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LABORATORY EVALUATION OF CHARACTERISTICS OF RECYCLED ASPHALT PAVEMENT IN KANSAS

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16 Abstract

The main objective of this research was to evaluate characteristics of milled Recycled Asphalt Pavements (RAP) collected from selected milled roadways in Kansas. The RAP was collected from three selected milled roadways including K-25 in Grant County, K-25 in Logan County, and US-83 in Scott County. The aggregates were extracted from RAP, and tested for characteristics including gradation, specific gravity, Fine Aggregate Angularity (FAA), Coarse Aggregate Angularity (CAA), flat and elongation (F&E), and Los Angeles Abrasion (LA) values. Binder from each source was extracted from the RAP, and recovered for a PG grade testing. The changes in the properties of aggregates after milling from the roadways as compared with the original aggregates are discussed. The variability of RAP aggregates was analyzed. In addition, the differences between the properties of aggregates extracted by centrifuge and ignition methods are compared.

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THE KANSAS DEPARTMENT OF TRANSPORTATION
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and

THE UNIVERSITY OF KANSAS
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PREFACE

The Kansas Department of Transportation's (KDOT) Kansas Transportation Research and New-Developments (K-TRAN) Research Program funded this research project. It is an ongoing, cooperative and comprehensive research program addressing transportation needs of the state of Kansas utilizing academic and research resources from KDOT, Kansas State University and the University of Kansas. Transportation professionals in KDOT and the universities jointly develop the projects included in the research program.

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Abstract

The main objective of this research was to evaluate characteristics of milled Recycled Asphalt Pavements (RAP) collected from selected milled roadways in Kansas. The RAP was collected from three selected milled roadways including K-25 in Grant County, K-25 in Logan County, and US-83 in Scott County. The aggregates were extracted from RAP, and tested for characteristics including gradation, specific gravity, Fine Aggregate Angularity (FAA), Coarse Aggregate Angularity (CAA), flat and elongation (F&E), and Los Angeles Abrasion (L.A.) values. Binder from each source was extracted from the RAP, and recovered for a PG grade testing. The changes in the properties of aggregates after milling from the roadways as compared with the original aggregates are discussed. The variability of RAP aggregates was analyzed. In addition, the differences between the properties of aggregates extracted by centrifuge and ignition methods are compared.

Acknowledgments

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Chapter 1: Introduction

1.1 Background

The use of Recycled Asphalt Pavement (RAP) has been in practice since the 1930s and is necessary to reduce the construction cost due to rising prices of virgin aggregates and binder, to conserve these rapidly depleting resources, and to minimize problems associated with disposal of aged mixes. Many states and the Kansas Department of Transportation (KDOT) have been using RAP for highway construction. According to the Federal Highway Administration (FHWA), nearly 30 million tons of RAP are recycled into Hot Mix Asphalt (HMA) pavements every year and thus RAP is the most recycled material in the United States.

In 1997, a subgroup of the FHWA Superpave Mixtures Expert Task Group developed interim guidance for the use of RAP based on the past experience. These guidelines established a tiered approach for the RAP usage. The Task Group suggested that up to 15% RAP could be used with no change in binder grade. Between 15% and 25% RAP, the virgin binder grade should be decreased by one increment on both the high and low temperature grades. Above 25% RAP, blending charts should be used to determine how much RAP can be used. Most research has shown that there is no significant difference in Superpave performance when a low RAP content (10%) is used. At a higher RAP content (for example, 40%), however, the difference in the performance becomes significant.

1.2 Research Problem Statement

As mentioned above, the use of RAP can reduce the total cost of road construction and become less dependent on depleting binder and aggregate sources. Due to the rapid increase in oil price, it has become cost effective to use a higher percentage of RAP in HMA mixes. In the past, KDOT limited the use of RAP to less than 20%. Recently, up to 40% RAP has been considered by KDOT for HMA mixes. Since most RAP are milled from state highways, they may be composed of multiple layers of HMA, asphalt seals (chip seals), Ultrathin Bonded Asphalt Surface (UBAS, i.e. Novachip), hot in-place recycle (HIR), cold in-place recycle (CIR), modified slurry seal (MSS), maintenance overlays, and/or crack sealant. Their compositions and properties vary highly and have not been well investigated. Therefore, it is essential to know the history of the roadways and the characteristics of the corresponding RAP.

The properties of RAP binder, such as viscosity, complex shear modulus, phase angle, and penetration, change because of aging. The change in the PG grade of binder in the RAP would affect the required PG grade of virgin binder. When a small percentage of RAP is incorporated into HMA mixes then the effect of binder aging is negligible, however, when a high amount of RAP is used, the effect of binder aging is significant. Therefore, it is important to know the change in PG grade of the RAP binder.

When a high percentage of RAP is used, aggregate in RAP may affect the volumetric properties and performance of the mixture. The properties of the RAP aggregate, such as specific gravity, gradation, Fine Aggregate Angularity (FAA), Coarse Aggregate Angularity (CAA), and Los Angeles (L.A.) abrasion value, may affect the mixture with use of a high percentage of RAP. Previous studies show that when RAP aggregate is burned to determine asphalt content, the FAA and CAA of the aggregate are increased. Aggregate angularity is known to influence the performance of the aggregate and mixture. For example, an increase of angularity may affect abrasion properties of the aggregate. Therefore, it is necessary to know the effect of ignition on the physical properties of the aggregate.

1.3 Objective

The main objective of this research was to evaluate the characteristics of milled RAP collected from three selected milled roadways in Kansas. The characteristics included the gradation, specific gravity, FAA, CAA, flat and elongation, and L.A. abrasion of RAP aggregate and properties and PG grades of the extracted asphalt binder. The changes of properties in RAP aggregate after milling from roadways as compared with original aggregate properties were evaluated. The properties of extracted asphalt binder including PG grade was investigated. The comparison of aggregate properties was made between aggregate extracted by ignition and centrifuge methods. The test data was analyzed and recommendations for the consideration of characteristics of RAP in the mix design and field construction are made.

1.4 Organization

This report contains five chapters:

Chapter 1 includes introduction, research problem statement, organization, and objective of this research.

Chapter 2 covers the literature review on the laboratory evaluation of physical and mechanical characteristics of RAP.

Chapter 3 presents the material characterization, maintenance history, and experimental study of the RAP from three selected milled roadways in Kansas. The experimental study includes test methods and procedures.

Chapter 4 includes the interpretation and analysis of the experimental data. This chapter evaluates characteristics of aggregate and binder extracted from the RAP. The variability in aggregate properties in terms of standard deviation (σ) and coefficient of variability (COV) was determined. The comparison of the properties of aggregates extracted by ignition and centrifuge methods is made.

Chapter 5 presents the conclusions from this research and the recommendations for a future study.

Chapter 2: Literature Review

2.1 Introduction

Recycled Asphalt Pavement (RAP) refers to reclaimed and reprocessed pavement material containing asphalt binder and aggregates. These materials are produced when asphalt pavements are reclaimed for resurfacing, reconstruction or accessing buried materials. RAP contains useful materials, including asphalt binder and aggregate, when crushed and screened properly. RAP is obtained either by milling or by a full depth recovery method. According to New Jersey Department of Environmental Protection (NJDEP, 2001), asphalt millings are defined as the bitumen and inorganic particles, generally varying from dust to smaller than 25-mm, that are produced by mechanical grinding of bituminous concrete surfaces. The KDOT specification for the size of RAP is milled asphalt that passes through 58-mm (2.25 inch) size sieve. These raw millings are subjected to a process of crushing and screening to achieve a particle size distribution for use in a new HMA mix. The use of RAP has multiple advantages; a few of them are listed below:

- **Economic benefit:** The availability of high-quality aggregate for use in asphalt pavements is a growing concern. The demand for these materials continues to rise, however, existing reserves are depleting. In such a situation, the use of recovered and reprocessed aggregate in the new pavement becomes necessary. The cost of petroleum product has also been rising. The asphalt recovered from RAP can reduce the amount of virgin binder needed.
- **Environmental benefit:** The use of RAP provides an environmental benefit by reducing the amount of disposable materials. Its use conserves natural resources, minimizes disposal problems, and reduces costs of projects.
- **Technical benefit:** A number of studies have shown that properly specified and produced recycled hot mix asphalt is comparable in quality and structural performance to conventional hot mix asphalt in terms of rutting, raveling, weathering, and fatigue cracking.

- **Conservation of energy:** Energy savings from 25 to 40% may be achieved by using RAP. There are also a few disadvantages of the use of RAP. One possible problem is leaching of carcinogens from the bituminous component of millings while the material is stockpiled or in service. However, this issue can be allayed by the use of appropriate plants and procedures in the production of recycled hot mix asphalt. Sadeci et al. (1996) conducted a research on concentration of leachate from a milling stockpile and they found that the concentration of polycyclic aromatic hydrocarbons (PAH) was near or below the detectable limit.

According to FHWA, the majority of RAP is used in construction and maintenance applications including:

- **Granular base aggregate:** The RAP aggregate is crushed, screened, and blended with virgin aggregate to produce a granular base or sub-base aggregate. Since RAP may exhibit somewhat lower compressive strength than conventional granular aggregate bases (Thakur et al., 2010), it is blended with suitable granular material to attain desirable compressive strength.
- **Asphalt concrete aggregate and asphalt cement supplement:** Since RAP contains both binder and aggregate, when it is used as an aggregate substitute it also serves as an asphalt cement binder substitute.
- **Stabilized base aggregate:** To produce stabilized base or sub-base aggregate, RAP is crushed, screened, and blended with stabilization reagents and then it is compacted to gain desirable strength.
- **Embankment or fill:** According to FHWA user's guidelines (1997) for "Waste and By-Product Materials in Pavement Construction", stockpiled RAP can be used as granular fill for embankment or backfill construction. However, stockpiled RAP material as embankment fill is not widely used because it does not represent the economical and most suitable use of RAP.

- **Hot mix asphalt (central processing facility):** RAP is processed to a desired gradation using crusher and screener then it is stockpiled by conveyor and stacker. This product is finally mixed in a hot mix plant with new aggregate, asphalt, and recycling agent. A heat transfer method is used to soften the bitumen. Hot mix recycling is currently the most used recycling method in the world. The ratio of RAP aggregate to virgin aggregate used in hot recycling has been 85% to 90%. However, the typical ratio is 30% for a batch plant and 50% for a drum mix plant.
- **Hot mix asphalt (in-place recycling):** In this process no processing is required prior to the actual recycling operation. Specialized heating, scarifying, rejuvenating, lay down, and compaction processes are done to repave. With in-place recycling, 100 percent recycling of existing pavement is completed on site.
- **Cold mix asphalt (central processing facility):** The use of RAP in cold mix is similar to hot mix asphalt except that the graded aggregate is blended into cold mix asphalt paving mixture as an aggregate substitute. In this method, RAP material is reused by reprocessing and adding binder without any use of heat.
- **Cold in-place asphalt:** In this technology, processing of RAP is not required before actual recycling operation. Existing pavement surface is milled to a depth up to 150 mm, processed, mixed with asphalt emulsion, and then placed and compacted in single pass.
- **Full depth reclamation:** In this technology, full thickness of asphalt pavement and predetermined thickness of sub-base or base course are pulverized, more materials are added if necessary, and blended to provide an upgraded homogenous material.

RAP has been used since 1930s. However; interest in recycling asphalt pavement rose significantly in response to increased construction costs of asphalt pavements during OPEC's oil embargo in the mid 1970’s. Initially, RAP materials were used on roads having low traffic. However, due to considerable gain in experience in RAP, it is also used for heavy traffic roads these days. The use of RAP in HMA mixes has been increasing considerably. Mike Acott, the president of National Asphalt Pavement Association, pointed out that “The recycling of asphalt pavement is an everyday business practice” (http://www.gahotmix.com/asphalt-recycling.aspx). The FHWA and EPA report (1993) estimated that 73 million metric tons out of 91 million metric tons of asphalt that is removed each year during resurfacing and widening projects is used as part of new roads, roadbeds, shoulders, and embankments. In other words, the recycling rate of asphalt pavement is 80%. This recycling rate is only second to very few used auto batteries (93%) based on the US Environmental Agency’s estimates. Figure 2.1 shows the amount of materials in tons recycled each year in the United States.

The RAP is used in HMA mixes at varying percentages. In the past, 10 to 20% RAP was generally incorporated into HMA mixes; however, due to a rapid increase in price of bituminous products, interest in the use of higher percentage of RAP is increasing. Also past experience gained in field of RAP encourages the use of high percentage of RAP. According to McDaniel et al. (2000), a tiered approach should be used for the use of RAP up to 15 to 30% without any extensive testing and extensive testing should be conducted for higher RAP content. Some of the projects using a high percentage of RAP are listed in Table 2.1.

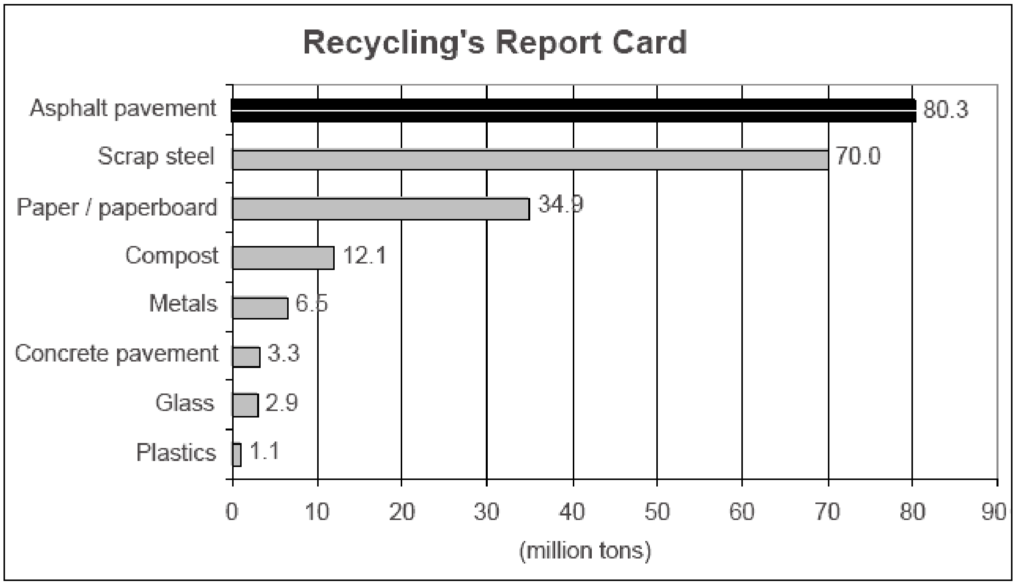


Figure 2.1. Recycling report card
(http://www.gahotmix.com/asphalt-recycling.aspx)

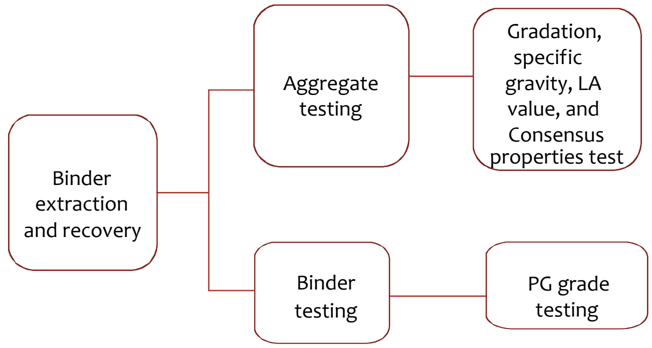
Table 2.1. Location,% RAP, and dates of construction of projects where high percentage of RAP was used
(http://www.fhwa.dot.gov/PAVEMENT/recycling/rap/index.cfm)

Location	RAP (%)	Dates of Construction
North Carolina	40	Sep-07
South Carolina	30 and 50	Oct-07
Wisconsin	25	Nov-07
Florida	45	Dec-07
Kansas	**30 to 40**	**May-08**
Delaware	35	Summer 2008
Minnesota	30	2008
Illinois	10 to 50 allowed	2008

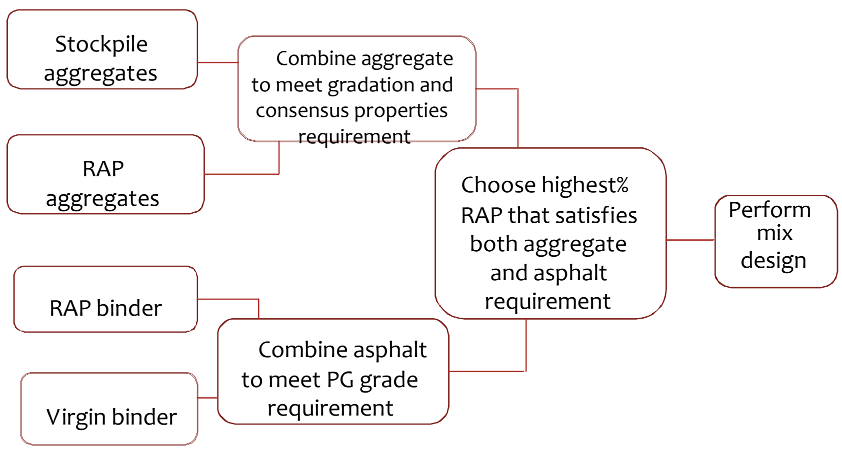
2.2 Designing HMA with High Percentage of RAP

In 1997 a subgroup of the FHWA Superpave Mixtures Expert Task Group developed interim guidance for the use of RAP based on the past experience. These guidelines established a tiered approach for the RAP usage. The Task Group suggested that up to 15% RAP could be used without any change in binder grade. Between 15 and 25% RAP, the virgin binder grade should be decreased by one increment on both the high and low temperature grades. Above 25% RAP, blending charts should be used to determine how much RAP can be used.

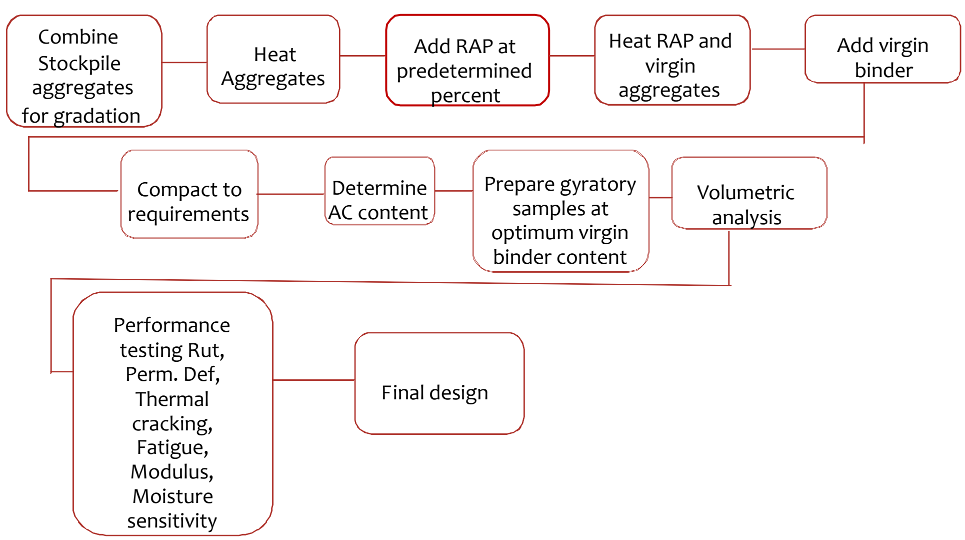
Most research has shown that there is no significant difference in Superpave performance when a low RAP content (10%) is used. At a higher RAP content (for example, 40%), however, the differences in the performance become significant. According to the NCHRP report (McDaniel and Anderson, 2001), in Superpave mix design, when RAP is used in amount greater than 20%, it is suggested that both the RAP and virgin binder should be tested, and a blending chart should be used. In addition, combined virgin and RAP aggregates should meet the requirements of gradation and Superpave consensus properties. Figure 2.2 shows flow charts to design high percentage of RAP mixes (Newcomb et al., 2007).



(a) Step 1



(b) Step 2



(b) Step 3

Figure 2.2. RAP mix design procedure

When high percentage of RAP is to be used in a new HMA mix, gradation, specific gravity, consensus properties, and L.A. abrasion properties of aggregates as shown in Figure 2.2(a) should be checked. It is also necessary to determine PG grade of binder since asphalt stiffens due to aging. Once the RAP aggregate and asphalt have been characterized, the combined aggregate and the combined asphalt should meet the following requirements (Figure 2.2(b)): the gradation, consensus properties, and L.A. abrasion value for the combined aggregate and the PG grade for the combined binder using blending charts. Figure 2.2(c) presents an overview of the mix design incorporating RAP. This process is quite similar to the virgin mix design of HMA. The only difference is the handling of the RAP material. When the virgin aggregate is heated, RAP is added and heated together, and followed by the addition of the virgin binder. All the materials are mixed and compacted in molds using a gyratory compactor. Specimens are prepared at four virgin binder contents. A plot of the density relative to the theoretical maximum specific gravity versus the number of gyrations is plotted, and the asphalt content which produces 96.5% Gmm (i.e., 3.5% air voids) at the design number of gyrations is chosen as the optimum binder content. Three samples prepared at the optimum binder content are tested for volumetric properties and performance. Plant verification of the mix design is the final step before production.

2.3 Extraction and Recovery of Asphalt Binder

In the design mixture that incorporates high percentage of RAP, it is important to determine asphalt content, properties of asphalt binder, aggregate gradation, FAA, CAA, F&E, and L.A. of RAP aggregate. The only way to get the above information is to separate the asphalt binder from the aggregates. Solvent extraction (Figure 2.3), nuclear asphalt content gauge (Figure 2.4), pycnometer method, automatic recordation method, and ignition method (Figure 2.5) have been used for separation of binder and aggregate. In the nuclear asphalt content gauge, a neutron source, such as Americium-241: Beryllium, is placed inside the gauge and the nuclear detector counts the number of hydrogen atoms in the asphalt binder. The number of hydrogen present in the asphalt binder is proportional to asphalt content. It is noticeable that water also contains hydrogen atom and will affect nuclear asphalt content measurements. Since the nuclear asphalt content gauge does not separate asphalt binder and aggregate, it cannot be used to determine properties of aggregate. Solvent extraction and ignition oven are the most widely used methods, which can determine both binder content and aggregate gradation (Oliver et al. 1996).

Figure 2.3. Typical set-up for extraction and recovery of binder by a rotovapor

Figure 2.4. Nuclear asphalt content gauge

Figure 2.5. Ignition furnace

In the solvent extraction method, a solvent, such as ethylene chloride or trichloroethylene, is used to dissolve and separate asphalt from the mineral aggregate. Asphalt content is calculated from the difference in the mass before and after the extraction. In the ignition method, the mix sample is heated to 538oC for 30 to 40 minutes until all the asphalt is burned off. The mass difference before and after ignition is determined as the asphalt content. The main disadvantage of the solvent extraction method is to have a high standard deviation of test results (Brown et al. 1994). The disadvantage associated with the ignition method is the degradation of aggregate because of combustion in oven. Research has shown that when RAP is burned off for extraction of binder, FAA, bulk specific gravity, and absorption properties of the aggregate are changed (Prowell and Carter, 2000). Solvent extraction and the Abson recovery method must be followed if the properties of asphalt binder are desired. However, the solvent extraction method is widely banned in many countries because one of the solvents used is Trichloroethylene which is hazardous to man and environment. Peterson et al. (1999) showed that the amount of binder content extracted differs by 0.3% to 0.5% when comparing different extraction methods using solvents. According to NCAT (1996), the ignition method is accurate and precise. ASTM D2172 “Standard Test Methods for Quantitative Extraction of Bitumen from Bituminous Paving Mixtures” can be used for extraction of bitumen while recovery of asphalt from the solution can be done following the Abson method (ASTM D1856, “Standard Test Method for Recovery of Asphalt From Solution by Abson Method”) or the Rotavapor Apparatus (ASTM D5404). According to McDaniel et al. (2000) after evaluating the methods for extraction and recovery of asphalt, the centrifuge extraction method (ASTM D2172, Method A) appeared to be the most likely candidate for solvent extraction and N-Propyl-Bromide was identified as the best alternative to trichloroethylene. Stroup and Nelson (2001) found that N-Propyl-Bromide solvents can be used as direct replacements for the chlorinated solvents historically used for hot mix asphalt extraction and binder recovery. The reflux method of extraction (ASTM D2172, Method B) appeared to cause an increase in the solvent aging, so this method was discarded. Both the Abson recovery method and the Rotavapor method (ASTM D5404, Standard Practice for Recovery of Asphalt from Solution Using the Rotary Evaporator) can be used for recovery of asphalt cement from solvent.

Asphalt millings contain approximately 5% to 7% asphalt (NJDEP, 2001). Peploe (2006) found that the recovered binder contents of millings obtained from different pavement sources in New Zealand varies from 4.1% to 5.9%.

2.4. RAP Aggregate Tests

Properties of aggregate structure are complex and they are technically classified into three groups: source aggregate properties, consensus aggregate properties, and aggregate gradation (Prowell et al., 2005). Source aggregate properties include soundness, toughness of aggregate, and deleterious material contained. These properties depend on properties of parent rock. Toughness of the aggregate is determined by Los Angeles Abrasion Test (ASTM C131 “Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine”). SHRP recommends characterization of aggregate consensus properties including FAA, CAA, F&E ratios of coarse aggregate particles, and clay content (McGennis et al., 1995). Clay content is difficult to determine in the case of RAP. The properties of RAP aggregate including gradation, consensus aggregate properties (excluding clay content), L.A. abrasion, and specific gravity are discussed below.

2.4.1 Gradation of RAP Aggregate

The gradation analysis is used to determine aggregate particle size distribution. The aggregate gradation is one of the most influential properties associated with the control of HMA mixes. Roberts et al. (1996) found that gradation affects every important HMA property including stiffness, stability, durability, permeability, workability, fatigue resistance, and resistance to moisture damage. The rutting characteristics of pavements are also controlled by asphalt cement and aggregate gradation. The standard gradation and sieve analysis can be conducted according to AASHTO T27 and ASTM C136 “Sieve Analysis of Fine and Coarse Aggregate”.

The aggregate gradation of processed RAP in HMA mixes is finer and denser than virgin aggregate because of mechanical degradation of aggregate by milling or crushing during pavement removal, and processing of RAP. Millings are a term referred to describe the material that is produced by the milling process when it removes the existing pavement material. Both milling and crushing cause degradation of RAP aggregate, however, RAP obtained from milling is finer than RAP obtained from crushing. It has been found that RAP aggregate generally meets the ASTM requirements based on ASTM D692 “Coarse Aggregates for bituminous pavement mixtures” and ASTM D1073 “Fine Aggregate for Bituminous Pavement Mixtures”. The particle size distribution of a milled pavement may vary to some extent depending on the type of aggregate in the pavement and the type of equipment used to produce the RAP. The particle size distribution also depends on whether any underlying base or sub-base aggregate has been mixed in with the reclaimed asphalt pavement material during the pavement removal and/or pavement degradation during service and processing of RAP. Generally, all RAP produced are milled or crushed down below 1.5” or less with a maximum allowable top size of either 2” or 2.5” (http://www.tfhrc.gov/hnr20/recycle/waste/rap131.htm). Table 2.2 presents a typical range of grain size distribution for RAP.

Studies on pavements in California, Utah, North Carolina, and Virginia have shown that before and after milling, the material fraction passing a 2.36 mm (No.8) increased from a pre-milled range of 41 to 69% to a post-milled range of 52 to 72%. The fraction passing a 0.075 mm (No. 200) sieve increased from approximately 6 to 10% to 8 to 12% (Kallas, 1984).

