DEVELOPMENT OF QUALITY STANDARDS FOR INCLUSION OF HIGH RECYCLED ASPHALT PAVEMENT CONTENT IN ASPHALT MIXTURES

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16. ABSTRACT

The main objective of this research is to examine the effects that different methods of RAP stockpile fractionation would have on the volumetric mix design properties for high-RAP content surface mixes, with the goal of meeting all specified criteria for standard HMA mix designs. To determine the distribution of fine aggregates and binder in RAP stockpile, RAP materials were divided by each sieve size. The composition of RAP materials retained on each sieve was analyzed to determine the optimum fractionation method. Fractionation methods were designed to separate the stockpile at a specified sieve size to control the amount of fine RAP materials which contain higher amounts of fine aggregates and dust contents. These fine RAP materials were used in reduced proportions or completely eliminated, thereby decreasing the amount of fine aggregate materials introduced to the mix. Mix designs were performed using RAP materials from four different stockpiles and the two fractionated methods were used with high-RAP contents up to 50% by virgin binder replacement. By using a fractionation method, a mix with up to 50% RAP was successfully designed while meeting all Superpave criteria and asphalt film thickness requirement by controlling the dust content from RAP stockpiles.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

The main objective of this research is to examine the effects that different methods of RAP stockpile fractionation would have on the volumetric mix design properties for high-RAP content surface mixes, with the goal of meeting all specified criteria for standard HMA mix designs. To determine the distribution of fine aggregates and binder in RAP stockpile, RAP materials were divided by each sieve size. The composition of RAP materials retained on each sieve was analyzed to determine the optimum fractionation method. Fractionation methods were designed to separate the stockpile at a specified sieve size to control the amount of fine RAP materials which contain higher amounts of fine aggregates and dust contents. These fine RAP materials were used in reduced proportions or completely eliminated, thereby decreasing the amount of fine aggregate materials introduced to the mix. Mix designs were performed using RAP materials from four different stockpiles and the two fractionated methods were used with high-RAP contents up to 50% by virgin binder replacement. By using a fractionation method, a mix with up to 50% RAP was successfully designed while meeting all Superpave criteria and asphalt film thickness requirement by controlling the dust content from RAP stockpiles.

1. INTRODUCTION

Recycled asphalt pavement (RAP) materials have been used widely in the U.S. and are the world's most recycled product. In 2008, NAPA set a goal to double the national average RAP content from 12% to 24% in five years (*1*). McDaniel et al. recommended that, based on the results from this regional study, mixes with higher RAP contents up to 50% can be designed under the Superpave mix design system (*2*).

One of the most difficult aspects of high-RAP mix design is meeting the volumetric mix design criteria specifications, namely the film thickness and dust-binder ratio limits, due to the large amount of fine aggregate material introduced to the HMA mix by the RAP materials. The increased amount of fine aggregate in the RAP materials, compared to the original mix design gradation, is attributed to the aggregate degradation during the milling and processing operations (*3*). The Iowa Department of Transportation currently limits the maximum RAP use for the surface course to 15% (*4*). More than 15% RAP material can only be used when there is quality control sampling and testing of the RAP material; however, at least 70% of the total asphalt binder must be from a virgin source (*4*).

High-RAP contents also require changes in the performance grade of the virgin binder used because of the increased stiffness of the aged RAP binder. McDaniel et al. reported that, based on indirect tensile strength, the stiffness of mixtures with a high RAP content (>20%) were so high that they may be susceptible to low temperature cracking (*5*). Beeson et al. (*6*) concluded that up to 22% RAP can be added to the mixture before changing the low temperature grade of the -22 binder and up to 40% RAP can be added to a mixture as long as the virgin binder grade is one grade lower than what is expected. It was also concluded that it was more helpful to evaluate high-RAP content mixtures in terms of percent virgin binder replacement of the RAP material, rather than the percent of the weight added. If the amount of recycled binder from the RAP material exceeds 20% of the total asphalt binder, the Iowa DOT requires that the designated virgin binder grade for the mix must be lowered by one temperature grade (*4*, *7*).

1.1 Research Objective

The objective of this research is to examine the effects of different methods of RAP stockpile fractionation on the volumetric mix design properties of high-RAP content surface mixes while meeting all specified criteria for standard HMA mix designs. Fractionation methods were designed to separate the stockpile at predetermined sizes to isolate RAP materials within the stockpile that contained higher amounts of fine aggregate and negatively impacted the volumetric properties of the HMA mix design. These isolated materials were then used in reduced proportions or completely eliminated from the total RAP included in the mixture, thereby decreasing the amount of fine aggregate material introduced by the RAP. Mix designs were performed for a low-volume (300,000 ESAL), ½" mix-size surface mixture with RAP contents accounting for replacement of up to 50% of the total mixture's asphalt binder. RAP materials were used from both the original stockpile and lab-produced stockpiles created by the designed fractionation methods. The resulting properties of each mix design were compared to determine if the volumetric improvements towards meeting Iowa DOT mix design criteria can be attributed to the fractionation methods.

1.2 Benefits of the Study

Increasing the amount of RAP materials used in low-volume, surface course mixtures will substantially improve the long-term sustainability of the transportation network in Iowa. The 300,000 ESAL mixture designed in this study is applicable to a majority of the local, city road network as well as a significant portion of the rural, farm-to-market road networks. High-RAP content mix designs would decrease the cost of maintaining and resurfacing these networks because the increased use of RAP materials significantly reduces the amount and cost of virgin aggregate and asphalt binder needed by the contractor to produce the asphalt mixture, thereby decreasing the amount of aggregate that must be quarried and the amount of oil that must be purchased. The percentage of savings in material cost should be equal to the amount of RAP material used in the mixture.

2. HIGH-RAP USAGE IN PRACTICE

Recycled asphalt pavement (RAP) materials consist of the components used to create the original pavement's mix design; therefore the material composition of the individual RAP particles is a collection of the original mixture's aggregate materials held together by the original asphalt binder. These original pavements have been constructed under a specified mix design procedure that established requirements for material properties such as the aggregate gradation, aggregate source and binder quality as well as for the volumetric properties of the mixture at the optimum asphalt binder content. Inspection of the materials at the top of Figure 2-1 shows that these large pieces of recycled asphalt pavement contain a range of aggregate sizes similar to what would be expected from an original HMA mix design.

These larger sections of removed pavements exhibit material composition very similar to the homogeneous mixture of the original HMA mix design because the material is largely undisturbed during recycling. RAP materials with recovered aggregate gradation and asphalt content equivalent to the original mix design are ideal for use in high-RAP content mixtures because they can be combined with a virgin HMA mixture and still meet all mix design criteria. However, in construction practice these large RAP "chunks" will not break apart sufficiently when heated in the asphalt plant to allow for proper blending with virgin material. As a result, the pavement material milled from the roadway must be processed further (see bottom right of Figure 2-1) and the material composition should be reanalyzed to account for the material degradation (*3*).

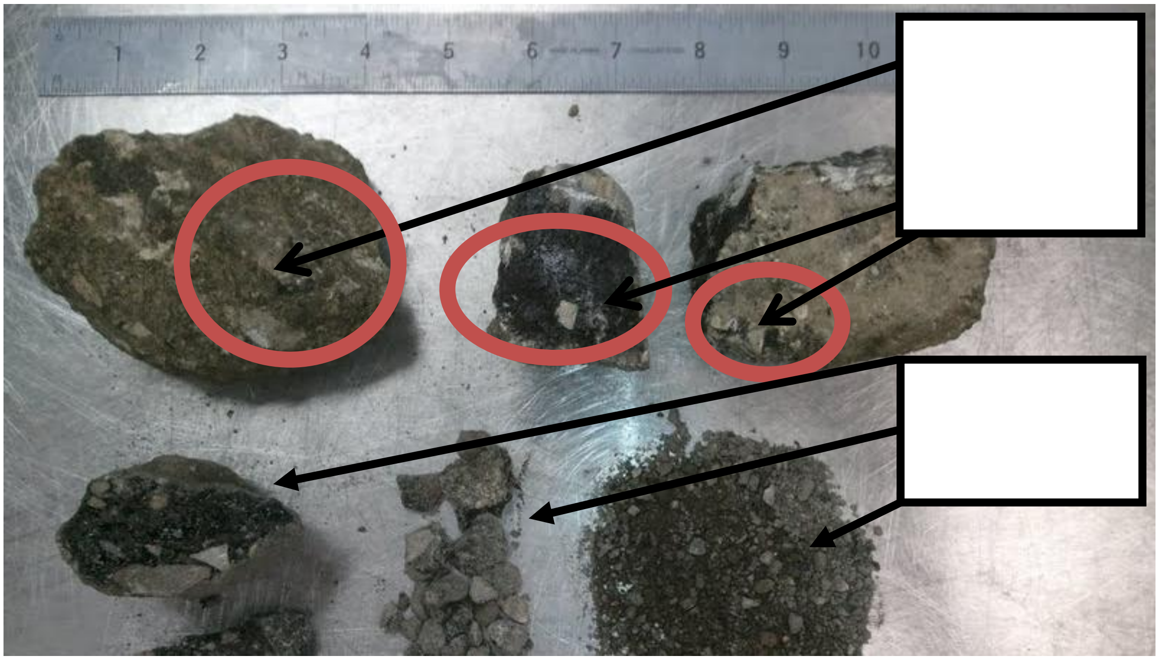


Figure 2-1: Recycled Asphalt Pavement Material Composition

2.1 RAP Usage and Regulation in 10 Midwestern States

The procedures that involve the processing/stockpiling of RAP materials and how they are to be used in HMA surface mixtures vary considerably around the nation. The allowable amount of RAP material that can be included in the surface course is limited by the state DOT's in order to mitigate the negative impacts that high-RAP contents would have on the volumetric mix design, asphalt binder properties and long-term performance of the pavement. Additional specifications are often included to ensure that the asphalt binder and aggregate properties of the combined mixture are equivalent to HMA mixtures without RAP materials. Table 2-1 summarizes the specifications regarding RAP usage from the 10 Midwestern states of Illinois, Indiana, Iowa, Kansas, Michigan, Minnesota, Missouri, Nebraska, South Dakota and Wisconsin.

2.2 RAP Stockpile Categorization and Processing Methods

Table 2-1 shows that, while all the Midwestern states allow RAP materials to be used in the surface course, certain states have adopted specifications intended to more strictly control the amount and the procedure how these materials are introduced to the mixture. For example, Iowa DOT and Illinois DOT have adopted the categorization system that classifies the RAP stockpiles by the source so that the RAP with high-quality aggregate properties (friction classification, angularity, bulk specific gravity, etc.) can be identified for usage in higher percentages for the surface course mixtures. Table 2-2 outlines the criteria for the three RAP categories established by the Iowa DOT and their allowable usage in different pavement layers. No other Midwestern states specify any requirement for the stockpiling of RAP materials other than to prevent segregation and foreign material.

Table 2-1: Iowa DOT RAP Stockpile Categorization Criteria & Allowable Usage

Classified RAP	Certified RAP	Unclassified RAP
Requirements	Requirements	Requirements
- Documented source	- Undocumented Source	- Undocumented source
- High Aggregate Quality	- Lower Aggregate Quality	- Unknown/Poor Aggregate
- Stockpiled Separately	- Poor Stockpiling	- Poor Stockpiling
- Meets Quality Control	- Meets Quality Control	- No Quality Control
Allowable Usage	Allowable Usage	Allowable Usage
-15% weight in surface	-10% surface $\leq$ 300K ESAL	- 0% surface for all ESAL
-Min. 70% virgin AC	-20% Interm. $\leq$ 1M ESAL	- 10% Interm. $\leq$ 1M ESAL
-No limit in other layers	-20% Base for all ESAL	- 10% Base for all ESAL

Source: Section 2303. Hot Mix Asphalt Mixtures. Iowa DOT Standard Specifications (*4*)

Table 2-2: DOT Standards and Specifications for RAP Usage in Midwestern States

State	Stockpile Categorization	Processed Material Requirements	Fractionation Specification
Illinois(8)	▪ Categorized based on source and aggregate type ▪ 'Homogeneous'; 'Conglomerate'; 'Conglomerate "D" Quality' and 'Other'	▪ 'Homogeneous' – Single-pass millings allowed by Engineer if gradation & AC% meet tolerances ▪ 'Conglomerate' – processed to 5/8 inch top size	▪ No mention of increased allowable RAP content for usage of Fractionated RAP materials
Indiana(9)	▪ No stockpile classifications mentioned ▪ RAP source not tracked ▪ RAS materials must be from manufacturing facility waste only and stockpiled separately	▪ All RAP processed to 2 inch top size at plant ▪ For ESAL $\geq$ 3 million RAP processed so that 100% passing 3/8" and min. 95% passing No. 4 to ensure high friction of recovered aggregate	▪ No mention of increased allowable RAP content for usage of Fractionated RAP materials
Iowa(10)	▪ Categorized based on source and aggregate type 1. 'Classified RAP' 2. 'Certified RAP' 3. 'Unclassified RAP'	▪ All RAP processed to 1.5 inch top size ▪ Once RAP material has been categorized it must remain separately stockpiled to prevent contamination	▪ "*Additional actions to improve RAP consistency including further crushing, screening into coarse and fine fractions, or blending by proportioning*" ▪ No mention of increased allowable RAP content
Kansas(11)	▪ No stockpile classifications mentioned ▪ Prevent segregation and foreign material	▪ All RAP processed to 2¼ inch top size before entering HMA plant	▪ No mention of increased allowable RAP content for usage of Fractionated RAP materials
Michigan(12)	▪ No stockpile classifications mentioned ▪ Prevent segregation and foreign material	▪ Process RAP to "compatible size" for HMA mix ▪ Perform mixture analysis for every 1000 tons of processed RAP material	▪ No mention of increased allowable RAP content for usage of Fractionated RAP materials
Minnesota(13)	▪ No stockpile classifications mentioned ▪ RAP with objectionable material NOT allowed ▪ RAS materials only from manufacturing facility	▪ No processing procedures mentioned ▪ 97% passing max. aggregate size of mix design allowed if oversized material comes from RAP	▪ No mention of increased allowable RAP content for usage of Fractionated RAP materials
Missouri(14)	▪ No stockpile classifications mentioned ▪ Prevent segregation and foreign material	▪ No processing procedures mentioned for RAP ▪ RAS materials must be ground to 3/8" minus	▪ No mention of increased allowable RAP content for usage of Fractionated RAP materials
Nebraska(15)	▪ No stockpile classifications mentioned ▪ Prevent segregation, remove foreign material, and smooth surface of stockpile site	▪ All RAP processed to 2 inch top size	▪ No mention of increased allowable RAP content for usage of Fractionated RAP materials
South Dakota(16)	▪ No stockpile classifications mentioned ▪ Prevent segregation and foreign material	▪ No processing procedures mentioned for RAP	▪ No mention of increased allowable RAP content for usage of Fractionated RAP materials
Wisconsin(17)	▪ No stockpile classifications mentioned ▪ Prevent segregation and foreign material	▪ No processing procedures mentioned for RAP	▪ FRAP defined as "*existing asphaltic pavement processed to control gradation properties*" ▪ "*Treated the same as RAP and allows for slight increase to binder replacement percentages*"

Table 2-2 (cont): DOT Standards and Specifications for RAP Usage in Midwestern States

