TEST METHODS FOR USE OF RECYCLED ASPHALT PAVEMENT IN ASPHALT MIXES

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16 . ABSTRACT: Usage of recycled asphalt pavement (RAP) in the construction of new pavements has increased in recent years due to the movement to conserve energy and raw materials, and reuse waste materials. To assess the effectiveness of RAP materials in new asphalt mixes, it is important to evaluate the properties of the recovered binders and aggregates. The widely used “Abson” method is employed in this study to recover asphalt binder from RAP. Also, the frequently used “NCAT Ignition” method is used to extract aggregates. A laboratory study comprising of two field RAP materials, four simulated RAP materials and corresponding virgin materials, was undertaken to assess possible influences of the aforementioned recovery processes. Gradation, specific gravity, durability (L.A. Abrasion and Micro-Deval), sand equivalent, and insoluble residue of the extracted aggregates, and performance grade (PG), viscosity and penetration values of the recovered binders were evaluated as per the AASHTO and Oklahoma Department of Transportation (ODOT) standards. It was observed that gradation, specific gravity, durability and sand equivalent of the extracted aggregate were inconsistent with their virgin counterparts, and would result in conservative designs in a majority of cases. On the other hand, acid solubility, percentage of crushed face and surface properties were not influenced by the NCAT ignition oven processes. Binder test results showed that the Abson method positively influenced the critical PG temperatures of the recovered binder by about 4^{o}C. The Abson method did not show any statistically significant influence on the viscosity values of the recovered binders at ODOT mixing and compaction temperatures. The penetration test results of recovered binder via the Abson method were found to be higher than laboratory aged binder in 75% of the time. In regard to the PG grade, based on limited test results, the Abson method is less conservative than the Rotavapor method. The findings of this study are expected to be helpful in the evaluation of RAP for reuse in asphalt paving.

17. KEY WORDS
RAP, Abson, NCAT Ignition Oven, Asphalt Binder, Performance Grade, Durability, Gradation

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS				
SYMBOL	**WHEN YOU KNOW**	**MULTIPLY BY**	**TO FIND**	**SYMBOL**
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
AREA				
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS				
SYMBOL	**WHEN YOU KNOW**	**MULTIPLY BY**	**TO FIND**	**SYMBOL**
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
AREA				
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
TEMPERATURE (exact degrees)				
^oC	Celsius	1.8C+32	Fahrenheit	^oF
ILLUMINATION				
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
FORCE and PRESSURE or STRESS				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

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1 INTRODUCTION

1.1 BACKGROUND AND MOTIVATION

Asphalt recycling has become an important research topic in recent years because of its enhanced use in the construction of new asphalt concrete (AC) pavements. The increasing demand of recycled asphalt pavement (RAP) is mainly due to the increasing cost of asphalt binders and scarcity of good quality virgin aggregates, as well as due to increasing environmental awareness. RAP has already become one of the most widely used recycled materials in the United States. Nationally, when compared to 2009 usage, the use of RAP in new pavements is expected to double by 2014, (NAPA, 2009). During the asphalt recycling process, processed RAP is blended with virgin materials to prepare new mixes. Therefore, the characterization of the recovered binders and aggregates from RAP is essential to attain proper blending in the mix design.

Among existing recovery techniques, the “Abson” method (AASHTO T 170) is widely used by the Oklahoma Department of Transportation (ODOT) and the transportation industry. In this method, the asphalt binder is recovered by distilling previously solvent-extracted asphalt residues in a centrifuge, in accordance with the AASHTO T 164 method (AASHTO, 2008). This method involves boiling the solvent (i.e., trichloroethylene [TCE]) off and leaving the asphalt binder behind. The solvent is then condensed back into a liquid. Sometimes the removal of solvent may be incomplete. It is also possible that the asphalt binder is overheated or fine particles escape through the filter during the recovery process. Several studies (e.g. Anderson, 2001; Loh and Olek, 1999; McDaniel and Anderson, 2001) have raised some concerns on the inconsistency of test results when recovering binder in accordance with the Abson method. In the commonly used aggregate extraction technology, the National Center for Asphalt Technology (NCAT) ignition method (AASHTO T 308), aggregates are extracted by burning off the asphalt binder at a very high temperature (1000^{o}F [538^{o}C]). Therefore, it is important to examine the influences, if any, of these recovery techniques on the recovered materials.

1.2 SCOPE

This study is limited to the laboratory evaluation of local RAPs and virgin materials (aggregates and binders). Specifically, four laboratory simulated RAPs prepared from virgin HMA mixes were evaluated. Virgin aggregates and binders used in these mixes were also collected from the same sources and evaluated. Out of four HMA mixes, two mixes were prepared with a soft binder (PG 64-22), and the other two mixes were prepared with a relatively hard binder (PG 76-28). Aggregates were extracted from RAPs by burning off the binder using an NCAT ignition oven. Similarly, binders were recovered from RAPs by following two recovery techniques: the Abson method and the Rotavapor method (AASHTO, 2008). Tests to evaluate mechanical and surface properties of extracted and virgin counterparts included gradation, durability (LA Abrasion and Micro-Deval), specific gravity, sand equivalent, insoluble residue, and aggregate imaging system (AIMS). Tests to evaluate properties of recovered binders and virgin counterparts included viscosity, penetration, and performance grading. Additionally, elemental analyses on selective binder samples were conducted to determine their chemical compositions.

1.3 OBJECTIVES AND STUDY TASKS

The current study was undertaken to achieve the following objectives:

i. Evaluate the effects of the Abson method on the PG grading, consistency (viscosity and penetration) of the recovered binder.

ii. Evaluate the influence of the NCAT ignition oven on the engineering properties (gradation, durability, specific gravity, sand equivalent, and insoluble residue) and surface properties (sphericity, angularity and texture) of the extracted aggregates.

iii. Examine the differences in chemical compositions of recovered and virgin binders.

iv. Demonstrate if an alternate binder recovery technique, Rotavapor, is better than the Abson method.

v. Assess whether ODOT needs to revise its test methods (i.e., apply any shift factors) for evaluating the aforementioned properties of recovered (via NCAT oven) aggregates and recovered (via the Abson method) binders.

To accomplish the aforementioned objectives, the following tasks were performed:

a) Conduct a comprehensive literature review;

b) Collect bulk RAPs, plant mixes, virgin aggregates and virgin binders;

c) Extract aggregates from bulk RAPs and simulated RAPs;

d) Evaluate mechanical and surface properties of recovered and virgin aggregates;

e) Recover binders from bulk and simulated RAPs;

f) Evaluate rheological properties of recovered and virgin binders,

g) Analyze test results and rationalize findings, and

h) Report findings of the study.

1.4 ORGANIZATION OF THE REPORT

This report is organized into six chapters and an appendix. Following the introduction and objectives in Chapter 1, Chapter 2 provides a literature review focusing on aggregate and binder recovery techniques along with their adverse impacts on the properties of the recovered materials. Chapter 3 presents the materials and mythologies followed to meet objectives of the current study. Chapter 4 presents the effects of the NCAT ignition oven on the mechanical and surface characteristics of the extracted aggregates. Detail test results of surface characteristics, based on an AIMS, are presented in Appendix A. The effects of the Abson recovery method of the recovered binders' PG grades and consistency data are presented in Chapter 5. Finally, the conclusions and recommendations of this study are presented in Chapter 6.

2 LITERATURE REVIEW

2.1 INTRODUCTION

The commonly used aggregate extraction technique, the National Center for Asphalt Technology (NCAT) ignition method (AASHTO T 308), extracts aggregates by burning off the binder at a very high temperature (538^{o}C) (AASHTO, 2008). The high operating temperature of the NCAT ignition oven may alter some engineering properties (i.e., LA Abrasion loss) of the extracted aggregates. Such effects may be more prominent in some aggregates (e.g., dolomite, limestone) as the chemical structures of these aggregates may change due to their exposure to high heat in the NCAT ignition oven.

Among the existing recovery techniques, the “Abson” method (AASHTO T 170) is widely used by transportation agencies and researchers. In this method, binder is recovered by distilling solvent-extracted (AASHTO T 164) asphalt residues for several hours in a centrifuge (AASHTO, 2008). This method involves boiling the solvent (i.e., trichloroethylene [TCE]), thus leaving the asphalt binder behind. The solvent is then condensed back into a liquid. Sometimes the solvent removal may be incomplete. It is also possible that the binder is overheated during the recovery process. Even though the Abson method is used frequently to recover asphalt binder from RAP, several studies [e.g., Loh and Olek, 1999; Anderson, 2001; and McDaniel and Anderson, 2010] have warned that it may cause excessive hardening of the binder. This excessive oxidative hardening of the recovered binder is partly due to chemical and physical hardening processes which the asphalt binder experiences during the removal process of the solvent.

2.2 AGGREGATE EXTRACTION AND CHARACTERIZATION

2.2.1 Engineering Properties

McKeen (1997) conducted a round-robin study involving ten laboratories, five mixtures, and three replicates for each mix to obtain data for determining the precision of the NCAT ignition method for measurement of asphalt content and gradation. For validation purposes, asphalt binder contents of these mixes were also determined using reflux and centrifuge extractions as well as nuclear asphalt gauge measurements. It was reported that the "test results indicated the precision is equal to that reported for reflux extractions and nuclear asphalt gauges. Aggregate gradations were not changed by the ignition test based on a comparison of before and after gradation data." McKeen (1997) recommended adopting the use of the NCAT ignition oven for aggregate extraction from HMA mixes in the AASHTO specifications.

Ahmad et al. (2004) studied the abrasion of RAP aggregates after extracting them from RAP using an ignition oven (burner temperature 900^{o}C). Extracted aggregates were found to be finer than their virgin counterparts. These researchers also compared the aggregate crushing value (ACV) of recovered and virgin aggregates under compressive loading. Compared to virgin aggregates, the ACV of recovered aggregates was lower, which means the RAP aggregates were weaker than their virgin counterpart. Similarly, the aggregate impact value (AIV) of recovered aggregates was lower than those of the virgin aggregates. However, all three parameters (gradation, ACV and AIV) of RAP aggregates were within their corresponding acceptable ranges.

Huang et al. (2005) analyzed the blending process of RAP with virgin mix. These researchers studied a blended mix containing 20% of screened RAP, which was subjected to staged extraction and recovery as per AASHTO T 170. It was reported that only a small portion (Layer 1: about 11%) of aged asphalt in RAP actually participated in the remixing process; other portions (Layers 2, 3, and 4: about 89%) formed a stiff coating around RAP aggregates, and RAP functionally acted as “composite black rock.” Rheological properties of binder for these layers were evaluated. It was found that the asphalt binder’s viscosity increased going from the outside layers to the inside layer. The asphalt binder in Layers 3 and 4 (outer layers) was much stiffer than the asphalt binder in Layers 1 and 2 (inner layers). It was also reported that the resulting composite layered structure was desirable to improve the performance of the hot-mix asphalt mixture.

Watson et al. (2008) studied the LA Abrasion loss of blended aggregates composed of different percentages (0%, 10%, 20% and 30%) of recycled stone matrix asphalt (SMA) mixes and four virgin aggregates. Both RAP and virgin aggregates were granite materials used by the Georgia DOT. It was reported that properties of the combined blend such as LA abrasion loss were mainly influenced by the source of the virgin aggregate. The variation of the LA abrasion losses among RAP materials was found to be minimal (within 3% difference). It was also observed that RAP materials consisted of aggregate that had many of its rough edges broken during original production, through the milling process and additional crushing. Thus, aggregates in the processed RAPs were mostly cubical in shape. It was concluded that up to 20% RAP can be used without significantly affecting the mechanistic performance. The fatigue life was expected to be reduced significantly with the addition of 30% RAP.

A recent study (ARC, 2010) by researchers at Asphalt Research Consortium (ARC) evaluated aggregates extracted via different extraction techniques including the NCAT ignition oven method. The best approximation of true binder content was obtained by following the NCAT ignition oven method, which was followed by the reflux method. The centrifuge extraction method provided the worst approximation of true binder content. In this study, for RAP samples with soft limestone and hard limestone aggregates, the NCAT ignition oven method estimated the binder contents as 5.1% and 5.8%, where the true binder contents were 5.3% and 6.0%, respectively.

In regard to gradation, the ARC study did not find any particular trend in the gradation chart for RAP aggregates extracted via the NCAT ignition oven. In particular, particles passing No. 200 sieve, were over-estimated in 50% of the time and under-estimated in the other 50% of the time. The measured LA Abrasion loss values for different aggregates extracted via the NCAT ignition oven method was comparatively higher than the measured values for virgin aggregates. Such over-estimation of LA Abrasion loss values was observed in 75% of the time. A quite different observation was made for aggregates extracted via other extraction methods (centrifuge and reflux); the measured LA Abrasion loss values were close to the actual values in 75% of the time for these extraction methods. The LA Abrasion loss values were under-estimated in 25% of the time with the centrifuge method, and they were over-estimated in 25% of the time with the reflux method. The sand equivalent values of aggregates extracted via the NCAT ignition oven over-estimated 50% of the time, indicating non-conservative designs.

2.2.2 Surface Properties

Surface characteristics of aggregates used in asphalt pavements play an important role on the performance of asphalt mixes. Bhasin et al. (2006) reported that aggregates with a higher percentage of rounded and low-angularity particles might be more susceptible to rutting. Similar observations were made by another study performed by Masad et al. (2003). These researchers reported that the higher angularity and texture indices of aggregates in the mix, the less rutting could be expected in pavements.

Gudimettla et al. (2010) studied surface properties (form, angularity and texture) different types of virgin aggregates (granite, limestone, and gravel) and RAP by using an AIMS. It was reported that granite aggregates showed the maximum texture values followed by RAP, limestone, and gravel. Furthermore, it was noted that even though RAP had the second highest texture, it possibly consisted of a combination of other aggregate types. Gradient angularity data indicated that granite aggregates were more angular than the other type of aggregates. Gravel aggregates had the least average angularity values suggesting that they are rounder than granites and limestones. Sphericity (i.e., the degree of cubicalness of an aggregate) data showed that gravels had the highest sphericity of the four aggregate types followed by RAP, limestone, and granite.

2.3 BINDER RECOVERY AND CHARACTERIZATION

The Abson method (AASHTO T 170) is used frequently to recover asphalt binder from RAP with reagent-grade trichloroethylene or reagent-grade methylene chloride (AASHTO 2008). Proponents of this method claimed that the properties of the recovered binder are essentially same as those in the asphalt mixture. However, several researchers have warned about using the Abson recovery method as it may cause hardening of the binder; also, the high temperature applied in the procedure can cause changes to the properties of the recovered binder (Loh and Olek 1999).

Stroup-Gardiner and Nelson (2000) evaluated trichloroethylene (TCE) and four normal propyl bromide (nPB) solvents (Lenium, Leksol, Hypersolv, and EnSolv) for use as chlorinated solvent replacements in extraction and recovery of binders from hot mix asphalt (HMA). No statistically significant differences on the effects of solvent were observed on the Superpave test results, except for a few instances. It was reported that the extraction and recovery processes with TCE solvent produced a more stiff recovered binder than its virgin counterpart. The study also reported that Hypersolv was found to be incompatible with polymer modified PG 76-28 binder. It was recommended that nPB solvents be used as direct replacements for the TCE solvent.

Anderson (2001) presented some concerns on the variability of test results when binder is recovered in accordance with the Abson recovery method (AASHTO T 170). As reported earlier, sometimes the solvent removal may be incomplete. It is also possible that the binder can be overheated during the recovery process. This method has been found to significantly alter the binder properties. The NCHRP 9-12 project reported that the Abson recovery method produced samples with the highest variability in test results among the recovery procedures studied (Anderson 2003). On the other hand, the Rotavapor method is expected to show less influence on binder grading as the solvent-asphalt mixture is heated more gently in a rotating flask in water.

In another laboratory study, Kennedy et al. (1998) measured PG grading for different combinations and percentages of four virgin binders and of two aged binders. These researchers chose core asphalt binders used in the Strategic Highway Research Program (SHRP) and simulated RAP binders by aging virgin binders in the laboratory. This aging was accomplished by heating the binder in an RTFO oven at 163^{o}C for several hours (21 to 44 hours) to achieve a target penetration of between 10 and 20. Engineering properties of virgin, recovered and blended binders were determined by conducting Superpave tests (DSR, BBR). As expected, it was reported that the stiffness of a blended binder is higher at higher percentages of RAP binder. It was observed that the PG grading of the blended binder with a lower percentage (15%) of recovered binder remains the same. Homzah et al. (2006) studied selected binders to correlate the complex modulus of binder with the corresponding HMA mixes. In that study, they conditioned loose mixes for short-term and long-term aging in the laboratory, as per AASHTO R30-02, and evaluated stiffness modulus.

Tao et al. (2010) reiterated concerns of using the Abson method to recover binder from RAPs. A major concern is that some chemicals may remain as residuals in the extracted binder. Even a small percentage of the residuals can lead to significant influences on binder properties. Furthermore, reactions of asphalt binders while in solution during extraction and recovery processed can alter the binder properties. Realizing these concerns, the researchers proposed a new testing procedure to estimate the low-temperature properties of the RAP binder without extraction and/or any chemical treatments. In the proposed method, they prepared RAP mortar (mix of fresh binder and RAP materials passing #8 sieve) and tested mortar beam samples using a modified bending beam rheometer (BBR). The researchers evaluated RAPs from two different sources and two virgin binders (PG 64-22 and PG 58-22), and they reported low temperature properties with good repeatability.

Daniel et al. (2010) studied some selected HMA mixtures (plant mixes in New Hampshire) with different amounts of RAP, and evaluated the PG grading of the binders and their critical temperatures for cracking. The binders were recovered by centrifuge (using trichloroethylene as a solvent) in accordance with the Abson method. The researchers also used an additional procedure to remove the last traces of trichloroethylene, if any, from the recovered binder. The additional process consisted of placing 35-gm of recovered binder in a RTFO bottle, placing the bottle in the oven rack, and then rotating the rack for 10 minutes at 163^{o}C. The RTFO residue was considered as the “original” condition of the binder tested in a DSR at desired temperatures. They also performed further RTFO and PAV aging of the “original” binder to maintain consistent testing procedures with the virgin binders. These researchers observed that the high PG temperature remained the same, or only increased one grade for the various percentages of RAP and the low PG temperature remained the same, or only increased one grade from the virgin mixture. They also observed that the critical cracking temperatures changed by a few degrees as the RAP percentages increased.

Dong et al. (2010) studied two PG binders (PG 58-22 and PG 64-22) and an aged binder (recovered from RAP of unknown original binder grade) while evaluating the performance of additives in RAP. The aged binder was recovered from RAPs using the Abson method. They reported significant aging of the recovered binder in terms of kinematic viscosity and penetration, among others. For example, the kinematic viscosities at 135^{o}C of the recovered binder, and the PG 64-22 binder were found to be 5275 mPa.s, and 412 mPa.s, respectively. Similarly, the penetration values at 25^{o}C of the recovered binder, and the PG 64-22 binder were found to be 16 mm, and 64 mm, respectively.

As presented above, the high operating temperature of the NCAT ignition oven is suspected to alter some engineering properties of the extracted aggregates. Such effects may be more prominent in some aggregates as the chemical structures of these aggregates may change during the extraction processes. Likewise, the Abson method may alter the rheological properties of the recovered binder due to chemical and physical processes that the asphalt binder experiences during the extraction and removal processes.

3 MATERIALS AND METHODOLOGY

3.1 INTRODUCTION

An overview of the adopted flow charts, binder and aggregate recovery techniques, sample collections, and subsequent performance tests of this study is presented in this chapter. As shown in Figure 3-1, the following major steps were undertaken: collection of test materials (RAP, HMA mix, virgin aggregates and binder), recovery of the binder and aggregates from RAP (field and simulated) samples via the Abson method and the NCAT ignition oven method, respectively, and evaluation of properties of the recovered and virgin materials.

3.2 SAMPLE COLLECTION

Two field RAP (FRAP) samples, four simulated RAP (SRAP) samples and corresponding virgin materials were evaluated in this study. About 1200 lbs (600 kg) of material was collected from each selected field and simulated RAP. Simulated RAPs were prepared from loose HMA mixes of which two of the HMA mixes were prepared with a polymer-modified asphalt binder (PG 76-28), and the other two HMA mixes were prepared with an unmodified asphalt binder (PG 64-22). Roughly 5 gallons (five one-gallon canisters) of each binder was collected from the corresponding refinery. Notations used to reference these materials are shown in Table 3.1.

The collected first field RAP material is referred to as FRAP1. The source of FRAP1 is a seven year old pavement section located at Shields Blvd. in Moore, Oklahoma. The original pavement of this RAP was a Type B Insoluble (Oklahoma) mix with a PG 76-28 binder, constructed in May, 2003. Relevant properties of aggregates and the mix are shown in Figure 3-2. The FRAP1 was collected from the contractor's plant site where it was separated from other stockpiles (Figure 3-3). The asphalt binder and aggregates corresponding to FRAP1 were collected from the same physical location. The PG 76-28 binder (Canadian crude) was collected from Ergon Asphalts and Emulsion, Inc. located at Muskogee, Oklahoma. Virgin aggregates were collected from four different quarries: 16 mm (5/8 inch) chips (limestone) from Cyril, coarse screenings (limestone) from Richard Spur, sandstone from Davis, and asphalt sand from Meridian Pit, all from Oklahoma. Based on the mix design properties of the original pavement of FRAP1, a new loose mix (HMAMix1) was prepared in the laboratory using the corresponding virgin aggregates and asphalt binder (PG 76-28), as noted earlier. The aggregate used in the preparation of HMAMix1 is referred to as AGR1.

The HMAMix1 sample was then subjected to accelerated aging (short-term and long-term) as per the AASHTO T 30 method. In this method, the short-term conditioning of HMA mixes simulates the pre-compaction phase of the construction process. To accomplish this aging, loose mixes were placed in a force-drift conditioning oven for 4 hours $\pm$ 5 minutes at a temperature of 135 $\pm$ 3^{o}C. The long-term-conditioning of HMA mixes simulates the aging that occurs over the service life. The short-term-conditioned loose mixes were cooled at room temperature for 16 $\pm$ 1 hours. The specimen was then placed in the conditioning oven for 120 $\pm$ 0.5 hours at a temperature of 85 $\pm$ 3^{o}C. Even though this method does not take into account the effects of HMA mix properties and environmental factors, the long-term conditioning is designed to simulate the aging the mix undergoes during seven to ten years of service. Thus, it is stipulated that the age hardening of the asphalt binder experiences in this method is similar to that which the asphalt binder undergoes in the PAV-aging process (AASHTO R 28). The simulated RAP corresponding to HMAMix1 is called SRAP1.

The location of FRAP2 was a city street named North May Avenue in Oklahoma City, constructed in 1995. This pavement section of FRAP2 was a Type B Recycled (Oklahoma) mix, which included 25% RAP from an unknown source (Figure 3-4). Bulk FRAP2 sample was collected from the contractor's plant site where it was kept in a separate stockpile (Figure 3-5). Based on the mix design sheet for the original pavement section, virgin materials (binder and aggregates) were collected from the same geographical locations. Thus, the PG 64-22 binder was collected from Valero refinery at Ardmore, Oklahoma, and virgin aggregates were collected from different sources: 3/4 inch (19 mm) rock (limestone) from Davis, screenings (limestone) from Davis, sandstone from Davis, and natural sand from Yukon, all from Oklahoma.

As mentioned earlier, the original pavement of FRAP2 included 25% RAP. Since the aim of this study was to assess the influence of the recovery methods rather than the performance of the RAP itself, the evaluation of the simulated RAP was considered a better approach than that of the field RAP. This was because the simulated RAP had fewer unknowns and assumptions than the field RAP. For example, the mix of the original pavement section of FRAP2 had 25% RAP from an unknown source. Thus, it was not practical to reproduce a new mix with the same type of RAP in the laboratory. Because of such anomalies in FRAP2, it was not evaluated further in this study. For the same reason, SRAP2 (simulated RAP from HMAMix2) was prepared only with virgin aggregates and asphalt binder from the same geographical locations of FRAP2 except that 25% RAP was substituted by other aggregates to maintain the overall gradation within the specification limits. Thus, a new HMA mix (HMAMix2) was prepared by using the corresponding virgin aggregates (AGR2) and asphalt binder (PG 64-22), as noted earlier. The HMAMix2 mix was also aged in the laboratory as per AASHTO T 30, and the simulated RAP is called SRAP2.

The third HMA mix (HMAMix3) was collected from Silver Star Construction Co. located in Moore, Oklahoma. The collected mix was a Type A mix with Gary William's PG 64-22 binder, and about 5 gallons (18.9 liters) of the virgin binder (Gary Williams) was also collected. Furthermore, virgin aggregates (1.5 -inch (37.5 mm) rocks from Hansen Aggregate at Davis; 5/8-inch (15.6 mm) rock from Martin Marietta at Davis; Screenings from Hansen Aggregate at Davis; Sand (GMI) from Meridian Pit), as per the mix design sheet (Figure 3-6), were collected. Figures 3-7a and 3-7b show a photographic view of the collection of HMAMix3 and virgin aggregates, respectively, from the plant site. The fourth HMA mix (HMAMix4), which is a S4 mix with a PG 76-28 binder from Valero, was also collected from the Silver Star Construction Co. located in Moore, OK. Also, virgin materials (binder and aggregate) used in preparing this mix were collected. The mix design sheet of HMAMix4 is shown in Figure 3-8. The simulated RAPs corresponding to HMAMix3 and HMAMix4 are referred to as SRAP3 and SRAP4, respectively.

Roughly 0.9 lb (400 gm) of binder was recovered from a representative sample of each RAP in accordance with the Abson method (AASHTO T 170). Since the Abson method can recover only a small amount of asphalt binder at a time, the recovered binder samples from several trials of each RAP were blended for homogeneity. The blended recovered binder was then tested to determine its PG grade and consistency (viscosity and penetration). Also, collected virgin binders were long-term aged by using a pressure aging vessel (PAV) as per AASHTO R 28, which exposes the asphalt binder to heat and pressure simultaneously to simulate in-service aging over a period of 7 to 10 years. The PG grades, viscosity measurements and penetration values of the recovered and PAV-aged binder were then compared.

Aggregates were extracted from representative samples of RAP by burning the asphalt binder off in an NCAT ignition oven, as per the AASHTO T 308 method. The extracted aggregates were then blended for homogeneity and tested to determine their engineering properties. Engineering (gradation, LA Abrasion, Micro-Deval loss, sand equivalent, acid solubility) and surface properties (crush face count, texture, angularity and form) of burned off aggregates were then compared with those of their virgin counterparts.

3.3 EXTRACTION AND RECOVERY PROCESS

3.3.1 NCAT Ignition Oven Extraction Method

As noted previously, aggregates were extracted from RAP samples and the binder content was determined by using a NCAT ignition oven (Figure 3-9), as per the AASHTO T 308 method (*Standard Method of Test for Determining the Asphalt Binder Content of Hot Mix Asphalt by the Ignition Method*). Representative samples of RAP were obtained as per AASHTO T 168 (Sampling of Bituminous Paving Mixtures). The moisture content of the representative sample was determined by oven drying it at 110^{o}C until a constant mass was achieved. Based on the nominal maximum size (NMAS) of RAP1 (19 mm), a 2000-gm sample was used in each test according to the AASHTO T 308 test method. The ignition oven was preheated at 538^{o}C and the 2000-

gm representative sample was ignited at a temperature close to the flashpoint of the binder in a furnace. The automated ignition oven process was set up by inputting the calibration based correction factor, the set point temperature of 538^{o}C and the initial mass of the specimen. Each test was concluded in approximately 45 minutes.

3.3.2 The Abson Recovery Method

The extraction and recovery of binder from RAP was performed as per AASHTO T 164 (*Quantitative Extraction of Asphalt Binder from Hot Mix Asphalt*) and AASHTO T 170 (*Recovery of Asphalt Binder from Solution by the Abson Method*), respectively. Unprocessed field RAP materials were sieved by using a standard 1½″ (37.5 mm) sieve. The RAP material passed through this sieve was used to extract and recover binder. A commercial laboratory named PaveTex, located in Dripping Springs, TX, and the ODOT Materials Division laboratory recovered about 0.9 lb (400 gm) of binder from about 60-lb (27 kg) of a RAP sample.

Initially, the asphalt binder in the RAP was extracted using a vacuum extractor as per AASHTO T 168 (AASHTO, 2008). In this method, trichloroethylene (TCE: $C_2H_3Cl_3$) was used as a solvent. The RAP was placed in a large, flat pan and warmed in a 110 ± 5ºC oven until it could be separated. The loose RAP materials were then placed in a bowl along with the solvent (sufficient to cover the RAP), and sufficient time (up to one hour) was allowed for the solvent to disintegrate the loose RAP. The bowl containing the RAP and solvent was then placed in the vacuum extraction apparatus, allowing the extract to then be collected and centrifuged. The centrifuge was started slowly with the speed gradually being increased to a maximum of 3600 RPM until the solvent stopped flowing through the drain. At this stage 200 ml or more trichloroethylene was added and the procedure was repeated (at least three times).

Once the binder was extracted from the RAP, the recovery process was done in accordance with AASHTO T 170 (AASHTO, 2008). The solution from the previous extraction was centrifuged for a minimum of 30 minutes at 770 times gravity in 250-ml to 500-ml wide-mouth bottles (Figure 3-10). The extracted solution was concentrated by a primary distillation operation. The residue was then transferred from the primary distillation flask, using several washes of solvent to rinse the residue into the distillation flask. Next, carbon dioxide (CO_2) gas was introduced at a low rate (approximately 100 mL/min). This distillation process was continued until the temperature reaches 157ºC to 160ºC. The CO_2 gas flow was then increased to approximately 900 ml/minute. This flow rate and a temperature of 160ºC to 166ºC were maintained for 10 minutes before the process was considered complete.

3.3.3 The Rotavapor Recovery Method

The Rotavapor method (*Quantitative Extraction and Recovery of Asphalt Binder from Asphalt Mixtures*) is an alternative procedure for the extraction and recovery of asphalt binder from asphalt mixes (AASHTO, 2008). The Rotavapor method (AASHTO T 319) is similar to the AASHTO T 170 method, but the solvent-asphalt mixture is heated more gently in a rotating flask in water. This method is designed to minimize solvent softening of the binder and provides better removal of the solvent and better extraction of the asphalt binder from the aggregate. Some researchers (e.g., Stroup-Gardiner and Nelson, 2000) have reported that the Rotavapor procedure is the preferred method to extract and recover asphalt binder because this method is believed to result in less severe changes to the binder properties. This extraction-and-recovery technique uses an extraction cylinder that is rotated on its side allowing the solvent and the asphalt to mix thoroughly. The solvent and binder in the mix are removed from the sample by attaching a vacuum at the bottom of the flask. The extracted solution is then filtered to remove fine aggregate particles then collected in a recovery flask. The Rotavapor method is then used to recover the binder from the solutioin. The current study used a Rotavapor located at the Western Regional Superpave Center (WRSC) in Reno, Nevada. The extraction of the binder was done using 85% toluene and 15% alcohol as a solvent, as recommended by the WRSC.

3.4 PERFORMANCE EVALUATION OF AGGREGATES AND BINDERS

Test methods involving the determination of PG grades of asphalt binders and engineering properties of aggregates are listed in Table 3.2. While determining the high PG temperature of the recovered binder, DSR tests were conducted on binder specimens as if the asphalt binder was unaged. The remainder of the binder was subjected to RTFO aging with additional DSR tests conducted at high temperatures. Even though the recovered binder went through long-term aging in the field, the RTFO-aging was done to comply with linear blending equations for recovered and virgin binders, as per recommendation of the National Cooperative Highway Research Program (NCHRP) Report No. 452 (McDaniel and Anderson, 2001). The RTFO-aged recovered binder was also subjected to BBR tests for evaluating its low PG temperature as if the binder were PAV-aged (McDaniel and Anderson, 2001). Furthermore, elemental analysis of selected binders was conducted using a CE 440 Elemental Analyzer. In this study all test protocols for evaluating engineering properties of aggregates followed AASHTO specifications, except for an ODOT standard (OHD L-25). The OHD L-25 method determines the acid insolubility of coarse aggregates with concentrated HCL, an indicator for skid resistance in high volume traffic road.

3.4.1 Gradation

The extracted aggregates were analyzed in accordance with the AASHTO T 30 test method (*Mechanical Analysis of Extracted Aggregate*) for gradation by using a series of sieves, as given in the original mixes. Gradations of aggregates extracted from RAPs were then compared with their virgin counterparts. Furthermore, attention was paid whether the extracted aggregates met the ODOT specified job mix formula (JMF) for the corresponding mix. Three replicates of each sample were sieved to find the average gradation.

3.4.2 Specific Gravity

The extracted aggregates were divided into coarse and fine using a No. 4 sieve. Aggregates retained on the No. 4 sieve were classified as coarse aggregates and those passing the No. 4 sieve were classified as fine aggregates. Three replicates of each were tested for the bulk specific gravity (G_{sb}) using standard AASHTO T 85 (*Specific Gravity And Absorption of Coarse Aggregate*) and T 84 test (*Specific Gravity And Absorption of Fine Aggregate*) procedures for coarse and fine aggregates, respectively.

3.4.3 Los Angeles Abrasion

The toughness and abrasion characteristics of coarse aggregates (dry condition) were determined as per AASHTO T 96 (*Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine*). This test is performed to check the resistance to degradation of particles by abrasion and impact. Each test sample, retained on the No. 4 sieve of approximately 5000g, was rotated in the LA machine drum at a speed of 32 rpm (Figure 3-11a). The samples were subject to 500 revolutions with 12 steel spheres used as “charges.” Finally, the tested material was sieved through a No.12 sieve to calculate the percent loss.

3.4.4 Micro-Deval Abrasion

The toughness and abrasion characteristics of aggregates (wet condition) were determined as per AASHTO T 327 (*Standard Method of Test for Resistance of Coarse Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus*). In this method, a sample of approximately 1500 gm was soaked in 2 liters of water and placed in a rotating steel drum for 120 minutes at 100 RPM speed (Figure 3-11b). In this test percent loss was then calculated after sieving the tested material through a No. 16 sieve. A percent loss less than 25.0 is acceptable by ODOT (ODOT, 2008).

3.4.5 Sand Equivalent

Relative proportions of fine dust or claylike material in graded aggregates are measured by using a Sand Equivalent test in accordance with AASHTO T 176 (*Plastic Fines in Graded Aggregates and Soils by Use of the Sand Equivalent Test*) (Figure 3-12). This test is performed on fine aggregates (passing No. 4 sieve).

3.4.6 Total Insoluble Residue

The acid insoluble material in coarse aggregates was determined as per OHD L-25 (*Method of Test for Total Insoluble Residue in Coarse Aggregate*). The extracted aggregates were washed and those passing through a 1/2 inch (12.5 mm) sieve and retained on a No. 4 sieve were used to measure the insolubility in hydrochloric acid (HCl). In this test, 400 ml of water was added to 0.44 lb (200 gm) of coarse aggregate (Figure 3-13), then approximately 30 ml of concentrated hydrochloric acid was added per 1 oz (30 gm) of coarse aggregate. The mixture was stirred over a period of days until all reaction ceased.

3.4.7 Aggregate Imaging System (AIMS) Results

Pine's Aggregate Imaging System (AIMS) (Figure 3-14) was used to evaluate the shape, texture, angularity, and sphericity of virgin and extracted aggregates as per AASHTO TP-XX. The AIMS device can evaluate aggregate surface properties including texture, sphericity, 2D form, and angularity. The AIMS device uses a wavelet analysis to determine the texture (relative smoothness or roughness) of an aggregate particle. Sphericity is a measure of the overall 3D shape of a particle, i.e. spherical, elliptical, and flat. The angularity is a measure of the sharpness of corners in a 2D image. The AIMS device uses two methods to measure angularity: gradient method and radius method. The 2D form is a measure of how circular a 2D cross-section of an aggregate is. For example, a circle would have a 2D-form index of zero. For coarse aggregates, the AIMS can measure texture, sphericity, 2D-form, and angularity. While for fine aggregates, the AIMS can measure 2D form and angularity.

3.4.8 Dynamic Shear Rheometer Testing

Dynamic testing of asphalt binder samples was conducted as per AASHTO T 315 (*Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer*). Asphalt binder test samples were formed by using two different sizes of silicon rubber molds manufactured by Gilson Company. Molds with 19-mm diameter and 1.5-mm depth were used while testing unaged and RTFO-aged samples, and molds with 8-mm diameter and 3-mm depth were used while testing PAV-aged samples.

3.4.9 Flexural Beam Testing

The flexural creep stiffness of asphalt binders was determined as per AASHTO T 313 (*Determining the Flexural Creep Stiffness of Asphalt Binder Using the Bending Beam Rheometer*) by means of a bending beam rheometer (BBR). In this method, simply supported asphalt beam samples (length = 127 mm, width = 12.7 mm, and thickness = 6.35 mm) were subjected to a constant load (980 ± 50 mN) applied at the mid-point at low temperatures. The test beams were placed in the controlled temperature fluid bath and loaded for 240 seconds. The stiffness (S) (maximum bending stress divided by the maximum strain) and the rate of stress relaxation (m-value) (slope of stiffness versus time) for loading times 8, 15, 30, 60, 120, and 240 seconds were calculated. These values at time t = 60 seconds were used to quantify thermal cracking resistance of the asphalt binder.

3.4.10 Viscosity and Penetration

Viscosity tests were conducted on virgin and recovered binders around the mixing and compaction temperatures by using a Brookfield rotational viscometer (RV) in accordance with the AASHTO T 316 method (*Standard Method of Test for Viscosity Determination of Asphalt Binder Using Rotational Viscometer*). The RV test helps ensure that the asphalt binder is sufficiently fluid for pumping and mixing (Roberts et al., 1996). The basic RV test measures the torque required to maintain a constant rotational speed (20 RPM) of a cylindrical spindle while submerged in an asphalt binder at a constant temperature.