Table 2.2. Typical range of particle size distribution for reclaimed RAP
(http://www.tfhrc.gov/hnr20/recycle/waste/rap131.htm)

Sieve Size	Percent Finer after Processing or Milling
37.5 mm (1.5 in)	100
25 mm (1.0 in)	95 - 100
19 mm (3/4 in)	84 - 100
12.5 mm (1/2 in)	70 - 100
9.5 mm (3/8 in)	58 - 95
75 mm (No. 4)	38 - 75
2.36 mm (No. 8)	25 - 60
1.18 mm (No. 16)	17 - 40
0.60 mm (No. 30)	10 - 35[a]
0.30 mm (No. 50)	5 - 25[b]
0.15 mm (No. 100)	3 - 20[c]
0.075 mm (No. 200)	2 - 15[d]
a. Usually less than 30 percent	
b. Usually less than 20 percent	
c Usually less than 15 percent	
d. Usually less than 10	

2.4.2 Specific Gravity

Specific gravity is one of the important properties of aggregate and HMA and used for the volumetric analysis of the HMA mixes. Several methods are available to evaluate specific gravity of aggregate, i.e., the traditional saturated surface dry method, the CoreLok method, the height diameter method, and the core reader method. Williams (1981) performed the above-mentioned specific gravity tests on 25.0 and 37.5-mm nominal maximum size aggregates (NMASs). Results of these tests indicated that specific gravity obtained from the traditional saturated surface dry method exhibited the lowest degree of variation. The Gamma ray method is also used to determine specific gravity of aggregates. The standard test methods for determining specific gravity of coarse and fine aggregates are described in ASTM C127 and ASTM C128, respectively. The specific gravity of coarse and fine aggregates can also be determined by KT-6 (Kansas Standard) Procedure 1 and Procedure 2, respectively.

There are two methods available for determining the specific gravity of RAP aggregates:

Method 1: RAP aggregate is obtained after a solvent extraction or ignition oven procedure. The aggregate is sieved into coarse and fine aggregate fractions. Specific gravity tests are conducted on individual fractions following ASTM C127 and ASTM C128. The combined specific gravity is then determined. The disadvantage of this method is that the extraction procedure may change the specific gravity of the aggregate. However, Mallick et al. (1998) found that the difference in the specific gravity between virgin and ignition-burned aggregates is insignificant.

Method 2: This method uses the properties of RAP and binder to determine the theoretical specific gravity of the RAP aggregate. Once the binder content of RAP is determined, the effective specific gravity of the RAP aggregate can be calculated as follows (NCHRP, 2001):

$$G_{se} = \frac{100 - P_b}{\frac{100}{G_{mm}} - \frac{P_b}{G_b}}$$

Where:

G_{se} = effective specific gravity of aggregate;

G_{mm}= theoretical maximum specific gravity of the paving mixture from the AASHTO T209 test;

P_b = RAP binder content at which the AASHTO T209 test is performed (percent by total mass of mixture); and

G_b= specific gravity of RAP binder.

Once G_{se} is calculated, G_{sb} can be calculated by assuming the absorbed binder content (P_{ba}) based on the past experience on the same virgin aggregate as follows (NCHRP, 2001):

$$G_{sb} = \frac{G_{se}}{\left(\frac{P_{ba} \cdot G_{se}}{100 \cdot G_b}\right) + 1}$$

Where:

P_{ba}= absorbed binder (percent by weight G_{sb} of aggregate);

G_{se}= effective specific gravity of aggregate;

G_{sb}= bulk specific gravity of aggregate; and

G_b = specific gravity of RAP binder.

The disadvantage associated with this method is that one has to assume the absorbed binder content in the aggregate and determine the binder content of the mix. The exact binder content of RAP is hard to know, and the estimate of the absorbed binder content may not be accurate.

2.4.3 L.A. Test

RAP aggregate must be tough and abrasion resistant enough to prevent crushing, degradation, and disintegration when placed with pavers, compacted with rollers, and subjected to traffic loadings. Aggregates lacking sufficient toughness and abrasion resistance may cause construction and performance problems. There are a number of test methods available to evaluate toughness and abrasion resistance, however, the survey of specifications of different state transportation agencies indicated that 94 percent of the states use the Los Angeles abrasion test (Wu et al., 1998). The standard Los Angeles abrasion test is included in AASHTO T96 and ASTM C131 "Resistance to Degradation of Small- Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine". When RAP aggregate does not have adequate toughness, it may cause premature structural failure and/or loss of skid resistance of the pavement. Lack of abrasion resistance also produces excessive dust particles which ultimately may cause environmental pollution. There is no standard L.A. abrasion specification for the Superpave mix design. The L.A. value varies from state to state; however, the typical value ranges from 25% to 55%. For Stone Matrix Asphalt (SMA), AASHTO specifies a maximum value of 30%. Figure 2.6 presents the statistical data from 49 states (Maine uses the micro-duval), FHWA, Federal

Aviation Administration (FAA), and California District 2 specifications for a total of 52 "agencies".

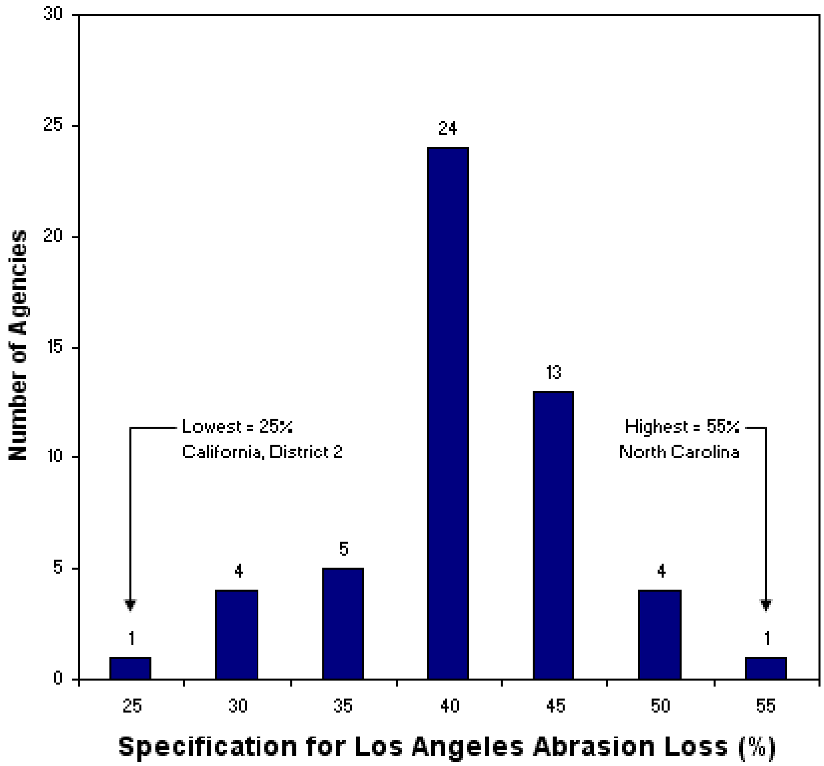


Figure 2.6. Agency L.A. abrasion specifications

Ahmad et al. (2004) performed research on degradation and abrasion of RAP aggregate in Malaysia. This study was focused on aggregates extracted from RAP from both full-depth recovery and milling, which could cause degradation to the aggregates. This study concluded that the aggregate obviously degraded by further refinement of aggregate size but still retained substantial strength to resist wear and abrasion. This study also showed that milling and scrapping caused degradation of aggregate, which is finer and denser than virgin aggregate, and the milling caused more degradation of aggregate than the full depth recovery.

2.4.4 CAA

Coarse aggregate angularity (CAA) is determined manually by visually inspecting a small sample of coarse aggregates, separating the sample into the aggregates with or without fracture faces, and counting the number of aggregates with fractured faces in the sample. Angularity is the measure of degree of roughness and sharp angle of aggregate particles. Angular particles are desirable in HMA mix because they tend to lock together and resist deformation after initial compaction, however, rounded particle may not produce sufficient inter-particle interlocking to prevent pavement deformation or rutting. The percentage of weight of the aggregates with fractured faces to the total weight of the sample is CAA. CAA is used to ensure adequate aggregate interlock and prevent excessive deformation under loading. A minimum percentage of CAA is specified to achieve improved durability for aggregate used in surface treatments and to obtain increased friction and texture for aggregates used in pavement surface courses. The standard CAA test procedure is described in AASHTO TP61 and ASTM D5821 "Standard Test Method for Determining the Percentage of Fractured Particles in Coarse Aggregate". Uncompacted void content is another measure to evaluate coarse aggregate angularity. The higher the uncompacted void content indicates a higher CAA. Table 2.3 presents the CAA requirements based on the expected axle load in the design lane for a 20-year period.

Table 2.3. Coarse aggregate angularity specifications for Superpave mixes

20-yr ESALs (millions)	Depth from Surface	
	= 100 mm (4 inches)	> 100 mm (4 inches)
< 0.3	55/-	-/-
0.3 to < 3	75/-	50/-
3 to < 10	85/80	60/-
10 to < 30	95/90	80/75
= 30	100/100	100/100

The number before "/" is a minimum requirement for one or more fractured faces and the number after "/" is a minimum requirement for two or more fractured faces.

2.4.5 FAA

Fine aggregate angularity (FAA) is also important for the same reasons as for CAA. An excessive amount of rounded particles in fine aggregate can lead HMA to rutting. FAA is quantified by measuring loose uncompacted void content of a fine aggregate sample. This test ensures that a blend of fine aggregates has adequate angularity and texture to resist rutting. The uncompacted void content indicates relative angularity and surface texture of the sample. The rounded particles are easy to compact, however, angular particles tend to lock up and offer resistance to compaction. The higher uncompacted void content indicates more angular particles in the sample. It is believed that higher FAA will result in a stable HMA mix if other properties are satisfactory. FAA test was developed by National Aggregate Association (NAA). ASTM C1252 (also AASHTO T304) "Uncompacted void content of fine aggregate" is available for determining fine aggregate angularity. Although the uncompacted void content test has been extensively used for estimating aggregate angularity and texture, there are some limitations associated with this method. The paving and aggregate industries have found that cubical shape particles even with 100 percent fractured faces may not meet the FAA requirement for high volume traffic (Chowdhury et al., 2001). Hence, other alternative methods were developed to estimate degree of angularity of aggregate including (1) the test methods for characterizing aggregate shape, texture, and angularity (NCHRP 4-30), (2) the compacted aggregate resistance (CAR), and (3) the aggregate imaging system. Table 2.5 shows the FAA requirements based on the expected load in the design lane for a 20-year period. The typical value of uncompacted void content for fine aggregates ranges from 38% to 52%.

Table 2.4. Specification of uncompacted void content of fine aggregate for Superpave mixes

20-yr ESALs (millions	**Depth from Surface**	
	= 100 mm (4 inches)	**> 100 mm (4 inches)**
< 0.3	-	-
0.3 to < 3	40	40
3 to < 10	45	40
10 to < 30	45	40
= 30	45	45

2.4.6 F&E Particles

According to the KDOT specification, flat and elongated (F&E) particles are defined as aggregates with a length to thickness ratio equal to or greater than five. An excessive amount of F&E particles in the HMA mix may lead to production, placement, and compaction problems. Current Superpave mix design allows maximum 10% F&E particles for the aggregate coarser than 4.75 mm (No.4 sieve size) when using the F&E ratio of 5:1. The test can be conducted following ASTM D 4791 "Flat Particles, Elongated Particles, or Flat and Elongated Particles in Coarse Aggregate."

2.5. Binder Test and Aging

While designing asphalt mixtures containing RAP, RAP aggregate is blended with virgin aggregate at different sizes to meet the requirement for aggregate gradation for a specific project. A binder content is selected based on the Superpave design philosophy that maximizes the strength of the HMA mix and satisfies agency-specified volumetric criteria of compacted mixes to fulfill durability requirement. The amount of virgin binder to be added to the blend is determined by taking into account the binder already present in the RAP. Hence, a successful design of asphalt mixture containing RAP will depend on the precise determination of aggregate gradation and binder content. In addition, the performance of the mixture containing RAP is known to be governed by properties of aggregate as shape and texture. Shape and texture of aggregates are known to affect the interlocking characteristics of mixture and pavement rutting. The performance of a road containing RAP is also known to be dependent on the change in the properties of binder and RAP because of aging. The aging is reflected in the change in rheological properties of asphalt, such as decrease in the penetration value and increase in viscosity. The following factors are reported to contribute the age hardening of asphalt during mixing and/or service (Vallegra et al., 1957 and Finn and Fred, 1967):

- **Oxidation:** Oxidation is the process in which oxygen reacts with hydrocarbon molecules of asphalt cement, producing a heavier branched chain structure causing hardening of asphalt cement with time. The rate of hardening due to oxidation depends on the characteristics of the asphalt cement and the temperature. Oxidation makes the pavement more brittle to result in cracking and raveling of pavements.
- **Volatilization:** Volatilization is the evaporation of the lighter oils, or volatiles from the asphalt cement. It usually does not contribute to long-term aging in the pavement and is primarily a function of temperature.
- **Polymerization:** It is a combination of like molecules to form a large molecule to cause progressive hardening.
- **Thixotropy:** It is also progressive hardening caused by formation of a structure within the asphalt cement over a period of time, which can be destroyed to a certain degree by reheating and remolding the material.
- **Syneresis:** Syneresis is hardening of asphalt by exudation of lighter constituents.

- **Separation:** The removal of oil constituents and resins by adsorptive aggregate, is called separation.

Asphalt binder demonstrates two stages of aging: short term and long term. Short-term aging occurs during construction stage when the asphalt binder is exposed to hot air at high temperature, causing significant increase in viscosity and changes in other rheological properties. Long-term aging occurs during service stage through various above-mentioned mechanisms. The level of aging also depends on the void content of HMA. Test results showed that recovered binder from porous HMA had significantly higher stiffness than regular HMA (Kemp and Predoehl 1981). Additionally, the properties of aged binder depend on the level of damage to the recycled pavement (Smilijanic et al., 1993). Since damaged highways have more oxidation susceptibility, they are more affected by aging.

The properties of aged binder are affected by the level of moisture damage on the existing highway before recycling. In principle, stripped HMA should not be recycled, since the problem is likely to occur in the new HMA (Karlsson and Isaacsson, 2006). However, when small amount of RAP (15%) used with anti-strip agent, the mix produced significantly higher strength than that using only virgin material (Amikhanian and Williams 1993). The result gathered in this study also indicated that the mix containing 15% RAP did not display more moisture susceptibility than the virgin mix. Some other researchers indicated that RAP materials might in fact provide stronger moisture resistance than virgin HMA because the aggregates are already covered and protected with binder (Karlsson and Isaacsson 2006). Aging can be accelerated by stockpiling as the material is more prone to air exposure (McMillan and Palsat, 1985).

The rheological behavior of aged binder differs from virgin binder because asphalt binder reacts and loses some of its components during the aging process and hence affects the PG grade. Therefore, care should be taken while designing a mix using RAP. If the RAP binder is too stiff, the blend between aged and virgin binders cannot perform as expected. At a small percentage of RAP (up to 20%), an aged binder does not significantly affect the properties of the blend of virgin and RAP binders (Kennedy et al., 1998). According to the FHWA Superpave Mixtures Expert Task Group guideline for the use of RAP, up to 15% RAP could be used with no change in the binder grade. When 16 to 25% of RAP is used, the virgin binder grade should be decreased by one increment (6 degrees) on both the high and low temperature grades. If more than 25% RAP is used, blending charts should be used to determine the amount of RAP that can be used.

It was observed that compressive strength and stiffness of the mix increased and the ductility decreased as the amount of RAP binder was increased (Soupharath, 1998). Lee et al. (1999) evaluated the mechanical and rheological properties of asphalt binders containing RAP binders. In their study, two virgin binders (PG 58-28 and PG 64-22) were blended with 0, 10, 20, 30, 40, 50, 75, and 100% recycled asphalt binders obtained from two different stockpiles. Dynamic Shear Rheometer (DSR) testing was carried out according to AASHTO TP5-93 on recycled and virgin binders. It was found that the recycled binder could be as much as 10 times stiffer than the virgin binder. This study also found that rheological stiffness values for a reclaimed binder obtained from one asphalt plant RAP stockpile were 10 times higher than those for a recycled binder obtained from a different RAP stockpile located in the same region. In addition, there was variability in rheological stiffness of a recycled binder obtained from the same source but different time. An axial compression test following ASTM D1074-93 on asphalt binder blends at 22°C revealed that recycled binders were twice as stiff as virgin binders but they yielded at same or nearly same strain. High stiffness is good for rutting but not so good for cracking. Lee et al.'s analysis did not indicate whether the above-mentioned differences were statistically significant or not. Therefore, it is necessary to study the hardening of asphalt because the mechanisms of asphalt binder hardening are thought to be contributing factors responsible for asphalt pavement thermal and fatigue cracking failures.

The aging of mixture containing RAP occurs at a slower rate than that of virgin mixture (Kiggundu et al. 1985). Many methods have been developed to examine and simulate the field actual aging process of the asphalt mixture. Rolling Thin Film Oven (RTFO) test is used to simulate short-term aging and Pressure Aging Vessel (PAV) is used to simulate long-term aging. A binder aging that occurs during the service life of a pavement is simulated by PAV. In this test, binder is subjected to heat (100^{o}C) and pressure (2.07MPa) for 20 hours to simulate long-term aging. Resulted viscosity of a paved asphalt binder is approximately 8+ times the viscosity of the un-aged asphalt binder (http://www.asphaltinstitute.org/lab_services/Indiv_Binder_Tests_List_New.asp).

2.6 Blending of RAP and Virgin Binders

The degree of blending of aged and virgin binders is one of the major concerns related to the performance of HMA mixes. It has been observed that when a low percentage of RAP is used (up to 10%), the change in binder grade is negligible. At a higher percentage (e.g. 40%), the effect of the RAP becomes pronounced. The research has shown that aged binder behaves neither like black rock nor full blending between aged and virgin binders (Al-Qadi et al., 2009).

Huang et al. (2005) analyzed the blending process of different percentages of screened RAPs with virgin mixtures through a controlled experiment. The results from this experiment showed that only a small portion of aged asphalt in RAP was blended with the virgin mixture, however, other portions formed stiff coating around RAP aggregates and RAP functionally acted as “composite black rock”. They also found that a layered system in RAP helped to reduce the stress concentration of HMA mixtures and enhance the pavement performance.

2.7 Softening and Rejuvenating Agents

Softening agents are used to lower the viscosity of aged binders. Asphalt flux oil, lube stock, and slurry oil are common softening agents. Asphalt binder ages during service and causes an increase in its viscosity and stiffness. Rejuvenating agents are used to restore the properties of aged binders to a condition that resembles to virgin binders. Recycling agents are divided into three broad categories: “super-soft” asphalt cements, napthenic (aromatic) oils, and paraffin oils. ASTM D4552 “Standard Practice for Classifying Hot-Mix Recycling Agents” provides the classification for recycling and rejuvenating agents while ASTM D4887 “Standard Practice for Preparation of Viscosity Blends for Hot Recycled Bituminous Materials” provides the procedure for selecting a quality cement or recycling agent. Using ASTM D4887, one can determine the percentage of a recycling or rejuvenating agent to be added to the total binder to achieve a specified value of absolute viscosity. Properties of a rejuvenating agent must be such that the RAP asphalt will have the same properties as the virgin asphalt with the least addition of a modifier possible (Dunning et al., 1978). During an aging process, asphalt binder loses its oil constituent resulting in high proportion of asphaltenes. Asphaltenes are molecular substance found in asphalt. Dunning et al. (1978) found that the modifier should contain polar and aromatic compounds. They recommended minimum 9 and 60% of polar and aromatic compounds in a rejuvenating agent and they also found that paraffin and saturate content must be kept as low as possible because their presence tends to flocculate asphaltenes.

As shown in Figure 2.7, recycling agents reduce the viscosity of the binder. Figure 2.7 was plotted based on the absolute viscosity of each combination by blending various percentages of No.2, No. 8, and No. 10 oils with asphalt cement recovered from RAP.

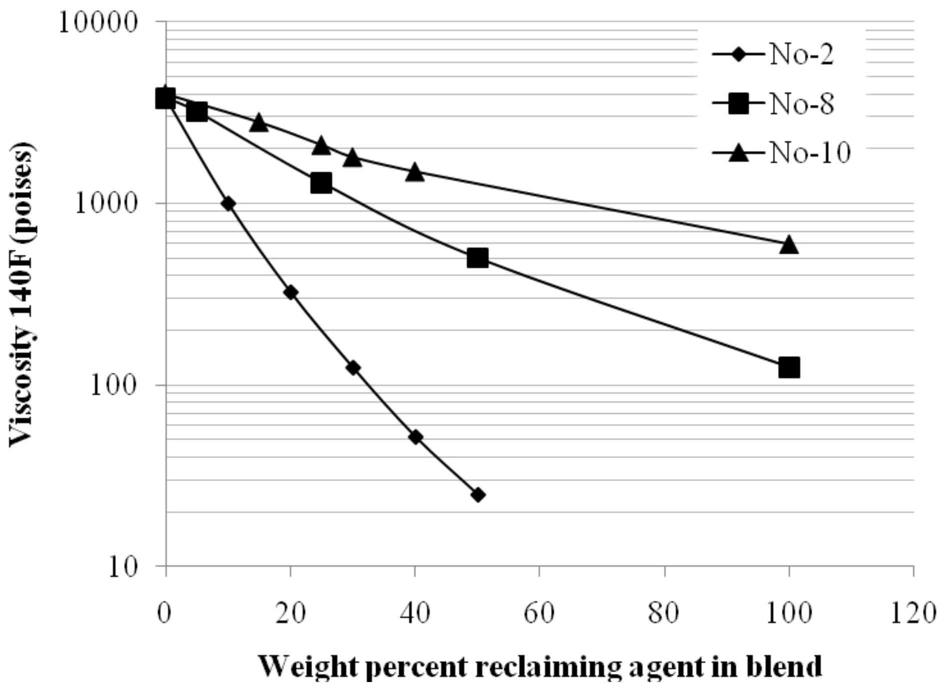


Figure 2.7. Effects of recycling agents on viscosity of asphalt

Shen et al. (2007) investigated the effects of recycling agents on Superpave mixtures containing RAP. A total of 12 Superpave mixtures, ten containing RAP and two virgin binders, were designed. The results indicated that the properties of the asphalt mixtures using a recycling agent were better than those containing a softer binder based on Asphalt Pavement Analyzer (APA) and Indirect Tensile Strength (ITS) tests. They concluded that more than 10% RAP can be incorporated in the Superpave mixtures by using a recycling agent than using a soft binder. The recycling agent content required for recycling can be determined from the blending charts established under the Superpave binder specification. Chen et al. (2007) found that a recycling or rejuvenating agent generally causes a reduction in stiffness of an aged binder by reducing the complex modulus.

Romera et al. (2006) found that aged bitumen needed a high mixing temperature (>200^{o}C) to behave like a fluid material, which is able to wet, adhere, and envelope aggregate. They concluded that an addition of rejuvenating agents considerably reduced mixing and compaction temperatures.

Carpenter and Wolosick (1980) found that a blending process between an aged binder and a recycling agent did not take place solely during mixing and compaction. Instead, a diffusion process between a recycling agent and an aged binder took place over a certain period of time. Carpenter and Wolosick (1980) also concluded that the diffusion process had a large influence on the HMA properties. Another method to soften the aged binder is to mix it with a softer grade virgin binder. Selection of a virgin binder grade depends on the amount of RAP to be used and the desired final grade of the blend.

2.8 Variability Study of RAP

One of the main concerns while incorporating a large percentage of RAP in HMA mixes is variability. Since RAP can be obtained from different kinds of pavements, i.e., hot-in-place recycle, cold-in-place recycle, modified slurry seal, novachips, modified slurry seal, maintenance overlays, and crack sealant etc., it is obvious that the composition of RAP from different sources varies. The exact composition and properties of milled RAP materials depend on a number of variables: such as age of mix, type of mix, properties of bitumen used in the mix, configuration and performance of the milling process, and clipping of underlying layers during the milling. When a virgin mixture is incorporated with RAP, it is hoped that the resulting mixture gives comparable results with regard to a conventional virgin mix. However, limited studies have been performed to determine the uniformity of RAP materials within the asphalt mixture as well as the uniformity of RAP itself. Few test methods are available to determine if the mixture is homogenous once the RAP is introduced into the mixture. The uniformity of aggregate can be determined by comparing gradation, specific gravity, coarse aggregate angularity, and fine aggregate angularity. The uniformity of binder can be evaluated by using parameters, such as fatigue parameter (G*sin (δ)), complex modulus (G*), and phase angle (δ°). These parameters can be obtained from direct shear rheometer tests.

Lee et al. (1983) carried out a study to quantify the plant mixing efficiency of asphalt mixtures with incorporation of RAP. Their results showed that the performance of the recycled mix mainly depends upon how well the recycled asphalt interacts with the virgin aggregate and asphalt binder. Literature review shows that there is very little information regarding the mixing process and mixing efficiency. According to Lee et al. (1983), mixing efficiency is the degree of attainment of equilibrium with respect to rate and cost. It means that there should be a uniform distribution of ingredients from sample to sample of a batch as well as within the sample itself. Mixing efficiency is generally measured by appearance of bituminous mixtures in terms of distribution and coating. The determination of the mixing efficiency becomes difficult when rejuvenating agents and virgin materials are mixed. This problem was resolved by Lee et al. (1983) using a “Dye Print Technique”. They found that the plant mixtures were mixed efficiently. The use of this technique has proven to be an effective method for determining the uniformity of RAP within the virgin mixture.

Solaimanaian and Tahmoressi (1996) conducted a research to determine the variability of RAP that existed in a stockpile (Figure 2.8) in the plant-produced hot mix asphalt concrete containing 35% to 50% RAP. They provided statistical information on RAP variability and its influence on HMA concrete through data analysis. In this research, four construction projects were selected; two of the projects used 35% RAP, while the other two used 40% and 50% RAP. Different test results, such as gradation of aggregate, asphalt content, air void, penetration and viscosity, and stability, were included in their analysis. Figure 2.9 shows the variations in gradation obtained in their research. When a high percentage of RAP was used, a higher variation in gradation was observed as shown in Figure 2.10. It was also found that RAP from different sources had different variability in gradation. Additionally, the results from this research indicated higher variability in air voids as the amount of RAP was increased. Figure 2.11 shows the changes in the viscosity of the binder from the RAP and plant mix. An increase in viscosity and a decrease in penetration value of the extracted binder were observed.