State	Maximum RAP % in Surface	Binder Grade Change	Volumetric Mix Design Criteria
Illinois (8)	▪ No specified max. for High & Low ESAL Mixes ▪ Engineer can adjust quantity based on test results ▪ Only 'Homogeneous' or 'Conglomerate' allowed	▪ RAP > 15% may require softer binder as determined by engineer ▪ RAP not allowed with polymer-modified binder	▪ % Pass #200 – Max 6% or 8% (High/Low ESAL) ▪ Dust/Binder – Max 1.0 @ design ▪ VMA – Min. 14.0% (1/2" mix); VFA – 65-75%
Indiana (9)	▪ Max 15% RAP (3% RAS) by weight for surface course mixtures with ESAL $\geq$ 3 million ▪ Max 25% RAP (5% RAS) by weight all other mix	▪ RAP > 15% and up to 25% requires reduction of upper and lower PG grade by one temp. classification	▪ % Pass #200 – Max 10% (1/2" mix size) ▪ Dust/Binder – 0.6 to 1.2 (% pass > PCS ctrl. pt.) ▪ VMA – Min 14.0% (1/2" mix); VFA – 65-78%
Iowa (10)	▪ Max 15% Classified RAP by weight in surface for all ESAL levels (min. 70% virgin binder) ▪ Max 10% Certified RAP by weight in surface for ESAL $\leq$ 300K (not allowed for ESAL < 300K)	▪ RAP > 20% binder replacement requires lower PG grade by one temperature classification ▪ RAP > 30% requires blending analysis	▪ % Pass #200 – Max 10% (1/2" mix size) ▪ Dust/Binder – 0.6 to 1.4 for all mixtures ▪ VMA – Min 14.0% (1/2" mix); VFA – 70-80% ▪ Film Thickness – Min 8.0 μm
Kansas (11)	▪ Max RAP % specified in project's Contract Documents ▪ No Maximum Allowable % specified for state	▪ No % RAP threshold specified for modification of virgin asphalt binder PG grade	▪ % Retained #200 – Max 10% (1/2" mix size) ▪ Dust/Binder – 0.6-1.2 (1/2" A) or 0.8-1.6 (1/2" B) ▪ VMA – Min 14.0% (1/2" mix)
Michigan (12)	▪ No specification for Maximum Allowable RAP %	▪ No % RAP threshold specified for modification of virgin asphalt binder PG grade	▪ Mix design evaluated by entering the Superpave Mix Design data with MDOT's Bituminous Mix Design Computer Program
Minnesota (13)	▪ Max. 30% RAP by weight allowed in surface course for all ESAL levels ▪ Max 5% RAS by weight	▪ Section 2360.2 G1 gives virgin grade for RAP% ▪ Certain virgin binder not allowed RAP > 20% ▪ Any RAS use requires virgin binder for > 20%	▪ % Pass #200 – Max 7% (all mix size) ▪ Dust/Binder – 0.6 to 1.3 (Level 2 wearing course) ▪ VMA – Min 15.0% (1/2" mix); VFA – 65-78%
Missouri (14)	▪ RAP > 30% allowed provided AASHTO M323 testing ensures PG grade meets contract specs. ▪ No specification for Maximum Allowable RAP %	▪ Max. 30% virgin binder replacement by RAP without changing virgin PG grade ▪ RAP > 30% may require binder grade change to meet PG grade specified in contract	▪ % Pass #200 – Max 10% (1/2" mix size) ▪ Dust/Binder – 0.8 to 1.6 (all mixtures) ▪ VMA – Min 14.0% (1/2" mix); VFA – 65-78%
Nebraska (15)	▪ Max. 35% RAP allowed (< 300K ESAL) ▪ Max. 25% RAP allowed (300K to 10M ESAL) ▪ Max. 15% RAP allowed (10M to 30M ESAL)	▪ If maximum allowable RAP % is exceeded for agiven mix design (Table 1028.01) the PG grade must be lowered one grade	▪ % Pass #200 – Max 10% (1/2" mix size) ▪ Dust/Binder – 0.7 to 1.7 (all mixtures) ▪ VMA – Min 14.0% (1/2" mix); VFA – 65-78%
South Dakota (16)	▪ No specification for Maximum RAP%	▪ No % RAP threshold specified for modification of virgin asphalt binder PG grade	▪ Gyratory mix design submitted to SD DOT Mix Design Lab by Contractor for verification and testing of mineral aggregate and asphalt mixture
Wisconsin (17)	▪ Max. > 25% binder replacement by RAP, FRAP or RAS combination allowed for surface layers without virgin binder PG grade change ▪ RAP > 25% allowed if binder meets contract specs	▪ If RAP usage exceeds maximum allowable percentage specified in Section 460.2.5 the virgin asphalt PG grade must be modified so that the resultant binder meets the contract spec.	▪ % Pass #200 – Max 10% (1/2" mix size) ▪ Dust/Binder – 0.6 to 1.2 (all mixtures) ▪ VMA – Min 14.0% (1/2" mix); VFA – 65-78%

The Midwestern states also have varying specifications regarding how the RAP material must be processed prior to stockpiling, namely the maximum ‘top size’ of material that can be introduced to the asphalt plant. Regarding the top size criterion, Iowa is among the most conservative states in the region by requiring that all RAP material be processed to a maximum of 1.5 inches. The top size is controlled to allow for the materials to break apart and blend with the virgin material when heated and mixed in the asphalt plant. Reducing the top size of the processed RAP material can also improve the consistency of the stockpiled material and increase the frictional properties of the recovered aggregate (as intended by the Illinois’ ‘Conglomerate’ material requirement and the Indiana’s requirement for high-ESAL mixtures) (*8, 9, 18*). However, the increased processing required to achieve a smaller top size will increase the dust content (minus No. 200 material) of the RAP leading to a difficulty in meeting required mix design criteria (such as combined gradation, VMA, film thickness and dust-binder ratio) at high-RAP content mixes (*18*).

The increased dust content created during the processing is caused by the crushing operation used to break down the RAP material in the recycling plant. Certain crushing operations, such as impact crushers or hammer mills, will create more dust out of the processed materials because their mechanical processes result in many aggregates being broken and crushed as the RAP is processed (*18*). For example, the Astec Prosizer™ recycling plant (shown in Figure 2-2) utilizes a horizontal impact crusher to break apart the RAP materials that are fed into the system (see Figure 2-3). This system uses a 6-inch screen at the point where material is fed into the plant to remove very large chunks. All materials that enter the plant (regardless of size) pass through the crushing operation before they are screened to the required top size. This process allows for smaller RAP materials, which already meet the top size requirement, to be unnecessarily crushed resulting in a higher amount of the dust material.

Other states in the Midwestern region (Indiana, Kansas and Nebraska) have larger allowable top size requirements for their processed RAP material, which would reduce the amount of processing that is required and result in lower amount of dust content material (*18*). Also, Illinois allows its highest category of RAP material (‘Homogenous RAP’) to be used directly from “*single-pass millings*” without any processing, crushing or screening required. Fractionation of RAP materials has been identified as a processing method that can improve the properties of the RAP material and allow for increased allowable usage (*17*). Fractionation methods have been applied by contractors for many years and for many different purposes; however, this generally involves splitting the RAP materials into coarse and fine stockpiles (*18*).

Figure 2-2: Recycled Asphalt Pavement Processing Equipment - Astec Prosizer™

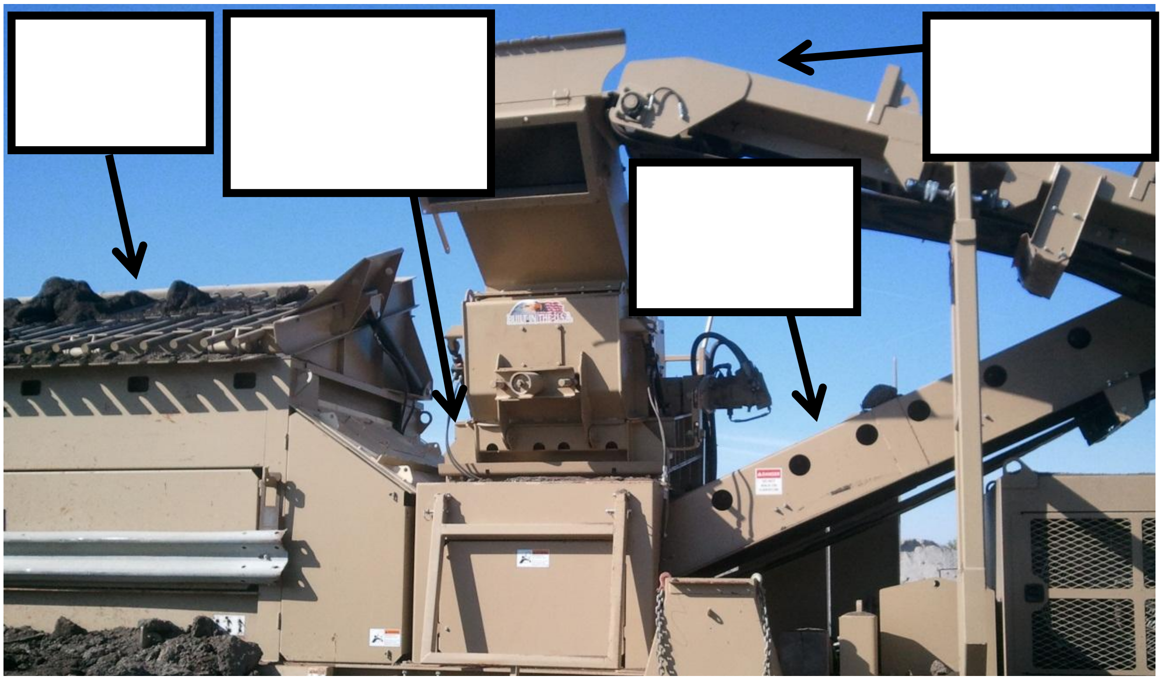


Figure 2-3: RAP Processing Equipment - Hammer Mill Crusher

2.3 High-RAP Mix Design Requirements

The maximum RAP percentage allowed in surface course mixtures is limited due to the exposure to traffic loading and environmental conditions. The maximum allowable RAP usage for the surface layer is further reduced for higher ESAL pavements. The Iowa DOT specifications are on the conservative side of the Midwestern region by only allowing a maximum of 15% Classified RAP usage in the surface course for any ESAL category and only 10% Certified RAP in the surface course for pavements with less than or equal to 300,000 ESAL's.

A primary concern with high-RAP content mixtures is the resultant performance grade of the blended asphalt binder. Assuming that all volumetric mix design criteria are met, many of the state DOT specifications require the use of a 'softer' virgin asphalt binder (i.e. lower PG grade) when the RAP materials account for a certain percentage of virgin binder replacement or mixture weight. The Iowa DOT specifications for this criterion are similar to other Midwestern states (*5, 6*). The modification of the virgin binder PG grade is to ensure that the blended asphalt mixture would meet the specified binder grade of the project's contract specifications.

All high-RAP content mixtures that reach the binder grade change threshold must still meet all volumetric mix design criteria associated with virgin HMA mixtures. The required mix design properties pertaining to high-RAP content mixtures are consistent throughout the region (i.e. maximum dust content, dust-binder ratio, VMA, VFA); however the numerical tolerances for each property vary slightly for each state. Due to the high amount of fine aggregate material in the RAP, these volumetric mix design properties are usually the controlling criteria for the amount of RAP material that can be used by the contractors. This increased dust content of the RAP material, attributed to the removal and processing operations, impacts the combined aggregate structure to the point that these criteria cannot be met for high-RAP content mixtures.

Iowa DOT requires an additional specification for the volumetric mix design criteria of HMA mix designs, the asphalt film thickness of the combined mixture. This property accounts for the total aggregate surface area that must be coated with the available asphalt binder in the mixture. The dust content increases the combined aggregate surface area which would result in a difficulty of meeting the film thickness requirement for high-RAP content mixtures (*19*). The film thickness and voids in mineral aggregate (VMA) criteria evolved from 1950's research to improve HMA mix durability (*20*).

2.4 Methods to Improve High-RAP Mix Design

It is important to evaluate the effectiveness of these specifications on limiting the negative impacts of the volumetric properties associated with high-RAP contents on the HMA mixture (increased dust content and decreased low-temperature binder performance). Also, new procedures that can mitigate the negative impacts of those high-RAP properties should be explored so that contractors have alternatives available in order to use the maximum percentage of RAP materials allowed under the current specifications.

The properties of the existing pavement (before removal) should be very similar to the mix design criteria requirements of the new pavement to be constructed. If the composition of the original mixture could be maintained throughout the removal and processing operations, most of those RAP materials could be reused without any negative impact on the volumetric properties of the new mixture. However; the properties of the original mix design, namely the aggregate gradation, are significantly modified as the pavement is milled from the roadway and processed into stockpiles. As a result, the extent to which these stockpiled RAP materials can be reused in new mix designs is limited.

The focus of this research is to investigate methods of addressing the potential negative impacts of the recycled asphalt pavement materials and thereby increase the amount of RAP material that can be used in the target mix design (300K ESAL ½" HMA surface mixture). As stated in the Wisconsin DOT specifications, the fractionation of RAP materials can improve the properties of the RAP material and allow for increased allowable usage (*17*). The purpose of fractionation for this research is to decrease the amount of fine aggregate material that would be introduced to the HMA mixture by the RAP material. To effectively design these fractionation methods, all RAP materials used in the study were extensively analyzed to determine the appropriate sieve size thresholds for separation of the original RAP stockpiles.

3. DETAILED RAP MATERIAL COMPOSITION ANALYSIS

Samples of four different RAP materials were obtained from stockpiles at a local, eastern-Iowa contractor's asphalt plant facility. All four materials had already been analyzed by the Iowa DOT Central Materials Laboratory for chemical binder extraction testing, recovered aggregate gradation analysis, aggregate testing and stockpile categorization. A detailed analysis was performed on each RAP stockpile to investigate the material composition of the four RAP stockpiles.

3.1 Composition Analysis of Classified RAP from Airport

The first RAP stockpile used in the study (referred to herein as Stockpile A) is composed solely of millings from the removal of an Eastern Iowa Airport runway in June 2010. The pavement was designed in the early 1990's as a 3/4" FAA P401 mix design. The stockpiled material met the criteria of 'Classified RAP'. Figure 3-1 shows the recovered aggregate gradation after extraction, the allowable gradation range for the original mix design and the gradation of the RAP materials. As can be seen from Figure 3-1, the RAP materials exhibited a coarser gradation than extracted aggregates because each RAP particle contains a range of aggregate sizes still held together by the asphalt binder. The recovered aggregate gradation from the RAP material shows an extremely fine gradation (16% dust content) that is outside the control points for the original mix design due to the aggregate degradation that occurred during the removal and processing operations (*3*).