The consistency or hardness of binder was obtained by performing penetration test as per the AASHTO T 49 method (*Standard Method of Test for Penetration of Bituminous Materials*). The basic principle of the penetration test is to determine the depth a truncated No. 2 sewing needle can penetrate an asphalt binder sample while using specified conditions of load (100 gm), time (5 sec) and temperature (25^{o}C (77^{o}F)).

3.4.11 Short-term and Long-term Aging

Short term aging of virgin binders was conducted using a rotational thin film oven (RTFO) in accordance with the AASHTO T 240 method (*Standard Method of Test for Effect of Heat and Air on a Moving Film of Asphalt*). In this method, asphalt binder is exposed to elevated temperatures to simulate manufacturing and placement aging. The basic RTFO procedure requires unaged asphalt binder samples in cylindrical glass bottles be placed in an oven with a rotating carriage. The carriage rotates within the oven while the 325°F (163°C) temperature ages the samples for 85 minutes.

Long term aging procedures were conducted on short-term aged samples by using a pressure aging vessel (PAV) in accordance with the AASHTO R 28 method (*Standard Practice for Accelerated Aging of Asphalt Binder Using a Pressurized Aging Vessel*). In this method, asphalt binder is exposed to heat and pressure to simulate in-service aging over a 7- to 10-year period. The basic PAV procedure requires RTFO-aged asphalt binder samples be placed in stainless steel pans and then aged in a heated vessel pressurized to 305 psi (2.10 MPa or 20.7 atmospheres) for 20 hours.

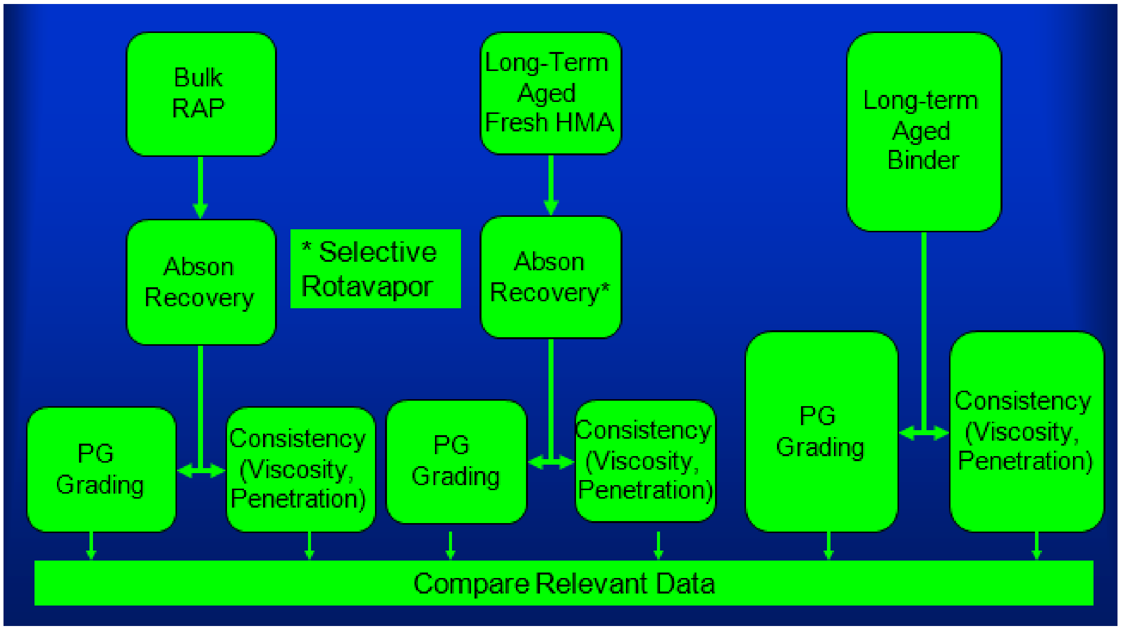
Table 3-1 Major Notations to be used in the current study

Meaning	Notation
Field RAP sample1	FRAP1
Field RAP sample2	FRAP2
Simulated RAP sample1	SRAP1
Simulated RAP sample2	SRAP2
Simulated RAP sample3	SRAP3
Simulated RAP sample4	SRAP4
HMA mix to prepare SRAP1	HMAMix1
HMA mix to prepare SRAP2	HMAMix2
HMA mix to prepare SRAP3	HMAMix3
HMA mix to prepare SRAP4	HMAMix4
Aggregates used to prepare HMAMix1	AGR1
Aggregates used to prepare HMAMix2	AGR2
Aggregates used to prepare HMAMix3	AGR3
Aggregates used to prepare HMAMix4	AGR4
Binder used to prepare HMAMix1	PG76-28Ergon
Binder used to prepare HMAMix2	PG64-22Valero
Binder used to prepare HMAMix3	PG64-22GW
Binder used to prepare HMAMix4	PG76-28Valero

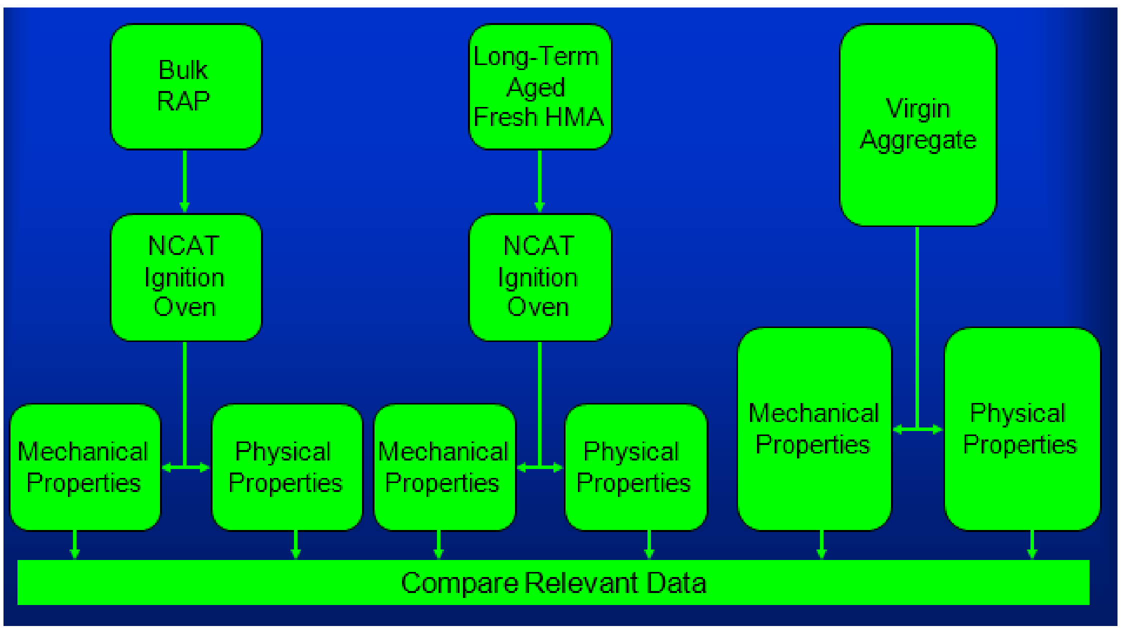
Table 3-2 List of Tests and Their Designations

Material	Test name and designation	FRAP1	FRAP2	SRAP1	SRAP2	SRAP3	SRAP4	AGR1	Binder1/ AGR2	Binder2/ AGR3	Binder3/ AGR4
Binder	PG grade: AASHTO M 320	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	DSR: AASHTO T 315	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	RTFO: AASHTO T 240	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	PAV: AASHTO R 28	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	BBR: AASHTO T 313	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Aggregate	Gradation: AASHTO T 30, T 27	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	LA Abrasion: AASHTO T 96	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Micro-Deval: AASHTO T 327	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Sp. Gr.: AASHTO T 84, T 85	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Sand equivalent: AASHTO T 176	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Insoluble residue: OHD L-25	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Note: RV = Rotational viscosity, DSR = Dynamic shear rheometer, RTFO = Rotational thin film oven, PAV = Pressure aging vessel, and BBR = Bending beam rheometer.



(a)



(b)

Figure 3-1 High Level Project Flow Diagram: (a) Binders and (b) Aggregates.

A.D. No. 006-027-001	Asph. Conc. Type B Insoluble	**Design No.**	3012-EST-02033
Project No. I-IMY-35-3(74)121	00292(15) **Hwy.** J35	**Avg. Daily Traffic**	3M+
Contractor: Sherwood Construction Co., Inc.		**Producer**	Haskell Lemon Const. Co.

MATERIAL	**SOURCE**	**% USED**
5/8" Chips	The Dolese Co. @ Cyril, Okla.(0801)	51
Coarse Screenings	The Dolese Co. @ Richard Spur, Okla.(1601)	13
Stone Sand	The Dolese Co. @ Davis, Okla.(5002)	25
Asphalt Sand	G.M.I.(Meridian Pit) @ Oklahoma City, Okla.	11
Asphalt Cement PG76-28OK	Koch @ Muskogee, Okla.	

Laboratory No. **Aggregate Percent Passing**	**5/8" Chips**	**Coarse Scrns**	**Stone Sand**	**Asph. Sand**	**Combined Aggregate**	**Job Formula**	**JMF Tolerance**
3/4"	100				100	100	±0
1/2"	90				95	95	±7
3/8"	66	100	100	100	83	83	±7
No. 4	11	92	98	98	53	53	±7
No. 10	4	47	56	97	33	*38	±4
No. 40	4	17	10	85	16	16	±4
No. 80	4	12	4	27	8	8	±4
No. 200	2.5	9.8	4.7	2.0	3.9	3.9	±2
% Asphalt Cement PG76-28OK						4.7	±0.4
Mix Temperature @ discharge from Mixer, °F						325	±20
Optimum Roadway Compaction Temperature, °F						305	

Tests on Asphalt Cement:

	Found	**Required**
Abs. Visc. @ 140°F		
Kin. Visc. @ 275°F		
Spec. Grav. @ 77°F	1.0218	

Tests on Aggregates:

	Found	**Required**
Sand Equivalent	81	45 Min.
L.A. Abrasion % Wear	27.0	40 Max.
Durability (DC)	77	40 Min.
IOC	0.48	
Insoluble Residue (Cal)	40.2	40 Min.
Fractured Faces	100	75 w/2
ESG	2.681	
Hveem Wt.	1230	

Tests on Compressed Mixtures:

Percent Asphalt	**Spec. Grav. Specimen**	**Max. Theo. Spec.Grav.**	**Dens. % of Max. Theo.**	**Dens. % Req'd. of Max. Theo.**	**V.M.A. (%)**	**V.M.A. (Min.%)**	**Hveem Stab.**	**Hveem Stab.(Min.)**
4.3	2.354	2.506	93.9		16.0		50	
4.8	2.374	2.487	95.5	94-96	15.7	15	51	40
5.3	2.406	2.469	97.4		15.0		49	

Retained Strength 87% *75% Mininum Required*
Compacted Wt. 109.6 *lbs./sq.yd./1" thickness*

* *REVISED(GRAD.) as per Contractor's request effective 7/29/02.*
TIED: IM-NHIY-35-3(246)121.

MEETS SPECIFICATION REQUIREMENTS

Figure 3-2 Mix Design Data of HMA Mix of FRAP1 and SRAP1

(a)

(**b)**

Figure 3-3 (a) FRAP1 stockpile at TJ Campbell Plant Site at Sunny Lane, Oklahoma City and (c) Collection of FRAP1.

RECYCLE

A.D. No.	011-002-094	Asph. Conc. Type B Binder Recycle	**Design No.**	3012-56876
Project No.	STP-109B(18)AG	17169(04) **Hwy.** CITY ST.	**Avg. Daily Traffic**	0.3M+
Contractor:	Swartz Paving		**Producer**	McConnell Const. Co.

MATERIAL	**SOURCE**	**% USED**
3/4" Rock	Dolese Co. @ Davis, Okla.	17
Screenings	Western Rock @ Davis, Okla.	36
Stone Sand	Dolese Co. @ Davis, Okla.	12
Milled Asph. Pav.(MAP)	Plant Site	25
~~Sand~~	~~Dolese Co. @ Yukon, Okla.~~	~~10~~
Asphalt Cement PG64-22OK	Total Petroleum @ Ardmore, OK	

Laboratory No. Aggregate Percent Passing	**60074 3/4" Rock**	**56879 Scrns**	**56880 Stone Sand**	**56882 MAP**	**56881 Sand**	**Combined Aggregate**	**Job Formula**	**JMF Tolerance**
3/4"	100	100	100	100	100	100	100	±0
1/2"	41	100	100	98	100	90	90	±7
3/8"	8	100	100	95	100	83	83	±7
No. 4	4	81	99	74	99	70	70	±7
No. 10	3	43	64	54	97	47	47	±4
No. 40	2	18	14	32	74	24	24	±4
No. 80	2	12	4	16	20	11	11	±4
No. 200	0.6	8.2	2.0	9.2	2.0	5.8	5.8	±2
% Asphalt Cement PG64-22OK				5.0			5.6	±0.4
Mix Temperature @ discharge from Mixer, °F							305	±20
Optimum Roadway Compaction Temperature, °F							290	

Tests on Asphalt Cement:

	Found	**Required**
Abs. Visc. @ 140°F		
Kin. Visc. @ 275°F		
Spec. Grav. @ 77°F	1.01 Est.	

Tests on Aggregates:

	Found	**Required**
Sand Equivalent	63	40 Min.
L.A. Abrasion % Wear	23.5	40 Max.
Durability (DC)	69	40 Min.
IOC	0.32	
Insoluble Residue (Cal)		N.A.
Fractured Faces	100	75 w/2
ESG	2.669	
Hveem Wt.	1210	

Tests on Compressed Mixtures:

Percent Asphalt	Spec. Grav. Specimen	Max. Theo. Spec.Grav.	Dens. % of Max. Theo.	Dens. % Req'd. of Max. Theo.	V.M.A. (%)	V.M.A. (Min.%)	Hveem Stab.	Hveem Stab.(Min.)
4.7	2.355	2.477	95.1		15.7		45	
5.2	2.373	2.458	96.7	95-97	15.5	15	43	40
5.7	2.391	2.440	98.0		15.3		41	

Retained Strength 79.9% *75% Mininum Required*
Compacted Wt. 107.5 *lbs./sq.yd./1" thickness*
Recommended 4.4% *New Asphalt Cement PG64-22OK*

Figure 3-4 Mix Design Data of HMA Mix of FRAP2 and SRAP2.

(a)

(b)

Figure 3-5 (a) Stockpile of RAP2 and the collected FRAP2 and (b) Transportation of FRAP2.

Silver Star
Construction Co., Inc.

2401 S. Broadway - Moore, Oklahoma 73160 - (405) 793-1725 / 1-800-375-7725 / Fax (405) 793-9989

Mix Design **Mix Type:** Type "A" **Design #:** 3011-OAPA-05076

Project # :	Various Streets. City of Oklahoma City	ESALs	N/A
County :	N/A		
Contractor :	Silver Star Construction	Producer:	Silver Star Construction, Inc.

Aggregate Type	Aggregate Used	% USED
1 1/2" rock	Hanson Agg. @ DAVIS, OK	15%
5/8" rock	Martin Marietta @ Davis	32%
Screenings	Hanson Agg. @ DAVIS, OK	38%
Sand	GMI @ Meridian Pit	15%
PG 64-22 OK	VALERO @ Ardmore, OK	
		100.00%

Sieve Size	1" - #4 Stone	Screenings	5/8" Chips	Sand	Combined Aggregate	JMF	% Tol.
1 1/2"	100	100	100	100	100	100	± 7
1"	100	100	100	100	100	100	± 7
1/2"	23	100	82	100	83	83	± 7
No. 4	1	76	1	99	44	44	± 7
No. 10	0	40	1	96	30	30	± 4
No. 40	0	18	1	79	19	19	± 4
No. 80	0	11	1	19	7	7	± 4
No. 200	0.3	7.7	1	1.5	3.4	3.4	± 2
% Asphalt Cement						4.2%	+/- 0.4
% Anti-Stripping Agent							
Mix temperature @ discharge from mixer, F						305	+/- 20
Optiumum Roadway Compaction Temperature, Deg. F						290	

Test on Asphalt Cement	
Specific Grav.	1.0097

Test on Aggregates	Found	Required
Sand Equivalent	79	40 Min.
L.A. Abrasion % Wear	16.3	40 Max.
Durability Index	73	40 Min.
IOC	55.00%	
% Insoluble residue		
Fractured Faces	100	75 w/2
ESG	2.654	
Hveem Weight	1220	

Test on Compressed Mixtures:

Percent Asphalt	Specific Gravity Specimen	Max. Th. Specific Gravity	Dens. % of Max. Th.	Dens. % Req'd. of Max. Th.	V.M.A. (%)	V.M.A. (MIN.%)	Hveem Stab.	Hveem Stab (Min.%)
3.8	2.348	2.499	93.9	94-96	14.9	13	60	40
4.3	2.362	2.480	95.2	94-96	14.8	13	63	40
4.8	2.380	2.462	96.7	94-96	14.6	13	70	40

Retained Strength : 83.20% (75% Min.)
lbs / cy / 1" thick = 109.7 @ 4.2 % Asphalt Cement
Recommended 4.20% New Asphalt Cement (64-22)
Maximum Theo. Specific Gravity @ 4.2 % Asphalt Cement is 2.484 155 PCF
MEETS SPECIFICATION REQUIREMENTS

Figure 3-6 Mix Design Data of HMA Mix of SRAP3.

(a)

(b)

Figure 3-7 Collection of (a) Plant produced HMAMix3 in Paper Sacks (b) Collection of Virgin Aggregates.

STATE OF OKLAHOMA
DEPARTMENT OF TRANSPORTATION
MATERIALS DIVISION

A.D. No. 008-010-007 S4 Insoluble **Design No.** s4pv0160702100

Project No. STP-114B(194)AG 24279(04) **Hwy.** City Street **ESALS** 10M+

Contractor PMI - Silver Star Const. Co. **Producer** PMI - Silver Star Const. Co.

MATERIAL	SOURCE		%USED
5/8" Chips	Hanson Aggregates @ Davis, OK(5008)	0.25×1100 =275 lb	25
1/2" Chips	Hanson Aggregates @ Davis, OK(5008)	=198 lb	18
Screenings	Hanson Aggregates @ Davis, OK(5008)	= 462 lb	42
Sand	GMI (MacArthur Pit) @ Oklahoma City, OK(1402)	= 165	15
Asphalt Cement (PG76-28OK)	Valero @ Ardmore, OK(m00352)		

Aggregate Percent Passing	5/8" Chips	1/2" Chips	Scrns	Sand	Combined Aggregate	Job Formula	JMF Tolerance
3/4"	100				100	100	± 0
1/2"	83	100			96	96	± 7
3/8"	58	93	100	100	88	88	± 7
No. 4	20	34	73	99	57	57	± 7
No. 8	3	7	45	95	35	35	± 5
No. 16	2	2	31	91	28	28	± 4
No. 30	2	2	23	83	23	23	± 4
No. 50	2	1	17	47	15	15	± 4
No. 100	2	1	13	6	7	7	± 3
No. 200	1.3	1.7	9.0	1.0	4.6	4.6	± 2
%AC Asphalt Cement (PG76-28OK)						5.3	± 0.4
Mix Temperature @ discharge from Mixer, °F						325	± 20
Optimum Roadway Compaction Temperature, °F						305	

Tests on Asphalt Cement:

	Found
Spec. Grav. @ 77 °F	1.0142

Tests on Compressed Mixtures (at Design AC Content):

	SGC	Dens. % o Gmm	Dens. % of Gmm Req'd
Nini	8	87.2	85.5-89
Ndes	100	96	96
Nmax	160	96.3	< 98

Tests on Aggregates:

	Found	Required
F.A.A. %U	46.9	45 Min.
Sand Equivalent	67	45 Min.
L.A. Abrasion	24	40 Max.
Durability (DC)	74	40 Min.
IOC	0.72	
Insoluble Residue	89.7	40 Min.
Fractured Faces	100/100	95/90 Min.
Gse	2.696	
Gsb	2.670	
Specimen Wt..	4840	

Tests on Compressed Mixtures:

Percent Asphalt	Gmb	Gmm	Dens. % of Gmm	Dens. % of Req'd of Gmm	V.M.A. (%)	V.M.A. (Min.%)	%VFA	%VFA Req'd	%DP	%DP Req'd
4.6	2.361	2.505	94.2		15.6		63.2		1.08	
5.1	2.368	2.486	95.3	95-97	158	14	70.1	65-76	0.96	0.6-1.6
5.6	2.390	2.467	96.9		15.5		78.9		0.87	

Layer Depth: $\leq$ 4" TSR: 0.88 0.80 Min. (0.75 Min. Field) Req'd

Compacted Wt. 109.0 lbs./sq.yd./1" thickness

Lab Permeability Test(cm/sec) - 0 x10^{-5} (Required: 12.5x10^{-5} Max.)

APA Rut Test(mm) - 0.683 (Required: 5 mm Max.)

MEETS SPECIFICATION REQUIREMENTS for SP 708-3(a-g)99 Rev. 6/3/04
708-15(a-b)99 Rev. 6/3/04

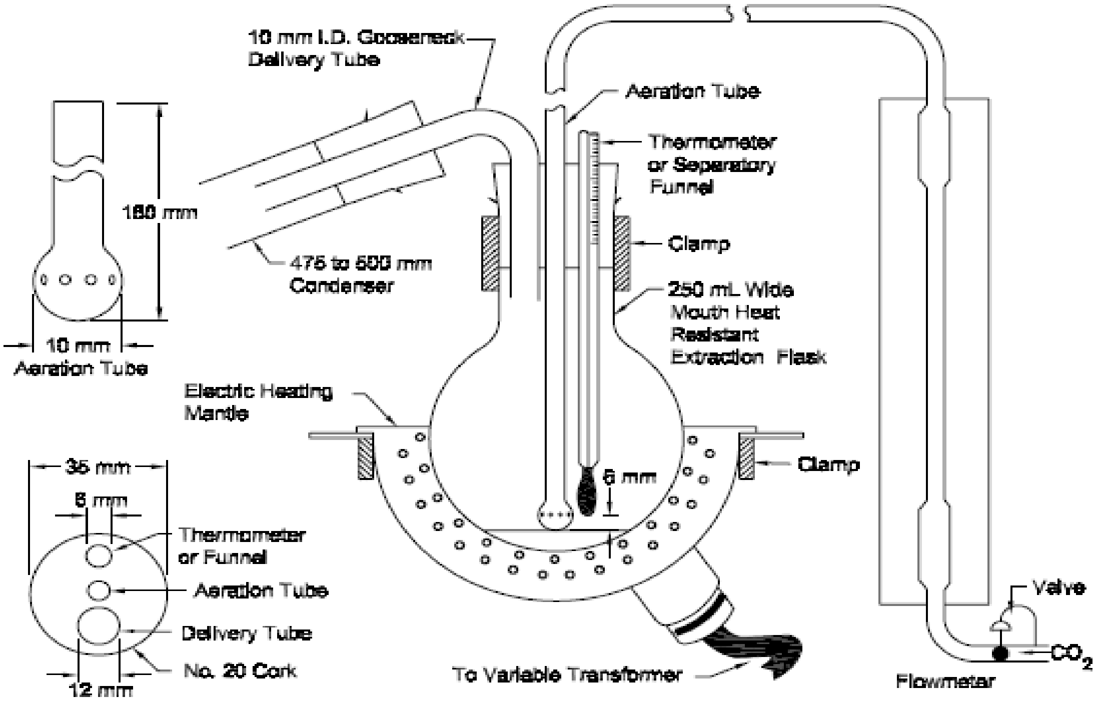
Figure 3-8 Mix Design Data of HMA Mix for SRAP4

(a)

(b)

(c)

Figure 3-9 Photographic View of (a) An NCAT Ignition Oven, (b) Virgin Aggregates, and (c) Aggregates Extracted From FRAP1.



(a)

(b) **(c)** **(d)**

Figure 3-10 (a) the Abson Assembly (AASHTO, 2008), (b) Simulated RAP, (c) Recovered Binders in Small Canisters, and (d) Aggregates Extracted via Abson.

(a)

(b)

Figure 3-11 Photographic View of: (a) LA Machine, and (b) Micro-Deval Apparatus.

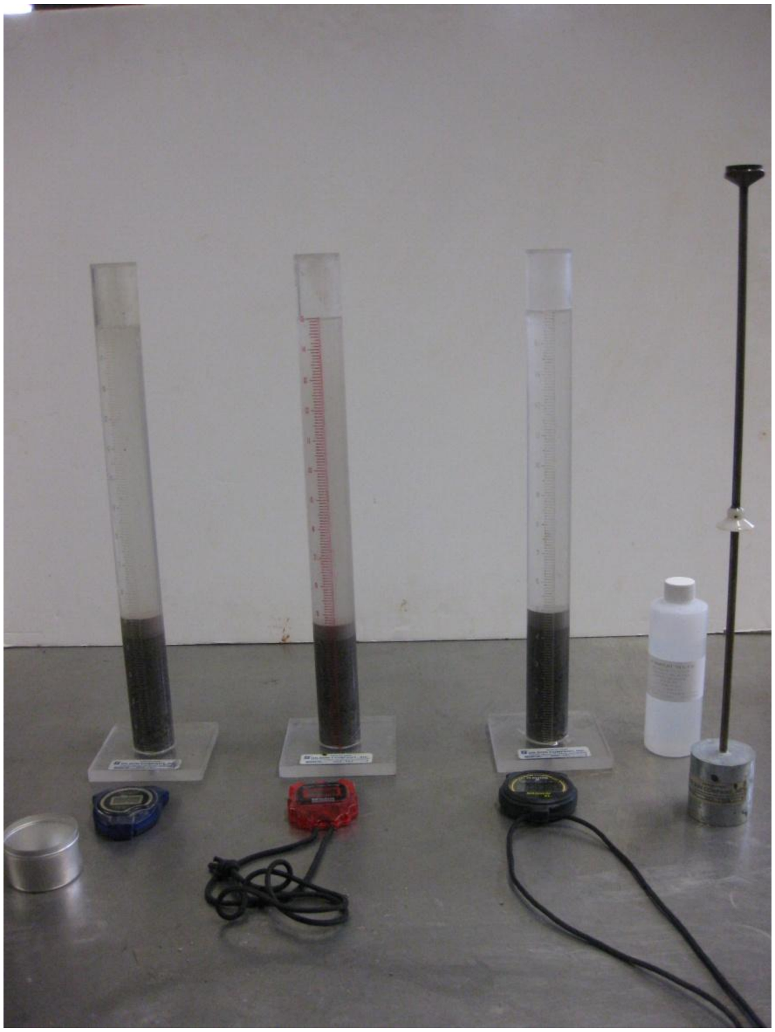
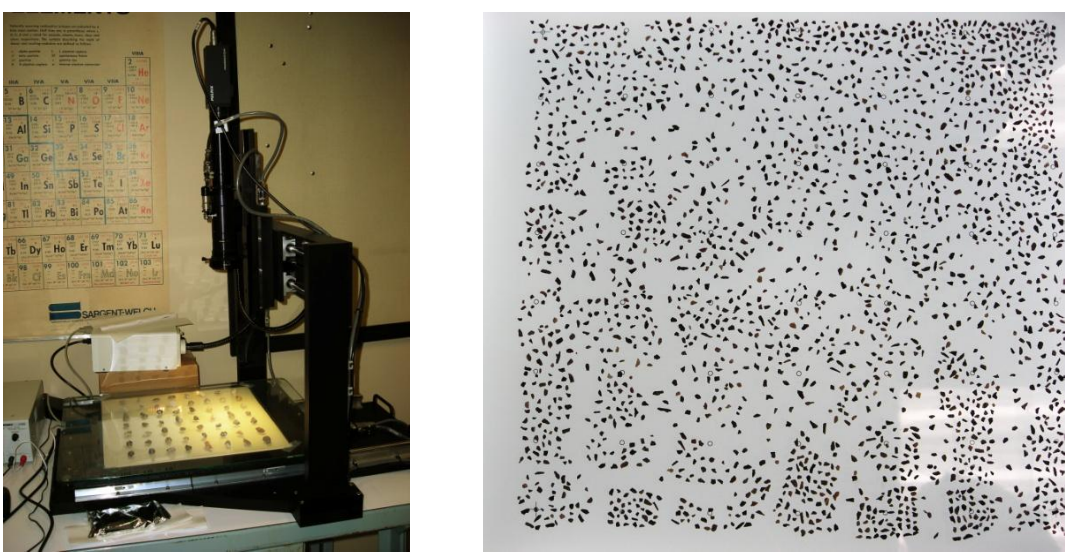


Figure 3-12 Sand Equivalent Test Setup.

Figure 3-13 Snapshots of Total Insoluble Residue Test (OHD L-25).



(a) **(b)**

Figure 3-14 AIMS Sample Layout for: a) Coarse Aggregates, b) Fine Aggregates.

4 AGGREGATE PROPERTIES

4.1 INTRODUCTION

This chapter is devoted to presenting and discussing the gradation, specific gravity, abrasion resistance, sand equivalent, total insoluble residue, and percent crushed particle results of aggregates extracted from simulated RAPs and their virgin counterparts. The shape and texture measurements of aggregates obtained from AIMS are also presented and discussed in this chapter. Additionally, selected results of aggregates extracted from field RAP are presented and compared with their virgin counterparts.

4.2 GRADATION

The gradations of virgin (AGR) and extracted (SRAP and FRAP) aggregates of HMAMix1 (Mix#1), HMAMix2 (Mix#2), HMAMix3 (Mix#3), and HMAMix4 (Mix#4) are presented in Figures 4-1 through 4-4, respectively. Each gradation curve presented in these figures is an average from three trials. It is evident from Figures 4-1 through 4-4 that virgin aggregates and aggregates extracted from SRAP are well within the minimum and maximum limits of the corresponding job mix formula (JMF). On the other hand, aggregates extracted from both SRAP and FRAP showed a slight deviation from the JMF limits. For example, FRAP1 aggregates showed percent passing more (approximately 3%) than the maximum JMF limit for finer sieves (#200). The sieve analysis of FRAP2 aggregates showed percent passing approximately 2-4% more than the corresponding maximum JMF limit for coarser sieves (½ inch (12.5 mm), 3/8 inch (9.5 mm)). One of the reasons for the excessive amount of fines in the FRAP aggregates could be due to the weathering action, traffic load, and processes involved with millings and handling, which the old pavement experienced throughout its life cycle (Hossain et al., 2011). These factors could break down the asperities of aggregates in an old pavement (Kurkoswki, 2005). The comparison of gradations of virgin and SRAP aggregates indicates a slight increase (1 – 3%) in percent passing values for finer sieves (#100, #200) (Figures 4-1 through 4-4).

An additional comparison would be the average and standard deviation values of aggregates for selected sieves (½ in., #4, # 200), which are presented in Table 4-1. Two-tail F-tests were performed on the gradation test results from the virgin and extracted aggregates to compare sample variance. Table 4-1 shows the probability (P) that the calculated F value exceeds the critical F value. A probability value of less than 0.05 ($\alpha = 0.05$) implies that the results of samples of virgin and extracted aggregates have significant variance. Thus, the probability values less than 0.05 are shown in bold font in Table 4-1. It is evident from Table 4-1 that HMAMix2 had significant variation for finer sieve (#200) size. HMAMix3 showed significant variance between virgin and extracted aggregates for coarse sieves (½ in., #4). On the other hand, HMAMix4 showed no significant variance at the 95% confidence level.

Additionally, two-tail T tests were performed to compare sample means. Table 4.1 shows the probability of the calculated T values exceeding the critical T value. Probabilities less than 0.05 are considered significant and appear in bold font in Table 4.1. All three mixes (HMAMix2, HMAMix3, and HMAMix4) indicated significant differences between the mean percent passing for the virgin and extracted samples at the 95% confidence level. All aforementioned mixes had differences with ½ in. and #200 sieves. The average difference between the percent passing in the ½ in. sieve for

HMAMix2, HMAMix3, and HMAMix4 were approximately 2.6%, 5.3%, and 1.7%, respectively. Similarly, the average difference between the percent passing in the #200 sieve for HMAMix2, HMAMix3, and HMAMix4 were approximately 0.3%, 1.2%, and 1.2%, respectively. Thus, it appears that the NCAT ignition test influences the representative gradation. However, the ARC (2010) and Prowell and Carter (2000) studies did not show any particular trend in the gradation chart for aggregates extracted via NCAT ignition oven. For example, the particles passing through the #200 sieve of aggregates extracted from FRAP were over-estimated 50% of the time and under-estimated the other 50% of the time by the ARC (2010) study. The study conducted on aggregates extracted from SRAP by Prowell and Carter (2000) indicated only 4 of 30 samples showed significant differences between the mean percent passing of virgin and SRAP aggregates.

4.3 BULK SPECIFIC GRAVITY

The average and standard deviation values of bulk specific gravity values of both coarse and fine parts of virgin and SRAP extracted aggregates are presented in Table 2. The bulk specific gravity values are in agreement with the ODOT Materials Division database (ODOT, 2011). The two-tail F and T test results, are also presented in Table 4-2. It is evident from Table 2 that the bulk specific gravity values of coarse aggregates were significantly different for three out of four aggregates with a 95% confidence level. Of the three significantly different bulk specific gravity values, two values of coarse aggregates extracted from SRAP were lower compared to the corresponding values of virgin coarse aggregates. The specific gravity values of fine aggregates were significantly different for one out of four aggregates (Table 4.2) while three out of four fine aggregates showed lower bulk specific gravity values for aggregates extracted from RAP compared to the corresponding virgin fine aggregates. A similar trend of decrease in bulk specific gravity was reported by Brian and Prowell (2000). Brian and Prowell (2000) reported that the bulk specific gravity of four out of ten of coarse aggregates and six out of ten of fine aggregates was significantly lower for NCAT ignition extracted aggregates as compared to corresponding virgin aggregates.

4.4 LOS ANGELES ABRASION LOSS

The average percent loss and standard deviation values from LA abrasion tests are presented in Figures 4-5 and 4-6, respectively. Each value presented in Figure 4-5 is an average from three trials. The "S" symbol in Figure 4-5 denotes significant difference in the sample means at the 95% confidence level using two-tail T tests. It is evident from Figure 4-5 that the LA abrasion loss values for all tested aggregates are within the limits specified by ODOT and are in agreement with the ODOT (2011) database. All LA abrasion loss values were found to be less than the ODOT upper limit of 40% (Figure 4-5). It is also observed from Figure 4-5 that the average percent loss values of 3 out of 4 aggregates extracted from SRAP are significantly higher (approximately 15 – 23%) than the corresponding percent loss values of virgin aggregates. This difference can be treated as the "shift factor," while reporting the percent LA abrasion loss value of the extracted aggregates. The increased LA abrasion loss for the SRAP aggregates could be related to the breakdown of the asperities of the aggregates due to excessive heat in the NCAT ignition oven, resulting in excessive wearing during the LA abrasion test (Hossain et al., 2011). It can be presumed that partial dissociations have occurred in some burned off aggregates and that some of these aggregates might have disintegrated during the LA abrasion process. Also, the possibility of internal changes that lead to greater voids and greater loss cannot be excluded, and it can be further investigated as a separate study. The observations of the current study are consistent with the findings reported in other studies (Ahmad et al., 2004; ARC, 2010). As presented in Figure 4-6, the standard deviation of the LA abrasion values of virgin aggregates varies between 0.16 – 1.00. The standard deviation values of the SRAP extracted aggregates ranges between 0.18 – 1.10. Watson et al. (2008) reported a variation of less than 3% for aggregates extracted from FRAP.

4.5 MICRO-DEVAL ABRASION LOSS

The average percent loss values from Micro-Deval tests are presented in Figure 4-7. It is evident from Figure 4-7 that three out of four aggregates showed significantly higher (approximately 2 – 41%) values for aggregates extracted from SRAP as compared to corresponding values of virgin aggregates. As discussed in Section 4.4, partial dissociations may have occurred in some burned off aggregates resulting in weaker aggregates producing more abrasion in Micro-Deval test. The corresponding standard deviation values of virgin and extracted aggregates are presented in Figure 4-8. The standard deviation value varies between 0.06 – 1.53 and 0.06 – 0.65 for virgin and extracted aggregates, respectively. It is also interesting to note from Figure 4-7 that SRAP2 aggregates had percent loss higher than the upper limit (25%) of Micro-Deval abrasion loss value, which is recommended by ODOT for selection of pavement aggregates.

4.6 SAND EQUIVALENT

The sand equivalent test results of virgin and extracted aggregates are presented in Figure 4-9. The virgin aggregate data are in agreement with the values reported in the ODOT (2011) database. Overall, the sand equivalent values of the extracted aggregates were higher (5 – 60%) than that of the corresponding virgin samples for all 4 aggregates. The corresponding standard deviation values of three trials of virgin and extracted aggregates are presented in Figure 4-10. The sand equivalent values from all three replicates of all tested samples had low standard deviation (4%) and were within 4 points, as recommended by the AASHTO T 176 test method for ascertaining repeatability. The significant differences occurred with samples that had relatively low (approximately 55 or less) virgin sand equivalent values. Such over-estimates of sand equivalent test data for burned off aggregates imply that a “correction factor” is needed to consider the influence of the NCAT ignition oven. Similar findings were reported in other studies (e.g., Prowell and Carter, 2000; ARC, 2010). For example, Prowell and Carter (2000) found that for eight out of ten cases, the sand equivalent values of the burnt samples were considerably higher than that of the corresponding virgin samples. The ARC study (2010) also reported that the sand equivalent values of aggregates extracted via the NCAT ignition oven over-estimated 50% of the time, indicating un-conservative designs.