Figure 2.8. Stockpiling of RAP
(http://www.fhwa.dot.gov/pavement/recycling/rap/index.cfm)

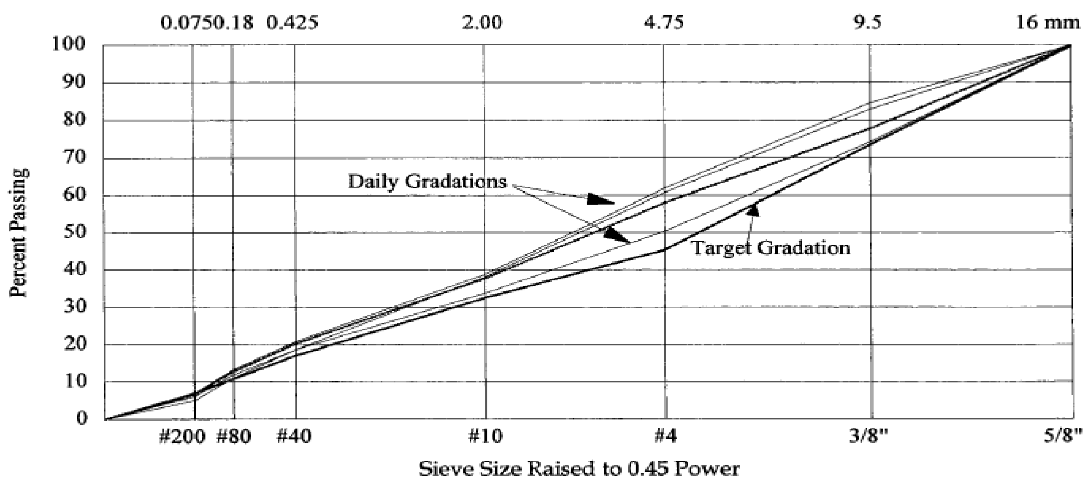


Figure 2.9. Daily gradations from extraction

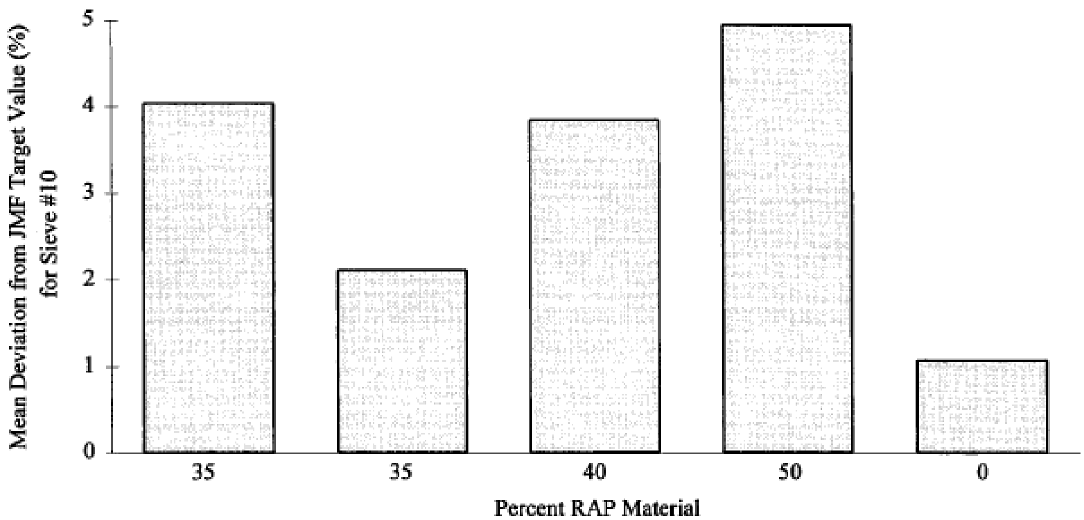


Figure 2.10. Mean deviations from Job Mix Formula (JMF) for Sieve #10

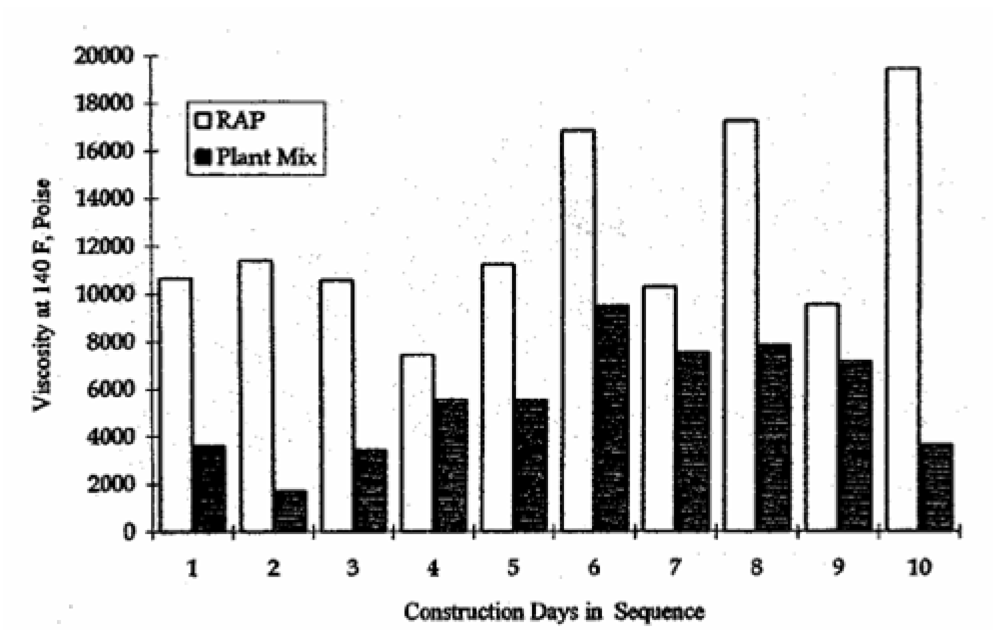


Figure 2.11. Sample daily viscosities

Table 2.5 shows that RAP obtained from road cores were highly variable and the aggregate gradation became finer after milling and processing.

Table 2.5. RAP compositions of cores and stockpiles

Location of roads		**% passing 2.36 mm**		**% passing 0.075 mm**		**Asphalt Cement Content**	
	n	ave.	σ_{n-1}	ave.	σ_{n-1}	ave.	σ_{n-1}
California Road Cores	12	54	8.30	9.9	2.01	5.4	0.71
California Stockpiled after Milling	5	69	6.50	11.8	0.34	5.2	0.04
North Carolina Road Cores	12	69	3.20	6.1	0.66	5.7	0.11
North Carolina Stockpiled after Milling	5	72	0.90	8.0	0.11	5.7	0.11
Utah Road Cores	12	52	3.80	8.7	2.60	6.5	0.28
Utah Stockpiled after Milling	10	58	2.80	9.9	1.15	6.2	0.44
Virgina Road Cores	12	41	2.10	9.7	0.79	5.3	0.20
Virginia Stockpiled after Milling	6	52	1.10	13.0	0.30	5.2	0.12
Average σ of HMA Surface Course			2.81		0.94		0.28

Huang and Vukosavljevic (2006) conducted a laboratory study on fatigue characteristics of HMA surface mixtures containing RAP. Four types of mixtures were used in this study which consisted of limestone and gravel with different types of binder (PG 64-22, PG 70-22, and PG 76-22). Each of the mixtures contained 0, 10, 20, and 30% RAP. The mixture containing 0% RAP was used as a controlled mixture. Different tests including resilient modulus, indirect tensile strength, dissipated creep strain, semi-circular bending, beam fatigue, asphalt mixture uniformity, and screened RAP uniformity were done to characterize fatigue cracking of pavements. They found that the variability of screened RAP can greatly affect the mixture property of virgin mixtures. Screened RAP uniformity testing was conducted by evaluating both binder and aggregate. All of the asphalt binder used for the evaluation of mixture uniformity was obtained using the AASHTO T319-03 extraction and recovery method. The aggregate properties were evaluated by gradation, specific gravity, and fine aggregate angularity tests. Gradation tests were done according to AASHTO T 30-93 while the tests for specific gravity and fine aggregate angularity of RAP aggregates were done according to AASHTO T 84-00 and T 85-91 and AASHTO T 304-96, respectively. The binder of the RAP was evaluated through DSR testing where its fatigue properties (G*sin (Delta)), complex modulus (G*), and phase angle (delta) were determined and evaluated according to AASHTO T 315-05. In order to resist fatigue cracking, an asphalt binder should be elastic but not too stiff. Hence, the viscous portion of the complex shear modulus G*sin (delta) should be a minimum. For sieve analysis, materials were obtained from four job sites: CNC 294, CNC 297, CNC 302, and CNC 186. Three samples were obtained from each job site. Figure 2.12 shows no significant difference in the gradation of the aggregates from the stockpiles located at each site. There was slight variation in the gradation between stockpiles at different job sites. Figure 2.13 shows the change in specific gravity and FAA of RAP aggregates from different job sites. There was no significant difference in FAA and specific gravity between the three samples collected from different places of the same stockpile; however, there was slight variation in specific gravity and FAA between different job sites. Figure 2.14 shows that the binder from the job site CNC 302 had higher values of complex modulus and G*sin (delta) than those from other job sites. Complex shear moduli (G*) and G*Sin (delta) of different samples from the same stockpile were nearly same. According to the Superpave specification, G*sin (delta) of a binder should be less than or equal to 5000 kPa. Figure 2.15 shows that the phase angle of the binder from the job site CNC 302 was significantly smaller than that from other job sites. A slight difference in the phase angle of the binders for three samples from the same stockpile was observed.

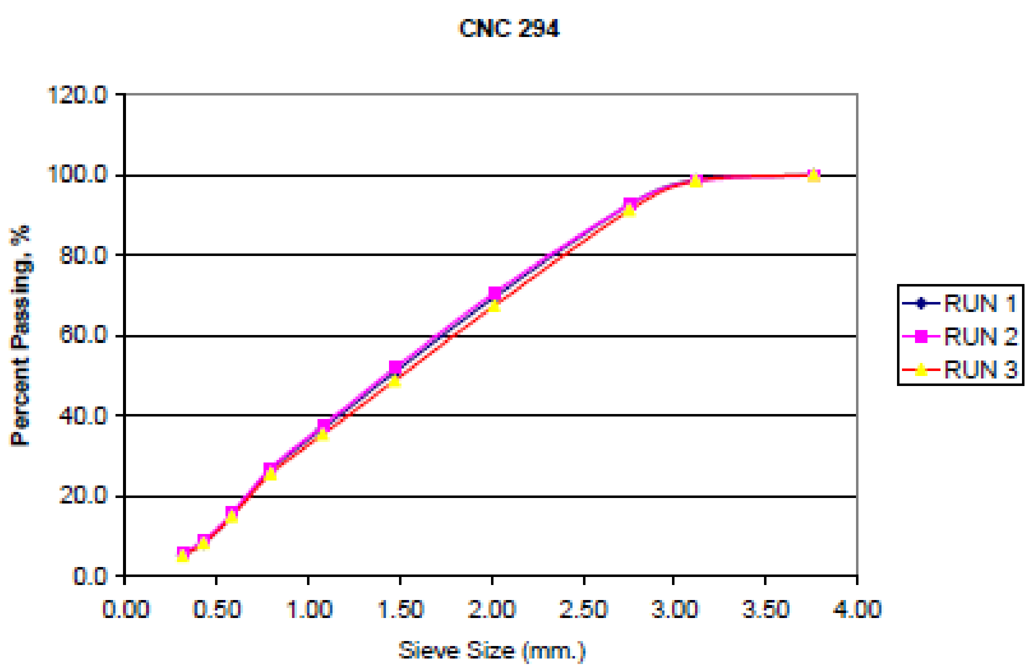


Figure 2.12. Gradation analyses for the RAP at different job sites (a)

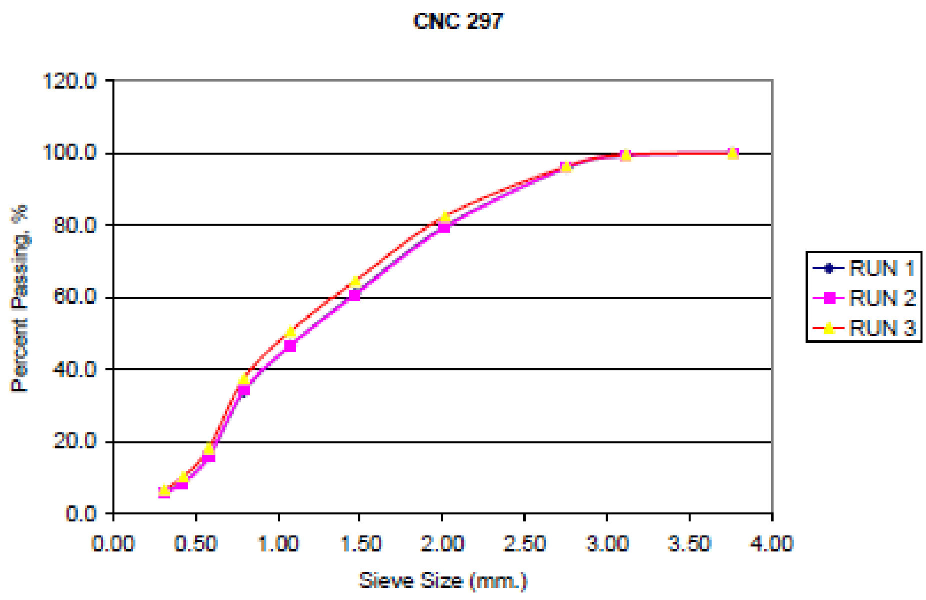
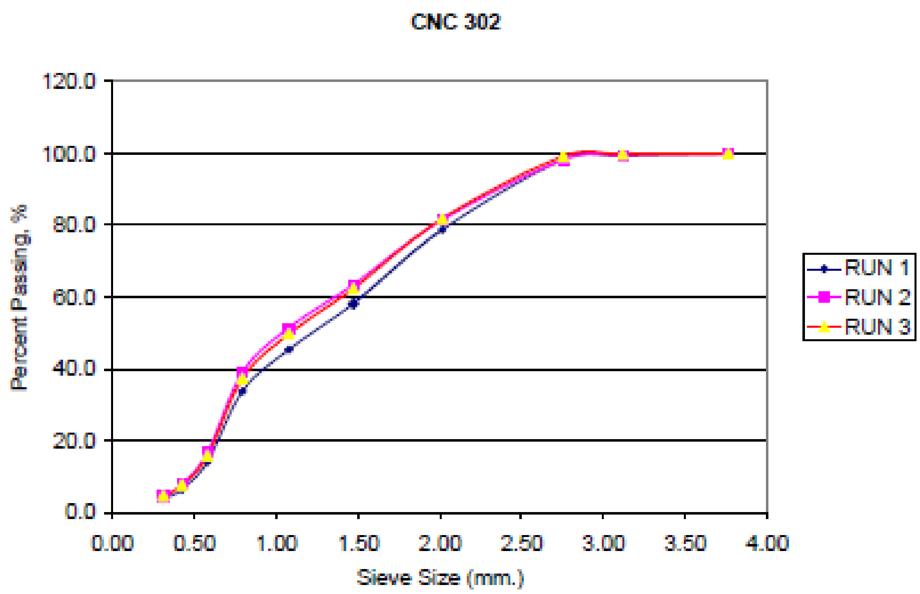


Figure 2.12. Gradation analyses for the RAP at different job sites (continued) (b)



(c)

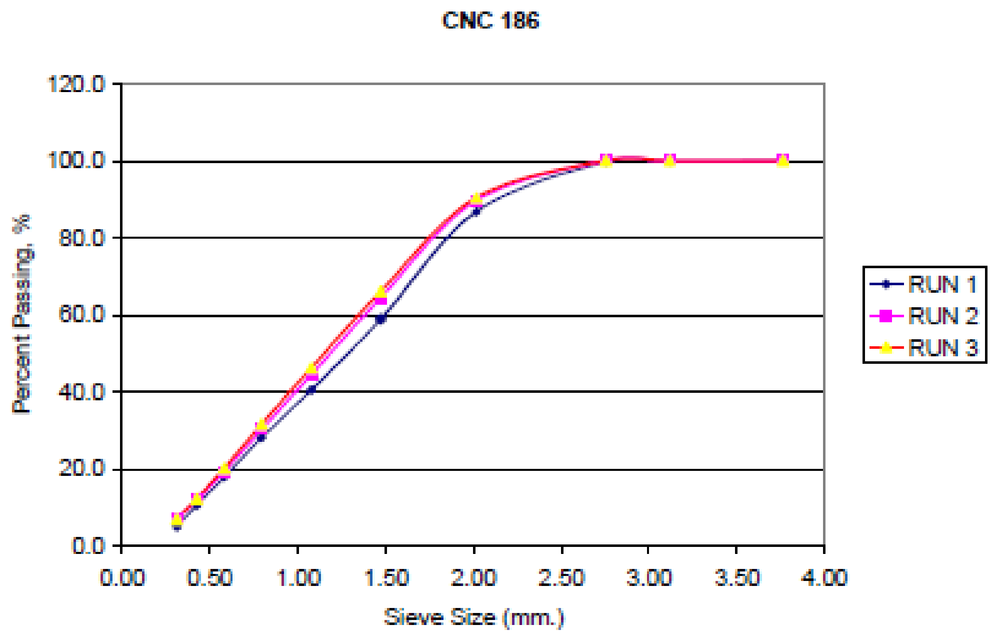


Figure 2.12. Gradation analyses for the RAP at different job sites (continued) (d)

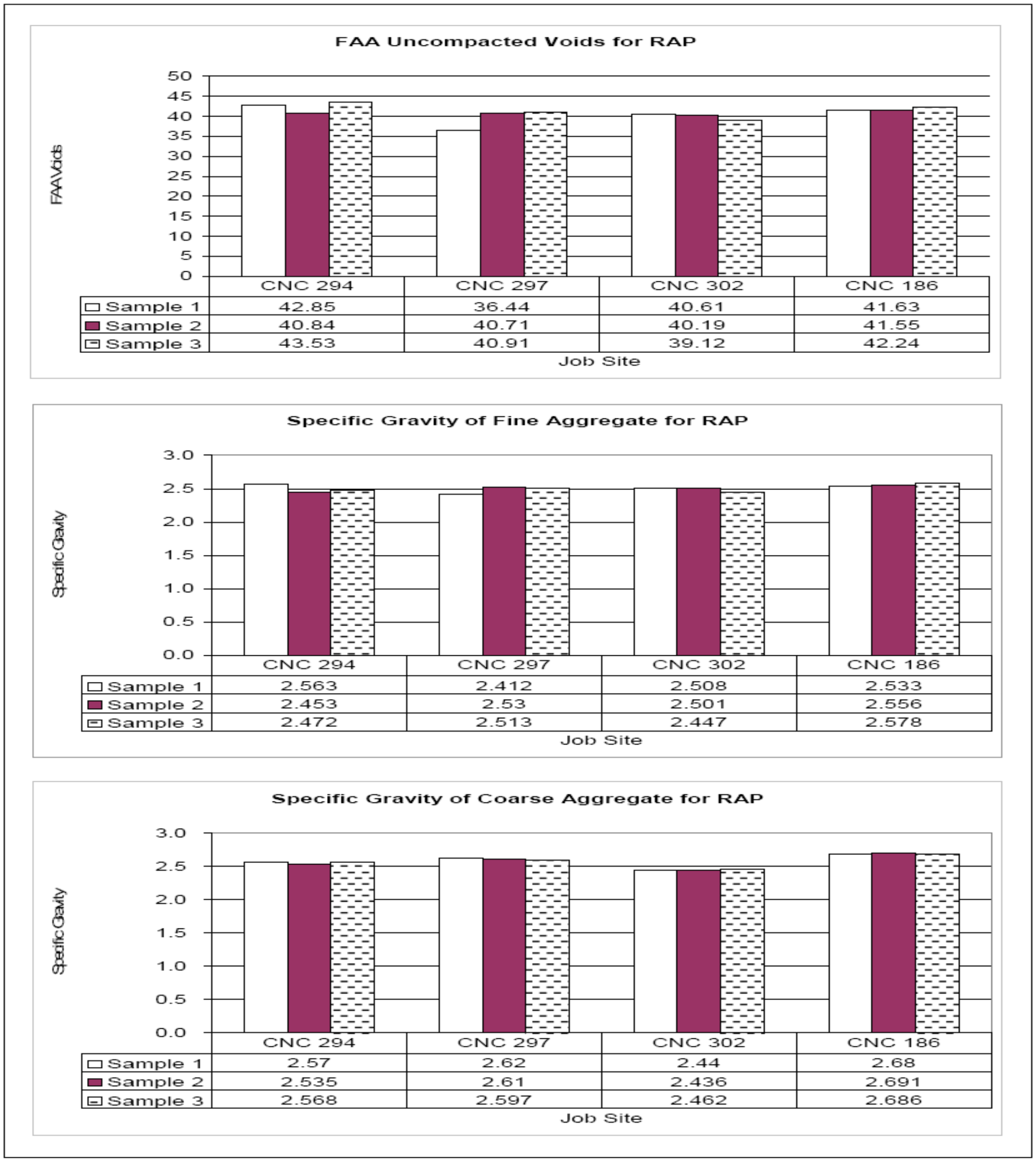


Figure 2.13. SG and FAA of RAP from different job sites

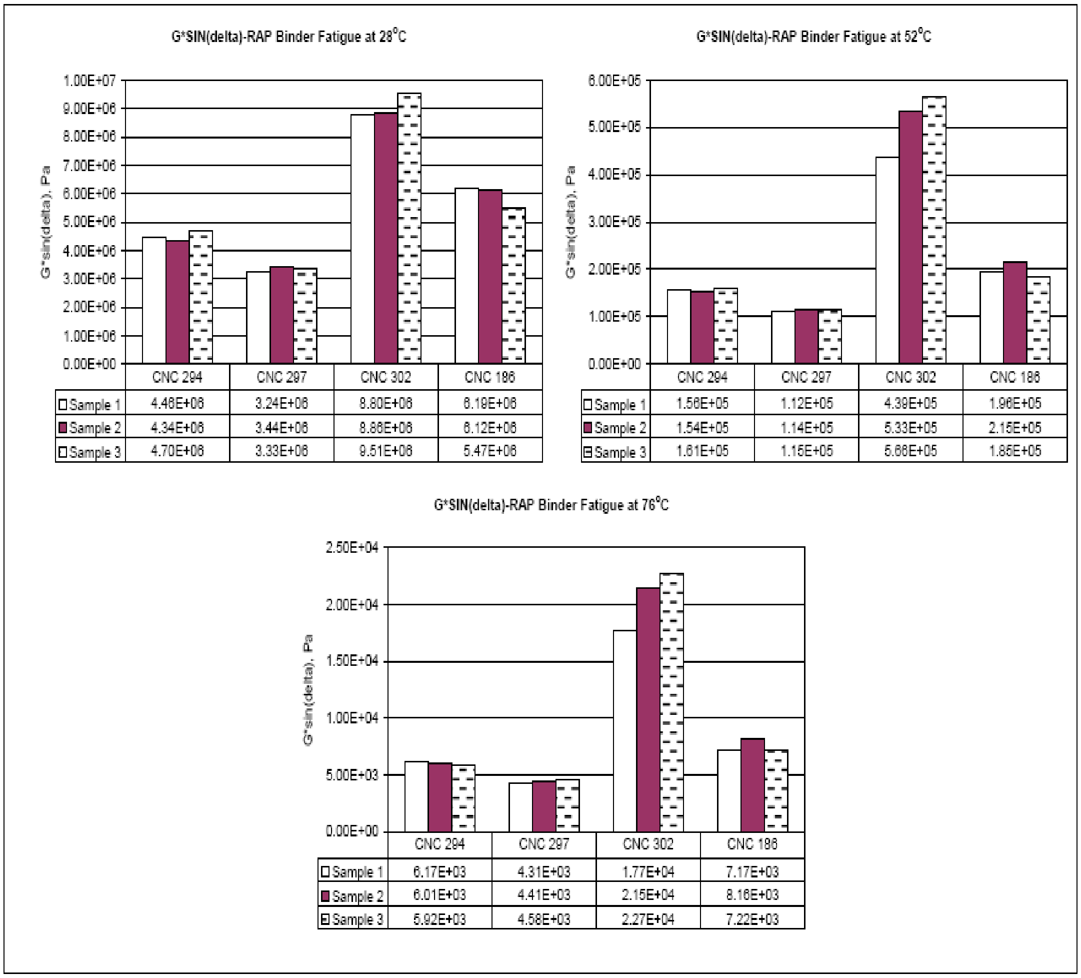


Figure 2.14. G*sin (delta) for different job sites

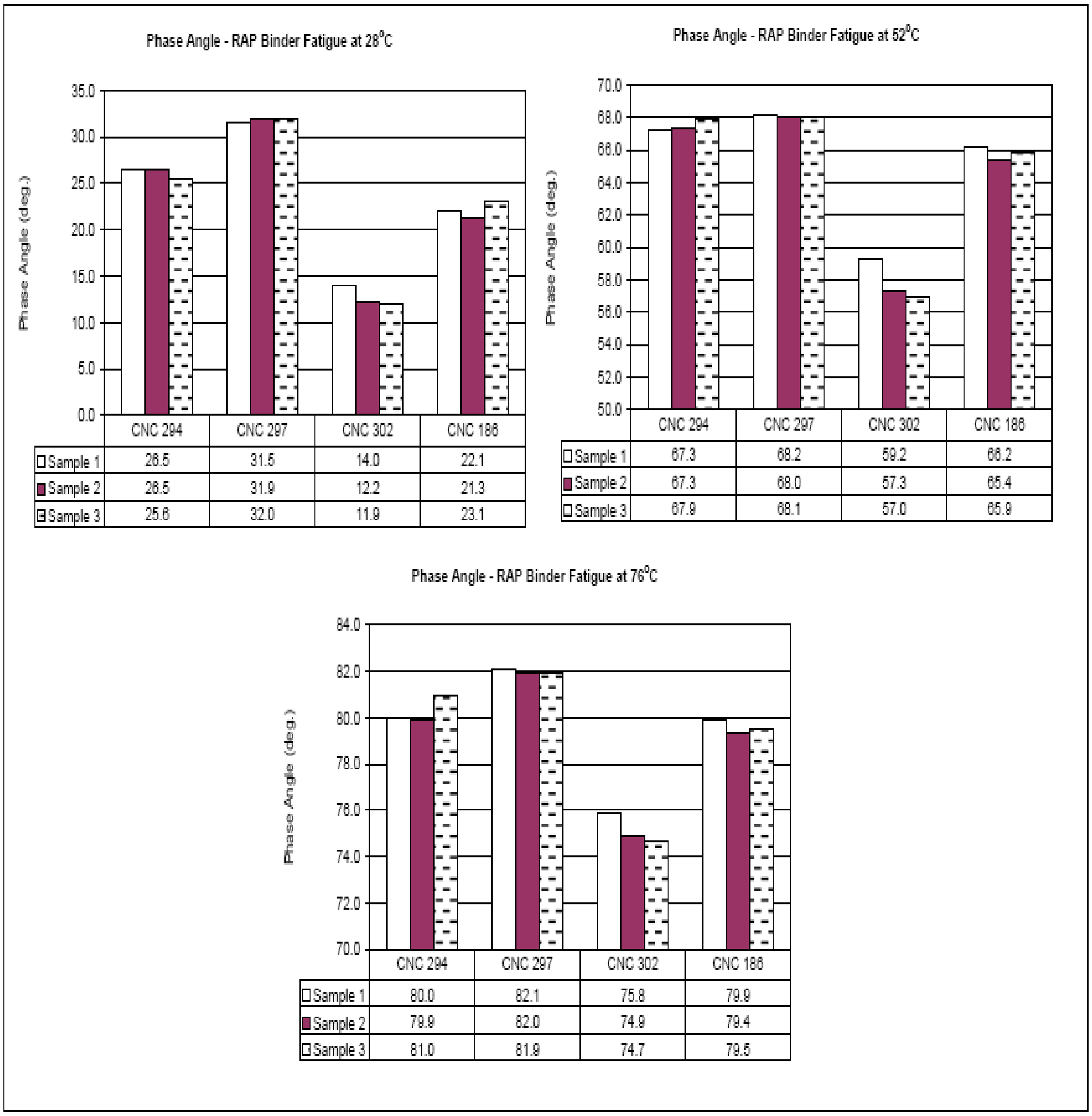


Figure 2.15. Phase angles of RAP at different job sites

The following conclusions were made from this study:

- Semi-circular bending results showed similar results as IDT tests. For the mixture with limestone, incorporation of RAP reduced the toughness index and increased the tensile strength of the mix. There was no significant difference in the test results when 0 to 10% RAP was used. When 20 and 30% RAP was added, the tensile strength significantly increased and the strain at peak load decreased. An increase in the percentage of RAP made the mix stiffer and more brittle, which resulted in a decrease of their fatigue life.

- To investigate the uniformity of aggregates from RAP, gradation, specific gravity, and FAA tests were conducted. These tests showed that the RAP aggregate was uniform within stockpiles as well as between stockpiles of each job site in this study. For the uniformity of the recovered binder, G*, G*sin (delta), and delta were evaluated. RAP from one job site had a significantly stiffer binder as compared with that from other job sites.

Variability of RAP can be controlled by treating the RAP like the material from another stockpile, practicing good stockpile management, and processing of the RAP if needed. Contractors should stockpile the millings from different sources at separate places to minimize variability of the material. Solaimanain and Tahmoressi (1996) suggested that the use of a higher percentage of RAP should be limited or restricted until a method is available to reduce the mix variability at the higher percentage of RAP.

2.9 Effect of Ignition Testing on Aggregate Properties

Ignition furnace is most commonly used to extract aggregate from RAP. Therefore, it is necessary to study the effect of ignition on different properties of aggregate. Mallick et al (1998) studied the effects of the ignition furnace on gradation, bulk specific gravity, absorption, FAA, and fracture face count for four aggregate types. Their study showed that particular aggregate properties were significantly affected and the effects appeared to be aggregate-specific. Table 2.6 shows the effect of burning on bulk specific gravity, absorption, gradation, and National Aggregate Association (NAA) uncompacted void content of granite aggregate. It is shown that that the bulk specific gravity of coarse and fine aggregates decreased slightly after burning. However, the absorption of fine and coarse aggregates increased. The NAA uncompacted void content decreased after burning aggregate only, however, it remained nearly the same for the burned mix. This study also revealed that percent passing through 4.75 mm and 0.075 mm sieves did not change significantly after ignition for granite aggregate. It should be noted that the changes in the properties for the burnt aggregate only and the burnt mix are different. The reason for this difference is because the amount of heat produced in each case was different.

