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Fractionation of recycled asphalt pavement materials: improvement of volumetric mix design driteria for High-RAP content surface mixtures

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FRACTIONATION OF RECYCLED ASPHALT PAVEMENT MATERIALS:

IMPROVEMENT OF VOLUMETRIC MIX DESIGN CRITERIA

FOR HIGH-RAP CONTENT SURFACE MIXTURES

by

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CERTIFICATE OF APPROVAL

MASTER'S THESIS

This is to certify that the Master's thesis of

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ABSTRACT

The objective of this research is to examine the effects that different methods of RAP stockpile fractionation 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. The processing of RAP materials results in the degradation of the aggregate structure of the original pavement. The increased presence of fine RAP materials in the stockpile can be attributed to the amount of crushing done on the RAP millings. Fractionation methods were designed to separate the stockpile at certain sizes to isolate the fine RAP materials which contained higher amounts of fine aggregate and negatively impacted the volumetric properties of the mix design. These isolated RAP materials were used in reduced proportions or completely eliminated, thereby decreasing the amount of fine aggregate material introduced to the mix. Mix designs were created using RAP materials included from each original stockpile and the two fractionated stockpiles created from each original stockpile at high-RAP contents of 30%, 40% and 50% by virgin binder replacement. Fractionation of RAP materials was effective in improving the volumetric properties of high-RAP content mixtures through reduction of fine aggregate material introduced by the RAP materials.

TABLE OF CONTENTS

LIST OF TABLES

Table

LIST OF FIGURES

Figure

CHAPTER 1:

INTRODUCTION

Reclaimed 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*).

The most difficult aspect 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 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 a -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 reduced 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, with the goal of 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 the volumetric improvements attributed to the fractionation methods as well as whether or not compliance with Iowa DOT mix design criteria was achieved.

CHAPTER 2:

HIGH-RAP USAGE IN PRACTICE

Recycled asphalt pavement (RAP) materials consist solely 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 a certain amount of recoverable asphalt binder. These original pavements have been constructed under a specified mix design procedure (i.e. Hveem, Marshall or Superpave mix design) 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 common 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 reanalyzed to account for material degradation (*3*).

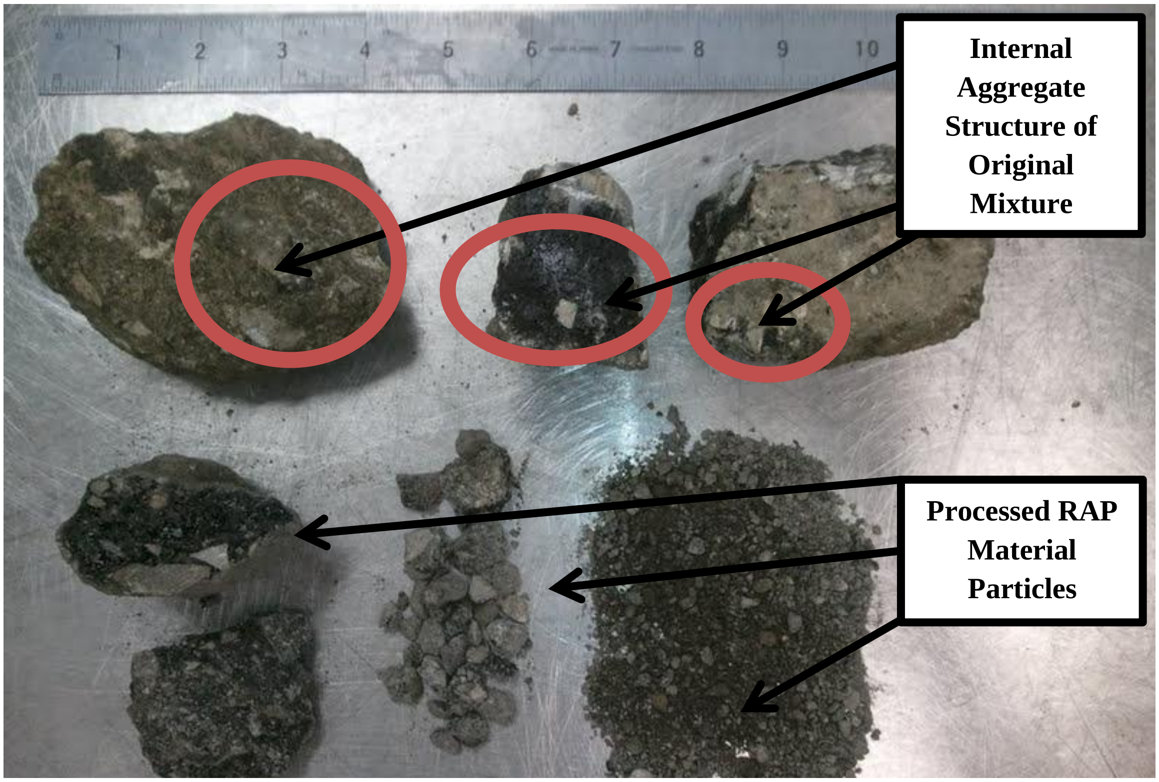

Figure 2-1: Recycled Asphalt Pavement Material Composition

2.1 – RAP Usage and Regulation in 10 Midwestern States

The procedures involving 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 surface course is generally limited by the state DOT's to reduce the negative impacts that high-RAP contents 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.

Table 2-1: 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 2-1 continued: 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 ≥ 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 ≤ 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 a given 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%

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 manner in which these materials are introduced to the mixture. A unique requirement of the Iowa DOT is the three-tier categorization system it uses to identify the stockpiled RAP materials. This categorization system, which is similar to the system utilized by the State of Illinois, is intended to separate materials by source so that recycled pavements with high-quality aggregate properties (friction classification, angularity, bulk specific gravity, etc.) can be identified for usage in higher percentages of 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. None of the other Midwestern states specify any procedures for the stockpiling of RAP materials other than to "*prevent segregation and foreign material*".

Table 2-2: Iowa DOT RAP Stockpile Categorization Criteria and 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 ≤ 300K ESAL	- 0% surface for all ESAL
-Min. 70% virgin AC	-20% Interm. ≤ 1M ESAL	- 10% Interm. ≤ 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*)

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. Table 2-1 shows that, with respect to the top size criterion, the State of 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 State of Illinois 'Conglomerate' material requirement and the State of Indiana 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 problems 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 processing is mostly 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*). The Astec Prosizer™ recycling plant used by many local contractors (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) then pass through the crushing operation before they are screened to the required top size. This process can allow for smaller RAP materials, which already meet the top size requirement, to be unnecessarily crushed resulting in a higher amount of the dust material.

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

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

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 created (*18*). Also, the State of 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 (defined in Table 2-1 by the Iowa and Wisconsin DOT specifications) has also 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*).

2.3 – High-RAP Mix Design Requirements

The maximum percentage of RAP material allowed in surface course mixtures is more controlled than other pavement lift courses due to the increased exposure to traffic loading and environmental conditions. The maximum allowable surface usage is therefore reduced for higher ESAL pavement designs. 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 State of Iowa specifications for this criterion are similar to other Midwestern states and follow the suggestions of recent research studies (*5, 6*). The ultimate intent of modification of the virgin binder PG grade is to ensure that the blended asphalt mixture meets the specified binder grade of the project's contract specifications.

All high-RAP content mixtures that reach these binder grade change thresholds 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 is actually used by the contractors in HMA mixtures. 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.

The State of Iowa has an additional specification for the volumetric mix design criteria of HMA mix designs by setting a requirement for 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 leads to problems meeting the film thickness requirement for high-RAP content mixtures (*19*). Heitzman et al. described that the generation of film thickness and voids in mineral aggregate (VMA) criteria evolved from 1950's research to improve HMA mix durability (*20*). The film thickness requirement is intended to ensure that HMA mixtures contain sufficient asphalt binder for a given aggregate structure; however, this criterion also has the effect of limiting the total amount of RAP that can be used in the mixture due to the increased dust content coming from the RAP materials.

2.4 – Methods to Improve High-RAP Mix Design

The state DOT specifications are intended to ensure that all HMA mixtures perform well throughout their design life. 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 options available in order to use the maximum percentage of RAP materials allowed under the current DOT 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 reality of the current state of practice is that 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 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 State of 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 size thresholds for separation of the original RAP stockpiles.

CHAPTER 3:

DETAILED RAP MATERIAL COMPOSITION ANALYSIS

Samples of three different RAP materials were obtained from stockpiles at a local, eastern-Iowa contractor's asphalt plant facility and brought to the University of Iowa Asphalt Research Laboratory to analyze their material composition. All three 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 conducted on each RAP material to investigate the material composition of the three 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 stockpiled RAP materials. The recovered aggregate gradation from the RAP material shows an extremely fine gradation (16% dust content) that is completely outside the control points for the original mix design due to the aggregate degradation that likely occurred during the removal and processing operations (*3*). The chemical binder extraction and aggregate testing results are attached in Appendix A.

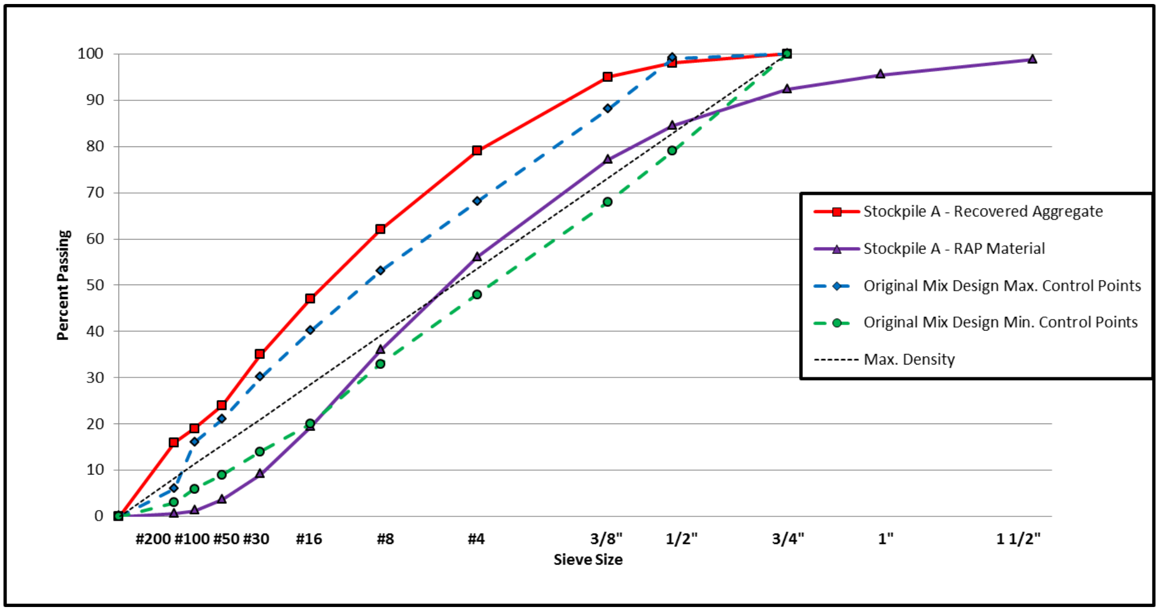

Figure 3-1: Recovered Aggregate & RAP Material Gradation Comparison – Stockpile A

The stockpiled RAP materials are milled and processed pieces of the original pavement; therefore each RAP particle consists of a collection of the original mixture's aggregate particles which are held together by the recoverable asphalt binder. This is supported by Figure 3-1 which compares the gradations of the stockpiled RAP materials before binder extraction compared to the recovered aggregate gradation after binder extraction (RAP gradation analysis results summarized in Appendix B). As expected, the RAP materials exhibit a much more coarse gradation because each particle's composition contains a range of aggregate sizes still held together by the asphalt binder; however, after binder extraction these particles are released to show the extremely fine aggregate structure that is expected to blend with the virgin materials in the HMA mixture. Again, using RAP materials with such high dust contents causes problems with meeting specified volumetric mix design criteria such as the combined aggregate gradation, dust-binder ratio and film thickness for high-RAP content mixes.

A connection needed to be made between the size of the RAP material and the distribution of aggregates contained in that material in order to create fractionation methods effective at reducing this fine aggregate material. The Stockpile A RAP material was separated by sieve sizes ranging from 1½" down to No. 200 and an ignition-oven binder burn-off was conducted on samples of each RAP material size. Next, a gradation analysis was conducted on the recovered aggregates from each RAP sample to determine the distribution of particle sizes held together by the asphalt binder.

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. Figure 3-2 shows that the reported recovered aggregate gradation after chemical binder extraction (as seen in Figure 3-1) is nearly identical to the estimated recovered aggregate gradation calculated using the normalized data from Table 3-1. The overall recovered aggregate gradation of Stockpile A can therefore be thought of as a composite of the recovered aggregate distributions of each size of RAP material normalized by the percentage of that RAP material size contained in the stockpile.

Table 3-1 also shows two distinctly identifiable categories of RAP material within Stockpile A based on the recovered aggregate composition of each RAP material size. The 'Coarse RAP' material sizes (RAP materials retained on No. 4 sieve or larger) have a much lower composition of the very fine aggregate materials (particles retained on the No. 50, No. 100, No. 200 and minus No. 200 sieves) than the smaller 'Fine RAP' sizes (RAP materials passing No. 4 sieve). These 'Fine RAP' materials (dark-shaded in Table 3-1) make up 56% of the mass of Stockpile A and contain 63% of the total dust content from the recovered aggregate. Some of these ‘Fine RAP’ materials also contain significant percentages of recoverable asphalt binder (No. 16 and No. 30 size RAP materials have the two richest asphalt contents of the stockpile), but some of these same materials are also clearly the main sources for the total dust content of the recovered aggregates from Stockpile A. The No. 8 and No. 16 size RAP materials each contribute 20% of the total dust content due to the fact that these materials contain a higher portion of minus No. 200 material and make up significant amounts of the RAP stockpile.

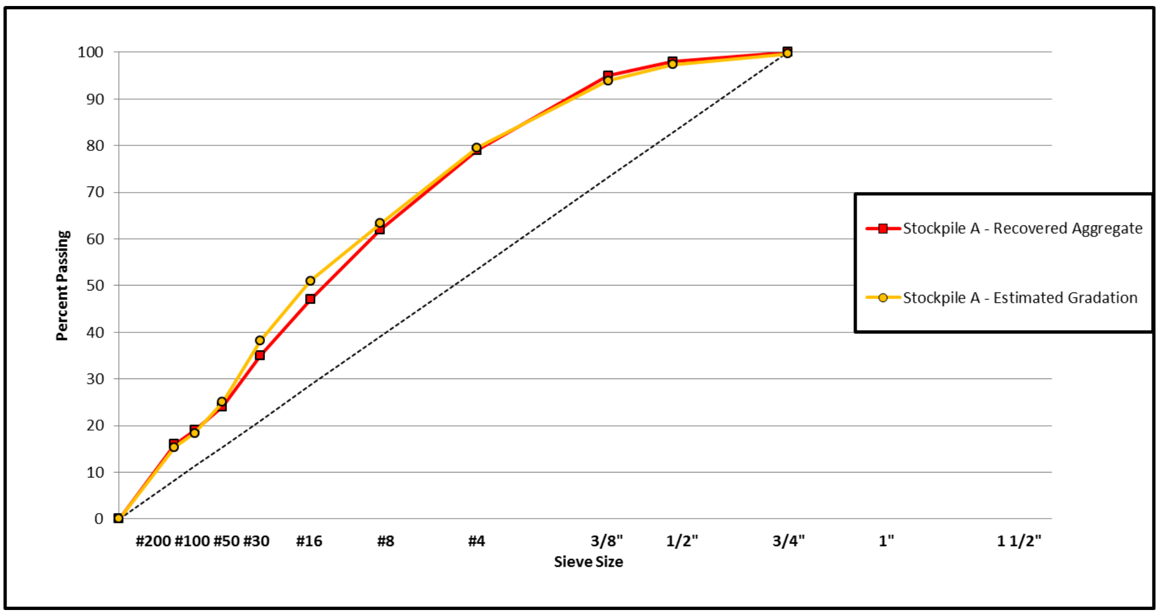

Figure 3-2: Recovered Aggregate vs. Estimated Gradation – Stockpile A

While materials from both categories contain significantly high dust contents, this data supports the claim that the smaller sizes of processed RAP material increase the dust content of the overall stockpile. Materials in the Fine RAP category contain higher proportions of fine aggregate material than the Coarse RAP materials from Stockpile A. The RAP-size categories established for Stockpile A show that a connection can be established between the size of the RAP particle and the proportion of fine aggregate contained in that material. Fractionation of this RAP stockpile for the purpose of fine aggregate reduction would suggest that the Fine RAP materials be targeted for removal; however, there are some negative impacts associated with the loss of this material. As mentioned above, this category represents over half of the total stockpile. Also the No. 16 and No. 30 RAP sizes have the richest asphalt contents of all other RAP sizes and each comprises a significant portion of the stockpile. Removal of this entire category could dramatically reduce the amount of usable material and the total asphalt content of the stockpile. These analyses were repeated for all RAP materials used in the study to determine whether these stockpiles could also be categorized according to this system.

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 of the stockpile not being from a "*single, documented source*"(*4*) the material lost its Classified RAP status and had to undergo further quality control testing to become 'Certified RAP' (see Appendix A for DOT extraction testing report). Figure 3-3 shows the reported recovered aggregate gradation for the Certified RAP of Stockpile B compared to the original airport runway mix design gradation range and the recovered aggregate gradation for the Stockpile A Classified RAP material (which makes up the overwhelming majority of Stockpile B).

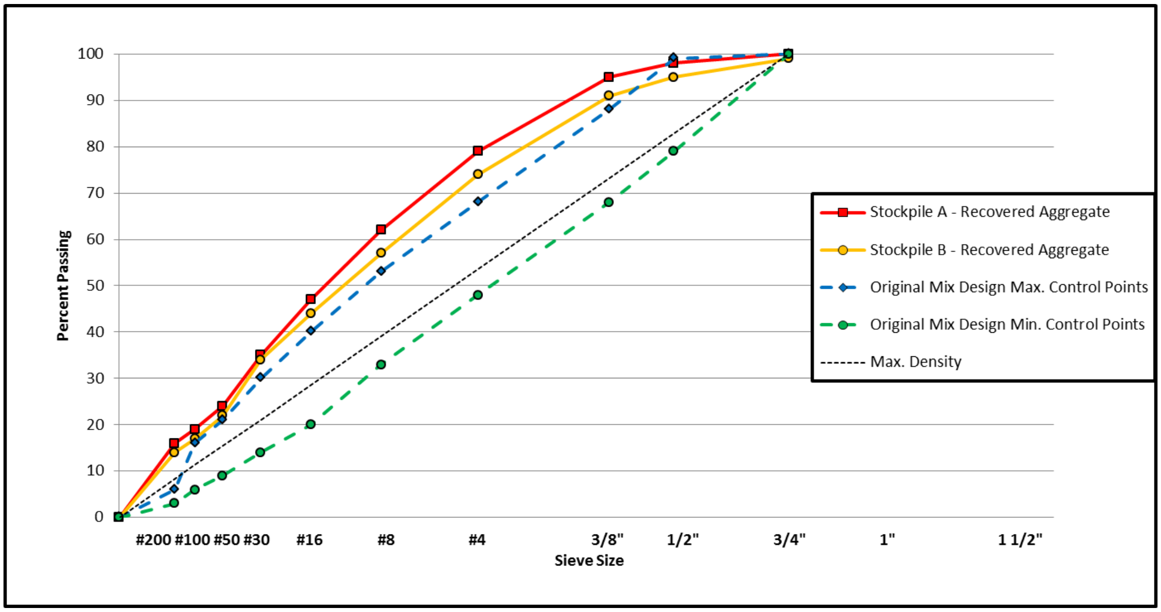

Figure 3-3: Recovered Aggregate Gradation vs. Original Mix Design – Stockpile A & B

The recovered aggregate gradation of the Certified RAP material from Stockpile B is very similar to the Classified RAP material from Stockpile A due to the fact that the vast majority of material in Stockpile B is from the same source as Stockpile A. There is some improved behavior with respect to the 'fineness' of the recovered aggregates of Stockpile B, as evident by the downward shift of the gradation curve with respect to Stockpile A. The gradation curve comes close to falling within the maximum control points of the original mix design; however, this Certified RAP material still has excessive amounts of fine aggregate with 14% dust content (determined by contractor).

The results of the composition analysis for the Stockpile B Certified RAP materials are detailed in Table 3-2. The same RAP categorization system used for the Stockpile A Classified RAP material is applicable to Stockpile B, with the Coarse RAP materials being those retained on a No. 4 sieve and larger and the Fine RAP materials being smaller than the No. 4 sieve. Figure 3-4 shows that the normalized composite gradation of all RAP material sizes contained in Stockpile B is also accurate at representing the reported recovered aggregate gradation after chemical binder extraction.

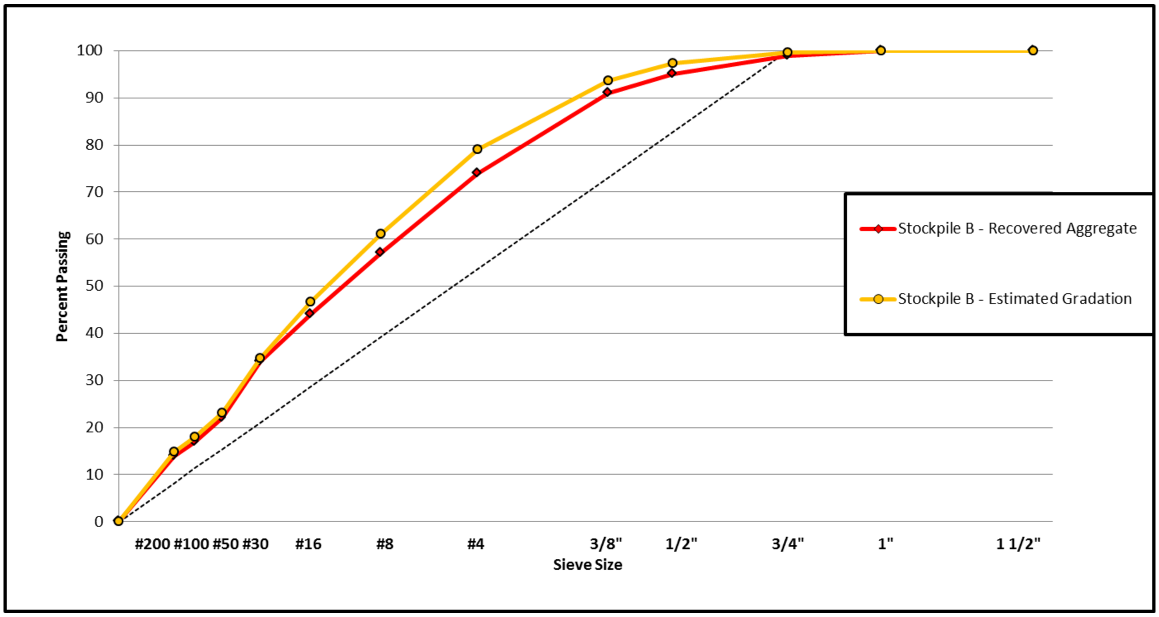

Figure 3-4: Recovered Aggregate vs. Estimated Gradation – Stockpile B

These RAP materials continue to show that the recovered aggregate composition of the very fine material sizes (aggregates retained on the No. 50, No. 100, No. 200 and minus No. 200 sieves) from each Coarse RAP material size is much lower than the Fine RAP material sizes (RAP materials passing No. 4 sieve). For Stockpile B the Fine RAP materials make up 50% of the material (compared to 56% of Stockpile A) and contain 61% of the dust content from the recovered aggregate (63% for Stockpile A). Similar to Stockpile A, some of these Fine RAP material sizes contain significant percentages of recoverable binder (No.16 and No.30 size RAP materials have the two richest asphalt contents of Stockpile B); but they are also clearly the main sources of the total dust content from the Stockpile B recovered aggregates. As seen in Stockpile A, the No. 8 and

No. 16 size RAP materials each contribute 20% of total dust content for Stockpile B due to the combination of their higher individual dust contents and the high prevalence of these RAP material sizes in Stockpile B.

Comparison of the composition analyses conducted on Stockpile A and B (summarized in Table 3-1 and Table 3-2 respectively) shows that, while the majority of the RAP materials in each stockpile are from the same runway millings source and each corresponding RAP size has comparable aggregate composition, the distribution of RAP sizes within the stockpile is different. Stockpile B contains a lower percentage of Fine RAP material (50% of Stockpile B compared to 56% of Stockpile A) and also has a reported recovered aggregate gradation that is coarser than Stockpile A (Figure 3-3). This confirms the idea that decreasing the amount of Fine RAP material used in the mixture results in the recovered aggregate gradation of the stockpile being controlled more by the aggregate distribution of the larger RAP materials that fall into the Coarse RAP category which have lower dust contents.

As previously discussed, the material composition of the larger RAP pieces can be expected to more closely reflect the properties of the original mix design because they have not been impacted as heavily by the material degradation that occurs when these pieces are processed into smaller RAP materials. Figure 3-5 shows the normalized composite gradation of the Coarse RAP materials from Stockpile A and B compared to the allowable gradation range for the original airport runway mix design. These gradation curves show that the recovered aggregate gradation of the normalized combination of Coarse RAP materials is much more representative of the original mix design gradation than the RAP stockpile as a whole. These aggregate distributions begin to show the typical S-curve behavior that crosses the maximum density line at the No. 4 sieve size; however, there is still an increased amount of fine aggregate material contained in these materials compared to the original mixture. Overall, it can be expected that increasing the amount of Coarse RAP materials contained in the total RAP material added to the HMA mixture will result in a reduction of fine aggregate contributed by the RAP.

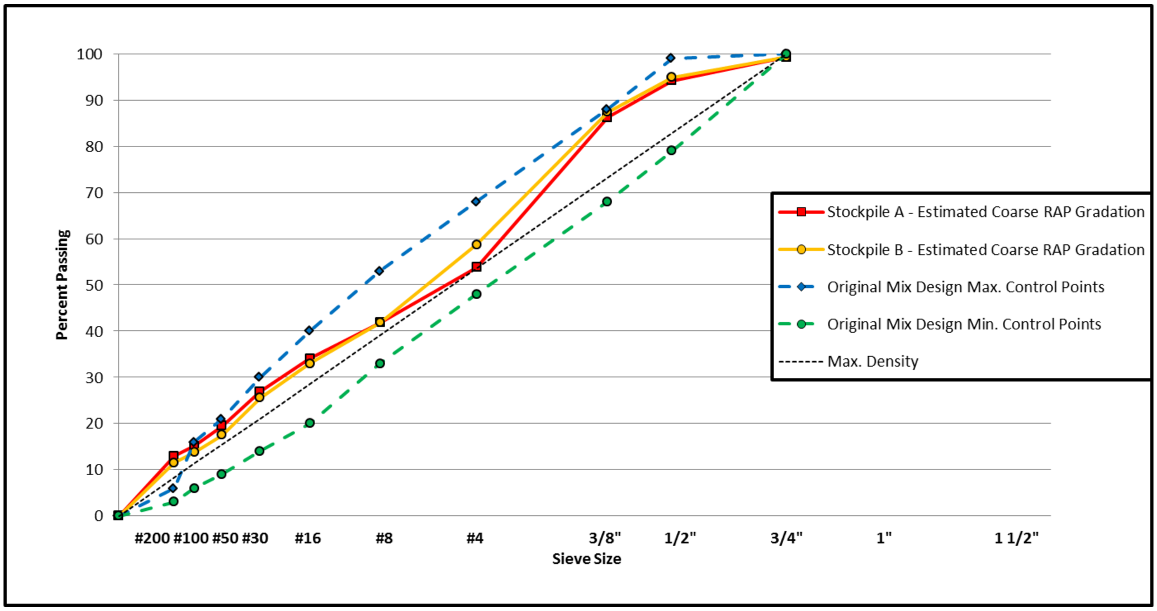

Figure 3-5: Estimated Coarse RAP Gradation vs. Original Mix Design – Stockpile A & B

3.3 – Composition Analysis of Certified RAP from Unknown Sources

The third RAP material used in the study (referred to herein as Stockpile C) was 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*). The complete report from the Iowa DOT detailing material properties after quality control testing can be found in Appendix A. Figure 3-6 shows the reported recovered aggregate gradation for the Certified RAP of Stockpile C compared to Stockpile A and B. The Certified RAP material of Stockpile C showed the best behavior by far in terms of recovered aggregate gradation with 10% dust content and the gradation curve following just above the maximum density line. There is a significant downward shift in the gradation curve compared to Stockpile A and B meaning that there is much less fine aggregate material contained in this RAP stockpile.