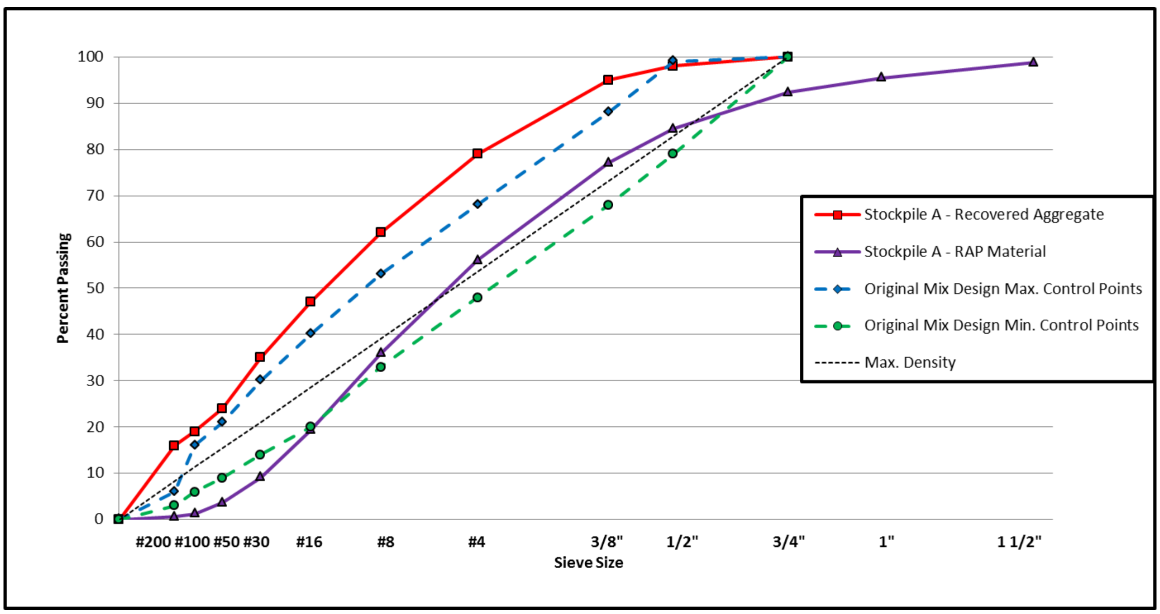


Figure 3-1: Recovered Aggregate & RAP Material Gradation Comparison - Stockpile A

The next step is to develop a relationship between the gradation of the stockpiled RAP materials and the gradation of the recovered aggregates. First, the Stockpile A RAP material was separated by sieve sizes ranging from 1½" down to No. 200 and an ignition-oven binder burn-off test was performed on the sample of each RAP material size. A gradation analysis was then performed on the recovered aggregates from each RAP-size sample.

Table 3-1 shows a summary of the material composition of each RAP particle size (i.e. recovered aggregate composition and binder content) as well as the distribution of those RAP material sizes in the overall stockpile. The 'Coarse RAP' materials (RAP materials retained on No. 4 sieve or larger) have a lower amount of the very fine aggregate materials (particles retained on the No. 50, No. 100, No. 200 and Pan) than the 'Fine RAP' materials (RAP materials passing No. 4 sieve). These 'Fine RAP' materials (dark-shaded in Table 3-1) make up 56% of Stockpile A and contain 63% of the total dust content from the recovered aggregate. It should be noted that the dust content is very high at 16%. Although the 'Fine RAP' materials are main source of dust content, they contain significant percentages of recoverable asphalt binder (especially No. 16 and No. 30 size RAP materials).

3.2 Composition Analysis of Certified RAP from Airport

The second RAP stockpile used in the study (referred to herein as Stockpile B) is composed primarily of millings from the same Eastern Iowa Airport runway as the Classified RAP material of Stockpile A. However, while the material was stockpiled at the contractor's facility there were small amounts of another RAP material added to the stockpile. As a result, the stockpile underwent further quality control testing to become 'Certified RAP'. The results of the composition analysis for the Stockpile B Certified RAP materials are shown in Table 3-2. The recovered aggregate gradation of the Certified RAP material from Stockpile B is very similar to the Classified RAP material from Stockpile A. Stockpile B is slightly coarser than Stockpile A with smaller amount of dust content than Stockpile A The Fine RAP materials make up 50% of the material and contain 61% of the dust content from the recovered aggregate.

3.3 Composition Analysis of Certified RAP from Unknown Sources

The third RAP material used in the study (referred to herein as Stockpile C) is a stockpile that contained a combination of RAP materials from multiple sources and was therefore initially categorized as 'Unclassified RAP'. The material then underwent extensive quality control testing to accurately determine the necessary properties of the material within specified levels of certainty to become 'Certified RAP' (*21*). As shown in Yable 3-3, Stockpile C is coarser than Stockpiles A and B with less dust content (10%). The increased amount of larger RAP materials in this stockpile can be attributed to the fact that the milling operation likely passed at a more shallow depth and faster speed; thereby not degrading the original pavement materials as extensively as Stockpile A and B.

Table 3-1: Sieve-Size-Separated RAP Material Composition Analysis - Stockpile A

Size of RAP	Recovered Aggregate Composition After Ignition Oven Burn-Off – (% Retained)											Asphalt Content %	% of Stockpile	% of Dust Content
	¾”	½”	3/8”	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200	Pan			
1 1/2”	0.0	7.9	9.7	19.8	16.4	11.4	8.3	7.5	4.4	2.1	12.5	**6.32**	**1.29**	**1.05**
1”	2.1	9.3	7.3	17.6	15.0	10.9	9.1	8.7	5.1	2.4	12.6	**5.81**	**3.22**	**2.63**
¾”	7.5	4.9	7.9	17.4	13.6	9.9	9.0	9.2	5.3	2.4	13.0	**5.62**	**3.14**	**2.66**
½”	---	21.9	11.9	14.1	10.1	7.6	7.3	7.6	4.7	2.3	12.4	**5.46**	**7.85**	**6.35**
3/8”	---	---	26.6	22.7	10.5	7.3	6.7	6.8	4.7	2.3	12.6	**5.16**	**7.36**	**6.01**
No. 4	---	---	---	47.8	12.3	7.0	6.5	7.2	3.9	1.9	13.4	**5.74**	**21.10**	**18.36**
No. 8	---	---	---	---	53.9	10.0	6.3	7.7	4.4	2.1	15.6	**5.07**	**20.14**	**20.41**
No. 16	---	---	---	---	---	40.9	17.6	11.8	6.8	3.5	19.4	**6.93**	**16.56**	**20.94**
No. 30	---	---	---	---	---	---	53.3	18.8	6.3	2.8	18.8	**6.79**	**10.25**	**12.50**
No. 50	---	---	---	---	---	---	---	81.1	4.6	1.4	13.0	**5.31**	**5.43**	**4.57**
No. 100	---	---	---	---	---	---	---	---	75.0	9.1	15.9	**5.69**	**2.44**	**2.52**
No. 200	---	---	---	---	---	---	---	---	---	65.5	34.5	**3.59**	**0.62**	**1.39**
Normalized Composite	0.3	2.3	3.5	14.3	16.2	12.3	12.8	13.2	6.7	3.0	15.4	**5.81**	**99.4%**	**99.4%**
DOT Extraction	0	2	3	16	17	15	12	11	5	3.0	16.0	**5.41**		
Coarse RAP Est. Gradation	0.7	5.2	8.0	32.4	12.0	7.8	7.1	7.4	4.4	2.1	13.0	**5.61**	**44.0%**	**37.1%**
Fine RAP Est. Gradation	0	0	0	0	19.6	15.8	17.4	17.7	8.5	3.6	17.3	**5.98**	**56.0%**	**62.9%**

Table 3-2: Sieve-Size-Separated RAP Material Composition Analysis - Stockpile B

Size of RAP	Recovered Aggregate Composition After Ignition Oven Burn-Off – (% Retained)											Asphalt Content %	% of Stockpile	% of Dust Content
	¾”	½”	3/8”	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200	Pan			
1 1/2”	0.0	3.1	4.1	16.2	20.9	14.0	11.2	11.1	4.9	2.7	11.8	**5.76**	**0.48**	**0.38**
1”	0.0	5.4	7.9	18.6	17.9	11.9	9.6	10.1	4.4	2.2	12.3	**5.72**	**3.91**	**3.22**
¾”	6.4	5.6	7.2	17.5	16.0	11.1	9.1	9.8	4.1	2.2	11.0	**5.64**	**5.64**	**4.16**
½”	---	14.8	11.2	15.9	13.6	9.7	8.4	9.1	4.0	2.3	11.0	**5.33**	**11.42**	**8.42**
3/8”	---	---	21.7	28.6	11.2	7.9	6.8	7.4	3.5	2.2	10.7	**4.55**	**8.14**	**5.84**
No. 4	---	---	---	40.8	20.8	7.4	6.2	7.0	3.4	2.3	12.1	**4.84**	**21.04**	**17.07**
No. 8	---	---	---	---	45.9	17.6	6.4	7.4	4.0	3.0	15.7	**5.52**	**20.32**	**21.39**
No. 16	---	---	---	---	---	43.4	17.6	9.8	5.2	3.7	20.3	**6.63**	**14.81**	**20.15**
No. 30	---	---	---	---	---	---	50.5	18.6	5.8	3.8	21.3	**6.78**	**8.41**	**12.00**
No. 50	---	---	---	---	---	---	---	71.5	7.8	3.4	17.3	**5.75**	**3.95**	**4.58**
No. 100	---	---	---	---	---	---	---	---	66.2	10.1	23.7	**6.25**	**1.09**	**1.73**
No. 200	---	---	---	---	---	---	---	---	---	75.0	25.0	**6.23**	**0.38**	**0.64**
Normalized Composite	0.4	2.2	3.8	14.6	17.9	14.5	12.0	11.5	5.0	3.2	14.9	**5.58**	**99.6%**	**99.6%**
DOT Extraction	1	4	4	17	17	13	10	12	5	3	14	**5.11**		
Coarse RAP Est. Gradation	0.7	4.4	7.5	28.7	16.9	8.8	7.4	8.1	3.7	2.3	11.5	**5.07**	**50.6%**	**39.1%**
Fine RAP Est. Gradation	0	0	0	0	19.1	20.4	16.6	15.0	6.3	4.1	18.4	**6.11**	**49.4%**	**60.9%**

Table 3-3: Sieve-Size-Separated RAP Material Composition Analysis - Stockpile C

Size of RAP	Recovered Aggregate Composition After Ignition Oven Burn-Off – (% Retained) ¾”	½”	3/8”	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200	Pan	Asphalt Content %	% of Stockpile	% of Dust Content
1 1/2”	---	---	---	---	---	---	---	---	---	---	---	---	---	0.00
1”	0.0	4.5	5.8	25.8	16.9	10.3	9.5	12.9	6.4	1.4	6.5	**5.17**	**1.19**	**0.86**
¾”	1.2	14.1	7.4	21.2	13.6	8.7	8.3	11.5	5.7	1.4	6.7	**4.95**	**5.71**	**4.23**
½”	---	10.7	18.0	22.7	11.4	7.4	6.9	9.7	5.0	1.5	6.8	**4.62**	**17.60**	**13.24**
3/8”	---	---	21.2	32.1	10.6	6.7	6.3	9.0	4.8	1.6	7.5	**4.47**	**12.24**	**10.21**
No. 4	---	---	---	49.3	15.0	5.4	5.0	8.8	5.5	2.1	8.8	**4.49**	**28.45**	**27.88**
No. 8	---	---	---	---	53.6	11.6	5.7	10.0	6.0	2.2	10.9	**5.18**	**14.60**	**17.61**
No. 16	---	---	---	---	---	51.3	14.2	13.3	7.5	2.5	11.2	**6.15**	**8.89**	**11.11**
No. 30	---	---	---	---	---	---	54.4	23.0	8.5	2.5	11.6	**6.62**	**6.34**	**8.21**
No. 50	---	---	---	---	---	---	---	78.9	6.9	2.0	12.2	**6.57**	**3.76**	**5.11**
No. 100	---	---	---	---	---	---	---	---	85.4	3.2	11.5	**7.22**	**0.92**	**1.17**
No. 200	---	---	---	---	---	---	---	---	---	87.6	12.4	**3.81**	**0.20**	**0.28**
Normalized Composite	0.1	2.7	6.3	23.5	16.4	10.5	9.6	13.2	6.6	2.2	9.0	**5.03**	**99.9%**	**99.9%**
DOT Extraction	0	12	8	19	15	10	9	10	5	2.0	10.3	**4.82**		
Coarse RAP Est. Gradation	0.1	4.2	9.6	36	13.1	6.6	6.2	9.4	5.3	1.8	7.8	**4.57**	**65.2%**	**56.4%**
Fine RAP Est. Gradation	0	0	0	0	22.5	18.0	16.0	20.3	9.0	2.9	11.3	**5.89**	**34.8%**	**43.6%**

3.4 Composition Analysis of Certified RAP from Interstate 80

The fourth RAP material used in the study (referred to herein as Stockpile D) consists of highway millings from Interstate 80 in eastern Iowa that were stockpiled at the contractor's asphalt plant. Millings were obtained at a high speed and a shallow depth from the surface, resulting in a small amount of dust content. As shown in Table 3-4, the recovered aggregate gradation was very similar to Stockpile C with a dust content of 10.7%. The RAP materials met the criteria for Iowa DOT's 'Classified RAP'.

3.5 Summary of RAP Material Composition Analysis

The RAP material composition analysis was conducted on each of four stockpiles. The 'Coarse RAP' category was defined as RAP materials retained on a No. 4 sieve. The gradation of recovered fine aggregates from the 'Coarse RAP' category was very consistent and the dust content was low whereas that of recovered aggregates from 'Fine RAP' category was highly variable and the dust content was high. As expected, the Fine RAP materials exhibited higher recovered asphalt binder content.

Figure 3-2 shows the gradations of four RAP stockpiles where Stockpiles C and D are coarser than Stockpiles A and B. The milling operation seemed to have influenced the amount of 'Coarse RAP' and 'Fine RAP' materials produced. Slower, deeper milling passes seemed to break down the pavement so that almost all of the millings will pass the maximum top size; however, the extensive material degradation increased the amount of 'Fine RAP' and dust content (Stockpile A and B). Faster and shallow depth milling seemed to have produced more 'Coarse RAP' materials and less dust content (Stockpile C and D. As can be seen from Figure 3-2, an excessive amount of RAP materials passing No. 200 sieve is the main cause for not meeting the gradation requirements specified by Iowa DOT.