Hall and Williams (1999) investigated the effect of the ignition method on physical properties of aggregate including gradation and specific gravity. Specimens were obtained from three hot mix plants in Arkansas. They did not find any significant difference in aggregate gradation after ignition as shown in Table 2.7. However, a slight decrease in specific gravity of coarse aggregate was measured after the aggregate was subjected to the ignition as shown in Table 2.8.

Table 2.6. Bulk specific gravity, absorption, percent passing through 4.75 mm and 0.075 mm of granite aggregate before and after ignition

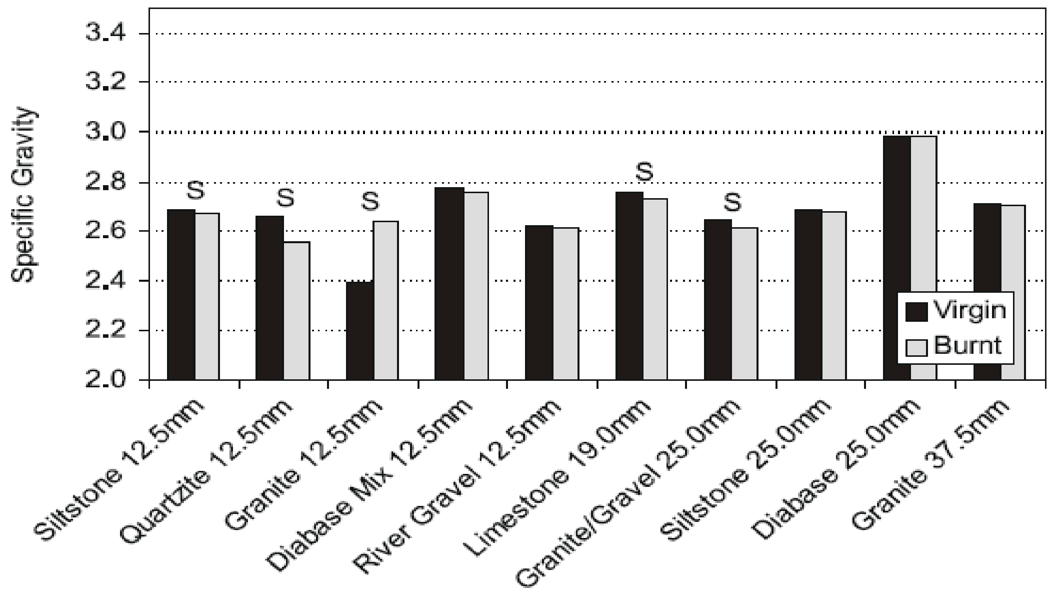
Description	Virgin average	Burnt aggregate average	Burnt mix average
Bulk specific gravity of coarse aggregate	2.688	2.680	2.653
Absorption of coarse aggregate,%	0.583	0.673	1.277
Bulk specific gravity of fine aggregate	2.659	2.687	2.640
Absorption of fine aggregate,%	0.627	0.467	1.020
Percent passing 4.75 mm sieve	56.0	56.6	56.7
Percent passing .075 mm sieve	4.0	4.1	5.8
NAA uncompacted void of fine aggregate	49.5	46.4	49.5

Table 2.7. Gradations of selected blends

	Delta Asphalt 19.0 mm medium		APAC 19.0 mm medium		L.J. Earnest 10.0 mm medium	
Sieve (mm)	Before	After	Before	After	Before	After
25.0	100.0	100.0	100.0	100.0	100.0	100.0
19.0	100.0	100.0	100.0	100.0	100.0	100.0
12.5	88.8	88.1	98.4	98.6	88.6	88.0
9.5	74.4	74.0	72.7	71.9	73.1	72.6
4.75	50.8	50.7	54.2	54.8	46.5	46.0
2.36	31.0	3.7	33.7	33.9	30.5	31.2
1.18	22.3	21.9	22.7	22.6	21.7	21.4
0.60	16.0	15.6	12.7	12.7	15.3	15.1
0.30	8.7	8.5	7.0	7.1	10.8	10.5
0.15	5.8	5.7	4.9	5.1	4.7	4.7
0.075	4.15	4.08	3.92`	4.05	2.73	2.65

Blend	Bulk Sp. Gr. Before Ignition	Bulk Sp. Gr. After Ignition	Difference	Percent Change
Delta 19mm Medium	2.577	2.531	-0.046	-1.79 %
Delta 25mm Coarse	2.688	2.622	-0.066	-2.46 %
A.P.A.C. 12.5mm Medium	2.615	2.592	-0.023	-0.88 %
A.P.A.C. 19mm Medium	2.649	2.597	-0.052	-1.96 %
A.P.A.C. 25mm Medium	2.677	2.612	-0.065	-2.43 %
Texarkana 19mm Medium	2.597	2.575	-0.022	-0.85 %
Texarkana 25mm Medium	2.548	2.538	-0.010	-0.39 %
Texarkana 25mm Coarse	2.547	2.542	-0.005	-0.20 %

Prowell and Carter (2000) studied the ignition effect on Superpave consensus aggregate properties, bulk specific gravity, and gradation of the aggregate extracted from RAP using the ignition furnace for typical Virginia aggregates. They found that although there was some difference in FAA values between virgin and recovered aggregates, the ignition method resulted in a reasonable FAA for the recovered aggregate. This study also revealed that flat and elongated particles and gradation of the aggregate were not significantly affected by extraction in the furnace despite of visually observed fractures in the aggregate. The specific gravity tests carried on burnt and virgin aggregates showed that the specific gravity decreased after ignition in most of cases as shown in Figures 2.16 and 2.17.



S denotes a significant difference in the sample means at the 95 percent confidence level.

Figure 2.16. Bulk specific gravity of virgin and burnt fine aggregates

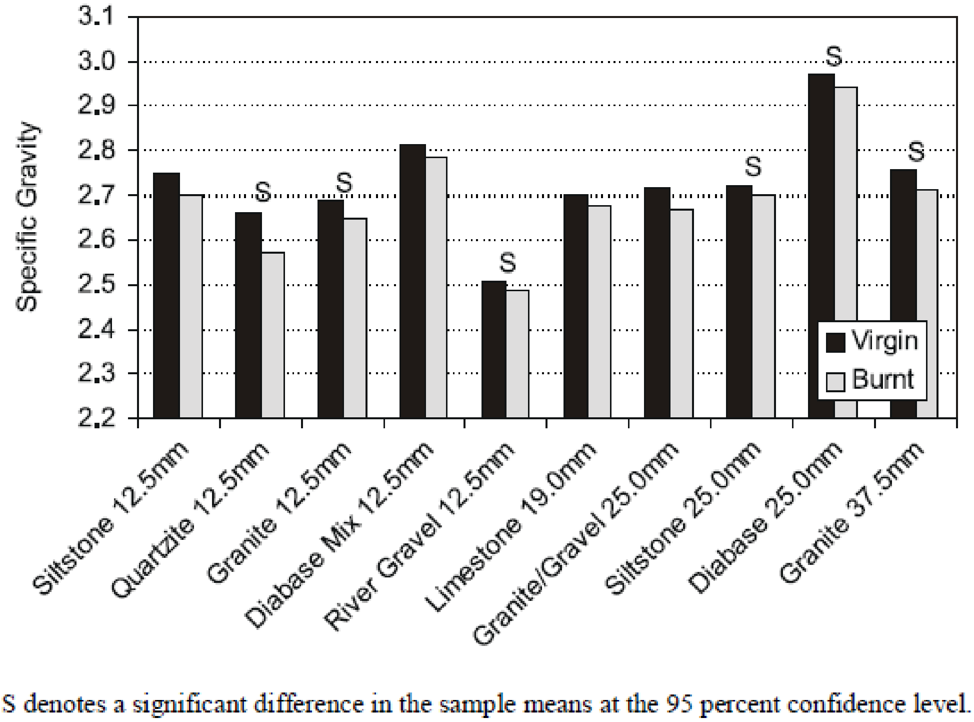


Figure 2.17. Bulk specific gravity of virgin and burnt coarse aggregates

2.10 Performance Tests on HMA Mixes Containing RAP

Distresses, such as thermal cracking, fatigue cracking, rutting, and moisture damage, develop on asphalt pavements due to environmental exposure and repeated traffic loading. Since RAP contains an aged binder, once blended with a virgin binder, it produces a stiffer mixture (Huang and Vukosavljevic, 2006). The durability or long-term fatigue resistance is a main concern when large quantity of RAP is used in pavement surface or load carrying layers. The incorporation of large quantity of RAP into a new HMA mix could cause a mixture to become too stiff which in turn, would greatly affect the fatigue performance of the asphalt mixture. Huang and Vukosavljevic (2006) conducted a research to determine the maximum percentage of RAP that can be incorporated without affecting the performance of mixture. In their study, 0, 10, 20, and 30% RAP were included. They concluded that long-term aging of a binder increased the stiffness of the mixture and in return affected its resistance to fatigue cracking. At a higher percentage of RAP, the mixture became stiffer and the fatigue characteristics of RAP were compromised. They found that 20% RAP could be included without compromising fatigue characteristics based on testing of field TDOT surface mixtures. The mixtures consisted of two types of aggregates (limestone and gravel) and three types of binders (PG 70-22, PG 64-22, and PG 76-22). The fatigue properties of the mixtures could also be affected by in-efficient mixing and non-uniform dispersion of RAP materials.

2.11 Change in Mechanistic and Volumetric Properties after Inclusion of RAP

Daniel and Lachance (2005) conducted research to study the change in mechanistic (strength and durability) and volumetric properties with the addition of RAP. Mixtures containing 15%, 25%, and 40% RAP were compared with a control mixture only containing virgin materials. Two types of RAP were used, one processed and another unprocessed (millings). For the processed RAP, VMA and VFA values for the mixtures with 25% and 40% RAP were higher than those for the control and the mixture with 15% mixtures. In case of millings, VMA values increased with the percentage of RAP. The VFA also increased with increase in percentage of RAP.

The VFA values for all the mixtures with RAP were higher than the control mixture. When 15% RAP was used, the stiffness of the mixture was increased whereas the creep compliance decreased. The increase in the stiffness indicated that the mixture would be more resistant to deformation but less resistant to thermal and fatigue cracking. For a mixture containing 25 and 40% RAP, the dynamic modulus and creep compliance were similar to those for the control mixture, which was not an expected trend. The cause for this behavior was thought to be a combination of factors influencing the behavior for these mixtures. For example, the mixture containing 25% RAP had a higher asphalt content and finer gradation than the control mixture. The mixture with 40% RAP had a finer gradation than that with 25% RAP. Additionally, the mixtures with 25 and 40% RAP had higher VMA and VFA values than those with 15% RAP and the control mixture. The combined effect was believed to cause the softening of the binder and increase the creep compliance of the mixture at a higher percentage.

2.12 Performance of Pavements Containing RAP Millings

The Washington State Department of Transportation (1985) evaluated the performance of 16 completed hot mix recycled projects. The laboratory and field data showed that the two initial projects, from Renslow to Ryegrass (constructed in 1977) and from Yakima River to West Ellensburg Interchange (constructed in 1978), were performing well until that time. The other 14 projects were constructed within 2½ years before the study. The early data from these projects also indicated equally promising results. The percentages of RAP in these projects ranged from 8% to 79%, half of them used RAP more than 70%.

In 1995, the Louisiana Department of Transportation and Development evaluated the performance of ten recycled projects (Paul, 1995). These projects contained 20% to 50% RAP and had been serviced for six to nine years. The evaluation was done in terms of pavement condition ratings, serviceability, structural analysis, and mix and binder properties (Paul, 1996). This research showed that pavements containing RAP performed similarly to those with conventional mixtures for a service period of six to nine years. However, pavements containing RAP exhibited slightly more distresses with respect to longitudinal cracking. The substitution of up to 15% RAP in the wearing courses provided acceptable performing pavements.

Ganuang and Larsen (1987) investigated the performance of hot mixed recycled pavements after 6-year service on Route 4, Burlington, Connecticut. A comparison was made between a conventional mixture and a mixture with 30% RAP. The findings from this study include: (1) no rutting was detected; (2) roughness of the pavement was low; and (3) the viscosity of the extracted asphalt was higher than that of the control mixture.

Kandhal et al. (1995) evaluated the performance of recycled hot mix asphalt in five projects in Georgia. In each project, a recycled section and a control section were investigated. The percentages of RAP used in these projects varied from 10 to 25%. In-situ mix properties, such as percent air void, resilient modulus, and indirect tensile strength, and binder properties, such as penetration, viscosity, G*sin(delta) and G*/sin(delta), were measured. A paired t-test statistical analysis showed no significant difference in these properties of virgin and recycled asphalt pavements that had been in service from 1.5 to 2.25 years. The results from additional ten virgin mix pavements and thirteen additional recycled pavements (evaluated as two independent groups) indicated no statistical difference in the penetration and viscosity of the recovered asphalt binder and virgin binder in service.

In Kansas, the first recycled hot mix asphalt project was constructed in 1978 on US-56 in Pawnee and Edward Counties (Maag and Parcells, 1982). A 210 mm recycled HMA layer was placed in 1978 after milling 135 mm of the existing cold mix asphalt pavement. The recycled HMA consisted of 50% RAP, 28% crushed limestone, and 22% gravel. Asphalt with Grade AC-5 was added at rates of 2.5% and 3% to the recycled HMA. After 11 years of service, the ride quality remained acceptable, and crack surveys conducted through 11 years indicated that the recycled HMA portion of the project had more reflected transverse and longitudinal cracks than the control section (Fager, 1990). The second recycled hot mix asphalt project was constructed on US-56 in Gray County during 1978 and 1979. 50, 60, and 70% RAP were used in the recycled HMA (Maag and Parcells, 1982). A control section of 610 m length consisting of all virgin HMA of the same thickness was also constructed (Maag and Parcells, 1982). Fager (1990) found that after 3.3 years of construction, both the recycled test section on US-56 in Gray County and the control section were performing comparably with less than 1% reflection cracking.

2.13 Summary

The cost of asphalt binder is increasing and good source of aggregate is depleting. The current market price of asphalt is $1300 to $1500/ ton in September 2008 (http://www.udot.utah.gov/main/uconowner.gf?n=3372285016471432143). According to the US Today magazine, many states, cities, and counties are forced to delay pavement maintenance projects because of rise in asphalt price. The asphalt price was 25.9% up from 2007 to 2008 (http://www.usatoday.com/news/nation/2008-06-05-asphalt_N.htm). In such a situation, the use of a high percentage of RAP is obviously beneficial.

In addition to the economic benefit, the use of a higher percentage of RAP has a environmental benefit, technical benefit, conservation of energy, conservation of aggregate and binders, and conservation of land fill space. When 15% to 30% RAP is incorporated in HMA mixes, a tiered approach should be used. However, when more than 30% RAP is added into the mixes, extensive testing on the properties of RAP aggregate and binder should be conducted. To assure the high quality and performance of HMA with an increased percentage of RAP, the characteristics of RAP, such as its composition, binder content and properties, and aggregate properties, are important. The earlier research indicated that the ignition oven method caused the change in physical properties of aggregate. The centrifuge method of binder extraction should be used in parallel to the ignition method to evaluate the effect of ignition.

The amount of virgin binder to be added into a mix should be determined by taking into account the binder already present in the RAP. Precise determination of binder content and aggregate gradation in the RAP is necessary. The gradation of aggregate from the RAP affects every important HMA property including stiffness, stability, durability, workability, fatigue resistance, and resistance to moisture damage.

Variability of RAP is one of the major concerns when a high percentage of RAP is used. Therefore, it is necessary to evaluate the variability of aggregate and binder from the RAP. The variability of the RAP aggregate includes its gradation, specific gravity, fine aggregate angularity, coarse aggregate angularity, and L.A. abrasion value. The variability of the RAP binder includes binder content, penetration, viscosity, complex shear modulus, and phase angle. Limited research has been performed by researchers on the variability of RAP but their results are not consistent.

The rheological properties of a RAP binder change because of aging due to one or more of the following factors: oxidation, volatilization, polymerization, thixotropy, syneresis, and separation. As a result of aging, a RAP binder can be as much as 10 times stiffer than a virgin binder. When more than 25% RAP is used, the blending chart should be used to determine the PG grade of a virgin binder. Softening and rejuvenating agents are used to reduce the viscosity of aged binders.

Literature review shows that no research was conducted on the change in CAA of RAP aggregate. However, CAA and FAA of aggregates are important for friction and texture of aggregates used in pavement surfaces.

The rutting performance is improved by the use of RAP, however, the effect of RAP on fatigue and thermal performance has been found inconsistent, especially when a higher percentage of RAP is incorporated into HMA mixes.

Chapter 3: Experimental Study

This chapter comprises of material characterization of aggregate and binder extracted from RAP and the test methodology used in this study.

3.1 Material Characterization

RAP Materials were collected from three KDOT project locations, namely K-25 in Grant County, K-25 in Logan County, and US-83 in Scott County for this study. The RAP material from K-25 in Grant County was composed of bituminous surface (SM-12.5A and PG64-22). The RAP material from Logan County was made up of bituminous surface (HR-2A and PG52-22) with 25% previous RAP. The RAP material from US-083 at Scott County contained the HMA surface (SR-12.5A and PG64-22) with 14% previous RAP. These materials were characterized in this study.

3.1.1 Original Mix Design

The original mix design formulas used for K-25 in Grant County, K-25 in Logan County, and US-83 in Scott County are shown in Tables 3.1, 3.2 and 3.3, and 3.4, respectively. Two mix designs were used for K-25 in Logan County, therefore, weighted average of aggregate and asphalt properties were taken into consideration.

Table 3.1. Original mix design for K-25 in Grant County

CMS [Mainframe]

DTMT254 HMA Design Mix

HMA Mix # : 6G03007A ◯E ◉M Lot # : 1 Matl Cd : 002060610 Name : SM-12.5A

Eff Date : 04 03 03 Term Date : 01 01 10 Design Avg High Temp : 35 C

	Matl Code	Name	Producer #	Name	% Blend
AC	021PG6422	PG64-22 ASPH PER GRD	00002101	VALERO (TX)	4.80
	002010312	CG-1 (CRUSHD GRAVEL)	00833301	EASTERN COLORADO AGG	20.94
	002010412	CG-2 (CRUSHD GRAVEL)	00833301	EASTERN COLORADO AGG	7.62
	002010512	CG-3 (CRUSHD GRAVEL)	00833301	EASTERN COLORADO AGG	33.32
	00201A919	SSG-1(NAT SAND GRVL)	00812809	KLOTZ SAND (047)	33.32

S PT	37.5	25	19	12.5	9.5	4.75	2.36	1.18	600	300	150	75	CA	Anglrity	FA
Virgin :				6	16	33	54	70	82	89	92	95.0	88		44
Rap :															

	Revs	% Gmm	Dens	% Voids	VMA	VFA	F/B Ratio	Film
N Dsgn :	75	96.1	2333	3.90	13.5	71.0	1.0	8.02
N MAX :	115	97.0						
N INTL :	7	89.7						

Design Easl(Mil) : 1.1

T Max Sg(Gmm) : 2.4350

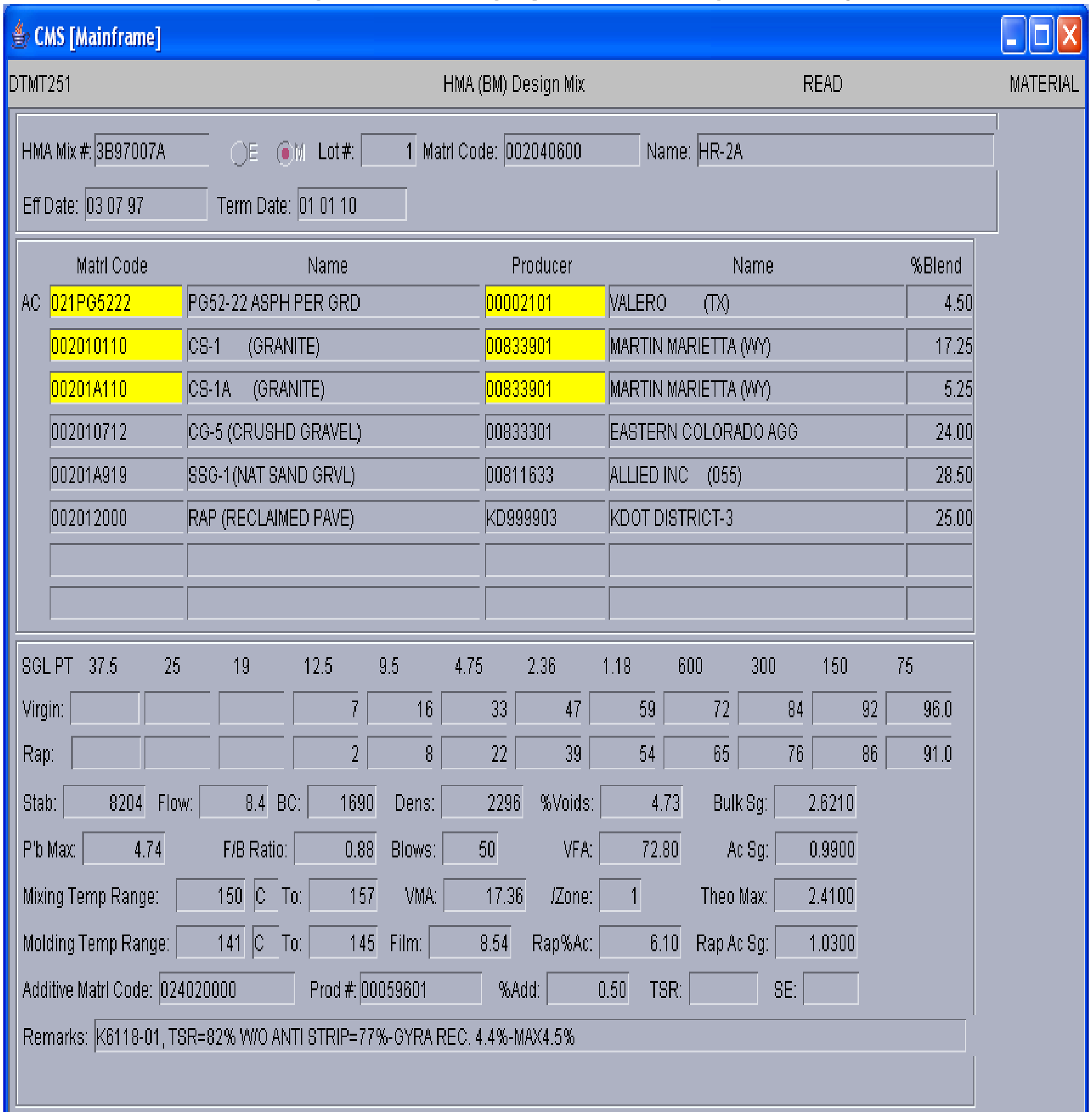
Mix Temp : 152 - 157 C % Sat : 56 TSR : 87 SE : 78 AC SG : 1.0016

Mold Temp : 142 - 146 C Rap % AC : Rap AC SG :

Additive Matl Cd : Prod # : % Add : Bulk SG : 2.5750

Remarks : 25-106 K 8876-01

Table 3.2. Original mix design for K-25 in Logan County–Mix 1



CMS [Mainframe]

DTMT251 HMA (BM) Design Mix READ MATERIAL

HMA Mix #: 3B97007A ○E ◉M Lot #: 1 Matrl Code: 002040600 Name: HR-2A

Eff Date: 03 07 97 Term Date: 01 01 10

	Matrl Code	Name	Producer	Name	%Blend
AC	021PG5222	PG52-22 ASPH PER GRD	00002101	VALERO (TX)	4.50
	002010110	CS-1 (GRANITE)	00833901	MARTIN MARIETTA (WY)	17.25
	00201A110	CS-1A (GRANITE)	00833901	MARTIN MARIETTA (WY)	5.25
	002010712	CG-5 (CRUSHD GRAVEL)	00833301	EASTERN COLORADO AGG	24.00
	00201A919	SSG-1 (NAT SAND GRVL)	00811633	ALLIED INC (055)	28.50
	002012000	RAP (RECLAIMED PAVE)	KD999903	KDOT DISTRICT-3	25.00

SGL PT	37.5	25	19	12.5	9.5	4.75	2.36	1.18	600	300	150	75
Virgin:				7	16	33	47	59	72	84	92	96.0
Rap:				2	8	22	39	54	65	76	86	91.0

Stab: 8204 Flow: 8.4 BC: 1690 Dens: 2296 %Voids: 4.73 Bulk Sg: 2.6210

P'b Max: 4.74 F/B Ratio: 0.88 Blows: 50 VFA: 72.80 Ac Sg: 0.9900

Mixing Temp Range: 150 C To: 157 VMA: 17.36 /Zone: 1 Theo Max: 2.4100

Molding Temp Range: 141 C To: 145 Film: 8.54 Rap%Ac: 6.10 Rap Ac Sg: 1.0300

Additive Matrl Code: 024020000 Prod #: 00059601 %Add: 0.50 TSR: SE:

Remarks: K6118-01, TSR=82% W/O ANTI STRIP=77%-GYRA REC. 4.4%-MAX4.5%

Table 3.3. Original mix design for K-25 in Logan County–Mix 2

CMS [Mainframe]

DTMT251 HMA (BM) Design Mix READ MATERIAL

HMA Mix #: 3B97007B ◯E ◉M Lot #: 2 Matrl Code: 002040600 Name: HR-2A

Eff Date: 06 02 97 Term Date: 01 01 10

	Matrl Code	Name	Producer	Name	%Blend
AC	021PG5222	PG52-22 ASPH PER GRD	00002101	VALERO (TX)	4.50
	002010110	CS-1 (GRANITE)	00833901	MARTIN MARIETTA (WY)	17.25
	00201A110	CS-1A (GRANITE)	00833901	MARTIN MARIETTA (WY)	5.25
	002010712	CG-5 (CRUSHD GRAVEL)	00833301	EASTERN COLORADO AGG	24.00
	00201A919	SSG-1(NAT SAND GRVL)	00811633	ALLIED INC (055)	28.50
	002012000	RAP (RECLAIMED PAVE)	KD999903	KDOT DISTRICT-3	25.00

SGL PT	37.5	25	19	12.5	9.5	4.75	2.36	1.18	600	300	150	75
Virgin:				7	16	33	47	60	73	85	92	96.0
Rap:				2	8	22	39	54	65	76	86	91.0

Stab: 8204 Flow: 8.4 BC: 1690 Dens: 2296 %Voids: 4.73 Bulk Sg: 2.6210

P'b Max: 4.74 F/B Ratio: 0.88 Blows: 50 VFA: 72.80 Ac Sg: 0.9900

Mixing Temp Range: 150 C To: 157 VMA: 17.36 /Zone: 1 Theo Max: 2.4100

Molding Temp Range: 141 C To: 145 Film: 8.54 Rap%Ac: 6.10 Rap Ac Sg: 1.0300

Additive Matrl Code: 024020000 Prod #: 00059601 %Add: 0.50 TSR: 82 SE: 68

Remarks: K6118-01, TSR=82% W/O ANTI STRIP=77%-SINGLE PT. #1.18,600,300

Table 3.4. Original mix design for US-83 in Scott County

CMS [Mainframe]

DTMT254 HMA Design Mix

HMA Mix # : 6G02006A ◯E ◉M Lot # : 1 Matl Cd : 002070610 Name : SR-12.5AM

Eff Date : 04 05 02 Term Date : 01 01 10 Design Avg High Temp : 35 C

	Matl Code	Name	Producer #	Name	% Blend
AC	021PG6422	PG64-22 ASPH PER GRD	00002101	VALERO (TX)	4.96
	002010312	CG-1 (CRUSHD GRAVEL)	00833301	EASTERN COLORADO AGG	14.26
	002010412	CG-2 (CRUSHD GRAVEL)	00833301	EASTERN COLORADO AGG	19.01
	00201A919	SSG-1 (NAT SAND GRVL)	00812602	KLOTZ SAND CO (028)	23.76
	00201D919	SSG-4(NAT SAND GRVL)	00812602	KLOTZ SAND CO (028)	23.75
	002012000	RAP (RECLAIMED PAVE)	KD999906	KDOT DISTRICT-6	14.26

S PT	37.5	25	19	12.5	9.5	4.75	2.36	1.18	600	300	150	75	CA	Anglrity	FA
Virgin :				8	14	28	47	61	76	88	94	96.1	78		42
Rap :				2	6	29	53	67	77	84	88	89.7			

	Revs	% Gmm	Dens	% Voids	VMA	VFA	F/B Ratio	Film
N Dsgn :	100	95.4	2322	4.59	14.8	69.02	0.87	8.11

Design Easl(Mil) : 4.1

T Max Sg(Gmm) : 2.4410

N MAX : 160 96.1 Mix Temp : 153 - 157 C % Sat : 56 TSR : 80 SE : 80 AC SG : 1.0208

N INTL : 8 91.7 Mold Temp : 143 - 147 C Rap % AC : 5.60 Rap AC SG : 1.0350

Additive Matl Cd : 024020000 Prod # : 00069701 % Add : 0.30 Bulk SG : 2.5980

Remarks : 86 K 8506-01

Figure 3.1 shows the original gradations of the three mixes used in K-25 in Grant County, K-25 in Logan County, and US-83 in Scott County.