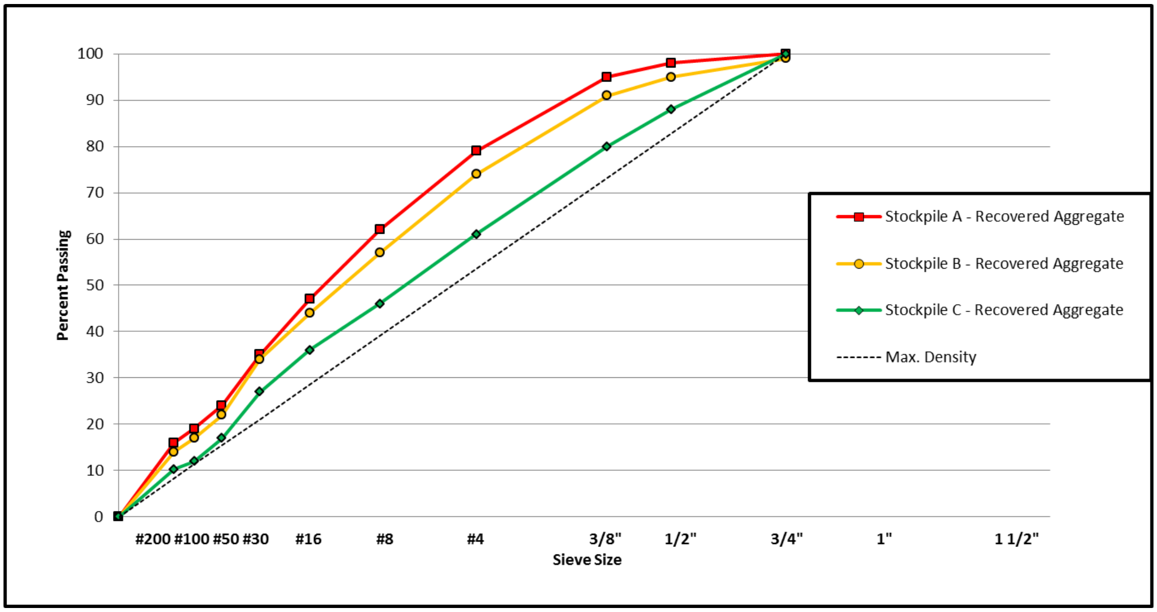

Figure 3-6: Recovered Aggregate Gradation Comparison – Stockpile A, B and C

The results of the composition analysis for the Stockpile C Certified RAP materials, detailed in Table 3-3, show that the RAP categorization system used for the Stockpile A and B remains applicable for differentiation based on fine aggregate composition. Figure 3-7 shows that the normalized composite gradation of all RAP material sizes contained in Stockpile C is not as accurate as Stockpile A and B at representing the reported recovered aggregate gradation for the coarse aggregate sizes; however, the very fine aggregate material composition is still very similar. Ultimately it was determined that the 'Sieve-Size-Separated RAP Material Composition Analysis' effectively showed that each RAP stockpile used in this study can be described in terms of their fine aggregate composition by the percentages of Coarse and Fine RAP material (split at the No. 4 sieve size) contained in that stockpile.

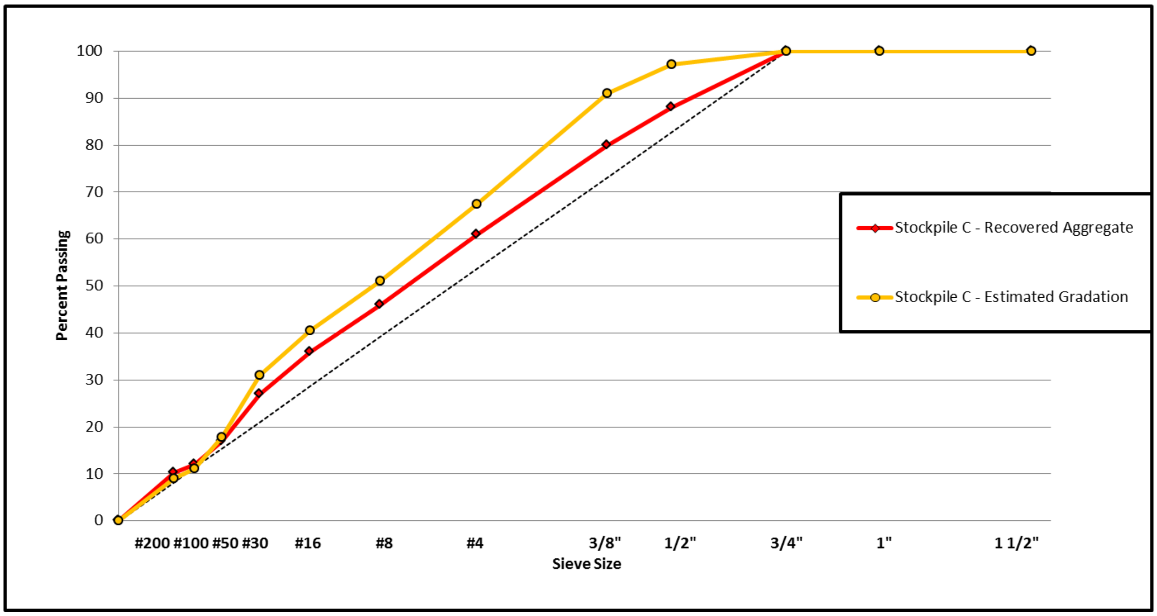

Figure 3-7: Recovered Aggregate vs. Estimated Gradation – Stockpile C

For Stockpile C, the fact that the Fine RAP materials make up only 35% of the material (compared to 56% of Stockpile A and 50% of Stockpile B) and that Stockpile C also has the best recovered aggregate gradation, in terms of dust content, further confirms the idea that decreasing the amount of Fine RAP material in the stockpile results in a reduction of the dust content contained in the RAP material. Figure 3-8 shows the normalized composite gradation of the Coarse RAP from Stockpile C compared to the control points for a ½” mix size (assumed to be average mix size of all recycled pavements included in Stockpile C). The recovered aggregate gradation of the normalized combination of Coarse RAP materials from Stockpile C is very representative of a ½” mix size gradation as it meets all specified control points. The overall recovered aggregate gradation of Stockpile C is dominated by the aggregate distributions of these Coarse RAP materials, due to the fact that they comprise 65% of the total stockpile. This leads to the overall stockpile having a much lower dust content than Stockpile A and B. The high amount of Coarse RAP material in Stockpile C also suggests that this material may not have been processed as extensively as Stockpiles A and B; therefore, the decreased dust content of each RAP size in Stockpile C compared to Stockpile A and B may be attributed to this decreased processing.

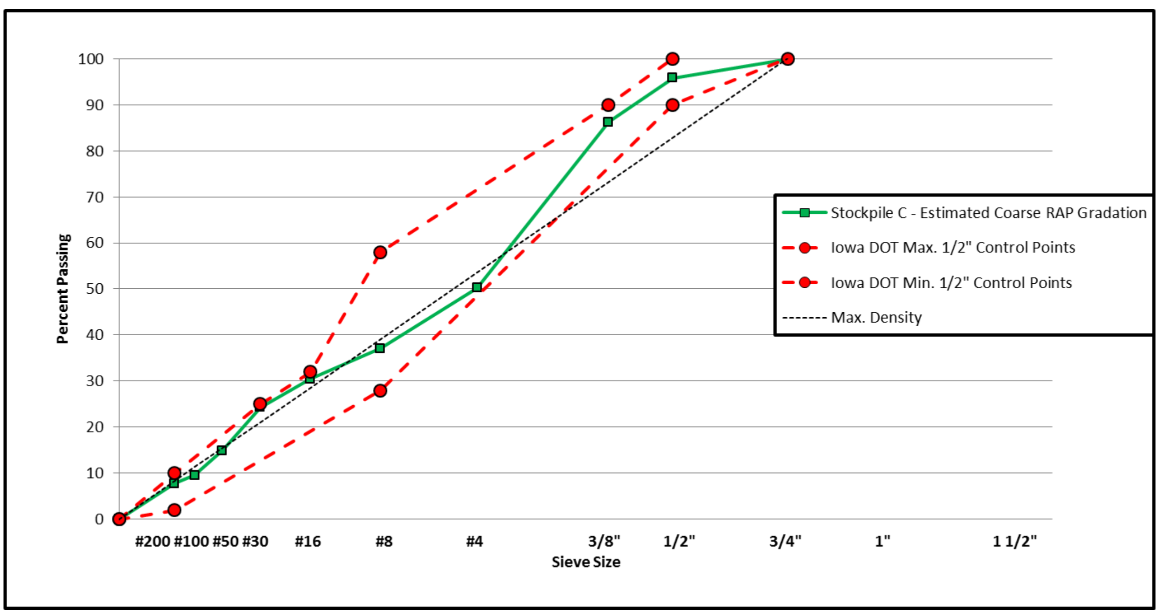

Figure 3-8: Estimated Coarse RAP Gradation vs. 1/2" Mix Size – Stockpile C

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

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”	0.0	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%**
Coarse RAP Fine Agg. Avg.	---	---	---	---	---	---	---	7.8	4.7	2.2	12.8			
Coefficient of Variation	---	---	---	---	---	---	---	12%	10%	8%	3%			

Source: Material testing conducted at University of Iowa Asphalt Research Laboratory and LL Pelling Co. QC Laboratory facilities

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%**
Coarse RAP Fine Agg. Avg.	---	---	---	---	---	---	---	9.1	4.0	2.3	11.5			
Coefficient of Variation	---	---	---	---	---	---	---	18%	13%	8%	6%			

Source: Material testing conducted at University of Iowa Asphalt Research Laboratory and LL Pelling Co. QC Laboratory facilities

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

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”	---	---	---	---	---	---	---	---	---	---	---	---	---	0.00
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%**
Coarse RAP Fine Agg. Avg.	---	---	---	---	---	---	---	10.4	5.5	1.6	7.3			
Coefficient of Variation	---	---	---	---	---	---	---	17%	11%	18%	13%			

Source: Material testing conducted at University of Iowa Asphalt Research Laboratory and LL Pelling Co. QC Laboratory facilities

3.4 – Summary of RAP Material Composition Analysis

The three different RAP material stockpiles used in this study were analyzed based on results of chemical binder extraction testing at the Iowa DOT Central Materials Lab and the 'Sieve-Size-Separated RAP Material Composition Analysis' conducted at the University of Iowa Asphalt Research Laboratory. Stockpile A was categorized as Classified RAP by the Iowa DOT and was composed solely of millings from an Eastern Iowa Airport runway. This stockpile was categorized as the highest level of material by Iowa DOT standards and came from a pavement with very high quality mix design criteria (maximum amount of initial aggregate material passing the No. 200 sieve was only 6%). However, the recovered aggregate gradation after chemical binder extraction showed that the dust content had increased to 16% after removal and processing. The Certified RAP material in Stockpile B was almost exclusively from the same source and had relatively identical fine aggregate composition with the dust content slightly reduced to 14%. The RAP material in Stockpile C showed significantly lower fine aggregate composition than Stockpile A and B and a much lower dust content of 10%. No information was available about the original mix design of these materials because the stockpile was composed of millings from multiple sources; therefore quality control testing was performed to accurately determine the necessary properties of this material and categorize the stockpile as Certified RAP by the Iowa DOT Central Materials Lab.

The 'Sieve-Size-Separated RAP Material Composition Analysis' conducted on all three stockpiles showed that a single RAP material categorization system could be identified based on the recovered aggregate composition of the different RAP sizes. The Coarse RAP category consisted of all RAP materials within each stockpile that would be retained on a No. 4 sieve. For each stockpile the recovered fine aggregate distribution from each of these RAP material sizes was very consistent and the dust contents were much lower than the smaller RAP material sizes. The Fine RAP category consisted of all RAP materials in the stockpile that would pass through a No. 4 sieve. For each stockpile the recovered aggregates from these materials were very highly variable and the dust contents were significantly higher than the Coarse RAP material. The Fine RAP materials did show much higher percentages of recovered asphalt binder.

The Coarse and Fine RAP aggregate distributions of the Stockpile A and B materials showed consistent behavior, as was expected for materials from the same source; therefore these stockpiles could be compared to determine why Stockpile B had reduced dust content. The main difference between these two materials is the percentage of Coarse and Fine RAP materials contained in each stockpile. Fifty percent of Stockpile B was Fine RAP material (smaller than No. 4 sieve) resulting in a total dust content of 14%, while fifty-six percent of Stockpile A was Fine RAP material resulting in a total dust content of 16%. This showed the connection that the increased amount of Fine RAP material in the stockpile resulted in an increased dust content of the recovered aggregate gradation from that stockpile. This connection was confirmed for Stockpile C which had a much higher percentage of Coarse RAP material in the stockpile (65%) and much lower dust content in the recovered aggregate gradation from this stockpile (10%).

The data from the 'Sieve-Size-Separated RAP Material Composition Analysis' was also used to estimate the combined recovered aggregate gradation of the Coarse RAP material from each stockpile by normalizing the aggregate distribution of each Coarse RAP material size by the percentage of that size of RAP material that exists in the stockpile. Comparisons of the estimated Coarse RAP aggregate gradation to the original pavement's mix design control points for each stockpile showed that these Coarse RAP materials are much more representative of the original mix design gradation than the stockpile as a whole. This further supported the claim that increasing the amount of Coarse RAP materials contained in the total RAP material that is introduced to the HMA mixture will decrease the amount of fine aggregate material contributed by the RAP. Ultimately, this correlation was used to design RAP stockpile fractionation methods that could reduce the amount of Fine RAP material introduced into the HMA mixture.

The analyses conducted on materials from all three different RAP stockpiles confirmed that the material compositions of larger RAP pieces more closely reflect the properties of the original mix design because they have not experienced the material degradation from processing into smaller RAP sizes. These analyses also support the statement that the selection 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 confirmation of these statements allows for the current practice of RAP processing to be reviewed in order to decrease the aggregate degradation that causes volumetric problems with high-RAP mix designs.

Given that the amount of dust created during processing depends on both the crushing system used and the top size selected for this operation, these areas should be the focus of modification (*18*). As mentioned, certain crushing operations will create excessive amounts of dust out of the processed materials due to the nature of their mechanical processes. Hammer mill impact crushers, like the one included on the Astec ProSizer™, 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 still 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 as necessary and then sampled and categorized separately. This sequence change for RAP processing will allow for the resulting RAP stockpiles to contain significantly higher proportions of Coarse RAP material. As discussed throughout this chapter, these materials tend to retain the aggregate gradation properties of the original mix design; therefore, they are more suitable for use in high-RAP content mixtures. Also, an increase in the top size requirement could further improve the properties of these RAP stockpiles. Additional fractionation methods can be applied to the RAP stockpile if it is necessary to further improve the material's properties for use in high-RAP mix designs.

CHAPTER 4:

DESIGN OF FRACTIONATION METHODS

The RAP Material Composition Analysis of all three stockpiles used in this study determined that significant aggregate degradation had occurred during the milling and processing of the RAP materials. The excessive amounts of fine aggregate material (namely the dust content) created during these procedures causes difficulty for high-RAP content mixes in meeting specified volumetric mix design criteria such as the combined aggregate gradation, dust-binder ratio and film thickness. Therefore, the purpose of RAP fractionation for this research was to create new stockpiles with reduced fine aggregate composition in order to mitigate the impact of this material on the high-RAP content HMA surface mix design.

Within each stockpile it was determined that the RAP materials could be divided into Coarse RAP and Fine RAP categories (split at the No. 4 sieve size), and that the Fine RAP materials contained significantly higher proportions of the fine aggregate material. Fractionation methods needed to be designed to mechanically split the original stockpile at a certain RAP size in order to isolate the Fine RAP materials so their inclusion in the mixture could be limited. Several impacts of the Fine RAP material's reduction/removal needed to be addressed for these methods to be used in practice. First, the method needed to limit the excessive reduction of the amount of usable material in the new stockpile. Second, the binder content of the original stockpile should not be significantly reduced. Finally, the method must be mechanically practical for contractors to use with equipment available at their facilities. Balancing these concerns with sufficient fine aggregate reduction resulted in design of the following two methods.

4.1 – 'Fractionated RAP' Method

The first fractionation method directly targeted the Fine RAP materials by physically removing the smallest of these RAP sizes from the stockpile during the processing operation. Conversations with local, eastern-Iowa asphalt contractors revealed that this type of 'Fine RAP removal' method had been attempted at the company's asphalt plant facilities using the Astec ProSizer^{TM} equipment shown in Chapter 2. This system uses a high-frequency vibration screening mechanism to effectively separate the RAP materials even at very 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.

The contractor's initial attempts with this fractionation method set the removal threshold at the No. 4 RAP size (i.e. all RAP material passing this screen size was removed from the original stockpile), which removed all material in the Fine RAP category. When this threshold was applied to the Classified RAP of Stockpile A the contractor noticed that a very significant amount of material (over 50%) was being removed from the original stockpile. Data from the RAP Material Composition Analysis displayed in Table 3-1 confirmed that these amounts follow the RAP material size distribution determined through the sieve analysis of Stockpile A -- 56% of the stockpiled RAP material passed No. 4 sieve. This was considered unacceptable for maintaining the amount of usable material; therefore, smaller RAP size removal thresholds were explored so that the entire Fine RAP material category would not be removed.

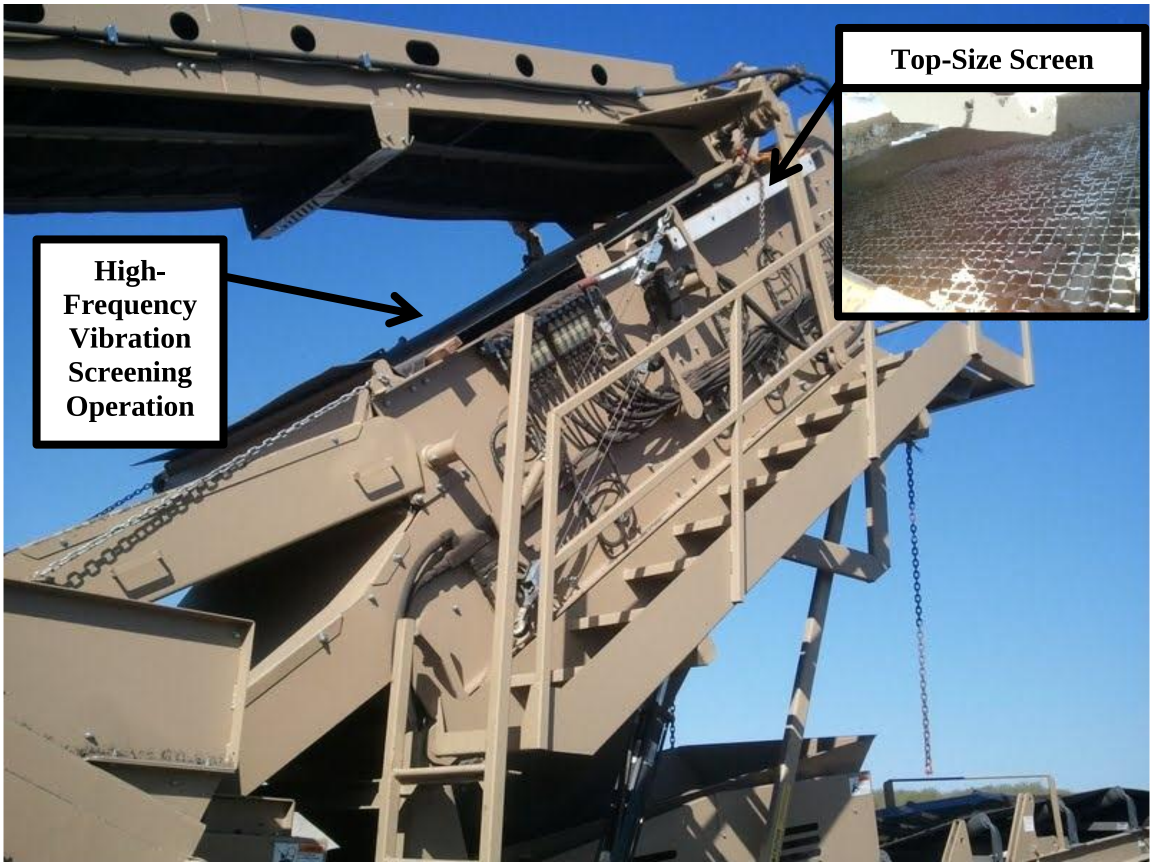

Figure 4-1: High-Frequency, Stacked-Screening Operation for Fine RAP Removal

The RAP Material Composition Analysis data for Stockpile A (Table 3-1) was consulted to determine the expected percent removal of the original stockpile's material for different Fine RAP removal thresholds. Removal of all RAP materials smaller than the No. 16 sieve removed 19% from the stockpile; however, the No. 30-size RAP material contains the second-highest asphalt content of Stockpile A and makes up 10% of the stockpile's material. In order to maintain the size *and* asphalt content of the new 'Fractionated RAP-A' stockpile it was decided that the No. 30 sieve size should be set as the removal threshold (all RAP passing No. 30 sieve removed from stockpile). This method resulted in only 9% of the original Stockpile A material being discarded while still effectively targeting the RAP materials with large fine aggregate composition.

This method was applied to the Stockpile A RAP materials in the University of Iowa Asphalt Research Laboratory where screening equipment was used to remove all RAP material that passed the No. 30 sieve to create a new Fractionated RAP-A stockpile. In order to determine the effectiveness of fine aggregate reduction, an ignition-oven binder burn-off was conducted on a sample from this new stockpile and a gradation analysis was done on the recovered aggregates. Testing results from this Fractionated RAP-A stockpile sample showed that the asphalt content increased to 5.70% and the dust content was reduced to 14.1%. Figure 4-2 shows the improved gradation of the Fractionated RAP-A stockpile compared to the original Stockpile A, as evident by the downward shift of the gradation curve. Table 4-1 summarizes the reduction of very fine aggregate material (smaller than No. 30 sieve size) in the Fractionated RAP-A stockpile. This method was determined to be successful at achieving the desired fine aggregate reduction while maintaining the total amount and asphalt content of the usable material.

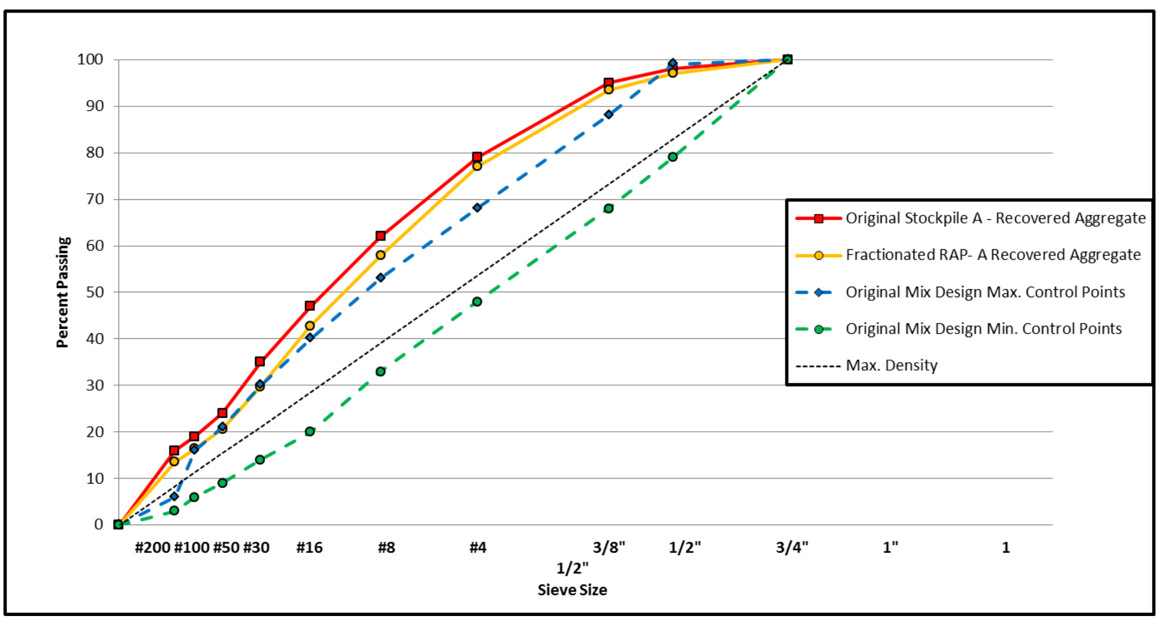

Figure 4-2: Gradation Improvement of ‘Fractionated RAP’ Method – Stockpile A

Table 4-1: Fine Aggregate Reduction of Fine RAP Removal – Fractionated RAP-A

RAP Stockpile Analysis	Fine Aggregate Composition – (% Retained) No. 50	No. 100	No. 200	Pan	% of Stockpile
Original Stockpile DOT Extraction	11.0	5.0	3.0	16.0	**35.0%**
'Fractionated RAP' Binder Burn-Off	9.0	3.6	2.6	14.1	**29.3%**
Fine Aggregate Mat'l. Percent Reduction	-18.2%	-28.0%	-13.3%	-11.9%	**-16.3%**

The No. 30 RAP removal threshold used for Stockpile A was also applied to Stockpile B and C for consistency of comparing the impact that the 'Fractionated RAP' method had on the mix design results. Application of this method resulted in an expected RAP material loss of 5.8% and 5.0% from Stockpile B and C respectively. Tables 4-2 and 4-3 summarize the reduction of very fine aggregate material (smaller than No. 30 sieve size) seen in the Fractionated RAP-B and Fractionated RAP-C stockpiles respectively.