Additionally, sand equivalent tests were conducted on aggregates extracted from FRAP1 and FRAP2 and the results are presented in Figure 4-11 (as requested by ODOT). The comparison of sand equivalent values of aggregates extracted from FRAP with corresponding virgin aggregates as found on the ODOT mix design sheet indicates significant decrease in the values. For example, the sand equivalent value of the FRAP1 aggregates decreased by approximately 16% as compared to the sand equivalent value of corresponding virgin aggregates from the design sheet. Similarly, the sand equivalent value of FRAP2 aggregates decreased by approximately 17% as compared to the sand equivalent value of the corresponding virgin aggregates from the mix design sheet. The decrease in the sand equivalent value is an indication of an increase in fine particles in FRAP aggregates. This behavior is consistent with the trends observed in the gradation of virgin and FRAP aggregates. Findings presented in Section 4.2 could be used for rationalizing this behavior. As requested by ODOT in the November 2010 semi-annual meeting, the sand equivalent tests were also conducted on virgin aggregate gradation constructed by using the gradation reported in the original mix design sheet (Figure 4-11). It is evident from Figure 4-11 that the virgin aggregate had a lower sand equivalent value as compared to the value reported in the mix design sheet. Changes in the source of the aggregates could be one of the reasons for virgin aggregates to have a lower sand equivalent value. For example, though from the same quarry, currently aggregates used in HMAMix1 appear to be limestone, while they were comprised mostly of sandstone several years ago when the original pavement sections were constructed.

4.7 TOTAL INSOLUBLE RESIDUE

The tested aggregates average and standard deviation values derived from three insoluble test trials are presented in Figures 4-12 and 4-13, respectively. It is evident from these figures that the results are repeatable with standard deviation values of less than 1.36 and 2.13 for virgin and SRAP aggregates, respectively. Although three out of four aggregates showed a higher (0.5 – 12%) percent residue for SRAP aggregates compared to corresponding virgin aggregates, this difference was found insignificant with a 95% confidence level using two-tail Student's T-tests. It is important to note that the insoluble residue test is a chemical test where aggregates are subjected to react with hydrochloric acid (HCl). Different aggregates will react differently with HCl depending on their mineralogical compositions. For example, limestone which is composed largely of calcite ($CaCO_3$), is expected to react well with HCl. However, sandstone, which is primarily composed of quartz and/or feldspar, is not expected to react with HCl. It is very unlikely that the NCAT ignition oven processes change the fundamental mineralogy (chemicals composition) of aggregates, reflecting that the percent residue should not change.

4.8 PERCENT CRUSHED PARTICLES

The results of percent crushed particles with one or more crushed faces are presented in Table 4-3. As seen in Table 4-3 there is no evidence of the influence of the NCAT ignition oven on the percent crushed particles. For example, both virgin and extracted aggregates of HMAMix1 showed a percent crushed particle value of 100. Additionally, shape and texture measurements of aggregates were evaluated using the AIMS, and they are presented and discussed in the following section.

4.9 AGGREGATE IMAGING SYSTEM (AIMS) RESULTS

The reproducibility of AIMS results was verified by testing two random samples (56 aggregates for each sample) from the same size range. It was observed that the test results of these replications were very reproducible as there was no statistical difference in test results (with 95% confidence).

The results of the AIMS tests are presented in Appendix A. Six different sizes (Passing 3/4" and Retained 1/2”, Passing 1/2” and Retained 3/8”, Passing 3/8” and Retained 1/4", Passing 1/4" and Retained #4, Passing #4 and Retained #8, and Passing #8 and Retained #16) of aggregates were analyzed. The detailed test results show no particular trend to conclude whether the shape indices (angularity, sphericity, texture, or form) of the extracted aggregates are higher than the virgin counterparts, or vice versa. For example, in the case of aggregates Passing 3/4" and Retained 1/2” for SRAP2, SRAP3 and SRAP4, the sphericity indices of the extracted (via NCAT) aggregates is slightly higher than those of their virgin counterparts (Figures A-12a, A-18a, and A-25a). An opposite observation was made for the same size of aggregates for SRAP1, indicating lower sphericity indices for the extracted aggregates compared to their corresponding virgin counterparts (Figure A-4a). For aggregates Passing 1/2” and Retained 3/8”, the sphericity indices of the aggregates extracted from SRAP1, SRAP2 and SRAP3 are higher than those of their corresponding virgin counterparts (Figures A-4b, A-12b, and A-18b). On the other hand, the sphericity indices of extracted aggregates (Passing 1/2” and Retained 3/8”) for SRAP4 are significantly lower than those of its virgin counterpart (Figure A-25b). The opposing trends in test results of shape indices make it quite difficult to conclude something specific regarding whether or not the NCAT ignition oven influences surface properties. Such complexity is augmented by the fact that this trend is not the same for all sizes of samples for a particular type of aggregate (e.g., sphericity of SRAP1 in Figures A-4a through A-4d). To simplify the complexity of this problem, weighted averages of shape indices of selected aggregates (SRAP1, SRAP2, and their counterparts) were computed and explained next.

A two step procedure was used to find weighted average of a shape factor. First, the average shape indices for each of the six tested sizes (Passing 3/4" and Retained 1/2", Passing 1/2” and Retained 3/8”, Passing 3/8” and Retained 1/4", Passing 1/4” and Retained #4, Passing #4 and Retained #8, and Passing #8 and Retained #16) of aggregates were determined. Next, the average shape indices of aggregates were then used to calculate the weighted average (Equation 4.1) based on the weight percentage of the size ranges in a given mix. Thus a single shape factor was obtained for all six sizes of tested aggregate.

$$\mathrm{Shape}_{\mathrm{weighted}} = \frac{\sum_{i=1}^{6} W_i \mathrm{Shape}_i}{\sum_{i=1}^{6} W_i} \qquad (4.1)$$

where,

W_i = Weight proportion of a tested aggregate size in the mix design sheet,

Shape_i = average shape factor of a tested aggregate size, and

$\mathrm{Shape}_{\mathrm{weighted}}$ = Weighted average shape factor for the mix

In the case of the SRAP1 and its virgin counterparts, the weights of the tested aggregates were considered based on the mix design sheet of HMAMix1. The weighted average shape factors for virgin aggregates of AGR1 (control), aggregates extracted from FRAP1 via NCAT ignition oven, aggregates extracted from SRAP1 via NCAT ignition oven, and aggregates extracted from SRAP1 via Abson are presented in Table 4.4. As noted in Table 4.4, the weighted average texture indices of FRAP1 (NCAT), SRAP1 (NCAT), and SRAP1 (Abson) are about 3%, 5% and 17%, respectively, which is higher than that of the control aggregate (AGR1). Such difference in texture is possibly due to the effects of high heat of the NCAT ignition oven during the extraction process. Thus, taking texture index of an extracted aggregate in the analysis and design would be an overestimate (i.e., non-conservative design) of the surface property. There are slight increases in radius angularity indices for FRAP1 (NCAT), SRAP1 (NCAT), and SRAP1 (Abson) when compared to the control aggregate, however, the differences in angularity indices are not statistically significant.

As seen in Table 4-4, it is also evident that there are significant differences in the texture, radius angularity and sphericity for SRAP1 (Abson) aggregates when compared to those of the control aggregate (AGR1). This could be due to the following two mechanisms. First, the centrifugal force in Abson method may have caused abrasion effects in the aggregates, causing a higher texture index. Secondly, the solvent (trichloroethylene) used in the extraction process may have chemically reacted with the aggregates' (limestone) surface compositions and changed the texture. However, the overall shape (2D form) indices of these aggregates remain very close, indicating no significant influence of the extraction process on the overall shape.

Likewise, the weighted average shape factors of aggregates extracted from SRAP2 via the NCAT oven and their virgin counterparts (AGR2), shown in Table 4-5, demonstrate a similar trend of surface properties, excluding the texture. The radius angularity of SRAP2 aggregate is not significantly different from the control (AGR2). For sphericity, there is roughly a 4% difference, which is similar to the 3% change from SRAP1. The texture index of SRAP2 aggregate is significantly lower (13%) than that of the virgin counterpart. Again, such difference could be due to the high temperatures used during NCAT ignition which could be causing morphological changes in the minerals that make up the aggregates.

Table 4-1 Comparison of Gradations of Virgin and SRAP Extracted Aggregates

Aggregate Type	Sieve	Virgin (AGR)		Extracted (SRAP)		P (F<=f) two-tail	P (T<=t) two-tail
		Av.	Stdev.	Av.	Stdev.		
HMAMix1	1/2 in.	95.4	NA	95.9	NA	NA	NA
	#4	54.6	NA	56.2	NA	NA	NA
	#200	2.8	NA	4.5	NA	NA	NA
HMAMix2	1/2 in.	83.9	0.81	86.5	0.64	0.387	0.023
	#4	72.4	1.05	72.4	0.30	0.073	0.977
	#200	1.5	0.14	5.5	1.84	0.005	0.039
HMAMix3	1/2 in.	85.7	0.32	80.4	2.66	0.015	0.049
	#4	45.1	0.74	39.3	5.78	0.016	0.228
	#200	1.3	0.54	2.5	0.19	0.112	0.038
HMAMix4	1/2 in.	94.7	0.29	93	0.20	0.324	0.003
	#4	56.6	0.41	45.9	0.23	0.243	0.000
	#200	1.7	0.25	2.9	0.12	0.198	0.004

Table 4-2 Bulk Specific Gravity of Coarse and Fine Aggregates

Aggregate Type	Virgin (AGR)		Extracted (SRAP)		P (F<=f) two-tail	P (T<=t) two-tail
	Av.	Stdev.	Av.	Stdev.		
Coarse Aggregates						
HMAMix1	2.656	0.005	2.659	0.005	0.500	0.581
HMAMix2	2.607	0.005	2.571	0.002	0.138	0.001
HMAMix3	2.699	0.012	2.665	0.010	0.410	0.037
HMAMix4	2.639	0.001	2.672	0.010	0.990	0.010
Fine Aggregates						
HMAMix1	2.635	0.006	2.637	0.006	0.500	0.756
HMAMix2	2.502	0.005	2.445	0.001	0.962	0.000
HMAMix3	2.585	0.001	2.558	0.014	0.005	0.053
HMAMix4	2.564	0.002	2.557	0.011	0.968	0.426

Table 4-3 A Summary of Percent Crushed Particles

Aggregate Type	HMAMix1	HMAMix2	HMAMix3	HMAMix4
Virgin (AGR)	100	98	98	99
Extracted from Simulated RAP (SRAP)	100	98	98	99

Table 4-4 Weighted Average of SRAP1 Extracted Aggregates and their Virgin Counterparts

Aggregate	Texture	Gradient Angularity	Radius Angularity	Sphericity	2D Form
AGR1 (Virgin)	172.31	3063.90	10.58	0.59	7.82
FRAP1 (NCAT)	177.44	3228.38	11.04	0.64	7.75
SRAP1 (NCAT)	181.35	2981.14	11.31	0.61	7.91
SRAP1 (Abson)	201.94	3046.18	11.07	0.66	7.65

Table 4-5 Weighted Average of SRAP2 Extracted Aggregates and their Virgin Counterparts

Aggregate	Texture	Gradient Angularity	Radius Angularity	Sphericity	2D Form
AGR2 (Virgin)	175.57	2947.94	10.29	0.67	7.17
SRAP2 (NCAT)	153.46	3059.57	10.32	0.69	7.46

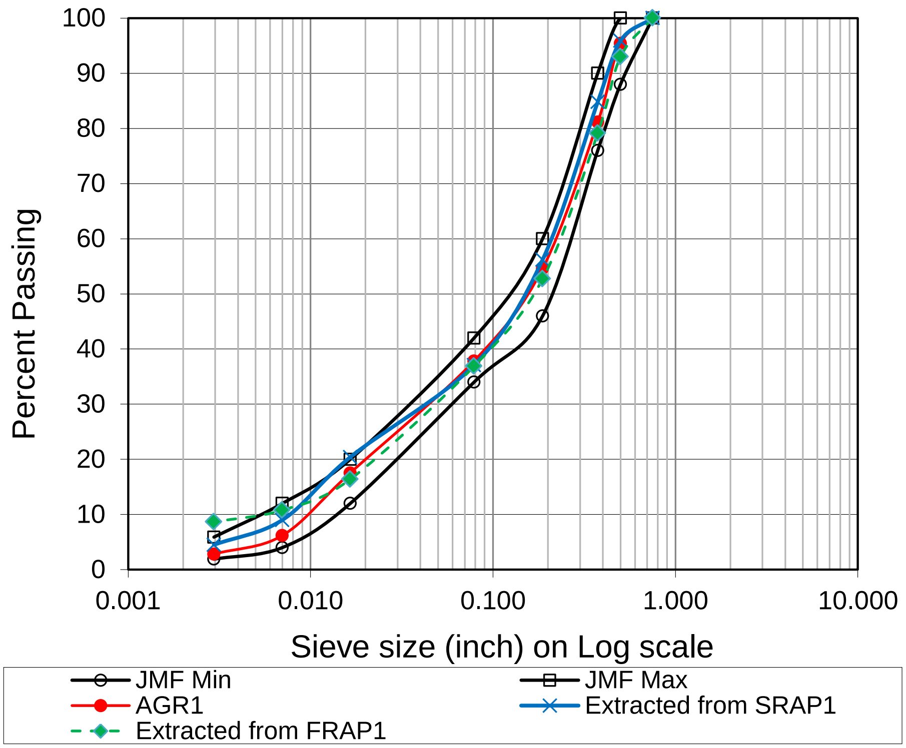


Figure 4-1 Gradation Charts of Virgin, SRAP1 and FRAP1 Extracted Aggregates.

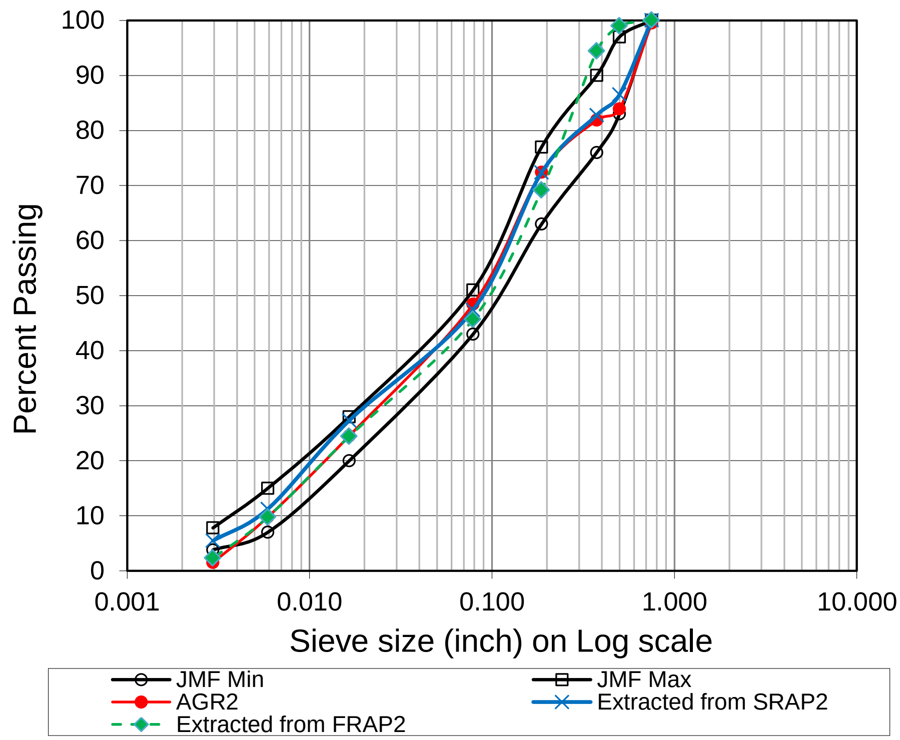


Figure 4-2 Gradation Charts of Virgin, SRAP2 and FRAP2 Extracted Aggregates.

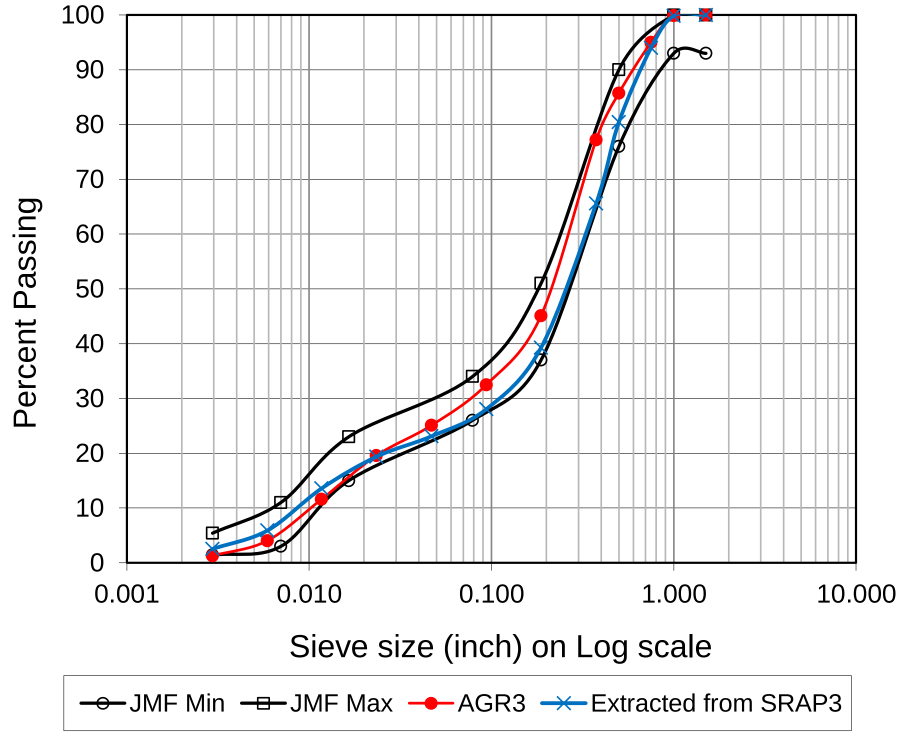


Figure 4-3 Gradation Charts of Virgin, SRAP3 and FRAP3 Extracted Aggregates.

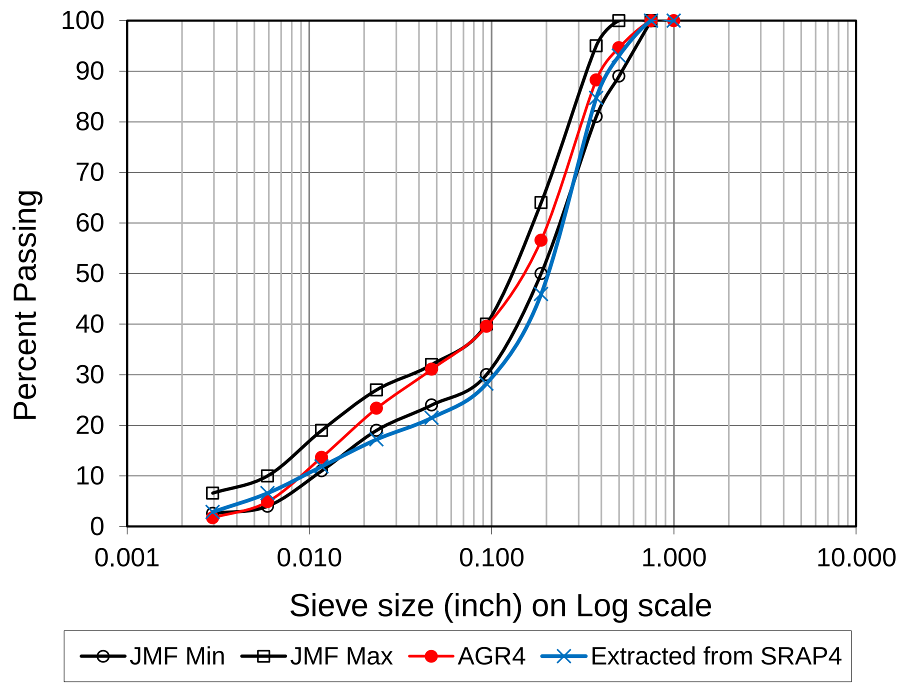


Figure 4-4 Gradation Charts of Virgin, SRAP4 and FRAP4 Extracted Aggregates.

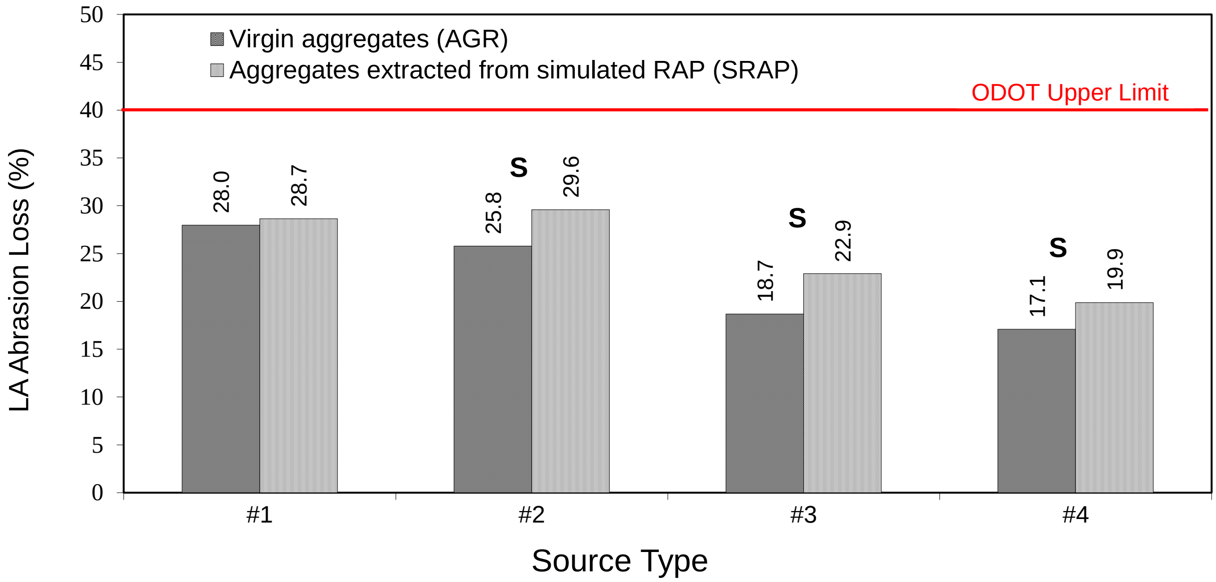


Figure 4-5 Average Percent Loss Values from LA Abrasion Test Results (S denotes a significant difference in the sample means at the 95% confidence level).

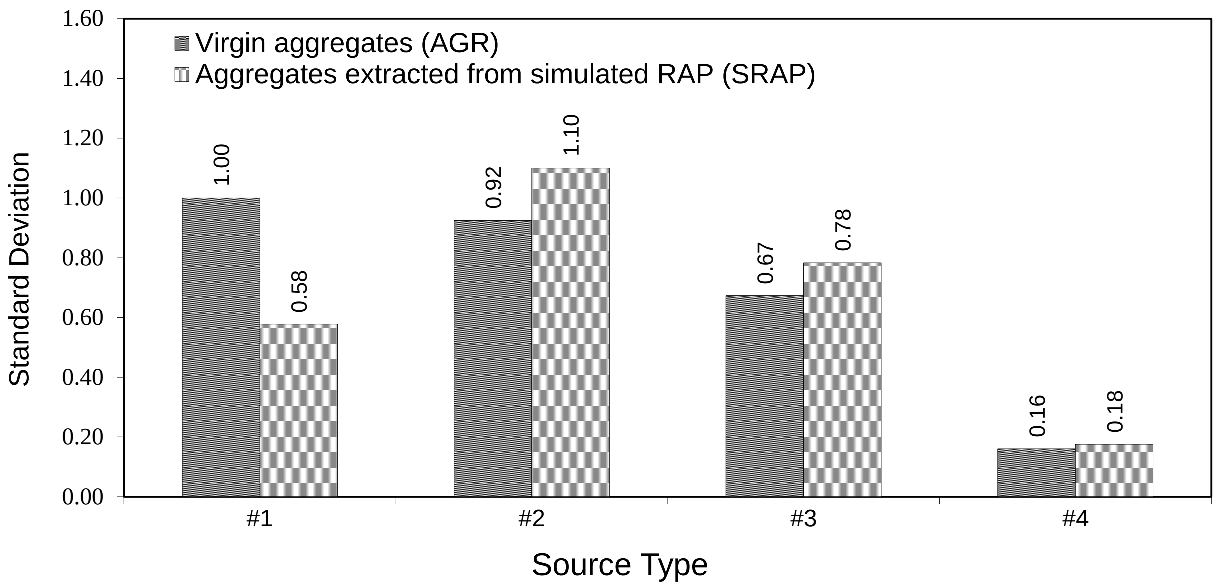


Figure 4-6 Standard Deviation Values from LA Abrasion Test Results.

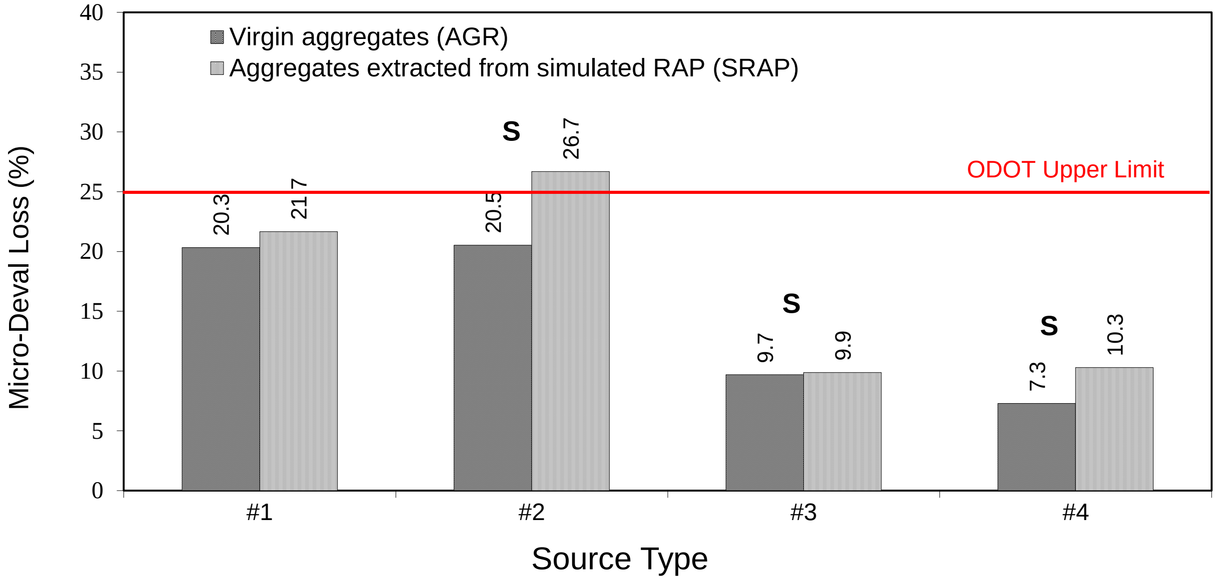


Figure 4-7 Average Percent Loss Values from Micro-Deval Test Results (S denotes a significant difference in the sample means at the 95% confidence level).

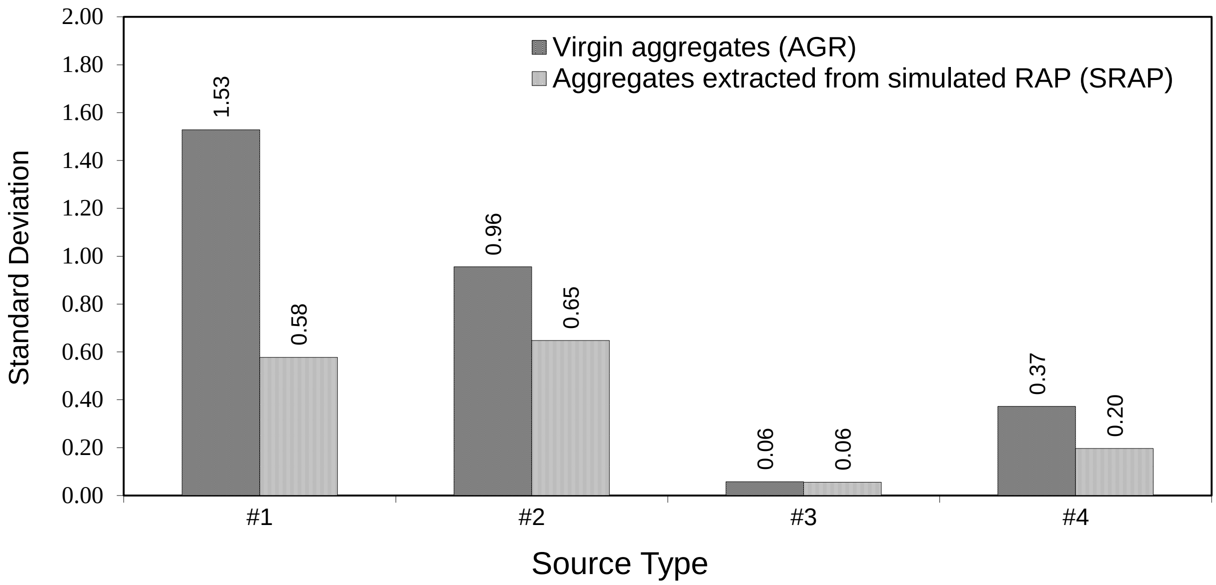


Figure 4-8 Standard Deviation Values from Micro-Deval Test Results.

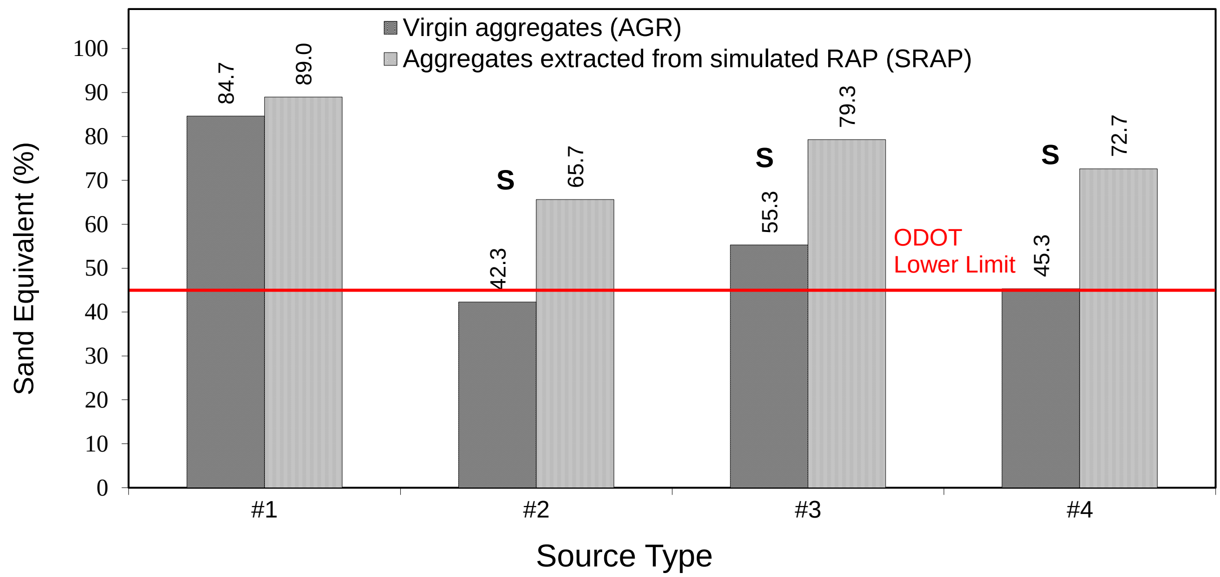


Figure 4-9 Average Percent Values from Sand Equivalent Test Results (S denotes a significant difference in the sample means at the 95% confidence level).

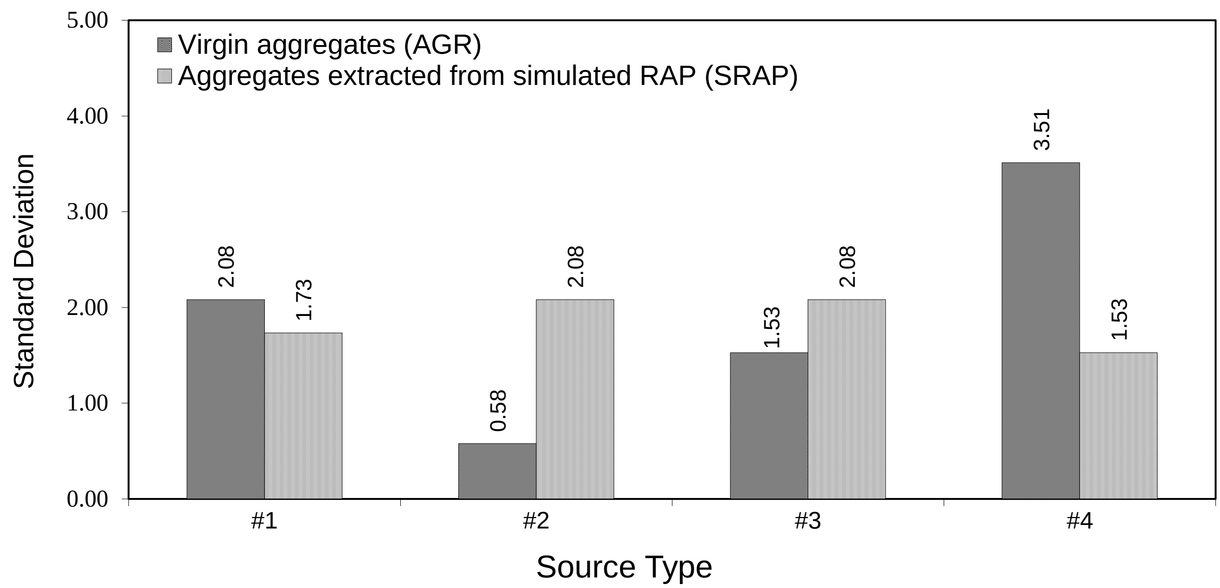


Figure 4-10 Standard Deviation Values from Sand Equivalent Test Results.

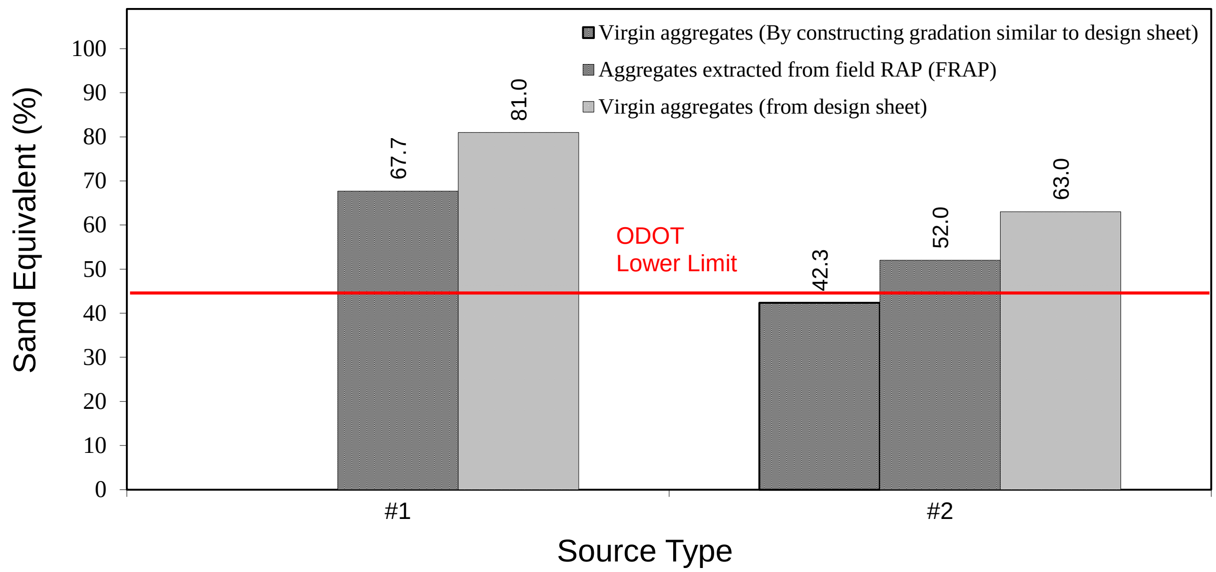


Figure 4-11 A Summary of Percent Values from Sand Equivalent Test Results Conducted on both Virgin and FRAP Aggregates of HMAMix1 and HMAMix2.

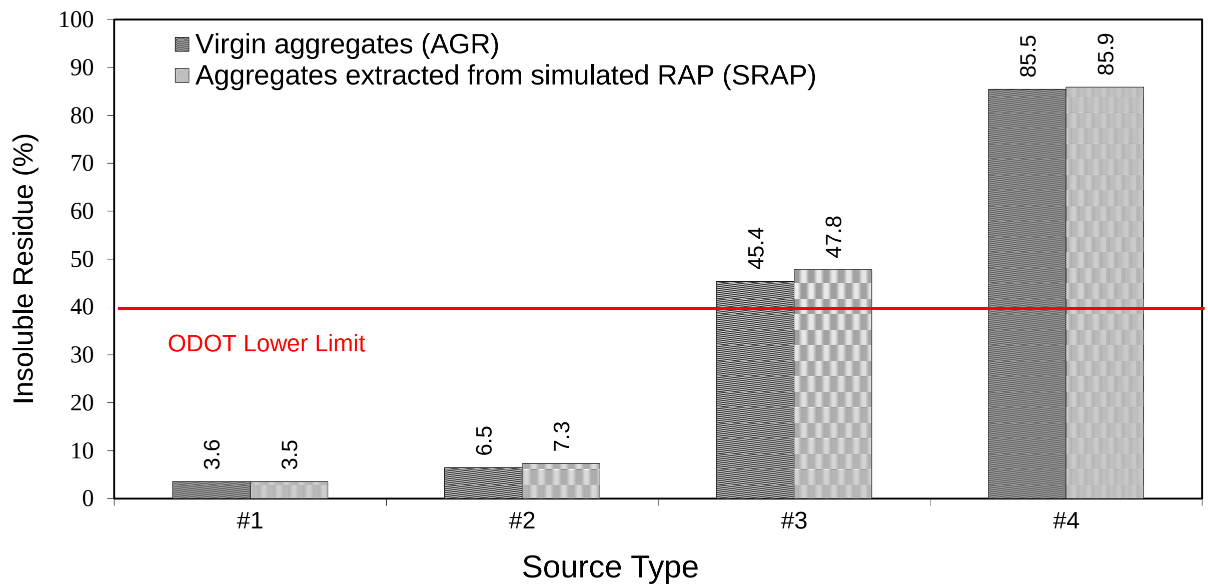


Figure 4-12 Average Percent Residue Values from Acid Insoluble Residue Test Results.