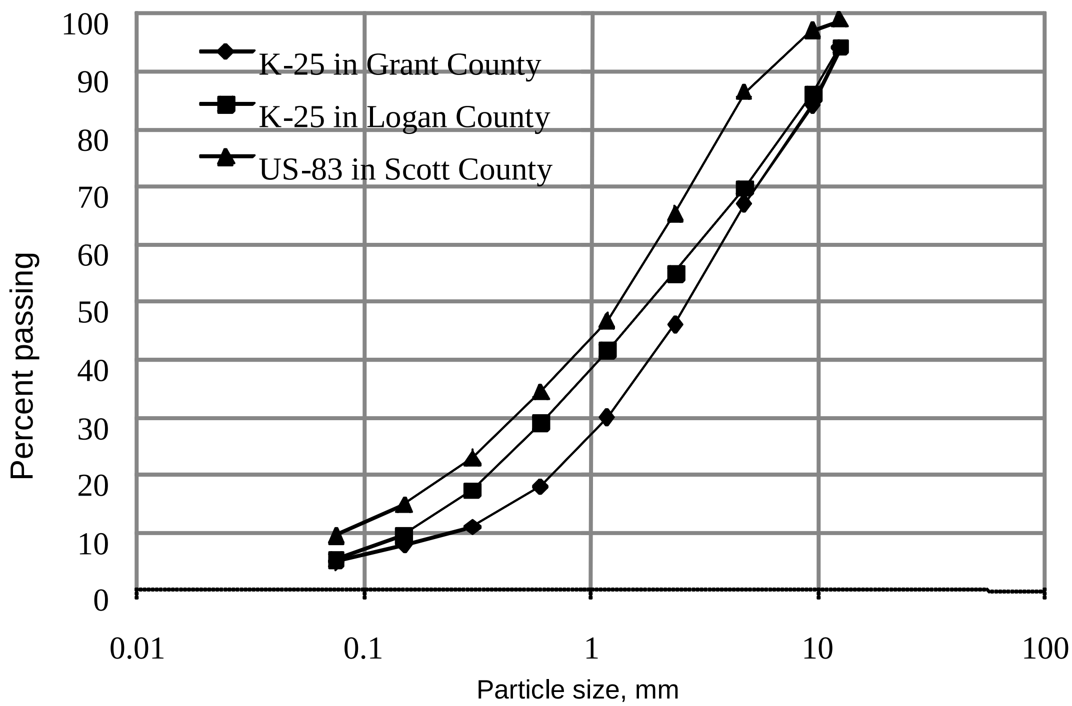


Figure 3.1. Original gradations of the mixes in K-25 in Grant County, K-25 in Logan County, and US-83 in Scott County.

3.1.2 Maintenance Histories

A 2003 chip seal and maintenance patches were applied on K-25 in Grant County as a routine maintenance.

A 2003 chip seal and many maintenance patches (BM-1 with MC-800) were applied on K-25 in Logan County as road maintenance.

The RAP from K-25 in Scott County contained two modified slurry seals in 1999 and 2004, and a BM-1B with MC-800 mix from 1990.

3.2 Test Methodology

3.2.1 Separation of Asphalt and Binder

The ignition test (ASTM D6307, "Standard Test Method for Asphalt Content of Hot-Mix Asphalt by Ignition Method") is one of the widely used methods to separate asphalt binder and aggregate by burning off asphalt at 540^{o}C. In this method, RAP is heated in an oven to burn the asphalt binder within the mixture and the difference before and after burning in the ignition oven gives a measure of the asphalt binder content. The binder content of samples from each source was determined following ASTM D6307 in this study. Eleven to twelve samples from each source were tested for the binder content. Binder and aggregate were also separated by the centrifuge method (Fig 3.2) of extraction following ASTM D2172. At the same time, the binder content was determined. Trichloroethylene of technical grade, type 1 was used as a solvent. Ashing method was used to determine the amount of minerals in the washings of the centrifuge. At least three samples from each source were tested for the binder content by the centrifuge method. The aggregates and binders extracted from the RAP were tested for the properties of aggregate and binder using the methods described below.

Figure 3.2. Centrifuge testing machine

3.2.2 Test Methods for Aggregate Properties

3.2.2.1 Gradation

RAP was sampled using the mechanical split sampler (Figure 3.3) in accordance with ASTM C702-98 Method A. After the removal of asphalt from the RAP in the ignition oven (Figure 3.4), eleven to twelve aggregate samples from each RAP source were washed (Figure 3.5) on a 0.075mm sieve, and a sieve analysis was conducted to obtain the gradation (Figure 3.6) of the aggregate in accordance with the KDOT standard (KT-34).

Figure 3.3. Sampling of RAP by the mechanical split sampler

Figure 3.4. Aggregate obtained after RAP burnt in the ignition furnace

Figure 3.5. Aggregate retained after washing fines through the 0.075 mm sieve.

Figure 3.6. Aggregate fractions after sieve analysis

3.2.2.2 Specific Gravity and Absorption

Specific gravity of aggregate is useful for weight-volume conversions. Bulk specific gravity, SSD bulk specific gravity, apparent specific gravity, and absorption of the aggregates were determined following KT-6 Procedures 1 and 2 for coarse and fine aggregates, respectively. The important steps of specific gravity tests for the fine aggregate are illustrated in the Figures. 3.7, 3.8, 3.9, and 3.10. Two samples were tested for specific gravity of the coarse aggregate; however, three samples were tested for specific gravity of the fine aggregate.


Figure 3.7. Fine aggregate in an SSD condition


Figure 3.8. Slump test to determine the SSD condition of fine aggregate

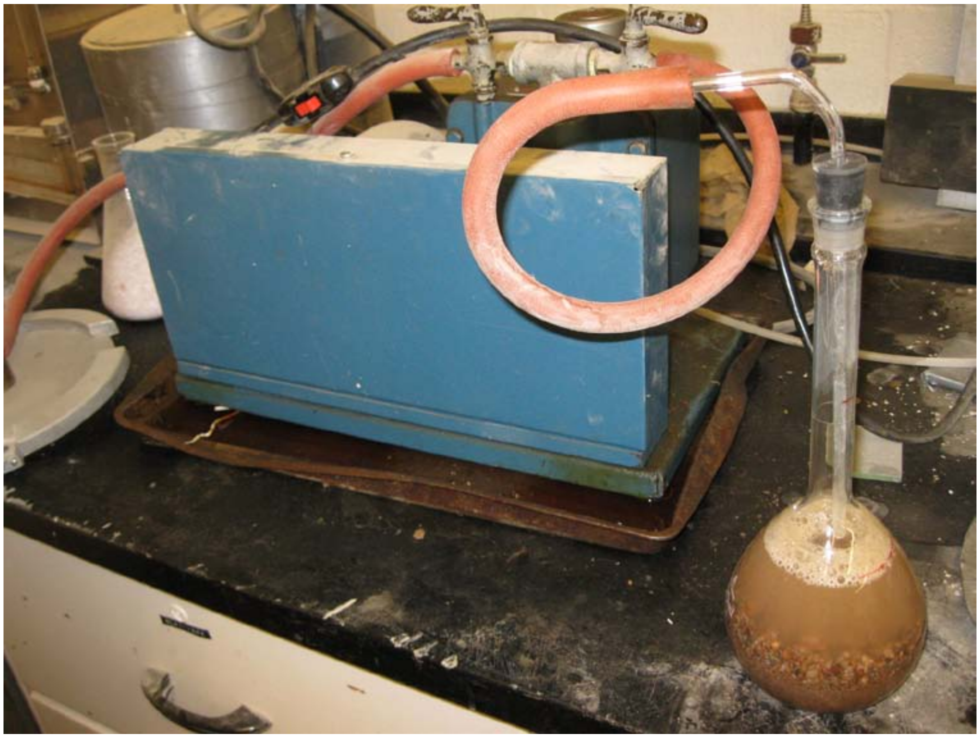


Figure 3.9. Removal of the air bubbles from the pycnometer using vacuum

Figure 3.10. Pycnometer after removal of air bubbles

3.2.2.3 FAA

The FAA test (Figure 3.11) is used to evaluate fine aggregate angularity by measuring the loose uncompacted void content in a fine aggregate sample. Six or more aggregate samples from each source were evaluated for FAA in accordance with KT-50 in this study.

Figure 3.11. FAA test set-up

3.2.2.4 CAA

The CAA test is a method of determining the angularity of coarse aggregate by visually inspecting a sample of coarse aggregates and separating the sample into the aggregates without fractured faces (Figure 3.12) and those with fractured (Figure 3.13) faces. An increase in the angularity is considered to increase the friction resistance of the aggregate. The CAA test was performed in this study using two 2.5-kg aggregate samples from each source in accordance with the KDOT standard (KT-31).

Figure 3.12. Particle without fractured faces

Figure 3.13. Particle with fractured faces

3.2.2.5 F&E

The flat and elongated (F&E) particle test is used to determine the dimensional ratios for aggregate particles of specific sieve sizes. This is the one of the consensus properties used in the

Superpave specification to identify F&E particles (Figure 3.14). The F&E particles may impede compaction and cause difficulty in meeting the Voids in Mineral Aggregate (VMA) requirement due to aggregate degradation. These flat particles have tendency to break up during compaction thus causing a change in final gradation and resulting rutting. F&E particles were determined using a proportional caliper (Figure 3.15) following KT-59 in this study. Two samples from each source were tested. Figure 3.16 shows fractions of aggregates retained on 12.5 mm, 9.5 mm, and 4.75 mm sieves. Figure 3.17 shows 100 particles of 9.5 mm and 4.75 mm sieve sizes each. It should be noted that particles retained on the 12.5 mm size was less than 10%, therefore, they were not tested for flatness and elongation.

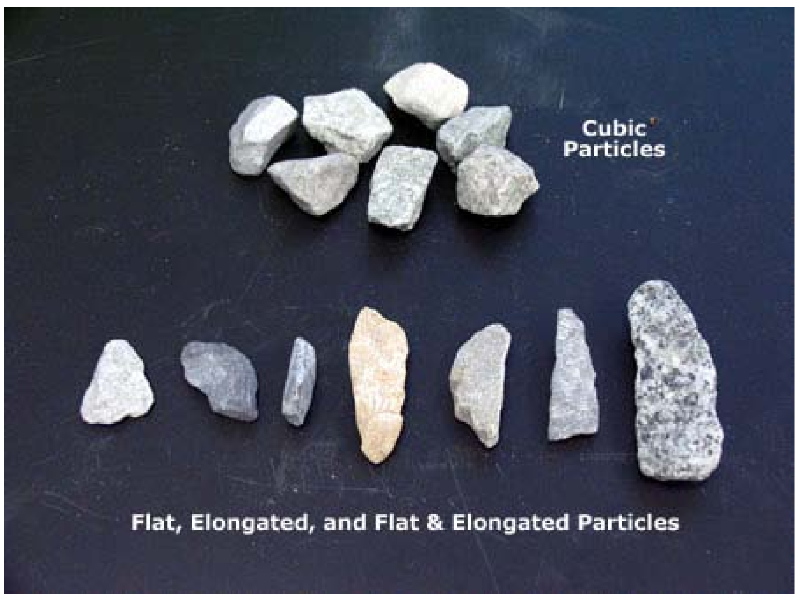


Figure 3.14. Flat, elongated, flat and elongated particles
(http://pavementinteractive.org/index.php?title=Flat_and_Elongated_Particles)

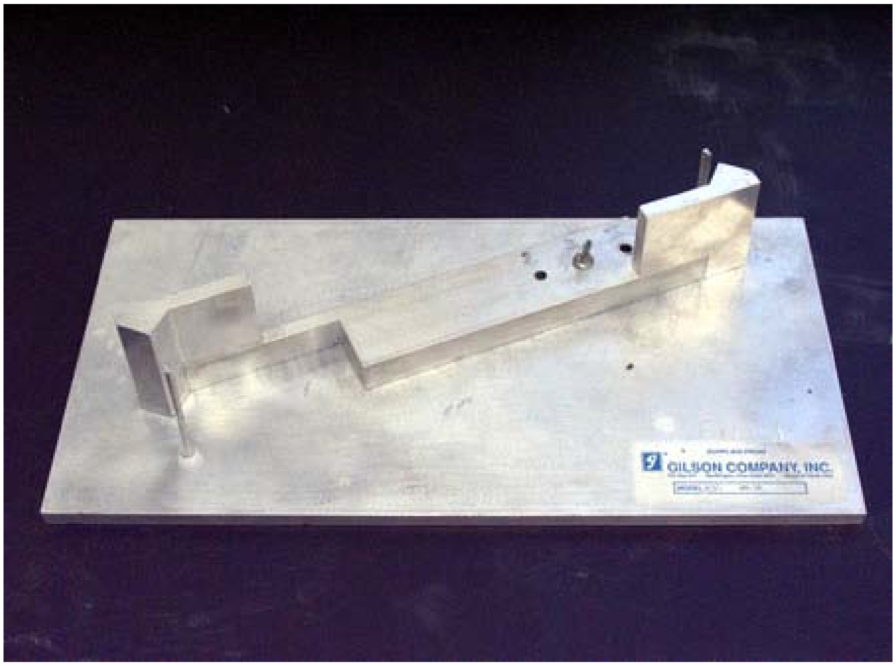


Figure 3.15. Proportional caliper device

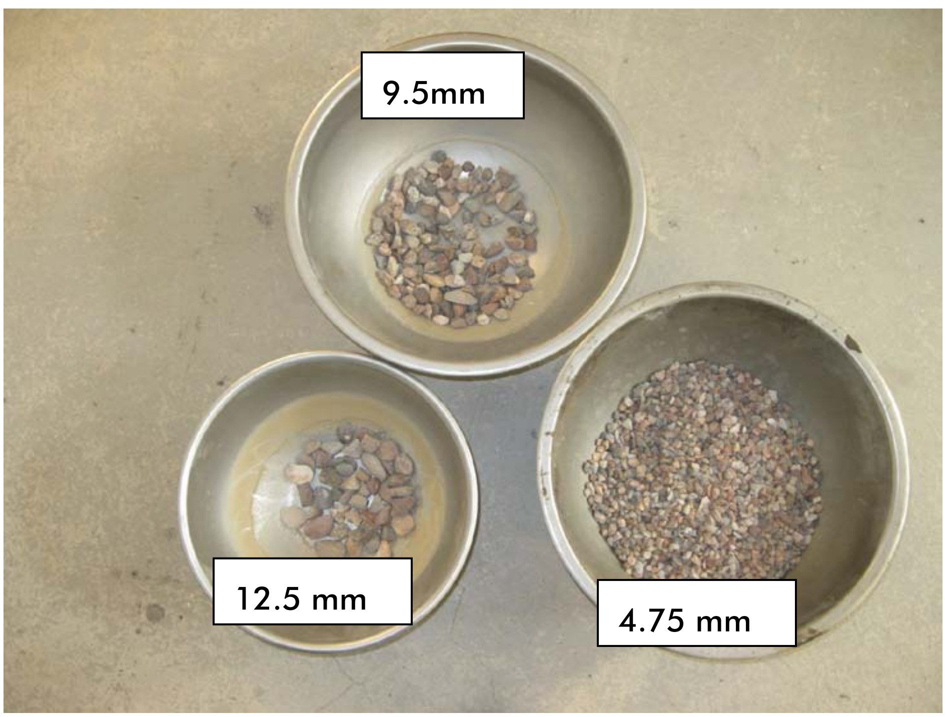


Figure 3.16. Size fractions retained on 12.5 mm, 9.5 mm, and 4.75 mm sieves

Figure 3.17. 100 particles of 4.75 mm and 9.5 mm sizes each

3.2.2.6 L.A. Abrasion Test

One 5-kg aggregate sample from each source was prepared according to Grading D and subjected to a Los Angeles Abrasion test (Figure 3.18) following ASTM C131. This test required that aggregates be placed with 6 steel spheres inside a metal drum that rotated at a speed of approximately 30 rpm for 500 revolutions. The weight loss, in percent, was computed from the initial sample weight and the final weight measured after the samples were washed on a No. 12 (1.7 mm) sieve and dried at 105^{o}C. To determine the uniformity of hardness of the samples, the samples were rotated in the drum for 100 revolutions to determine the weight loss and compare it with the weight loss after 500 revolutions. Figures 3.19, 3.20, and 3.21 show a representative sample for the L.A. abrasion test, the aggregate sample after crushing, and the aggregate sample obtained after being washed respectively.

Figure 3.18. L.A. abrasion machine

Figure 3.19. Test sample (particle fraction of 2.36 mm)


Figure 3.20. Aggregate sample after crushed in the L.A. abrasion machine


Figure 3.21. Particles obtained after washing on the 1.7 mm sieve

3.2.3. Binder Testing

3.2.3.1 Abson Recovery

Figure 3.22 shows the test set-up to recover asphalt binder using the Abson recovery method. This test was carried out following Tex-211-F "Recovery of Asphalt from Bituminous Mixture by the Abson Process". Figure 3.23 shows the recovered asphalt obtained from the Abson recovery test.

Figure 3.22. Abson recovery test set-up

Figure 3.23. Recovered asphalt binder

3.2.3.2 Determination of PG Grade

In the past, both penetration grading and viscosity grading were used to characterize asphalt binders; however, these properties are empirical and unable to fully characterize asphalt binders for the use in HMA pavements. In the effort to characterize the performance of asphalt binders in HMA, the Superpave research group developed new binder tests and specification. This specification was developed based on the performance of HMA pavements during construction and service including rutting, fatigue cracking, and thermal cracking. Following test methods are used for Superpave performance grading:

- Rolling Thin-Film Oven (RTFO)
- Pressure Aging Vessel (PAV)
- Rotational Viscometer (RV)
- Dynamic Shear Rheometer (DSR)
- Bending Beam Rheometer (BBR)
- Direct Tension Tester (DTT)

The Superpave grading is reported using two numbers, in which the first number represents the seven day maximum temperature (°C) and the second number represents the minimum pavement design temperature (°C). The binder test methods are described briefly as follows.

3.2.3.3 Rolling Thin Film Oven (RTFO)

Figure 3.24. Rolling thin film oven test

The RTFO (Figure 3.24) is used to simulate short-term aging that would happen when asphalt is exposed to an elevated temperature during mixing. In the RTFO procedure, unaged asphalt binder samples in cylindrical glass bottles are placed in a rotating oven. The temperature of 325°F (163°C) is maintained and the samples are aged for 85 minutes. Samples are then tested for mass loss and used in the DSR test. The RTFO test is carried out following the ASTM D 2872.

3.2.3.4 Pressure Aging Vessel (PAV)

The PAV (Figure 3.25) procedure is used to simulate long-term aging that would happen in binder during the service life of a pavement. In this procedure, the RTFO aged binder samples are placed in stainless steel pans and aged for 20 hours in a heated vessel pressurized to 305 psi. The samples are then tested for mass loss and used for DSR, creep stiffness, and BBR tests. The PAV test is carried out following the ASTM D6521 – 08.

3.2.3.5 Rotational Viscometer (RV)

The rotational viscometer (RV) (Figure 3.26) is used to determine the viscosity of the binder at 135^{o}C. This test is done to ensure that the asphalt binder is sufficiently fluid for mixing and pumping (Roberts et al., 1996). It measures the torque required to maintain a certain rotational speed of a cylindrical spindle while submerged in a thermostat containing the asphalt binder at a constant temperature. The RV test is performed following ASTM D 4402.

Figure 3.25. Pressure aging vessel (PAV) test

Figure 3.26. Rotational viscometer

3.2.3.6 Dynamic Shear Rheometer (DSR)

This test method (Figure 3.27) characterizes the viscous and elastic behavior of asphalt binders at medium to high temperatures. In this test method, a thin asphalt binder is sandwiched between two circular plates and the lower plate is fixed while the upper plate oscillates back and forth across the sample at 10 rad/sec to create a shearing action. This test is conducted using ASTM D7175 – 08.

Figure 3.27. Dynamic shear rheometer

3.2.3.7 Bending Beam Rheometer (BBR)

This method (Figure 3.28) characterizes low temperature stiffness and relaxation properties of asphalt binders. These parameters are important because they give an indication of the ability of asphalt binders to resist low temperature cracking. In this test method, a simply supported asphalt beam immersed in a cold liquid bath is loaded at the center and its deflection is measured against time. This test is conducted following ASTM D6648 – 08.

Figure 3.28. Bending beam rheometer

3.2.3.8 Direct Tension Tester (DTT)

This method (Figure 3.29) characterizes low temperature stiffness and relaxation properties of asphalt binders. Similar to the BBR test, these parameters can give an indication of the ability of asphalt binders to resist low temperature cracking. In this test method, a specimen of asphalt binder pulled apart at a constant rate of elongation. Test temperatures are maintained such that the failure will be from brittle or ductile-brittle fracture. This test was carried out using ASTM D 6723–02.

Figure 3.29. Direct tension tester
(http://pavementinteractive.org/index.php?title=Image:DirectTension.jpg)

Chapter 4: Test Results and Analysis

This chapter comprises of four sections: (a) test results from characterization of RAP aggregates by the ignition method, (b) test results from characterization of RAP binders, (c) comparison of physical and mechanical characteristics of RAP aggregates extracted by ignition and centrifuge methods, and (d) comparison between RAP and corresponding original mixes.

4.1 Characterization of RAP Aggregates

4.1.1 RAP from K-25 in Grant County

4.1.1.1 Moisture Content

Moisture content tests on 11 RAP samples were carried out. Table 4.1 presents the test data of moisture content, average moisture content, standard deviation, and coefficient of variation (COV). It is shown that the moisture content of the RAP was low.

Table 4.1. Moisture contents of RAP samples (K-25 in Grant County)

Sample No.	Moisture Content (%)	Average Moisture Content (%)	Standard Deviation (σ)	COV
1	0.17	0.22	0.048	0.215
2	0.19			
3	0.19			
4	0.22			
5	0.29			
6	0.23			
7	0.27			
8	0.17			
9	0.20			
10	0.22			
11	0.31			

4.1.1.2 Binder Content

Binder contests on eleven RAP samples were carried out by the ignition method. Table 4.2 presents the test data of binder content, average binder content, standard deviation, and coefficient of variation (COV). Moisture content correction was not applied to the binder content because RAP were placed directly into the ignition furnace after it is dried to a constant mass in the moisture content oven. The test results are reasonably consistent with a low COV.

Table 4.2. Binder contents of RAP samples (K-25 in Grant County)

Sample No.	Binder Content (%).	Average Binder Content (%)	Standard Deviation (σ)	COV
1	5.58	5.89	0.208	0.0352
2	5.67			
3	5.69			
4	5.86			
5	5.80			
6	5.89			
7	6.17			
8	6.22			
9	6.10			
10	5.98			
11	5.76			

4.1.1.3 Gradation

Sieve analysis was carried out on eleven extracted RAP aggregates using the ignition method. Table 4.3 shows the gradations of these RAP samples. Figure 4.1 presents the gradation curves of the extracted RAP aggregates. Figure 4.2 shows the comparison of the gradations of the RAP aggregates and the original mix. It is shown that the average gradation of the RAP aggregates is finer than that of the original mix. The power gradation curve of the RAP aggregates is presented in Figure 4.3, which shows that the gradation of the RAP aggregates falls within the upper and lower control points. It is also found that the nominal maximum size of RAP aggregate decreased to 9.5 mm from 12.5 mm in the original mix.