Table 4-2: 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%**
Fine Aggregate Mat'l. Percent Reduction	-23.3%	-16.0%	-6.7%	-2.9%	**-12.4%**

Table 4-3 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%**
Fine Aggregate Mat'l. Percent Reduction	+2.0%	+4.0%	+5.9%	-17.5%	**-4.8%**

Both of the Fractionated RAP-B and Fractionated RAP-C stockpiles showed decreased fine aggregate composition and dust content while losing a very small amount of RAP material from the original stockpile. The Fractionated RAP-B stockpile did not show as large of a dust content reduction as the Fractionated RAP-A and Fractionated RAP-C stockpiles; however, there was still significant reduction of the No. 50 and No. 100 aggregate materials. The Fractionated RAP-C stockpile actually saw slight increases in the amount of No. 50, No. 100 and No. 200 aggregate materials, but the very large dust content reduction resulted in this method still being effective. The recovered asphalt content from the Fractionated RAP-B sample increased from 5.11% for the original stockpile to 5.34%, similar to the Stockpile A materials; and the recovered asphalt content from the Fractionated RAP-C stockpile remained relatively constant, increasing only slightly from 4.82% to 4.83%. All testing results from the ignition-oven binder burn-off and recovered aggregate gradation analyses that were conducted on samples from each of these new 'Fractionated RAP' stockpiles are summarized in Appendix C.

The material properties obtained from these testing results were later used during the mix design process to design the high-RAP content mixtures. The resulting volumetric properties of high-RAP mix designs using these materials were compared to the 'Traditional RAP' inclusion method (material randomly added from original stockpile) to determine the impact that this fine aggregate reduction had on improving specified mix design criteria. The ultimate effect on the mix design properties was analyzed to determine if the No. 30 RAP removal threshold was applicable for all three original RAP materials used in the study or if different removal thresholds should be applied to each original stockpile.

4.2 – '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). Information from the RAP Material Composition Analyses described in Chapter 3 revealed that the No. 4 sieve size threshold best split each RAP stockpile into two distinct Coarse RAP and Fine RAP categories based on their fine aggregate composition (namely their dust contents). Therefore, the recovered aggregate gradation of the original stockpile is affected by the cumulative percentage of Fine RAP material sizes it contains (i.e. more Fine RAP yields more fine aggregates in the stockpile). Once the original RAP stockpile has been fractionated into 'Coarse FRAP' and 'Fine FRAP' stockpiles (split at the No. 4 sieve), these materials can be re-proportioned to reduce the percentage of Fine FRAP included in the total RAP added to the mixture; thereby diluting the gradation properties of the Fine FRAP.

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

The No. 4 RAP size fractionation threshold was applied in the University of Iowa Asphalt Research Laboratory to produce a Coarse FRAP and Fine FRAP stockpile from each original RAP material. An ignition-oven binder burn-off was done on a sample from each new stockpile to determine the asphalt content of the material. Also, a sieve analysis was done on the recovered aggregates from each sample to determine the differences of fine aggregate distribution between the Coarse and Fine FRAP materials from each original stockpile. Table 4-4 shows a comparison of the recovered aggregate gradation of the Coarse FRAP material and Fine FRAP material from Stockpile A, B and C.

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

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	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	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	0.0	0.0	0.0	22.0	20.0	15.9	18.5	7.8	2.7	13.1	**34.8%**

These recovered aggregate gradations from actual samples of the Coarse FRAP and Fine FRAP material from each stockpile confirmed the claim from the RAP Material Composition Analyses that the Fine RAP category has much 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 allowable gradation control point of 10% passing the No. 200 screen specified by most Midwestern states

Figure 4-4 shows the recovered aggregate gradation differences between the Coarse FRAP and Fine FRAP materials from Stockpile A compared to the original mix design's gradation tolerances. The recovered aggregate distributions of all Coarse FRAP materials follow very closely to the original pavement's mix design control points while the Fine FRAP recovered aggregates are not at all representative of the original pavement material. The Coarse FRAP-A recovered aggregate gradation also shows very similar behavior to the estimated Coarse RAP composite gradation from the normalized RAP Material Composition Analysis data. All testing results from the ignition-oven binder burn-off and recovered aggregate gradation analyses that were conducted on samples from each of these new Coarse FRAP and Fine FRAP stockpiles are summarized in Appendix C.

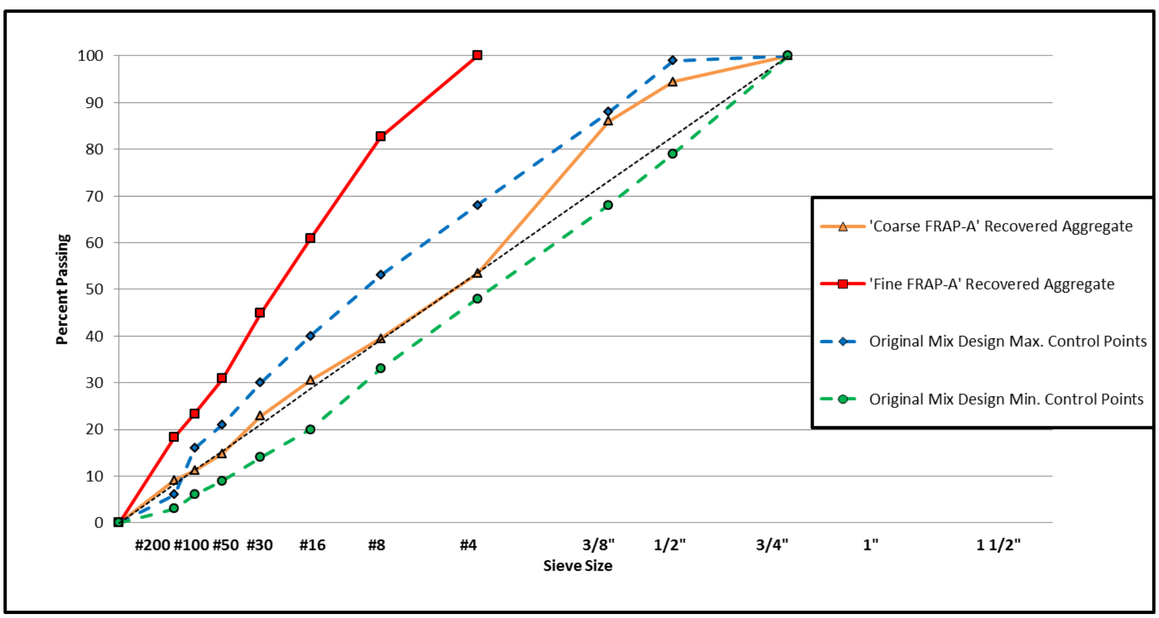

Figure 4-4: Gradation Comparison of Coarse FRAP and Fine FRAP – Stockpile A

The ultimate intent of this fractionation method is to modify the percentage split of Coarse FRAP and Fine FRAP material to decrease the total fine aggregate contribution from the total RAP material introduced to the mixture. Table 4-4, Figure 4-4 and all of the analyses conducted in Chapter 3 show that this is done by increasing the percentage contribution of material from the Coarse FRAP stockpile included in total RAP amount introduced to the mixture. This will cause the composite aggregate gradation of the re-proportioned RAP material to be 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 will be created for each original stockpile so that the combined aggregate gradation (virgin and recovered aggregates) of the High-RAP content mixture will fall as close as possible to the middle of the fine aggregate gradation control point ranges.

4.3 – Summary of Fractionation Methods

The purpose of these RAP fractionation methods was to create new stockpiles with reduced fine aggregate composition and therefore decrease the amount of this material that is introduced to high-RAP content HMA surface mixtures. The Fine RAP materials identified in Chapter 3 (RAP material smaller than No. 4 sieve size) were targeted for removal due to their increased composition of very fine aggregate material. All methods attempted to balance the goal of significant fine aggregate composition reduction with the concerns of maintaining the size and asphalt content of the stockpile as well as making sure that the method could be translated into practice by contractors.

The 'Fractionated RAP' method physically removes all of RAP material smaller than the No. 30 sieve size from the stockpile during the processing operation. Local contractors had experimented with larger RAP removal thresholds; however, too much material was being lost from the original stockpile. This method and size threshold (remove all RAP passing No. 30 sieve size) was applied to all three RAP stockpiles used in this study and resulted in fairly significant fine aggregate reduction, increased asphalt content and minimal material discarded from each original stockpile.

The ‘Optimum FRAP’ method splits each original RAP stockpile at the No. 4 sieve size during the processing operation to create a ‘Coarse FRAP’ stockpile (RAP material not smaller than No. 4 sieve size) and a ‘Fine FRAP’ stockpile (RAP material smaller than No. 4 sieve size) for each material used in the study. During the mix design process the percentages of ‘Coarse FRAP’ material used in the total amount of RAP added to the mixture is higher than the amount naturally present in the original stockpile; therefore, the increased fine aggregate composition of the ‘Fine FRAP’ materials is diluted. The percentage of ‘Coarse FRAP’ will be increased in order to bring the combined aggregate gradation as close as possible to the middle of the fine aggregate gradation control points of the mix design size for all high-RAP contents (up to 50%).

Mix designs would be created for high-RAP content mixtures using RAP materials included via the ‘Traditional RAP’ method (material added from the original stockpile), the ‘Fractionated RAP’ method (all RAP smaller than No. 30 removed from the original stockpile) and the ‘Optimum FRAP’ method (original stockpile split at No. 4 sieve and ‘Coarse FRAP’ percentage increased to meet optimum gradation of combined aggregates). Results of these mix designs were then compared to determine the effects that the fractionation methods have on improving the volumetric properties of high-RAP mix designs by reducing the fine aggregate composition of the stockpile.

CHAPTER 5:

HIGH-RAP CONTENT MIX DESIGN

The ultimate goal of this research is to design high-RAP content surface mixtures that accounted for up to 50% of the virgin binder being replaced by RAP materials and still meet all volumetric mix design criteria required for virgin HMA mixtures. The absolute 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*). For this study High-RAP mix designs were created for inclusion of 30%, 40% and 50% RAP material (measured by amount of virgin binder replaced) from each original RAP stockpile (Stockpile A, B and C) as well as the fractionated RAP stockpiles ('Fractionated RAP' and 'Optimum FRAP') created from each of those original materials. Table 5-1 details all high-RAP content mix designs created and compared during this phase of the project. This procedure allowed for comparison of the mix design properties between each RAP inclusion method, high-RAP content and original material source.

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

Original RAP Stockpile Source	**RAP/FRAP Content (% of Virgin Binder Replaced)**								
	30%			**40%**			**50%**		
Stockpile A Classified RAP Airport	Trad. RAP	Frac. RAP	Opt. FRAP	Trad. RAP	Frac. RAP	Opt. FRAP	Trad. RAP	Frac. RAP	Opt. FRAP
Stockpile B Certified RAP Airport	Trad. RAP	Frac. RAP	Opt. FRAP	Trad. RAP	Frac. RAP	Opt. FRAP	Trad. RAP	Frac. RAP	Opt. FRAP
Stockpile C Certified RAP Unknown	Trad. RAP	Frac. RAP	Opt. FRAP	Trad. RAP	Frac. RAP	Opt. FRAP	Trad. RAP	Frac. RAP	Opt. FRAP

5.1 – Mix Design Procedure

The Iowa DOT '*Method of Design of Hot Mix Asphalt Mixes*' (*7*) procedure details the entire process of aggregate and binder selection, material preparation and HMA mixture batching, curing and testing. This method was followed for all high-RAP mix designs created in this study. The first step of the mix design was selection of the virgin aggregate material and determination of the aggregate properties. All high-RAP mix designs were created for a 1/2" mix size which is typical for a surface course mixture. Local limestone materials were selected for mix design so that the results would be applicable to the contractors who provided the RAP materials. Testing on these materials showed a bulk aggregate specific gravity (G_{sb}) of 2.650 and water absorption of 1.14%. Table 5-2 shows the virgin aggregate gradation compared to the specified control points for the 1/2" mix size. The virgin aggregate gradation was kept strictly constant for each high-RAP mix designs by separating the limestone aggregates into each sieve size listed in Table 5-2 and then recombining each aggregate size according to the designed virgin aggregate gradation. This allowed for changes in the combined aggregate gradation to be attributed to the percentage of RAP added or to the method of RAP fractionation.

Table 5-2: Virgin Aggregate Gradation (% Passing) with 1/2" Mix Size 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**
Virgin Aggregate	100	91.4	80.0	60.0	43.3	32.1	20.5	11.9	4.4	3.5
½" Minimum Control Points	**100**	**90**			**28**					**2.0**

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

The next step required selection of the virgin binder material. The performance grade of the virgin binder was reduced one temperature classification to PG 58-28, as required by the Iowa DOT for RAP contents greater than 20% of virgin binder replacement (*4*, *7*). Also, performance grading was done by Iowa State University on blends of the 30%, 40% and 50% extracted RAP binder from each original stockpile with virgin binder, as required by the Iowa DOT for RAP contents greater than 30% of virgin binder replacement (*7*). All mixtures met a blended PG 64-22 binder grade making this virgin PG selection valid. Detailed results from this testing can be found in Appendix D.

The final step involves mixing and testing HMA samples using the different RAP materials to determine the optimum asphalt content of each mix design (percentage of binder that results in the specified air void percentage of the sample being met). Typically the SHADES computer program provided by the Iowa DOT is used by contractors 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 detailed in 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, rather than the percentage of virgin binder replacement. The program then calculated the amount of virgin binder to add to the mixture, in addition to the asphalt binder contributed by the RAP material, to achieve the target asphalt content as shown in the following equation:

$$P_{b(add)} = \frac{\left(P_{b(target)} * 100\right) - \left(\%RAP_{weight(added)} * P_{b(RAP)}\right)}{100 - \left(\%RAP_{weight(added)} * P_{b(RAP)} * 0.01\right)}$$

Due to the fact that the mix designs for this research were to be created based on the percentage of virgin binder replaced by the RAP material, a modified spreadsheet program was created that calculated the percentage weight of RAP material to add to the mixture to account for the specified percentage of virgin binder replacement of the targeted asphalt content, as shown by the following equation. This equation and other formulae in IM 501 were used to determine the weights of virgin aggregate, virgin binder and RAP material to be included in each high-RAP trial mixture.

$$\%RAP_{weight(add)} = \frac{(P_{b(target)} * \%RAP_{binder})}{(P_{b(RAP)} * 0.01) - (P_{b(RAP)} * P_{b(target)} * (1 - \%RAP_{binder}) * 0.0001)}$$

Ultimately 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 created in the laboratory 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 dramatically improve the combined gradation. The criteria for this new proportion selection were as follows:

1. 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 the No. 200 sieve)
2. The combined aggregate surface area and fine aggregate composition should be reduced from the original stockpile and the ‘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 to 75% of the total RAP weight added to the mixture for the 'Optimum FRAP-A' blend (original stockpile showed 44% Coarse RAP and 56% Fine RAP). The Coarse FRAP from Stockpile B was selected to be 80% of the 'Optimum FRAP-B' blend (increased from 50% of original stockpile), and the Coarse FRAP from Stockpile C was increased to 90% of the 'Optimum FRAP-C' blend (65% of original stockpile).

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 was developed to calculate the expected amount of leftover material, as a percentage of the original stockpile, based on the percentage split of Coarse and Fine RAP material in the original stockpile and the new, increased Coarse FRAP percentage:

$$\%\,Leftover = \frac{\left(\%\,Coarse_{new} - \%\,Coarse_{orig}\right) * \left(1 + \dfrac{\%\,Fine_{orig}}{\%\,Coarse_{orig}}\right)}{1 + \left(\%\,Coarse_{new} - \%\,Coarse_{orig}\right) * \left(1 + \dfrac{\%\,Fine_{orig}}{\%\,Coarse_{orig}}\right)}$$

In contrast to the Fractionated RAP method, these percentages are not actually removed from the original stockpile and discarded; but rather, the fact that the Fine FRAP stockpile materials are used in much lower proportions of the Optimum FRAP blend causes a build-up of this material. A summary of these analyses is found in Appendix E.

5.2 – High-RAP Content Mix Design Volumetric Results

Volumetric properties and mix design criteria were calculated for each mixture at the optimum binder content using formulae found in Iowa DOT Materials IM 501 (see Table 5-4, 5-5, 5-6 and Appendix F). Table 5-3 summarizes the volumetric design criteria for the HMA 300K ESAL 1/2" surface mixture designed for this study (*7*).

Table 5-3: Iowa DOT Volumetric Mix Design Criteria for 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 5-4 summarizes all of the properties calculated for each high-RAP mix design (30%, 40% and 50% binder replacement for each inclusion method) for RAP materials from Stockpile A. The effects of the extremely high dust content of the original RAP stockpile material were very evident in the 'Traditional RAP' mix designs. The dust content of the combined gradation for the 50% Traditional RAP-A mix design was on the verge of exceeding the maximum 1/2" mix size control point (maximum 10% passing No. 200 screen). The 30% and 40% 'Traditional RAP-A' mix designs also showed very high dust contents for the combined gradation. This caused very high aggregate surface areas for these mix designs which resulted in very low asphalt film thicknesses and very high ratios of dust content to effective asphalt binder. Both of these properties were outside the DOT specification for all 'Traditional RAP' mix designs for Stockpile A.

The mix designs using the ‘Fractionated RAP’ inclusion method showed significant volumetric improvements compared to the ‘Traditional RAP’ inclusion method for materials from Stockpile A. When mix designs with the same high-RAP content were compared between these two inclusion methods, the reduction in fine aggregate coming from the RAP material resulted in decreased dust content of the combined gradation, decreased aggregate surface area, increased film thickness and decreased dust-binder ratio. The improvements allowed the 30% ‘Fractionated RAP-A’ mix design to essentially meet all specified mix design criteria (film thickness very slightly below the 8.0 μm minimum). While the 40% and 50% ‘Fractionated RAP-A’ mix designs did not meet the film thickness or dust-binder requirements, there was significant improvement in each property compared to the ‘Traditional RAP-A’ mix designs at those RAP contents (attributed to the fine aggregate reduction of the fractionation method).

The ‘Optimum FRAP’ mix designs showed continued dust content reduction of the combined aggregate gradation, as was intended by the fractionation method design. This resulted in even further aggregate surface area reduction compared to the ‘Traditional RAP’ and ‘Fractionated RAP’ methods. At all corresponding RAP contents the film thicknesses were increased and the dust-binder ratios were decreased when compared to the Traditional RAP-A mix designs; however, the lower optimum binder contents (compared to Fractionated RAP-A mix designs) did not allow the 30% and 40% Optimum FRAP-A mix designs to increase film thickness from the corresponding Fractionated RAP-A mix designs. The Optimum FRAP-A mix designs also had trouble meeting the VMA because of the increased maximum density (G_{mm}) compared to the Traditional RAP-A mix designs (aggregate and AC% relatively constant).

Ultimately the dust content contributed by the RAP material from the original stockpile was decreased for the 'Fractionated RAP' method and even further decreased for the 'Optimum FRAP' method; however, the impact this reduction has on volumetric mix criteria improvement depends on the optimum asphalt content found for each individual mix design. Also, even when volumetric mix design criteria are improved as a result of stockpile fractionation, compliance with the Iowa DOT specifications still depends greatly on the properties of the original stockpile.

5.2.2 – Mix Design Results Using Stockpile B RAP Materials

Table 5-5 shows the summary of all of the mix design properties calculated for mixtures created using RAP materials from Stockpile B. The Traditional RAP-B mix designs are very similar to the Traditional RAP-A mix designs due to the fact that both stockpiles consist of generally the same material. The effects of the extremely high dust content of the original RAP stockpile material were again very evident in these mix designs. The dust contents of the combined gradations were slightly reduced compared to the Traditional RAP-A mix designs as a result of the lower dust content recovered from the stockpiled RAP materials (14% recovered aggregate passing No. 200 for Stockpile B compared to 16% for Stockpile A). This allowed all mix designs to meet the gradation control point for the dust content; however, the excessive amount of combined aggregate material still passing the No. 200 again caused very high aggregate surface areas for these mix designs resulting in very low asphalt film thicknesses and very high dust-binder ratios. These properties were slightly improved compared to the Traditional RAP-A mix designs, but were still outside the DOT specification at all high-RAP contents.

The 'Fractionated RAP' mix designs using RAP materials from Stockpile B also showed a similar reduction in the dust content of the combined aggregate materials from the Traditional RAP-B mix designs, as was seen for Stockpile A; however, the reduced optimum asphalt content of the Fractionated RAP-B mix designs (compared to the corresponding Traditional RAP-B RAP content mix) resulted in no real improvement in the film thickness or dust-binder ratio of these mix designs. Analysis of the 'Fractionated RAP' method's application to the Stockpile B materials, as discussed in Chapter 4, revealed that there was less significant dust content reduction of the new stockpile (compared to application to Stockpile A) and only 5.8% of the original stockpile material being discarded. While the No. 30 'Fine RAP removal' threshold was maintained for all original RAP stockpiles for consistency of comparison, this threshold could be increased to the No. 16 sieve for this stockpile (results in ~14% removal) to achieve further fine aggregate reduction and volumetric mix design criteria improvement.

The 'Optimum FRAP' mix designs for Stockpile B RAP materials again showed continued dust content reduction of the combined aggregate gradation compared to the 'Traditional RAP' and 'Fractionated RAP' inclusion methods. This further aggregate surface area reduction again resulted in increased film thicknesses and decreased dust-binder ratios at all corresponding RAP contents from both previous methods; however, the lower optimum binder contents of these mix designs again prevented significant improvement of these properties to the point of meeting the DOT specifications. The Optimum FRAP-B mix designs also had low VMA due to a combination of lower optimum AC% (higher aggregate percentage) and increased maximum density (G_{mm}) due to the increased 'Coarse FRAP' proportion.

The dust content contributed by the RAP material from the original stockpile was again decreased for the 'Fractionated RAP-B' mix designs and even further decreased for the 'Optimum FRAP-C' mix designs; however, the impacts were not as significant as seen for Stockpile A due to the reduced optimum asphalt content of the mixtures. Also, even though some volumetric mix design criteria were improved as a result of stockpile fractionation, the properties of the original stockpile (14% dust content) are again difficult to overcome and achieve Iowa DOT mix design criteria specification compliance. One option for improvement for high-RAP mix design using materials from Stockpile B is to increase the size threshold for the 'Fractionated RAP' method to allow for more Fine RAP removal from the original stockpile. The 'Coarse FRAP' proportion of the 'Optimum FRAP' blend may also need to be increased to achieve further fine aggregate and surface area reduction from the new 'Fractionated RAP' material; however, this should all result in improved volumetric properties due to increased fine aggregate removal from the original stockpile.

5.2.3 – Mix Design Results Using Stockpile C RAP Materials

Table 5-6 summarizes all of the properties calculated for each high-RAP mix design that used RAP materials from Stockpile C. The original RAP material from this stockpile showed a much lower dust content (10.3%) than the other original RAP stockpiles and this was reflected in the combined dust content of the Traditional RAP-C mix designs falling right in the middle of the specified gradation control points (~6.0%) for all RAP contents. This resulted in significant improvement of the volumetric properties of the Traditional RAP-C mix designs compared to the other stockpiles (30% Traditional RAP-C mix design passes all specifications). As the RAP content increases for this method (40% and 50% Traditional RAP-C mix designs) the film thickness decreases and the dust-binder ratio falls just outside the specified range (due again to the low optimum binder content of the mix design); however, these properties are greatly improved compared to the Traditional RAP-A and Traditional RAP-B mix designs.

Once the ‘Fractionated RAP’ method is applied to these materials the dust content and aggregate surface area are reduced to the point that dust-binder ratio is met for all high-RAP content Fractionated RAP-C mix designs even with reduction in the optimum binder content of the corresponding mix designs from Traditional RAP-C. The film thickness is also met for 30% and 40% Fractionated RAP-C mix designs, and while the film thickness for the 50% Fractionated RAP-C mix design does not meet the DOT specification it is improved compared to the 50% Traditional RAP-C mix design.

Application of the ‘Optimum FRAP’ method again results in even further dust content and aggregate surface area reduction resulting in dust-binder ratio compliance being maintained for all high-RAP content Optimum FRAP-C mix designs, film thickness requirements being met for the 30% and 40% Optimum FRAP-C mix designs and film thickness still being improved for the 50% Optimum FRAP-C mix design. As with the Fractionated RAP-C mix designs the compliance of these volumetric properties was maintained (and in some cases improved) even at very low optimum binder contents due to the significant reduction in fine aggregate material and dust content. The benefits of using RAP materials with minimal fine aggregate composition of the original stockpile and applying fractionation methods to further reduce the dust content are clearly seen for the mix designs from Stockpile C. The only real issue associated with these mix designs using Stockpile C RAP material was the low VMA due to reasons previously explained.

Table 5-4: 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 (%)	14.3	14.1	14.0	15.3	15.0	13.9	13.6	13.4	13.4
VFA (%)	75.4	75.2	74.9	77.0	76.7	74.8	74.3	73.9	74.0
Dust Content (Minus No. 200)	7.3	8.6	10.0	6.9	8.1	8.8	5.7	6.4	7.3
Film Thickness (μm)	6.8	6.0	5.4	7.9	7.0	5.9	7.5	6.8	6.3
Dust – Binder Ratio	1.6	1.9	2.2	1.4	1.6	2.0	1.3	1.7	1.7

Source: Mix Designs performed at University of Iowa Asphalt Laboratory

Table 5-5: 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 (%)	14.3	13.9	13.6	13.5	13.4	12.9	12.7	12.7	12.8
VFA (%)	75.5	74.9	74.2	74.0	73.8	72.9	72.5	72.4	72.7
Dust Content (Minus No. 200)	6.9	8.0	9.1	6.4	7.4	8.3	6.1	7.0	8.1
Film Thickness (μm)	7.1	6.2	5.5	6.9	6.2	5.5	7.4	6.8	5.6
Dust – Binder Ratio	1.5	1.8	2.1	1.5	1.7	2.1	1.4	1.6	1.7

Source: Mix Designs performed at University of Iowa Asphalt Laboratory

Table 5-6: 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 (%)	14.1	13.6	13.0	13.4	12.7	12.5	12.6	12.1	12.2
VFA (%)	75.2	74.2	73.0	73.8	72.4	71.9	72.2	71.1	71.2
Dust Content (Minus No. 200)	5.7	6.3	6.8	5.0	5.5	5.9	4.8	5.2	5.6
Film Thickness (μm)	8.0	7.1	7.1	8.8	7.9	7.3	8.5	8.7	7.5
Dust – Binder Ratio	1.2	1.5	1.5	1.1	1.2	1.4	1.1	1.2	1.3

Source: Mix Designs performed at University of Iowa Asphalt Laboratory

5.3 – High-RAP Mix Design Summary

The ultimate goal of this research is to design high-RAP content surface mixtures that accounted for up to 50% of the virgin binder being replaced by RAP materials and still meet 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) as outlined in Table 5-1. This produced a total of twenty-seven different mix designs to compare the effectiveness of the fractionation methods on the three different RAP stockpiles used in this study.

The Iowa DOT '*Method of Design of Hot Mix Asphalt Mixes*' (*7*) procedure was followed to select virgin aggregate and binder materials, determine weights of mixture components, and ultimately mix and test those samples. For each mix design the optimum binder content was determined that gave the desired air voids after the specified number of gyrations for the 300K ESAL ½" HMA mixture being designed. Volumetric properties of each mixture were determined at that binder content and compliance with the Iowa DOT specifications for the VMA, VFA, combined aggregate gradation, film thickness and dust-binder ratio were analyzed for each mix design. The results of each mix design are detailed in Table 5-4, 5-5 and 5-6. These results allowed mix design properties to be compared for differences of each original source of RAP material, each inclusion method of RAP material from that given source and for each high-RAP content of that inclusion method.