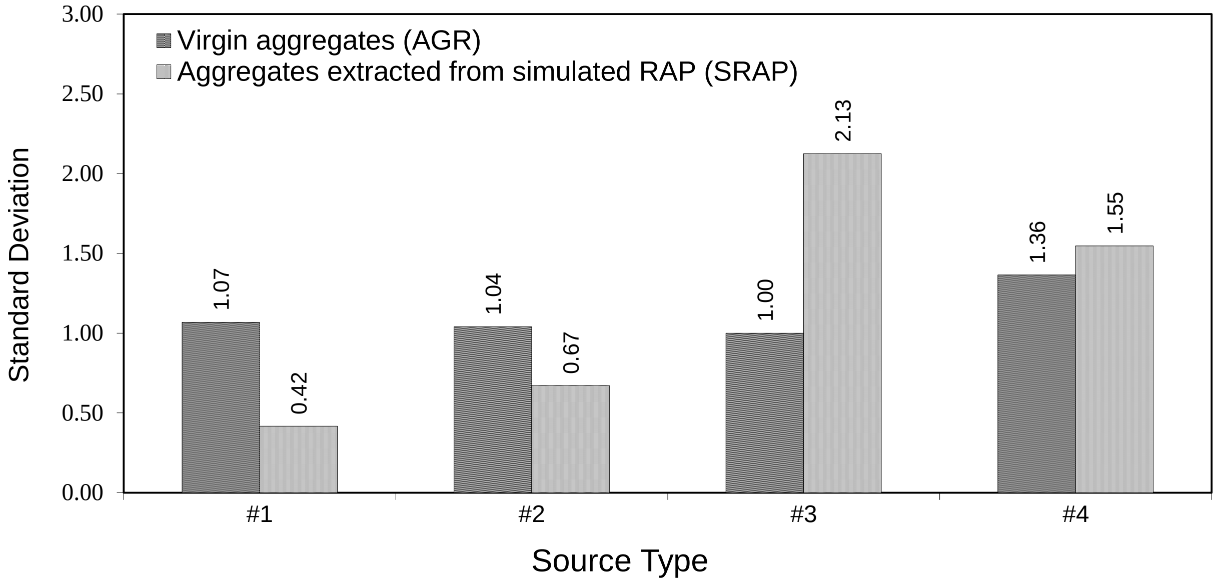


Figure 4-13 Standard Deviation Values from Acid Insoluble Residue Test Results.

5 ASPHALT BINDER PROPERTIES

5.1 INTRODUCTION

As mentioned previously, four binders were tested to evaluate the influence of the Abson method on PG grade, viscosity and penetration values of the recovered binder. Of these, two PG 76-28 binders were relatively hard, and these were collected from two different sources, SRC1 (Ergon at Muskogee; P/S#00511) and SRC4 (Valero at Ardmore P/S# m00352). The remaining PG 64-22 binders were relatively soft, and these were collected from two different sources, namely, SRC2 (Gary Williams at Wynnewood; P/S#00357) and SRC3 (Valero at Ardmore; P/S# 00352).

5.2 PERFORMANCE GRADE

The continuous PG grades of tested binders based on DSR and BBR test results are presented in Figures 5-1 through 5-4.

5.2.1 Hard Binder

From DSR and BBR test results, the continuous PG grade of the tested virgin SRC1 (Ergon PG 76-28) binder was calculated to be PG 79.8-33.7. The DSR and BBR test results of the virgin binder from Ergon were found to be in agreement with the certification data of the binder. The PG grades of the PAV-term aged virgin SRC1 binder, the binder recovered from FRAP1, and the binder recovered from SRAP1 were found to be PG 94.8-30.6, PG 81.1-19.8, and PG 98.9-27.7, respectively (Figure 5-1). According to the Superpave™ specifications, PG binders need to meet rutting criteria for both unaged and RTFO-aged conditions. Thus, DSR test results of binders either under unaged or RTFO-aging conditions govern the high PG temperature. On the other hand, either stiffness (S-value) or rate of stress relaxation (m-value) from BBR test results governs the low PG temperature. In regard to the aging condition, the current study did not show any trend in controlling the high PG temperatures. That is, the unaged condition dictated the high PG temperatures in some cases, and the RTFO-aged condition governed the high critical temperatures in other cases. However, the m-values from BBR test results governed the low PG temperatures in all cases. For example, in the case of SRAP1 binder, the low critical temperatures corresponding to stiffness (S) and m-value were found to be -32.5^{o}C and -27.7^{o}C, respectively.

It is also important to note that the continuous PG grade of the recovered binder from FRAP1 was slightly higher than that of the virgin (PG 76-28) binder; the continuous PG grade of the former was found to be PG 81.1-19.8 and that of the later was PG 79.8-33.7. However, the actual PG grade of the recovered binder from FRAP1 was expected to be significantly higher, with at least an increase of one PG grade on both sides. Since the actual PG grade and the modifier (polymer) of the binder used in the original mix of the pavement of FRAP1 in 2003 were not available, the true causes of such unexpected behavior remained unknown. However, such unavailability of historical information of the binder revealed that it would not be worthwhile to compare the PG grade of the FRAP1 binder with the virgin PG 76-28 binder collected from SRC1. Thus, the binder recovered from SRAP1 was used for comparison purposes as the same binder (Ergon PG 76-28) was used to prepare its corresponding HMA mix (HMAMix1).

From Figure 5-1, it is observed that the PG grade for the binder recovered from SRAP1 shifted upward from that of the PAV-aged SRC1 PG 76-28 binder. The high PG temperature and the low PG temperature for the binder recovered from the SRAP1 binder were 4.1^{o}C and 2.9^{o}C higher than the corresponding temperatures of the PAV-aged SRC1 binder, respectively. This variation was expected due to possible effects of the Abson method on the recovered binder as it went through prolonged oxidative hardening. As per the Superpave™ specifications (standard 6^{o}C interval), the PAV-aged SRC1 and SRAP1 binders would be graded as PG 94-28 and PG 94-22, respectively (Table 5-1). Even though the high PG temperatures remained the same, one full PG grade difference was observed at the low critical temperature end; similar observations were made in the case of the SRC4 binder (Valero PG 76-28). The continuous PG grade of the virgin SRC4 binder was found to be PG 77.2-28.3 (Figure 5-2). The PG grades of the long-term aged virgin SRC4 binder and the binder recovered from SRAP4 were found to be PG 94.1-24.1 and PG 97.2-22.0, respectively. The high PG temperature and the low PG temperature for the binder recovered from the SRAP4 binder were 3.1^{o}C and 2.1^{o}C, respectively, higher than the corresponding temperatures of the PAV-aged SRC4 binder. As per the Superpave™ PG grade (standard 6^{o}C interval), both the PAV-aged and the recovered binders would be labeled as PG 94-22.

The aforementioned findings imply that the use of the PG grade of the Abson recovered RAP binder is expected to lead to a non-conservative design. These differences in PG temperatures can be used as “shift” (correction) factors while evaluating PG grades of recovered binders. Thus, to compensate for the effect of Abson on PG temperatures, these “shift” factors should be deducted (arithmetic) to obtain a better approximation of PG grades of the recovered binders. Taking the average of differences in high PG and low PG temperatures of the tested hard binders, the “High PG Shift” and “Low PG Shift” factors were found to be 3.6^{o}C, and 2.5^{o}C, respectively.

5.2.2 Soft Binder

When comparing PG grades recovered from SRAP2 and laboratory aged (long-term) SRC2 (Valero PG 64-22) binders (Figure 5-3), it appears that the Abson method increased the high PG temperature by 3.7^{o}C. Even though a slight increase (-18.8^{o}C versus -18.6^{o}C) in low PG temperature was observed for the Abson recovered binder when compared to the laboratory aged binder, at a confidence level of 95%, this difference did not have any statistical significance. With regard to the second soft binder, the continuous PG grade of the Gary William's (SRC3) PG 64-22 virgin binder was found to be PG 64.9-23.9 (Figure 5-4). Comparatively, the continuous PG grades of PAV-aged SRC3 and SRAP3 recovered (via Abson) binders were found to be PG 77.8-21.1 and PG 81.1-22.2, respectively. Thus, the high and low PG temperatures of SRAP3 binder were 3.3^{o}C and 0.9^{o}C, respectively, which are higher than those of the PAV-aged GW PG 64-22 binder. Taking the average of differences in high PG and low PG temperatures of the tested soft binders, the "High PG Shift" and the "Low PG Shift" factors were found to be 3.5^{o}C and -0.4^{o}C, respectively.

Such differences were possibly due to the recovered binder undergoing excessive oxidative hardening (chemical and physical) in the centrifuge. The purge gas (CO_2) used in the recovery method may have accelerated the aforementioned age hardening. Furthermore, it is possible that very fine particles escaped through the filter which increased the complex modulus of the binder. It is believed that even small traces of the TCE solvent make the asphalt binder softer. The combined effect of prolong oxidative hardening and inadequate filtering may have offset the softening effect of the TCE; thus, it increased the overall stiffness of the recovered binder. To verify the aforementioned findings, elemental analyses of two selected binders were conducted to determine their composition under different aging conditions and the results are discussed later in this chapter.

Furthermore, it was observed the influence of the Abson recovery technique is relatively low in the case of the soft binder (PG 64-22) when compared to the hard binder (PG 76-28). There was virtually no influence of the Abson processes in the low PG temperature in the case of the soft binder. A relatively higher influence of the Abson method on the PG grade of the hard binder was suspected to be due to the presence of polymers with unknown properties. The presence of these polymers can be evaluated by evaluating the elastic recovery (ER) of these binders using techniques such as multiple stress creep recovery (MSCR).

5.2.3 Abson versus Rotavapor

As shown in Figure 5-4, the Rotavapor recovered SRAP3 binder was found to be stiffer than the Abson recovered binder. The PG grades of the SRAP3 binder recovered via Rotavapor and Abson methods were found to be PG 82.9-18.5 and PG 81.1-22.2, respectively. Such behavior is expected as the extraction process in the Rotavapor method is gentler than that of the Abson method. Furthermore, the extraction solvent (85% toluene and 15% alcohol) used in the Rotavapor method is believed to have less influence than the 100% TCE used in the Abson method, thus reducing the softening effects in the case of the former. Therefore, the net influence of the Abson method on the PG grade of the RAP binder is expected to be relatively less than that of the Rotavapor method. This implies that the use of the PG grade of the binder recovered via the Rotavapor method would be a more conservative design than that of the Abson method.

5.3 ROTATIONAL VISCOSITY

Rotational viscosity test results of SRAP binders and their virgin counterparts are shown in Figures 5-5 through 5-8. As seen in Figure 5-5, it is evident that the viscosity of the recovered binder from SRAP1 is slightly higher than that of the PAV-aged virgin binder (Ergon PG 76-28). However, Student's t-test (two-paired) results showed the variation was not significant with a confidence level of 95%. As expected, the variation in viscosity measurements of SRAP1 binder was found to be significantly higher than that of its virgin counterparts (unaged and PAV-aged). It was also observed that the SRAP1 binder is about four times more viscous than that of its unaged virgin counterpart. Similar observations were made for the PAV-aged and unaged PG 76-28 binder from Valero (SRC4) (Figure 5-6). It should be noted that the research team was not able to conduct viscosity test on the recovered binder from SRAP4 because of the shortage of the material. So, viscosity data of SRAP1 and its counterparts were considered to determine the "viscosity shift" of the hard binder. Thus, the use of viscosity data of the hard binder recovered (Abson) from the RAP would be considered a conservative design. Thus, the positive "viscosity shift" factor of the hard binders shown in Table 5-2 needs to be deducted to obtain a more accurate viscosity of the RAP binder.

Surprisingly, the binder recovered from FRAP1 was found to be significantly less viscous than the SRAP1 binder. The FRAP1 binder was also significantly less viscous than the virgin PG 76-28 binder from Ergon under unaged condition. Repeated RV tests revealed similar test results. It should be noted that that the viscosity data of unaged PG

76-28 binder from Ergon was found to be in agreement with certification data obtained from the refinery. It remained unknown why the viscosity of FRAP1 was found to be so low. A possible explanation could be that the polymer used in the PG 76-28 binder of the original pavement section of FRAP1 had broken down at high testing temperatures in the RV chamber, due to weathering and wearing actions during its service conditions, or a combination of both. It should be recalled that the PG grade of FRAP1 binder was also found to be significantly less than the expected PG grade of a RAP binder. As mentioned earlier, ER data obtained from MSCR tests on recovered binder from RAP can potentially provide some insight on the presence of polymer.

In the case of the soft binders, the observed trend was found to be quite opposite from that of the tested hard binders (Figures 5-7 and 5-8). The recovered binders from SRAP2 and SRAP3 were found to be slightly less viscous than the corresponding PAV-aged virgin binders, indicating a negative “viscosity shift” factor for the soft binder as shown in Table 5.2. However, the differences in viscosity measures of SRAP binders and their PAV-aged virgin counterparts were not statistically significant with a confidence level of 95%.

5.4 PENETRATION

Penetration values of recovered and virgin binders were determined as per AASHTO T 49 (AASHTO, 2008) and presented in Figures 5-9 through 5-12. In three out of four cases (75% of time), the penetration depth of SRAP binder was found to be higher than the corresponding PAV-aged virgin counterpart. The higher penetration value of the recovered binder could be due to the effect of additional aging or chemical reactions that might have occurred during the recovery process.

As shown in Figure 5-9, the penetration value of the recovered binder from SRAP1 was found to be 48. On the other hand, penetration values for the virgin PG 76-28 binder at unaged and PAV-aged conditions were found to be 106 and 38, respectively. As expected, the penetration value of the recovered binder is significantly lower than the unaged virgin counterpart, partly due to the aging (oxidative hardening) that occurred during the mixture preparation and compaction processes and to a great extent, due to accelerated short-term and long-term aging of the mix. It was also observed that the penetration depth of the recovered SRAP1 is 1.0 mm higher than the PAV-aged PG 76-28 binder. In the case of the PG 76-28 binder from Valero (SRC4), the penetration depth of SRAP4 binder was found to be 0.2 mm higher than the virgin counterpart at PAV-aged condition (Figure 5-10). The penetration depth for the binder recovered from SRAP2 was found to be 0.7 mm higher than the PAV-aged PG 64-22 binder (Figure 5-11). The penetration depth of SRAP3 binder was slightly lower (0.2 mm) than its PAV-aged virgin counterpart. The average “Penetration Shift” factors for hard and soft binders are presented in Table 5-3.

5.5 ELEMENTAL ANALYSIS

Elemental analyses of the PG 64-22 binder under unaged and PAV-aged conditions and SRAP2 binder are shown in Table 5-4. The hydrocarbon (carbon and oxygen) content of the binder under unaged condition was found to be roughly 94.5%, which is within the typical range of asphalt binders refined from Boscan crude source. The amount of hydrocarbon was found to decrease with the physical and chemical hardening that the binder experienced during the aging process. As expected, the content of oxygen in PAV-aged PG 64-22 binder was found to be 43% higher than that of the unaged binder.

In the case of SRAP2 binder, the amount of oxygen was found to be 241% higher than that of the unaged binder. The significant increase in the oxygen content in SRAP2 binder might be due to the increased oxidative hardening (i.e. carboxyl functional group) the binder experienced during the Abson recovery process. Similar observations were made for the SRAP3 binder and its virgin counterpart. The trend of increased oxygen content in SRAP3 binder compared to its PAV-aged virgin counterpart was similar to that of the SRAP2 binder. These observations support the PG grade data of the tested binders presented earlier; both high and low PG temperatures of the recovered (Abson) binder shifted upward compared to the PAV-aged binder.

5.6 SUMMARY

Four laboratory simulated RAP (SRAP) samples were evaluated for PG grading, rotational viscosity, and penetration value. Of these, two samples (SRAP1 and SRAP4) were prepared with a hard binder (PG 76-28) collected from two different sources, and the other two (SRAP2 and SRAP3) were prepared with a soft binder (PG 64-22) collected from two different sources. Virgin binders used in these simulated RAPs were also evaluated at unaged and PAV-aged conditions. The Abson method seemed to have some influence on the PG temperatures of the recovered binders. The influence in PG temperatures in the tested hard binder (PG 76-28) appeared to be slightly less than that of the soft binder (PG 64-22). The “High PG Shift” and “Low PG Shift” factors for the hard binders were about 3.6°C, and 2.5°C, respectively. On the other hand, the "High PG Shift" and "Low PG Shift" factors of the tested soft binders were about 3.5°C, and -0.4°C, respectively. It was also observed that the influence of the Abson recovery technique is relatively low in the case of the soft binder (PG 64-22) when compared to the hard binder (PG 76-28). Furthermore, the PG grade of the binder recovered via the Rotavapor method was comparable to that of the binder recovered via the Abson method. However, the use of PG grade of a RAP binder recovered via Rotavapor is expected to be more conservative than that of the same recovered via the Abson method.

The viscosity values of recovered binders from SRAPs were somewhat different from those of the PAV-aged virgin counterparts. In the case of the tested hard binder (PG 76-28), the viscosity of the SRAP binder was found to be higher than the corresponding PAV-aged virgin counterpart. An opposite trend in viscosity data was observed in the case of the tested soft binder (PG 64-22) tested in this study; however, the differences were not statistically significant. The penetration values of the recovered binders were found to be higher than those of the laboratory PAV-aged binder in 75% of the time. Elemental analysis of the selected soft binders demonstrated an increase in the oxygen content in the SRAP binder when compared to its PAV-aged virgin counterpart. Shift factors presented in Tables 5-1 through 5-3 can be used to obtain more accurate viscoelastic properties (PG grade, viscosity, and penetration) of recovered binders from RAPs.

Table 5-1 Changes of PG Temperatures Due to Abson Processes

Binder Source	Binder Type	Continuous PG (Superpave™ PG)	Continous PG of PAV-aged	Continuous PG grade of SRAP Binder	Diff. in High PG Temp. (°C)	Diff. in Low PG Temp. (°C)	"High PG Shift" Factor	"Low PG Shift" Factor
SRC1 (Ergon)	PG 76-28	PG 79.8-33.7 (PG 76-28)	PG 94.8-30.6 (PG 94-28)	PG 98.9-27.7 (PG 94-22)	4.1	2.9	3.6	2.5
SRC4 (Valero)	PG 76-28	PG 77.2-28.3 (PG 76-28)	PG 94.1-24.1 (PG 94-22)	PG 97.2-22.0 (PG 94-22)	3.1	2.1		
SRC2 (Valero)	PG 64-22	PG 64.8-24.0 (PG 64-22)	PG 82.5-18.8 (PG 76-16)	PG 86.2-18.6 (PG 82-16)	3.7	0.2	3.5	-0.4
SRC3 (Gary Williams)	PG 64-22	PG 64.9-24.9 (PG 64-22)	PG 77.8-21.1 (PG 76-16)	PG 81.1-22.2 (PG 76-22)	3.3	-0.9		

Table 5-2 Viscosity Shift Factors of Recovered (Abson) Binders

Binder Source and type	SRAP Binder Viscosity (mPa.s)			PAV-aged Binder Viscosity (mPa.s)			"Viscosity Shift" Factor (mPa.s)			Average "Viscosity Shift" factors		
	135°C	150°C	165°C	135°C	150°C	165°C	135°C	150°C	165°C	135°C	150°C	165°C
SRC1 PG 76-28	8360	3190	1429	7442	2825	1279	918	365	150	918	365	150
SRC4 PG 76-28[a]	-	-	-	11698	3552	1411	-	-	-			
SRC2 PG 64-22	1539	636	310	1545	656	321	-6	-19	-10	-75	-42.5	-23.5
SRC3 PG 64-22	1007	451	228	1151	517	265	-144	-66	-37			

[a] No viscoisty data is availavle for SRAP4 binder.

Table 5-3 Penetration Shift Factors of Recovered (Abson) Binder

Binder Source	Binder Type	SRAP Binder Penetration	PAV-aged Binder Penetration	"Penetration Shift" Factor	Average "Penetration Shift" factors
SRC1 (Ergon)	PG 76-28	48	38	10	6
SRC4 (Valero)	PG 76-28	32	30	2	
SRC2 (Valero)	PG 64-22	29	22	7	2.5
SRC3 (Gary Williams)	PG 64-22	19	21	-2	

Table 5-4 Elemental Analysis *of* Virgin and Recovered Binders

Binder Type and Source	Aging condition	Composition[1]			
		% C	% H	% N	% O
PG 64-22 from Valero	Unaged	85.06	10.43	0.69	0.81
	PAV-aged	84.69	10.44	0.72	1.16
	Recovered from SRAP2	77.12	9.14	0.62	2.76
PG 64-22 from Gary Williams	Unaged	85.85	11.59	0.57	1.01
		85.67**		0.61**	
	PAV-aged	85.39	11.48	0.58	1.57
		86.25**		0.61**	
	Recovered from SRAP3	84.60	11.43	0.55	1.70
		84.79**		0.58**	

[1] Sulfur content was not determined
** The quality control (QC) standard for Hydrogen failed the first time, automatically generating a second reading for carbon and nitrogen.

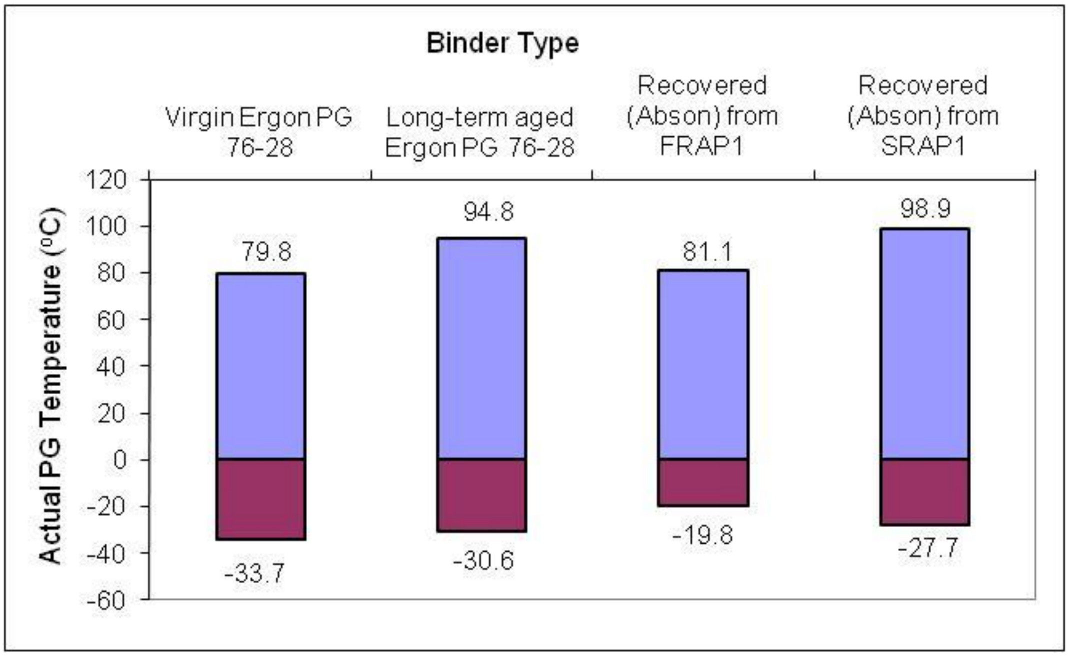


Figure 5-1 PG Grades of Virgin, Laboratory-conditioned and Recovered Binders of SRAP1 and its Counterparts.

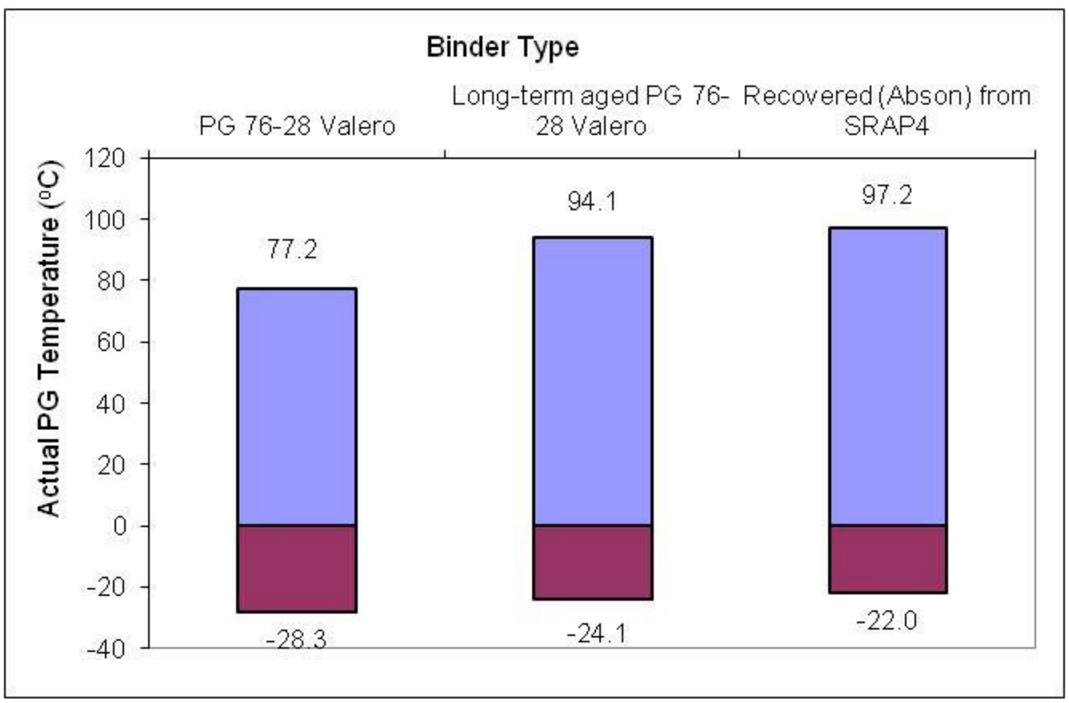


Figure 5-2 PG Grades of Virgin, Laboratory-conditioned and Recovered Binders of SRAP4 and its Counterparts.

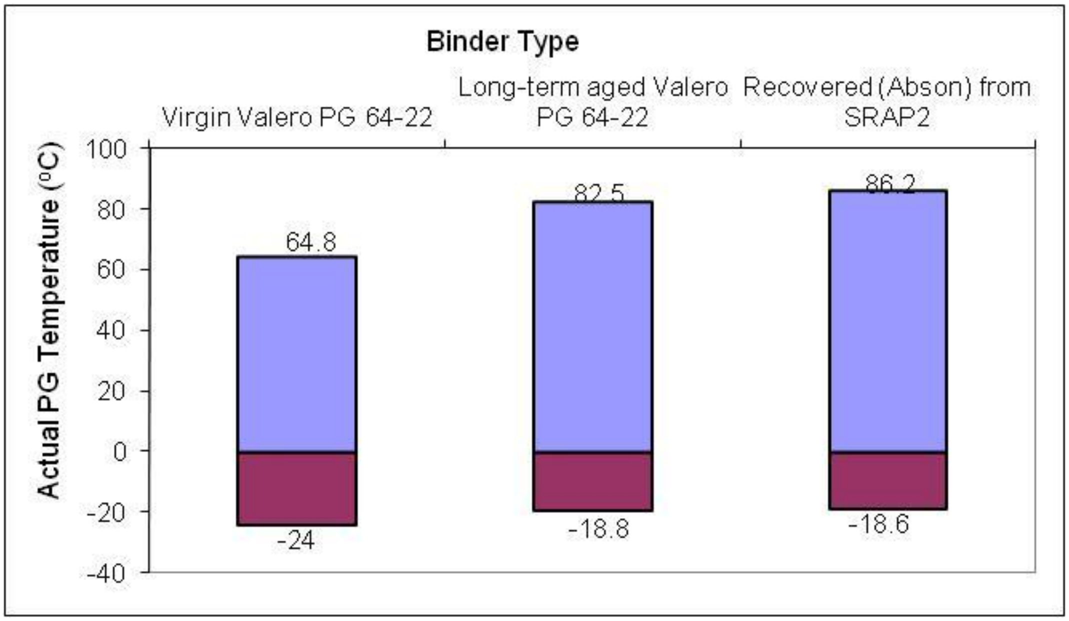


Figure 5-3 PG Grades of Virgin, Laboratory-conditioned and Recovered Binders of SRAP2 and its Counterparts.

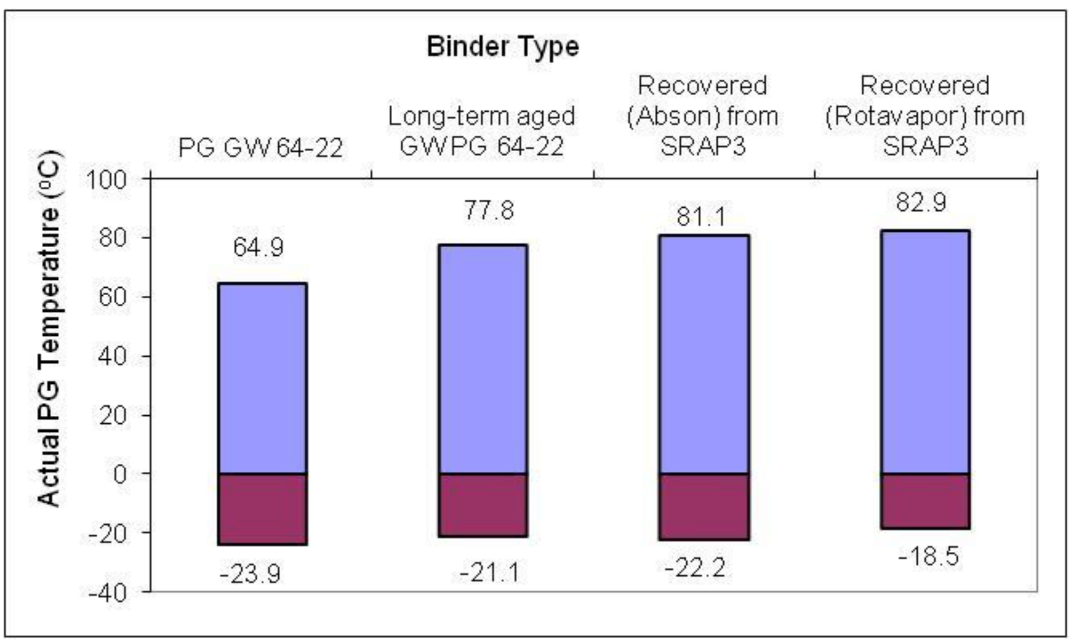


Figure 5-4 PG Grades of Virgin, Laboratory-conditioned and Recovered Binders of SRAP3 and its Counterparts.

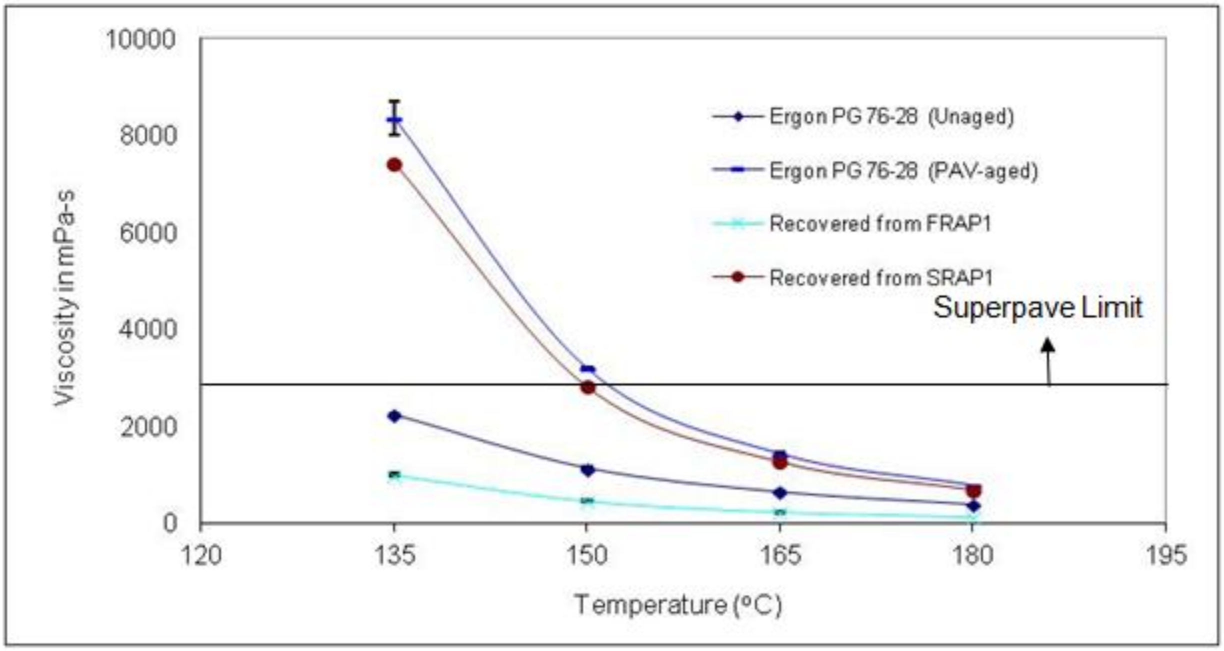


Figure 5-5 Viscosity Test Results of SRAP1 and its Counterparts.

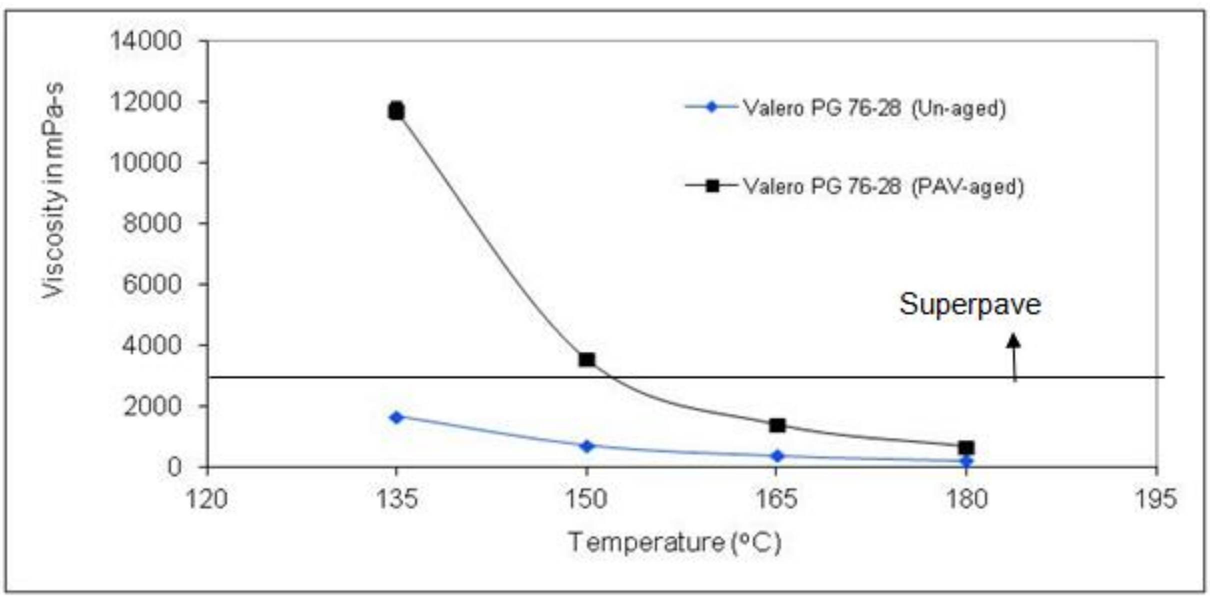


Figure 5-6 Viscosity Test Results of SRAP4 and its Counterparts.

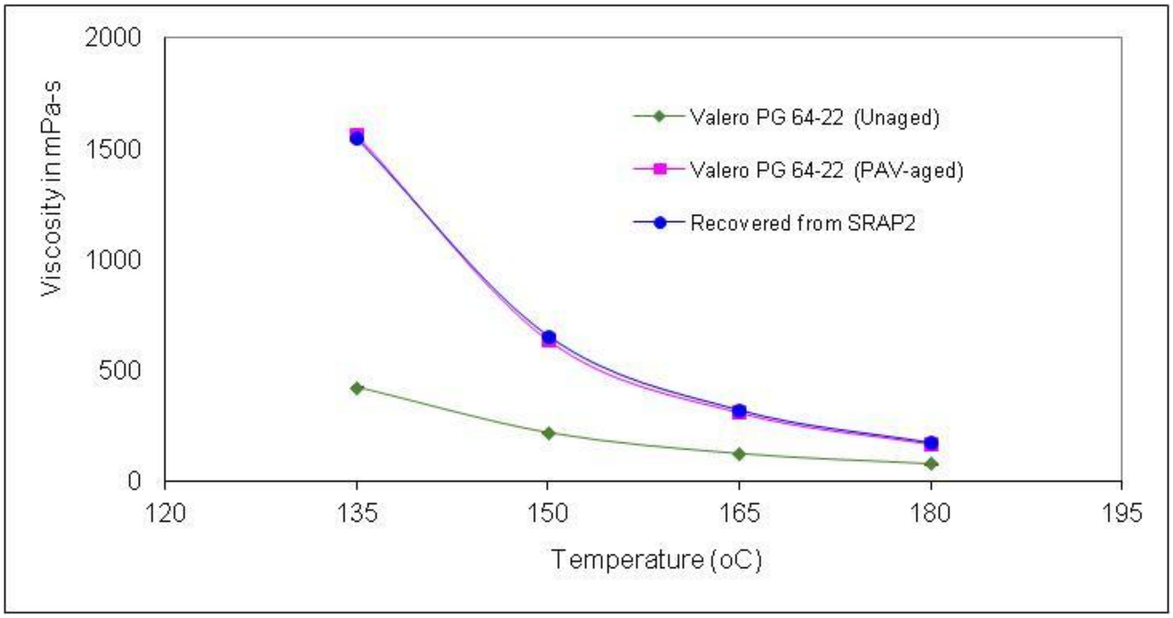


Figure 5-7 Viscosity Test Results of SRAP2 and its Counterparts.