Table 4.3. Gradations of the extracted RAP aggregates (K-25 in Grant County)

Sieve Size mm	Samples (Percent Passing)											Avg.	St.d. (σ)	COV
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**			
12.5	96	97	96	96	96	97	99	98	98	97	98	97	1.00	0.0103
9.5	90	93	92	93	92	92	97	95	96	94	93	93	1.84	0.0197
4.75	71	75	73	75	74	76	84	81	83	81	78	77	4.34	0.0561
2.36	51	53	52	54	54	56	66	62	66	63	59	58	5.49	0.0952
1.18	34	36	35	36	36	38	47	44	47	44	41	40	4.97	0.1250
0.6	24	25	24	25	26	27	34	31	34	32	29	28	3.78	0.1339
0.3	16	17	16	17	17	18	22	20	23	21	19	19	2.51	0.1353
0.15	10	11	10	11	11	12	15	13	15	13	12	12	1.66	0.1365
0.075	7	7	7	7	7	8	10	8	11	9	8	8	1.33	0.1634

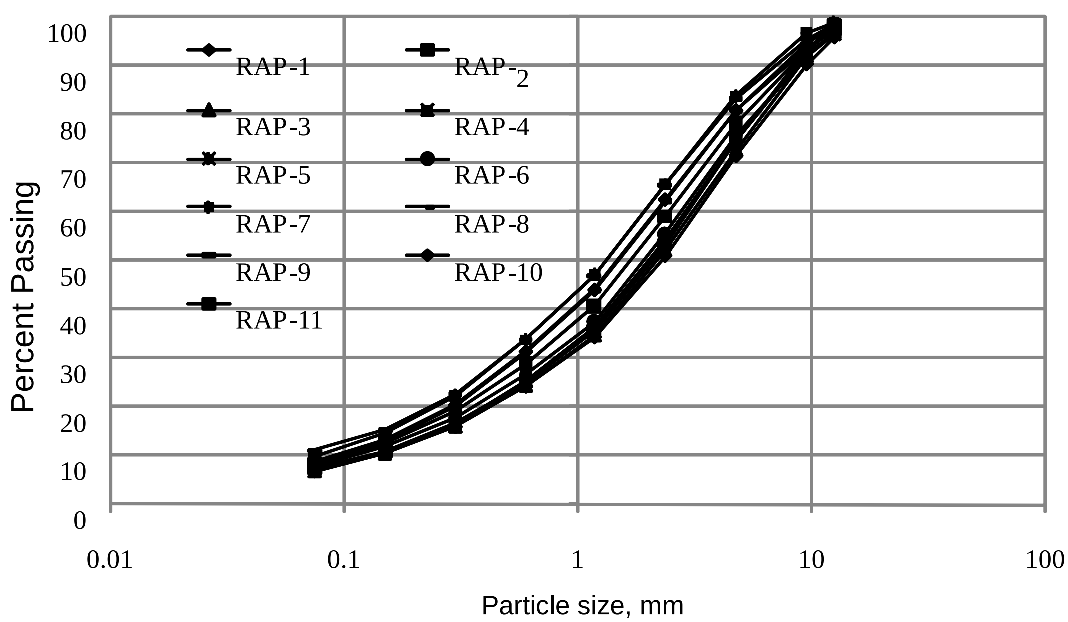


Figure 4.1. Gradation curves of extracted RAP aggregates (K-25 in Grant County)

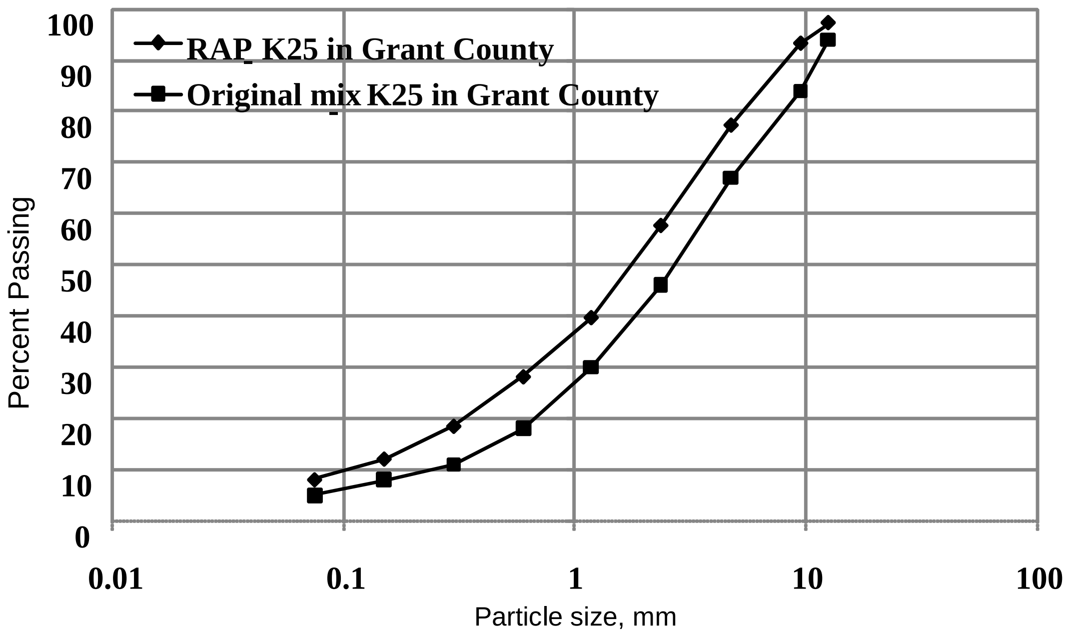


Figure 4.2. Original mix vs. average RAP gradation (K-25 in Grant County)

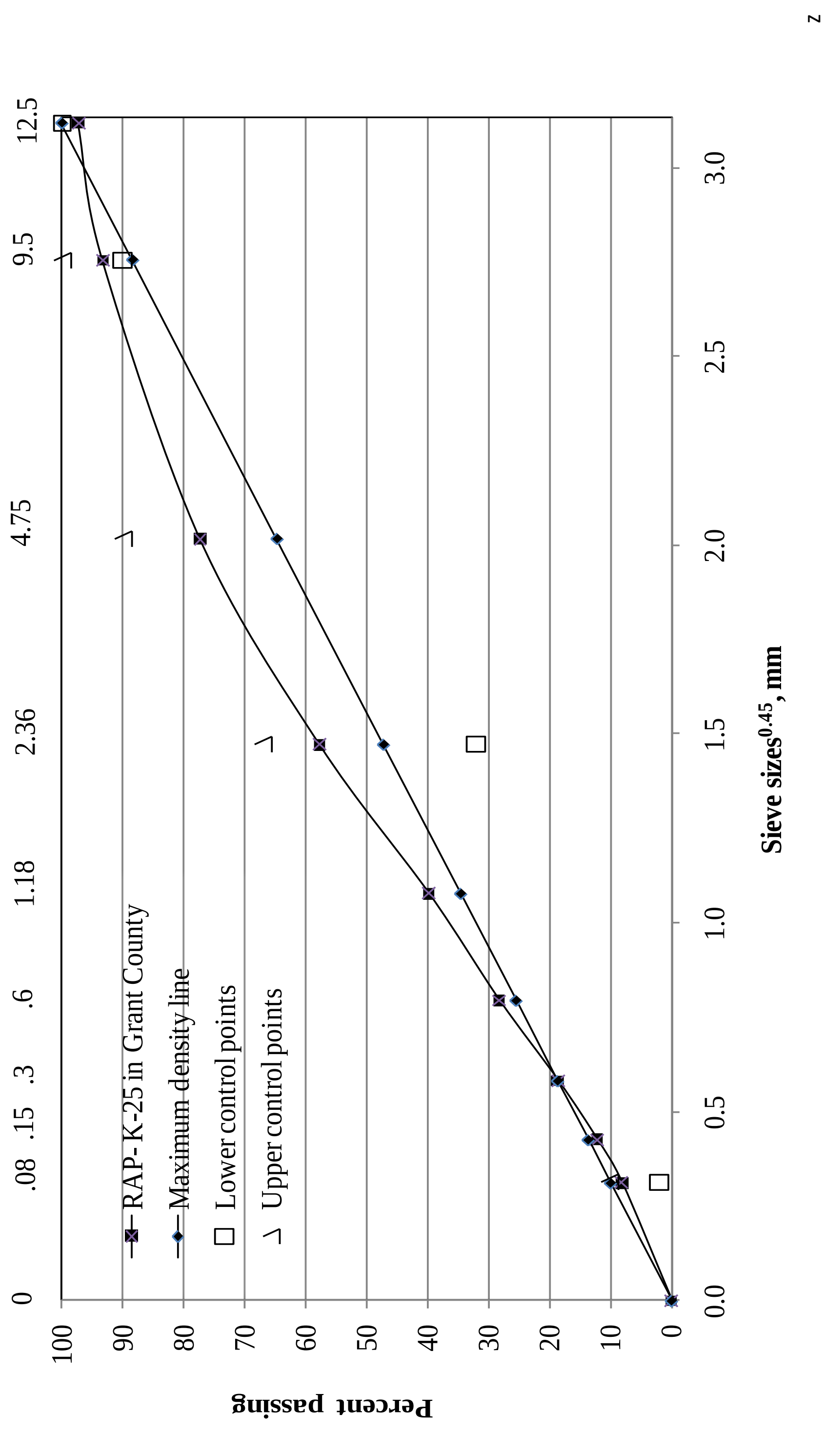


Figure 4.3. Power gradation curves of the extracted RAP aggregates (K-25 in Grant County)

4.1.1.4 Specific Gravity of Aggregate

Tables 4.4 and 4.5 present the test results of specific gravity and absorption of coarse and fine aggregates extracted by the ignition method, respectively. The combined bulk specific gravity of the aggregates from this RAP was found to be 2.537. The test results show that the coarse and fine aggregates had similar specific gravity but the coarse aggregate had higher absorption than the fine aggregate.

Table 4.4. Specific gravity and absorption of coarse aggregate (K-25 in Grant County)

Description	Sample 1	Sample 2	Average
Bulk specific gravity	2.520	2.531	2.525
Bulk specific gravity (SSD)	2.571	2.583	2.577
Apparent specific gravity	2.656	2.669	2.662
Absorption,%	2.04	2.04	2.04

Table 4.5. Specific gravity and absorption of fine aggregate (K-25 in Grant County)

Description	Sample 1	Sample 2	Sample 3	Average
Bulk specific gravity	2.546	2.536	2.542	2.541
Bulk specific gravity (SSD)	2.578	2.570	2.574	2.574
Apparent specific gravity	2.631	2.626	2.626	2.628
Absorption,%	1.27	1.36	1.26	1.30

4.1.1.5 L.A. Abrasion

The measured L.A. abrasion value for the extracted RAP aggregate by the ignition method was 38.2%. The ratio of mass loss after 100 revolutions to that after 500 revolutions was 0.35%. This result suggests that this RAP aggregate was not of uniform hardness.

4.1.1.6 CAA

The angularity of the coarse aggregate extracted by the ignition method was determined in two ways:% particles with fractured faces and% uncompacted voids. The measured% particles with fractured faces were 96.7% and 98.1% for two samples and the average value was 97.4%. The measured% uncompacted voids were 43.7% and 44.0% for two samples and the average value was 43.8%. The test results show that CAA increase significantly from the CAA value of the original mix.

4.1.1.7 FAA

Six tests were conducted on randomly selected samples to determine the angularity of fine aggregates extracted by the ignition method as shown in Table 4.6. The average angularity of fine aggregates was 43.2%.

Table 4.6. Fine aggregate angularity (%) of RAP aggregate (K-25 in Grant County)

Sample No.	FAA	Average FAA	Standard Deviation(σ)	COV
1	43.3	43.2	0.30	0.0068
2	43.8			
3	43.2			
4	43.0			
5	43.1			
6	43.0			

4.1.1.8 F&E Particles

The percentages of flat and elongated particles were determined as 1.9% and 3.2% respectively on 9.5 mm and 4.75 mm particle sizes. The average percentage of these two flat and elongated particles was 2.6%. The percentages of F&E particles were less than that specified by the Superpave specification (10%).

4.1.2 RAP from K-25 in Logan County

4.1.2.1 Moisture Content

Moisture content tests on twelve RAP samples were carried out. Table 4.7 presents the test data of moisture content, average moisture content, standard deviation, and coefficient of variation (COV). It is shown that moisture content of RAP was low.

4.1.2.2 Binder Content

Binder contents of twelve RAP samples were determined using the ignition method. Table 4.8 presents the test data of binder content, average binder content, standard deviation, and coefficient of variation (COV). Moisture content correction was not applied to the binder content because RAP was placed directly into the ignition furnace after it was dried to a constant mass in the moisture content oven. It is shown that the RAP sample had higher binder content and lower standard deviation than the other RAP samples.

Table 4.7. Moisture contents of RAP samples (K-25 in Logan County)

Sample No.	Moisture Content (%)	Average Moisture Content (%)	Standard Deviation (σ)	COV
1	0.42	0.45	0.0554	0.1245
2	0.47			
3	0.42			
4	0.46			
5	0.37			
6	0.40			
7	0.39			
8	0.47			
9	0.51			
10	0.43			
11	0.57			
12	0.44			

Table 4.8. Binder contents of RAP samples (K-25 in Logan County)

Sample No.	Binder Content (%)	Average Binder Content (%)	Standard Deviation (σ)	COV
1	6.74	6.76	0.082	0.012
2	6.69			
3	6.84			
4	6.77			
5	6.78			
6	6.65			
7	6.74			
8	6.71			
9	6.80			
10	6.61			
11	6.90			
12	6.83			

4.1.2.3 Gradation

Size analysis was carried out on twelve extracted RAP aggregate samples extracted by the ignition method. Table 4.9 shows the gradations of these RAP aggregate samples. Figure 4.4 shows the gradation curves of the extracted RAP aggregate samples. Figure 4.5 shows the average gradation of the RAP aggregates versus the original mix gradation. It is shown that the average gradation of the RAP aggregates is finer than that of the original mix. The power gradations of the original mix and RAP aggregate samples are shown in Figure 4.6. It is also found that the nominal maximum size of RAP aggregates decreased to 9.5 mm from 12.5 mm in the original mix.

Table 4.9. Gradations of the extracted RAP aggregates (K-25 in Logan County)

Sieve Size (mm)	**Samples (Percent Passing)**												**Avg.**	**St.d. (σ)**	**COV**
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**			
12.5	98	98	97	99	98	96	96	96	97	97	96	98	97	0.89	0.0091
9.5	94	94	94	96	94	93	91	93	94	94	91	95	94	1.27	0.0135
4.75	80	79	80	83	80	79	75	78	80	79	74	81	79	2.40	0.0304
2.36	63	62	63	66	62	61	58	60	63	61	57	63	61	2.62	0.0426
1.18	48	47	47	50	46	45	43	45	48	45	42	47	46	2.21	0.0481
0.6	35	34	34	36	33	33	31	33	35	32	31	34	34	1.56	0.0466
0.3	21	21	21	22	21	20	20	21	22	20	19	21	21	0.84	0.0402
0.15	13	13	13	13	13	13	12	13	13	12	12	13	13	0.57	0.0449
0.075	9	9	8	9	9	8	8	9	9	8	8	9	9	0.55	0.0641

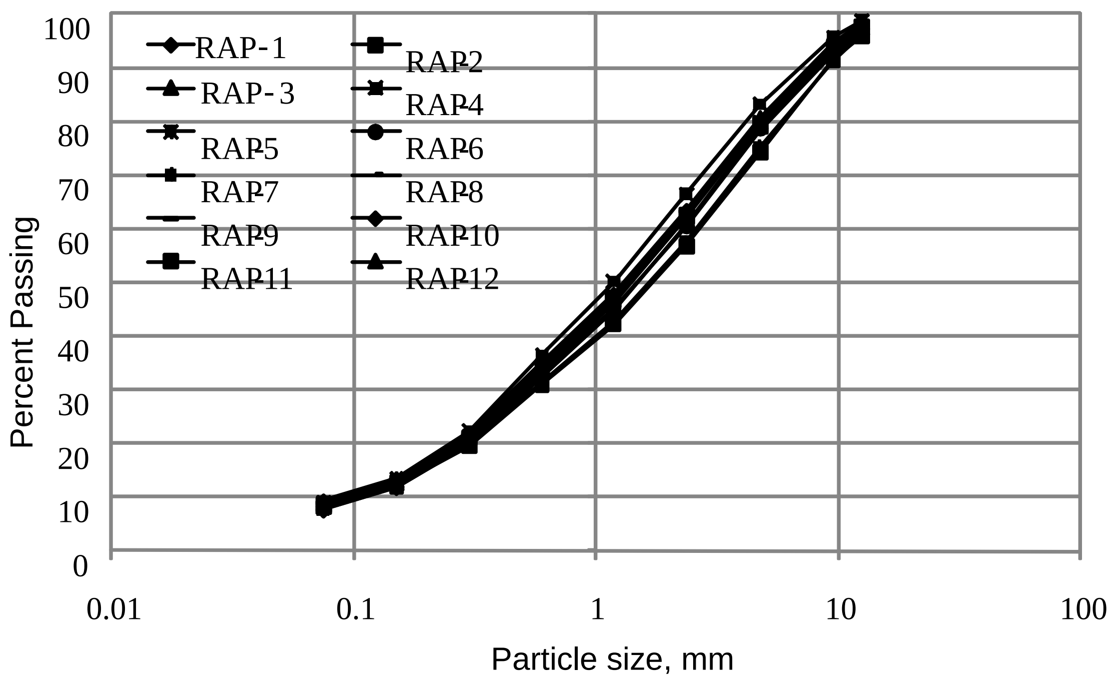


Figure 4.4. Gradation curves of the extracted RAP aggregates (K-25 in Logan County)

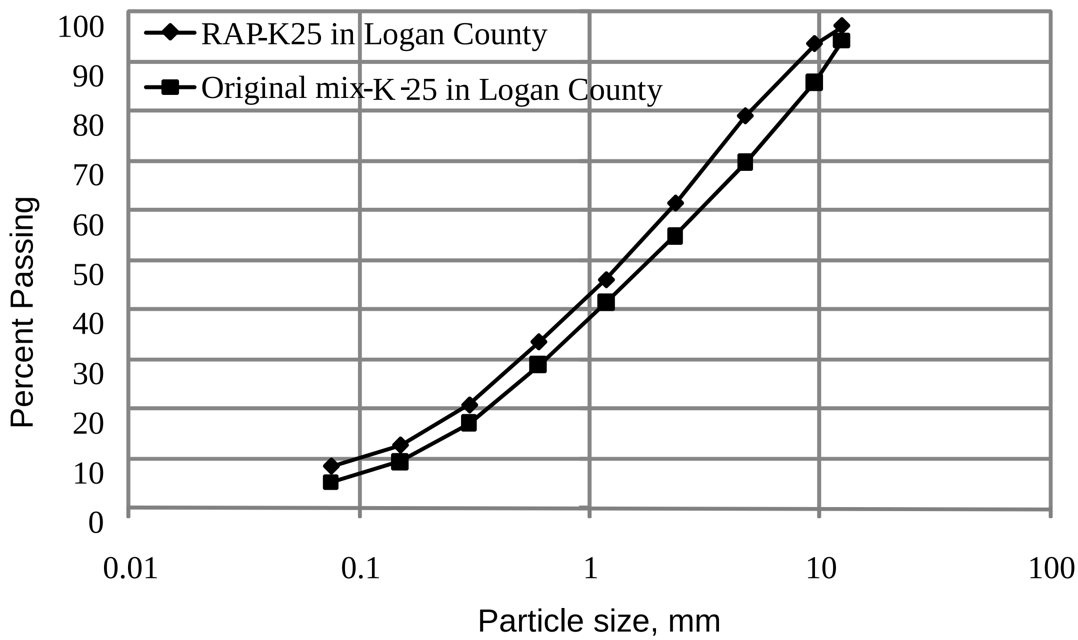


Figure 4.5. Original mix vs. average RAP aggregate gradations (K-25 in Logan County)

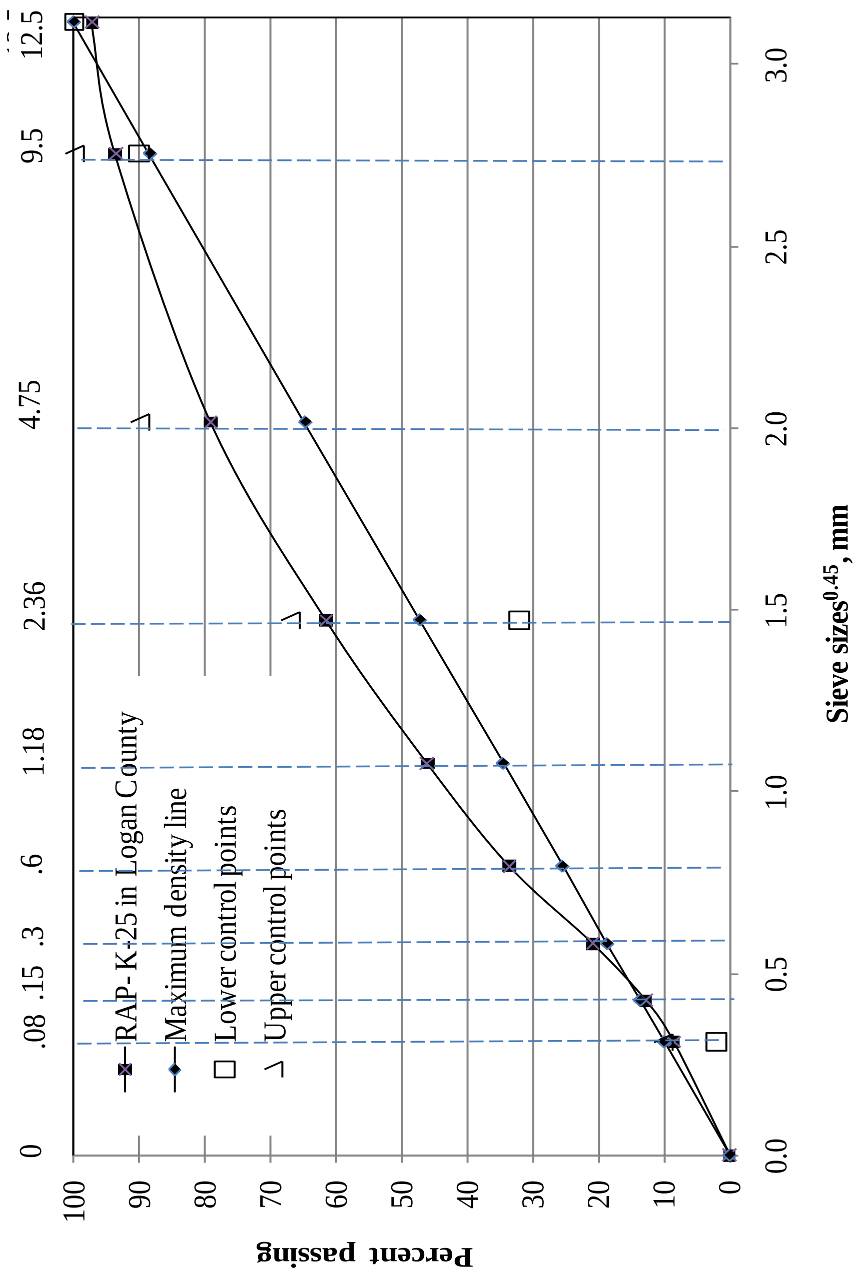


Figure 4.6. Power gradation curves of the extracted RAP aggregates (K-25 in Logan County)

4.1.2.4 Specific Gravity of Coarse and Fine Aggregates

Tables 4.10 and 4.11 show the bulk specific gravity and absorption of coarse and fine aggregates extracted by the ignition method, respectively. The combined bulk specific gravity of the aggregates was 2.512. The test results show that the coarse and fine aggregates had similar bulk specific gravity but the coarse aggregate had slightly higher absorption than the fine aggregate.

Table 4.10. Specific gravity and absorption of coarse aggregate (K-25 in Logan County)

Description	Sample 1	Sample 2	Average
Bulk specific gravity	2.536	2.538	2.537
Bulk specific gravity (SSD)	2.582	2.583	2.582
Apparent specific gravity	2.657	2.658	2.658
Absorption,%	1.80	1.78	1.79

Table 4.11. Specific gravity and absorption of fine aggregate (K-25 in Logan County)

Description	Sample 1	Sample 2	Sample 3	Average	Standard Deviation (σ)	COV
Bulk specific gravity	2.506	2.518	2.487	2.504	0.0155	0.0062
Bulk specific gravity (SSD)	2.546	2.552	2.528	2.542	0.0122	0.0048
Apparent specific gravity	2.610	2.605	2.593	2.603	0.0089	0.0034
Absorption,%	1.60	1.33	1.64	1.52	0.1703	0.1118

4.1.2.5 L.A. Abrasion

The measured L.A. abrasion value of the extracted RAP aggregates extracted by the ignition method was 38.6%. The ratio of mass loss after 100 revolutions to that after 500 revolutions was 0.29%. This ratio suggests that the RAP aggregates were not of uniform hardness.

4.1.2.6 CAA

The angularity of the coarse aggregate extracted by the ignition method was determined in two ways:% particles with fractured faces and% uncompacted voids. The measured% particles with fractured faces were 96.1% and 97.7% for two samples and the average value was 97.4%. The measured% uncompacted voids were 45.9% and 45.4% for two samples and the average value was 45.7%. The test results show that the CAA value of the extracted aggregate increased significantly from that of the original mix.

4.1.2.7 FAA

Six tests were conducted on randomly selected samples to determine the angularity of fine aggregates as shown in Table 4.12. The average angularity of fine aggregates was 42.9%.

Table 4.12. Fine aggregate angularity (%) of RAP aggregate (K-25 in Logan County)

Sample	FAA	Average FAA	Standard Deviation (σ)	COV
1	43.0	42.9	0.31	0.0072
2	42.9			
3	43.2			
4	43.1			
5	42.3			
6	42.7			

4.1.2.8 F&E Particles

The percentages of flat and elongated particles were determined as 2.0% and 5.0% respectively on 9.5 mm and 4.75 mm particle sizes. The average percentage of these two flat and elongated particles was 3.5%. The percentages of F&E particles were less than that specified by superpave specification (10%).

4.1.3 RAP from US-83 in Scott County

4.1.3.1 Moisture Content

Moisture content tests on twelve RAP samples were carried out. Table 4.13 presents the test data of moisture content, average moisture content, standard deviation, and coefficient of variation (COV). It is shown that moisture content of RAP was low.

Table 4.13. Moisture contents of RAP samples (US-83 in Scott County)

Sample No.	Moisture Content (%)	Average M.C. (%)	Standard Deviation (σ)	COV
1	0.24	0.22	0.0239	0.1068
2	0.19			
3	0.22			
4	0.24			
5	0.23			
6	0.20			
7	0.24			
8	0.19			
9	0.24			
10	0.26			
11	0.23			
12	0.21			

4.1.3.2 Binder Content

Binder contents of twelve RAP samples were determined using the ignition method. Table 4.14 presents the test data of binder content, average binder content, standard deviation, and coefficient of variation (COV). Moisture content correction was not applied to the binder content because RAP was placed directly into the ignition furnace after it was dried to a constant mass in the moisture content oven.

Table 4.14(a) presents the test data of binder content determined by weighing the burned RAP taken out of the ignition oven at the room temperature. However, Table 4.14(b) presents the test data of binder content determined by weighing the burned RAP immediately after completion of burning at 500ºC. It is shown that the binder content determined after measuring the weight of the burned RAP at the room temperature was less than that measured at 500°C.

Table 4.14 (a). Binder contents of RAP samples (US-83 in Scott County)

Sample No.	Binder Content (%)	Average B.C. (%)	Standard Deviation (σ)	COV
1	5.57	5.67	0.11	0.0187
2	5.67			
3	5.65			
4	5.65			
5	5.51			
6	5.89			
7	5.81			
8	5.74			
9	5.58			
10	5.69			
11	5.61			
12	5.70			

Table 4.14 (b). Binder contents of RAP samples (US-83 in Scott County)

Sample No.	Binder Content (%).	Average B.C. (%)	Standard Deviation (σ)	COV
1	6.24	6.29	0.119	0.0190
2	6.20			
3	6.42			

4.1.3.3 Gradation

Grain size analysis was carried out on twelve extracted RAP aggregate samples. Table 4.15 shows the gradations of these RAP aggregate samples. Figure 4.7 shows the gradation curves of the extracted RAP aggregate samples. Figure 4.8 shows the average gradation of the RAP aggregates versus the original mix gradation. It is shown that the average gradation of the RAP aggregates is finer than that of the original mix. The power gradations of the original mix and RAP aggregate samples are shown in Figure 4.9. The power gradation curve of the RAP aggregates shows that the gradation of the RAP aggregates falls within the upper and lower control points. It is also found that the nominal maximum size of RAP aggregate decreased to 9.5 mm from 12.5 mm in the original mix.