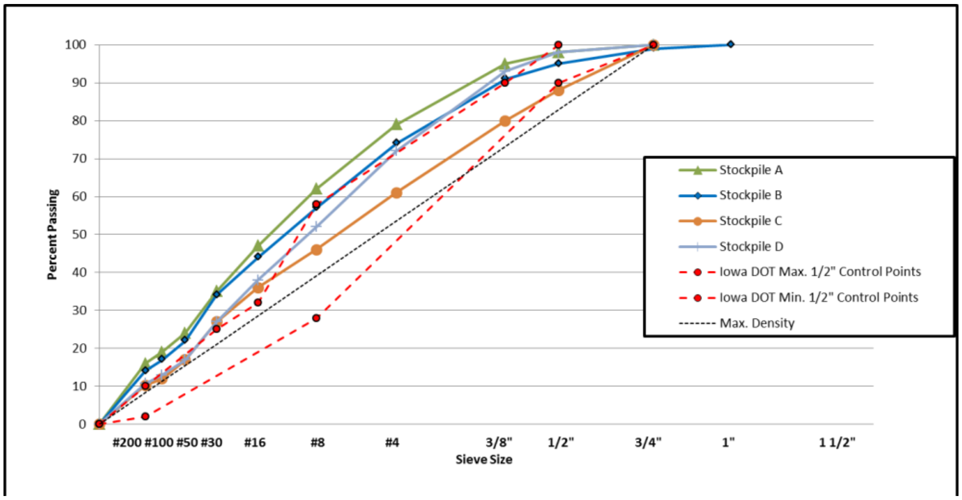


Figure 3-2: Recovered Aggregate Gradations of Four RAP Stockpiles

Table 3-4: Sieve-Size-Separated RAP Material Composition Analysis - Stockpile D

Size of RAP	Recovered Aggregate Composition After Ignition Oven Burn-Off – (% Retained)											Asphalt Content %	% of Stockpile	% of Dust Content
	¾”	½”	3/8”	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200	Pan			
1 1/2”	0.0	3.9	4.7	27.5	20.1	13.9	9.6	7.6	3.8	1.4	7.6	**4.66**	**4.15**	**3.30**
1”	0.0	5.5	5.7	27.7	18.8	12.8	8.7	7.6	3.8	1.4	8.0	**4.78**	**5.54**	**4.61**
¾”	1.1	1.1	10.0	6.2	27.6	16.2	10.9	8.3	7.8	3.7	7.2	**4.61**	**6.41**	**4.79**
½”	---	20.8	10.6	20.8	13.6	9.6	7.0	6.2	3.3	1.2	7.0	**4.09**	**12.68**	**9.26**
3/8”	---	---	39.81	21.9	10.2	7.2	5.2	5.0	2.7	1.0	5.7	**3.62**	**8.62**	**5.11**
No. 4	---	---	---	56.1	15.8	7.2	5.4	5.3	2.8	1.0	5.4	**3.66**	**22.18**	**14.91**
No. 8	---	---	---	---	65.2	12.0	5.5	5.7	3.1	1.1	7.5	**4.43**	**15.56**	**12.13**
No. 16	---	---	---	---	---	61.7	13.6	7.4	3.9	1.6	11.8	**5.55**	**10.38**	**12.82**
No. 30	---	---	---	---	---	---	60.8	14.9	5.0	1.9	17.4	**6.72**	**6.12**	**11.13**
No. 50	---	---	---	---	---	---	---	67.2	7.4	2.5	23.0	**7.98**	**4.35**	**10.45**
No. 100	---	---	---	---	---	---	---	---	64.2	7.5	28.3	**9.34**	**2.08**	**6.15**
No. 200	---	---	---	---	---	---	---	---	---	57.2	42.8	**9.74**	**0.98**	**4.37**
Normalized Composite	0	3	6	20	20	14	10	9	5	2.1	9.6	**4.75**	**99.1%**	**99.1%**
Binder Extraction	0	2	5	21	20	14	11	10	4	2.3	10.7	**4.00**		
Estimated Coarse RAP	0	5	10	34	16	10	7	6	4	1.4	6.7	**4.02**	**59.6%**	**42.0%**
Estimated Fine RAP	0	0	0	0	26	21	15	14	7	3.2	13.8	**5.86**	**40.4%**	**58.0%**

The combined recovered aggregate gradation of the Coarse RAP material from each stockpile was developed by normalizing the aggregate distribution of each Coarse RAP material size its percentage of the stockpile. Extracted aggregates from the Coarse RAP materials were similar to the original mix design gradation, whereas those from the Fine RAP materials were significantly different from the original mix design gradation with a higher amount of fine aggregate material. As a result the use of a smaller RAP top size will increase the dust content because this will increase the percentage of Fine RAP material in the stockpile.

The amount of dust created during processing the RAP depends on both the crushing system and the top size selected (*18*). Hammer mill impact crushers result in many aggregates being broken and crushed as the RAP is processed; while jaw crusher operations allow the chunks of RAP material to be separated and reduced to the desired top size without breaking and crushing the aggregates. Since it may not be practical for a contractor to change their crushing operation, the focus for limiting the impact of the crushing operation should be to reduce the amount of materials that go through this process while achieving the required top size of the RAP material.

RAP materials thought to be suitable for high-RAP mix design (i.e. original pavement with high-quality aggregate, binder and strictly controlled gradation) should be identified as they come into the contractor's possession and screened at the required top size prior to crushing, sampling and categorization. This preliminary material fractionation allows RAP materials that were already broken up sufficiently during the milling operation to bypass the crusher and avoid further material degradation. The screened RAP materials larger than the allowable top size can then be run through the RAP processing equipment and then sampled and categorized separately. This change for RAP processing operation result in RAP stockpiles containing significantly higher proportions of Coarse RAP material. Also, an increase in the top size requirement could further improve the properties of these RAP stockpiles.

4. DESIGN OF FRACTIONATION METHODS

During the milling/crushing process of RAP materials, a significant aggregate degradation has occurred resulting in the excessive amounts of fine aggregates. Due to the excessive fine materials, it is difficult for high-RAP content mixes to meet the volumetric mix design criteria such as the combined aggregate gradation, dust-binder ratio and film thickness. Therefore, to satisfy the mix design criteria, it is necessary to fractionate the RAP materials.

The main objective of fractionation is to remove fine aggregates from the original RAP stockpile while retaining the coarse aggregates with high asphalt content. Based on the sieve-by-sieve analysis of RAP materials, two fractionation methods are proposed: 1) 'Fractionated RAP' method and 2) 'Optimum FRAP' method. The 'Fractionated RAP' method is to remove the RAP materials passing through No. 30 sieve for Stockpile A, B and C and No. 16 sieve for Stockpile D. The Optimum FRAP method is to divide the stockpile into fine and coarse stockpiles (No. 4 sieve was selected as a threshold to divide Stockpiles of A, B and C and 3/8" sieve for Stockpile D) and then re-proportioned to reduce the percentage of fine stockpiles included in the Optimum FRAP mix.

Table 4.1 summarizes the gradation and asphalt content of Traditional, Fractionated, FRAP Coarse and FRAP Fine stockpiles. As can be seen from Table 4.1, the dust content (minus No. 200) decreased for both Fractionated and Optimum FRAP stockpiles. As expected, the FRAP Fine stockpile exhibited a significantly higher binder content than the FRAP Coarse stockpile. However, the binder content in the Fractionated stockpile is greater than that in the Traditional stockpile.

Table 4.1 Gradations and AC Contents of Original and Fractionated Stockpiles

RAP Material	Fractionation	3/4"	1/2"	3/8"	No.4	No.8	No.16	No.30	No.50	No.100	No.200	Gsb	%Abs.	AC%
Classified A	Traditional	100	98	95	79	62	47	35	24	19	16	2.614	1.38	5.41
	Frac.(-#30)	100	97.3	92.7	76.8	57.9	42.3	29.3	20.3	16.7	14.1	2.614	1.38	5.7
	FRAP CA (No.4)	100	94.5	86	53.4	39.5	30.5	22.9	14.8	11.2	9.1	2.614	1.38	5.57
	FRAP FA (No.4)	100	100	100	100	82.7	60.8	44.9	30.9	23.3	18.4	2.614	1.38	6.01
Classified-B	Traditional	100	95	91	74	57	44	34	22	17	14	2.58	2.22	5.11
	Frac.(-#30)	100	97	93.5	77	57.9	42.8	29.8	20.6	16.4	13.6	2.58	2.22	5.34
	FRAP CA (No.4)	100	94.4	86.6	57.4	40.5	32.1	24.8	16.9	13.3	11.1	2.58	2.22	4.92
	FRAP FA (No.4)	100	100	100	100	80.4	59.4	43.1	28.8	22.9	19.1	2.58	2.22	5.85
Classified-C	Traditional	100	88	80	61	46	36	27	17	12	10	2.597	1.5	4.82
	Frac.(-#30)	100	97	91.7	67.3	47.6	35.7	25.7	15.5	10.3	8.5	2.597	1.5	4.83
	FRAP CA (No.4)	100	91.1	81.4	50.8	34	27.6	21.8	13.4	8.7	7.2	2.597	1.5	4.41
	FRAP FA (No.4)	100	100	100	100	78	58	42.1	23.6	15.8	13.1	2.597	1.5	5.81
Classified-D	Traditional	100	98	93	72	52	38	27	17	13	10.7	2.65	1.19	4
	Frac.(-#16)	100	96.5	91.1	62.6	40.7	25.9	18.4	12	8.8	7.6	2.65	1.19	4.33
	FRAP CA (3/8")	100	88.1	74.7	51.3	36.1	25.8	18.8	11.9	8.5	7.3	2.65	1.19	4.31
	FRAP FA (3/8")	100	100	100	79.5	57.5	42.2	30.7	20.5	15.2	13.1	2.65	1.19	4.98

4.1 'Fractionated RAP' Method

The Astec Prosizer^{TM} processing equipment with a high-frequency vibration screening mechanism was used to effectively separate the RAP materials at small particle sizes. Figure 4-1 shows how the crushed RAP material is conveyed to the top of the screening system where it passes over the top size screen to retain any materials that must be sent for re-crushing (insert of Figure 4-1). The smaller processed materials pass through the top size screen and over a second stacked screen which fractionates the material based on the size of the lower screen's openings. Figure 4-2 shows the coarser gradation of four Fractionated Stockpiles than the original stockpile. The Fractionated Stockpile D was coarsest while meeting the Iowa DOT requirement. The Fractionated Stockpile C almost met Iowa DOT requirement whereas the Fractionated Stockpiles A and B did not.

The 9% of Stockpile A passed No. 30 sieve and they were discarded from the stockpile. Table 4-2 summarizes the reduction of very fine aggregate materials passing No. 30 sieve in the Fractionated stockpile A. After removing all RAP materials passing No. 30 sieve, the minus No. 200 is still very high at 14.1%.

Table 4-2: Fine Aggregate Reduction of Fine RAP Removal - Fractionated RAP-A

RAP Stockpile	Fine Aggregate Composition – (% Retained)				% of Stockpile
	No. 50	No. 100	No. 200	Pan	
Original Stockpile	11.0	5.0	3.0	16.0	**35.0%**
Fractionated RAP	9.0	3.6	2.6	14.1	**29.3%**

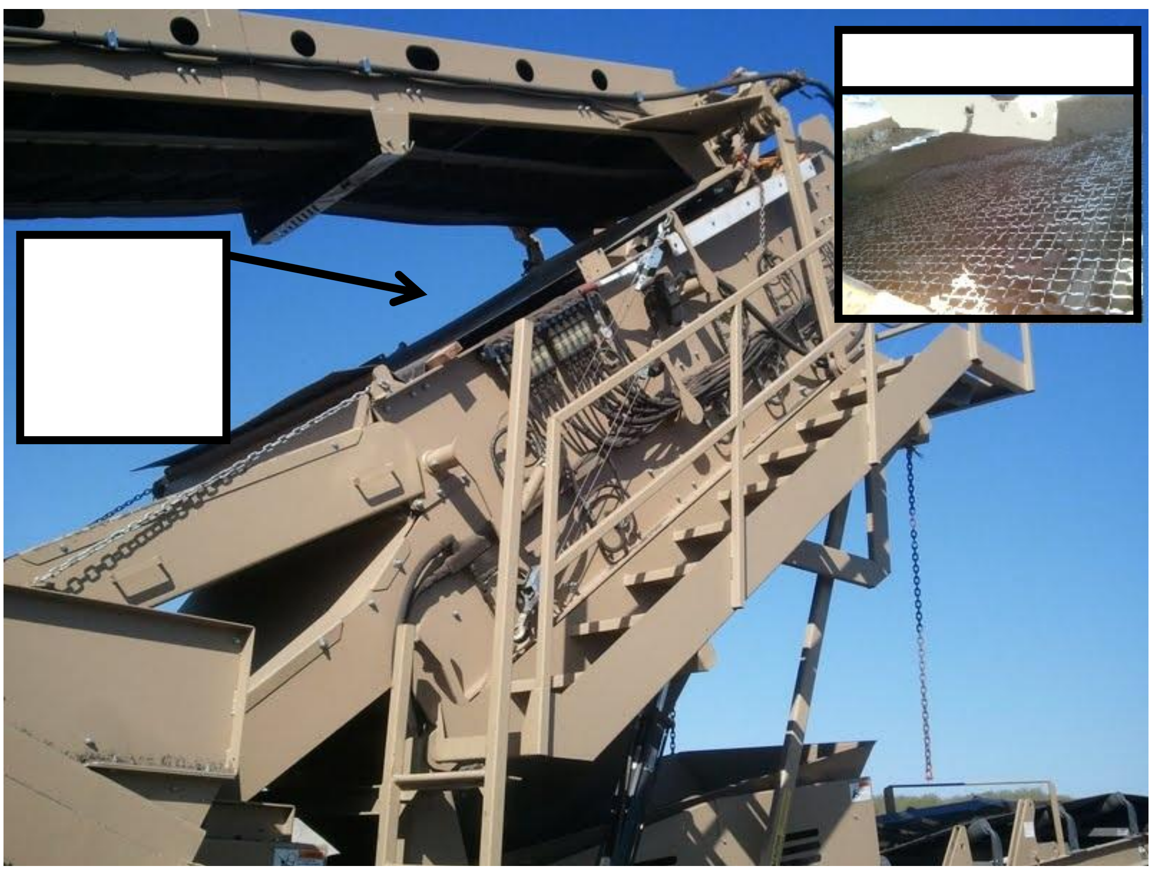


Figure 4-1: High-Frequency, Stacked-Screening Operation for Fine RAP Removal

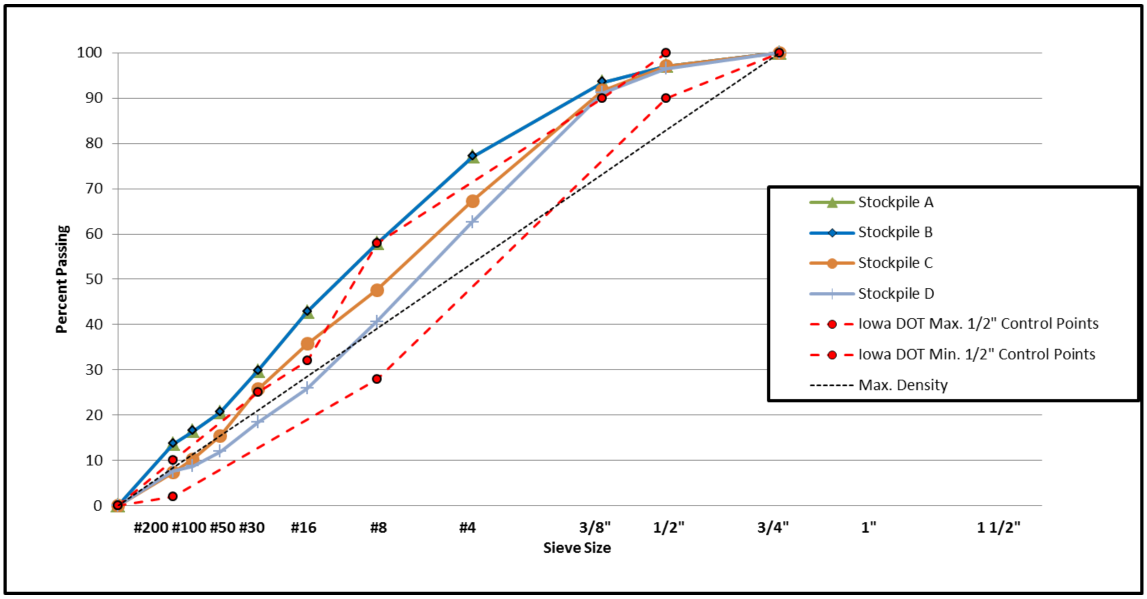


Figure 4-2: Gradations of the Four "Fractionated" Stockpiles

All RAP materials passing No. 30 sieve were removed resulting in removal of only 5.8% and 5.0% from Stockpiles B and C, respectively. Tables 4-3 and 4-4 show the reduction of very fine aggregate materials passing No. 30 sieve in the Fractionated Stockpiles B and C, respectively. After removing all RAP materials passing No. 30 sieve, the amount of the minus No. 200 aggregate decreased from 14.0% to 13.6% in Fractionated Stockpile B and from 10.3% to 8.5% in Fractionated Stockpile C.