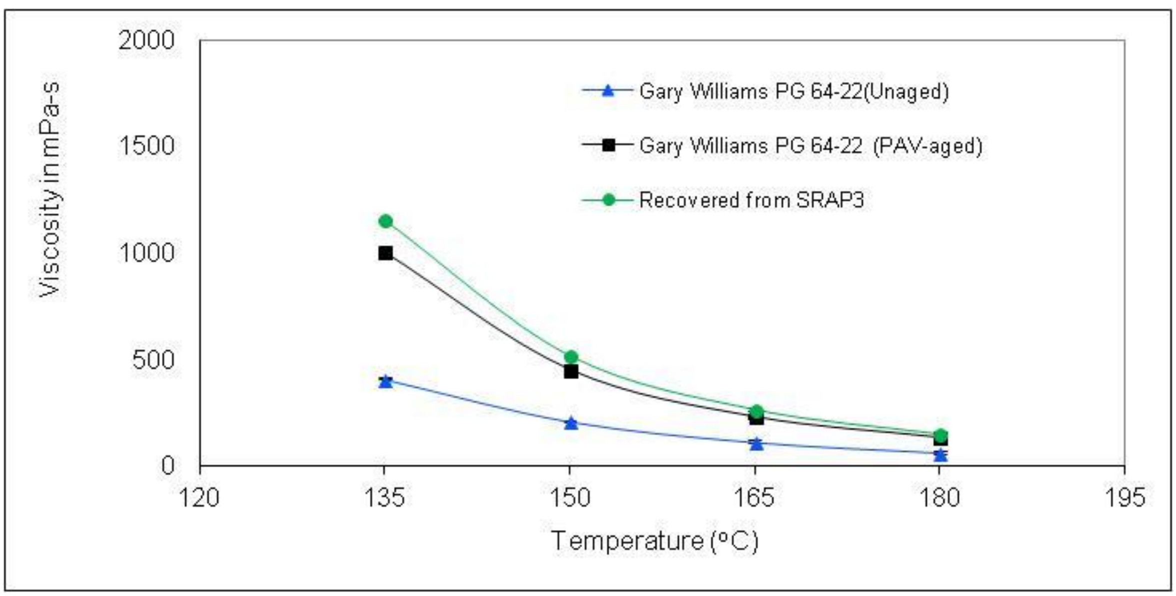


Figure 5-8 Viscosity Test Results of SRAP3 and its Counterparts.

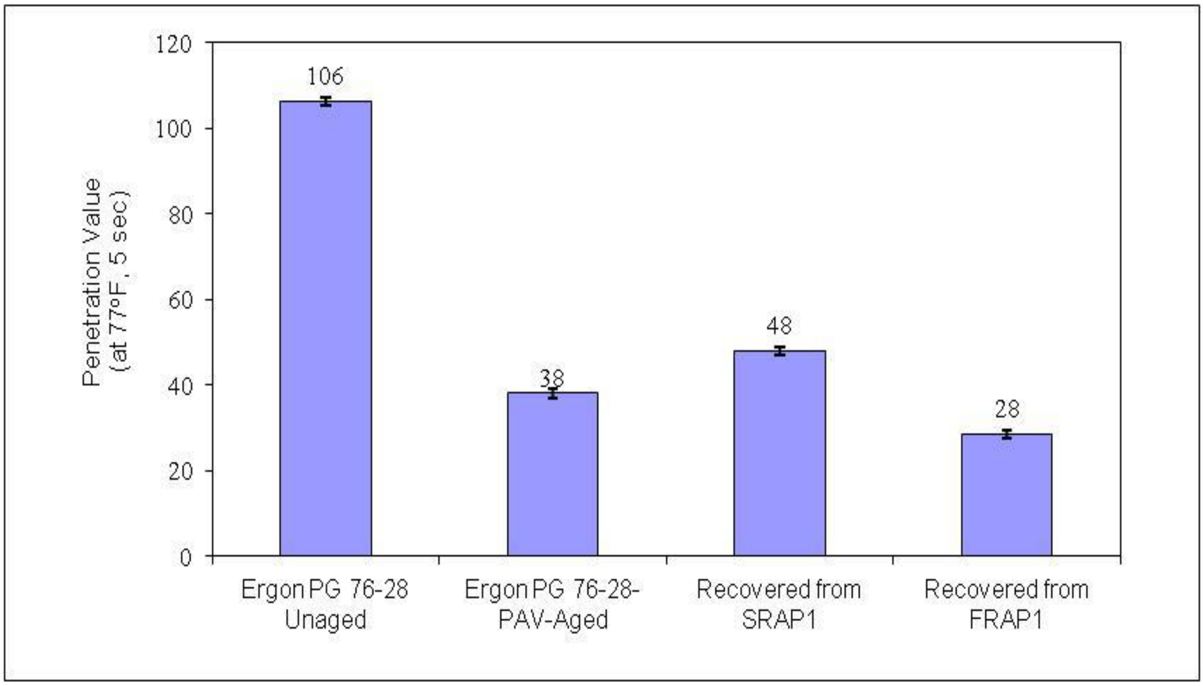


Figure 5-9 Penetration Test Results of SRAP1 and its Counterparts.

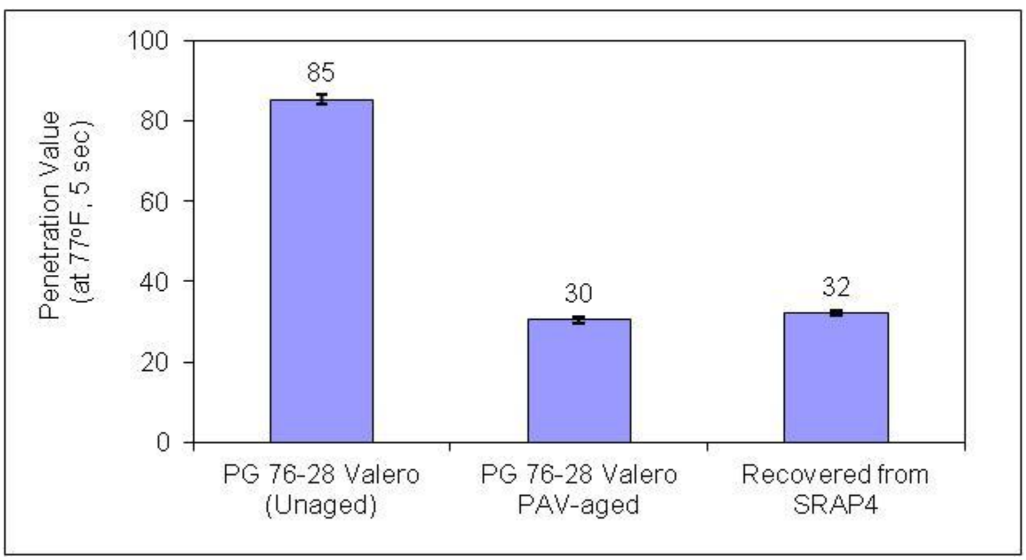


Figure 5-10 Penetration Test Results of SRAP4 and its Counterparts.

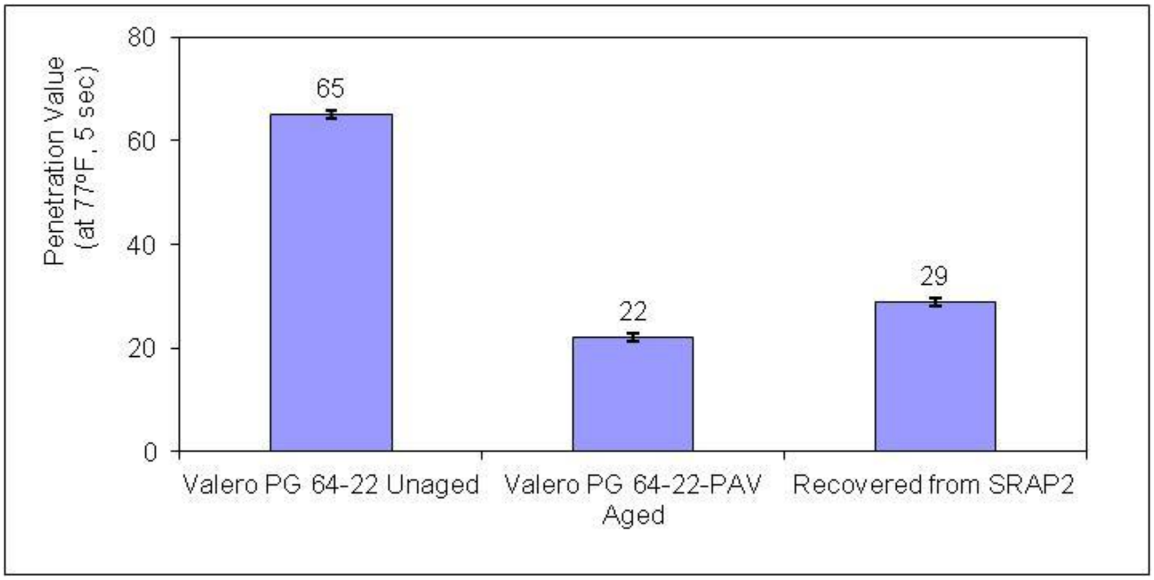


Figure 5-11 Penetration Test Results of SRAP2 and its Counterparts.

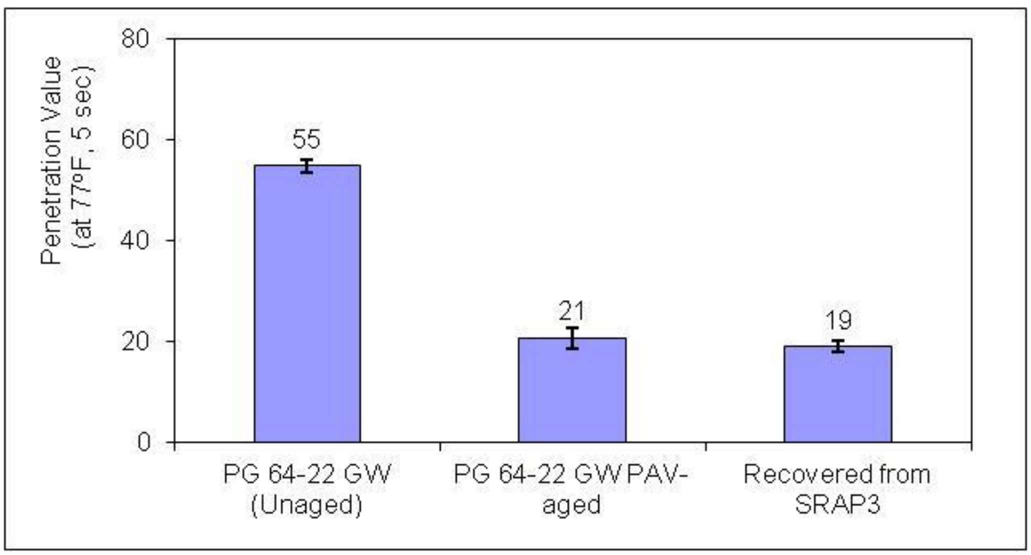


Figure 5-12 Penetration Test Results of SRAP3 and its Counterparts.

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

Based on the literature review, test results and discussions presented in the preceding chapters the following conclusions can be drawn:

6.2.1 Effects of NCAT Ignition Oven Method on Aggregate Properties

- The NCAT ignition oven appears to influence the gradation of the aggregates extracted from RAP. The presence of excessive fine particles in the extracted aggregates could be the result of partial disassociations of aggregates due to excessive heat in the NCAT ignition oven.
- The bulk specific gravity values of the extracted aggregates were lower than virgin aggregates in 75% of the time.
- Even though LA Abrasion loss values of the tested extracted aggregates were within the limits specified by ODOT, they were significantly higher than those of the virgin aggregates in 75% of the time. Thus, it would lead to a conservative approach if the L.A. Abrasion test results of extracted aggregates from RAP are considered in the design. The moist-durability, based on the Micro-Deval test results, showed a similar trend.
- The sand equivalent values of tested extracted aggregates were 5 to 60% higher than those of the corresponding virgin aggregates. Thus, taking sand equivalent values of extracted aggregates would also be a conservative design.
- The NCAT ignition oven did not seem to have any influence on the HCL solubility of the extracted aggregates.

- The percentage of crushed face count of extracted aggregates was not influenced by the NCAT ignition oven method.

6.2.2 Effects of the Abson Method on Asphalt Binder Properties

- The Abson method seemed to influence the PG temperatures of the recovered binders. The influence on PG temperatures in the tested hard binder (PG 76-28) appeared to be slightly less than that of the soft binder (PG 64-22). The “High PG Shift” and the “Low PG Shift” factors for the hard binders are about 3.6^{o}C, and 2.5^{o}C, respectively. On the other hand, the “High PG Shift” and the “Low PG Shift” factors of the tested soft binders are roughly 3.5^{o}C and -0.4^{o}C, respectively.
- The use of PG grade of a RAP binder recovered via Rotavapor is expected to be more conservative than that of the same recovered via the Abson method.
- The Abson method did not seem to have any statistically significant influence on the viscosity of the recovered binder at ODOT mixing and compaction temperatures.
- The penetration values of the recovered binders were found to be higher than those of the laboratory PAV-aged binder in 75% of the time.
- Elemental analysis of the selected soft binders show increased oxygen content in the SRAP binder compared to its PAV-aged virgin counterpart.

6.2 RECOMMENDATIONS FOR FUTURE STUDY

Based on the limited scope and findings of the current study, the following recommendations are made for future study:

- Institute a statewide inventory of millings and foster exchange between the ODOT Division offices to reduce storage time and the deterioration of millings that occurs with time. Improve records of aggregates and asphalt binders by requiring contractors to track the location of different construction materials and methods on highway sections.
- Due to the excessive heat in the NCAT ignition oven, the possibility of internal changes that lead to greater voids and greater LA Abrasion loss in the extracted aggregates cannot be excluded, and it can be further investigated.
- In case of field RAP, it is extremely hard, if not impossible, to trace the actual source and PG grade of the binder used during the construction of the original pavement, since the historical information of the mix does not exist in a majority of cases. The polymer type and content of the original binder also remain unknown. The elastic recovery, an indicator of the polymer characteristics of the recovered binder, can be evaluated by performing multiple stress creep recovery tests.
- The TCE solvent used in the extraction of binder from RAP is suspected to have a greater influence on the characteristics of the recovered binder. Thus, it will be worthwhile to evaluate if other solvents (e.g., toluene, and toluene mixed with alcohol) have less influence on the properties of the recovered binder.

REFERENCES

AASHTO (2008), "Standard Specification for Transportation Materials and Methods of Sampling and Testing," 28th Edition, *American Association of State Highway and Transportation Officials*, Washington D.C.

Ahmad, J., Rahman, M. Y. and Din, K. (2004), "Degradation And Abrasion of Reclaimed Asphalt Pavement Aggregates," *International Journal of Engineering and Technology*, Vol. 1, No. 2, Washington, D.C., pp. 139 –145.

Al-Qadi, I. L., Carpenter, S. H., Roberts, G. L., Ozer, H., Aurangzeb, Q., Elseifi, M. A., and Trepanier, J. (2009), "Determination of Usable Residual Asphalt Binder in RAP," Report No. FHWA-ICT-09-031, *Illinois Department of Transportation*, Bureau of Material and Physical Research, Springfield, IL.

Anderson, R. M. (2001), "Recommended Use of Reclaimed Asphalt Pavement in the Superpave Mix Design Method: Guidelines," NCHRP Research Result Digest, NCHRP Report 253, *National Cooperative Highway Research Program*, Transportation Research Board, National Research Council, National Academy Press, Washington, D.C.

Anderson, R. M., and Murphy, T. R. (2004), "Laboratory Mix Design Using RAP: Determining Adequate Properties," *Asphalt Magazine*, pg. 23-25.

ARC (2010), "Impact of current extraction techniques on properties of extracted RAP aggregates," *Presented at HMA Recycling Expert Task Group Meeting* by Asphalt Research Consortium (ARC), May 20, 2010, Auburn, Alabama.

Bhasin, A., J. E. Buton, Chowdhury, A., and Masad, E. (2006), "Selection of Optimum Gravel Aggregate Size to Resist Permanent Deformation in Hot-Mix Asphalt," *Transportation Research Record, Journal of the Transportation Research Board, No. 1952*, Washington D.C., pp. 39-47.

Burr, B. L., Davison, R.R., Glover, C.J. and Bullin, J.A. (1999), "Softening of Asphalts in Dilute Solutions at Primary Distillation Conditions," *Transportation Research Record*, No. 1436, pp. 47-53.

Daniel, J., Pochily, J. and Boisvert, D. (2010), "Can We Add More RAP? A Study of Extracted Binder Properties from Plant Produced Mixtures with up to 25% RAP," *89th Annual TRB Meeting Compendium for DVD paper*, January 10-14, 2010, Washington, D.C.

Doh, Y. S., Kim, J. C., Ryu, M. Y. and Kim, K. W. (2010), "Evaluation of Selected Warm-Mix Additives for Asphalt Recycling," *89th Annual TRB Meeting Compendium for DVD paper*, January 10-14, 2010, Washington, D.C.

Gudimettla, J., Myers, L. A., and Paugh, C. (2010). "AIMS: The Future in Rapid, Automated Aggregate Shape and Texture Measurement," White Paper, Federal Highway Administration online, http://www.pineinst.com/test/pdf/FHWA_Gudimettla-Myers-Paugh.pdf, Last Accessed July 2010, Washington, DC.

Hamzah, M. O., Mohamed, A. and Ismail, H. (2006), "Laboratory Investigation of the Properties of A Newly Developed Crumb Rubber Modified (CRI1) Asphalt Mixes," *Emirates Journal for Engineering Research*, 11(2), pp. 67-72.

Houston, W. N., Mirza, M. W., Zapata, C. E. and Raghavendra, S. (2005), "Environmental Effects in Pavement Mix and Structural Systems- Part 1 of Contractor's Final Report For NCHRP Project 9-23," Web-Only Document 113, *National Cooperative Highway Research Program*, Transportation Research Board National Research Council, Washington, D.C.

Huang, B., Li, G., Vukosavljevic, D., Shu, X., and Egan, B. K. (2005), "Laboratory Investigation of Mixing Hot-Mix Asphalt with Reclaimed Asphalt Pavement," *Transportation Research Record: Journal of the Transportation Research Board,* No. 1929, Washington, D.C., pp. 37-45.

Krukoswki, S. T. (2005), "Lime," *C*hapter 2, *Industrial Minerals and Rock,* edited by Boynonard, R., Gutschick, K., and Thompson, J., 5th Edition, *Society for Mining, Metallurgy, and Exploration, Inc*., New York.

Lewandowski, L.H. (1994), "Polymer Modification of Paving Asphalt Binders," *Journal of Rubber Chemistry and Technology*, volume 67, no. 3, pp. 447-480.

Loh, S. and Olek, J. (1999), "Contributions of PG Graded Asphalt to low Temperature Cracking Resistance of Pavement," *Joint Transportation Research Program*, Report FHWA/IN/JTRP-96/22, Purdue University, West Lafayette, Indiana.

Loizos, A., Partl, M. N., Scarpas, T., and Al-Qadi, I. L. (2009), "Advanced Testing and Characterization of Bituminous Materials," Chapter 2, Factors affecting recovered asphalt binder properties**:** A theoretical and experimental study, by Pratico, F.G., Dattola, V.**,** ISBN: 978-0-415-55854-9, *CRC Press*, pp. 13-21.

Masad, E. A., Little, D. N., Tashman, S., Saadeh, T. A., and Sukhwani, R., (2003), Evaluation of Aggregate Characteristics Affecting HMA Concrete Performance, Research Report ICAR 203-1, Texas Transportation Institute, TX.

McDaniel, R. and Anderson, R.M. (2001), “Recommended Use of Reclaimed Asphalt Pavement in the Superpave Mix Design Method: Technician’s Manual,” NCHRP Report No. 452, *National Cooperative Highway Research Program,* Transportation Research Board, National Research Council, National Academy Press, Washington, D.C..

McKeen, R. G. (1997), “Asphalt Content by Ignition: Round-Robin Experiment,” Final Project Report, *New Mexico State Highway and Transportation Department*, Santa Fe, NM.

NAPA (2009), “Testimony of Mike Acott, President National Asphalt Pavement Association: Hearing on Sustainable Energy Efficient Transportation Infrastructure,” submitted to *House Committee on Science and Technology’s Subcommittee on Technology and Innovation*, Nationals Asphalt Pavement Association, Lanham, Maryland.

O’Rear, E. A., Buddhala, A., Lewis, S., and Laguros, J. (2008), “Recycled Asphalt Mixes,” Research Report, *Oklahoma Department of Transportation*, Oklahoma City, OK.

ODOT (2010), “Materials and Te, sting e-Guide Aggregates and Stone Test Data,” Material Division, Oklahoma Department of Transportation (ODOT), http://www.okladot.state.ok.us/materials/aggreps.htm, Last Accessed, July 2010.

ODOT (2009), “State Planning and Research Work Program FFY 2010-SPR Item 2223 Test Methods for Use of Recycled Asphalt Pavement in Asphalt Mixes,” *Oklahoma Department of Transportation*, Oklahoma City, OK.

Prowell, B. D. and Carter, C. B. (2000), “Evaluation of the Effect on Aggregate Properties of Samples Extracted using the Ignition Furnace,” Interim Report, *Virginia Transportation Research Council*, VTRC 00-IR1, Charlottesville, VA.

Stroup-Gardiner, M. and Nelson, J. W. (2001), “Use of normal propyl Bromide solvents for Extraction and recovery of Asphalt cements,” *National Center for Asphalt Technology (NCAT)*, Report No. 00-06, Auburn University, Alabama.

Swirtz, D., Mahmoud, E., and Bahia H. (2010), “Estimating the Effect of RAP and RAS on PG Grade of Binders,” *RAP ETG Meeting*, October 2010, Oklahoma City, Oklahoma.

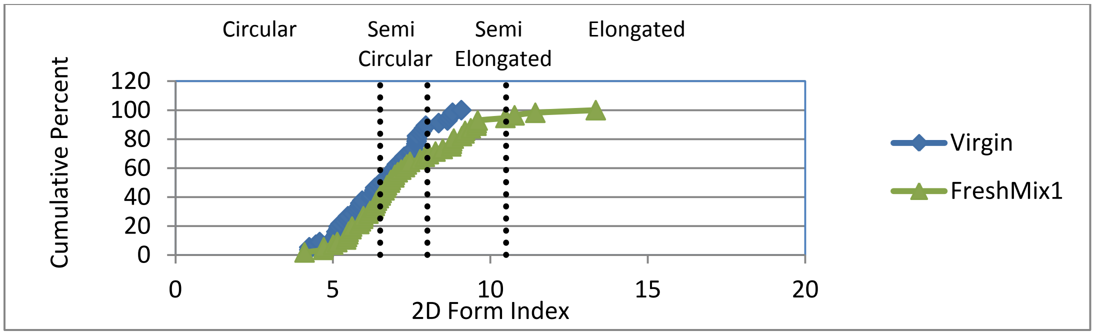
Tao, M., Enad, M. and Bahia, H. (2010), “Development of Testing Procedure for Estimation of RAP Binder Low-Temperature Properties without Extraction,” *89th*

Annual TRB Meeting Compendium for DVD paper, January 10-14, 2010, Washington, D.C.

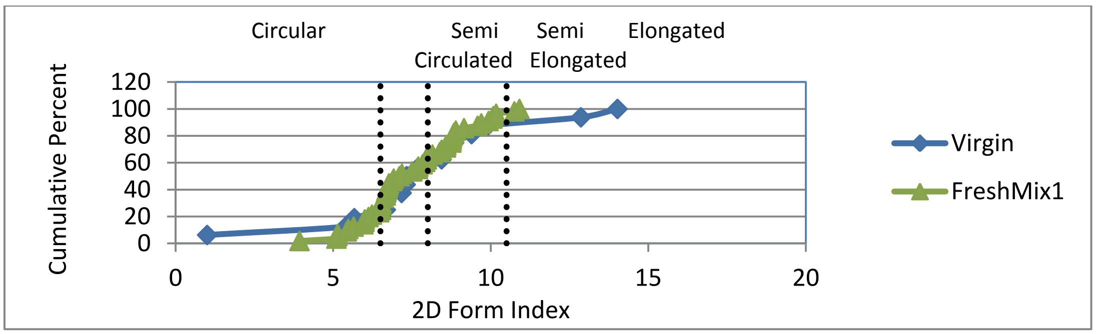
Watson, D. E., Moore, J. and Jared, D. (2008), “Evaluation of the Use of Reclaimed Asphalt Pavement in Stone Matrix Asphalt Mixtures,” *87th Annual Meeting of the Transportation Research Board*, Compendium of Papers DVD, Washington, D.C.

A. APPENDIX A AIMS TEST RESULTS

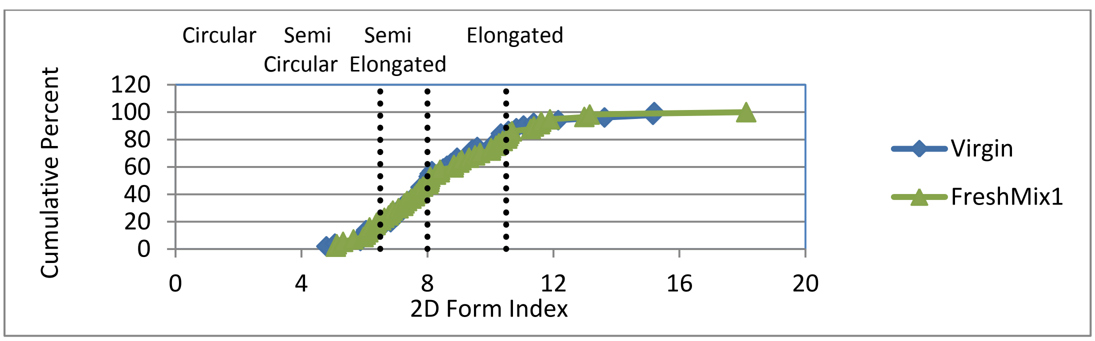
This appendix presents the AIMS test results of tested coarse and fine aggregates. Selected test results of aggregates extracted from SRAPs and their virgin counterparts are presented in Figures A-1 through A-26.



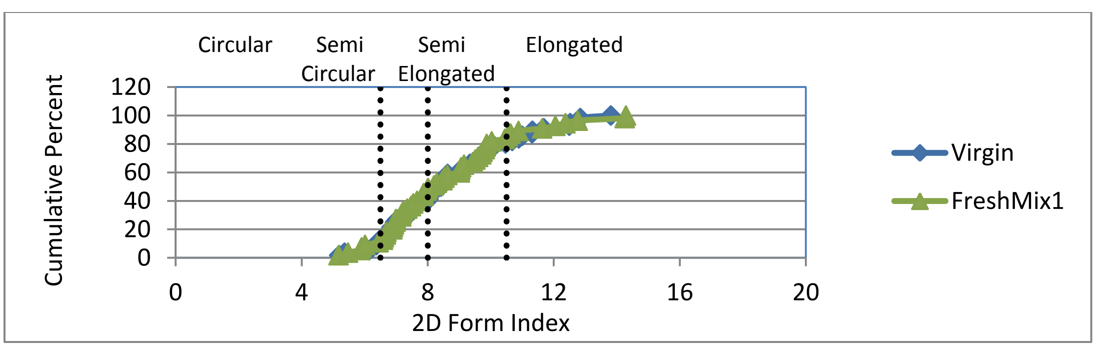
(a) Passing 3/4" and Retained 1/2”



(b) Passing 1/2” and Retained 3/8”

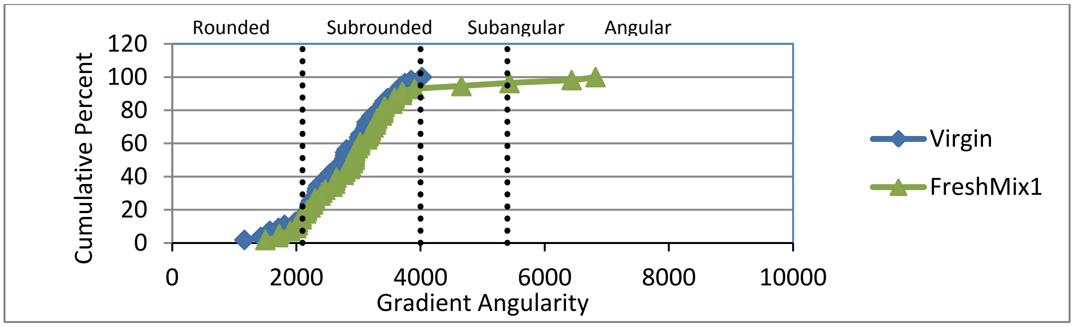


(c) Passing 3/8” and Retained 1/4"

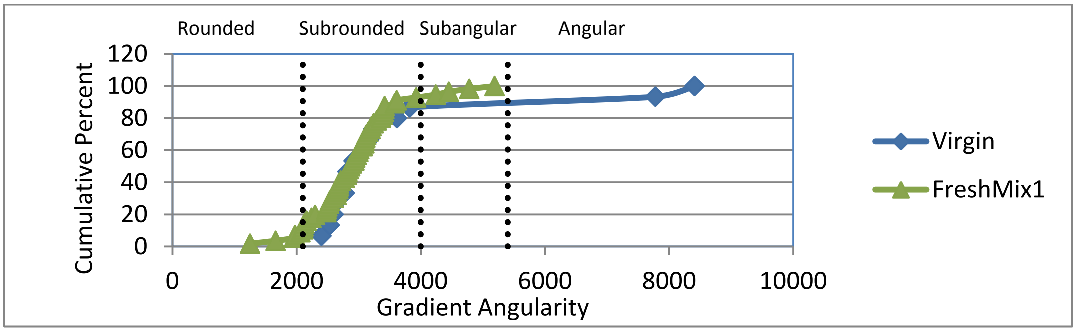


(d) Passing 1/4” and Retained #4

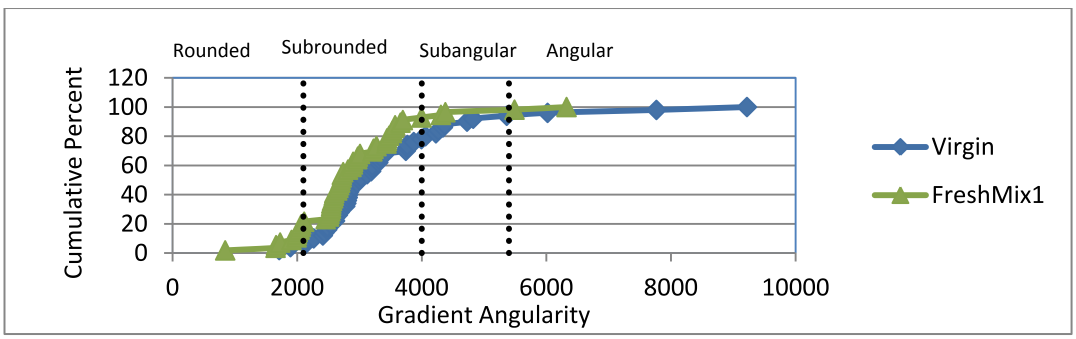
Figure A-1 SRAP1 Sample - 2D Form for Coarse Aggregates: (a) Passing 3/4” and Retained 1/2”, (b) Passing 1/2” and Retained 3/8”, (c) Passing 3/8” and Retained 1/4”, and (d) Passing 1/4” and Retained #4.



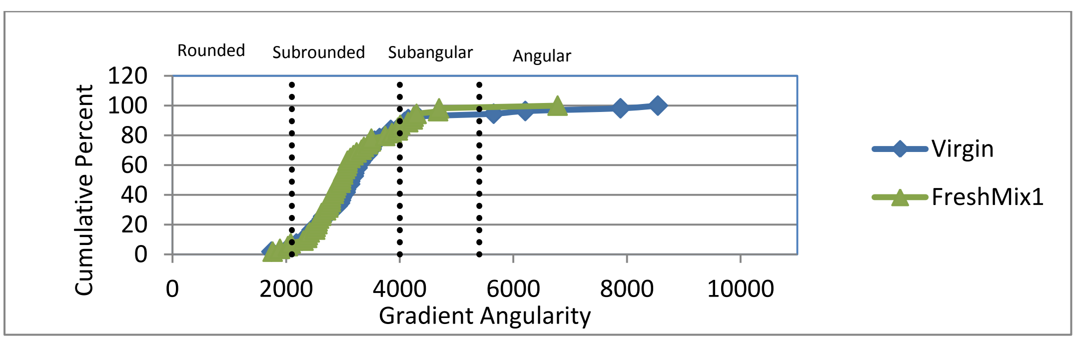
(a) Passing 3/4” and Retained 1/2”



(b) Passing 1/2" and Retained 3/8”

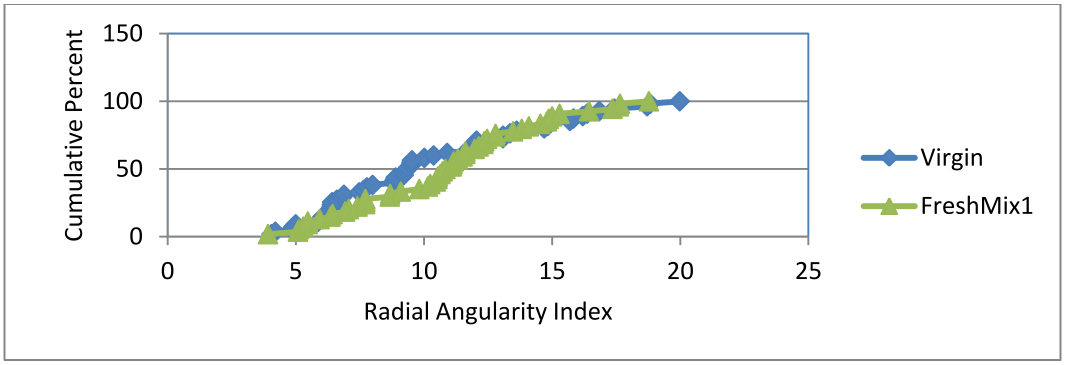


(c) Passing 3/8” and Retained 1/4”

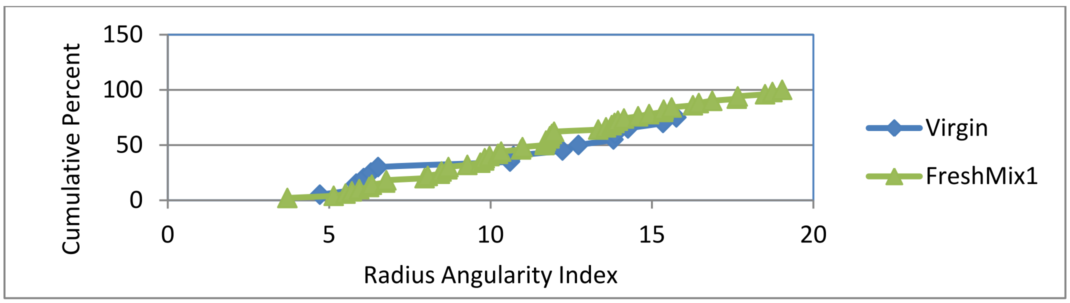


(d) Passing 1/4” and Retained #4

Figure A-2 SRAP1 Sample - Gradient Angularity for Coarse Aggregates: (a) Passing 3/4" and Retained 1/2", (b) Passing 1/2" and Retained 3/8”, (c) Passing 3/8” and Retained 1/4", and (d) Passing 1/4" and Retained #4.