Comparison of the results from these mix designs showed that the volumetric properties are highly dependent on the material composition of the original stockpile. Stockpile A and B contained very high recovered aggregate dust contents (16% and 14% respectively) which resulted in high aggregate surface areas for the Traditional RAP-A and Traditional RAP-B mix designs and caused very low asphalt film thicknesses and very high ratios of dust content to effective asphalt binder. The 'Fractionated RAP' and 'Optimum FRAP' methods were effective at reducing the fine aggregate composition of the new stockpiles from the original source material and thereby improving volumetric properties (combined gradation of all mix designs can be found in Appendix F); however, these improvements did not allow Iowa DOT specification compliance to be met for high-RAP contents greater than 30% for these stockpiles due to the poor results of each property from the 'Traditional RAP' method. For Stockpile C the initial dust content was relatively low (10%) which allowed the 30% Traditional RAP-C mix design to meet all design criteria. The application of the 'Fractionated RAP' and 'Optimum FRAP' methods built upon these good properties to allow the 30% and 40% RAP mix designs to meet all mix design criteria for these inclusion methods.

These results also showed that the volumetric improvement of each fractionation method depend on the optimum asphalt content of each mixture. All fractionation methods achieved their goal of reducing the amount of fine aggregate and dust content introduced to the mixture by the RAP materials; however, it was also noticed that 'Fractionated RAP' and 'Optimum FRAP' mix designs all had lower optimum asphalt contents than the corresponding 'Traditional RAP' mix design for the same original RAP source and high-RAP content (exception to this 'rule' seen for the Fractionated RAP-A mix designs). The benefits of fine aggregate and surface area reduction from the fractionation methods on improving the film thickness and dust-binder ratio criteria are limited when there is less effective binder to coat these aggregates.

There are possibilities for modifying the fractionation methods to improve upon the mix design results for each stockpile to increase their application to high-RAP content mixtures. First, the 'Fine RAP removal' threshold could be modified to remove more of the RAP material that contains significant amounts of fine aggregate and dust. This results in more material being lost from the stockpile, but this must be balanced by the desire to use the material at high-RAP contents up to 50%. Ultimately the methods and thresholds must be chosen based on the properties of the original stockpile. A RAP material with excessive amounts of fine aggregate will therefore require more removal of Fine RAP material to dramatically improve the recovered aggregate gradation.

As mentioned in Chapter 3, the best practice for creating high-RAP mix designs is to use RAP materials that have been processed in a manner that prevents further material degradation after removal from the roadway. These milled materials can be initially fractionated to meet the top size requirement of the stockpile and used directly via the 'Traditional RAP' inclusion method in high-RAP content mixtures. Further fractionation methods can be applied as necessary to remove Fine RAP material from the RAP added to the mixture and effectively reduce the introduction of fine aggregates contained in those materials.

CHAPTER 6:

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. Also, the asphalt binder of the RAP materials is aged during the pavements service life causing the blended binder of the new high-RAP mixture to be less flexible than the virgin asphalt binder. For RAP materials to be used in higher amounts these properties need to be modified or compensated for during the mix design process. This research investigates fractionation methods that physically modify the properties of RAP stockpiles before they are included in the mixture to produce high-RAP content mix designs that meet all specified volumetric criteria for up to 50% replacement of the mixture's asphalt binder content.

The recycling of asphalt pavement materials involves milling sections of the original pavement from the roadway and processing the material to create RAP stockpiles with known properties (i.e. recovered aggregate gradation and asphalt content). While the larger pieces of RAP exhibit a material composition very similar to the original mix design, these materials must be processed further to allow for sufficient blending with virgin materials in the asphalt plant. This research determined that the current state of practice of RAP processing, where the original pavement is broken down with a crushing operation, results in the recovered aggregates being modified to the point that the aggregate structure is no longer representative of the original pavement's mix design.

Analyses on three different RAP stockpiles used in this study revealed that each processed RAP material could be separated into the a Coarse RAP and Fine RAP category based on the recovered aggregate composition of the different sizes of RAP material. This categorization system showed that within each stockpile the Coarse RAP materials (larger than the No. 4 sieve size) contained much lower amounts of fine aggregate material and dust content than the Fine RAP materials (smaller than the No. 4 sieve size). Comparing the percentage split of each category within the stockpile to the recovered aggregate gradation of the total stockpile established the connection between increased amounts of Fine RAP material contained in the stockpile resulting in higher amounts of fine aggregate material contained in the recovered aggregate from that stockpile. It was also determined that the increased presence of Fine RAP material in the stockpile is caused by the crushing operation used to process to the required top size.

The main constraint for increasing the amount of RAP used in HMA mixtures is the negative impact that the increased fine aggregate composition of the RAP materials has on the combined mixture. The results of this research showed that fractionation methods, designed to increase the percentage of Coarse RAP material contained in the RAP added to the mixture, were effective at decreasing the amount of fine aggregate material introduced to the HMA mixture by the RAP. The application of these methods to stockpiles in this study and their usage in high-RAP content mix designs showed that the fine aggregate reduction resulted in improvements of volumetric mix design criteria and compliance with some Iowa DOT specifications for up to 50% binder replacement. The effectiveness of the fractionation methods on achieving volumetric compliance was determined to be highly dependent on the properties of the original RAP stockpile.

6.1 - Recommendations

Ultimately this research accomplished an extensive review of Midwestern state DOT RAP-related specifications, a detailed analysis of the composition the stockpiled RAP materials, the design of two effective methods for fractionating RAP materials to reduce fine aggregate composition and the application of these methods to improve volumetric mix design criteria for up to 50% RAP usage. Analysis of all of these results led to the development of the following recommendations to allow for an increase in the amount of RAP materials that can be used in HMA mixtures:

1. The top-size requirement for stockpiled RAP materials should be increased to reduce the amount of processing done to the pavement millings and allow for the RAP materials to better maintain the properties of the original pavement
2. RAP materials should be screened to the required top size before crushing to avoid unnecessary material degradation
3. RAP stockpiles can be described in terms of their Coarse RAP and Fine RAP categories (split at the No. 4 sieve size) with the Coarse RAP materials containing significantly lower proportions of fine aggregate material (namely dust content)
4. Gradation analysis of the stockpiled RAP materials can show the contractor the amount of Fine RAP material contained in the stockpile and the amount of that stockpile expected to be discarded after application of fractionation methods
5. Fractionation for the purpose of fine aggregate reduction should target the removal or reduction of materials in the Fine RAP category
6. The application of fractionation methods is effective at reducing fine aggregate composition and improving volumetric mix design criteria

6.2 – Future Research

Further investigation of high-RAP content HMA surface mixtures is currently being conducted at the University of Iowa Asphalt Research Laboratory and is planned to continue in the future. The research team plans to proceed to simple performance testing (i.e. dynamic modulus and flow number) of high-RAP content mixtures as well as mechanical testing such as Beam Fatigue, Loaded Wheel Tracker and Semi-Circular Bend tests to determine anticipated field performance. Concurrently with this testing, a field-constructible mix design is being developed using local, batch-mixed aggregates combined with recently obtained, high-RAP material milled from Interstate-80 in eastern-Iowa. The local contractor has already followed the recommendation to screen the material before processing and is open to further fractionation if necessary. These materials will be used to construct field test sections with up to 50% RAP by binder replacement for the same 300,000 ESAL ½" surface mix design as created in this research. Also, high-RAP content lab mixtures will be designed using Warm Mix Asphalt technologies to determine the effects that chemical additives and lower production temperatures have on high-RAP mixture performance. Ultimately this research will present the Iowa Department of Transportation with multiple options for increasing the amount of RAP materials used in the surface course in the State of Iowa.

APPENDIX A:

IOWA DOT STOCKPILE CATEGORIZATION REPORTS

A

ABC0-0111 MIX DESIGN
BC

IOWA DEPARTMENT OF TRANSPORTATION
OFFICE OF MATERIALS
TEST REPORT - ASPHALT CONCRETE
LAB LOCATION - AMES

LAB NO....:ABC10-0111

MATERIAL........:RAP CLASSIFIED
INTENDED USE....:VARIOUS MIX DESIGNS
PRODUCER........:PELLING
COUNTY..........:LINN CONTRACTOR:PELLING
UNIT OF MATERIAL:40 LBS
SAMPLED BY......:T.DUNLAY/G.NETSER SENDER NO.:CE10VS-670
DATE SAMPLED: 07/24/10 DATE RECEIVED: 08/30/10 DATE REPORTED: 09/17/10
LOCATION OF PRODUCING PLANT- MILLINGS FROM EASTERN IOWA AIRPORT
SAMPLED AT BEVERLY QUARRY STOCKPILE

SIEVE ANALYSIS PERCENT PASSING

SIEVE	IGNITION GRADATION	REFLUX GRADATION	COLD-FEED GRADATION	TARGET GRADATION	SPEC LOW LIMIT	SPEC HIGH LIMIT
3/4		100.0				
1/2		98.0				
3/8		95.0				
4		79.0				
8		62.0				
16		47.0				
30		35.0				
50		24.0				
100		19.0				
200		16.0				

% AC REFLUX METHOD	5.41
Gsa	2.712
Gsb	2.614
% Abs	1.38
RECOVERED AGGREGATE ANGULARITY	43.0

COPIES TO:
CENTRAL LAB TERRY DUNLAY L.L. PELLING
DIST6

DISPOSITION:

SIGNED: KEVIN B. JONES
TESTING ENGINEER

Figure A1: Iowa DOT Binder Extraction Testing Report – Stockpile A Classified RAP

April 18, 2006
Supersedes April 20, 2004

Matls. IM 505
Appendix A

CLASSIFIED

RAP STOCKPILE REPORT

820009r
(10/05)

Certified RAP Stockpile Report			**RAP Stockpile ID # ABC10-0111**		
Stockpile Owner: L.L.Pelling Co					
SOURCE OF RAP	Project No. ~~AIP AIP~~-19-0012-39		Dates of Removal 6/20/10		
Route No.	From FAA 3		To		
	Eastern Iowa Airport Runway				
Removal Depth	JMF No(s)	Mix Type/Size	Crushed Particle %		
13"	P401	¾" A 75 blow	85%		

LOCATION OF RAP STOCKPILE:
Wendling Quarries, Beverly

County	Section	Township	Range

Description of Stockpile Base: Limestone Aggt Base

Processing Remarks:

STOCKPILE QUANTITY INVENTORY LOG

Date	Quantity	Disposition (Project No. & Use)
6/2010	9000 tons	Total initial stockpile quantity

Average EXTRACTION TEST RESULTS Gradation	Lab Report nos.	**Aggregate Characteristics**	
3/4		Aggregate Type	
1/2			
3/8		Crushed Particles	%
No. 4	Pb =		
No. 8		Aggr Friction Type 2	%
No. 16	Gsb =		
No. 30		Aggr Friction Type 3	%
No. 50	Abs% =		
No. 100		Aggr Friction Type 4	%
No. 200	FAA =		

Shaded boxes to be completed by the District Materials Engineer

Stockpile Owner Representative	Gary Netser	Date 8/24/10
District Materials Representative		Date

1

Figure A2: LL Pelling RAP Stockpile Report – Stockpile A Classified RAP

WDAS ABC06-0173

ABC0-0079
BC

MIX DESIGN

IOWA DEPARTMENT OF TRANSPORTATION
OFFICE OF MATERIALS
TEST REPORT - ASPHALT CONCRETE
LAB LOCATION - AMES

LAB NO....:ABC10-0079

MATERIAL........:RAP CERTIFIED
INTENDED USE....:VARIOUS MIX DESIGNS
PRODUCER........:L.L. PELLING
COUNTY..........:LINN
CONTRACTOR:L.L. PELLING
UNIT OF MATERIAL:40 LBS
SAMPLED BY......:TERRY DUNLAY
SENDER NO.:CR10VS-635
DATE SAMPLED: 06/03/10 DATE RECEIVED: 06/15/10 DATE REPORTED: 08/05/10
LOCATION OF PRODUCING PLANT- STOCKPILE @ J-STREET FROM EASTERN IOWA AIRPORT

SIEVE ANALYSIS PERCENT PASSING

SIEVE	IGNITION GRADATION	REFLUX GRADATION	COLD-FEED GRADATION	TARGET GRADATION	SPEC LOW LIMIT	SPEC HIGH LIMIT
1.0		100.0				
3/4		99.0				
1/2		95.0				
3/8		91.0				
4		76.0				
8		60.0				
16		47.0				
30		36.0				
50		24.0				
100		19.0				
200		16.5				

% AC REFLUX METHOD	5.11
Gsa	2.737
Gsb	2.580
% Abs	2.22

RECOVERED AGGREGATE ANGULARITY 43.4

COPIES TO:
CENTRAL LAB
DIST6

L.L. Pelling-?
TERRY DUNLAY

L.L. PELLING

DISPOSITION:

SIGNED: KEVIN B. JONES
TESTING ENGINEER

Figure A3: Iowa DOT Binder Extraction Testing Report – Stockpile B Certified RAP

B

April 18, 2006
Supersedes April 20, 2004

Matls. IM 505
Appendix A

Certified

RAP STOCKPILE REPORT

820009r
(10/05)

Certified RAP Stockpile Report		**RAP Stockpile ID # ABC10-0079**
Stockpile Owner:L.L.Pelling Co		
SOURCE OF RAP	Project No. FAA 3-19-0012-33	Dates of Removal6/10-17/06

Route No.	From	To
TEIA	Runway 9/27 Taxiway C	

Removal Depth	JMF No(s)	Mix Type/Size	Crushed Particle %		
6"& 7"	P101	½" A	70%		

LOCATION OF RAP STOCKPILE: Wendling Quarries, Four County Quarry
Being transferred to Jst, Base 15, Cedar Rapids

County	Section	Township	Range

Description of Stockpile Base: Limestone Agg Base

Processing Remarks:

STOCKPILE QUANTITY INVENTORY LOG

Date	Quantity	Disposition (Project No. & Use)
6/17/06	17000 tons	Total initial stockpile quantity

Average EXTRACTION TEST RESULTS			Aggregate Characteristics	
Gradation		Lab Report nos.		
3/4	99		Aggregate Type	
1/2	95			
3/8	91	Pb =	Crushed Particles	%
No. 4	74			
No. 8	57	Gsb =	Aggr Friction Type 2	%
No. 16	44			
No. 30	34	Abs% =	Aggr Friction Type 3	%
No. 50	22			
No. 100	17	FAA =	Aggr Friction Type 4	%
No. 200	14			

Shaded boxes to be completed by the District Materials Engineer

Stockpile Owner Representative	Gary Netser	Date 6/3/10
District Materials Representative		Date

1

Figure A4: LL Pelling RAP Stockpile Report – Stockpile B Certified RAP

MAY-25-2011 WED 08:05 AM DOT MATERIALS LAB FAX NO. 5152391092 P. 01/01

C

CERT MILLINGS FROM CIVILLE

ABC1-	70	County	Johnson
Project #	Mix Designs	Date Received	18-May-11
Senders #	CR11VS-605	Date Reported	
% A.C. Intended		District	6

SIEVE ANALYSIS % Passing				
Sieve Size	Ignition	Reflux	Cold Feed	Research
1.5"				
1.000"				
3/4"		100		
0.500"		88		
3/8"		80		
No. 4		61		
No. 8		46		
No. 16		36		
No. 30		27		
No. 50		17		
No. 100		12		
No. 200		10.3		

EXTRACTION TESTS	
Aggregate Content (%)	
% AC Reflux Method	4.82
Water (%)	
Volatile (%)	
% AC Ignition Method	

RECOVERY TESTS	
Pen of Rec. AC @ 25 c	
DSR @ 70 c	
Rec. Agg Angularity	41.0

MARSHALL STABILITY TESTS	
Pounds	
Flow - 0.01 In.	

MISCELLANEOUS TESTS	
6	
6	
6	
Gsa	2.703
% Abs.	1.50
Gsb	2.597

Comments

Figure A5: Iowa DOT Binder Extraction Testing Report – Stockpile C Certified RAP

APPENDIX B:

RAP STOCKPILE GRADATION ANALYSIS

Table B1: RAP Gradation Sampling - Stockpile A (Classified Millings from Eastern Iowa Airport)

Sieve Size		Sample 1 Retained Mass (grams)	Sample 1 Percent Retained (%)	Sample 2 Retained Mass (grams)	Sample 2 Percent Retained (%)	Sample 3 Retained Mass (grams)	Sample 3 Percent Retained (%)	Sample 4 Retained Mass (grams)	Sample 4 Percent Retained (%)	Sample 5 Retained Mass (grams)	Sample 5 Percent Retained (%)
1 1/2 inch	(37.5 mm)	43.7	0.9	0.0	0.0	46.0	0.9	62.8	1.3	182.0	3.6
1 inch	(25 mm)	226.6	4.5	211.0	4.2	0.0	0.0	140.8	2.8	277.7	5.6
3/4 inch	(19 mm)	127.7	2.6	274.8	5.5	144.5	2.9	189.2	3.8	102.9	2.1
1/2 inch	(12.5 mm)	486.2	9.7	430.4	8.6	385.1	7.7	402.4	8.0	379.4	7.6
3/8 inch	(9.5 mm)	448.2	9.0	354.0	7.1	402.6	8.1	379.4	7.6	340.6	6.8
No. 4	(4.75 mm)	985.7	19.7	1018.8	20.4	1205.3	24.1	1035.0	20.7	1027.3	20.5
No. 8	(2.36 mm)	991.5	19.8	998.3	20.0	1034.0	20.7	1010.0	20.2	966.6	19.3
No. 16	(1.18 mm)	724.6	14.5	753.3	15.1	931.6	18.6	846.4	16.9	752.3	15.0
No. 30	(0.60 mm)	512.6	10.3	511.8	10.2	446.9	8.9	514.3	10.3	502.1	10.0
No. 50	(0.3 mm)	281.0	5.6	272.9	5.5	236.8	4.7	250.7	5.0	275.0	5.5
No. 100	(0.15 mm)	109.3	2.2	99.4	2.0	126.9	2.5	109.2	2.2	134.3	2.7
No. 200	(0.075 mm)	31.1	0.6	33.5	0.7	18.1	0.4	24.0	0.5	35.3	0.7
Pan		31.8	0.6	41.8	0.8	22.2	0.4	35.8	0.7	24.5	0.5
Fractionation		% Coarse	% Fine	% Coarse	% Fine	% Coarse	% Fine	% Coarse	% Fine	% Coarse	% Fine
at 3/8"		46.4	53.6	45.8	54.2	43.7	56.3	44.2	55.8	46.2	53.8
ctionated Mass		2318.1	2681.9	2289.0	2711.0	2183.5	2816.5	2209.6	2790.4	2309.9	2690.1
otal Retained		5000.0	100.0	5000.0	100.0	5000.0	100.0	5000.0	100.0	5000.0	100.0

Sieve Size		Sample 6 Retained Mass (grams)	Sample 6 Percent Retained (%)	Sample 7 Retained Mass (grams)	Sample 7 Percent Retained (%)	Sample 8 Retained Mass (grams)	Sample 8 Percent Retained (%)	Summary of 8 Samples @ 5,000 grams each: Sieve Size	Percent Retained (%)	Standard Deviation	Coefficient of Variation (%)
1 1/2 inch	(37.5 mm)	54.0	1.1	65.8	1.3	64.0	1.2	1 1/2 inch	1.29	1.038	80%
1 inch	(25 mm)	133.4	2.7	174.1	3.5	130.5	2.5	1 inch	3.23	1.671	52%
3/4 inch	(19 mm)	163.0	3.3	117.7	2.4	142.0	2.8	3/4 inch	3.14	1.090	35%
1/2 inch	(12.5 mm)	390.5	7.8	343.2	6.9	333.0	6.5	1/2 inch	7.85	1.007	13%
3/8 inch	(9.5 mm)	345.8	6.9	302.7	6.1	380.0	7.4	3/8 inch	7.36	0.877	12%
No. 4	(4.75 mm)	1088.2	21.8	1056.5	21.1	1054.4	20.5	No. 4	21.10	1.351	6%
No. 8	(2.36 mm)	1069.1	21.4	976.0	19.5	1041.4	20.2	No. 8	20.14	0.656	3%
No. 16	(1.18 mm)	936.0	18.7	851.3	17.0	854.5	16.6	No. 16	16.56	1.609	10%
No. 30	(0.60 mm)	447.5	9.0	575.0	11.5	603.2	11.7	No. 30	10.24	1.011	10%
No. 50	(0.3 mm)	215.0	4.3	316.0	6.3	331.0	6.4	No. 50	5.42	0.733	14%
No. 100	(0.15 mm)	81.7	1.6	160.0	3.2	157.6	3.1	No. 100	2.43	0.537	22%
No. 200	(0.075 mm)	34.6	0.7	33.5	0.7	38.8	0.8	No. 200	0.62	0.132	21%
Pan		41.2	0.8	28.2	0.6	19.6	0.4	Pan	0.61	0.171	28%
Fractionation		% Coarse	% Fine	% Coarse	% Fine	% Coarse	% Fine	Coarse %	Fine %	Std. Deviation	
at 3/8"		43.5	56.5	41.2	58.8	40.9	59.1	43.97	56.03	2.129	4.84%
ctionated Mass		2174.9	2825.1	2060.0	2940.0	2103.9	3046.1				
otal Retained		5000.0	100.0	5000.0	100.0	5150.0	100.0				

Table B2: RAP Gradation Sampling - Stockpile B (Certified Millings from Eastern Iowa Airport)

Sieve Size		Sample 1 Retained Mass (grams)	Sample 1 Percent Retained (%)	Sample 2 Retained Mass (grams)	Sample 2 Percent Retained (%)	Sample 3 Retained Mass (grams)	Sample 3 Percent Retained (%)	Sample 4 Retained Mass (grams)	Sample 4 Percent Retained (%)	Sample 5 Retained Mass (grams)	Sample 5 Percent Retained (%)
1 1/2 inch	(37.5 mm)	0.0	0.0	104.7	2.1	86.5	1.7	0.0	0.0	0.0	0.0
1 inch	(25 mm)	217.2	4.4	167.0	3.4	306.3	6.2	90.6	1.8	247.5	5.0
3/4 inch	(19 mm)	414.6	8.3	260.9	5.3	233.6	4.7	315.9	6.3	318.1	6.4
1/2 inch	(12.5 mm)	432.7	8.7	490.6	9.9	581.8	11.7	528.6	10.6	610.4	12.3
3/8 inch	(9.5 mm)	414.0	8.3	368.2	7.4	496.1	10.0	326.6	6.6	342.0	6.9
No. 4	(4.75 mm)	1039.9	20.9	1213.2	24.5	918.1	18.5	1152.0	23.1	1007.1	20.2
No. 8	(2.36 mm)	997.7	20.1	915.5	18.5	1006.8	20.3	1064.6	21.4	1008.7	20.3
No. 16	(1.18 mm)	739.4	14.9	733.4	14.8	697.5	14.0	757.2	15.2	742.8	14.9
No. 30	(0.60 mm)	427.6	8.6	433.6	8.7	378.5	7.6	434.6	8.7	421.8	8.5
No. 50	(0.3 mm)	198.5	4.0	199.6	4.0	174.5	3.5	210.4	4.2	189.0	3.8
No. 100	(0.15 mm)	52.2	1.0	48.0	1.0	49.8	1.0	60.3	1.2	52.6	1.1
No. 200	(0.075 mm)	17.2	0.3	13.9	0.3	18.1	0.4	21.0	0.4	18.6	0.4
Pan		16.9	0.3	10.1	0.2	20.0	0.4	20.6	0.4	20.0	0.4
Fractionation		% Coarse	% Fine	% Coarse	% Fine	% Coarse	% Fine	% Coarse	% Fine	% Coarse	% Fine
at 3/8"		50.7	49.3	52.5	47.5	52.8	47.2	48.4	51.6	50.7	49.3
ctionated Mass		2518.4	2449.4	2604.5	2354.1	2622.5	2345.1	2413.8	2568.7	2525.0	2453.6
otal Retained		4967.8	100.0	4958.6	100.0	4967.5	100.0	4982.5	100.0	4978.6	100.0

Sieve Size		Sample 6 Retained Mass (grams)	Sample 6 Percent Retained (%)	Sample 7 Retained Mass (grams)	Sample 7 Percent Retained (%)	Sample 8 Retained Mass (grams)	Sample 8 Percent Retained (%)	Summary of 8 Samples @ 5,000 grams each: Sieve Size	Percent Retained (%)	Standard Deviation	Coefficient of Variation (%)
1 1/2 inch	(37.5 mm)	0.0	0.0	0.0	0.0	0.0	0.0	1 1/2 inch	0.48	0.897	186%
1 inch	(25 mm)	105.4	2.1	368.8	7.4	52.2	1.0	1 inch	3.91	2.226	57%
3/4 inch	(19 mm)	259.5	5.2	233.8	4.7	208.7	4.2	3/4 inch	5.64	1.342	24%
1/2 inch	(12.5 mm)	723.0	14.4	599.4	12.0	582.9	11.7	1/2 inch	11.42	1.722	15%
3/8 inch	(9.5 mm)	404.3	8.1	477.0	9.6	414.9	8.3	3/8 inch	8.14	1.205	15%
No. 4	(4.75 mm)	1089.2	21.8	949.5	19.0	1010.6	20.3	No. 4	21.04	2.013	10%
No. 8	(2.36 mm)	1022.9	20.4	986.6	19.8	1091.8	21.9	No. 8	20.32	1.035	5%
No. 16	(1.18 mm)	689.8	13.8	718.3	14.4	818.9	16.4	No. 16	14.81	0.816	6%
No. 30	(0.60 mm)	399.7	8.0	384.0	7.7	467.6	9.4	No. 30	8.41	0.600	7%
No. 50	(0.3 mm)	204.2	4.1	174.5	3.5	222.6	4.5	No. 50	3.95	0.336	8%
No. 100	(0.15 mm)	59.0	1.2	52.3	1.0	60.4	1.2	No. 100	1.09	0.096	9%
No. 200	(0.075 mm)	21.3	0.4	20.2	0.4	22.7	0.5	No. 200	0.38	0.056	14%
Pan		25.4	0.5	22.4	0.4	25.3	0.5	Pan	0.40	0.099	25%
Fractionation		% Coarse	% Fine	% Coarse	% Fine	% Coarse	% Fine	Coarse %	Fine %	Std. Deviation	
at 3/8"		51.6	48.4	52.7	47.3	45.6	54.4	50.63	49.37	2.502	4.94%
ctionated Mass		2581.5	2422.4	2628.6	2358.2	2269.2	2709.4				
otal Retained		5003.8	100.0	4986.7	100.0	4978.6	100.0				

Table B3: RAP Gradation Sampling - Stockpile C (Certified Millings from Unknown Sources)