Table 4.15. Gradation of the extracted RAP samples (US-83 in Scott County)

Sieve Size mm	1	2	3	4	5	6	7	8	9	10	11	12	Avg.	St.d. (σ)	COV
	Samples (Percent Passing)														
12.5	99	98	99	99	99	99	99	99	98	99	99	99	99	0.44	0.0044
9.5	97	96	97	97	98	98	98	96	95	97	97	97	97	0.87	0.0089
4.75	86	85	86	88	87	90	89	83	85	86	85	85	86	1.94	0.0225
2.36	64	63	64	67	66	72	70	61	65	65	63	64	65	3.19	0.0489
1.18	45	45	45	48	47	53	52	43	46	47	44	45	47	3.10	0.0664
0.6	33	33	33	35	34	40	39	31	34	35	32	33	34	2.49	0.0725
0.3	22	22	22	23	23	26	26	21	23	23	21	22	23	1.64	0.0714
0.15	14	15	15	15	15	17	17	14	14	15	13	14	15	1.05	0.0713
0.075	10	10	10	10	10	11	11	9	9	9	8	9	9	0.79	0.0837

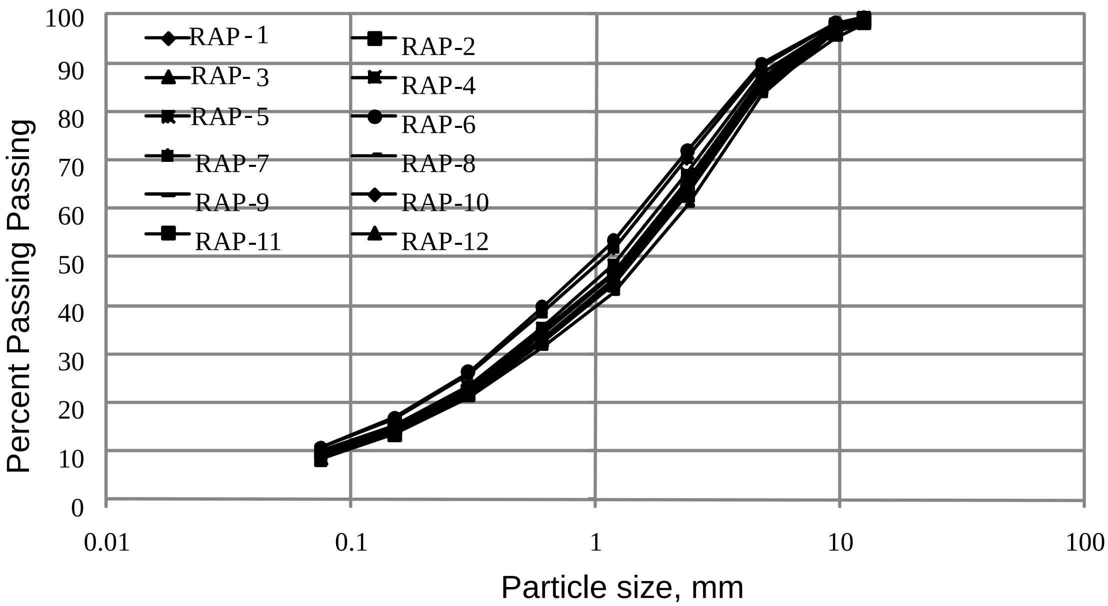


Figure 4.7. Gradation curves of the extracted RAP aggregates (US-83 in Scott County)

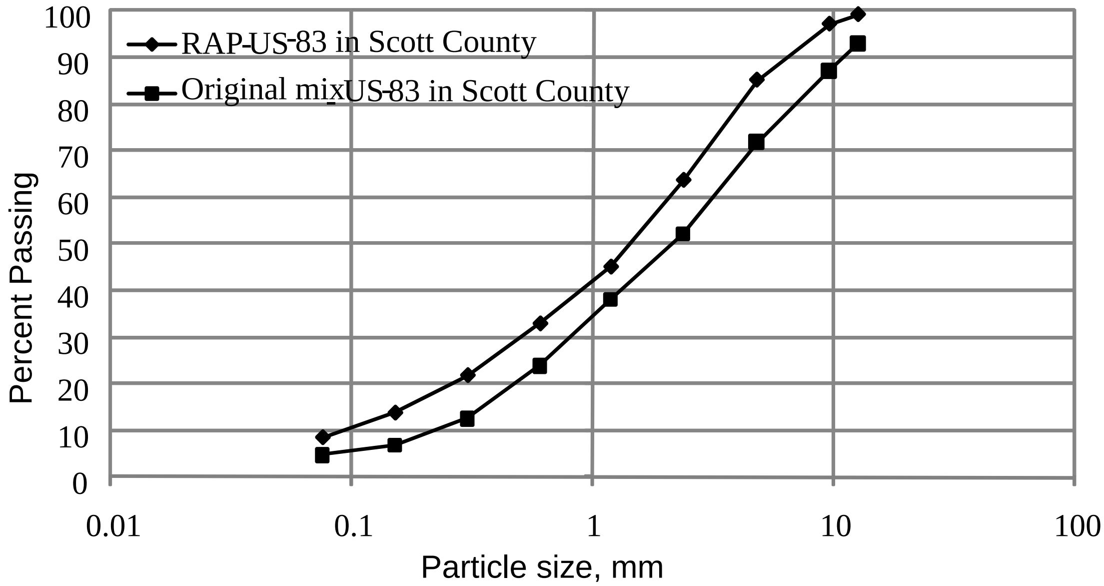


Figure 4.8. Original mix vs. average RAP aggregate gradations (US-83 in Scott County)

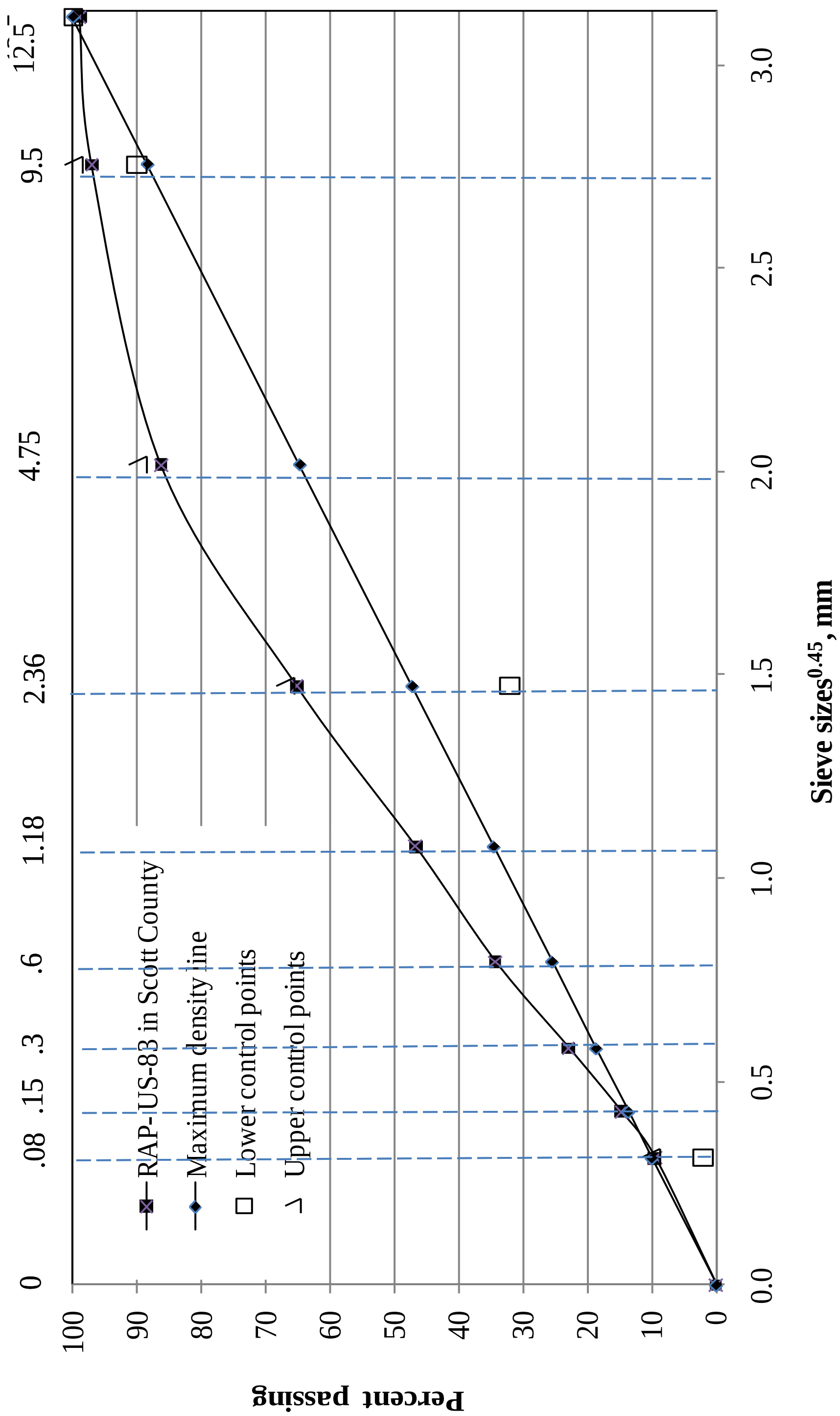


Figure 4.9. Power gradation curve of the extracted RAP aggregates (US-38 in Scott County)

4.1.3.4 Specific Gravity of Coarse and Fine Aggregate

Tables 4.16 and 4.17 show the bulk specific gravity and absorption of coarse and fine aggregates, respectively, extracted by the ignition method. The combined bulk specific gravity of the aggregates was 2.534. The test results show that the coarse aggregate had slightly lower bulk specific gravity than the fine aggregate, but the coarse aggregate had significantly higher absorption than the fine aggregate.

Table 4.16. Specific gravity and absorption of coarse aggregate (US-83 in Scott County)

Description	Sample 1	Sample 2	Average
Bulk specific gravity	2.492	2.491	2.492
Bulk specific gravity (SSD)	2.542	2.545	2.543
Apparent specific gravity	2.623	2.632	2.628
Absorption,%	2.01	2.14	2.08

Table 4.17. Specific gravity and absorption of fine aggregate (US-83 in Scott County)

Description	Sample 1	Sample 2	Sample 3	Average	St.d.	COV
Bulk specific gravity	2.554	2.529	2.543	2.542	0.012	0.0048
Bulk specific gravity (SSD)	2.579	2.560	2.567	2.568	0.009	0.0037
Apparent specific gravity	2.619	2.614	2.604	2.613	0.008	0.0029
Absorption,%	0.98	1.28	0.92	1.06	0.193	0.1823

4.1.3.5 L.A. Test

The measured L.A. abrasion value of the extracted RAP aggregates extracted by the ignition method was 38.5%. The ratio of mass loss after 100 revolutions to that after 500 revolutions was 0.32%. This ratio suggests that the RAP aggregates were not of uniform hardness.

4.1.3.6 F&E Particles

The percentages of flat and elongated particles extracted by the ignition method were determined as 3.5% and 7.1% respectively on 9.5 mm and 4.75 mm particle sizes. The average percentage of these two flat and elongated particles was 5.3%. The percentages of F&E particles were less than that specified by superpave specification (10%).

4.1.3.7 CAA

The angularity of the coarse aggregate extracted by the ignition method was determined in two ways:% particles with fractured faces and% uncompacted voids. The measured% particles with fractured faces were 96.9% and 96.6% for two samples and the average value was 96.8%. The measured% uncompacted voids were 45.4% and 45.3% for two samples and the average value was 45.4%. The test results show that the CAA value of the extracted RAP aggregate increased significantly from that of the original mix.

4.1.3.8 FAA

Six tests were conducted on randomly selected samples to determine the angularity of the fine aggregates extracted by the ignition method as shown in Table 4.18. The average angularity of fine aggregates was 44.8%.

Table 4.18. Fine aggregate angularity (%) of RAP aggregate (US-83 in Scott County)

Sample No.	FAA	Average FAA	Standard Deviation	COV
1	44.7	44.8	0.26	0.006
2	44.8			
3	44.5			
4	44.8			
5	45.2			
6	44.6			
7	45.2			
8	45.3			
9	44.9			
10	44.6			
11	44.6			
12	44.7			
13	44.9			
14	44.9			

4.2 Effects of Extraction Method on Binder Content and Properties of RAP Aggregates

Binder and aggregate in RAP can be separated by the ignition and centrifuge methods. The binder condition and the properties of aggregates may depend on the method used to extract them. To investigate the effect of the extraction method, the RAP from one source (K-25 at Grant County) was chosen. The same RAP material was used to determine binder content and extract aggregates using the ignition and centrifuge methods.

4.2.1 Binder Content

Table 4.19 shows the comparison of the binder contents obtained by the centrifuge and ignition methods of extraction. The binder content obtained by the centrifuge method was found to be lower than that obtained by the ignition method. This result can be explained that some asphalt remained in the pores of the aggregates and could not be removed by the centrifuge method. As a result, the estimated binder content was underestimated. However, the ignition method could burn off some mineral aggregates, therefore, it overestimated the binder content. Since more ignition test results were reported in Table 4.2; therefore, the average binder content in Table 4.2 will be used for later comparison.

Table 4.19. Comparison of the binder contents (%) determined by centrifuge and ignition methods

Sample No	Centrifuge method	Ignition method
1	4.50	5.69
2	4.59	5.67
3	4.63	5.80
Average	4.58	5.72

4.2.2 Gradation

Table 4.20 presents the comparison of the gradations of the aggregates extracted by the centrifuge and ignition methods. Table 4.20 and Figure 4.10 both show that no significant difference existed in the gradations of the aggregates obtained by the centrifuge and ignition methods. The aggregate samples extracted by the centrifuge and ignition methods are shown in

Figs. 4.11 and 4.12, respectively. Figure 4.12 shows some traces of burning of the aggregates.

Table 4.20. Comparison of the gradations of the aggregates extracted by centrifuge and ignition methods

Sieve Sizes, mm	Centrifuge Method			Ignition Method			Difference			Error(d2s)	d2s*
	Samples			Samples			Samples				
	1	2	3	1	2	3	1	2	3		
12.5	98.5	99.0	98.7	99.0	98.4	99.5	0.5	-0.7	0.7	1.4	3.1
9.5	95.4	96.7	96.1	95.8	95.7	96.1	0.3	-0.9	0.0	1.4	6.4
4.75	82.3	83.4	82.3	81.6	82.2	83.7	-0.7	-1.2	1.4	2.9	12.4
2.36	64.4	65.5	64.2	63.1	64.4	64.7	-1.2	-1.1	0.6	2.9	14.8
1.18	43.6	43.8	43.0	41.9	43.1	43.1	-1.7	-0.7	0.1	2.9	12.9
0.6	29.4	29.3	28.8	28.0	30.0	28.6	-1.4	0.7	-0.1	2.9	9.7
0.3	19.4	19.5	19.3	18.7	18.0	18.8	-0.8	-1.6	-0.5	2	6.7
0.15	12.9	13.2	13.2	12.5	11.0	12.3	-0.4	-2.2	-0.9	1.2	4.9
0.075	8.7	9.2	9.2	8.4	6.4	8.1	-0.3	-2.7	-1.2	0.9	4.3

In Table 4.20, d2s is an acceptable range of two results defined in ASTM D5444, “Standard Test Method for Mechanical Size Analysis of Extracted Aggregate” for extracted aggregates. d2s* is the difference between the minimum and maximum gradations among eleven extracted RAP aggregate samples by the ignition method.

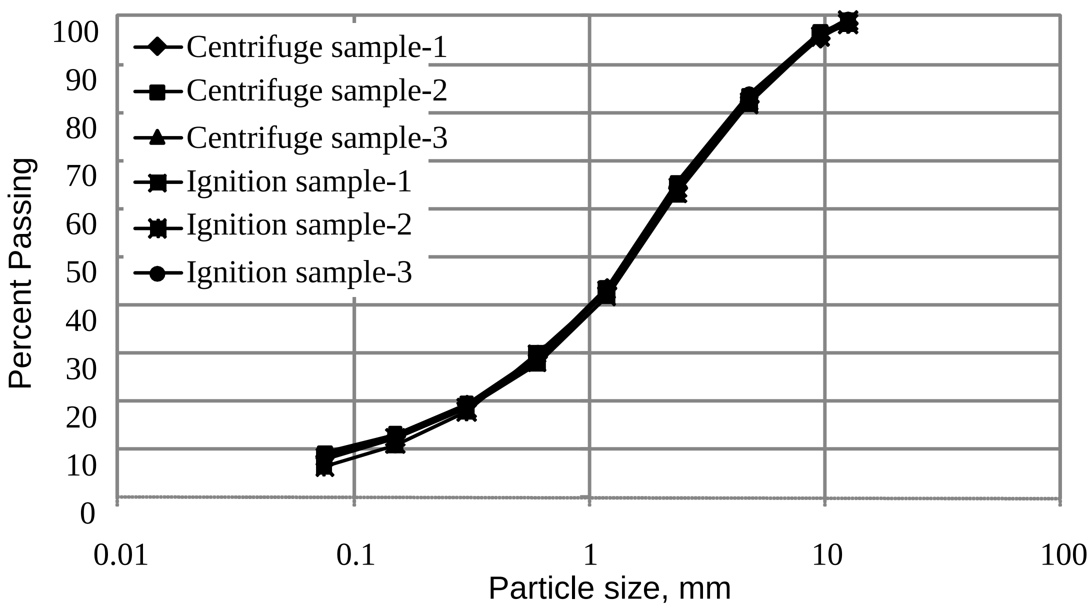


Figure 4.10. Comparison of the gradations of the aggregates extracted by the centrifuge and ignition methods

Figure 4.11. Sample extracted by the centrifuge method

Figure 4.12. Sample extracted by the ignition method

4.2.3 Specific Gravity and Absorption

Table 4.21 shows the comparison of the specific gravity values of coarse aggregates extracted by the centrifuge and ignition methods. It is shown that the bulk specific gravity of the coarse aggregate extracted by the centrifuge method was found higher than that from the aggregate extracted by the ignition method. The increase in the specific gravity of the coarse aggregate was also accompanied by the decrease in the absorption of the aggregate. Figure 4.13 shows the difference in the bulk specific gravity of the coarse aggregate extracted by the centrifuge and ignition methods while Figure 4.14 shows the difference in the absorption of the coarse aggregate extracted by the centrifuge and ignition methods.

Table 4.21. Comparison of specific gravity of coarse aggregates extracted by centrifuge and ignition methods

Description	Centrifuge			Ignition		
	Sample 1	Sample 2	Average	Sample 1	Sample 2	Average
Bulk specific gravity	2.583	2.563	2.573	2.520	2.531	2.525
Bulk specific gravity(SSD)	2.606	2.593	2.600	2.571	2.583	2.577
Apparent specific gravity	2.644	2.643	2.644	2.656	2.669	2.662
Absorption,%	0.90	1.17	1.04	2.04	2.04	2.04

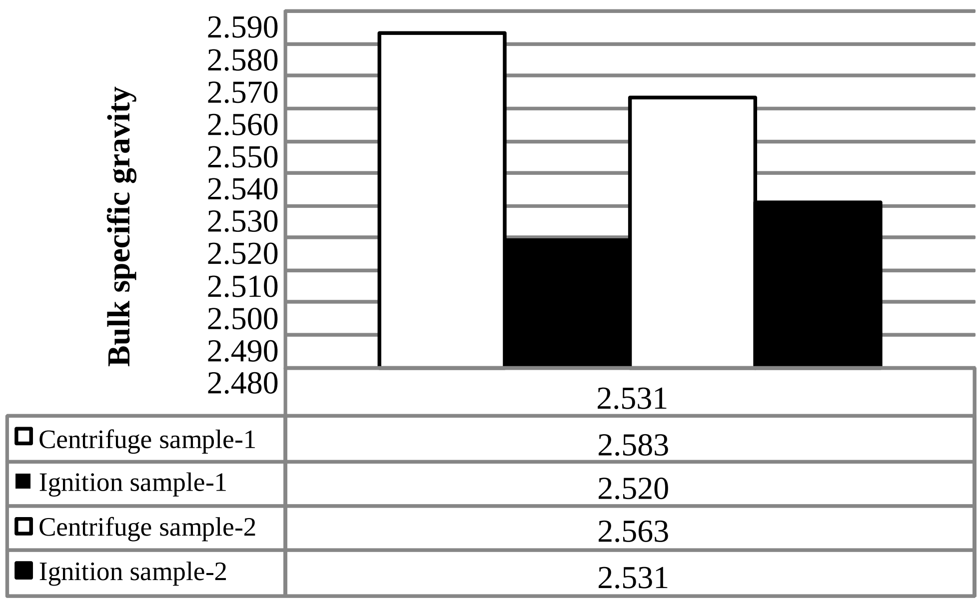


Figure 4.13. Comparison of the bulk specific gravity of the coarse aggregate extracted by the centrifuge and ignition methods

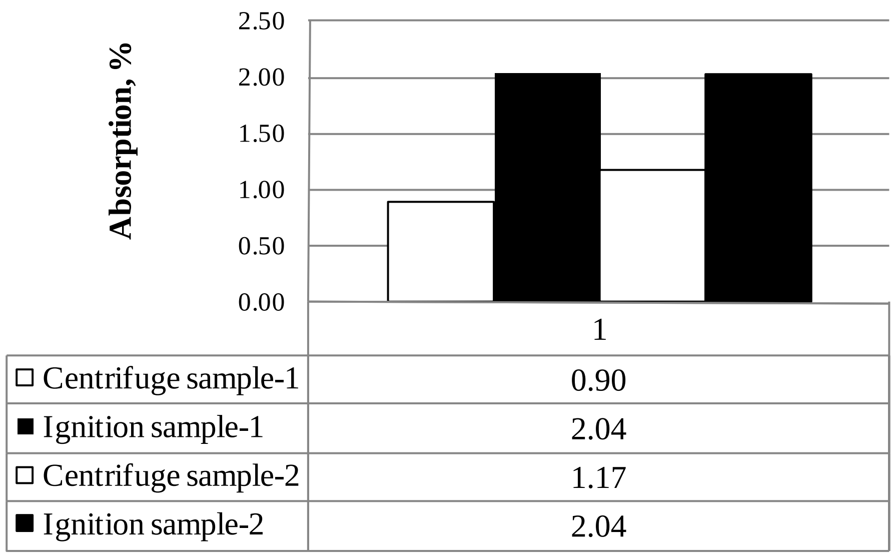


Figure 4.14. Comparison of the absorption of the coarse aggregate extracted by the ignition and centrifuge methods

Tables 4.22 and 4.23 show the specific gravity of the fine aggregates extracted by the centrifuge and ignition methods. It is shown that the bulk specific gravity of the fine aggregate extracted by the centrifuge method was found higher than that from the aggregate extracted by the ignition method. The increase in the specific gravity of the fine aggregate extracted by the centrifuge method was accompanied by the decrease in the absorption of the aggregate. Additional samples were tested and reported in Tables 4.22 and 23 as compared with those in Tables 4.4 and 4.5; therefore, the results in Tables 4.22 and 4.23 will be used in the later comparisons. Figure 4.15 shows the difference in the bulk specific gravity of the fine aggregate extracted by the centrifuge and ignition methods while Figure 4.16 shows the difference in the absorption of the coarse aggregate extracted by the centrifuge and ignition methods.

Table 4.22. Specific gravity of the fine aggregate extracted by the centrifuge method

Description	**Samples**						
	1	2	3	4	5	6	Average
Bulk specific gravity	2.550	2.542	2.531	2.535	2.542	2.544	2.541
Bulk specific gravity (SSD)	2.567	2.562	2.554	2.557	2.561	2.563	2.561
Apparent specific gravity	2.594	2.593	2.590	2.592	2.591	2.592	2.592
Absorption (%)	0.68	0.79	0.90	0.87	0.74	0.73	0.78

Table 4.23. Specific gravity of the fine aggregates extracted by the ignition method

Description	**Samples**						
	1	2	3	4	5	6	**Average**
Bulk specific gravity	2.546	2.536	2.514	2.514	2.525	2.525	2.527
Bulk specific gravity (SSD)	2.578	2.570	2.546	2.548	2.553	2.553	2.558
Apparent specific gravity	2.631	2.626	2.598	2.603	2.598	2.596	2.609
Absorption (%)	1.27	1.36	1.29	1.35	1.11	1.08	1.24

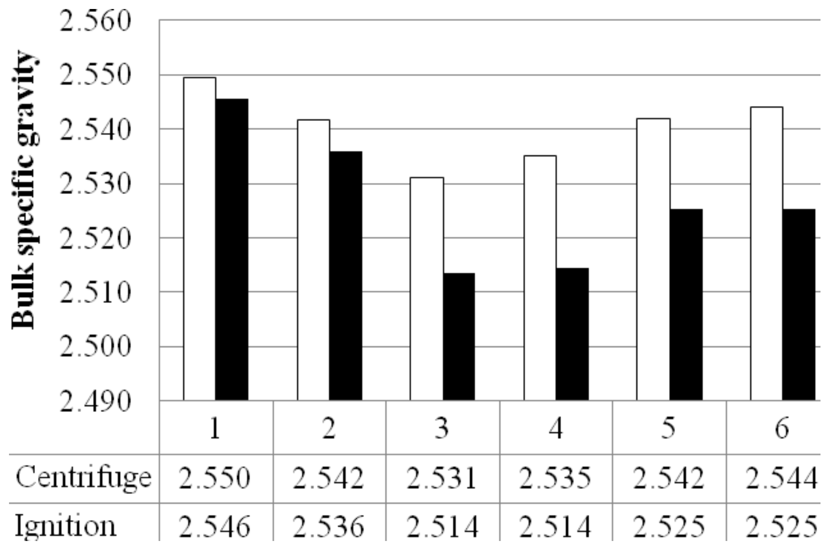


Figure 4.15. Comparison of the bulk specific gravity of the fine aggregates extracted by the centrifuge and ignition methods

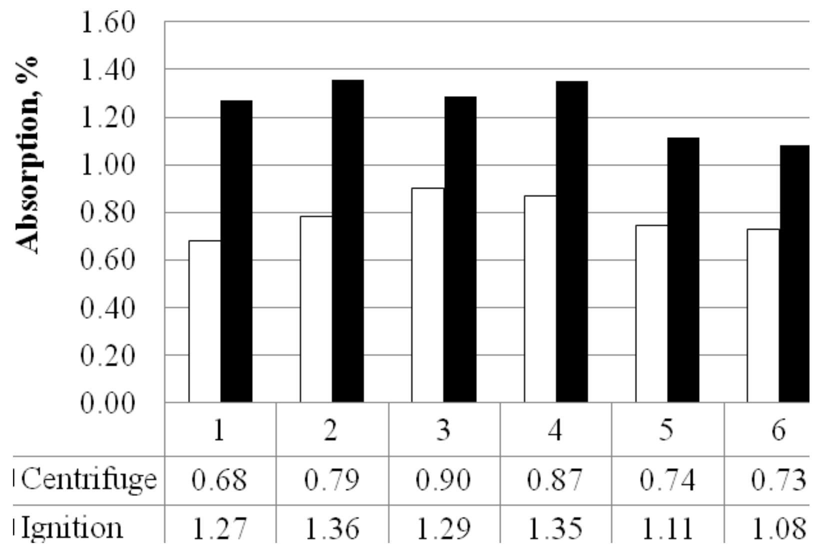


Figure 4.16. Comparison of the absorption of the fine aggregates extracted by the centrifuge and ignition methods

4.2.4 L.A. Abrasion

L.A. abrasion tests were conducted on the RAP aggregate samples extracted by the centrifuge and ignition methods. The L.A. abrasion value for 2.36 mm aggregate extracted by the centrifuge method was 35.4% while that for the same aggregate extracted by the ignition method was 38.2%. This increase in the L.A. abrasion value by the ignition method may result from micro-cracks in the aggregates induced while burning in the ignition furnace.

4.2.5 CAA

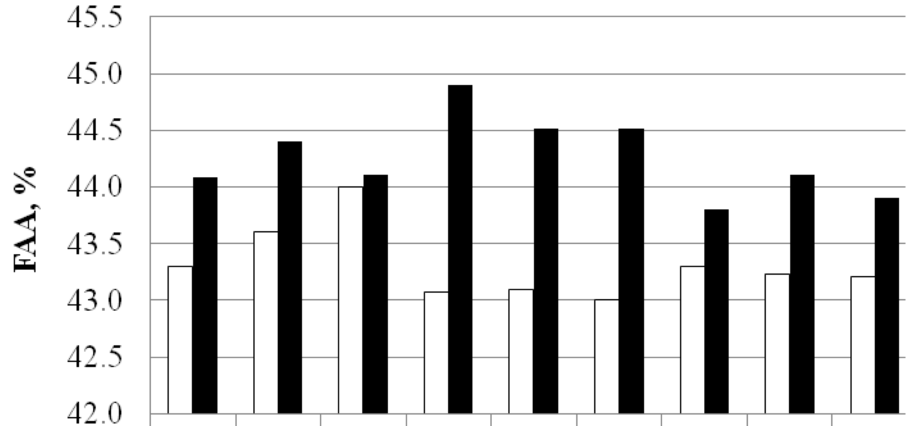
The CAA values of the two aggregate samples extracted by the centrifuge method were 97.7% and 98.0% with an average value of 97.9%. The CAA values of the two aggregate samples extracted by the ignition method were 96.7% and 98.1% with an average value of 97.4%. Therefore, these two methods resulted in similar CAA values.

4.2.6 FAA

Table 4.24 shows the comparison between FAA of the aggregates obtained by the centrifuge and ignition methods. An obvious increase in the FAA value of the aggregate extracted by the ignition method was found as compared with the centrifuge method. The burning process might cause breaking-up of particles which led to an increase in the FAA value. Although the fine particles broke up during the burning process, no significant change in the gradation of the aggregate was found. Figure 4.17 shows the comparison of FAA of the aggregates extracted by the centrifuge and ignition methods.

Table 4.24. Comparison of FAA (%) by the centrifuge and ignition methods

	FAA	**Ignition**	**Centrifuge**	**Difference**	
Sample 1	Sample 1	44.1	43.3	0.8	
	Sample 2	44.4	43.6	0.8	
	Sample 3	44.1	44.0	0.1	
	Average	44.2	43.6	0.6	
Sample 2	Sample 1	44.9	43.1	1.8	
	Sample 2	44.5	43.1	1.4	
	Sample 3	44.5	43.0	1.5	
	Average	44.6	43.1	1.6	
Sample 3	Sample 1	43.8	43.3	0.5	
	Sample 2	44.1	43.2	0.9	
	Sample 3	43.9	43.2	0.7	
	Average	43.9	43.3	0.7	



	1	2	3	4	5	6	7	8	9
Centrifuge	43.3	43.6	44.0	43.1	43.1	43.0	43.3	43.2	43.2
Ignition	44.1	44.4	44.1	44.9	44.5	44.5	43.8	44.1	43.9

Figure 4.17. Comparison of FAA of the aggregates extracted by the centrifuge and ignition methods

4.2.7 F&E Particles

The percentages of flat and elongated particles were determined on 9.5 mm and 4.75 mm size particles as 1.9% and 3.7% for the centrifuge extracted aggregates, however, 1.9% and 3.2% for the centrifuge extracted aggregates. Their average percentages of the flat and elongated particles were 2.8% and 2.6% for the centrifuge-extracted and ignition-extracted aggregates, respectively.