(a) Passing 3/4" and Retained 1/2"



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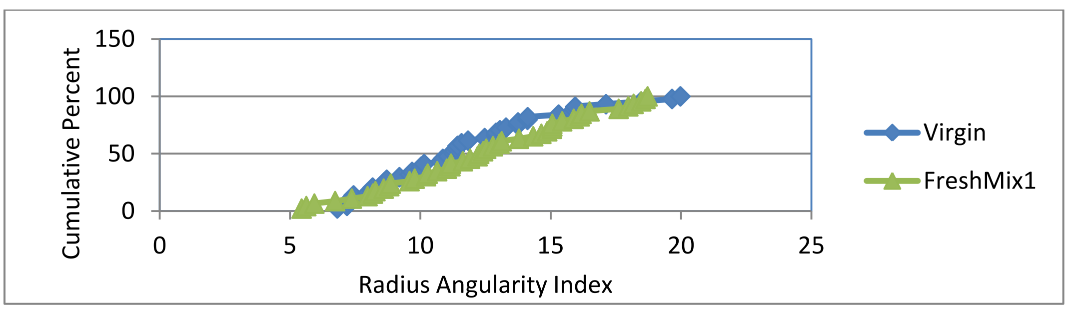

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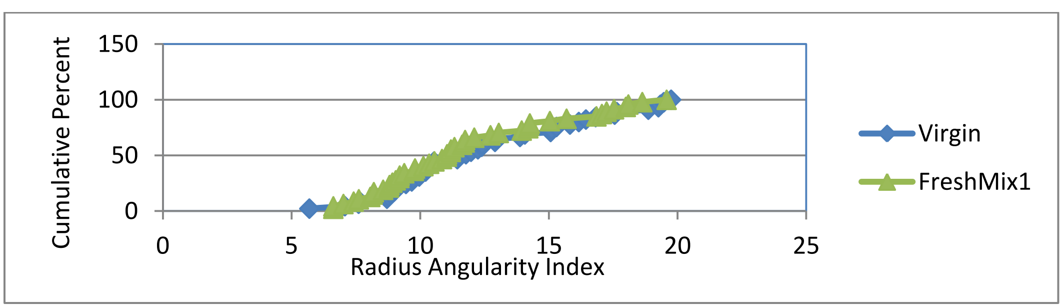
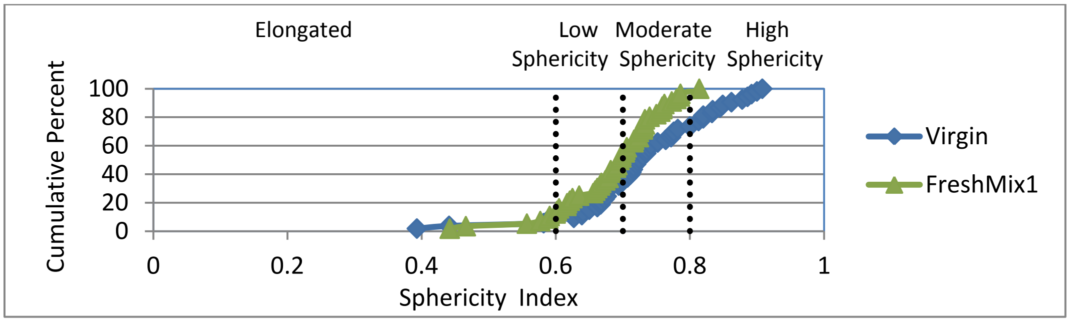
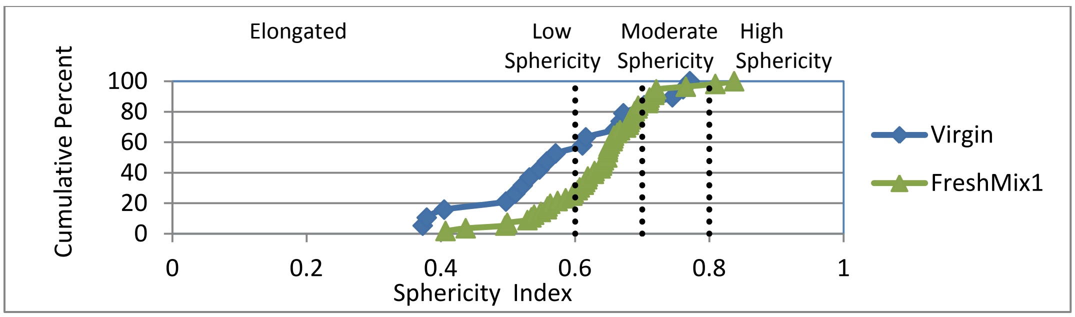


(d) Passing 1/4" and Retained #4

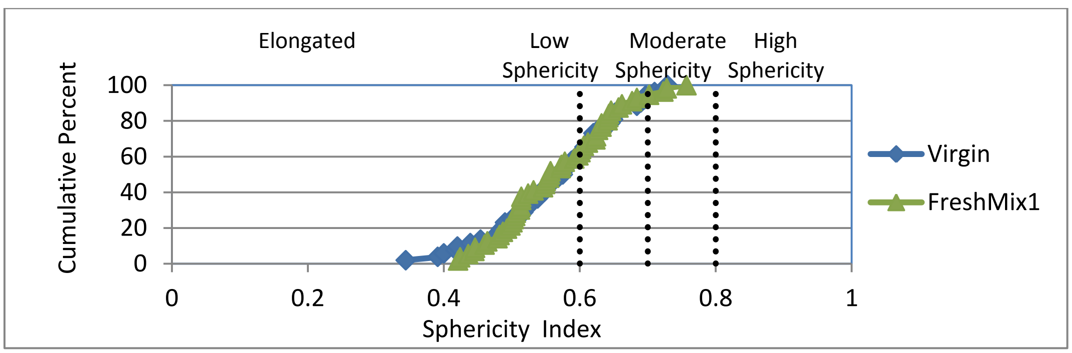
Figure A-3 SRAP1 Sample - Radius Angularity of Fine Aggregates: (a) Passing 3/4" and Retained 1/2”, (b) Passing 1/2” and Retained 3/8”, (c) Passing 3/8” and Retained 1/4", (d) Passing 1/4" and Retained #4.



a) Passing ¾" Retained ½"



a) Passing ½" Retained 3/8"



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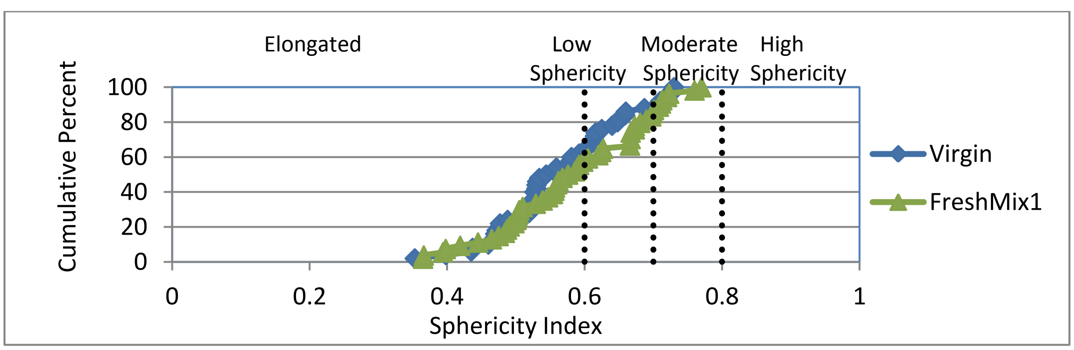
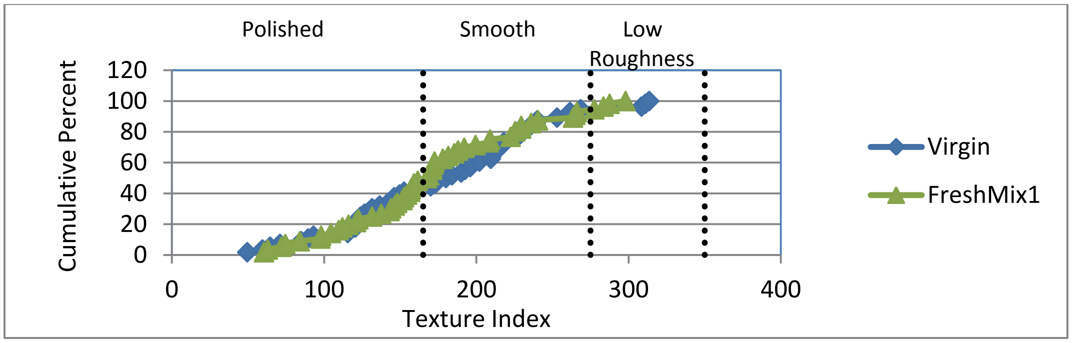
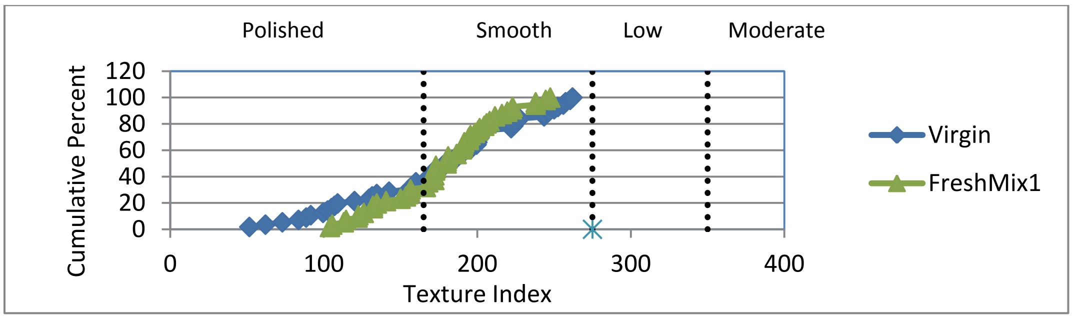


a) Passing ¼" Retained #4

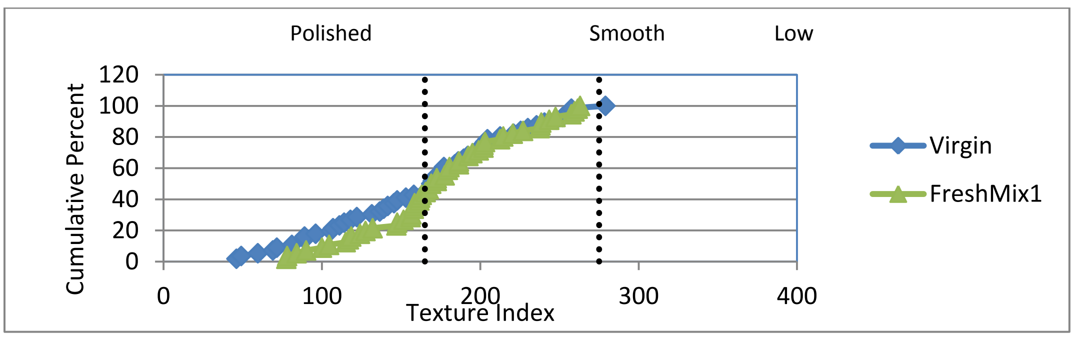
Figure A-4 SRAP1 Sample - Sphericity of Coarse Aggregates: (a) Passing 3/4" and Retained 1/2", (b) Passing 1/2" and Retained 3/8", (c) Passing 3/8" and Retained 1/4", and (d) Passing 1/4" and Retained #4.



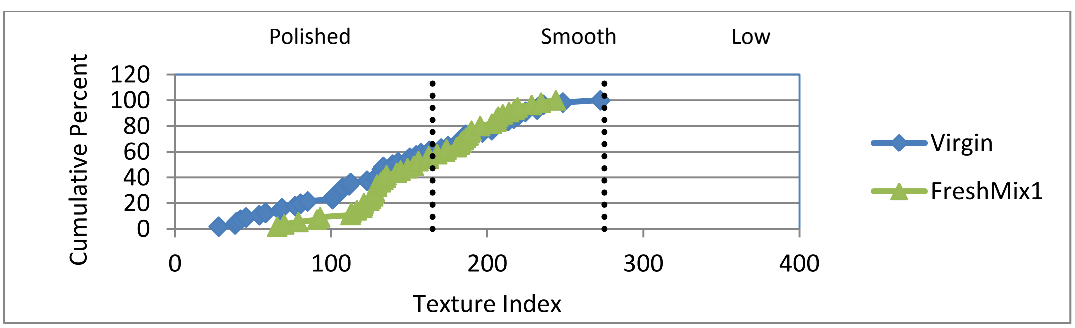
(a) Passing 3/4” and Retained 1/2”



(b) Passing 1/2” and Retained 3/8”

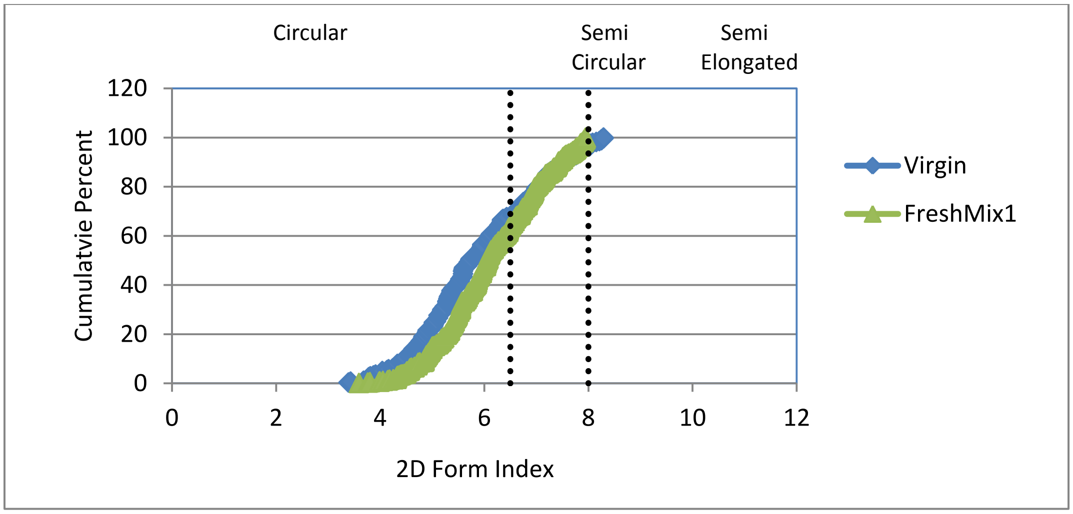


(c) Passing 3/8” and Retained 1/4”

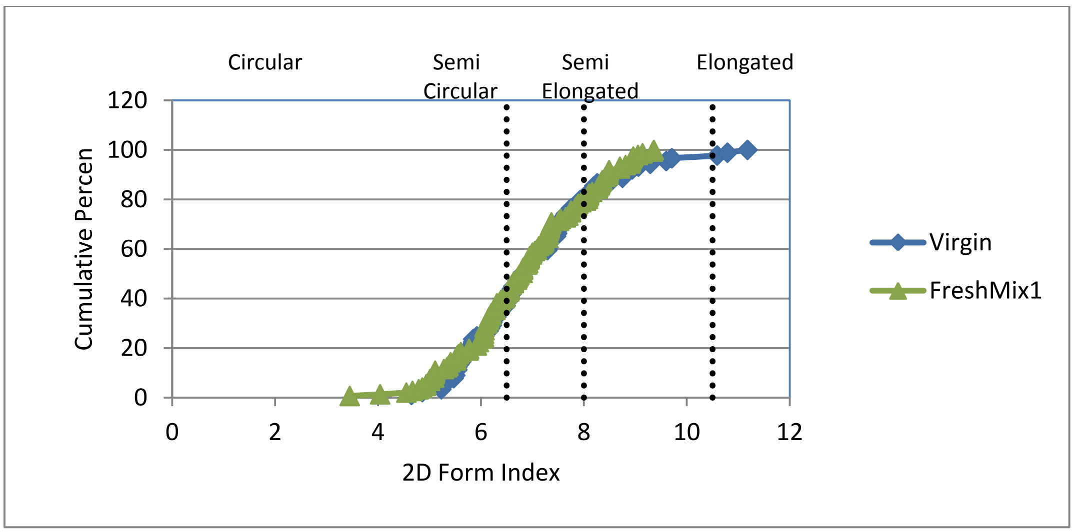


(d) Passing 1/4” and Retained #4

Figure A-5 SRAP1 Sample - Texture of Coarse Aggregates: (a) Passing 3/4” and Retained 1/2”, (b) Passing 1/2” and Retained 3/8”, (c) Passing 3/8”and Retained 1/4”, and (d) Passing 1/4” and Retained #4.

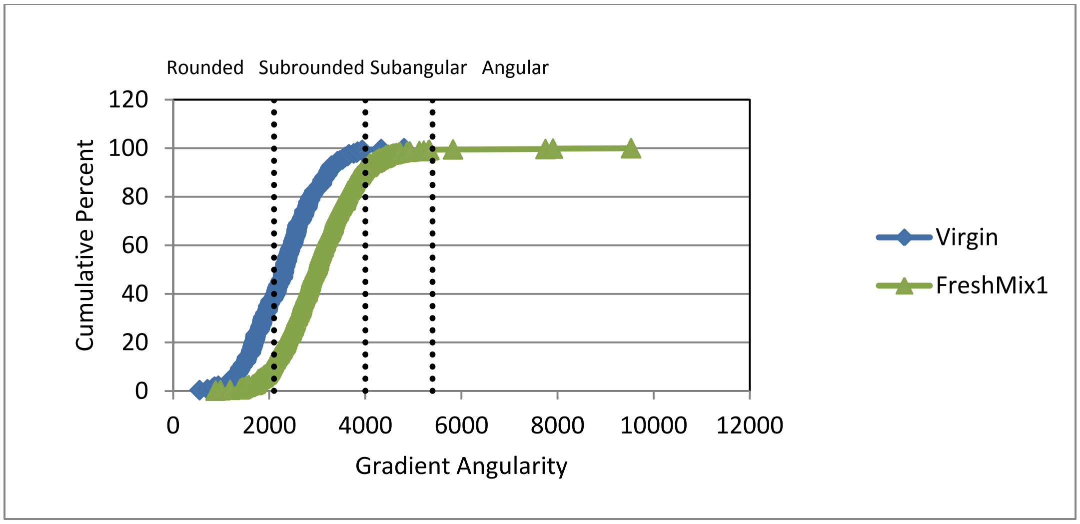


(a) Passing #4 and Retained #8

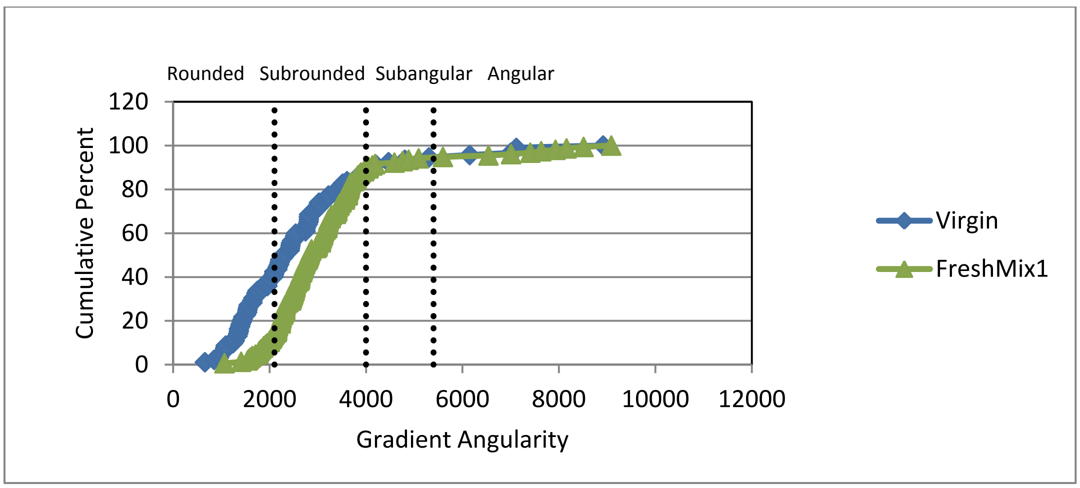


(b) Passing #8 and Retained #16

Figure A-6 SRAP1 Sample - 2D Form of Fine Aggregates: (a) Passing #4 and Retained #8, and (b Passing #8 and Retained #16.

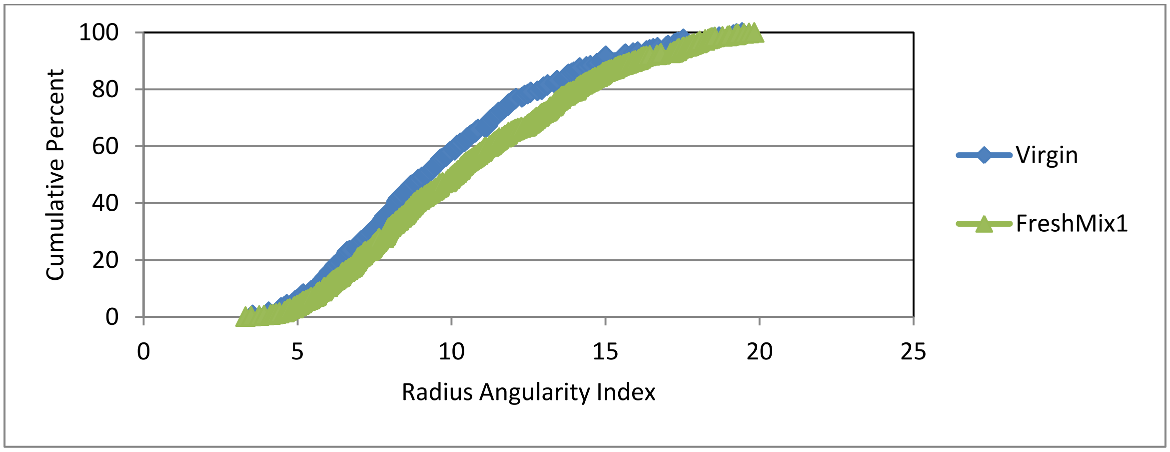


(a) Passing #4 and Retained #8

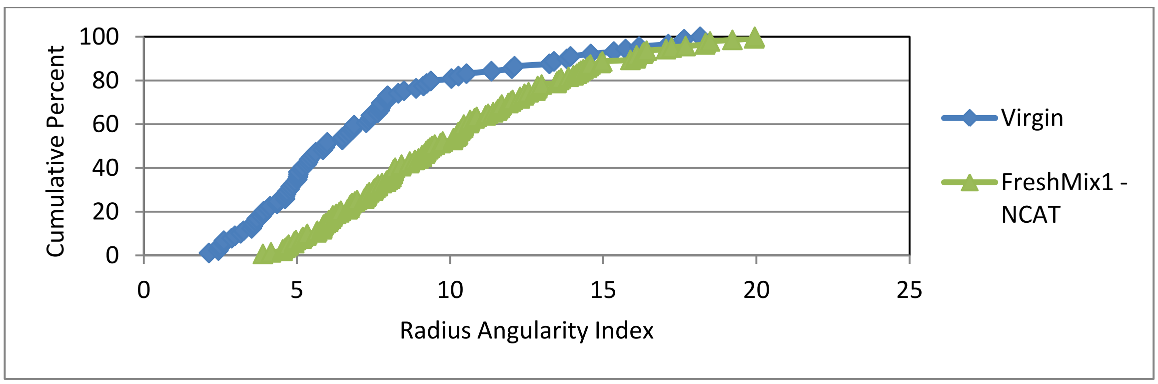


(b) Passing #8 and Retained #16

Figure A-7 SRAP1 Sample - Gradient Angularity of Fine Aggregates: (a) Passing #4 and Retained #8, and (b) Passing #8 and Retained #16.

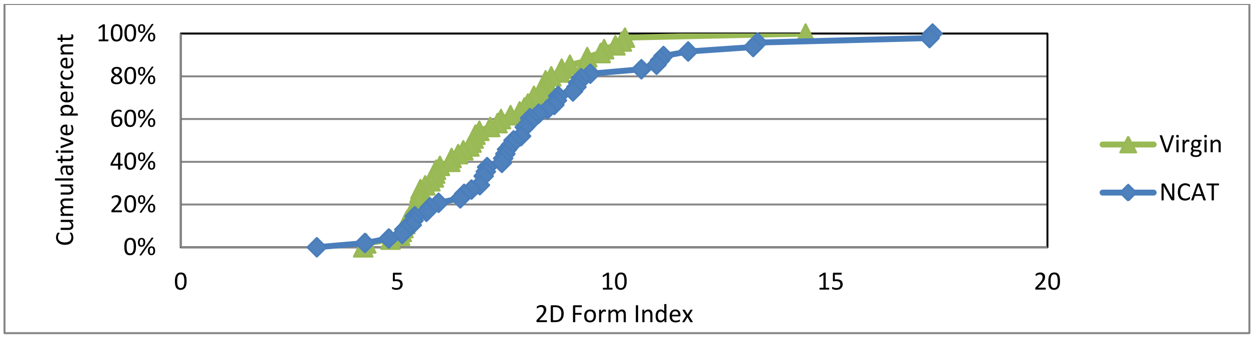


(a) Passing #4 and Retained #8

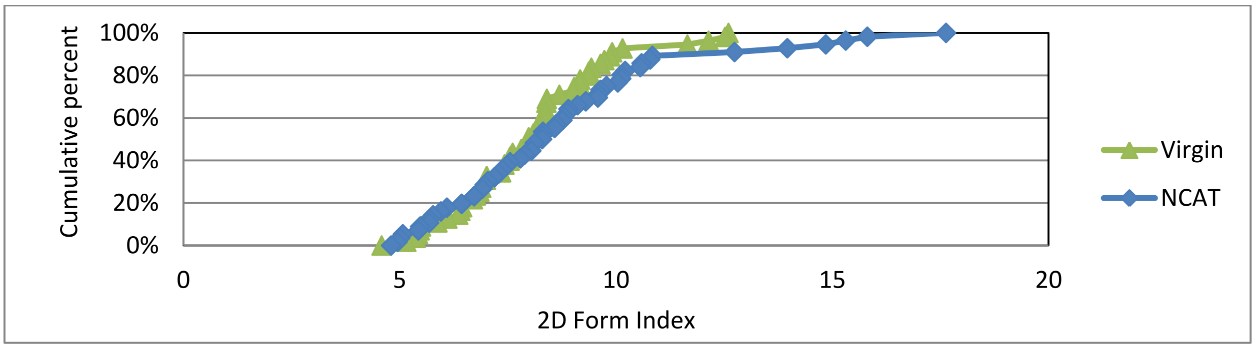


(b) Passing #8 and Retained #16

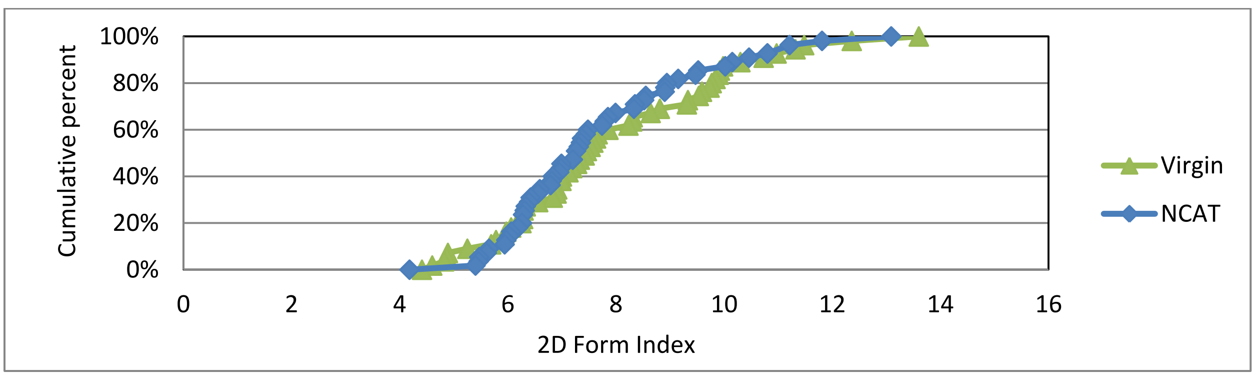
Figure A-8 SRAP1 Sample - Radius Angularity of Fine Aggregates: (a) Passing #4 and Retained #8, and (b) Passing #8 and Retained #16.



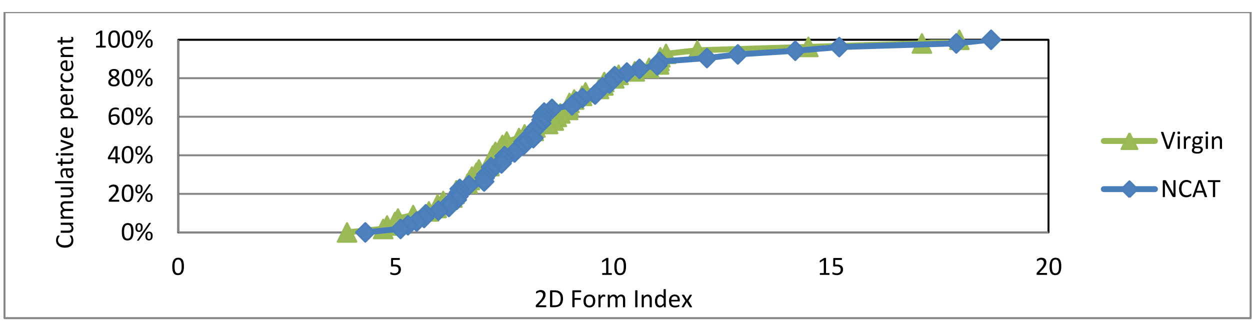
(a) Passing 3/4” and Retained 1/2”



(b) Passing 1/2” and Retained 3/8”

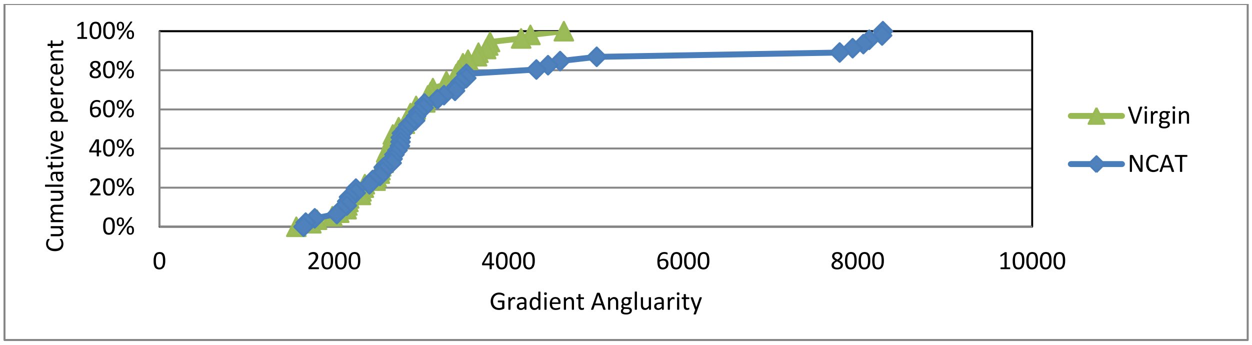


(c) Passing 3/8” and Retained 1/4”

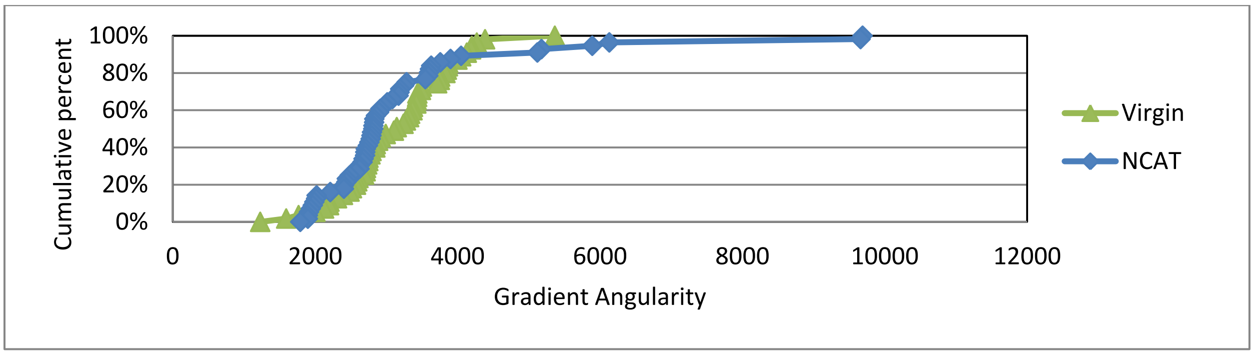


(d) Passing 1/4” and Retained #4

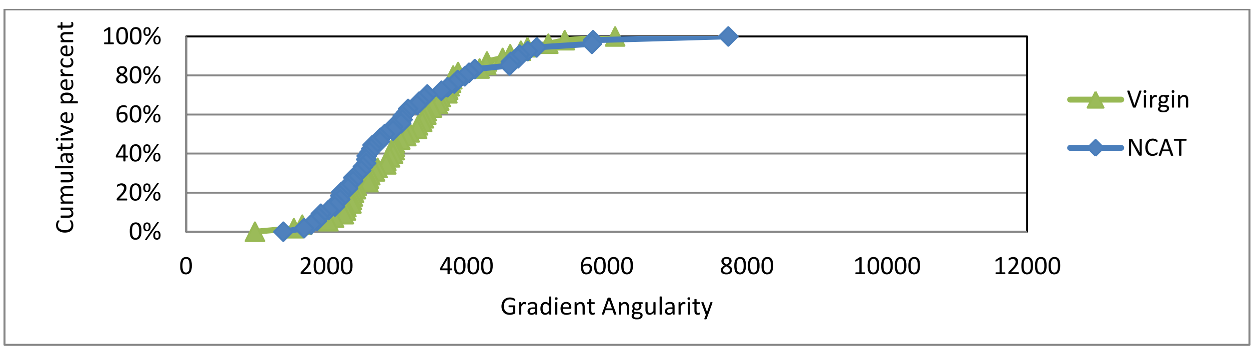
Figure A-9 SRAP2 Sample - 2D Form for Coarse Aggregates: (a) Passing 3/4” and Retained 1/2”, (b) Passing 1/2” and Retained 3/8”, (c) Passing 3/8” and Retained 1/4”, and (d) Passing 1/4” and Retained #4.



(a) Passing 3/4” and Retained 1/2”



(b) Passing 1/2” and Retained 3/8”



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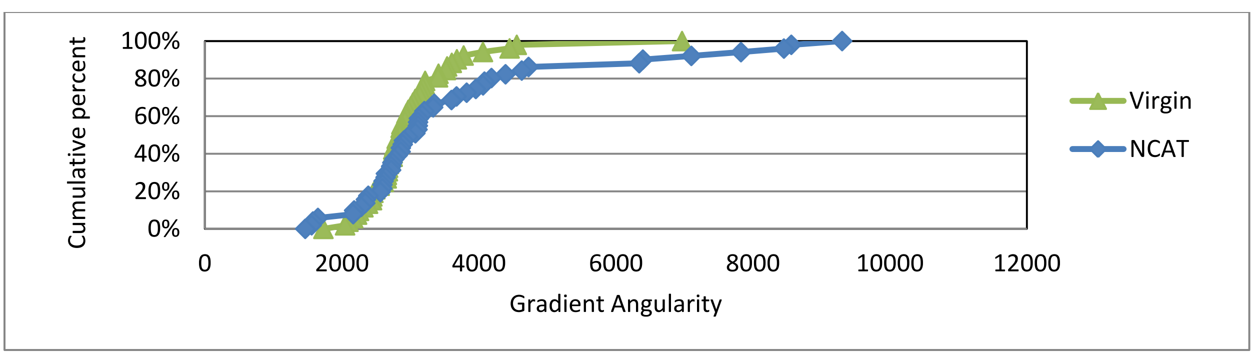
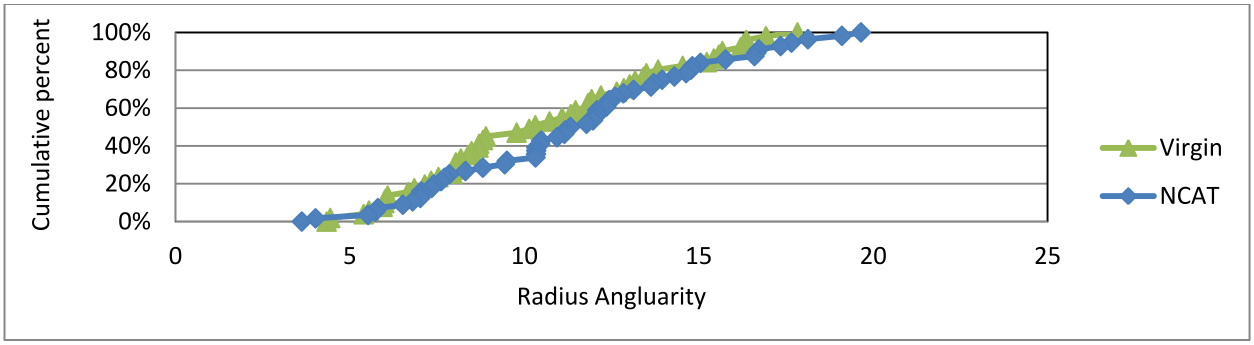
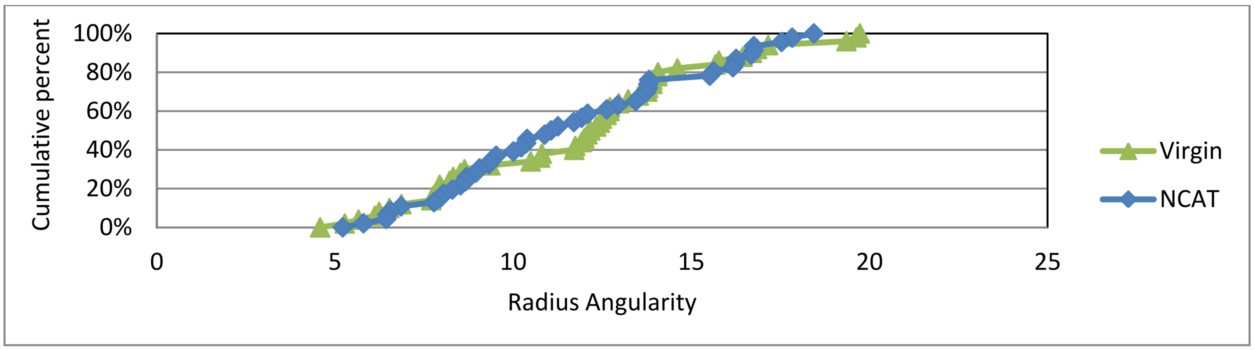


(d) Passing 1/4” and Retained #4

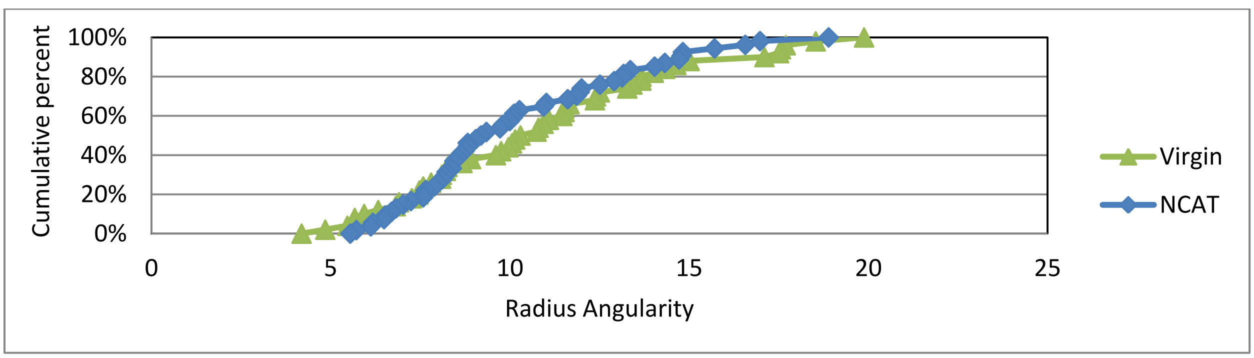
Figure A-10 SRAP2 Sample - Gradient Angularity for Coarse Aggregates: (a) Passing 3/4” and Retained 1/2”, (b) Passing 1/2” and Retained 3/8”, (c) Passing 3/8” and Retained 1/4”, and (d) Passing 1/4” and Retained #4.