Sieve Size		Sample 1 Retained Mass (grams)	Sample 1 Percent Retained (%)	Sample 2 Retained Mass (grams)	Sample 2 Percent Retained (%)	Sample 3 Retained Mass (grams)	Sample 3 Percent Retained (%)	Sample 4 Retained Mass (grams)	Sample 4 Percent Retained (%)	Sample 5 Retained Mass (grams)	Sample 5 Percent Retained (%)
1 1/2 inch	(37.5 mm)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1 inch	(25 mm)	0.0	0.0	46.5	0.9	60.5	1.2	63.9	1.3	119.2	2.4
3/4 inch	(19 mm)	300.6	6.0	197.3	3.9	339.0	6.8	264.2	5.3	255.1	5.1
1/2 inch	(12.5 mm)	1088.9	21.7	504.4	9.9	925.2	18.5	766.6	15.3	1279.1	25.5
3/8 inch	(9.5 mm)	451.8	9.0	653.4	12.8	701.1	14.0	663.2	13.2	658.4	13.1
No. 4	(4.75 mm)	1519.6	30.3	1566.1	30.7	1413.1	28.2	1371.1	27.3	1375.6	27.5
No. 8	(2.36 mm)	801.3	16.0	853.0	16.7	718.2	14.4	734.6	14.6	635.5	12.7
No. 16	(1.18 mm)	424.6	8.5	571.3	11.2	407.1	8.1	482.6	9.6	324.1	6.5
No. 30	(0.60 mm)	251.7	5.0	422.8	8.3	257.2	5.1	376.0	7.5	205.6	4.1
No. 50	(0.3 mm)	134.4	2.7	227.6	4.5	138.9	2.8	226.8	4.5	116.0	2.3
No. 100	(0.15 mm)	33.6	0.7	45.9	0.9	32.5	0.6	56.2	1.1	30.0	0.6
No. 200	(0.075 mm)	9.1	0.2	9.1	0.2	7.2	0.1	11.8	0.2	7.2	0.1
Pan		5.0	0.1	4.0	0.1	3.8	0.1	4.5	0.1	4.2	0.1
Fractionation		% Coarse	% Fine	% Coarse	% Fine	% Coarse	% Fine	% Coarse	% Fine	% Coarse	% Fine
at 3/8"		66.9	33.1	58.2	41.8	68.7	31.3	62.3	37.7	73.6	26.4
ctionated Mass		3360.8	1659.7	2967.7	2133.7	3438.8	1564.8	3129.0	1892.4	3687.4	1322.6
otal Retained		5020.5	100.0	5101.3	100.0	5003.6	100.0	5021.3	100.0	5010.1	100.0

Sieve Size		Sample 6 Retained Mass (grams)	Sample 6 Percent Retained (%)	Sample 7 Retained Mass (grams)	Sample 7 Percent Retained (%)	Sample 8 Retained Mass (grams)	Sample 8 Percent Retained (%)	Summary of 8 Samples @ 5,000 grams each: Sieve Size	Percent Retained (%)	Standard Deviation	Coefficient of Variation (%)
1 1/2 inch	(37.5 mm)	0.0	0.0	0.0	0.0	0.0	0.0	1 1/2 inch	0.00	0.000	#DIV/0!
1 inch	(25 mm)	24.2	0.5	122.5	2.4	41.2	0.8	1 inch	1.19	0.856	72%
3/4 inch	(19 mm)	281.8	5.6	238.2	4.8	416.5	8.3	3/4 inch	5.71	1.353	24%
1/2 inch	(12.5 mm)	959.2	19.1	747.1	14.9	798.8	15.9	1/2 inch	17.60	4.745	27%
3/8 inch	(9.5 mm)	538.7	10.7	569.6	11.4	685.6	13.7	3/8 inch	12.24	1.724	14%
No. 4	(4.75 mm)	1376.6	27.4	1368.6	27.3	1451.6	28.9	No. 4	28.45	1.380	5%
No. 8	(2.36 mm)	741.3	14.7	691.7	13.8	697.7	13.9	No. 8	14.60	1.266	9%
No. 16	(1.18 mm)	452.7	9.0	506.2	10.1	406.7	8.1	No. 16	8.89	1.443	16%
No. 30	(0.60 mm)	352.1	7.0	397.8	7.9	289.9	5.8	No. 30	6.34	1.542	24%
No. 50	(0.3 mm)	225.3	4.5	271.3	5.4	174.5	3.5	No. 50	3.76	1.111	30%
No. 100	(0.15 mm)	56.6	1.1	73.7	1.5	42.4	0.8	No. 100	0.92	0.300	33%
No. 200	(0.075 mm)	12.2	0.2	15.9	0.3	9.8	0.2	No. 200	0.20	0.058	28%
Pan		6.5	0.1	6.2	0.1	4.5	0.1	Pan	0.10	0.020	21%
Fractionation		% Coarse	% Fine	% Coarse	% Fine	% Coarse	% Fine	Coarse %	Fine %	Std. Deviation	
at 3/8"		63.3	36.7	60.8	39.2	67.6	32.4	65.18	34.82	4.964	7.62%
ctionated Mass		3180.3	1846.6	3046.0	1962.7	3393.7	1625.6				
otal Retained		5026.9	100.0	5008.7	100.0	5019.3	100.0				

APPENDIX C:

FRACTIONATED RAP STOCKPILE MATERIAL PROPERTIES

Table C1: Recovered Aggregate Gradation and Asphalt Content of Original RAP Stockpiles and Fractionated RAP Materials

RAP Material Description		3/4"	1/2"	3/8"	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200	G_{sb}	% Abs.	FAA	AC%
Classified	Traditional	100.0	98.0	95.0	79.0	62.0	47.0	35.0	24.0	19.0	16.0	2.614	1.38	43.0	5.41
Classified	Frac. (-#30)	100.0	97.3	92.7	76.8	57.9	42.3	29.3	20.3	16.7	14.1	2.614	1.38	43.0	5.70
Classified	Opt. FRAP Coarse	100.0	94.5	86.0	53.4	39.5	30.5	22.9	14.8	11.2	9.1	2.614	1.38	43.0	5.57
Classified	Opt. FRAP Fine	100.0	100.0	100.0	100.0	82.7	60.8	44.9	30.9	23.3	18.4	2.614	1.38	43.0	6.01
Certified - B	Traditional	100.0	95.0	91.0	74.0	57.0	44.0	34.0	22.0	17.0	14.0	2.580	2.22	43.4	5.11
Certified - B	Frac. (-#30)	100.0	97.0	93.5	77.0	57.9	42.8	29.8	20.6	16.4	13.6	2.580	2.22	43.4	5.34
Certified - B	Opt. FRAP Coarse	100.0	94.4	86.6	57.4	40.5	32.1	24.8	16.9	13.3	11.1	2.580	2.22	43.4	4.92
Certified - B	Opt. FRAP Fine	100.0	100.0	100.0	100.0	80.4	59.4	43.1	28.8	22.9	19.1	2.580	2.22	43.4	5.85
Certified - C	Traditional	100.0	88.0	80.0	61.0	46.0	36.0	27.0	17.0	12.0	10.0	2.597	1.50	41.0	4.82
Certified - C	Frac. (-#30)	100.0	97.0	91.7	67.3	47.6	35.7	25.7	15.5	10.3	8.5	2.597	1.50	41.0	4.83
Certified - C	Opt. FRAP Coarse	100.0	91.1	81.4	50.8	34.0	27.6	21.8	13.4	8.7	7.2	2.597	1.50	41.0	4.41
Certified - C	Opt. FRAP Fine	100.0	100.0	100.0	100.0	78.0	58.0	42.1	23.6	15.8	13.1	2.597	1.50	41.0	5.81

Source: Results taken from Iowa DOT Central Materials Lab Extraction Testing Reports and LL Pelling Ignition-Oven Burn-Off Reports

APPENDIX D:

BLENDED BINDER PERFORMANCE GRADING RESULTS

Table D1: Performance Grading of Recovered Asphalt Binder Blends

		Test at -18 °C		Test at -12 °C		Low Critical Temp	Critical High Original (°C)	Critical High RTFO	PG Grade
	Sample	M-Value	Stiffness	M-Value	Stiffness				
50%A	1	0.261	329	0.324	164	-22	67.96	67.82	64-22
	2	0.26	335	0.331	160		68.01	68.43	
40%A	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%A	1	0.289	283	0.356	125	-22	64.88	64.1	64-22
	2	0.281	301	0.35	132		64.69	64.85	
50%C	1	0.245	412	0.302	212	-22	72.35	71.11	70-22
	2	0.245	366	0.3	180		71.7	71.58	
40%C	1	0.255	374	0.313	190	-22	70.51	69.03	64-22
	2	0.255	358	0.307	192		69.2	69.26	
30%C	1	0.268	315	0.332	152	-22	67.42	68.12	64-22
	2	0.274	312	0.333	137		67.22	68.19	
Control Group	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 Group	1	0.299	269	0.356	123	-28	60.95	62.05	58-28
	2	0.304	276	0.361	119		61.02	63.3	

Source: Testing Conducted at Iowa State University Research Laboratory

APPENDIX E:

OPTIMUM FRAP PROPORTION SELECTION

Table E1: Optimum FRAP Proportion Selection – Stockpile A

	RAP Stockpile Extracted Aggregate Gradation										
	3/4"	1/2"	3/8"	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200	AC %
Traditional	100.0	98.0	95.0	79.0	62.0	47.0	35.0	24.0	19.0	16.0	5.41
Coarse FRAP	100.0	94.5	86.0	53.4	39.5	30.5	22.9	14.8	11.2	9.1	5.57
Fine FRAP	100.0	100.0	100.0	100.0	82.7	60.8	44.9	30.9	23.3	18.4	6.01
Frac. (- No. 30)	100.0	97.3	92.7	76.8	57.9	42.3	29.3	20.3	16.7	14.1	5.70
	Virgin Aggregate Gradation										
	100.0	91.4	80.0	60.0	43.3	32.1	20.5	11.9	4.4	3.5	

30% Classified RAP

	FRAP Properties					Effects on 6.00% AC Mix Design						
Split %	Coarse	Fine	AC %	RAP % Wt.	Agg. % Wt.	No. 50	% Change	No. 200	% Change	Surf. Area	% Change	Stockpile
Traditional			5.41	34.73%	65.27%	16.10	9.77%	7.84	12.11%	7.12	9.13%	
Frac. (Minus #30 Removed)			5.70	32.96%	67.04%	14.67	0.00%	6.99	0.00%	6.52	0.00%	9.1%
Original	44%	56%	5.816	32.30%	67.70%	15.75	7.37%	6.99	-0.04%	6.73	3.12%	0.0%
1 to 1	50%	50%	5.790	32.45%	67.55%	15.45	5.35%	6.83	-2.40%	6.60	1.14%	12.0%
3 to 2	60%	40%	5.746	32.70%	67.30%	14.95	1.94%	6.55	-6.38%	6.38	-2.21%	26.7%
3.7 to 2	65%	35%	5.724	32.83%	67.17%	14.70	0.22%	6.41	-8.40%	6.27	-3.90%	32.3%
2 to 1	67%	33%	5.715	32.88%	67.12%	14.60	-0.47%	6.35	-9.21%	6.22	-4.57%	34.3%
7 to 3	70%	30%	5.702	32.95%	67.05%	14.45	-1.51%	6.26	-10.43%	6.16	-5.60%	37.1%
3 to 1	75%	25%	5.680	33.08%	66.92%	14.19	-3.26%	6.12	-12.48%	6.05	-7.31%	41.3%

											% Left Over	
Split %	3/4"	1/2"	3/8"	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200	Stockpile	Fine FRAP
Traditional	100	93.7	85.2	66.6	49.8	37.3	25.5	16.10	9.47	7.84		
Frac (Minus #30)	100	93.3	84.2	65.5	48.1	35.5	23.4	14.67	8.45	6.99		9.1%
Original	100	93.4	84.5	66.3	49.9	37.1	25.3	15.75	8.79	6.99	0.0%	0.0%
1 to 1	100	93.3	84.2	65.4	49.1	36.5	24.8	15.45	8.57	6.83	12.0%	21.4%
3 to 2	100	93.1	83.8	63.9	47.7	35.5	24.2	14.95	8.21	6.55	26.7%	47.6%
3.7 to 2	100	93.0	83.6	63.2	47.0	35.1	23.8	14.70	8.02	6.41	32.3%	57.7%
2 to 1	100	93.0	83.5	62.9	46.7	34.9	23.7	14.60	7.95	6.35	34.3%	61.3%
7 to 3	100	93.0	83.4	62.4	46.3	34.6	23.5	14.45	7.84	6.26	37.1%	66.3%
3 to 1	100	92.9	83.1	61.7	45.6	34.1	23.1	14.19	7.65	6.12	41.3%	73.8%

40% Classified RAP

	FRAP Properties					Effects on 6.00% AC Mix Design						
Split %	Coarse	Fine	AC %	RAP % Wt.	Agg. % Wt.	No. 50	% Change	No. 200	% Change	Surf. Area	% Change	Stockpile
Traditional			5.41	46.02%	53.98%	17.47	12.20%	9.25	13.81%	7.96	11.00%	
Frac. (Minus #30 Removed)			5.70	43.68%	56.32%	15.57	0.00%	8.13	0.00%	7.17	0.00%	9.1%
Original	44%	56%	5.816	42.80%	57.20%	17.00	9.19%	8.13	-0.04%	7.44	3.76%	0.0%
1 to 1	50%	50%	5.790	43.00%	57.00%	16.61	6.68%	7.91	-2.74%	7.27	1.37%	12.0%
3 to 2	60%	40%	5.746	43.33%	56.67%	15.95	2.43%	7.54	-7.28%	6.98	-2.66%	26.7%
3.7 to 2	65%	35%	5.724	43.49%	56.51%	15.61	0.28%	7.35	-9.57%	6.84	-4.69%	32.3%
2 to 1	67%	33%	5.715	43.56%	56.44%	15.48	-0.59%	7.28	-10.50%	6.78	-5.51%	34.3%
7 to 3	70%	30%	5.702	43.66%	56.34%	15.28	-1.89%	7.16	-11.89%	6.69	-6.75%	37.1%
3 to 1	75%	25%	5.680	43.83%	56.17%	14.94	-4.07%	6.97	-14.22%	6.54	-8.81%	41.3%

											% Left Over	
Split %	3/4"	1/2"	3/8"	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200	Stockpile	Fine FRAP
Traditional	100	94.4	86.9	68.7	51.9	39.0	27.2	17.47	11.12	9.25		
Frac (Minus #30)	100	94.0	85.5	67.3	49.7	36.6	24.3	15.57	9.77	8.13		9.1%
Original	100	94.0	85.9	68.3	52.0	38.7	26.8	17.00	10.21	8.13	0.0%	0.0%
1 to 1	100	93.9	85.6	67.2	51.0	37.9	26.3	16.61	9.93	7.91	12.0%	21.4%
3 to 2	100	93.7	85.0	65.2	49.1	36.7	25.4	15.95	9.44	7.54	26.7%	47.6%
3.7 to 2	100	93.6	84.7	64.2	48.2	36.0	24.9	15.61	9.20	7.35	32.3%	57.7%
2 to 1	100	93.5	84.6	63.8	47.9	35.8	24.7	15.48	9.10	7.28	34.3%	61.3%
7 to 3	100	93.5	84.5	63.2	47.3	35.4	24.4	15.28	8.95	7.16	37.1%	66.3%
3 to 1	100	93.4	84.2	62.2	46.4	34.7	24.0	14.94	8.71	6.97	41.3%	73.8%

50% Classified RAP

	FRAP Properties					Effects on 6.00% AC Mix Design						
Split %	Coarse	Fine	AC %	RAP % Wt.	Agg. % Wt.	No. 50	% Change	No. 200	% Change	Surf. Area	% Change	Stockpile
Traditional			5.41	57.17%	42.83%	18.82	14.34%	10.65	15.07%	8.79	12.54%	
Frac. (Minus #30 Removed)			5.70	54.26%	45.74%	16.46	0.00%	9.25	0.00%	7.81	0.00%	9.1%
Original	44%	56%	5.816	53.17%	46.83%	18.24	10.81%	9.25	-0.05%	8.15	4.28%	0.0%
1 to 1	50%	50%	5.790	53.42%	46.58%	17.75	7.85%	8.98	-2.99%	7.93	1.56%	12.0%
3 to 2	60%	40%	5.746	53.82%	46.18%	16.93	2.85%	8.52	-7.94%	7.58	-3.03%	26.7%
3.7 to 2	65%	35%	5.724	54.03%	45.97%	16.51	0.33%	8.28	-10.45%	7.39	-5.35%	32.3%
2 to 1	67%	33%	5.715	54.12%	45.88%	16.34	-0.69%	8.19	-11.46%	7.32	-6.29%	34.3%
7 to 3	70%	30%	5.702	54.24%	45.76%	16.09	-2.22%	8.05	-12.98%	7.21	-7.69%	37.1%
3 to 1	75%	25%	5.680	54.45%	45.55%	15.67	-4.78%	7.82	-15.53%	7.03	-10.05%	41.3%

											% Left Over	
Split %	3/4"	1/2"	3/8"	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200	Stockpile	Fine FRAP
Traditional	100	95.2	88.6	70.9	54.0	40.6	28.8	18.82	12.75	10.65		
Frac (Minus #30)	100	94.6	86.9	69.1	51.2	37.6	25.3	16.46	11.07	9.25		9.1%
Original	100	94.7	87.4	70.4	54.1	40.3	28.3	18.24	11.62	9.25	0.0%	0.0%
1 to 1	100	94.5	86.9	68.9	52.8	39.3	27.7	17.75	11.26	8.98	12.0%	21.4%
3 to 2	100	94.3	86.2	66.5	50.6	37.8	26.5	16.93	10.67	8.52	26.7%	47.6%
3.7 to 2	100	94.1	85.9	65.2	49.4	37.0	26.0	16.51	10.36	8.28	32.3%	57.7%
2 to 1	100	94.1	85.7	64.8	49.0	36.6	25.7	16.34	10.24	8.19	34.3%	61.3%
7 to 3	100	94.0	85.5	64.0	48.3	36.2	25.4	16.09	10.06	8.05	37.1%	66.3%
3 to 1	100	93.8	85.2	62.7	47.1	35.4	24.8	15.67	9.75	7.82	41.3%	73.8%

Table E2: Optimum FRAP Proportion Selection – Stockpile B

	RAP Stockpile Extracted Aggregate Gradation										
	3/4"	1/2"	3/8"	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200	AC %
Traditional	100.0	95.0	91.0	74.0	57.0	44.0	34.0	22.0	17.0	14.0	5.11
Coarse FRAP	100.0	94.4	86.6	57.4	40.5	32.1	24.8	16.9	13.3	11.1	4.92
Fine FRAP	100.0	100.0	100.0	100.0	80.4	59.4	43.1	28.8	22.9	19.1	5.85
Frac. (- No. 30)	100.0	97.0	93.5	77.0	57.9	42.8	29.8	20.6	16.4	13.6	5.34
	Virgin Aggregate Gradation										
	100.0	91.4	80.0	60.0	43.3	32.1	20.5	11.9	4.4	3.5	

30% Certified B RAP

	FRAP Properties					Effects on 6.00% AC Mix Design						
Split %	Coarse	Fine	AC %	RAP % Wt.	Agg. % Wt.	No. 50	% Change	No. 200	% Change	Surf. Area	% Change	Stockpile
Traditional			5.11	36.77%	63.23%	15.61	4.36%	7.36	4.35%	6.85	3.69%	
Frac. (Minus #30 Removed)			5.34	35.19%	64.81%	14.96	0.00%	7.05	0.00%	6.60	0.00%	5.8%
Original	50%	50%	5.39	34.89%	65.11%	15.72	5.08%	7.55	7.00%	6.94	5.16%	0.0%
3 to 2	60%	40%	5.29	35.50%	64.50%	15.37	2.70%	7.33	3.98%	6.77	2.60%	16.7%
3.7 to 2	65%	35%	5.25	35.82%	64.18%	15.18	1.48%	7.23	2.43%	6.69	1.28%	23.1%
2 to 1	67%	33%	5.23	35.95%	64.05%	15.11	0.99%	7.18	1.80%	6.65	0.75%	25.4%
7 to 3	70%	30%	5.20	36.14%	63.86%	15.00	0.24%	7.11	0.85%	6.60	-0.06%	28.6%
3 to 1	75%	25%	5.15	36.47%	63.53%	14.81	-1.02%	7.00	-0.75%	6.51	-1.43%	33.3%
4 to 1	80%	20%	5.106	36.80%	63.20%	14.62	-2.31%	6.89	-2.39%	6.42	-2.81%	37.5%

											% Left Over	
Split %	3/4"	1/2"	3/8"	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200	Stockpile	Fine FRAP
Traditional	100	92.7	84.0	65.1	48.3	36.5	25.5	15.61	9.03	7.36		
Frac (Minus #30)	100	93.4	84.8	66.0	48.4	35.9	23.8	14.96	8.62	7.05		5.8%
Original	100	93.4	84.6	66.5	49.3	36.9	25.2	15.72	9.18	7.55	0.0%	0.0%
3 to 2	100	93.3	84.2	65.1	48.0	36.0	24.6	15.37	8.92	7.33	16.7%	33.3%
3.7 to 2	100	93.2	84.0	64.4	47.3	35.5	24.3	15.18	8.79	7.23	23.1%	46.2%
2 to 1	100	93.1	84.0	64.1	47.0	35.3	24.2	15.11	8.74	7.18	25.4%	50.7%
7 to 3	100	93.1	83.8	63.7	46.6	35.1	24.0	15.00	8.66	7.11	28.6%	57.1%
3 to 1	100	93.0	83.6	62.9	45.9	34.6	23.7	14.81	8.52	7.00	33.3%	66.7%
4 to 1	100	92.9	83.4	62.2	45.2	34.1	23.4	14.62	8.38	6.89	37.5%	75.0%

40% Certified B RAP

	FRAP Properties					Effects on 6.00% AC Mix Design						
Split %	Coarse	Fine	AC %	RAP % Wt.	Agg. % Wt.	No. 50	% Change	No. 200	% Change	Surf. Area	% Change	Stockpile
Traditional			5.11	48.72%	51.28%	16.82	5.42%	8.62	4.96%	7.60	4.44%	
Frac. (Minus #30 Removed)			5.34	46.62%	53.38%	15.96	0.00%	8.21	0.00%	7.28	0.00%	5.8%
Original	50%	50%	5.39	46.23%	53.77%	16.96	6.31%	8.86	7.97%	7.73	6.21%	0.0%
3 to 2	60%	40%	5.29	47.05%	52.95%	16.49	3.36%	8.58	4.53%	7.50	3.12%	16.7%
3.7 to 2	65%	35%	5.25	47.46%	52.54%	16.25	1.84%	8.44	2.77%	7.39	1.54%	23.1%
2 to 1	67%	33%	5.23	47.63%	52.37%	16.15	1.23%	8.38	2.05%	7.34	0.90%	25.4%
7 to 3	70%	30%	5.20	47.89%	52.11%	16.00	0.30%	8.29	0.97%	7.27	-0.07%	28.6%
3 to 1	75%	25%	5.15	48.32%	51.68%	15.75	-1.27%	8.14	-0.86%	7.15	-1.71%	33.3%
4 to 1	80%	20%	5.11	48.76%	51.24%	15.50	-2.87%	7.99	-2.72%	7.03	-3.38%	37.5%

											% Left Over	
Split %	3/4"	1/2"	3/8"	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200	Stockpile	Fine FRAP
Traditional	100	93.2	85.4	66.8	50.0	37.9	27.1	16.82	10.54	8.62		
Frac (Minus #30)	100	94.0	86.3	67.9	50.1	37.1	24.8	15.96	9.99	8.21		5.8%
Original	100	94.1	86.1	68.6	51.2	38.4	26.7	16.96	10.73	8.86	0.0%	0.0%
3 to 2	100	93.9	85.6	66.8	49.5	37.2	26.0	16.49	10.39	8.58	16.7%	33.3%
3.7 to 2	100	93.8	85.4	65.8	48.6	36.6	25.6	16.25	10.22	8.44	23.1%	46.2%
2 to 1	100	93.7	85.2	65.5	48.2	36.4	25.4	16.15	10.15	8.38	25.4%	50.7%
7 to 3	100	93.6	85.1	64.9	47.7	36.0	25.2	16.00	10.04	8.29	28.6%	57.1%
3 to 1	100	93.5	84.8	63.9	46.8	35.4	24.8	15.75	9.86	8.14	33.3%	66.7%
4 to 1	100	93.4	84.5	62.9	45.8	34.8	24.4	15.50	9.68	7.99	37.5%	75.0%

50% Certified B RAP

	FRAP Properties					Effects on 6.00% AC Mix Design						
Split %	Coarse	Fine	AC %	RAP % Wt.	Agg. % Wt.	No. 50	% Change	No. 200	% Change	Surf. Area	% Change	Stockpile
Traditional			5.11	60.52%	39.48%	18.01	6.34%	9.86	5.41%	8.35	5.05%	
Frac. (Minus #30 Removed)			5.34	57.92%	42.08%	16.94	0.00%	9.35	0.00%	7.94	0.00%	5.8%
Original	50%	50%	5.39	57.43%	42.57%	18.19	7.38%	10.16	8.69%	8.50	7.06%	0.0%
3 to 2	60%	40%	5.29	58.44%	41.56%	17.60	3.93%	9.81	4.94%	8.23	3.55%	16.7%
3.7 to 2	65%	35%	5.25	58.96%	41.04%	17.30	2.15%	9.63	3.02%	8.08	1.75%	23.1%
2 to 1	67%	33%	5.23	59.17%	40.83%	17.18	1.44%	9.56	2.24%	8.02	1.02%	25.4%
7 to 3	70%	30%	5.20	59.49%	40.51%	17.00	0.35%	9.45	1.06%	7.94	-0.08%	28.6%
3 to 1	75%	25%	5.15	60.02%	39.98%	16.69	-1.49%	9.26	-0.93%	7.79	-1.95%	33.3%
4 to 1	80%	20%	5.11	60.57%	39.43%	16.37	-3.36%	9.07	-2.96%	7.64	-3.85%	37.5%

											% Left Over	
Split %	3/4"	1/2"	3/8"	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200	Stockpile	Fine FRAP
Traditional	100	93.6	86.7	68.5	51.6	39.3	28.7	18.01	12.03	9.86		
Frac (Minus #30)	100	94.6	87.8	69.8	51.8	38.3	25.9	16.94	11.35	9.35		5.8%
Original	100	94.7	87.6	70.7	53.1	39.9	28.2	18.19	12.27	10.16	0.0%	0.0%
3 to 2	100	94.5	87.0	68.4	51.0	38.5	27.3	17.60	11.85	9.81	16.7%	33.3%
3.7 to 2	100	94.3	86.7	67.3	49.9	37.7	26.8	17.30	11.63	9.63	23.1%	46.2%
2 to 1	100	94.3	86.5	66.8	49.4	37.4	26.6	17.18	11.54	9.56	25.4%	50.7%
7 to 3	100	94.2	86.3	66.1	48.8	37.0	26.3	17.00	11.41	9.45	28.6%	57.1%
3 to 1	100	94.0	86.0	64.8	47.6	36.2	25.8	16.69	11.18	9.26	33.3%	66.7%
4 to 1	100	93.9	85.6	63.6	46.4	35.4	25.3	16.37	10.95	9.07	37.5%	75.0%

Table E3: Optimum FRAP Proportion Selection – Stockpile C

	3/4"	1/2"	3/8"	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200	AC %
	RAP Stockpile Extracted Aggregate Gradation										
Traditional	100.0	88.0	80.0	61.0	46.0	36.0	27.0	17.0	12.0	10.3	4.82
Coarse FRAP	100.0	91.1	81.4	50.8	34.0	27.6	21.8	13.4	8.7	7.2	4.41
Fine FRAP	100.0	100.0	100.0	100.0	78.0	58.0	42.1	23.6	15.8	13.1	5.81
Frac. (- No. 30)	100.0	97.0	91.7	67.3	47.6	35.7	25.7	15.5	10.3	8.5	4.83
	Virgin Aggregate Gradation										
	100.0	91.4	80.0	60.0	43.3	32.1	20.5	11.9	4.4	3.5	

