Gravel, Inc.	Mansfield, TX
	26	Type D	Fordyce	Showers Pit, MD
	27	Type D, Coarse Aggregate	Hanson Delight	Arkansas, AK
	28	Gr. 4 Aggregate	Capitol Sand & Gravel	San Antonio, TX
	29	Type D	Vulcan Material	Knippa, Lubbock, TX
	30	Type D Asphalt Concrete	Valley Caliche	Beck Pit, Pharr, TX
	31	Gr. 4 Aggregate	Wright Brothers	Realitos, TX
	32	Type D	E.D. Baker	Johnson Pit, OK
	33	Type D	Trans-Pecos	Hoban, Odessa, TX
	34	Type D	Trinity Material	Cresslenn, Tyler, TX
Igneous	35	3/8 inch aggregate	Jobe Products	El Paso, TX
	36	340 (1/2 inch)	Western Rock	Davis, OK
	37	Crushed Granite	Meridian Aggregates	Mill Creek, OK
	38	Crushed Granite	Jobe Products	El Paso, TX
	39	Type D	Granite	-
	40	Gr. 4 Trap Rock	Vulcan Material	El Paso, TX