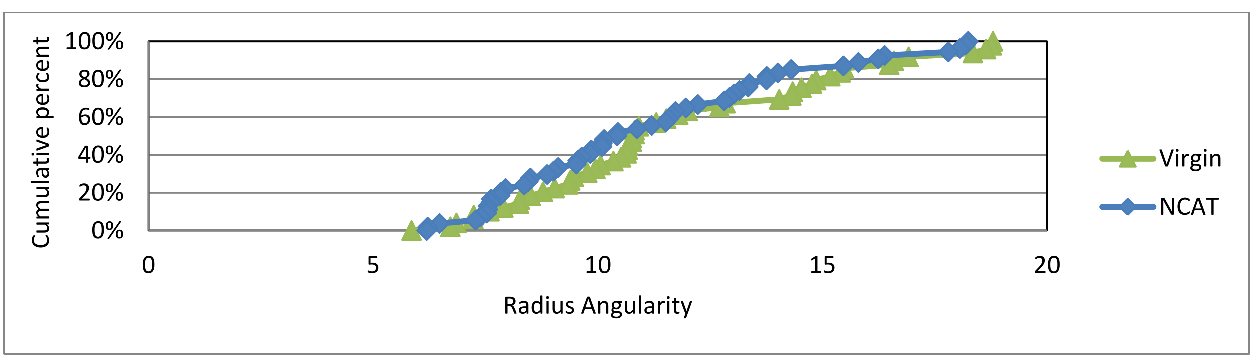
(a) Passing 3/4” and Retained 1/2”



(b) Passing 1/2” and Retained 3/8”

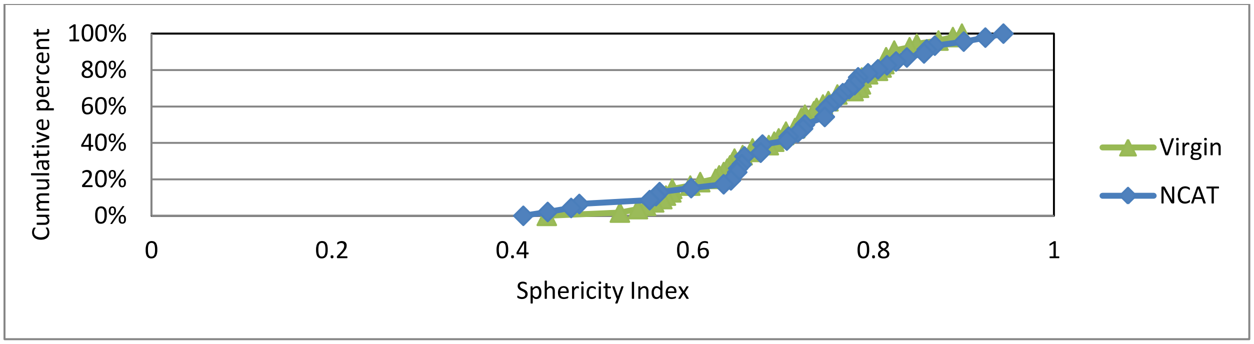


(c) Passing 3/8” and Retained 1/4”

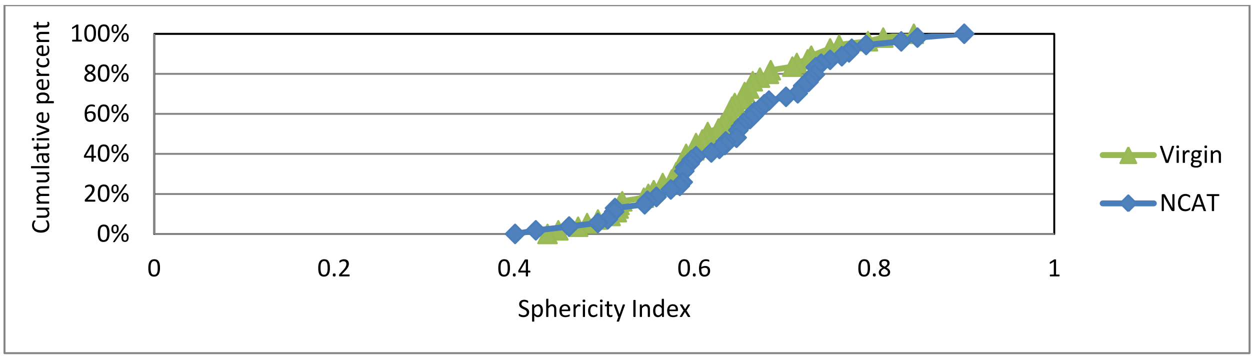


(d) Passing 1/4” and Retained #4

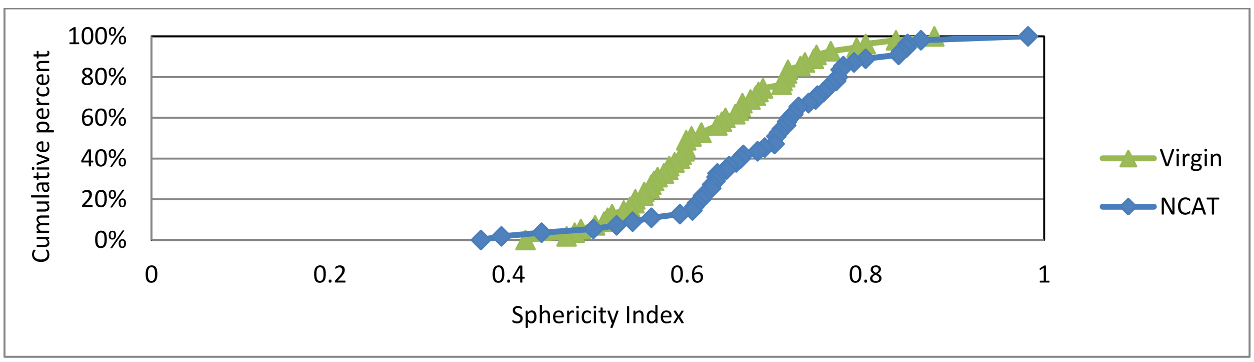
Figure A-11 SRAP2 Sample - Radius Angularity of Fine Aggregates: (a) Passing 3/4” and Retained 1/2”, (b) Passing 1/2” and Retained 3/8”, (c) Passing 3/8” and Retained 1/4”, (d) Passing 1/4” and Retained #4.



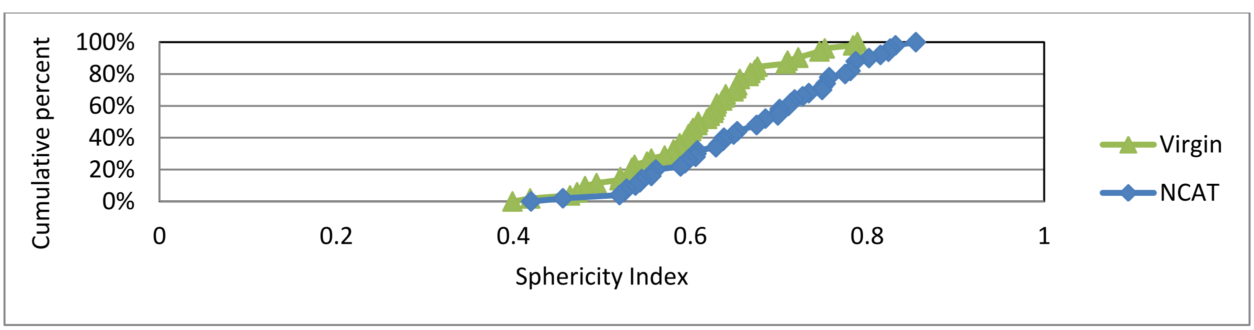
(a) Passing 3/4” and Retained 1/2”



(b) Passing 1/2” and Retained 3/8”

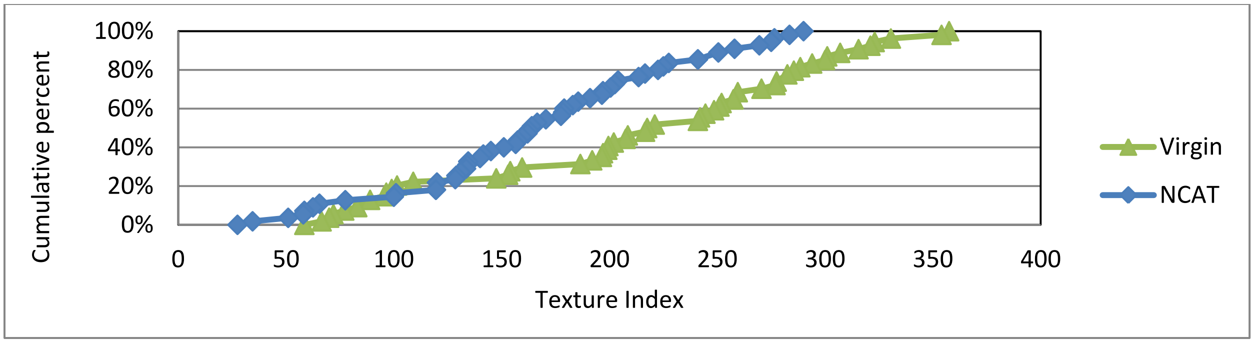


(c) Passing 3/8” and Retained 1/4”

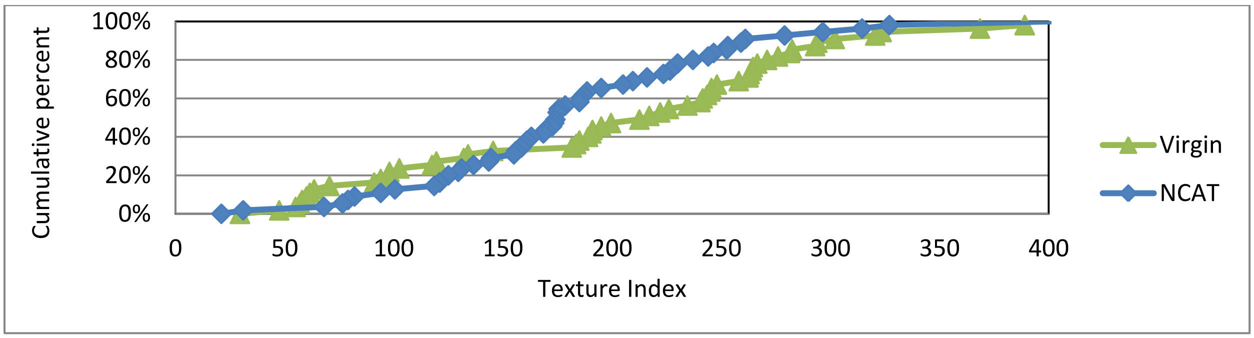


(d) Passing 1/4” and Retained #4

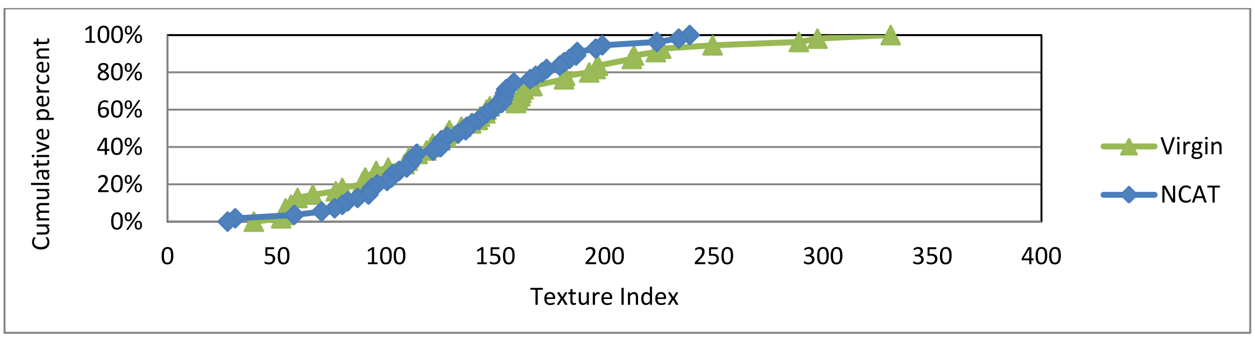
Figure A-12 SRAP2 Sample - Sphericity of Coarse Aggregates: (a) Passing 3/4” and Retained 1/2”, (b) Passing 1/2” and Retained 3/8”, (c) Passing 3/8” and Retained 1/4”, and (d) Passing 1/4” and Retained #4.



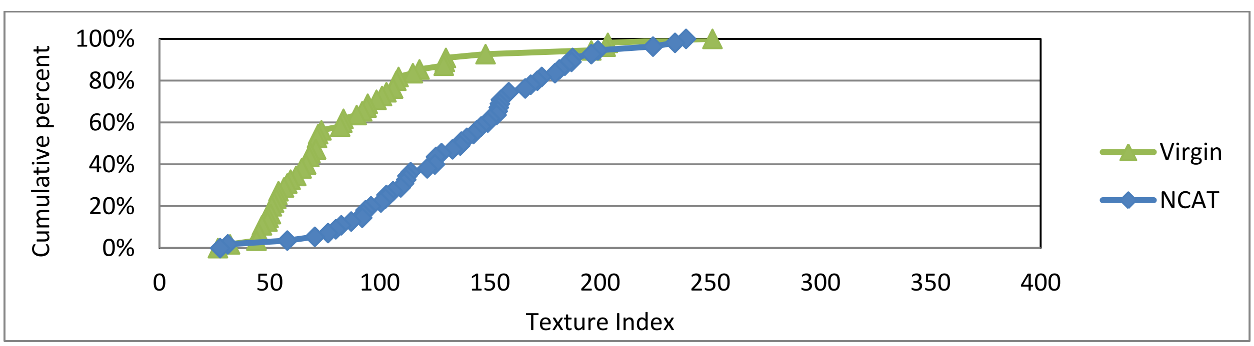
(a) Passing 3/4" and Retained 1/2"



(b) Passing 1/2" and Retained 3/8"

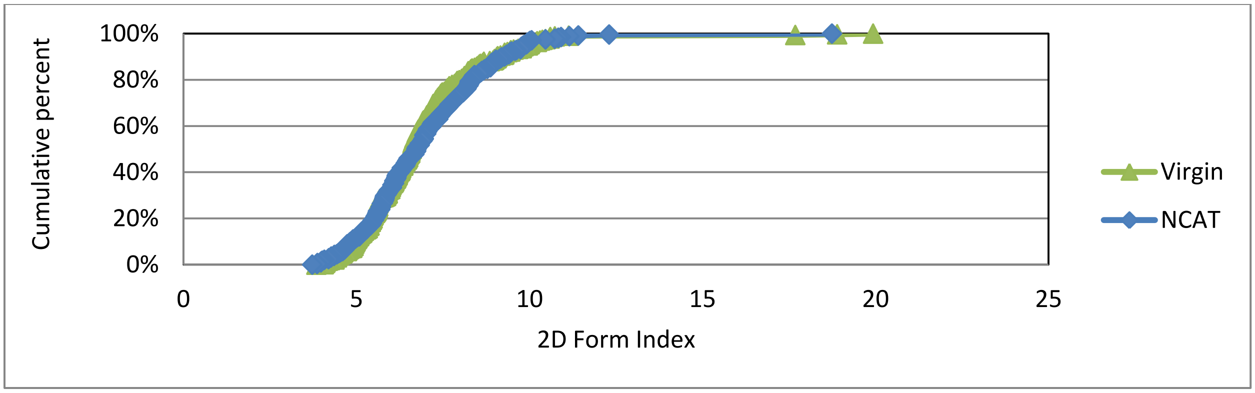


(c) Passing 3/8" and Retained 1/4"

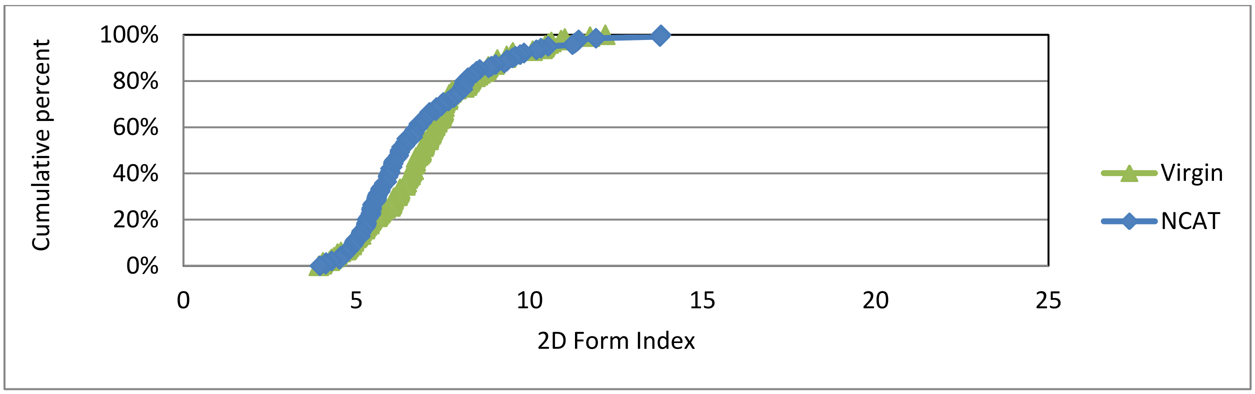


(d) Passing 1/4" and Retained #4

Figure A-13 SRAP2 Sample - Texture of Coarse Aggregates: (a) Passing 3/4" and Retained 1/2", (b) Passing 1/2" and Retained 3/8", (c) Passing 3/8" and Retained 1/4", and (d) Passing 1/4" and Retained #4.

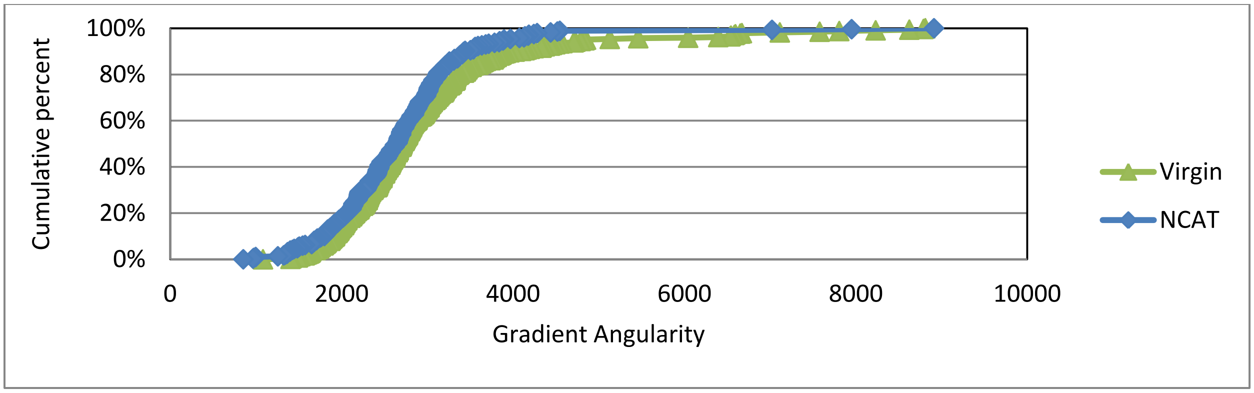


(a) Passing #4 and Retained #8

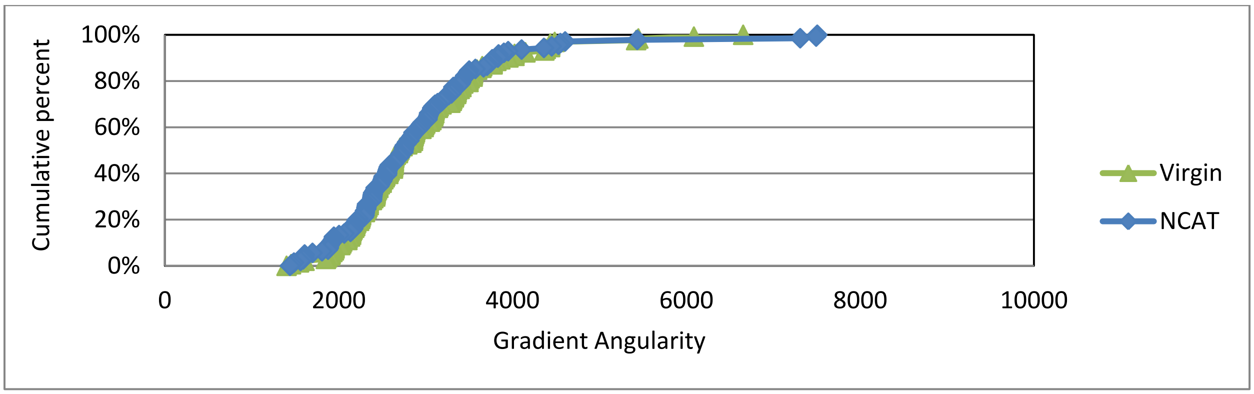


(b) Passing #8 and Retained #16

Figure A-14 SRAP2 Sample - 2D Form of Fine Aggregates: (a) Passing #4 and Retained #8, and (b) Passing #8 and Retained #16.

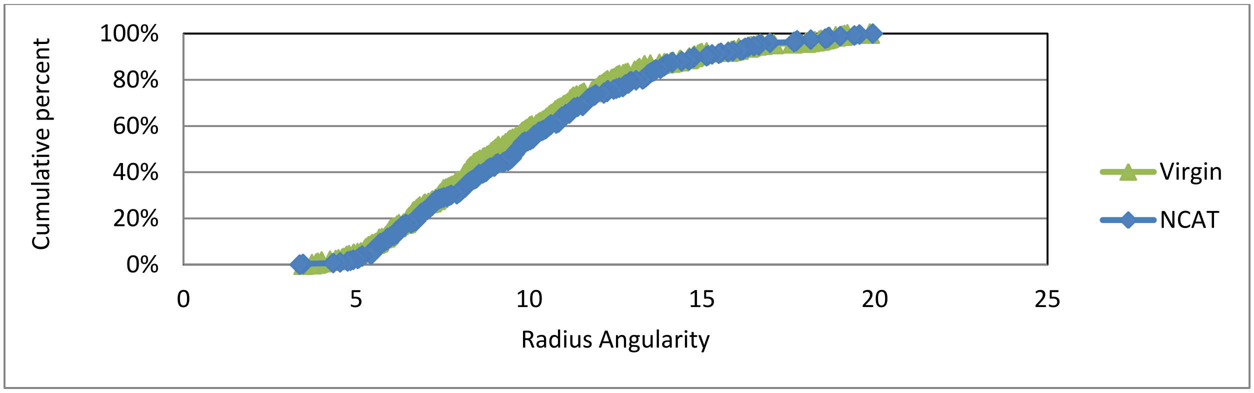


a) Passing #4 and Retained #8

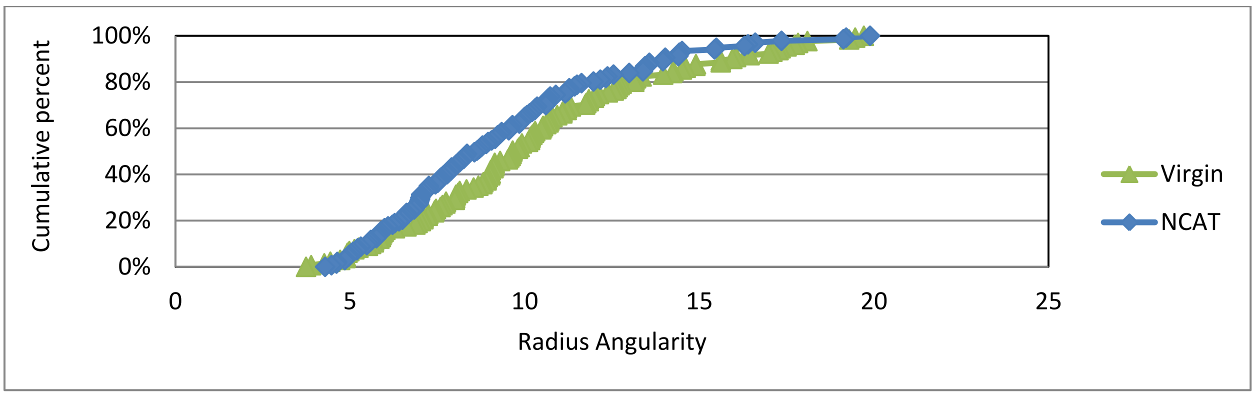


a) Passing #8 and Retained #16

Figure A-15 SRAP2 Sample - Gradient Angularity of Fine Aggregates: (a) Passing #4 and Retained #8, and (b) Passing #8 and Retained #16.

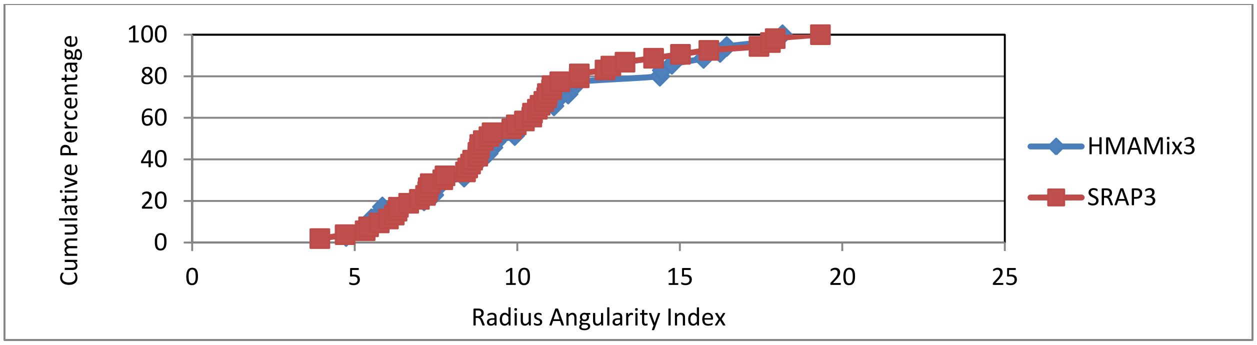


(a) Passing #4 and Retained #8

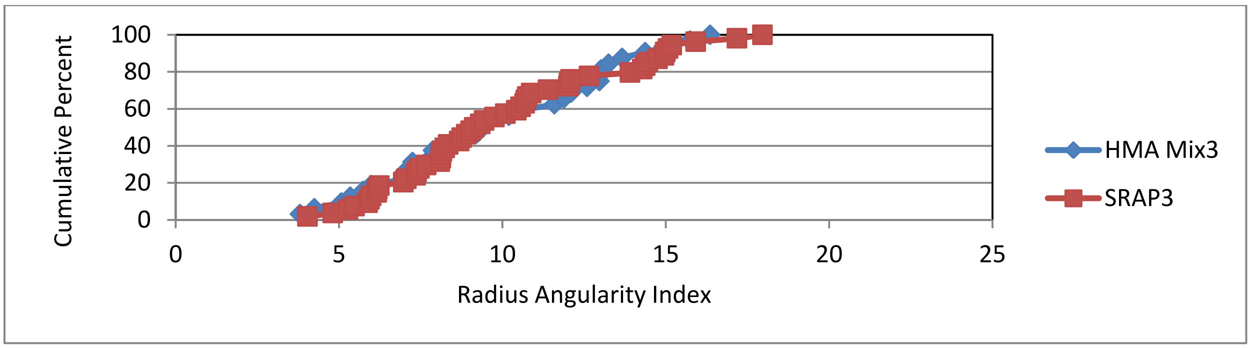


(b) Passing #8 and Retained #16

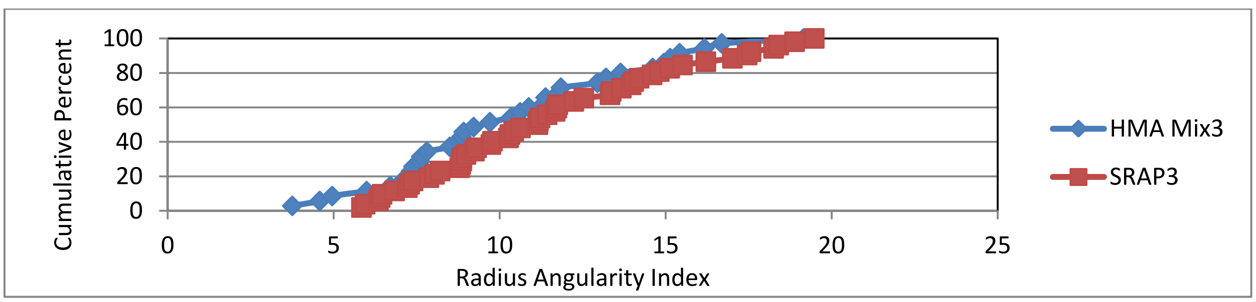
Figure A-16 SRAP2 Sample - Radius Angularity of Fine Aggregates: (a) Passing #4 and Retained #8, and (b) Passing #8 and Retained #16.



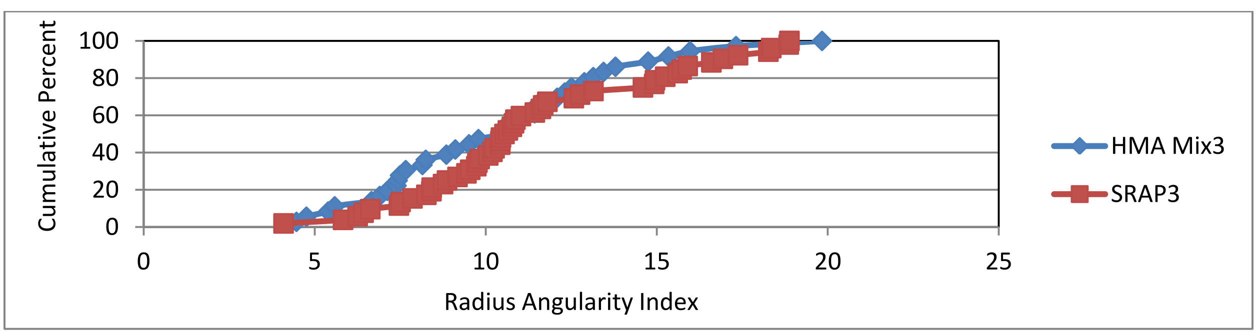
(a) Passing 3/4” and Retained 1/2”



(b) Passing 1/2” and Retained 3/8”

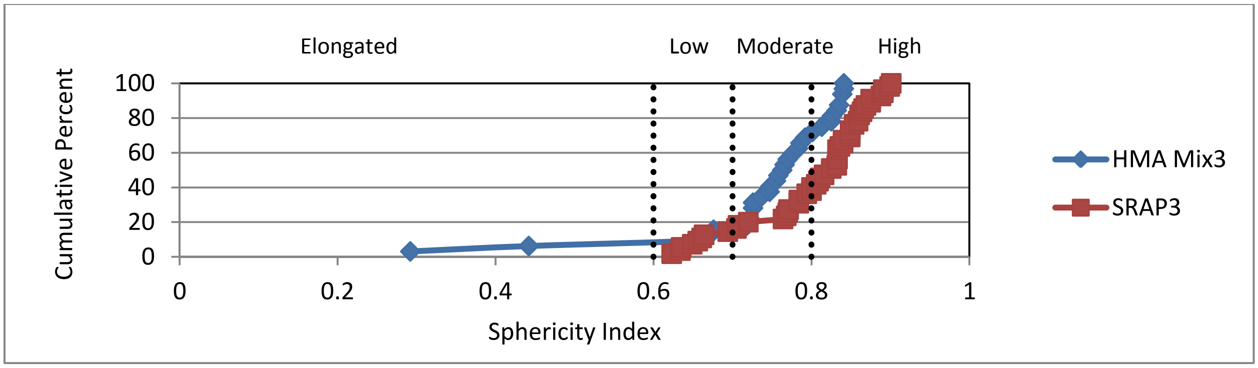


(c) Passing 3/8” and Retained 1/4”

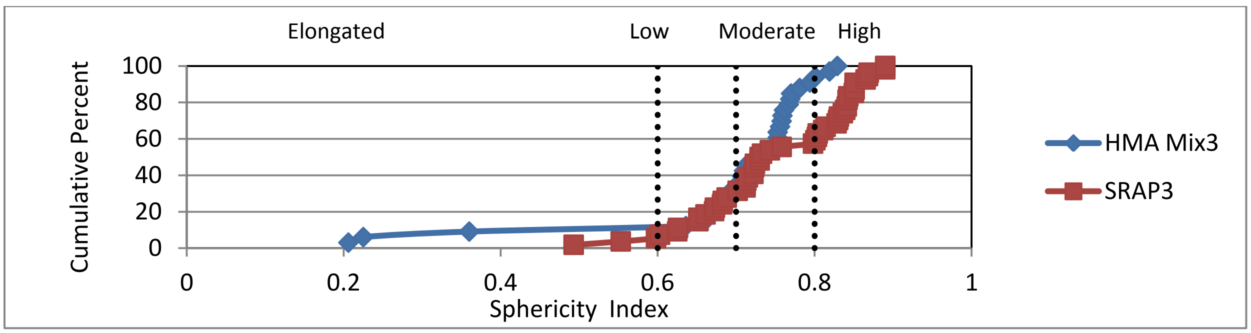


(d) Passing 1/4” and Retained #4

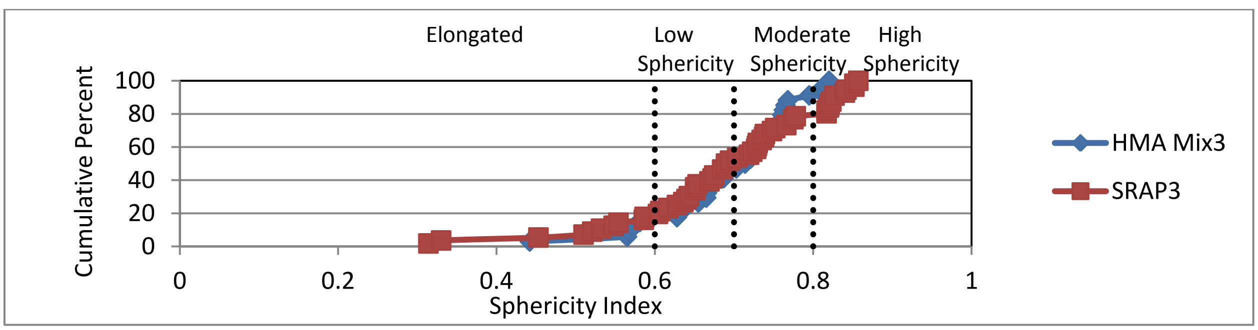
Figure A-17 SRAP3 Sample - Radius Angularity of Coarse Aggregates: (a) Passing 3/4” and Retained 1/2”, (b) Passing 1/2” and Retained 3/8”, (c) Passing 3/8” and Retained 1/4”, (d) Passing 1/4” and Retained #4.