Table 4-3: Fine Aggregate Reduction of Fine RAP Removal - Fractionated RAP-B

RAP Stockpile Analysis	Fine Aggregate Composition – (% Retained) No. 50	No. 100	No. 200	Pan	% of Stockpile
Original Stockpile DOT Extraction	12.0	5.0	3.0	14.0	**34.0%**
'Fractionated RAP' Binder Burn-Off	9.2	4.2	2.8	13.6	**29.8%**

Table 4-4: Fine Aggregate Reduction of Fine RAP Removal - Fractionated RAP-C

RAP Stockpile Analysis	Fine Aggregate Composition – (% Retained) No. 50	No. 100	No. 200	Pan	% of Stockpile
Original Stockpile DOT Extraction	10.0	5.0	1.7	10.3	**27.0%**
'Fractionated RAP' Binder Burn-Off	10.2	5.2	1.8	8.5	**25.7%**

In order to further decrease the amount of fine materials, for Stockpile D, the removal threshold was changed from No. 30 to the No. 16. Although 14.5% of RAP materials were discarded from the Stockpile D, as shown in Table 4-5, a significantly higher amount of fine aggregates were removed including a significant reduction of the minus No. 200 aggregate from 10.7 to 7.6%.

Table 4-5: Fine Aggregate Reduction of Fine RAP Removal - Fractionated RAP-D

RAP Stockpile Analysis	Fine Aggregate Composition – (% Retained)				Fine Agg. % of Total
	No. 50	No. 100	No. 200	Pan	
Original Stockpile DOT Extraction	10.0	4.0	2.3	10.7	**27.0%**
Fractionated RAP Binder Burn-Off	6.4	3.2	1.2	7.6	**18.4%**

4.2 Analysis of 'Optimum FRAP' Method

The second fractionation method followed more traditional practices by splitting the original RAP material into two separate stockpiles during processing (see Figure 4-3). To evenly divide the stockpile into fine and coarse stockpiles, No. 4 sieve was selected as a threshold to divide Stockpiles of A, B and C and 3/8" sieve for Stockpile D. The 'Coarse FRAP' and 'Fine FRAP' stockpiles was then be re-proportioned to reduce the percentage of Fine FRAP included in the 'Optimum FRAP' mix.

Figure 4-3: RAP Fractionation into 'Coarse FRAP' (right) and 'Fine FRAP' (left)

Figure 4-4 shows the coarser gradation of four stockpiles than the original stockpile. The Optimum FRAP Stockpile C met the Iowa DOT requirement. The Optimum FRAP Stockpile A, B and D almost met the Iowa DOT requirement.

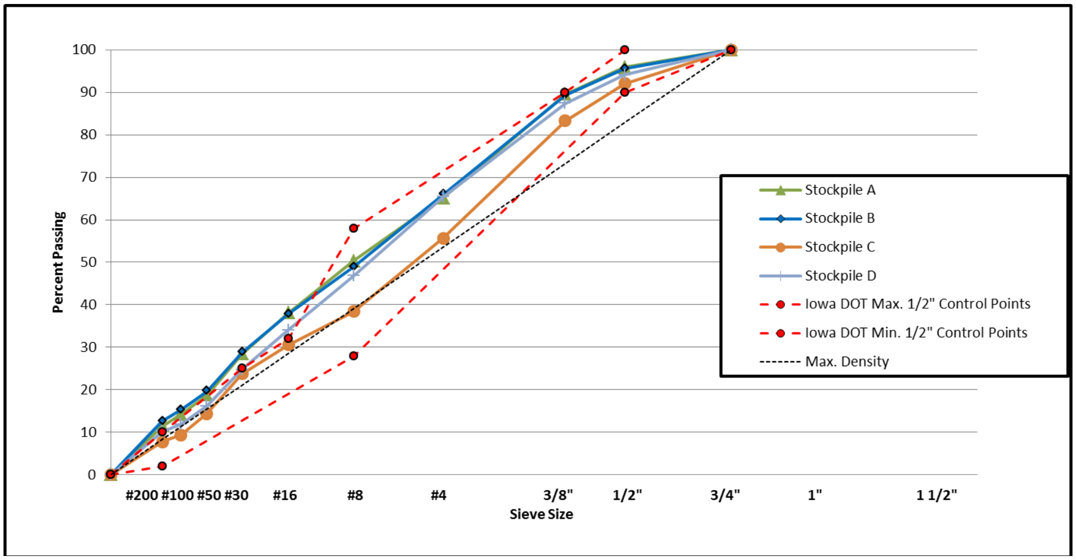


Figure 4-4: Gradations of Four "Optimum FRAP" Stockpiles

Table 4-6 shows a comparison of the recovered aggregate gradation of the Coarse and Fine FRAP materials from all stockpiles. The Fine RAP category has significantly higher proportion of very fine aggregate than the Coarse RAP materials. The dust contents of all of the Coarse FRAP materials are much lower than their respective original stockpile, and the Coarse FRAP-A and Coarse FRAP-C materials meet the maximum gradation control point of 10% passing the No. 200 screen.

Table 4-6: Recovered Aggregate Composition of Coarse and Fine FRAP Stockpiles

RAP Stockpile	Recovered Aggregate Composition – (% Retained)										% of Stockpile
	1/2"	3/8"	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200	Pan	
Coarse FRAP-A	5.5	8.5	32.6	13.9	9.0	7.6	8.1	3.6	2.1	9.1	**44.0%**
Fine FRAP-A passing No. 4	0.0	0.0	0.0	17.3	21.9	15.9	14.0	7.6	4.9	18.4	**56.0%**
Coarse FRAP-B	5.6	7.8	29.2	16.9	8.4	7.3	7.9	3.6	2.2	11.1	**50.6%**
Fine FRAP-B passing No. 4	0.0	0.0	0.0	19.6	21.0	16.3	14.3	5.9	3.8	19.1	**49.4%**
Coarse FRAP-C	8.9	9.7	30.6	16.8	6.4	5.8	8.4	4.7	1.5	7.2	**65.2%**
Fine FRAP-C passing No. 4	0.0	0.0	0.0	22.0	20.0	15.9	18.5	7.8	2.7	13.1	**34.8%**
Coarse FRAP-D	11.9	13.5	23.4	15.2	10.3	7.0	6.9	3.4	1.2	7.3	**34.7%**

Fine FRAP-D passing 3/8”	0.0	0.0	20.5	22.1	15.3	11.5	10.2	5.3	2.2	13.1	**65.3%**

To achieve the desired gradation properties, the following Coarse FRAP proportions were adopted:

- Optimum FRAP of Stockpile A – Coarse RAP proportion was increased from 44.0% to 75.0%
- Optimum FRAP of Stockpile B – Coarse RAP proportion was increased from 50.6% to 80.0%
- Optimum FRAP of Stockpile C – Coarse RAP proportion was increased from 65.2% to 90.0%
- Optimum FRAP of Stockpile D – Coarse RAP proportion was increased from 34.7% to 50.0%

The increased Coarse FRAP proportion in Optimum FRAP stockpile resulted in much higher amounts of material being ‘discarded’ from the original stockpile (41.3% of Stockpile A, 39.2% from Stockpile B, 27.8% from Stockpile C and 30.6% from Stockpile D).

The composite aggregate gradation of the re-proportioned RAP material is dominated by the properties of the Coarse FRAP stockpile, which are much more representative of the original pavement’s mix design. During the mix design process an ‘Optimum FRAP’ blend of Coarse and Fine FRAP materials was created for each original stockpile so that the combined aggregate gradation (virgin and recovered aggregates) of the High-RAP content mixture would fall as close as possible to the middle of the fine aggregate gradation control point ranges.

4.2 Summary of Fractionation Methods

The purpose of these RAP fractionation methods was to create new stockpiles with reduced fine aggregate composition. The Fine RAP materials (RAP material smaller than No. 4 sieve size) were targeted for removal due to their increased composition of very fine aggregate material. The ‘Fractionated RAP’ method removes all of RAP material smaller than the No. 30 sieve size from the Stockpiles A, B and C or the No. 16 sieve size for Stockpile D during the processing operation. This method resulted in fairly significant fine aggregate reduction and minimal material discarded from each original stockpile.

The ‘Optimum FRAP’ method splits each original RAP stockpile at the No. 4 (Stockpile A, B and C) or 3/8” sieve size (Stockpile D) to produce a ‘Coarse FRAP’ stockpile (RAP materials retained a specified sieve) and a ‘Fine FRAP’ stockpile (RAP materials passing a specified sieve). The percentage of ‘Coarse FRAP’ was increased to bring the combined aggregate gradation to the middle of the fine aggregate gradation control points. Mix designs were performed for high-RAP content mixtures using RAP materials included as the ‘Traditional RAP’ method, the ‘Fractionated RAP’ method and the ‘Optimum FRAP’ method. Results of these mix designs were then compared to determine the effects of the fractionation methods on the volumetric properties of high-RAP mix designs.

5. HIGH-RAP CONTENT MIX DESIGN

The main goal of this research is to design high-RAP surface mixtures that accounts for up to 50% of the virgin binder being replaced by RAP materials while meeting all volumetric mix design criteria. The maximum amount of RAP material currently allowed in the surface course by the Iowa DOT is limited to 30% of the virgin binder replacement by Classified RAP materials (*4*). High-RAP mix designs were created for inclusion of 30%, 40% and 50% RAP materials (measured by amount of virgin binder replacement) from each of four RAP stockpiles (Stockpile A, B, C and D) as well as two fractionated RAP stockpiles ('Fractionated RAP' and 'Optimum FRAP') created from each of four original stockpiles. Table 5-1 summarizes all high-RAP content mix designs that were performed and evaluated against the mix design criteria.

Table 5-1: High-RAP Mix Design Experimental Procedure

Fractionation Method	RAP Percentage (% of Virgin Binder Replaced)								
	Traditional RAP			Fractionated RAP			Optimum FRAP		
Stockpile A Classified RAP Airport	30%	40%	50%	30%	40%	50%	30%	40%	50%
Stockpile B Certified RAP Airport	30%	40%	50%	30%	40%	50%	30%	40%	50%
Stockpile C Certified RAP Unknown	30%	40%	50%	30%	40%	50%	30%	40%	50%
Stockpile D Classified RAP I-80	30%	40%	50%	30%	40%	50%	30%	40%	50%

5.1 Iowa DOT HMA Mix Design Procedure

The Iowa DOT '*Method of Design of Hot Mix Asphalt Mixes*' (*7*) procedure describes the entire process of aggregate and binder selection, material preparation and HMA mixture batching, curing and testing. The first step of the mix design is the selection of the virgin aggregate material and determination of the aggregate properties. All high-RAP mix designs were performed as the 1/2" mix which is typical for a surface course mixture in Iowa. Local limestone materials with a bulk aggregate specific gravity (G_{sb}) of 2.650 and the water absorption of 1.14% were used for mix design. Table 5-2 shows the virgin aggregate gradation compared to the specified control points for the 1/2" mix. In order to produce the consistent virgin aggregate gradation for all high-RAP mix designs, the limestone aggregates were divided into each sieve size, which were then recombined to produce the desired aggregate gradation.

Table 5-2: Virgin Aggregate Gradation (% Passing) with 1/2” Control Points

Sieve Size	3/4”	1/2”	3/8”	No.4	No.8	No.16	No.30	No.50	No.100	No.200
½” Maximum Control Points		**100**	**90**		**58**					**10.0**
Aggregates used for A, B, and C	100	91.4	80.0	60.0	43.3	32.1	20.5	11.9	4.4	3.5
Aggregates used for D	100	96.8	86.6	44.5	24.2	17.7	12.1	7.5	5.5	4.5
½” Minimum Control Points	**100**	**90**			**28**					**2.0**

5.1.1 Performance Grading of Binder Blends

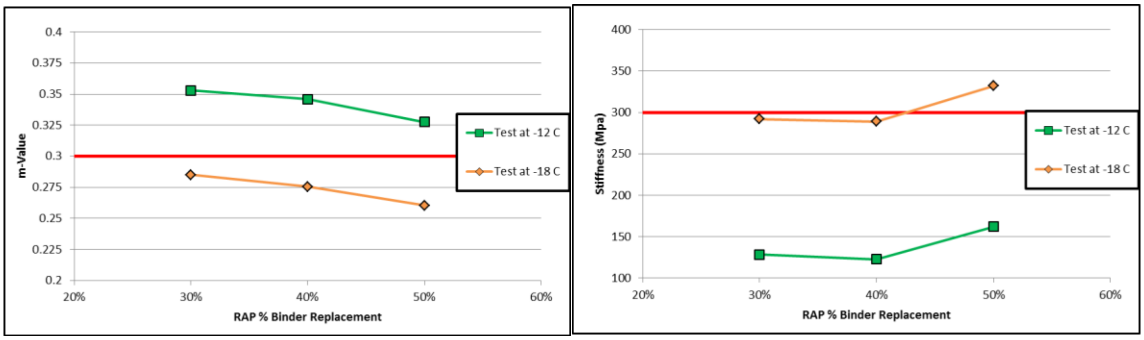
The first step required the selection of the virgin binder material. The performance grade of the virgin binder was reduced by one temperature classification to PG 58-28, as required by the Iowa DOT for greater than 20% virgin binder replacement by RAP (*4, 7*). Both Bending Beam Rheometer (BBR) and Dynamic Shear Rheometer (DSR) tests were performed on blended asphalt of the extracted RAP binder from Stockpile A with the virgin PG 58-28 binder with RAP binder replacements of 30%, 40% and 50% to determine if the blended asphalt would be equivalent to the PG 64-22 binder.

As shown in Table 5-3, DSR testing on the original and short-term aged samples (RTFO) showed that all blends met the minimum critical high temperature of 64ºC confirming that all blends met PG 64-XX. The samples tested at -12ºC passed both the minimum m-value (greater than 0.300) and the maximum stiffness criteria (less than 300 MPa) indicating that the low temperature performance grade of the blended binder met PG XX-22 binder specification for up to 50% binder replacement by the Stockpile A RAP material.

Table 5-3: Performance Grading of Blend of Virgin Asphalt and Extracted RAP Binder from Stockpile A

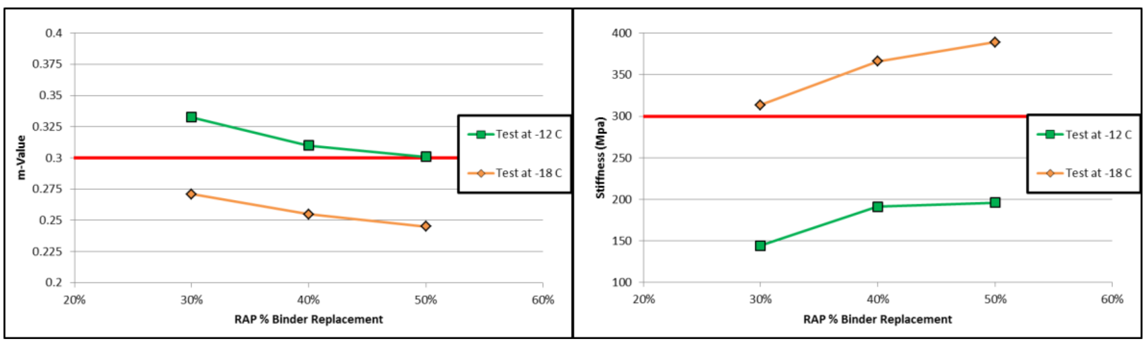
Sample Description		Test at -18ºC		Test at -12ºC		Low Critical Temp.	Critical High Original	Critical High RTFO	PG Grade
		M-Value	Stiffness	M-Value	Stiffness				
50% RAP	**#1**	0.261	329	0.324	164	-22	67.96	67.82	**64-22**
	#2	0.260	335	0.331	160		68.01	68.43	
40% RAP	**#1**	0.277	272	0.345	116	-22	65.88	65.81	**64-22**
	#2	0.274	306	0.347	130		65.29	65.28	
30% RAP	**#1**	0.289	283	0.356	125	-22	64.88	64.1	**64-22**
	#2	0.281	201	0.350	132		64.69	64.85	
Control Binder	**#1**	0.299	269	0.355	122	-28	61.46	60.5	58-28
	#2	0.299	256	0.369	112		61.76	60.63	
Recovered Binder	**#1**	0.299	269	0.356	123	-28	60.95	62.05	58-28
	#2	0.304	276	0.361	119		61.02	63.30	

The BBR test results of the blended asphalt virgin asphalt binder blended with extracted binder from the Stockpile A and Stockpile C RAP materials are plotted in Figure 5-1 and Figure 5-2, respectively. The BBR test results confirm that the blended asphalt up to 50% RAP materials from both Stockpiles A and C.