30% Certified C RAP

Split %	Coarse	Fine	AC %	RAP % Wt.	Agg. % Wt.	No. 50	% Change	No. 200	% Change	Surf. Area	% Change	Stockpile
	FRAP Properties					Effects on 6.00% AC Mix Design						
Traditional			4.82	38.98%	61.02%	13.89	4.42%	6.15	12.96%	5.98	6.17%	
Frac. (Minus #30 Removed)			4.83	38.90%	61.10%	13.30	0.00%	5.45	0.00%	5.63	0.00%	5.0%
Original	65%	35%	4.900	38.35%	61.65%	13.84	4.09%	5.71	4.88%	5.84	3.79%	0.0%
2 to 1	67%	33%	4.872	38.57%	61.43%	13.78	3.58%	5.68	4.27%	5.81	3.23%	3.0%
7 to 3	70%	30%	4.830	38.90%	61.10%	13.67	2.81%	5.63	3.36%	5.76	2.38%	7.1%
3 to 1	75%	25%	4.760	39.47%	60.53%	13.50	1.49%	5.54	1.79%	5.68	0.94%	13.3%
4 to 1	80%	20%	4.690	40.06%	59.94%	13.32	0.13%	5.46	0.18%	5.60	-0.55%	18.8%
9 to 1	90%	10%	4.550	41.29%	58.71%	12.94	-2.71%	5.27	-3.19%	5.42	-3.67%	27.8%
100	100%	0%	4.410	42.61%	57.39%	12.54	-5.72%	5.08	-6.77%	5.24	-6.98%	35.0%

Split %	3/4"	1/2"	3/8"	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200	Stockpile	Fine FRAP
											% Left Over	
Traditional	100	90.1	80.0	60.4	44.4	33.6	23.0	13.89	7.36	6.15		
Frac (Minus #30)	100	93.6	84.6	62.8	45.0	33.5	22.5	13.30	6.70	5.45		5.0%
Original	100	92.5	83.0	63.1	45.6	34.5	23.7	13.84	7.00	5.71	0.0%	0.0%
2 to 1	100	92.4	82.9	62.7	45.3	34.2	23.6	13.78	6.96	5.68	3.0%	8.5%
7 to 3	100	92.3	82.7	62.2	44.8	33.9	23.4	13.67	6.90	5.63	7.1%	20.4%
3 to 1	100	92.2	82.4	61.2	44.0	33.3	23.0	13.50	6.80	5.54	13.3%	38.1%
4 to 1	100	92.0	82.1	60.3	43.1	32.7	22.6	13.32	6.69	5.46	18.8%	53.6%
9 to 1	100	91.6	81.3	58.2	41.3	31.5	21.9	12.94	6.47	5.27	27.8%	79.4%
100	100	91.3	80.6	56.1	39.3	30.2	21.1	12.54	6.23	5.08	35.0%	100.0%

40% Certified C RAP

Split %	Coarse	Fine	AC %	RAP % Wt.	Agg. % Wt.	No. 50	% Change	No. 200	% Change	Surf. Area	% Change	Stockpile
	FRAP Properties					Effects on 6.00% AC Mix Design						
Traditional			4.82	51.65%	48.35%	14.53	5.66%	7.01	15.39%	6.45	7.69%	
Frac. (Minus #30 Removed)			4.83	51.55%	48.45%	13.76	0.00%	6.08	0.00%	5.99	0.00%	5.0%
Original	65%	35%	4.900	50.81%	49.19%	14.48	5.24%	6.43	5.79%	6.27	4.72%	0.0%
2 to 1	67%	33%	4.872	51.10%	48.90%	14.39	4.59%	6.39	5.07%	6.23	4.03%	3.0%
7 to 3	70%	30%	4.830	51.55%	48.45%	14.25	3.60%	6.32	3.99%	6.16	2.97%	7.1%
3 to 1	75%	25%	4.760	52.30%	47.70%	14.02	1.91%	6.21	2.13%	6.06	1.17%	13.3%
4 to 1	80%	20%	4.690	53.08%	46.92%	13.78	0.17%	6.09	0.22%	5.95	-0.69%	18.8%
9 to 1	90%	10%	4.550	54.72%	45.28%	13.28	-3.47%	5.85	-3.78%	5.71	-4.57%	27.8%
100	100%	0%	4.410	56.45%	43.55%	12.75	-7.33%	5.59	-8.04%	5.47	-8.70%	35.0%

Split %	3/4"	1/2"	3/8"	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200	Stockpile	Fine FRAP
											% Left Over	
Traditional	100	89.6	80.0	60.5	44.7	34.1	23.9	14.53	8.33	7.01		
Frac (Minus #30)	100	94.3	86.0	63.8	45.5	34.0	23.2	13.76	7.44	6.08		5.0%
Original	100	92.8	84.0	64.1	46.4	35.2	24.8	14.48	7.85	6.43	0.0%	0.0%
2 to 1	100	92.7	83.9	63.6	46.0	34.9	24.6	14.39	7.79	6.39	3.0%	8.5%
7 to 3	100	92.6	83.6	62.9	45.3	34.5	24.3	14.25	7.71	6.32	7.1%	20.4%
3 to 1	100	92.4	83.2	61.6	44.2	33.7	23.8	14.02	7.58	6.21	13.3%	38.1%
4 to 1	100	92.2	82.7	60.3	43.0	32.9	23.3	13.78	7.44	6.09	18.8%	53.6%
9 to 1	100	91.7	81.8	57.7	40.6	31.3	22.3	13.28	7.14	5.85	27.8%	79.4%
100	100	91.2	80.8	54.8	38.0	29.6	21.2	12.75	6.83	5.59	35.0%	100.0%

50% Certified C RAP

Split %	Coarse	Fine	AC %	RAP % Wt.	Agg. % Wt.	No. 50	% Change	No. 200	% Change	Surf. Area	% Change	Stockpile
	FRAP Properties					Effects on 6.00% AC Mix Design						
Traditional			4.82	64.17%	35.83%	15.17	6.81%	7.86	17.33%	6.91	9.02%	
Frac. (Minus #30 Removed)			4.83	64.03%	35.97%	14.21	0.00%	6.70	0.00%	6.34	0.00%	5.0%
Original	65%	35%	4.900	63.12%	36.88%	15.10	6.30%	7.14	6.52%	6.69	5.54%	0.0%
2 to 1	67%	33%	4.872	63.48%	36.52%	14.99	5.52%	7.08	5.72%	6.64	4.72%	3.0%
7 to 3	70%	30%	4.830	64.03%	35.97%	14.82	4.33%	7.00	4.49%	6.56	3.48%	7.1%
3 to 1	75%	25%	4.760	64.97%	35.03%	14.53	2.30%	6.86	2.40%	6.43	1.37%	13.3%
4 to 1	80%	20%	4.690	65.94%	34.06%	14.23	0.21%	6.72	0.25%	6.29	-0.81%	18.8%
9 to 1	90%	10%	4.550	67.97%	32.03%	13.61	-4.17%	6.42	-4.26%	6.00	-5.36%	27.8%
100	100%	0%	4.410	70.13%	29.87%	12.95	-8.82%	6.09	-9.05%	5.69	-10.20%	35.0%

Split %	3/4"	1/2"	3/8"	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200	Stockpile	Fine FRAP
											% Left Over	
Traditional	100	89.2	80.0	60.6	45.0	34.6	24.7	15.17	9.28	7.86		
Frac (Minus #30)	100	95.0	87.5	64.7	46.1	34.4	23.8	14.21	8.18	6.70		5.0%
Original	100	93.2	85.0	65.1	47.2	36.0	25.8	15.10	8.68	7.14	0.0%	0.0%
2 to 1	100	93.1	84.8	64.5	46.6	35.6	25.6	14.99	8.62	7.08	3.0%	8.5%
7 to 3	100	92.9	84.5	63.6	45.8	35.1	25.2	14.82	8.52	7.00	7.1%	20.4%
3 to 1	100	92.7	83.9	62.0	44.4	34.1	24.6	14.53	8.35	6.86	13.3%	38.1%
4 to 1	100	92.4	83.4	60.4	43.0	33.1	24.0	14.23	8.17	6.72	18.8%	53.6%
9 to 1	100	91.8	82.2	57.1	40.0	31.1	22.8	13.61	7.81	6.42	27.8%	79.4%
100	100	91.2	81.0	53.5	36.8	28.9	21.4	12.95	7.42	6.09	35.0%	100.0%

APPENDIX F:

HIGH-RAP MIX DESIGN COMBINED GRADATION DATA

Combined Gradation at Optimum Binder Content										
Sieve Size (in.)	3/4"	1/2"	3/8"	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200
Maximum % Passing		100	90		58					10
Combined Gradation	100.0	93.4	84.6	65.8	49.0	36.7	24.9	15.6	8.8	7.3
Minimum % Passing	100	90			28					2

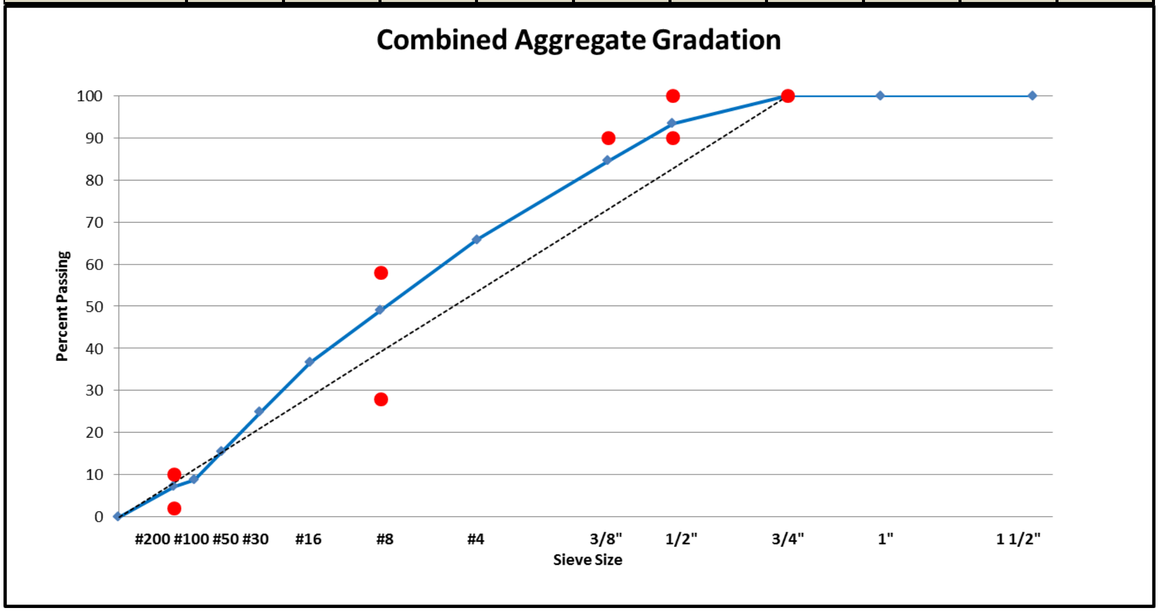

Figure F1: Combined Aggregate Gradation – 30% Traditional RAP-A Mix Design

Combined Gradation at Optimum Binder Content										
Sieve Size (in.)	3/4"	1/2"	3/8"	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200
Maximum % Passing		100	90		58					10
Combined Gradation	100.0	94.1	86.1	67.8	51.0	38.2	26.5	16.8	10.4	8.6
Minimum % Passing	100	90			28					2

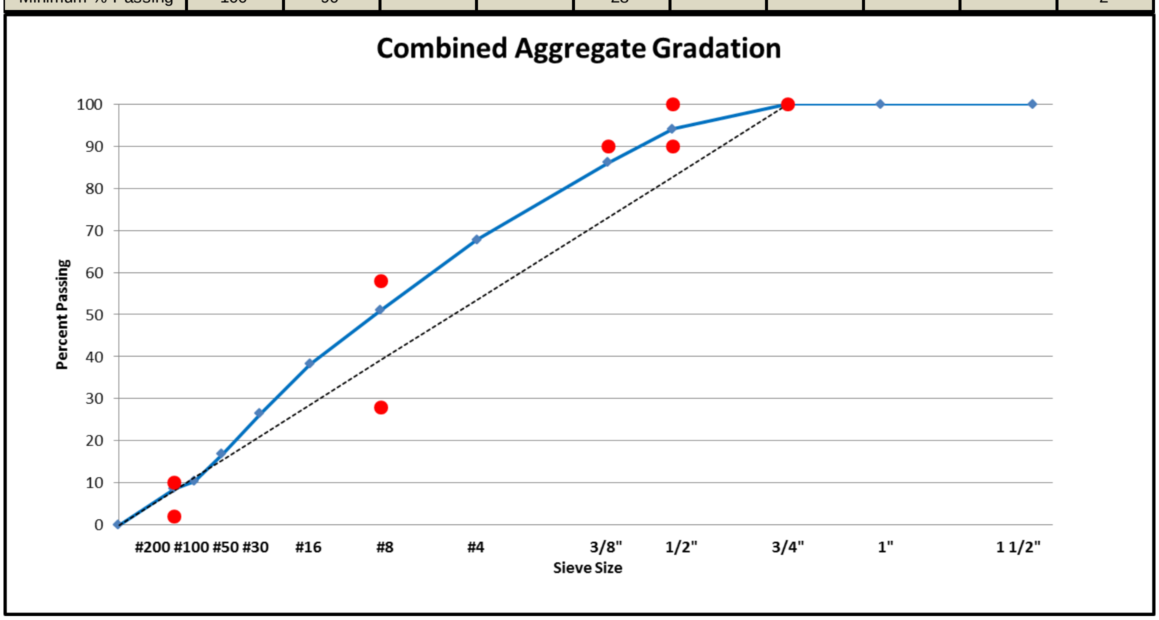

Figure F2: Combined Aggregate Gradation – 40% Traditional RAP-A Mix Design

Combined Gradation at Optimum Binder Content										
Sieve Size (in.)	3/4"	1/2"	3/8"	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200
Maximum % Passing		100	90		58					10
Combined Gradation	100.0	94.8	87.8	69.9	53.0	39.8	28.0	18.2	12.0	10.0
Minimum % Passing	100	90			28					2

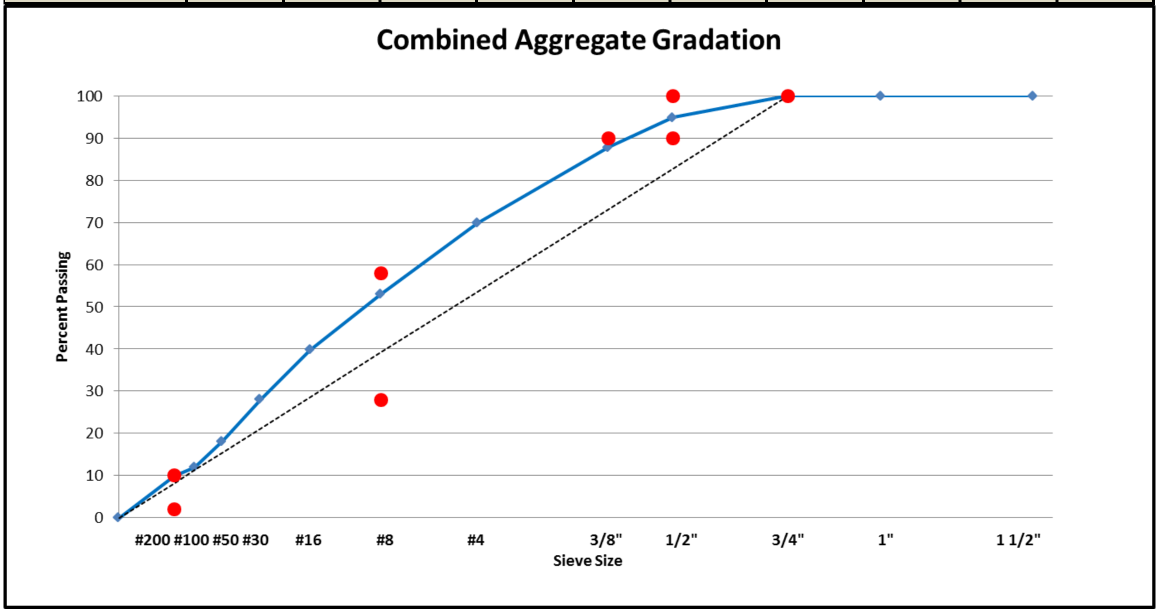

Figure F3: Combined Aggregate Gradation – 50% Traditional RAP-A Mix Design

Combined Gradation at Optimum Binder Content										
Sieve Size (in.)	3/4"	1/2"	3/8"	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200
Maximum % Passing		100	90		58					10
Combined Gradation	100.0	93.3	84.1	65.4	48.0	35.4	23.3	14.6	8.3	6.9
Minimum % Passing	100	90			28					2

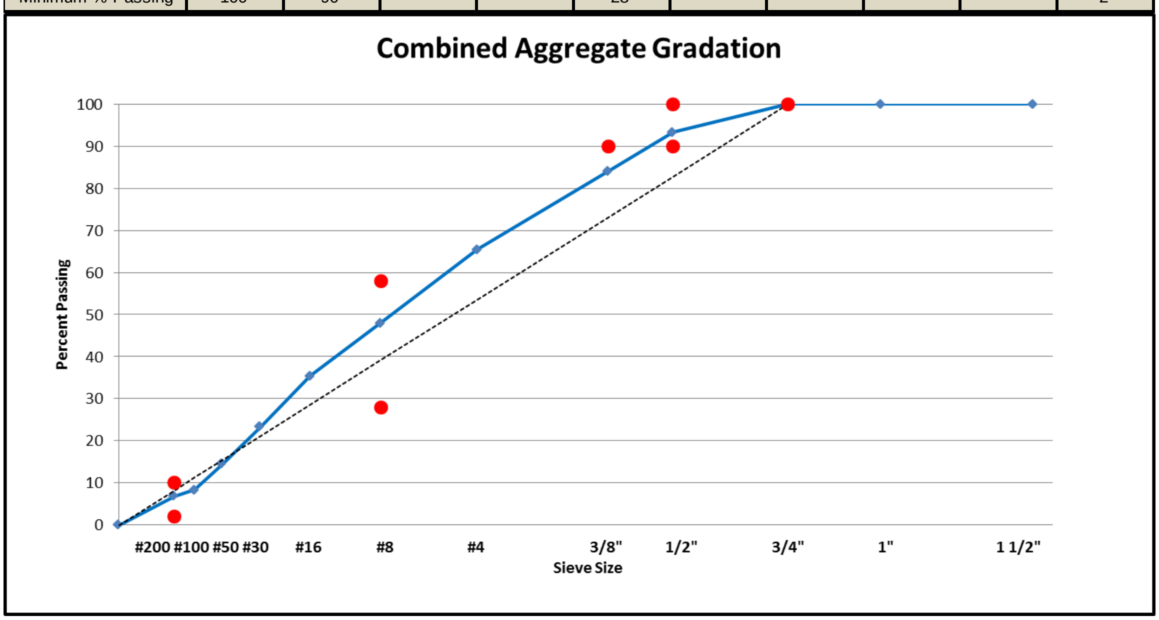

Figure F4: Combined Aggregate Gradation – 30% Fractionated RAP-A Mix Design

Combined Gradation at Optimum Binder Content										
Sieve Size (in.)	**3/4"**	**1/2"**	**3/8"**	**No. 4**	**No. 8**	**No. 16**	**No. 30**	**No. 50**	**No. 100**	**No. 200**
Maximum % Passing		100	90		58					10
Combined Gradation	100.0	94.0	85.5	67.3	49.6	36.5	24.3	15.5	9.7	8.1
Minimum % Passing	100	90			28					2

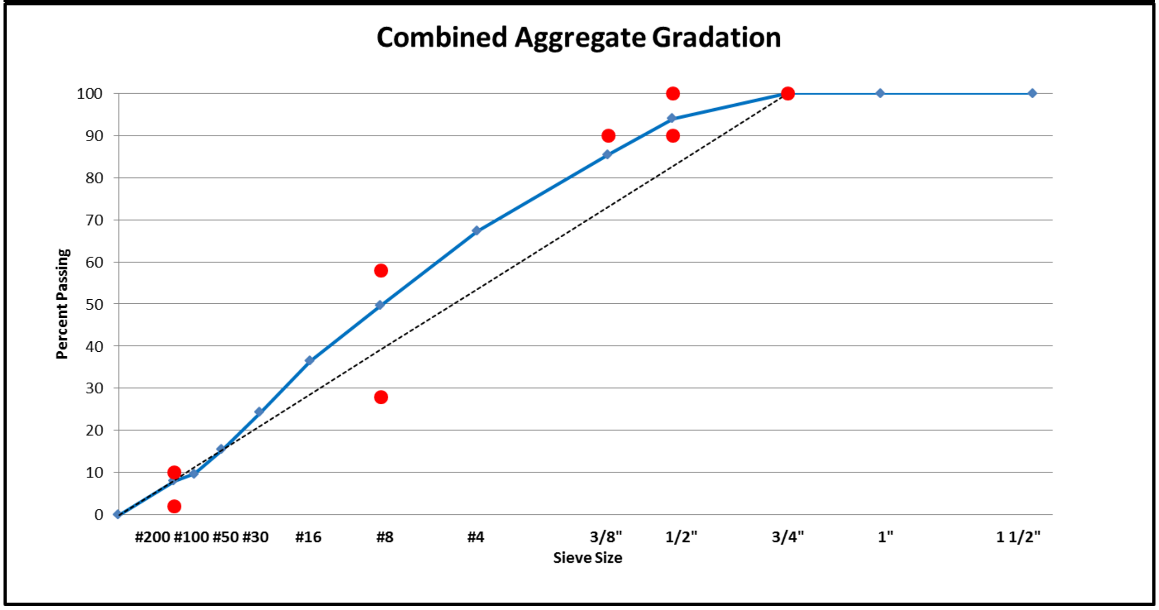

Figure F5: Combined Aggregate Gradation – 40% Fractionated RAP-A Mix Design

Combined Gradation at Optimum Binder Content										
Sieve Size (in.)	**3/4"**	**1/2"**	**3/8"**	**No. 4**	**No. 8**	**No. 16**	**No. 30**	**No. 50**	**No. 100**	**No. 200**
Maximum % Passing		100	90		58					10
Combined Gradation	100.0	94.4	86.4	68.4	50.6	37.2	24.9	16.1	10.6	8.8
Minimum % Passing	100	90			28					2

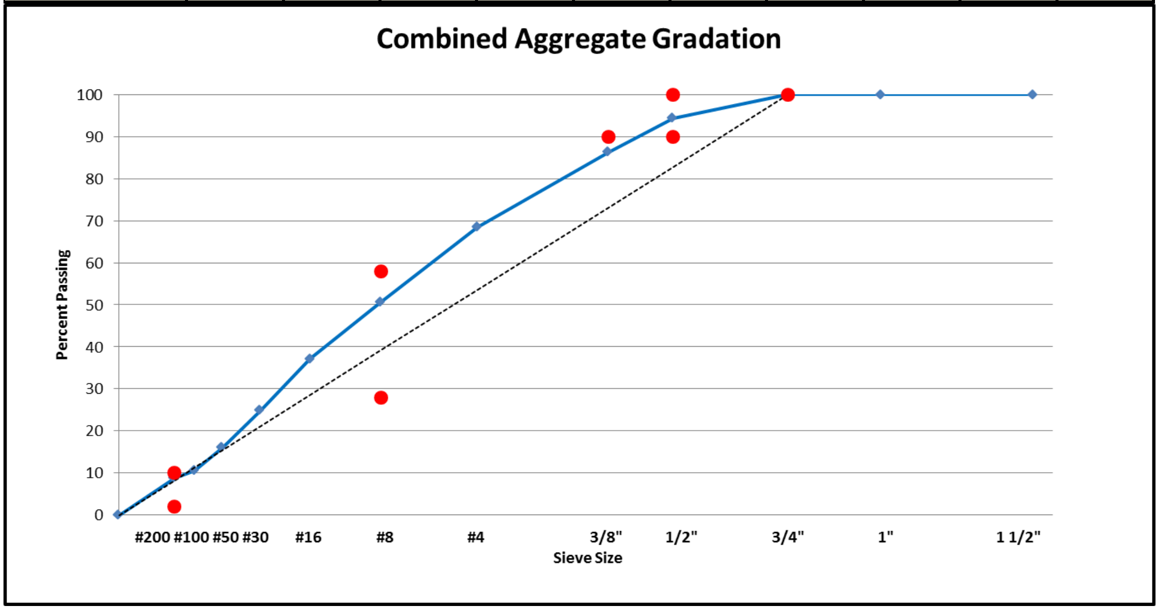

Figure F6: Combined Aggregate Gradation – 50% Fractionated RAP-A Mix Design

Combined Gradation at Optimum Binder Content										
Sieve Size (in.)	3/4"	1/2"	3/8"	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200
Maximum % Passing		100	90		58					10
Combined Gradation	100.0	92.7	82.6	61.4	45.3	33.8	22.7	13.8	7.1	5.7
Minimum % Passing	100	90			28					2

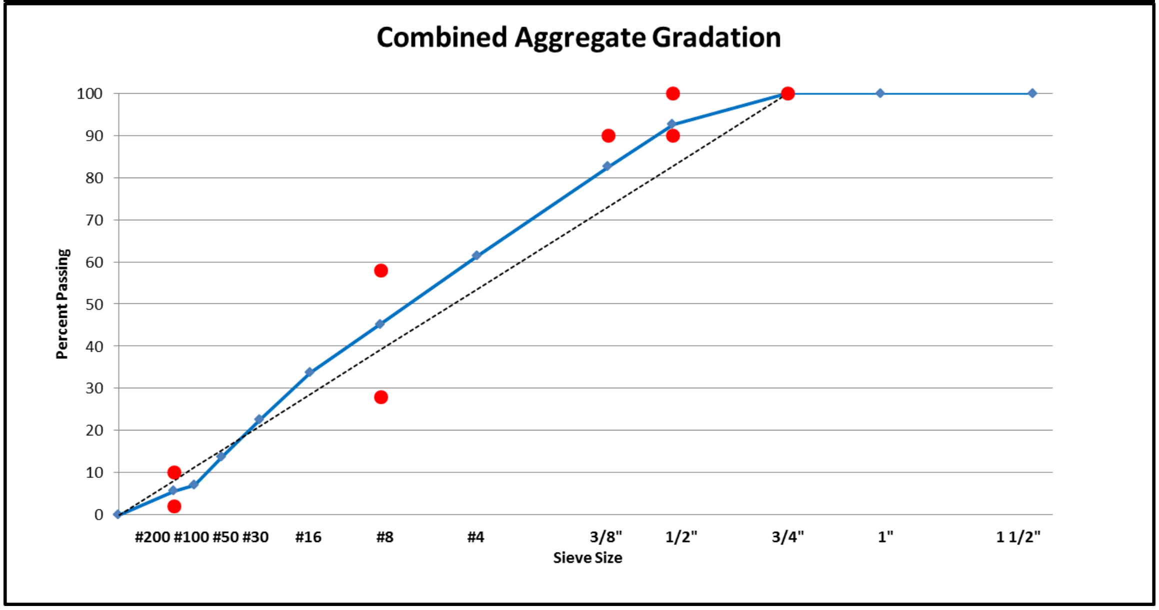

Figure F7: Combined Aggregate Gradation – 30% Optimum FRAP-A Mix Design

Combined Gradation at Optimum Binder Content										
Sieve Size (in.)	3/4"	1/2"	3/8"	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200
Maximum % Passing		100	90		58					10
Combined Gradation	100.0	93.1	83.5	61.9	45.9	34.3	23.5	14.5	8.1	6.4
Minimum % Passing	100	90			28					2