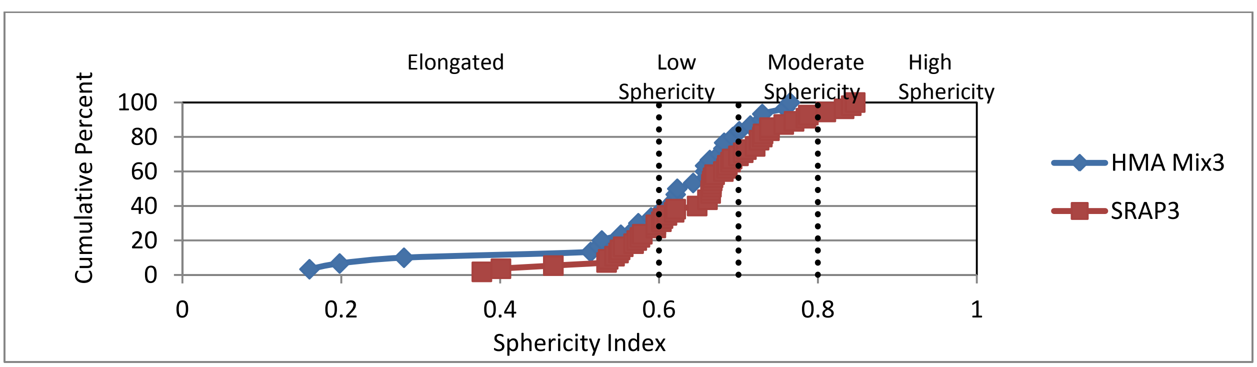
(a) Passing 3/4” and Retained 1/2”



(b) Passing 1/2” and Retained 3/8”

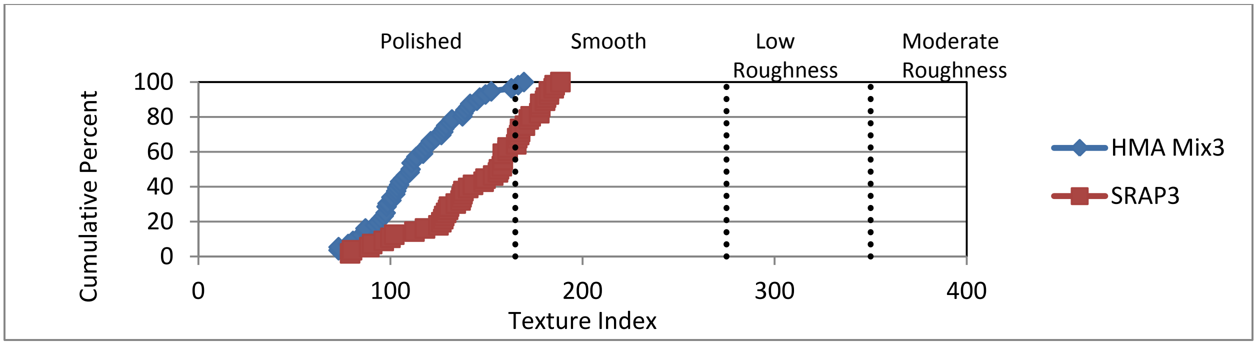


(c) Passing 3/8” and Retained 1/4”

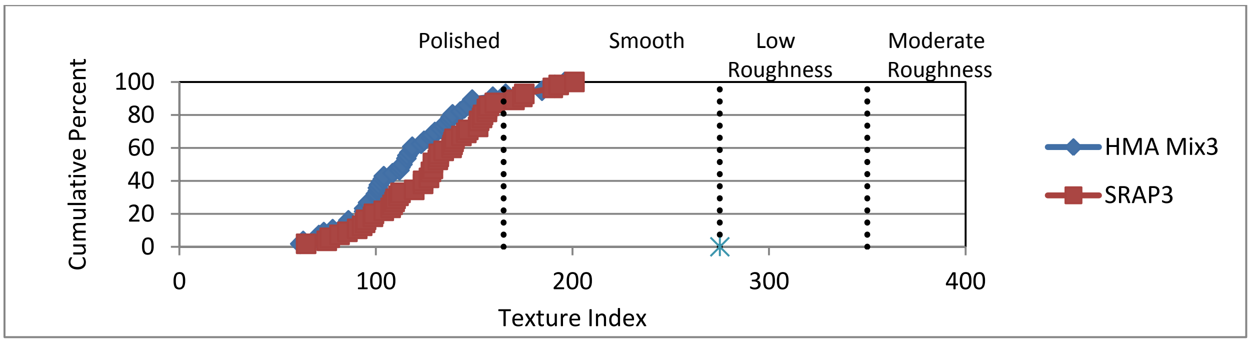


(d) Passing 1/4” and Retained #4

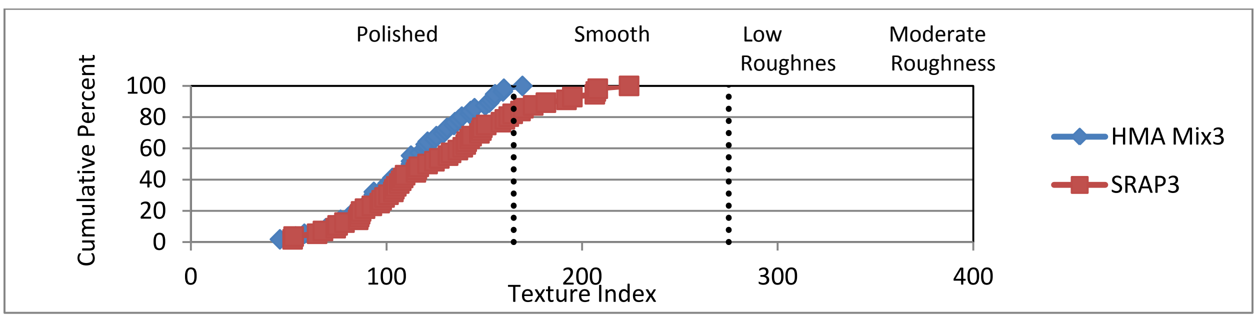
Figure A-18 SRAP3 Sample - Sphericity of Coarse Aggregates: (a) Passing 3/4” and Retained 1/2”, (b) Passing 1/2” and Retained 3/8”, (c) Passing 3/8” and Retained 1/4”, and (d) Passing 1/4” and Retained #4.



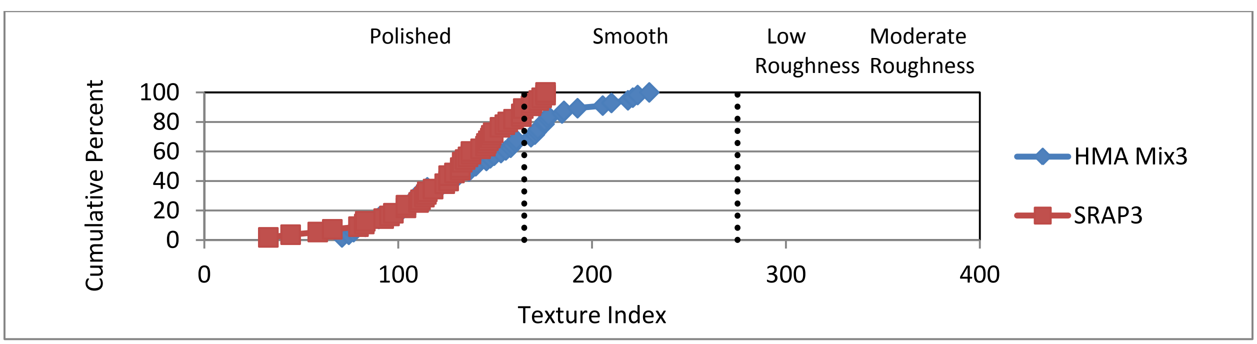
(a) Passing 3/4” and Retained 1/2”



(b) Passing 1/2” and Retained 3/8”

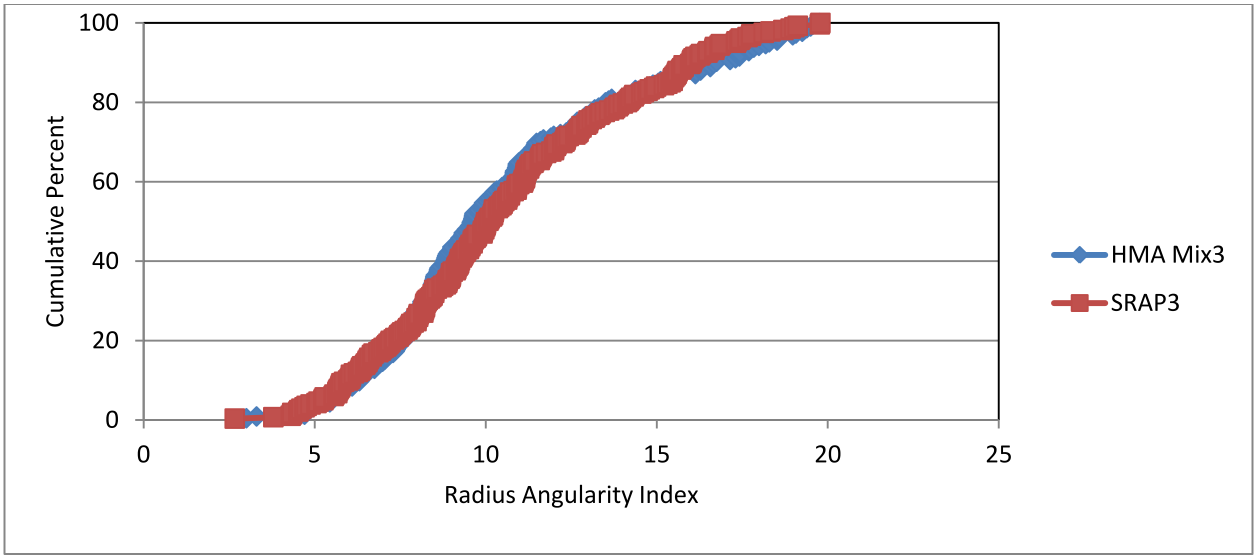


(c) Passing 3/8” and Retained 1/4”

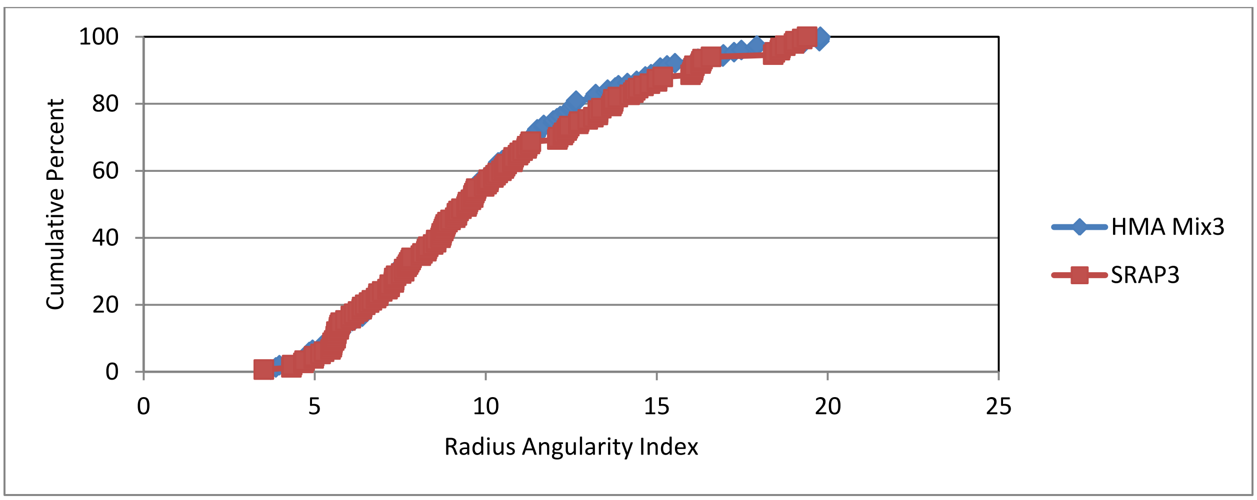


(d) Passing 1/4” and Retained #4

Figure A-19 SRAP3 Sample - Texture of Coarse Aggregates: (a) Passing 3/4” and Retained 1/2”, (b) Passing 1/2” and Retained 3/8”, (c) Passing 3/8” and Retained 1/4”, and (d) Passing 1/4” and Retained #4

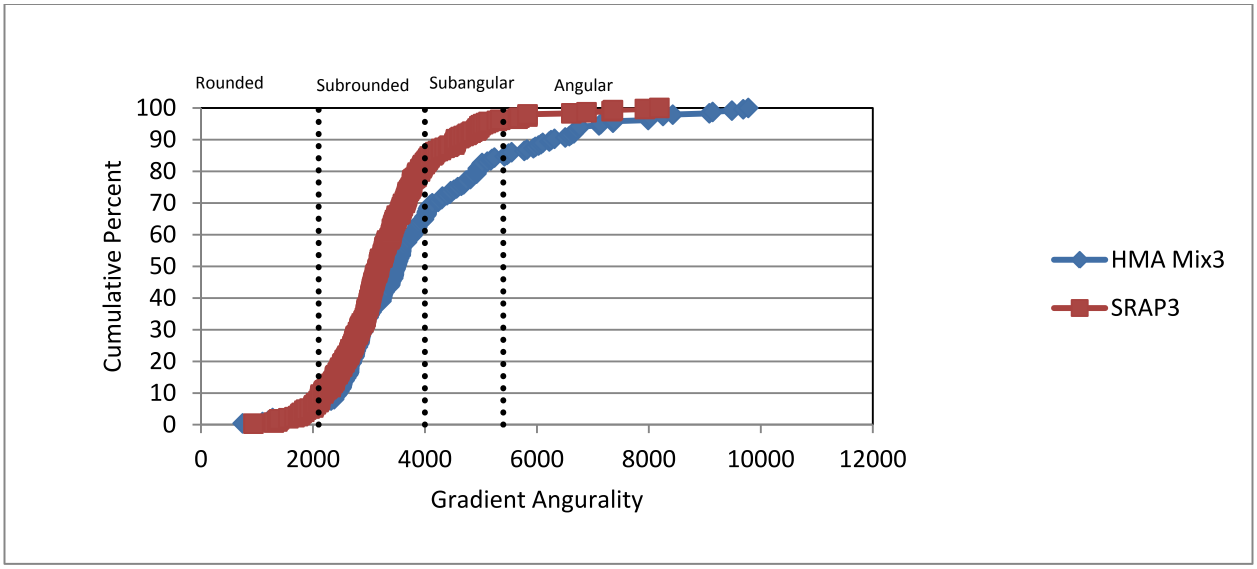


(a) Passing #4 and Retained #8

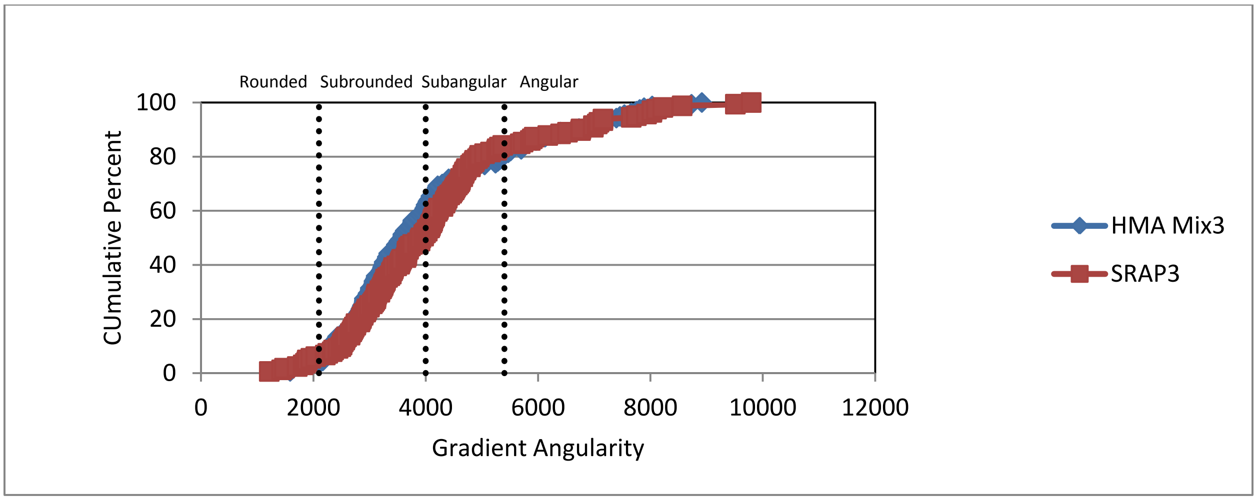


(b) Passing #8 and Retained #16

Figure A-20 SRAP3 Sample - Radius Angularity of Fine Aggregates: (a) Passing #4 and Retained #8, and (b) Passing #8 and Retained #16.

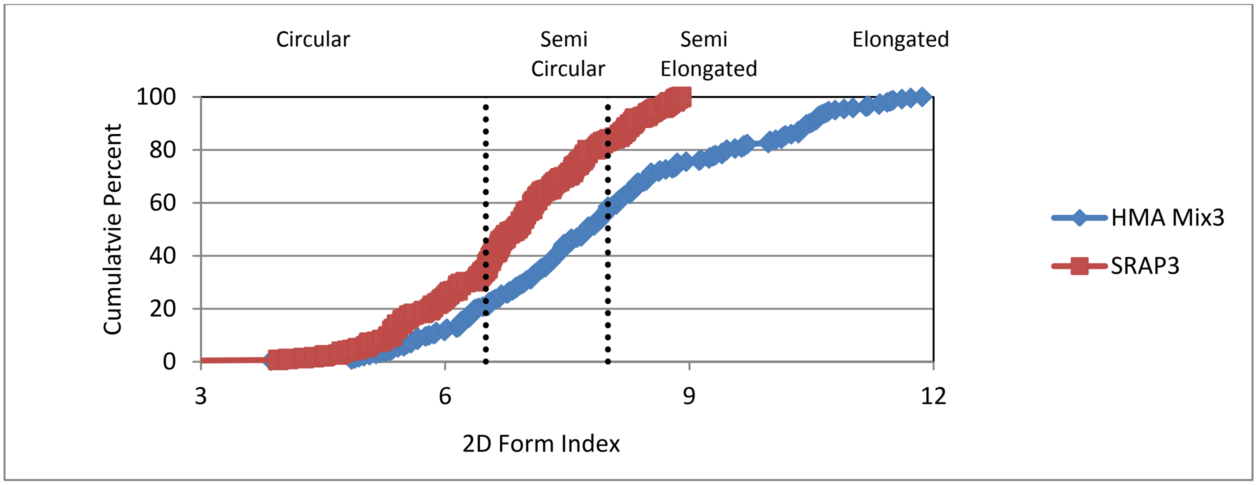


(a) Passing #4 and Retained #8

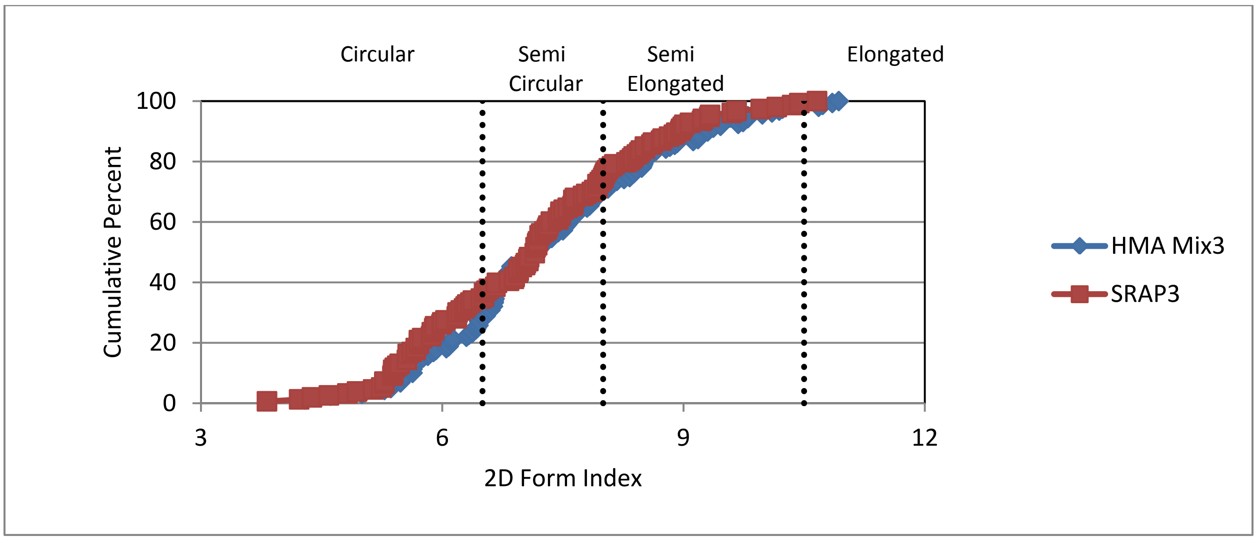


(b) Passing #8 and Retained #16

Figure A-21 SRAP3 Sample - Gradient Angularity of Fine Aggregates: (a) Passing #4 and Retained #8, and (b) Passing #8 and Retained #16.

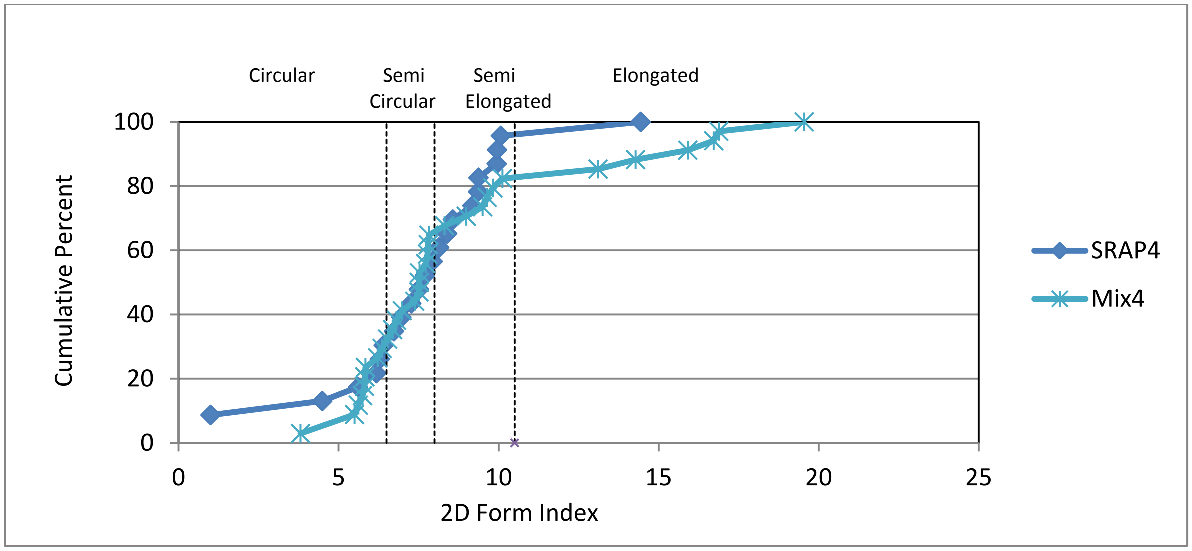


(a) Passing #4 and Retained #8

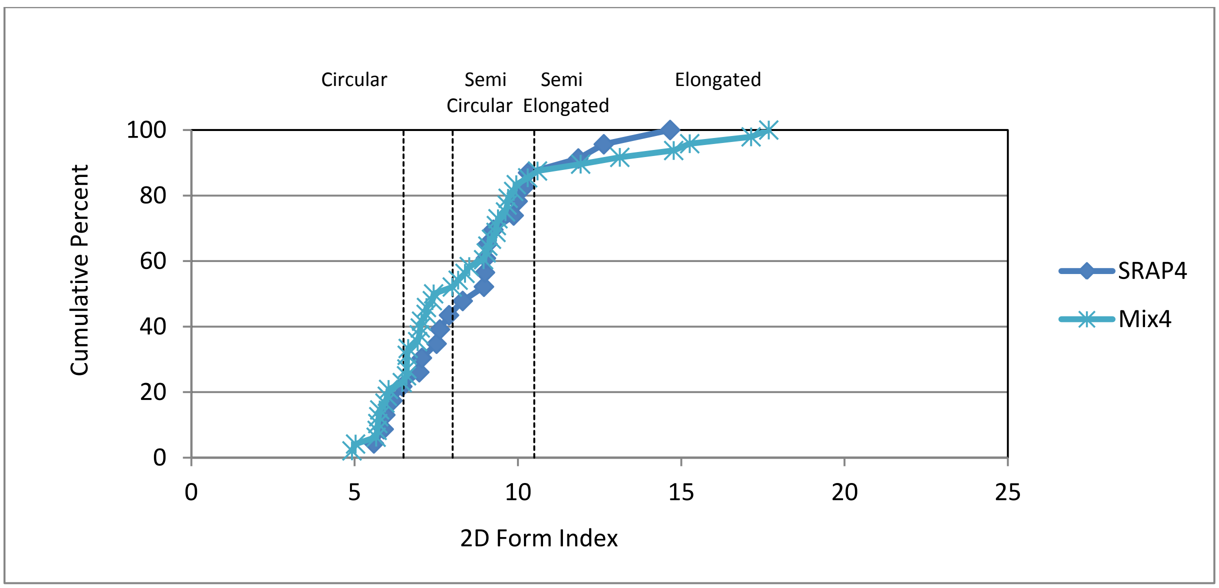


(b) Passing #8 and Retained #16

Figure A-22 SRAP3 Sample - 2D Form of Fine Aggregates: (a) Passing #4 and Retained #8, and (b) Passing #8 and Retained #16.

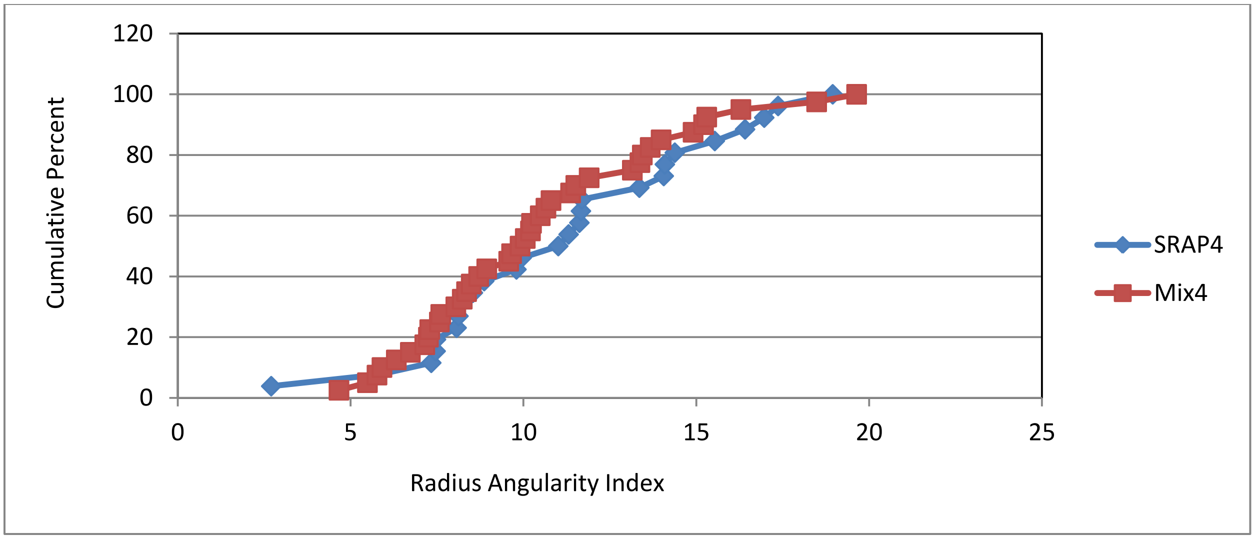


(a) Passing 3/4" and Retained 1/2"

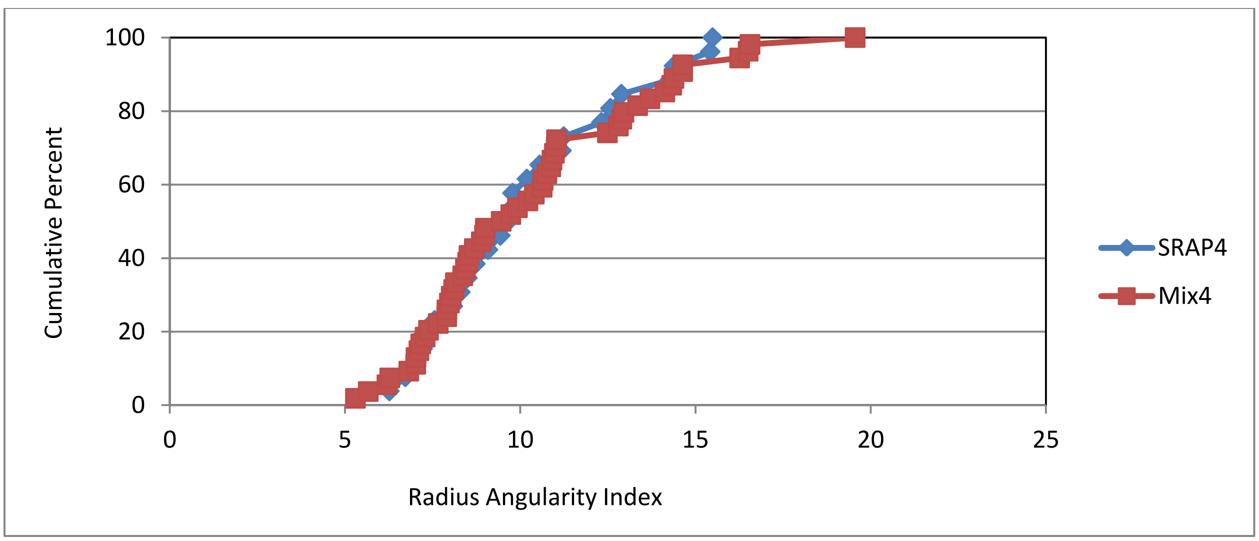


(b) Passing 1/2" and Retained 3/8".

Figure A-23 SRAP3 Sample - 2D Form of Coarse Aggregates: (a) Passing 3/4" and Retained 1/2", and (b) Passing 1/2"and Retained 3/8".

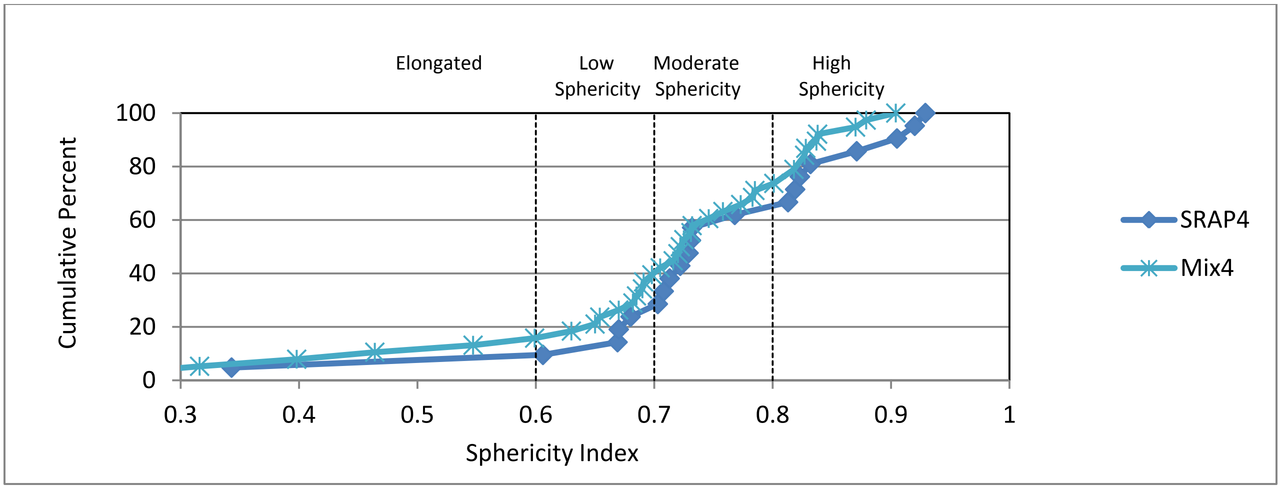


(a) Passing 3/4” and Retained 1/2”

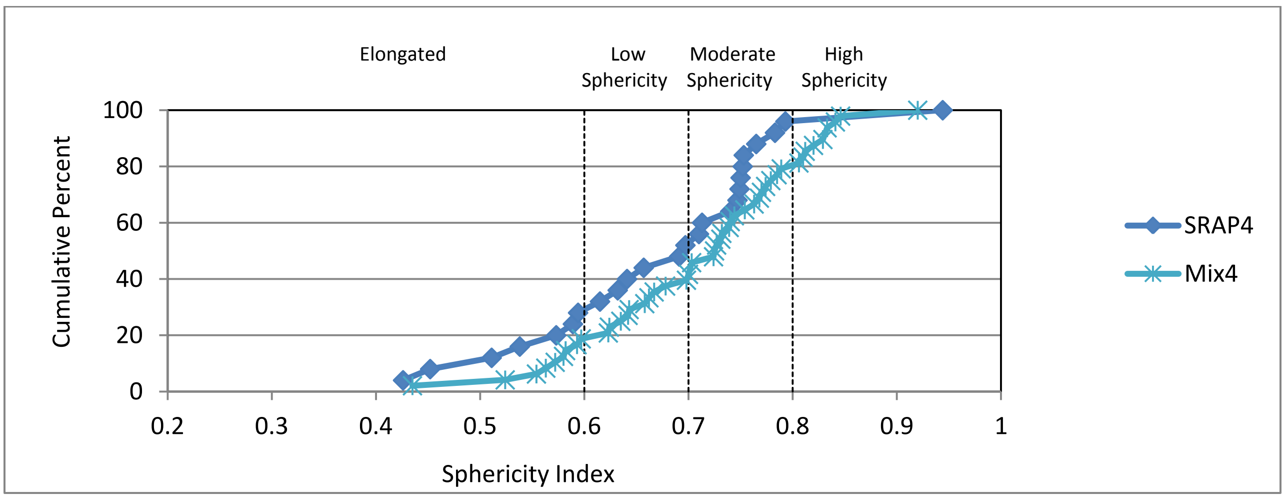


(b) Passing 1/2” and Retained 3/8”

Figure A-24 SRAP4 Sample-Radius Angularity of Coarse Aggregates: (a) Passing 3/4” and Retained 1/2”, (b) Passing 1/2” and Retained 3/8”.

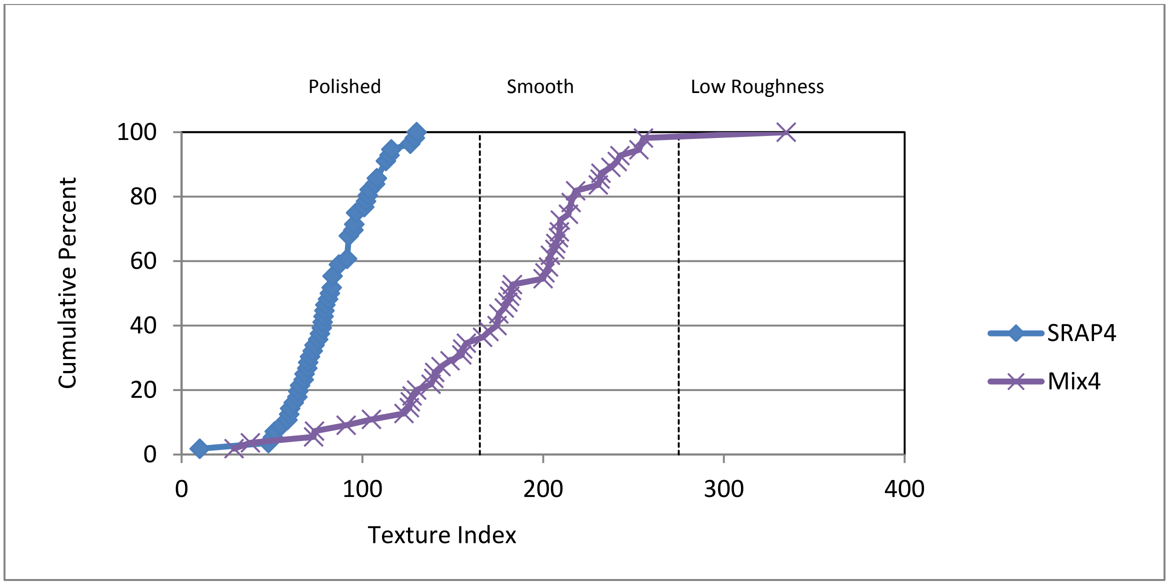


a) Passing 3/4” and Retained 1/2”

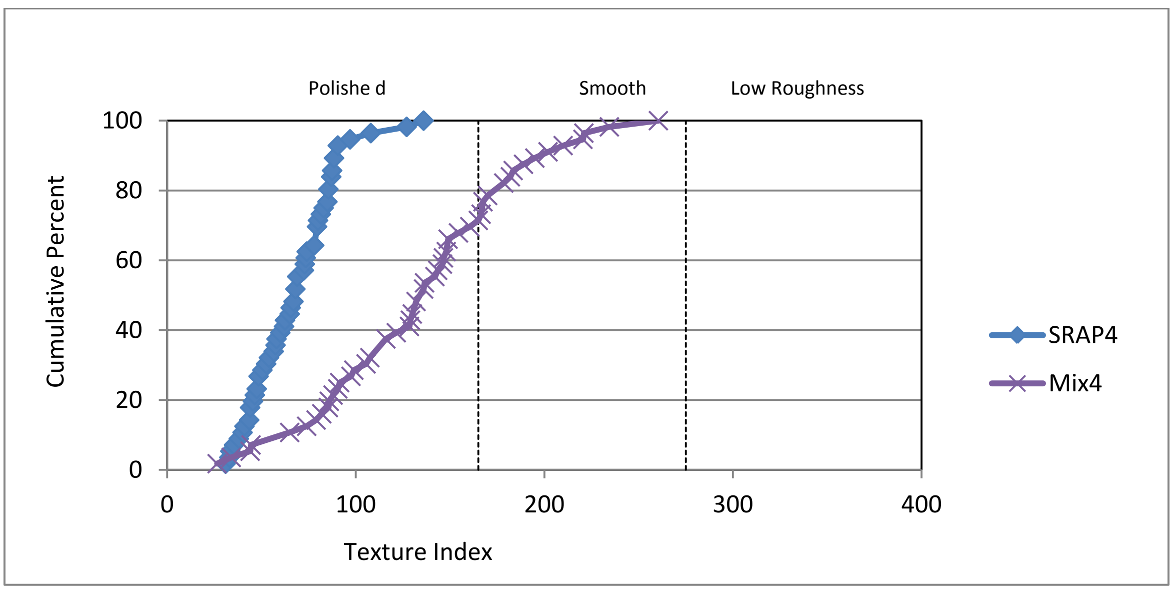


(b) Passing 1/2” and Retained 3/8”

Figure A-25 SRAP4 Sample -Sphericity of Coarse Aggregates: (a) Passing 3/4” and Retained 1/2”, and (b) Passing 1/2” and Retained 3/8”.



(a) Passing 3/4” and Retained 1/2”



(b) Passing 1/2” and Retained 3/8”

Figure A-26 SRAP4 Sample-Texture of Coarse Aggregates: (a) Passing 3/4” and Retained 1/2”, and (b) Passing 1/2” and Retained 3/8”.