(a) m-Value **(b) Stiffness (MPa)**

Figure 5-1: BBR Test Result of Blended RAP/Virgin Binder - Stockpile A



(b) m-Value **(b) Stiffness (MPa)**

Figure 5-2: BBR Test Result of Blended RAP/Virgin Binder - Stockpile C

5.1.2 Beam Fatigue Test of High-RAP Mixtures

High amounts of RAP materials in asphalt mixtures may increase the stiffness of the mixtures resulting in a premature fatigue cracking of pavements. To determine the influence of RAP materials on the fatigue performance, the beam fatigue test was performed with varying amounts of RAP materials from Stockpile A. Six beams were prepared with 7% 1% air voids and tested at six strain levels that range from 1000 to 375 micro-strains. All tests were performed at 21ºC. As shown in Figure 5-3, the fatigue test results are similar to a typical 300K mix and there is no significant change in fatigue life as RAP materials are increased up to 50%.

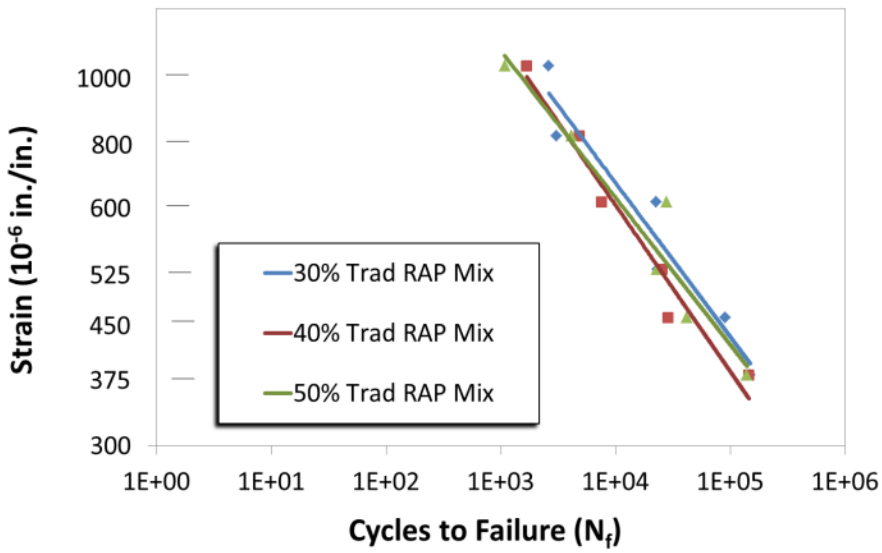


Figure 5-3: Beam Fatigue Test Results for Specimens with up to 50% of Stockpile A RAP Materials

5.1.3 SHADES Program to Calculate the Quantity of Materials

The final step involves mixing and testing HMA samples using the different RAP materials to determine the optimum asphalt content of each mix design. The SHADES spreadsheet program provided by the Iowa DOT was used to determine the weights of materials to be added to the trial mixtures to achieve the target asphalt content of each sample. When RAP materials are included in the mixture this program uses formulae from Iowa DOT Materials IM 501 to account for the binder and aggregate contributed by the RAP (*19*). The problem with using the SHADES program for this research was that the percent of RAP material input into the system was taken as the percentage of dry material weight of the total mixture ($\%RAP_{weight}$), rather than the percentage of virgin binder replacement ($\%RAP_{binder}$). The SHADES program calculates the necessary amount of virgin binder to be added to the mixture ($AC_{(add)}$), in addition to the binder contributed by the asphalt content of the RAP material ($P_{b(RAP)}$), to achieve the target asphalt content of the mixture ($AC_{(total)}$) as shown below:

Example:

*To produce a mixture with total asphalt content of 5.50% where 50% of the mixture's dry weight is from RAP material, which has a recovered asphalt content of 5.00%, it would require adding virgin asphalt binder of 3.08% of the total mixture's dry weight.

Due to the fact that the mix designs for this research were to be created based on the fixed percentage of virgin binder replaced by the RAP material ($\%RAP_{binder}$), a modified spreadsheet program was created that calculates the percentage weight of RAP material ($\%RAP_{weight}$) to be added to the mixture to account for the specified percentage of virgin binder replacement of the total target asphalt content. The above equation was modified to solve for the weight of RAP material ($\%RAP_{weight}$) as follows:

This new equation gives the desired output; however, further modification was necessary to calculate this value for a fixed percentage of virgin binder replacement. The numerator of this new equation is equivalent to the amount of RAP binder present in the total mixture ($AC_{(RAP)}$) and the amount of virgin binder replaced ($\%RAP_{binder}$) as shown below:

Substitution of these expressions into the $\%RAP_{weight}$ formula gives the following equation to calculate the amount of RAP material required to achieve the target binder replacement for a given trial mixture:

Example:

*A mixture with total asphalt content of 5.50% where 50% of the mixture's asphalt binder is from RAP material would require that 56.6% of the mixture's dry weight is from RAP.

This equation and other formulae in IM 501 were used to determine the weights of virgin and RAP material to be included in each high-RAP trial mixture. These trial mixtures were prepared and tested at specified binder contents for each mix design according to the procedure outlined in Materials IM 510. Materials from the original stockpile ('Traditional RAP' method) and materials from the fractionated stockpile with all Fine RAP material smaller than the No. 30 sieve removed ('Fractionated RAP' method) were included as 100% of the total RAP weight added to the mixture, as calculated from the above formula.

For the 'Optimum FRAP' method, the amount of material added from the 'Coarse FRAP' stockpile was increased (as a proportion of the total RAP weight added to the mixture) to improve the combined gradation. The criteria for this new proportion selection are as follows:

- ✓ The dust content of the combined aggregate gradation should fall in the middle of the control point range for the 1/2" mix (~6.0% passing No. 200)
- ✓ The combined aggregate surface area and fine aggregate composition should be less than those of the original and 'Fractionated RAP' stockpile

The modified mix design spreadsheet program was used to determine these expected gradation properties for increasing the proportion of Coarse FRAP material in the total RAP weight added to the mixture. To achieve the desired combined gradation properties, the Coarse FRAP proportion for the Stockpile A material was increased from the original 44% to 75% of the total RAP weight added to the mixture for the 'Optimum FRAP-A' blend. The Coarse FRAP from Stockpile B was increased from the original 50% to 80% for the 'Optimum FRAP-B' blend, and the Coarse FRAP from Stockpile C was increased from original 65% to 90% for the 'Optimum FRAP-C' blend.

The large increase in Coarse FRAP percentage included in the total RAP material resulted in much higher amounts of material being 'discarded' from the original stockpile (41.3% of Stockpile A original material, 37.5% from Stockpile B and 27.8% from Stockpile C). The following equation calculates the expected amount of leftover material ($\%RAP_{unused}$), as a percentage of the original stockpile, based on the original proportion of Coarse and Fine RAP material and the new, increased Coarse FRAP percentage:

Example:

*Increasing Coarse FRAP proportion from 44% to 75% leaves 41.3% of original stockpile discarded.

5.2 High-RAP Content Mix Design Results

Volumetric properties and mix design criteria were calculated for each mixture at the optimum binder content. Table 5-4 summarizes the volumetric design criteria for the HMA 300K ESAL 1/2" surface mixture designed for this study (*7*).

Table 5-4: Volumetric Mix Design Criteria - 300K ESAL 1/2" Surface Mix

Mixture Property	Design Air Voids P_a (%)	Voids Filled w/ Asphalt VFA (%)	Voids in Aggregate VMA (%)	Film Thickness (μm)	Dust-Binder Ratio D:B	Maximum Dust Content (% -No. 200)
DOT Spec.	3.5	70 – 80	Min. 14.0	8.0 – 13.0	0.6 – 1.4	10.0

Source: IM 510 Appendix A. Hot Mix Asphalt Design Criteria. Iowa DOT Materials IM (*7*)

5.2.1 Mix Design Results Using Stockpile A RAP Materials

Table 5-5 summarizes the mix design results of 30%, 40% and 50% binder replacement with the Traditional, Fractioned and Optimum FRAP materials from Stockpile A. Figure 5-4 shows plots of five critical mix design parameters against three fractionation types and three RAP percentages.

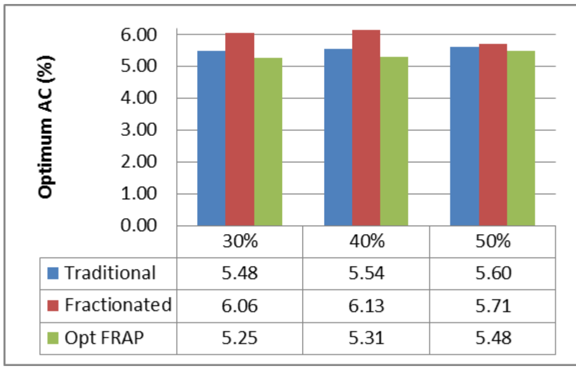
Despite a high dust content of the original RAP stockpile material, all mix design met the dust content requirement of 10% where the dust content of the combined gradation for the 50% Traditional RAP mix design was at the maximum limit of 10% passing No. 200 sieve. Both Fractional and Optimum FRAP mix designs showed the reduced dust content compared to the Traditional RAP method. Both Traditional and Fractionated mixes met VMA requirement whereas Optimum FRAP did not.

For Traditional and Optimum FRAP mixes, the optimum asphalt content remained around 5.5% whereas for the Fractionated mix the optimum asphalt content remained around 6.0%. Overall, the optimum asphalt content was not significantly affected by the RAP percentage.

Overall, the high dust content up to 10% resulted in a very thin asphalt film thickness and a very high dust-binder ratio. However, the Fractionated RAP mix required the higher optimum asphalt content than both Traditional and Optimum FRAP mixes. As a result, the only Fractionated RAP mix with 30% RAP mix design met all mix design criteria (film thickness slightly below the 8.0 µm minimum).

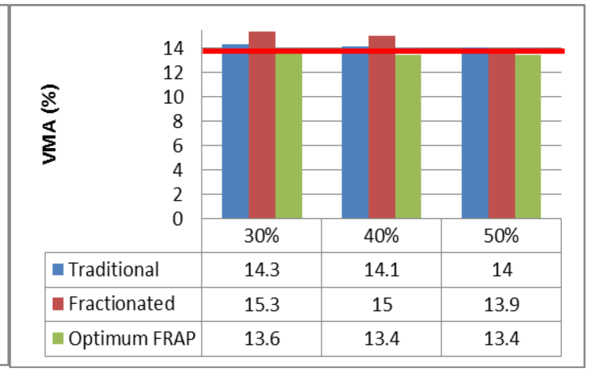
Table 5-5: Volumetric Mix Design Result Comparison - Stockpile A

RAP Method	'Traditional RAP'			'Fractionated RAP'			'Optimum FRAP'		
RAP Design	**30%**	**40%**	**50%**	**30%**	**40%**	**50%**	**30%**	**40%**	**50%**
% Virgin AC	70%	60%	50%	70%	60%	50%	70%	60%	50%
Air Voids (P_a)	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%
Optimum AC	5.48%	5.54%	5.60%	6.06%	6.13%	5.71%	5.25%	5.31%	5.48%
RAP Weight	31.6%	42.3%	53.3%	33.3%	44.7%	51.6%	28.8%	38.7%	49.6%
% RAP AC	1.64%	2.21%	2.80%	1.82%	2.45%	2.86%	1.58%	2.13%	2.74%
% ADD AC	3.84%	3.32%	2.80%	4.24%	3.68%	2.86%	3.68%	3.19%	2.74%
Volumetrics @ Optimum AC	**5.48%**	**5.54%**	**5.60%**	**6.06%**	**6.13%**	**5.71%**	**5.25%**	**5.31%**	**5.48%**
Max. Sp. Gr. (G_{mm})	2.481	2.483	2.485	2.467	2.471	2.490	2.494	2.498	2.498
Core Sp. Gr. (G_{mb})	2.394	2.397	2.398	2.381	2.385	2.403	2.407	2.411	2.411
Binder Sp. Gr. (G_b)	1.036	1.036	1.036	1.036	1.036	1.036	1.036	1.036	1.036
Agg. Sp. Gr. (G_{sb})	2.639	2.635	2.631	2.638	2.634	2.632	2.640	2.637	2.633
Water Absorp. (% Abs)	1.21	1.24	1.26	1.22	1.24	1.26	1.21	1.23	1.26
Effective Sp. Gr. (G_{se})	2.700	2.705	2.710	2.708	2.717	2.722	2.705	2.713	2.721
Aggregate Surface Area	6.83	7.62	8.45	6.50	7.18	7.60	5.82	6.27	6.77
% Binder Abs. (P_{ba})	0.88	1.01	1.15	1.01	1.19	1.30	0.95	1.10	1.28
Effective Binder (P_{be})	4.65	4.58	4.52	5.11	5.01	4.49	4.36	4.27	4.27
Mix Design Criteria	**30% Trad-A**	**40% Trad-A**	**50% Trad-A**	**30% Frac-A**	**40% Frac-A**	**50% Frac-A**	**30% Opt-A**	**40% Opt-A**	**50% Opt-A**
VMA (%) >14	14.3	14.1	14.0	15.3	15.0	13.9	13.6	13.4	13.4
70<VFA (%)<80	75.4	75.2	74.9	77.0	76.7	74.8	74.3	73.9	74.0
Dust Content<10	7.3	8.6	10.0	6.9	8.1	8.8	5.7	6.4	7.3
8<Film Thick <13	6.8	6.0	5.4	7.9	7.0	5.9	7.5	6.8	6.3
0.6<DB Ratio<1.4	1.6	1.9	2.2	1.4	1.6	2.0	1.3	1.7	1.7



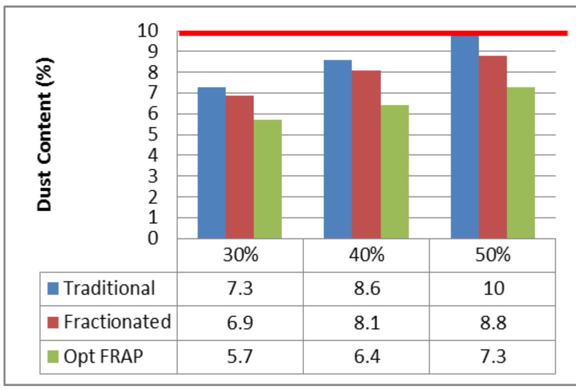
	30%	40%	50%
Traditional	5.48	5.54	5.60
Fractionated	6.06	6.13	5.71
Opt FRAP	5.25	5.31	5.48