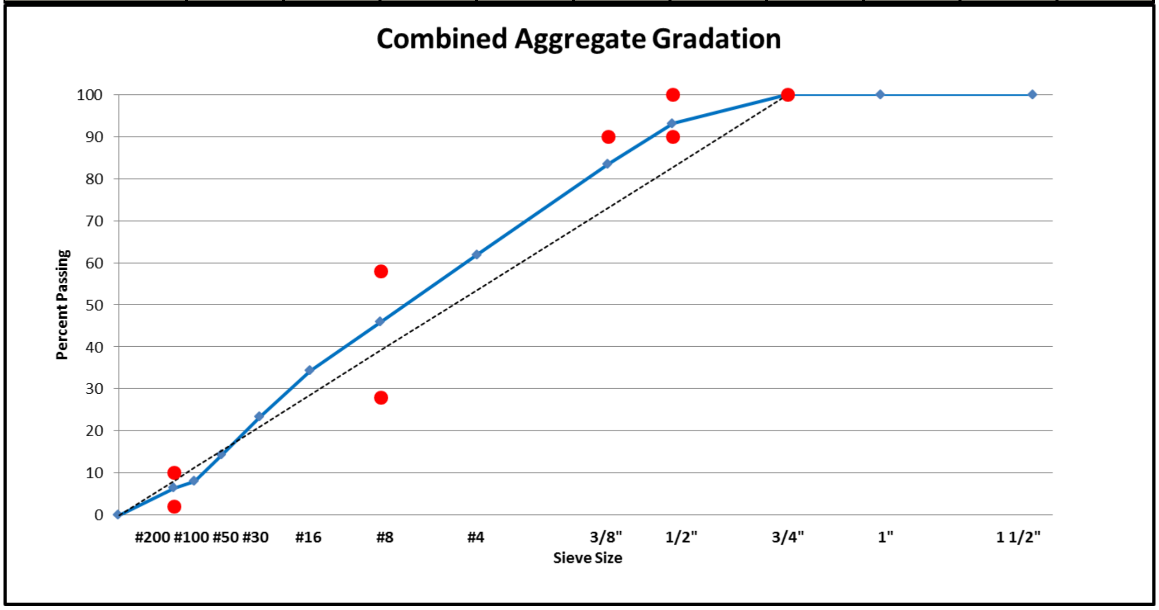

Figure F8: Combined Aggregate Gradation – 40% Optimum FRAP-A Mix Design

Combined Gradation at Optimum Binder Content										
Sieve Size (in.)	3/4"	1/2"	3/8"	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200
Maximum % Passing		100	90		58					10
Combined Gradation	100.0	93.6	84.6	62.4	46.7	35.0	24.3	15.2	9.1	7.3
Minimum % Passing	100	90			28					2

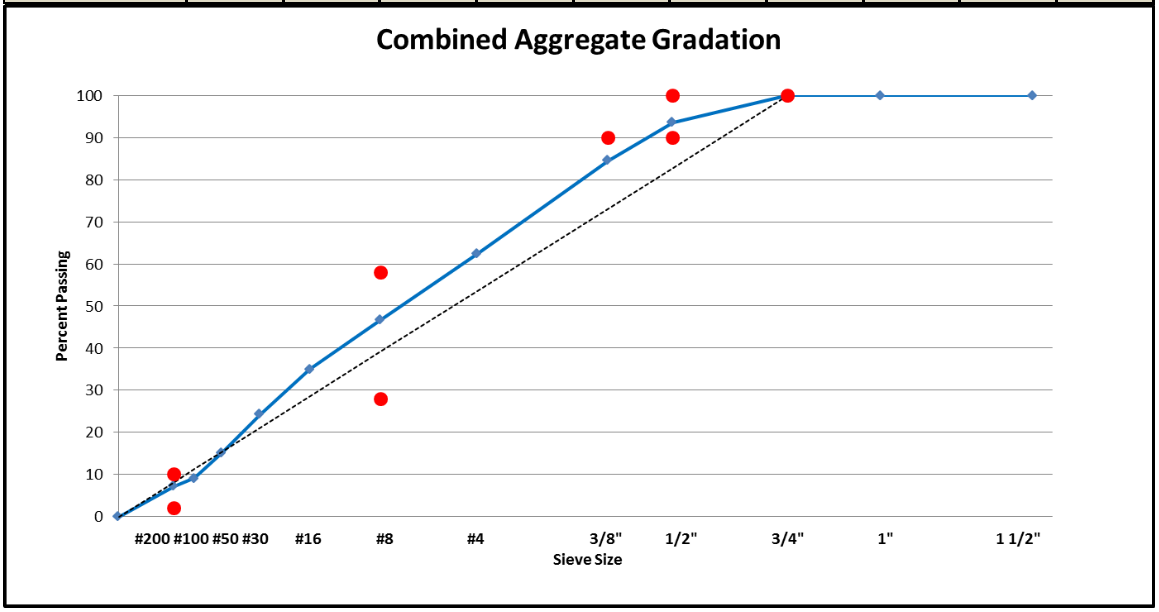

Figure F9: Combined Aggregate Gradation – 50% Optimum FRAP-A Mix Design

Combined Gradation at Optimum Binder Content										
Sieve Size (in.)	3/4"	1/2"	3/8"	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200
Maximum % Passing		100	90		58					10
Combined Gradation	100.0	92.6	83.6	64.6	47.8	36.0	24.9	15.2	8.5	6.9
Minimum % Passing	100	90			28					2

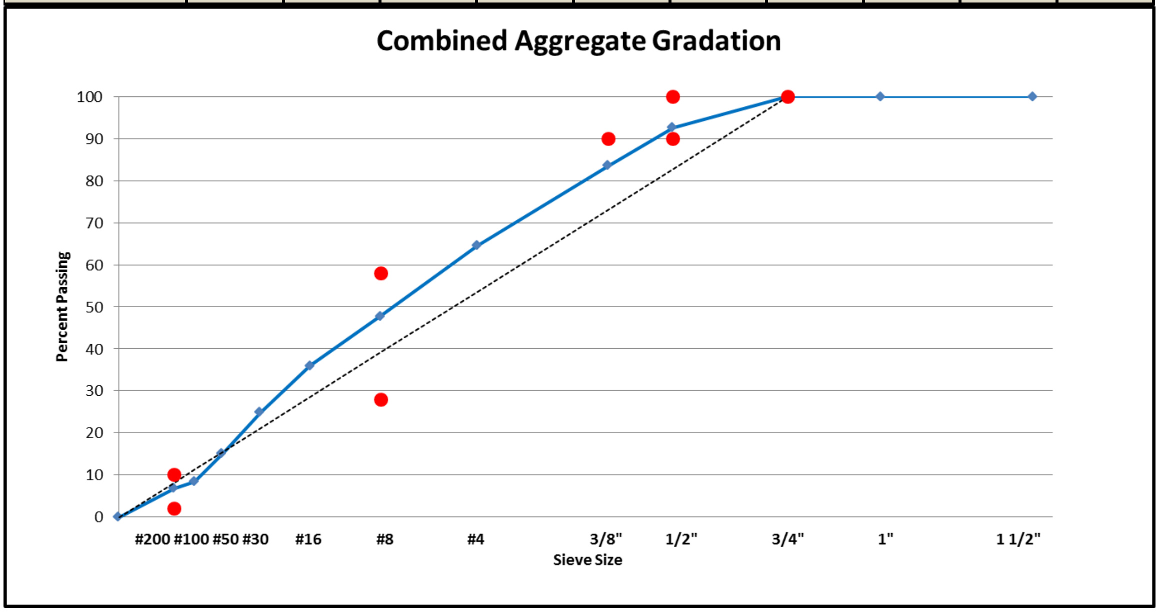

Figure F10: Combined Aggregate Gradation – 30% Traditional RAP-B Mix Design

Combined Gradation at Optimum Binder Content										
Sieve Size (in.)	3/4"	1/2"	3/8"	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200
Maximum % Passing		100	90		58					10
Combined Gradation	100.0	93.0	84.8	66.1	49.2	37.3	26.3	16.2	9.8	8.0
Minimum % Passing	100	90			28					2

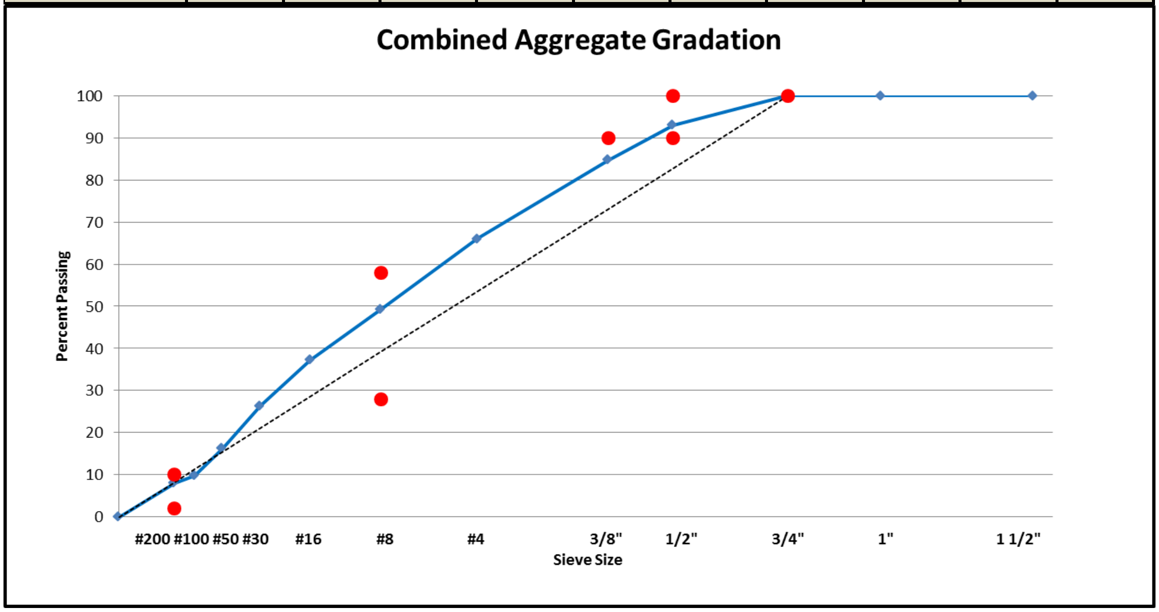

Figure F11: Combined Aggregate Gradation – 40% Traditional RAP-B Mix Design

Combined Gradation at Optimum Binder Content										
Sieve Size (in.)	3/4"	1/2"	3/8"	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200
Maximum % Passing		100	90		58					10
Combined Gradation	100.0	93.3	85.9	67.5	50.6	38.5	27.7	17.3	11.1	9.1
Minimum % Passing	100	90			28					2

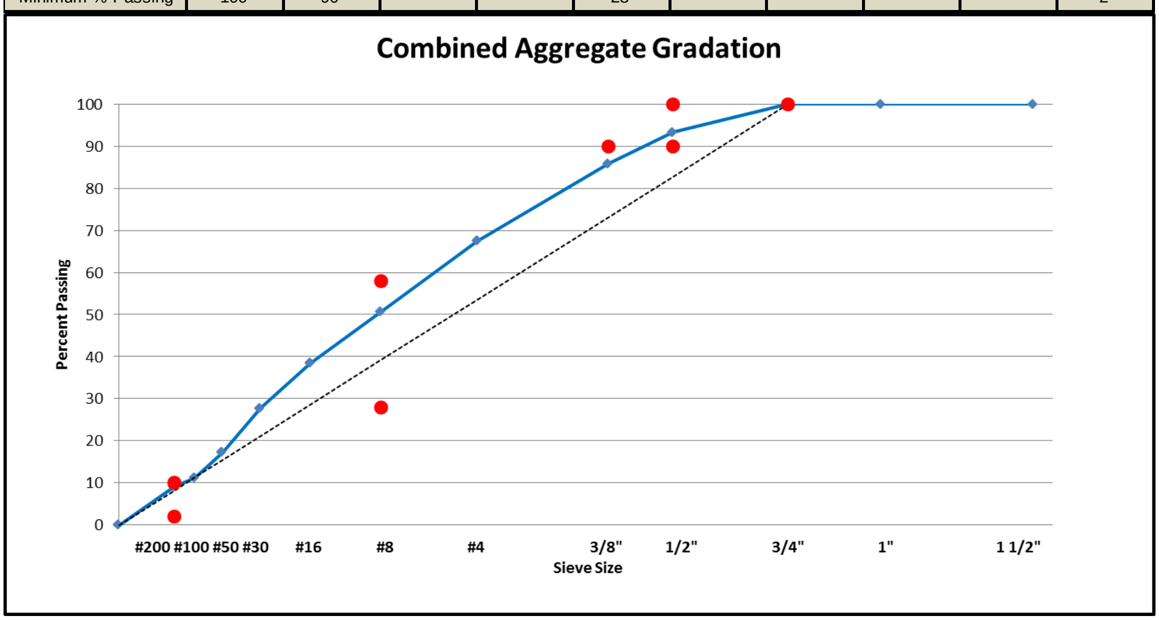

Figure F12: Combined Aggregate Gradation – 50% Traditional RAP-B Mix Design

Combined Gradation at Optimum Binder Content										
Sieve Size (in.)	**3/4"**	**1/2"**	**3/8"**	**No. 4**	**No. 8**	**No. 16**	**No. 30**	**No. 50**	**No. 100**	**No. 200**
Maximum % Passing		100	90		58					10
Combined Gradation	100.0	93.0	83.9	64.9	47.5	35.2	23.2	14.4	7.8	6.4
Minimum % Passing	100	90			28					2

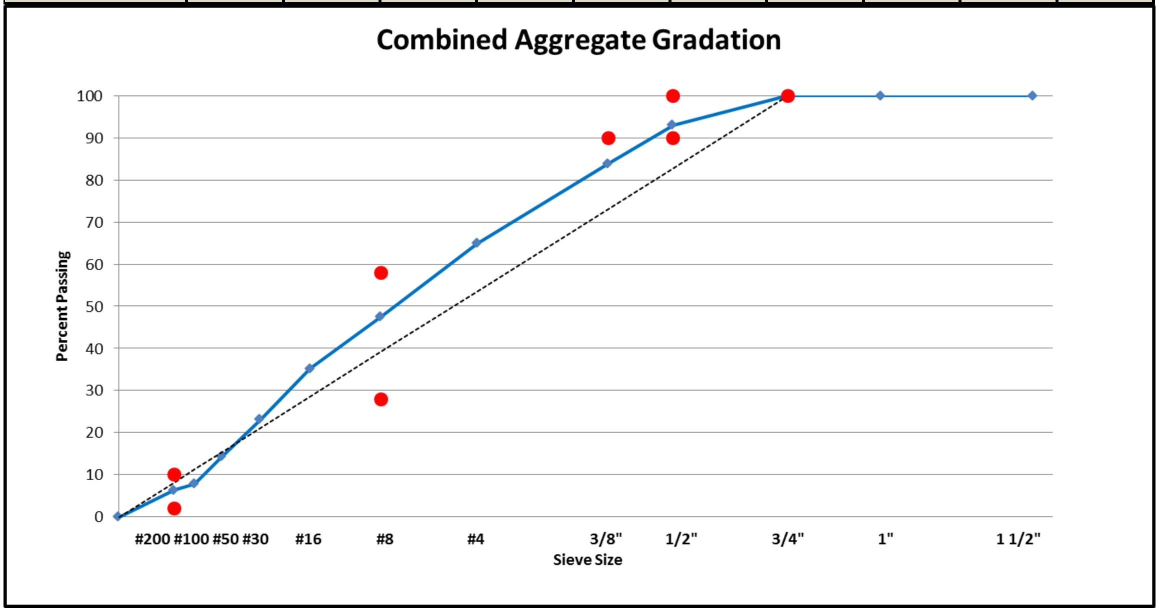

Figure F13: Combined Aggregate Gradation – 30% Fractionated RAP-B Mix Design

Combined Gradation at Optimum Binder Content										
Sieve Size (in.)	**3/4"**	**1/2"**	**3/8"**	**No. 4**	**No. 8**	**No. 16**	**No. 30**	**No. 50**	**No. 100**	**No. 200**
Maximum % Passing		100	90		58					10
Combined Gradation	100.0	93.6	85.3	66.7	49.0	36.3	24.2	15.3	9.1	7.4
Minimum % Passing	100	90			28					2

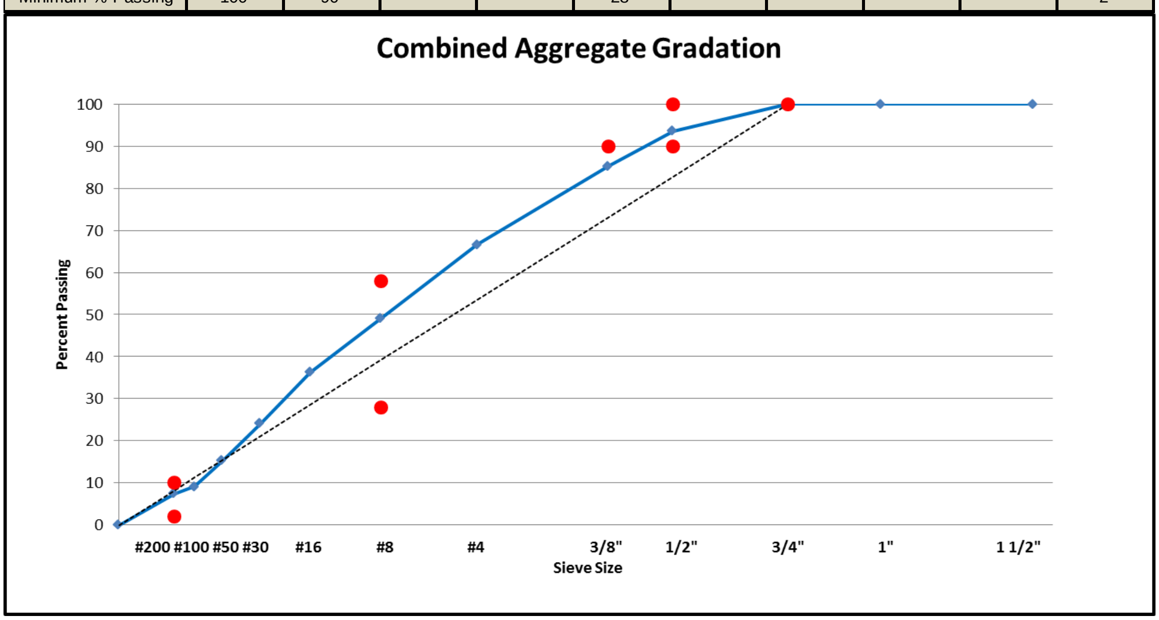

Figure F14: Combined Aggregate Gradation – 40% Fractionated RAP-B Mix Design

Combined Gradation at Optimum Binder Content										
Sieve Size (in.)	3/4"	1/2"	3/8"	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200
Maximum % Passing		100	90		58					10
Combined Gradation	100.0	94.1	86.5	68.2	50.3	37.2	25.0	16.1	10.1	8.3
Minimum % Passing	100	90			28					2

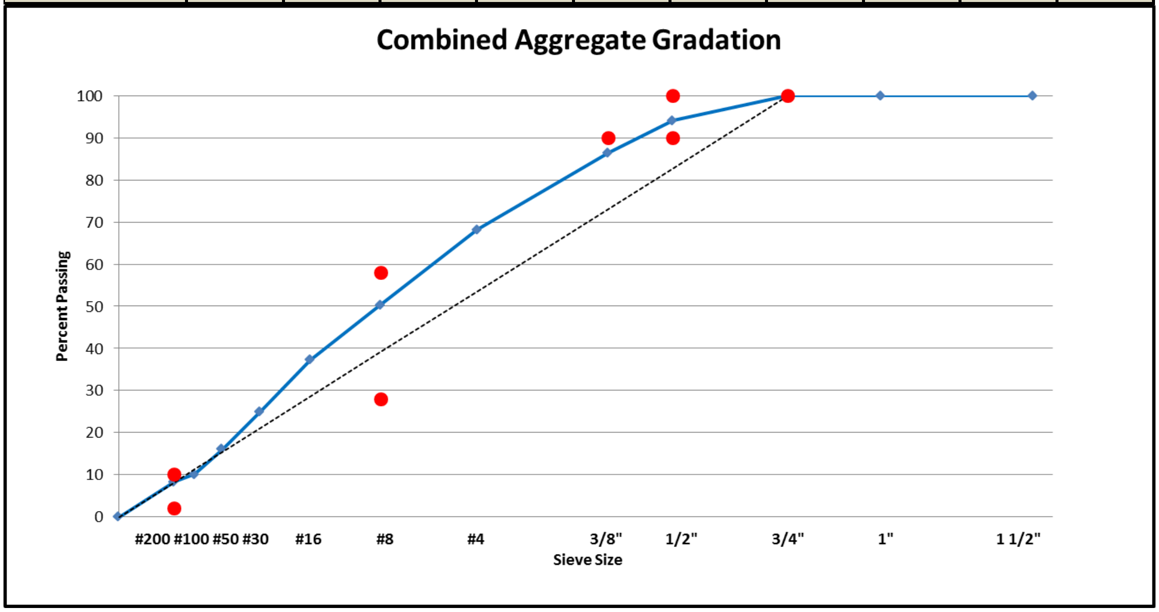

Figure F15: Combined Aggregate Gradation – 50% Fractionated RAP-B Mix Design

Combined Gradation at Optimum Binder Content										
Sieve Size (in.)	3/4"	1/2"	3/8"	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200
Maximum % Passing		100	90		58					10
Combined Gradation	100.0	92.6	82.6	61.7	44.8	33.7	22.8	14.0	7.4	6.1
Minimum % Passing	100	90			28					2

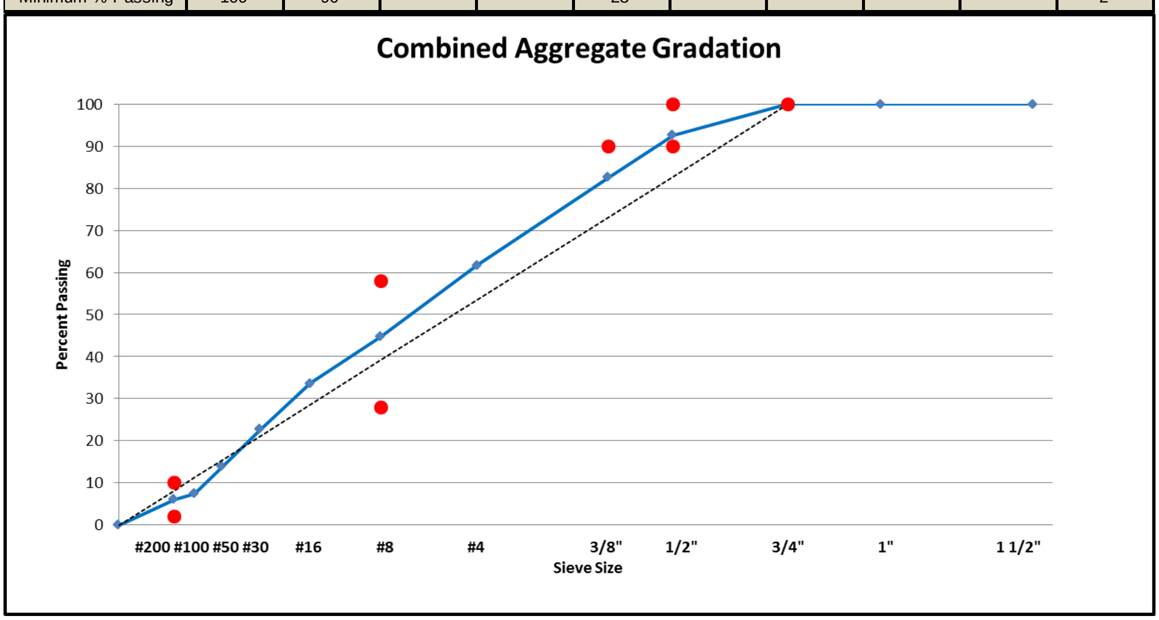

Figure F16: Combined Aggregate Gradation – 30% Optimum FRAP-B Mix Design

Combined Gradation at Optimum Binder Content										
Sieve Size (in.)	3/4"	1/2"	3/8"	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200
Maximum % Passing		100	90		58					10
Combined Gradation	100.0	93.0	83.6	62.3	45.3	34.2	23.6	14.7	8.6	7.0
Minimum % Passing	100	90			28					2

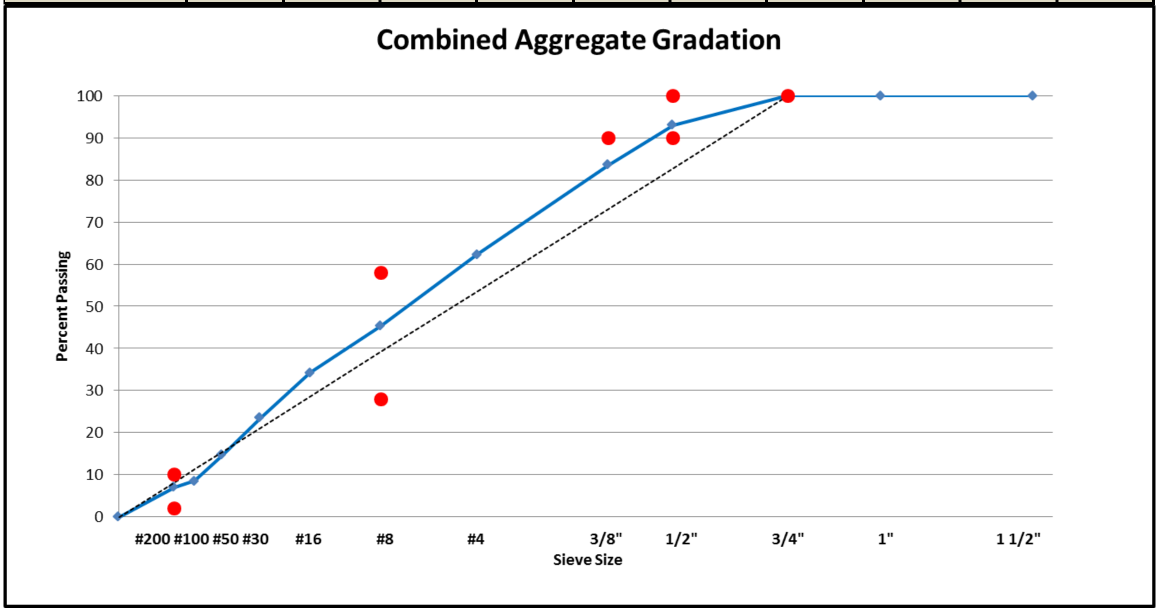

Figure F17: Combined Aggregate Gradation – 40% Optimum FRAP-B Mix Design

Combined Gradation at Optimum Binder Content										
Sieve Size (in.)	3/4"	1/2"	3/8"	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200
Maximum % Passing		100	90		58					10
Combined Gradation	100.0	93.5	84.7	63.0	45.9	34.9	24.5	15.6	9.8	8.1
Minimum % Passing	100	90			28					2