4.3 Asphalt Test Results

Table 4.25 shows the test results from PG grade testing done at Kansas Department of Transportation. The PG grades of the asphalt binders were PG 91+6, PG 78-12, and PG 78-10, respectively for the RAP from K-25 in Grant County, K-25 in Logan County, and US-83 in Scott County, respectively, while the original PG grades were PG 64-22, PG 52-22, and PG 64-22, respectively. This comparison shows that the asphalt binders have aged. The PG grade obtained for the asphalt extracted from the RAP samples in Grant County was higher than that from the other RAP. The tests showed that the ash content in the binder from K-25 in Grant County was 8-

12% while that from K-25 in Logan County or US-83 in Scott County was less than 1%. .The reason for the increase in the PG grade of the asphalt from Grant County is because high amount of ash was present in the asphalt sample.

Table 4.25. Asphalt binder characteristics of RAP

Sample	**K-25 (Grant)**	**K-25 (Logan)**	**US-83 (Scott)**
Viscosity, 135°C, Pa·s	2.595	0.935	1.08
Original DSR, G*/sin δ, 58°C	NA	NA	18.31
Original DSR, G*/sin δ, 64°C	36.75	6.54	7.96
Original DSR, G*/sin δ, 70°C	16.72	2.98	NA
RTFO DSR, G*/sin δ, 58°C	NA	NA	61.46
RTFO DSR, G*/sin δ, 64°C	109.8	17.86	27.36
RTFO DSR, G*/sin δ, 70°C	63.34	8.2	NA
PAV DSR, G*sin δ, 22°C	7206	5793	8020
PAV DSR, G*sin δ, 25°C	5952	4399	6181
Creep Stiffness, S, MPa, -12°C	232	149	196
Creep Stiffness, S, MPa, -18°C	370	284	354
Slope, m, -12°C	0.216	0.261	0.25
Slope, m, -18°C	0.198	0.238	0.226
Grade of Binder	91+6	78-12	78-10

4.4 Maximum Allowable Percentage of RAP Based on Test Results

The maximum allowable percentage of RAP that can be used based on the material properties from K-25 in Grant County is calculated by using both tiered and grading systems below. Since the RAP aggregates do not exceed any control points and there is little to no variability found in the properties of aggregate and binder, the RAP at K-25 in Grant County can be graded as TIER 1 following the NJDOT's recommendation (Table 4.26). NJDOT (2009) provided grading impact based on RAP variability factors and their importance as shown in

Table 4.27. The allowable percentage of RAP based on this grading system can be calculated as follows:

- Maximum percentage of RAP (Figure 4.18) = 48% for standard deviation of asphalt content = 0.21;
- Reduction factor due to variability as calculated in Table 4.28 = 83%; and
- RAP limited due to variability (%) = 48%*0.83 = 40%.

The maximum percentage of RAP that can be used is taken as the minimum of those determined by both the tiered and grading approaches. Therefore, the maximum percentage of RAP that can be used is 40%. Similarly, the percentages of RAP that can be used in K-25 in Logan County and US-83 at Scott County are 45% and 42%, respectively. It should be noted that although the standard deviations of binder content were less than 0.2% for RAP at Logan and Scott Counties, the maximum allowable percentage of RAP determined based on the MDOT's recommendation (Figure 4.18) is 50%.

Table 4.26. Tired hierarchy chart for maximum allowable RAP (NJDOT, 2009)

Grading Tiers	Criteria	Maximum Allowable RAP
1	Asphalt Content Deviation ($x<0.3$) Gradation (Meets all control points) Aggregate Properties (Little to No Variability) Binder Properties (Little to No Variability)	50%
2	Asphalt Content Deviation ($0.3<x<0.4$) Gradation (Meets all control points) Aggregate Properties (Little to No Variability) Binder Properties (Small Variability)	35%
3	Asphalt Content Deviation ($0.4<x<0.7$) Gradation (Meets all control points) Aggregate Properties (Medium Variability) Binder Properties (Small Variability)	20%
4	Asphalt Content Deviation ($x>0.7$) Gradation (Doesn’t meet control points) Aggregate Properties (Large Variability) Binder Properties (Large Variability)	15%

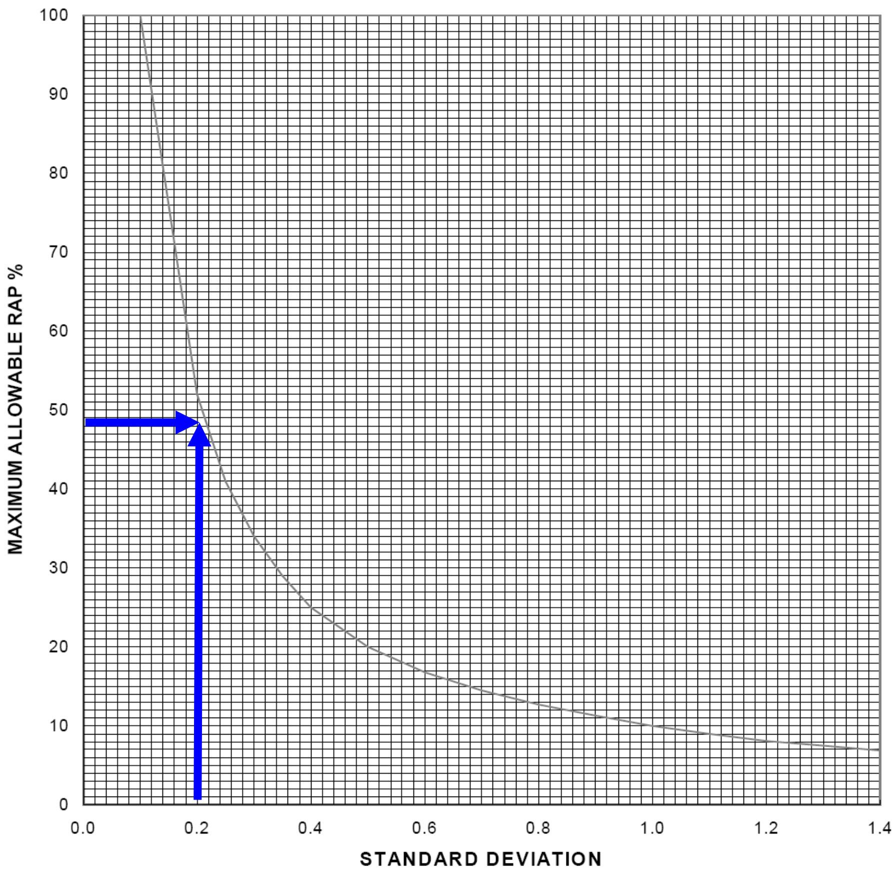


Figure 4.18. Maximum allowable RAP vs. standard deviation of asphalt content (MSHA, 1999)

Table 4.27 Impact of RAP variability factors on grading (NJDOT, 2009)

RAP Variability Factors	**Importance**	**Grading Impact (Concept ONLY)**
AC Content	High	From Equation Gives Starting Allowable RAP Percentage
		Max Score
Gradation	High	45%
CAA	Low	5%
FAA	Low	5%
F&E	Low	5%
Rotational Viscometer	Med	20%
DSR (unaged)	Med	20%

Table 4.28. Calculation of the maximum allowable percentage of RAP (K-25 in Grant County)

RAP Variability factors	**Grading Impact**	
AC Content	48% from Figure 4.18	
	Max Score (%) Table 4.27	Plant Score (%)
Gradation	45.0	40.0
CAA	5.0	5.0
FAA	5.0	5.0
F&E	5.0	3.0
Rotational viscosity	20.0	15.0 (assumed)
DSR (unaged)	20.0	15.0 (assumed)
	Final plant score	83.0

4.5 Comparison of Test Results with Original Mixes

Table 4.29 shows the binder contents determined by the centrifuge and ignition methods as compared with those in the original mixes. This comparison indicates that the binder content obtained by the centrifuge method is similar to that by the ignition method after the aggregate correction. The aggregate correction factor was obtained after burning the centrifuge-extracted RAP aggregate in the ignition oven, and loss of mass after ignition is reported as the aggregate correction factor. The comparison also indicates that the binder content of RAP did not change much due to maintenance as compared with that in the original mix except the RAP from K-25 in Logan County, in which the binder content for the RAP increased by 0.57% from the original mix. Table 4.29 also shows the asphalt binder recovered by the Abson recovery method.

Table 4.29. Comparison of binder contents in the RAP and the original mix

Source of RAP (binder grade, life period)	Presence of RAP	Orig. binder content (%)	Binder content by centrifuge method (%)	Recov. asphalt (%)	Agg. correct. factor (%)	Binder content by ignition method (%)	Correct. binder content (%)
K-25 Grant County (PG 64-22, 2003-10)	No RAP	4.80	4.54	4.12	1.12	5.89	4.77
K-25 Logan County (PG 52-22, 1997-10)	25% RAP (RAP AC 6.2%)	4.93	5.50	5.02	1.35	6.76	5.41
US-83 Scott County (PG 64-22, 2002-10)	14.26% RAP (RAP AC 5.6%)	5.05	4.85	4.63	1.23	6.29	5.06

Table 4.30 shows the comparison of bulk specific gravity and absorption of the aggregates in the RAP and the original mix. The comparison shows that the bulk specific gravity of coarse and fine aggregates did not change significantly, however, the absorption value of the aggregate extracted by the ignition method was found to increase in most cases. The reason for this increase may result from the formation of microcracks near the surface of each aggregate due to burning. However, the absorption values of the aggregates extracted by the centrifuge

method were lower than those in the original mix. The lower absorption values may result from small amount of asphalt remaining in the aggregates.

Table 4.30. Comparison of bulk specific gravity and absorption of aggregates in the RAP and the original mix

Description of Material	Fine aggregate specific gravity		Coarse aggregate specific gravity		Fine aggregate absorption (%)		Coarse aggregate absorption (%)	
	Orig.	**RAP**	**Orig.**	**RAP**	**Orig.**	**RAP**	**Orig.**	**RAP**
K-25 in Grant County(Coarse Aggregate-Granite, Fine aggregate- Klotz Sand)	2.551	2.527 (2.541)	2.556	2.525 (2.573)	1.1	1.24 (0.79)	1.5	2.04 (1.04)
K-25 in Logan County (Coarse Aggregate-Granite, Fine aggregate- Klotz Sand)	2.558	2.504	2.556	2.537	1.1	1.52	1.5	1.79
US-83 in Scott County (Coarse Aggregate-Granite, Fine aggregate- Klotz Sand)	2.551	2.542	2.556	2.492	1.1	1.06	1.5	2.08

Note: All properties of aggregates in RAP were determined using the aggregates extracted by the ignition method except those in parenthesis by the centrifuge method.

Table 4.31 shows the comparison of FAA, CAA, dust to binder ratio, and L.A. abrasion value of the aggregates in the RAP and the original mix. The CAA values increased significantly from the original values to 97% in all cases, however, the FAA values almost remained the same for the RAP from K-25 in Grant County but increased by 3% for the RAP from US-83 in Scott County. The L.A. abrasion values varied from 35% to 39% for the aggregates in all RAP, in which the aggregate extracted by the centrifuge method had the lowest value. Table 4.31 also shows a significant increase of the dust to binder ratio. This increase may result from the burning of the aggregates.

Table 4.31. Comparison of FAA, CAA, Dust to Binder (D/B), and L.A. of the aggregates in the RAP and the original mix

Description of Material	FAA (%)		CAA* (%)		D/B		% UV**	L.A. (%)
	Orig.	RAP	Orig.	RAP	Orig.	RAP	RAP	RAP
K-25 in Grant County (Coarse Aggregate-Granite, Fine aggregate- Klotz Sand)	44	43.2 (44.2)	88	97.4 (97.9)	1.00	1.81	43.8	38.2 (35.4)
K-25 in Logan County (Coarse Aggregate-Granite, Fine aggregate- Klotz Sand)	~	42.9	~	97.4	~	1.56	45.7	38.6
US-83 in Scott County (Coarse Aggregate-Granite, Fine aggregate- Klotz Sand)	42	44.8	78	96.8	0.87	1.77	45.4	38.5

Note: All properties of aggregates in RAP were determined using the aggregates extracted by the ignition method except those in parenthesis by the centrifuge method. *% particles with fractured faces and **% UV is% uncompacted voids.

Figure 4.19 shows the difference in the percent passing of the aggregates at different particle sizes between the RAP and the original mix. Figure 4.19 indicates that the difference in percent passing is the highest for the particle sizes ranging from 1.18 to 2.36 mm. Figure 4.20 shows the power gradation curves for all aggregate samples from the RAP. It is shown that the aggregates from the RAP follow all the Superpave control points.

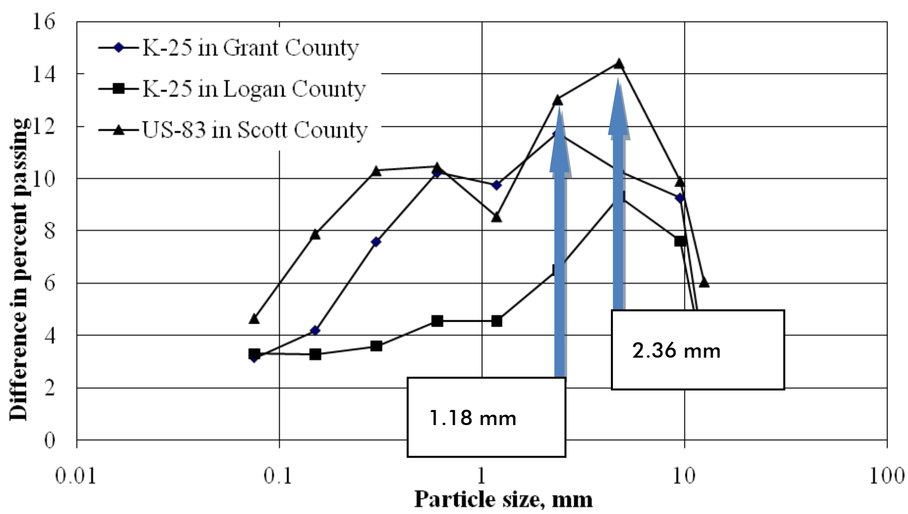


Figure 4.19. Difference in percent passing between RAPs and original mixes

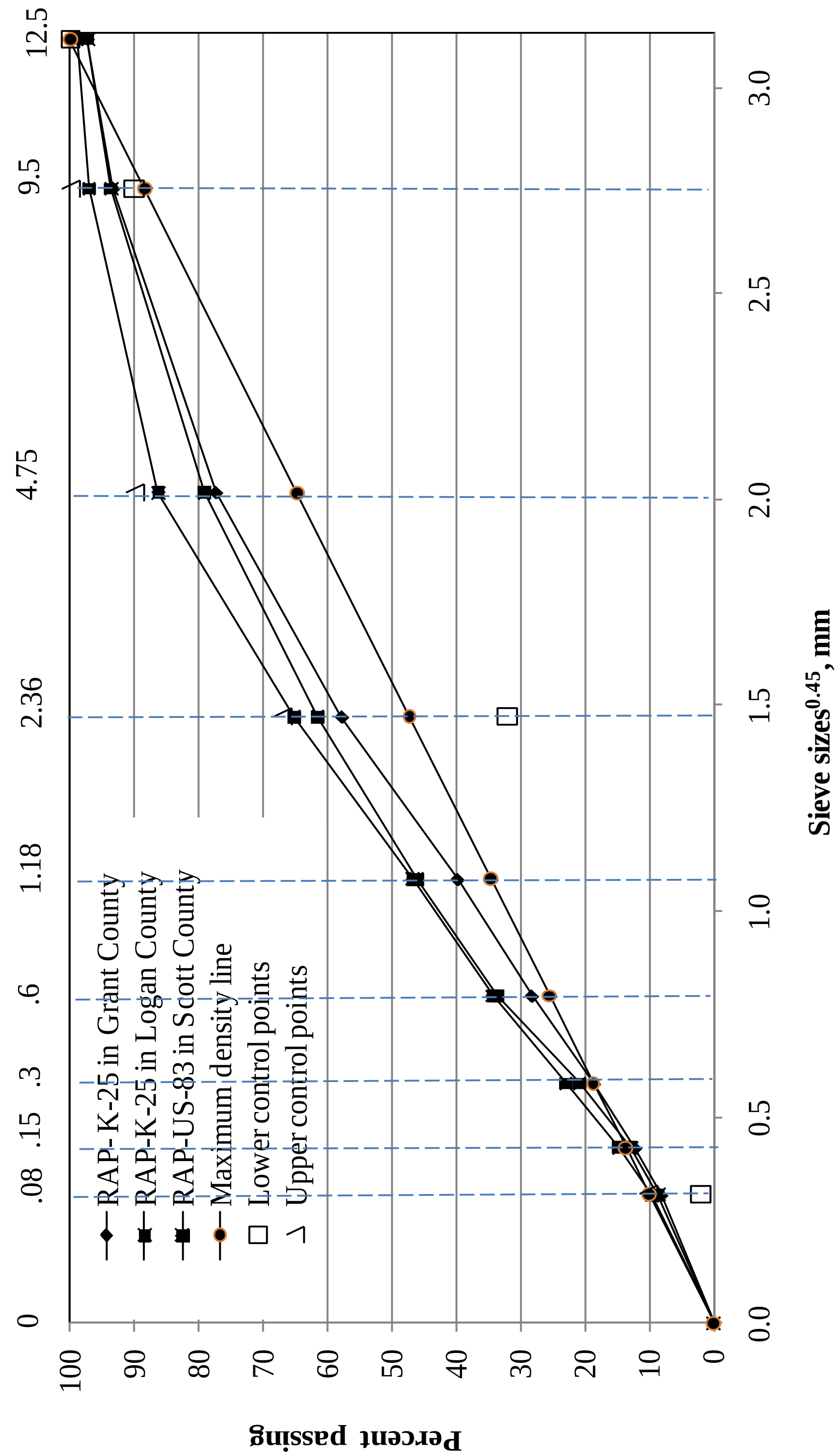


Figure 4.20. Power gradation of the RAPs

4.6 Summary of Test Results on RAP Aggregates

Table 4.32 summarizes the test results on binder contents and properties of RAP aggregates extracted by the ignition method.

Table 4.32. Summary of test results on RAP aggregates

Property	K-25 at Grant County	K-25 at Logan County	US-83 at Scott County
Binder Content	The average binder content and standard deviation of eleven RAP samples were 5.89% and 0.2%, respectively.	The average binder content and standard deviation of eleven RAP samples were 6.76% and 0.08%, respectively.	The average binder content and standard deviation of three RAP samples determined by the ignition method were 6.29% and 0.12%, respectively
Specific Gravity and Absorp.	The bulk specific gravity of coarse and fine aggregates from RAP decreased by 1.22% and 0.95%, respectively from the original mix. The absorption for coarse and fine aggregates increased by 25% and 13%, respectively.	The bulk specific gravity of coarse and fine aggregates from RAP decreased by 0.75% and 1.83%, respectively from the original mix. The absorption for coarse and fine aggregates increased by 25% and 17%, respectively.	The bulk specific gravity of coarse and fine aggregates from RAP decreased by 2.57% and 0.35%, respectively from the original mix. The absorption for coarse aggregate increased by 25% and that for fine aggregate remained unchanged.
CAA	The CAA value of RAP aggregate increased by 9.4% from the original mix.	The CAA value of RAP aggregate increased to 97% in the RAP.	The CAA value of RAP aggregate increased by 18.8% from the original mix.
FAA	The FAA value of RAP aggregate decreased by 1% from the original mix.	The FAA value of RAP aggregate was 43%.	The FAA value of RAP aggregate increased by 3% from the original mix.
F & E Particles	The percentage of F & E particles of RAP aggregate was 2.6%.	The percentage of F & E value of RAP aggregate was 3.5%.	The percentage of F & E value of RAP aggregate was 5.3%.
L.A. Test	The L.A. abrasion value of the RAP aggregate extracted by the ignition method was 38.2%. This test revealed that the RAP aggregate was not of uniform hardness.	The L.A. abrasion value of the RAP aggregate extracted by the ignition method was found to be 38.6%. This test revealed that the RAP aggregate was not of uniform hardness.	The L.A. abrasion value of the RAP aggregate extracted by the ignition method was found to be 38.5%. This test revealed that the RAP aggregate was not of uniform hardness.

Table 4.32. Summary of test results on RAP aggregates (continued)

Property	K-25 at Grant County	K-25 at Logan County	US-83 at Scott County
Gradation	The percentage of fine particles increased from the original mix to the RAP samples due to compaction and milling processes. The percent passing on the median sieve size (No 8, 2.36 mm) increased by 12% from the original mix. The median size remained unchanged before and after RAP. The percent passing on the 75 micron sieve increased by 3%. The standard deviation for the 2.36 mm size was the maximum (5.5%). The dust to binder ratio increased by 0.81%. The power gradation of the RAP aggregate follows all the control points.	The percentage of fine particles increased from the original mix to the RAP samples due to compaction and milling processes. The percent passing on median sieve size (No 16, 1.18 mm) increased by 4% from the original mix. The median size changed before (2.36 mm) and after RAP (1.18 mm). The percent passing on 75 micron sieve increased by 4%. The standard deviation for the 2.36 mm sieve size was the maximum (2.62%). The dust to binder ratio was 1.56%. The power gradation of RAP aggregate follows all the control points.	The percentage of fine particles increased from the original mix to the RAP samples due to compaction and milling processes. The percent passing on median sieve size (No 16, 1.18 mm) increased by 9% from the original mix. The median size changed before (2.36 mm) and after RAP (1.18 mm). The percent passing on 75 micron sieve increased by 4%. The standard deviation for the 2.36 mm sieve size was the maximum (3.19%). The dust to binder ratio increased by 0.9%. The power gradation of RAP is within upper and lower control points.

4.7 Summary of Comparison of Ignition and Centrifuge Tests Conducted on RAP Samples from K-25 in Grant County

Ignition and centrifuge extraction methods may result in different binder contents and properties of aggregates. Below are the summary of the findings from this study:

- The binder content obtained by the ignition method after the aggregate correction was 0.03% less than that obtained by the centrifuge method.
- The difference in the gradation of RAP aggregates extracted by the ignition and centrifuge methods was within a permissible range.
- The bulk specific gravity of coarse and fine aggregates extracted by the ignition method was 1.87% and 0.55% less than that by the centrifuge method respectively. However, the absorption of the coarse and fine aggregates extracted by the ignition method was 96% and 59% higher than that by the centrifuge method, respectively.

- The L.A. abrasion value for the aggregate extracted by the ignition method was 2.8% higher than that by the centrifuge method.
- The CAA values for the aggregate extracted by the centrifuge and ignition methods were almost same.
- The FAA value for the aggregate extracted by the ignition method was approximately 1% higher than that of the centrifuge method.
- The percentage of F&E particles for the aggregate extracted by the ignition method was 0.6% lower than that by the centrifuge method.

As compared with the centrifuge method, the ignition method is easier, quicker, and less costly to determine binder content and produce sufficient amount of aggregate for property testing. However, the ignition method may change the properties of aggregate more than the centrifuge method due to the generation of micro-cracks in aggregate by heat. The ignition method can be a preliminary method to determine binder content and properties of aggregate. The binder content determined by the ignition method should be corrected for loss of aggregate mass due to burning-off. Correlations may be developed for properties of specific aggregate between ignition and centrifuge methods. Since the ignition method overestimates L.A. abrasion values, it would be considered acceptable if the estimated L.A. abrasion value is less than a required value. Under such a circumstance, no centrifuge method is necessary.

Chapter 5: Conclusions and Recommendations

5.1 Conclusions

Based on the test results and analyses, the following conclusions can be drawn from this study:

- The binder contents of RAP from three counties in Kansas varied from 4.77% to 5.06% (after correction for the ignition method). The standard deviation for the binder contents of the RAP varied from 0.08% to 0.21%.
- The bulk specific gravity of the coarse aggregates extracted from the RAP by the ignition method decreased by 0.8% to 2.6% from the original mixes, however, the bulk specific gravity of the fine aggregates decreased by 0.4% to 1.9%.
- The absorption of the coarse aggregates extracted by the ignition method increased by 25% for each source of RAP from the original mixes, however, the absorption of the fine aggregates increased by 0 to 17% from the original mixes. A small standard deviation was found in the absorption and specific gravity values.
- The nominal maximum sizes of the aggregates extracted from the RAP by the ignition method decreased by one size (from 12.5 mm in the original mix to 9.5 mm in the RAP) in all cases. The percentage of the finer particles on the median sieve size (1.18 mm for the RAP in Logan County and Scott County, and 2.36 mm for the RAP in Grant County) increased by 4% to 12% from the original mixes. The percent passing through the 75 micron sieve increased by 3 to 4% for the RAP. The dust to binder ratio increased by 0.8 to 0.9%. The power gradations of the RAP did not exceed any control points.
- The CAA values of aggregates extracted by the ignition method increased from 78% to 88% for the original mixes to 96.8% to 97.4% for the RAP. The FAA values decreased from 44% for the original mix to

43.2% for the RAP at K-25 Grant County, and increased from 42% for the original mix to 44.8% for the RAP at US-83 Scott County.

- The L.A. Abrasion values of the extracted RAP aggregates by the ignition method varied from 38.2% to 38.5%. The percentage of flat and elongated particles varied from 2.6% to 5.3%.
- The ignition method provided comparable results to the centrifuge method of extraction for gradation, CAA value, and percentage of flat and elongated particles for the RAP from K-25 in Grant County. However, the FAA value was 1% higher in the ignition-extracted aggregate than in the centrifuge-extracted aggregate. The L.A. abrasion value obtained for the ignition-extracted aggregate was 2.8% higher than that for the centrifuge-extracted aggregate. The bulk specific gravity obtained by the centrifuge method was higher than that by the ignition method. It was also found that the increase in the bulk specific gravity was accompanied by the decrease in the absorption of the aggregates.
- The ignition method can be used as a preliminary method to determine binder content and properties of aggregate. The binder content determined by the ignition method should be corrected for loss of aggregate mass due to burning-off. Correlations may be developed for properties of specific aggregate between ignition and centrifuge methods.
- The PG grade of the RAP from K-25 in Grant County changed from PG 64-22 to PG 91+6. This result was affected by the high amount (8-12%) of ash present in the binder before testing.
- The PG grade of the RAP from K-25 in Logan County changed from PG 52-22 to PG 78-12. The ash content in the RAP was less than 1%.
- The PG grade of the RAP from US-83 in Scott County changed from PG 64-22 to PG 78-10. The ash content in the RAP was less than 1%.

Based on MDOT (1999) and NJDOT (2009) recommendations, the maximum allowable percentage of RAP that can be used varied from 40% to 45% based on the properties of the RAP investigated in this study.

5.2 Recommendations

This study has mainly focused on the laboratory evaluation of characteristics of the RAP from three project sites in Kansas. The maximum allowable percentage of RAP to be incorporated in new HMA calculated in this study just gives a rough estimate. This percentage depends on the variability of binder content and properties of aggregates extracted from RAP. In this study, their variability was small. Based on the tiered and grading systems suggested by NJDOT (2009), a higher percentage of RAP is allowed. To make a recommendation about the use of a higher percentage of RAP, performance testing and more extensive lab testing on characteristics of RAP should be done to cater the variability of RAP, but they are beyond the scope of this research. The binder test results show that the binders in RAP from three project sites in this study were significantly aged. This fact should be considered in the selection of virgin binder PG when a higher percentage of RAP is included. Aggregate property testing shows that the coarse aggregates from the RAP had one-size smaller nominal maximum particles and higher coarse aggregate angularity than those in the original mix. These changes will affect the volumetric analysis of the Superpave mix design. The effect of these changes should be investigated and is beyond the scope of this research.

In this study, the comparison was made between the properties of RAP aggregates extracted by the ignition and centrifuge methods for only one source of the RAP from K-25 in Grant County. It should be noted that the effect of the extraction method may be different for different types of aggregate. The aggregate properties evaluated in this study may be used as a reference to determine composite properties of virgin and RAP using a blending formula.

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