(a) Optimum AC Content



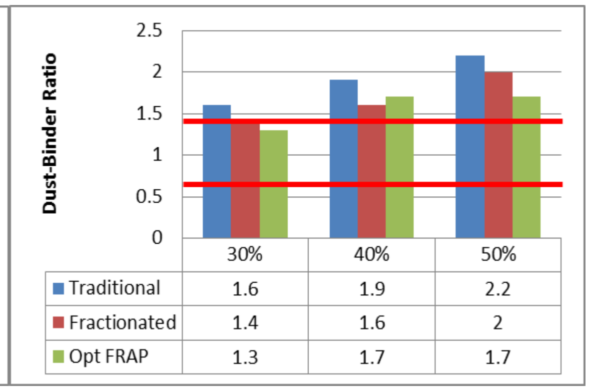
	30%	40%	50%
Traditional	14.3	14.1	14
Fractionated	15.3	15	13.9
Optimum FRAP	13.6	13.4	13.4

(b) Voids in Mineral Aggregate (VMA)



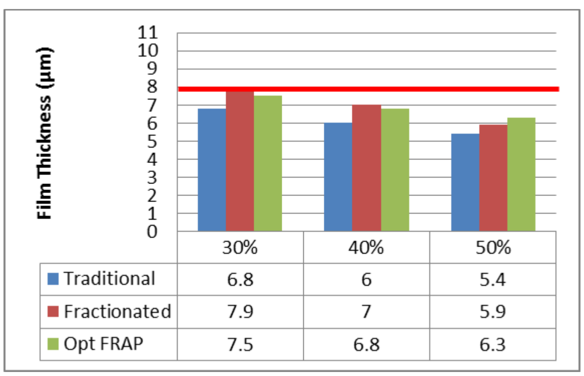
	30%	40%	50%
Traditional	7.3	8.6	10
Fractionated	6.9	8.1	8.8
Opt FRAP	5.7	6.4	7.3

(c) Minus No. 200 Dust Content



	30%	40%	50%
Traditional	1.6	1.9	2.2
Fractionated	1.4	1.6	2
Opt FRAP	1.3	1.7	1.7

(d) Dust-Binder Ratio



	30%	40%	50%
Traditional	6.8	6	5.4
Fractionated	7.9	7	5.9
Opt FRAP	7.5	6.8	6.3

(e) Asphalt Film Thickness (μm)

Figure 5-4: Mix Design Results of Three Processing Methods for Stockpile A

5.2.2 Mix Design Results Using Stockpile B RAP Materials

Table 5-6 summarizes the mix design results of 30%, 40% and 50% binder replacement with the Traditional, Fractioned and Optimum FRAP materials from Stockpile B. Figure 5-5 shows plots of five critical mix design parameters against three fractionation types and three RAP percentages.

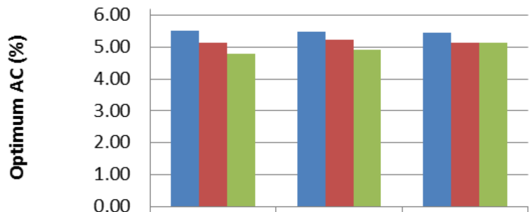
All mix designs met the gradation control points due to the slightly lower dust content of the Stockpile B (14% minus No. 200 for Stockpile B compared to 16% for Stockpile A). However, the only Traditional mix with 30% RAP met VMA requirement.

The optimum asphalt content for Traditional mix was around 5.5% which is very close to that of RAP-A Traditional mix. However, contrary to RAP-A mix, the optimum asphalt contents for both Fractionated and Optimum FRAP mixes decreased by up to 0.5%. The Traditional mix required the highest optimum asphalt content followed by Fractionated and Optimum FRAP mixes. Overall, the optimum asphalt content was not significantly affected by the RAP percentage.

Overall, both Fractionated (removing only 5.8% of the stockpile) and Optimum FRAP mixes decreased the dust content; however, the optimum asphalt content was lower than the Traditional mix. As a result, the film thickness decreased and the dust-binder ratio increased. None of RAP-B mixes met the mix design criteria.

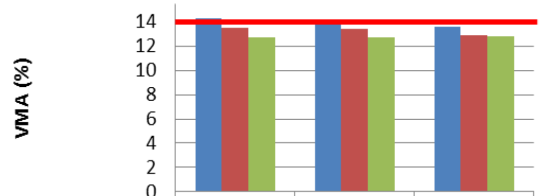
Table 5-6: Volumetric Mix Design Result Comparison - Stockpile B

RAP Method	'Traditional RAP'			'Fractionated RAP'			'Optimum FRAP'		
RAP Design	**30%**	**40%**	**50%**	**30%**	**40%**	**50%**	**30%**	**40%**	**50%**
% Virgin AC	70%	60%	50%	70%	60%	50%	70%	60%	50%
Air Voids (P_a)	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%
Optimum AC	5.51%	5.49%	5.45%	5.14%	5.23%	5.13%	4.80%	4.92%	5.14%
RAP Weight	33.7%	44.5%	54.8%	29.9%	40.4%	49.3%	29.2%	39.7%	51.7%
% RAP AC	1.65%	2.20%	2.73%	1.54%	2.09%	2.57%	1.44%	1.97%	2.57%
% ADD AC	3.86%	3.30%	2.73%	3.60%	3.14%	2.57%	3.36%	2.95%	2.57%
Volumetrics @ Optimum AC	**5.51%**	**5.49%**	**5.45%**	**5.14%**	**5.23%**	**5.13%**	**4.80%**	**4.92%**	**5.14%**
Max. Sp. Gr. (G_{mm})	2.471	2.472	2.475	2.486	2.484	2.489	2.499	2.497	2.491
Core Sp. Gr. (G_{mb})	2.384	2.386	2.388	2.399	2.397	2.402	2.412	2.410	2.404
Binder Sp. Gr. (G_b)	1.036	1.036	1.036	1.036	1.036	1.036	1.036	1.036	1.036
Agg. Sp. Gr. (G_{sb})	2.627	2.620	2.613	2.630	2.623	2.616	2.630	2.623	2.615
Water Absorp. (% Abs)	1.49	1.61	1.72	1.45	1.56	1.66	1.44	1.56	1.68
Effective Sp. Gr. (G_{se})	2.688	2.689	2.690	2.690	2.692	2.693	2.691	2.693	2.696
Aggregate Surface Area	6.61	7.29	7.95	6.25	6.87	7.39	6.00	6.53	7.15
% Binder Abs. (P_{ba})	0.89	1.02	1.14	0.88	1.01	1.13	0.89	1.03	1.20
Effective Binder (P_{be})	4.67	4.54	4.37	4.31	4.27	4.06	4.47	4.44	4.01
Mix Design Criteria	**30% Trad-B**	**40% Trad-B**	**50% Trad-B**	**30% Frac-B**	**40% Frac-B**	**50% Frac-B**	**30% Opt-B**	**40% Opt-B**	**50% Opt-B**
VMA (%) >14	14.3	13.9	13.6	13.5	13.4	12.9	12.7	12.7	12.8
70<VFA (%)<80	75.5	74.9	74.2	74.0	73.8	72.9	72.5	72.4	72.7
Dust Content<10	6.9	8.0	9.1	6.4	7.4	8.3	6.1	7.0	8.1
8<Film Thick <13	7.1	6.2	5.5	6.9	6.2	5.5	7.4	6.8	5.6
0.6<DB Ratio<1.4	1.5	1.8	2.1	1.5	1.7	2.1	1.4	1.6	1.7



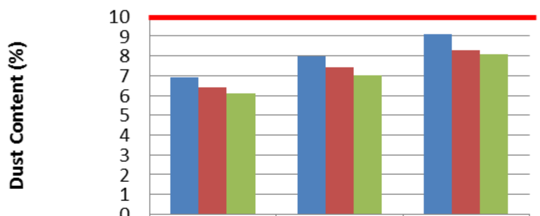
	30%	40%	50%
Traditional	5.51	5.49	5.45
Fractionated	5.14	5.23	5.13
Opt FRAP	4.80	4.92	5.14

(a) Optimum AC Content



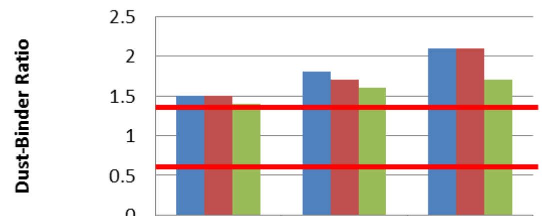
	30%	40%	50%
Traditional	14.3	13.9	13.6
Fractionated	13.5	13.4	12.9
Optimum FRAP	12.7	12.7	12.8

(b) Voids in Mineral Aggregate (VMA)



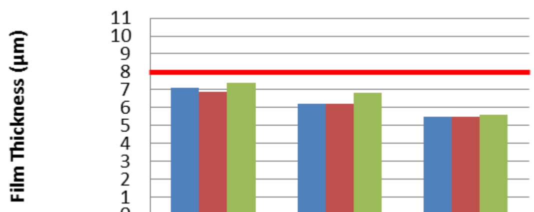
	30%	40%	50%
Traditional	6.9	8	9.1
Fractionated	6.4	7.4	8.3
Opt FRAP	6.1	7	8.1

(c) Minus No. 200 Dust Content



	30%	40%	50%
Traditional	1.5	1.8	2.1
Fractionated	1.5	1.7	2.1
Opt FRAP	1.4	1.6	1.7

(d) Dust-Binder Ratio



	30%	40%	50%
Traditional	7.1	6.2	5.5
Fractionated	6.9	6.2	5.5
Opt FRAP	7.4	6.8	5.6

(e) Asphalt Film Thickness (µm)

Figure 5-5: Mix Design Results of Three Processing Methods for Stockpile B

5.2.3 Mix Design Results Using Stockpile C RAP Materials

Table 5-7 summarizes the mix design results of 30%, 40% and 50% binder replacement with the Traditional, Fractioned and Optimum FRAP materials from Stockpile C. Figure 5-6 shows plots of five critical mix design parameters against three fractionation types and three RAP percentages.

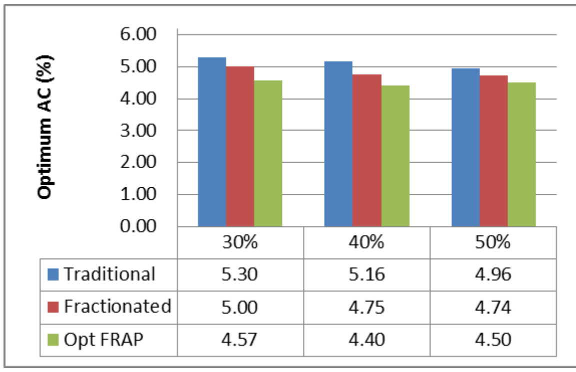
RAP materials from this stockpile exhibited a lower dust content (10.3%) than Stockpiles of A and B, resulting in the final gradation of approximately 6.0% of minus No. 200. Only the Traditional mix with 30% RAP met the VMA requirement of 14%.

The optimum asphalt content for Traditional mix for 30% RAP was 5.33%, which is lower than those of RAP-A and RAP-B, and decreased as the RAP percentage increased. However, the optimum asphalt contents for both Fractionated and Optimum FRAP mixes decreased by up to 0.5%. Similar to RAP-B, Traditional mix required the highest optimum asphalt content followed by Fractionated and Optimum FRAP mixes.

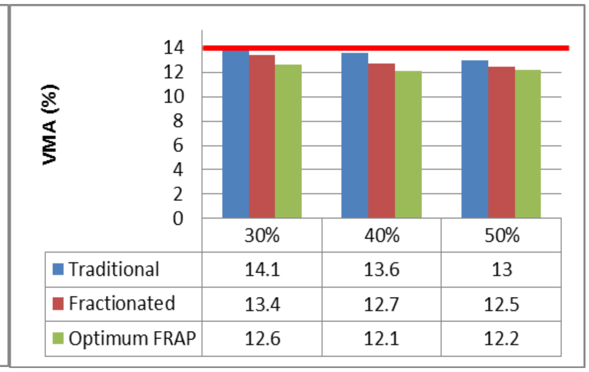
Overall, due to the reduced amount of fine materials in the Stockpile C, more mixes met the critical mix design criteria such as film thickness and dust-binder ratio. The film thickness criteria were met by all 30% RAP mixes, the Optimum FRAP mix with 40% RAP and the dust-binder ratio was satisfied for all mixes except the Traditional mix with 40% and 50% RAP materials. However, due to the low VMA in the mixes, only the Traditional mix with 30% RAP met all mix design criteria

Table 5-7: Volumetric Mix Design Result Comparison - Stockpile C

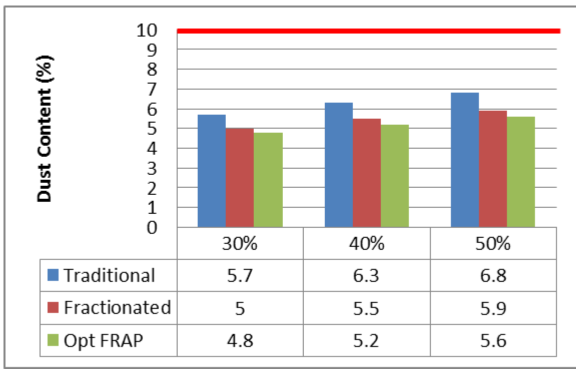
RAP Method	**'Traditional RAP'**			**'Fractionated RAP'**			**'Optimum FRAP'**		
RAP Design	**30%**	**40%**	**50%**	**30%**	**40%**	**50%**	**30%**	**40%**	**50%**
% Virgin AC	70%	60%	50%	70%	60%	50%	70%	60%	50%
Air Voids (P_a)	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%
Optimum AC	5.33%	5.16%	4.96%	5.00%	4.75%	4.74%	4.57%	4.40%	4.50%
RAP Weight	34.5%	44.2%	52.7%	32.2%	40.5%	50.3%	31.1%	39.7%	50.6%
% RAP AC	1.60%	2.06%	2.48%	1.50%	1.90%	2.37%	1.37%	1.76%	2.25%
% ADD AC	3.73%	3.10%	2.48%	3.50%	2.85%	2.37%	3.20%	2.64%	2.25%
Volumetrics @ Optimum AC	**5.33%**	**5.16%**	**4.96%**	**5.00%**	**4.75%**	**4.74%**	**4.57%**	**4.40%**	**4.50%**
Max. Sp. Gr. (G_{mm})	2.475	2.482	2.489	2.488	2.498	2.499	2.500	2.505	2.501
Core Sp. Gr. (G_{mb})	2.388	2.395	2.402	2.401	2.411	2.412	2.412	2.418	2.413
Binder Sp. Gr. (G_b)	1.036	1.036	1.036	1.036	1.036	1.036	1.036	1.036	1.036
Agg. Sp. Gr. (G_{sb})	2.632	2.627	2.623	2.634	2.629	2.624	2.634	2.630	2.624
Water Absorp. (% Abs)	1.26	1.29	1.33	1.25	1.28	1.32	1.25	1.28	1.32
Effective Sp. Gr. (G_{se})	2.685	2.686	2.686	2.687	2.687	2.688	2.681	2.680	2.679
Aggregate Surface Area	5.76	6.11	6.42	5.43	5.66	5.94	5.20	5.39	5.62
% Binder Abs. (P_{ba})	0.78	0.86	0.93	0.78	0.85	0.94	0.69	0.74	0.81
Effective Binder (P_{be})	4.60	4.35	4.58	4.77	4.45	4.35	4.41	4.70	4.23
Mix Design Criteria	**30% Trad-C**	**40% Trad-C**	**50% Trad-C**	**30% Frac-C**	**40% Frac-C**	**50% Frac-C**	**30% Opt-C**	**40% Opt-C**	**50% Opt-C**
VMA (%) >14	14.1	13.6	13.0	13.4	12.7	12.5	12.6	12.1	12.2
70<VFA (%)<80	75.2	74.2	73.0	73.8	72.4	71.9	72.2	71.1	71.2
Dust Content<10	5.7	6.3	6.8	5.0	5.5	5.9	4.8	5.2	5.6
8<Film Thick <13	8.0	7.1	7.1	8.8	7.9	7.3	8.5	8.7	7.5
0.6<DB Ratio<1.4	1.2	1.5	1.5	1.1	1.2	1.4	1.1	1.2	1.3