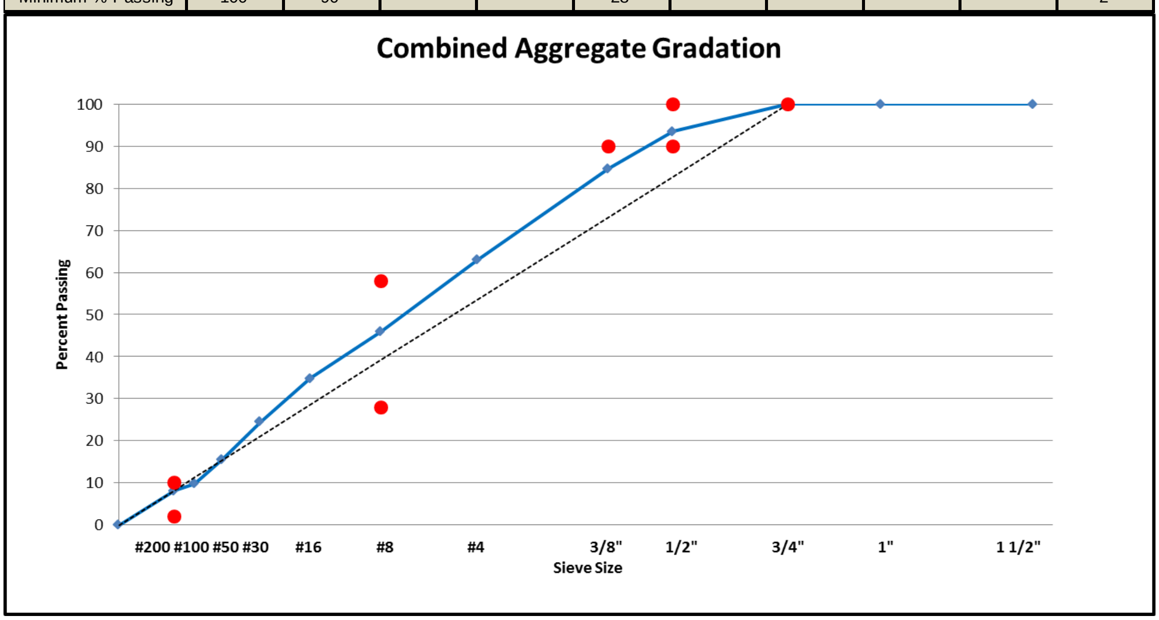

Figure F18: Combined Aggregate Gradation – 50% Optimum FRAP-B Mix Design

Combined Gradation at Optimum Binder Content										
Sieve Size (in.)	3/4"	1/2"	3/8"	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200
Maximum % Passing		100	90		58					10
Combined Gradation	100.0	90.3	80.0	60.4	44.2	33.4	22.7	13.6	6.9	5.7
Minimum % Passing	100	90			28					2

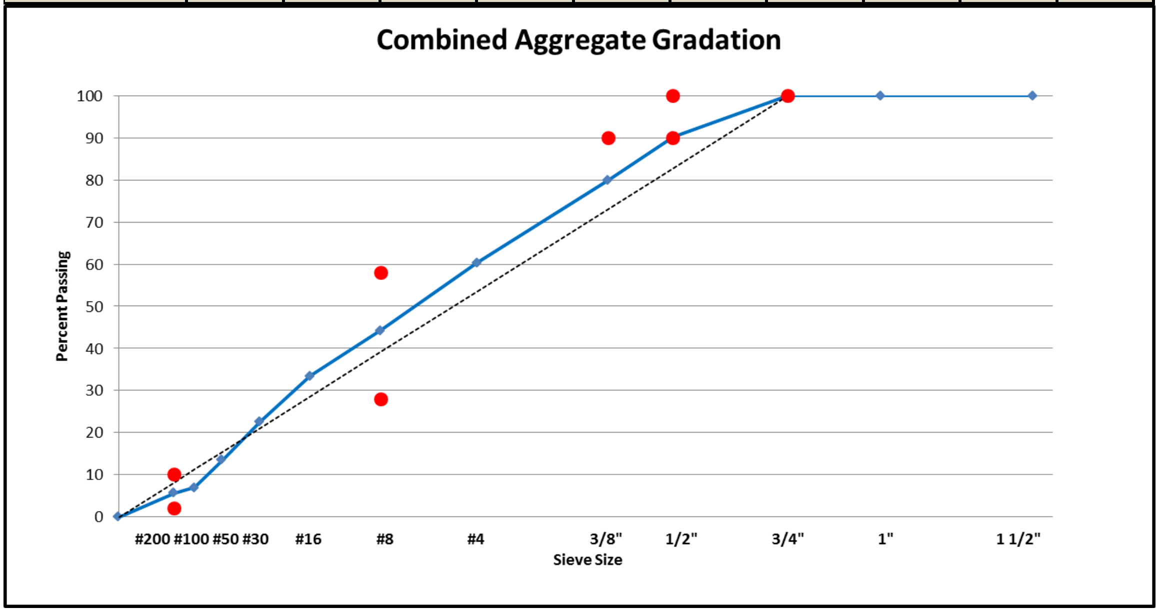

Figure F19: Combined Aggregate Gradation – 30% Traditional RAP-C Mix Design

Combined Gradation at Optimum Binder Content										
Sieve Size (in.)	3/4"	1/2"	3/8"	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200
Maximum % Passing		100	90		58					10
Combined Gradation	100.0	90.0	80.0	60.4	44.5	33.8	23.3	14.1	7.7	6.3
Minimum % Passing	100	90			28					2

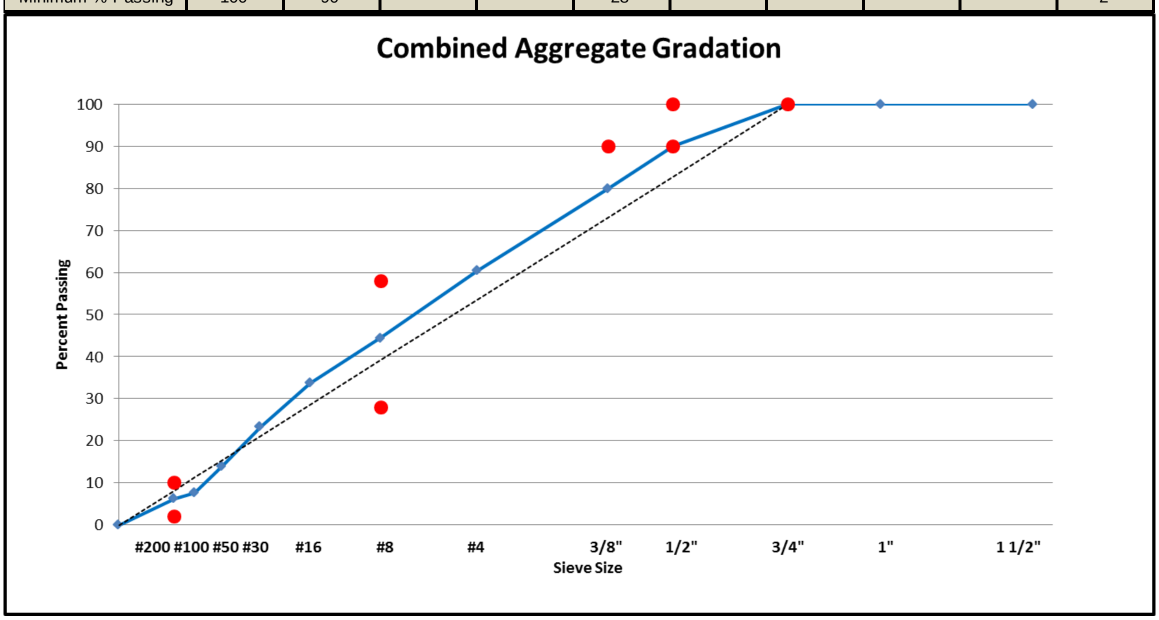

Figure F20: Combined Aggregate Gradation – 40% Traditional RAP-C Mix Design

Combined Gradation at Optimum Binder Content										
Sieve Size (in.)	**3/4"**	**1/2"**	**3/8"**	**No. 4**	**No. 8**	**No. 16**	**No. 30**	**No. 50**	**No. 100**	**No. 200**
Maximum % Passing		100	90		58					10
Combined Gradation	100.0	89.7	80.0	60.5	44.7	34.1	23.9	14.5	8.3	6.8
Minimum % Passing	100	90			28					2

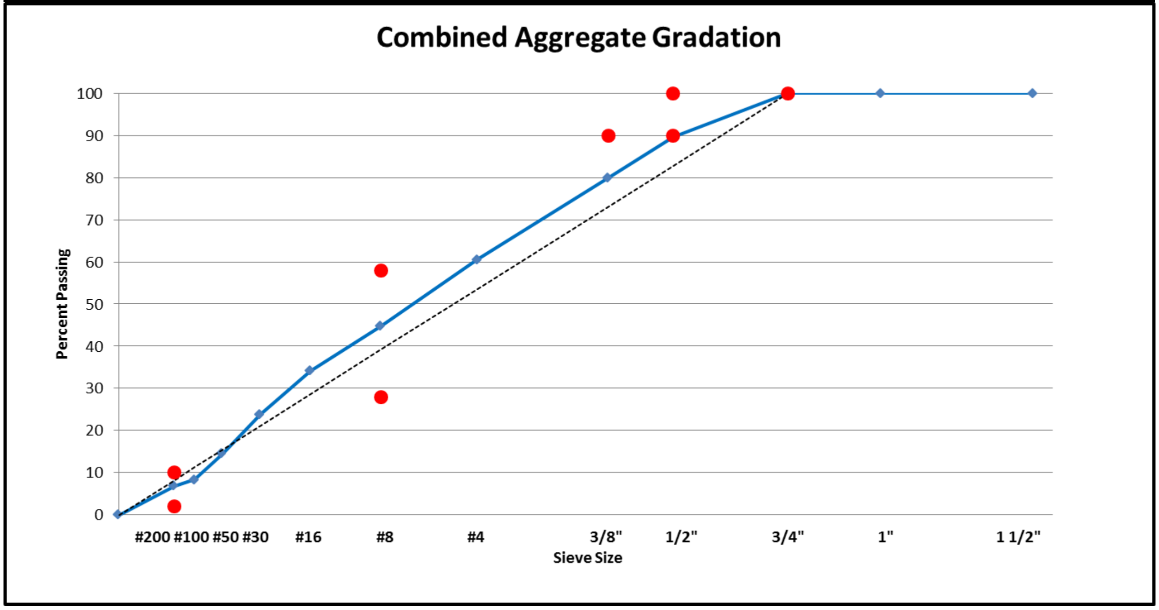

Figure F21: Combined Aggregate Gradation – 50% Traditional RAP-C Mix Design

Combined Gradation at Optimum Binder Content										
Sieve Size (in.)	**3/4"**	**1/2"**	**3/8"**	**No. 4**	**No. 8**	**No. 16**	**No. 30**	**No. 50**	**No. 100**	**No. 200**
Maximum % Passing		100	90		58					10
Combined Gradation	100.0	93.2	83.6	62.3	44.7	33.2	22.1	13.0	6.2	5.0
Minimum % Passing	100	90			28					2

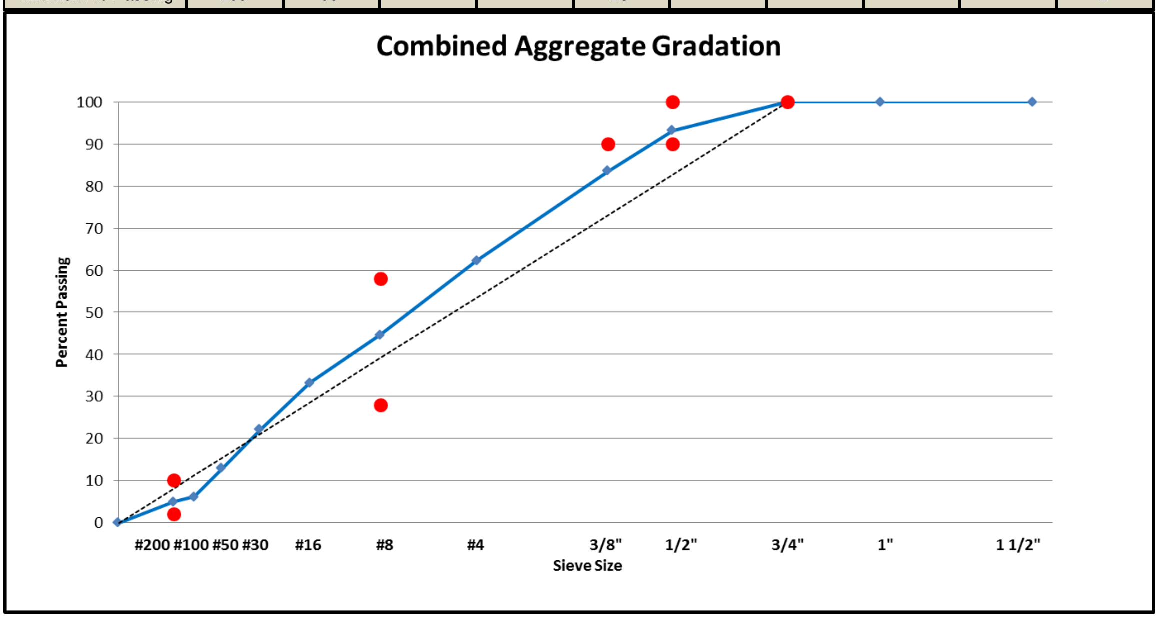

Figure F22: Combined Aggregate Gradation – 30% Fractionated RAP-C Mix Design

Combined Gradation at Optimum Binder Content										
Sieve Size (in.)	3/4"	1/2"	3/8"	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200
Maximum % Passing		100	90		58					10
Combined Gradation	100.0	93.6	84.6	62.9	45.0	33.5	22.6	13.3	6.7	5.5
Minimum % Passing	100	90			28					2

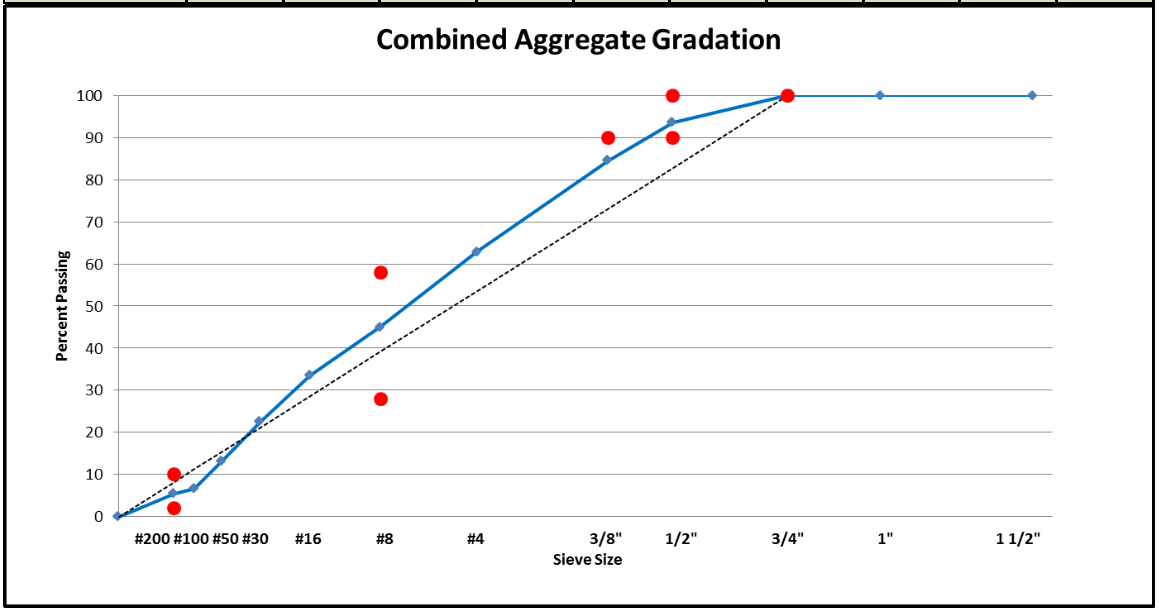

Figure F23: Combined Aggregate Gradation – 40% Fractionated RAP-C Mix Design

Combined Gradation at Optimum Binder Content										
Sieve Size (in.)	3/4"	1/2"	3/8"	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200
Maximum % Passing		100	90		58					10
Combined Gradation	100.0	94.2	85.7	63.6	45.4	33.9	23.1	13.6	7.3	5.9
Minimum % Passing	100	90			28					2

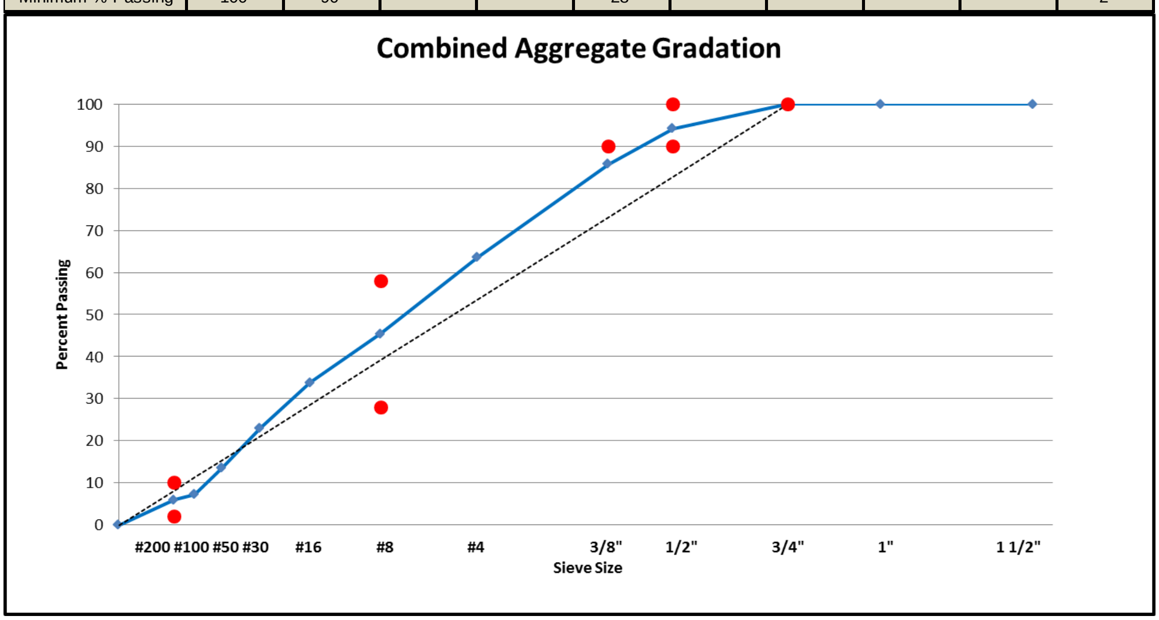

Figure F24: Combined Aggregate Gradation – 50% Fractionated RAP-C Mix Design

Combined Gradation at Optimum Binder Content										
Sieve Size (in.)	3/4"	1/2"	3/8"	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200
Maximum % Passing		100	90		58					10
Combined Gradation	100.0	91.6	81.0	58.7	41.8	31.7	21.5	12.6	5.9	4.8
Minimum % Passing	100	90			28					2

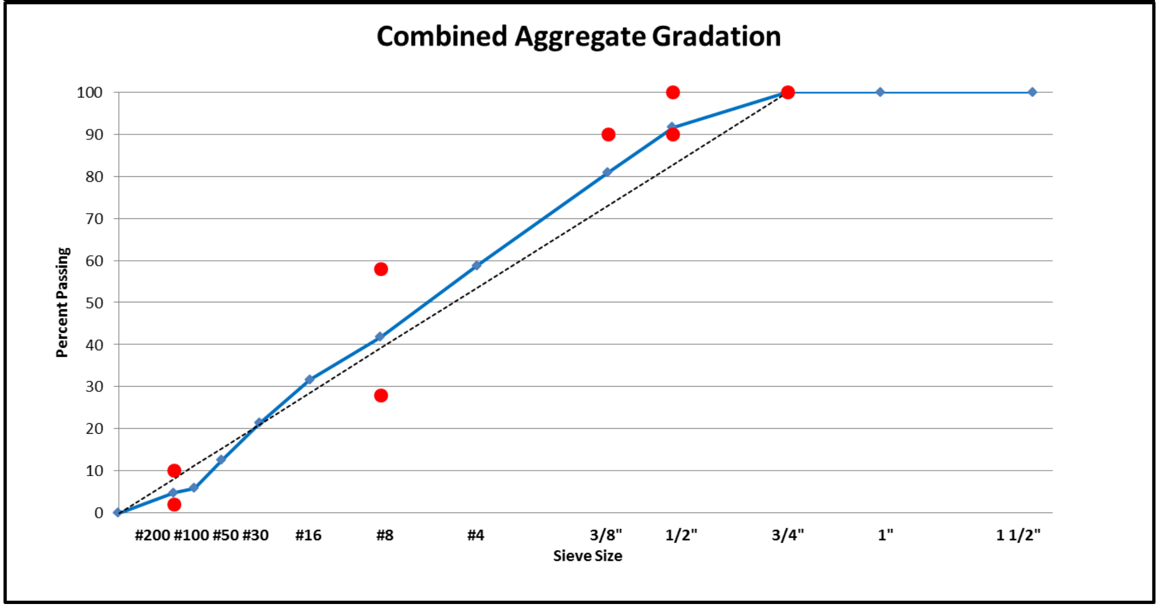

Figure F25: Combined Aggregate Gradation – 30% Optimum FRAP-C Mix Design

Combined Gradation at Optimum Binder Content										
Sieve Size (in.)	3/4"	1/2"	3/8"	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200
Maximum % Passing		100	90		58					10
Combined Gradation	100.0	91.6	81.3	58.4	41.4	31.6	21.8	12.9	6.3	5.1
Minimum % Passing	100	90			28					2

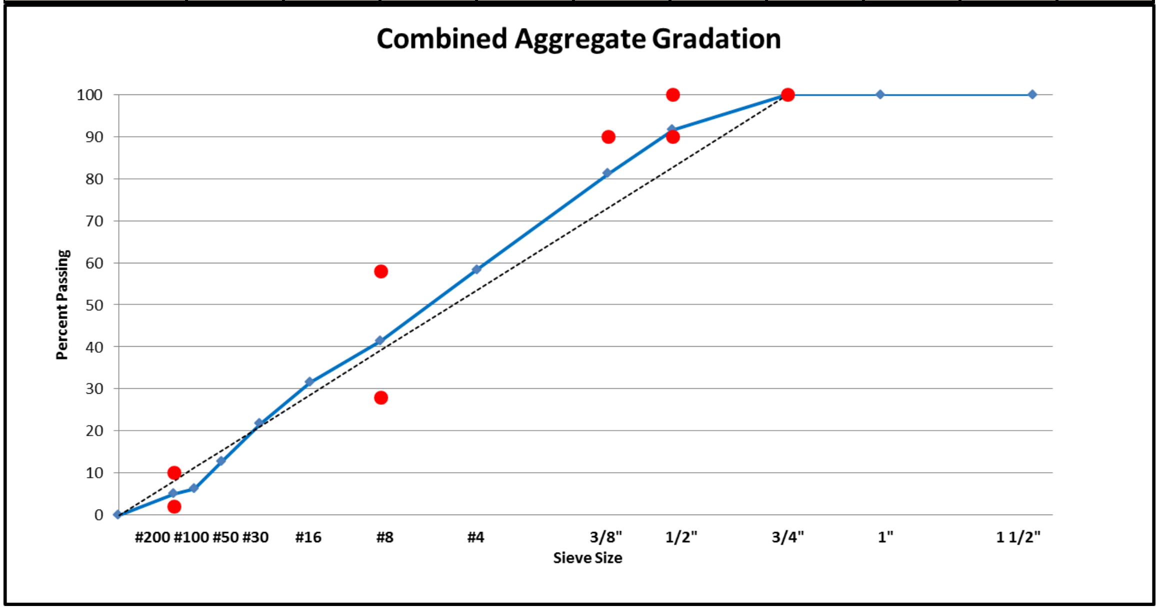

Figure F26: Combined Aggregate Gradation – 40% Optimum FRAP-C Mix Design

Combined Gradation at Optimum Binder Content										
Sieve Size (in.)	3/4"	1/2"	3/8"	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200
Maximum % Passing		100	90		58					10
Combined Gradation	100.0	91.7	81.6	57.9	40.9	31.4	22.2	13.1	6.9	5.6
Minimum % Passing	100	90			28					2

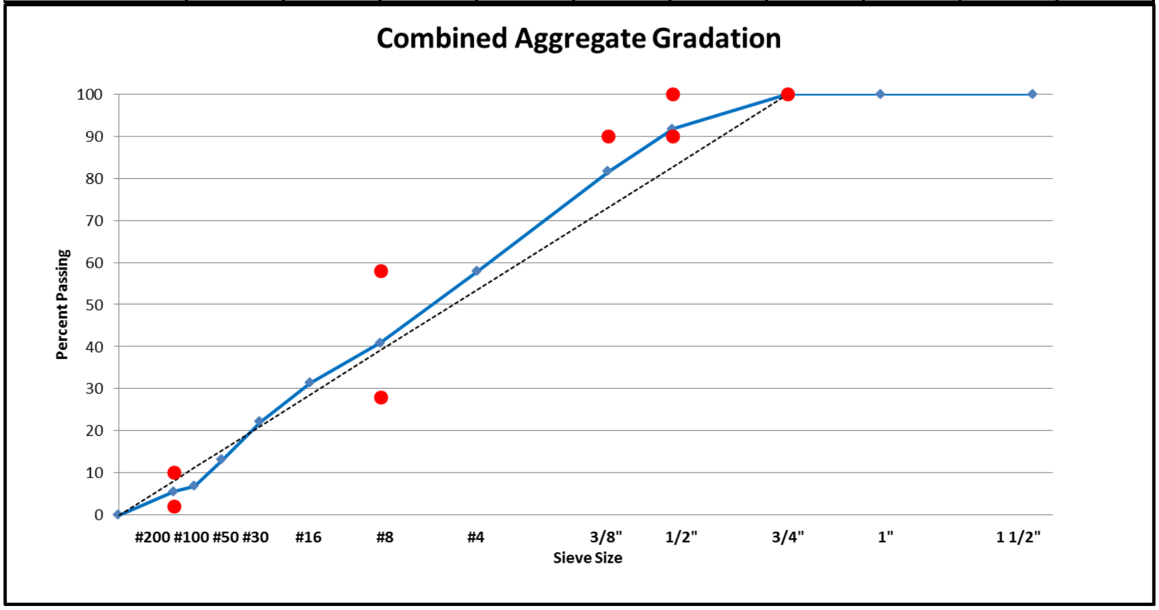

Figure F27: Combined Aggregate Gradation – 50% Optimum FRAP-C Mix Design

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