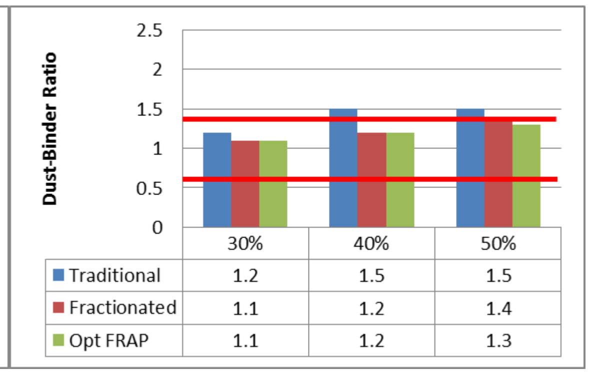
(a) Optimum AC Content



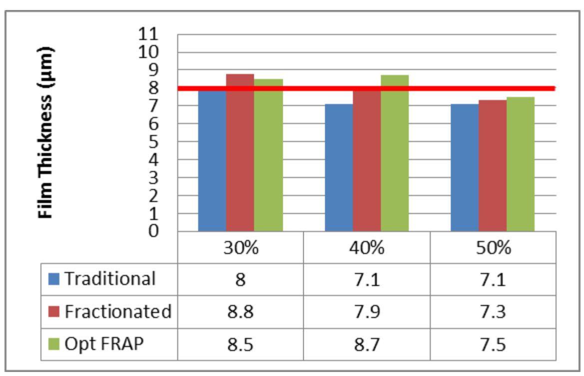
(b) Voids in Mineral Aggregate (VMA)



(c) Minus No. 200 Dust Content



(d) Dust-Binder Ratio



(e) Asphalt Film Thickness (µm)

Figure 5-5: Mix Design Results of Three Processing Methods for Stockpile C

5.2.4 Mix Design Results Using Stockpile D RAP Materials

Table 5-8 summarizes the mix design results of 30%, 40% and 50% binder replacement with the Traditional, Fractioned and Optimum FRAP materials from Stockpile D. Figure 5-7 shows plots of five critical mix design parameters against three fractionation types and three RAP percentages.

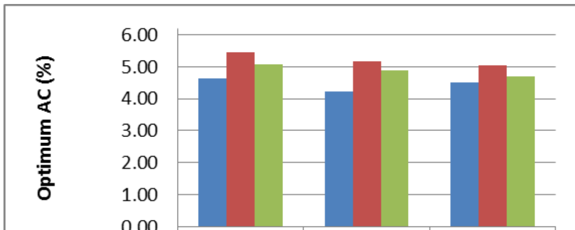
RAP materials from this stockpile exhibited a relatively low dust content (10.7%) and, for Fractionated mixes, more fine materials were discarded at threshold sieve of No. 16 rather than No. 30 which was adopted for all other stockpiles. The increased fractionation threshold from No. 30 to the No. 16 sieve for the Fractionated RAP method resulted in significant reduction in surface area and an increase in optimum asphalt content. The Optimum FRAP was coarser because the threshold of 3/8” was adopted rather No. 4 to divide the fine and coarse stockpiles. The Fractionated mix with 30% and 40% RAP met the VMA requirement of 14%.

The optimum asphalt content for Traditional mix was around 4.5% which was significantly lower than those of 5.5% for RAP-A and RAP-B and 5.3% for 30% RAP-C. The Fractionated mix exhibited the highest optimum asphalt content followed by the Optimum FRAP and Traditional mixes. Overall, the optimum binder content decreased as the RAP percentage increased.

Overall, due to the reduced amount of fine materials in the Stockpile D, more mixes met the critical mix design criteria such as film thickness and dust-binder ratio. The film thickness criteria were met by all Fractionated mixes and the Optimum FRAP mix with 30% RAP and the dust-binder ratio was satisfied for Fractionated mixes with 30% and 40% RAP and Optimum FRAP with 30% RAP. However, due to the low VMA in the mixes, only the Fractionated mixes with 30% and 40% RAP met all mix design criteria.

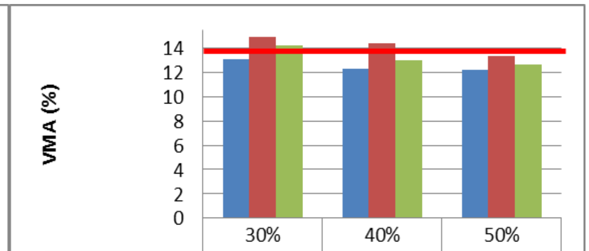
Table 5-8: Volumetric Mix Design Result Comparison - Stockpile D

RAP Method	**'Traditional RAP'**			**'Fractionated RAP'**			**'Optimum FRAP'**		
RAP Design	**30%**	**40%**	**50%**	**30%**	**40%**	**50%**	**30%**	**40%**	**50%**
% Virgin AC	70%	60%	50%	70%	60%	50%	70%	60	50%
Air Voids (P_a)	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%
Optimum AC	4.63%	4.22%	4.5%	5.45%	5.18%	5.04%	5.06%	4.87%	4.71%
RAP Weight	34.8%	42.2%	44%	37.7%	47.9%	57.1%	32.7%	42%	49%
% RAP AC	1.39%	1.69%	2.25%	1.66%	2.07%	2.52%	1.52%	1.95%	2.35%
% ADD AC	3.24%	2.53 %	2.25%	3.79%	3.11%	2.52%	3.54%	2.92%	2.36%
Volumetrics @ Optimum AC	**4.63%**	**4.22%**	**4.5%**	**5.45%**	**5.18%**	**4.74%**	**5.06%**	**4.87%**	**4.71%**
Max. Sp. Gr. (G_{mm})	2.496	2.508	2.511	2.466	2.474	2.502	2.476	2.505	2.515
Core Sp. Gr. (G_{mb})	2.408	2.420	2.402	2.379	2.388	2.414	2.389	2.418	2.425
Binder Sp. Gr. (G_b)	1.036	1.036	1.036	1.036	1.036	1.036	1.036	1.036	1.036
Agg. Sp. Gr. (G_{sb})	2.643	2.644	2.645	2.643	2.645	2.646	2.643	2.644	2.645
Water Absorp. (% Abs)	0.981	1.010	1.040	0.988	1.017	1.046	0.975	0.999	1.024
Effective Sp. Gr. (G_{se})	2.679	2.675	2.692	2.679	2.677	2.706	2.674	2.702	2.706
Aggregate Surface Area	5.57	5.91	6.56	4.82	5.04	5.28	5.29	5.66	6.01
% Binder Abs. (P_{ba})	0.52	0.45	0.67	0.51	0.48	0.87	0.45	0.84	0.88
Effective Binder (P_{be})	4.13	3.79	3.86	4.96	4.73	4.22	4.63	4.08	3.87
Mix Design Criteria	**30% Trad-D**	**40% Trad-D**	**50% Trad-D**	**30% Opt-D**	**40% Frac-D**	**50% Frac-D**	**30% Frac-D**	**40% Frac-D**	**50% Opt-D**
VMA (%) >14	13.1	12.3	12.23	14.9	14.4	13.35	14.2	13.0	12.63
70<VFA (%)<80	73.3	71.6	74.01	76.5	75.7	73.58	75.3	73.1	71.69
Dust Content<10	6.52	7.0	7.92	5.62	5.9	6.26	6.27	6.8	7.29
8<Film Thick <13	7.42	6.4	5.88	10.3	9.4	7.99	8.77	7.2	6.43
0.6<DB Ratio<1.4	1.59	1.9	2.05	1.13	1.3	1.49	1.35	1.7	1.89



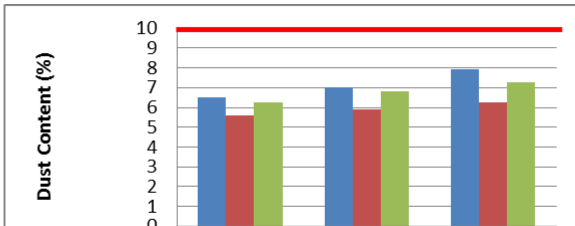
	30%	40%	50%
Traditional	4.63	4.22	4.50
Fractionated	5.45	5.18	5.04
Opt FRAP	5.06	4.87	4.71

(a) Optimum AC Content



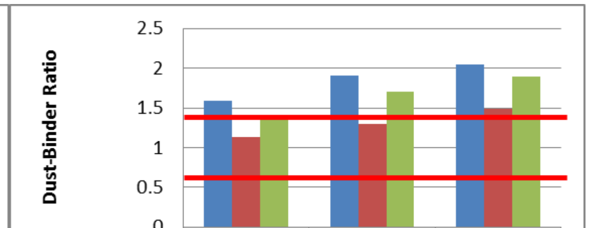
	30%	40%	50%
Traditional	13.1	12.3	12.23
Fractionated	14.9	14.4	13.35
Optimum FRAP	14.2	13	12.63

(b) Voids in Mineral Aggregate (VMA)



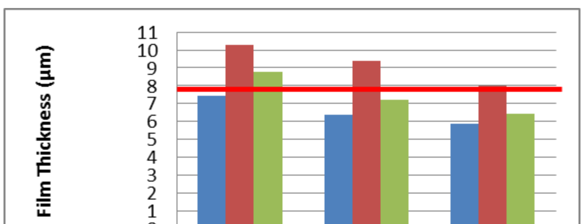
	30%	40%	50%
Traditional	6.52	7	7.92
Fractionated	5.62	5.9	6.26
Opt FRAP	6.27	6.8	7.29

(c) Minus No. 200 Dust Content



	30%	40%	50%
Traditional	1.59	1.9	2.05
Fractionated	1.13	1.3	1.49
Opt FRAP	1.35	1.7	1.89

(d) Dust-Binder Ratio



	30%	40%	50%
Traditional	7.42	6.4	5.88
Fractionated	10.3	9.4	7.99
Opt FRAP	8.77	7.2	6.43

(e) Asphalt Film Thickness (µm)

Figure 5-5: Mix Design Results of Three Processing Methods for Stockpile D

5.3 High-RAP Mix Design Summary

The main goal of this research is to design high-RAP content surface mixtures that account for up to 50% of the virgin binder being replaced by RAP materials while meeting all volumetric mix design criteria required for virgin HMA mixtures. An experimental procedure was established to create High-RAP content mix designs that accounted for 30%, 40% and 50% replacement of the mixture's virgin binder using RAP materials from each original stockpile ('Traditional RAP' inclusion method) and from stockpiles created using two different fractionation methods ('Fractionated RAP' and 'Optimum FRAP' inclusion methods). A total of thirty-six different mix designs were performed to determine the effectiveness of the fractionation methods using four different RAP stockpiles in this study.

For each mix design the optimum binder content was determined that produced the desired air voids after the specified number of gyrations for the 300K ESAL ½" HMA mixture. Volumetric properties of each mixture were determined at the optimum binder content and VMA, VFA, combined aggregate gradation, film thickness and dust-binder ratio were analyzed for each mix design.

The volumetric properties were influenced by the gradation of the original stockpile. Stockpile A and B contained very high dust contents (16% and 14%, respectively) which led to a low asphalt film thicknesses and a high dust-binder ratio. The 'Fractionated RAP' and 'Optimum FRAP' methods were effective in reducing the amount of fine aggregates from the original stockpile and thereby improving volumetric properties. A dust content of the Stockpile C was relatively low (10%) and the 30% Traditional RAP-C mix design met all mix design criteria. For Stockpile D, the 'Fractionated RAP' method for 30%, 40% and 50% RAP materials met nearly all mix design criteria (except VMA for 50% RAP).

The volumetric properties of mixtures are influenced by the optimum asphalt content of each mixture. Although the fractionation methods reduced the amount of fine aggregate and dust content, for Stockpiles of A, B and C, both 'Fractionated RAP' and 'Optimum FRAP' mix designs exhibited lower optimum asphalt contents than the corresponding 'Traditional RAP' mix design (with an exception to the Fractionated RAP-A). The improvement of mixture's volumetric properties was often offset by the lower optimum asphalt content resulting in a lower asphalt film thickness and a high dust-binder ratio. For stockpile D, however, both 'Fractionated RAP' and 'Optimum FRAP' mix designs exhibited higher optimum asphalt contents than the corresponding 'Traditional RAP' mix design.

6. SUMMARY AND CONCLUSIONS

While reclaimed asphalt pavement (RAP) materials are widely used around the country, their usage has been limited due to a difficulty in meeting the required volumetric properties for high-RAP content mixtures. The original aggregate structure of the existing pavement is changed during the milling and processing operations resulting in the creation of excessive amounts of fine aggregate. In order for RAP materials to be used in higher amounts, these volumetric properties must be improved to meet the mix design criteria.

Various fractionation methods were designed and applied to four different stockpiles for up to 50% RAP binder replacement. The component analysis of four different RAP stockpiles identified the distribution of aggregates and binder associated with RAP materials retained on each sieve. This sieve-by-sieve analysis helped identify the critical sieve to divide the stockpiles and its impacts on the resulting fractionated mix designs. The component analysis confirmed that asphalt content varied depending on the size of RAP materials with very little asphalt content in minus 200 RAP materials. Fine aggregates were stuck with nearly all RAP materials and it is very difficult to remove them. It is concluded that the fractionation methods were effective in improving volumetric properties of the HMA mixture with a high RAP content.

Findings from the research project are summarized below:

1. Milling at a high speed for a shallow depth would result in desirable RAP materials with minimum amounts of fine aggregates.
2. A single virgin asphalt binder performance grade modification was effective in mitigating the negative effect of the aged RAP binder.
3. Based on beam fatigue test, there is no significant change in predicted fatigue life of asphalt mixtures with high Rap contents.
4. Component analysis of RAP materials retained on each sieve is effective in identifying the distribution of fine aggregates and asphalt binder for a different size of RAP materials.
5. Coarse RAP materials contained lower proportions of fine aggregate material including dust content.
6. Fractionation methods designed to increase the amount of Coarse RAP material are effective in reducing the fine aggregates and dust content.
7. The optimum binder content could be lower when the fractionation methods are used due to the improved aggregate structure achieved through the fractionation process.
8. When the fractionation methods are used for the High-RAP mix design, the film thickness increases while the dust-binder ratio decreases.
9. Fraction methods are effective in producing the High-RAP mixture that meets Iowa DOT’s mix design criteria.
10. When designing the fractionation methods, the amounts of discarded RAP materials should be considered.

11. The fractionation method to discard RAP materials passing No. 16 sieve was very effective in improving the design volumetrics with up to 50% RAP materials.

6.1 Proposed Phase 2 Research

1. Moisture sensitivity test using Hamburg testing device: Hamburg test should be performed on various amounts of RAP materials up to 50% and different aggregate types
2. Field Test section: Test section should be built using various amounts of RAP materials up to 50% and different aggregate types.
3. Threshold to change PG grade: Binder test like DCT test should be performed to identify the threshold to change the PG binder grade in consideration of rejuvenating additives.
4. Performance test: Dynamic Modulus and Flow Number tests should be performed on various amounts of RAP materials up to 50% and different aggregate types

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