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Use of High-Volume Reclaimed Asphalt Pavement for Asphalt Pavement Rehabilitation Due to Increasing Highway Truck Traffic from Freight Transportation

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16. Abstract

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Abstract

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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, the National Asphalt Pavement Association (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 of 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 hot mix asphalt (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 analyze the material composition of different RAP stockpiles in order to better understand the source of the increased fine aggregate material contributed by the RAP. This material analysis allows for the design of improved fractionation methods that are effective at reducing the fine aggregate composition of the recovered aggregates from that RAP material. 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.

1.2 Benefits of the Study

Increasing the amount of RAP materials used in low-volume, surface course mixtures will substantially improve the long-term sustainability of the transportation network in the state of Iowa. The 300,000 equivalent single axle loads (ESAL) mixture designed in this study is applicable to the overwhelming majority of the local, city road network, as well as a significant portion of the rural, farm-to-market road networks. High-RAP content mix designs provide a great opportunity to decrease the cost of maintaining and resurfacing these networks to the local municipality and county agencies. The increased use of RAP materials significantly reduces the amount and cost of virgin aggregate and asphalt binder needed by the contractor to produce the asphalt mixture, thereby decreasing the amount of aggregate that must be quarried and the amount of oil that must be purchased. The percentage of savings in material cost is relatively equal to the amount of RAP material used in the mixture (i.e. 40% RAP usage results in 40% material cost savings of HMA mixture).

Chapter 2 High-RAP Usage in Practice

Reclaimed 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 fig. 2.1) and the material composition reanalyzed to account for material degradation (3).

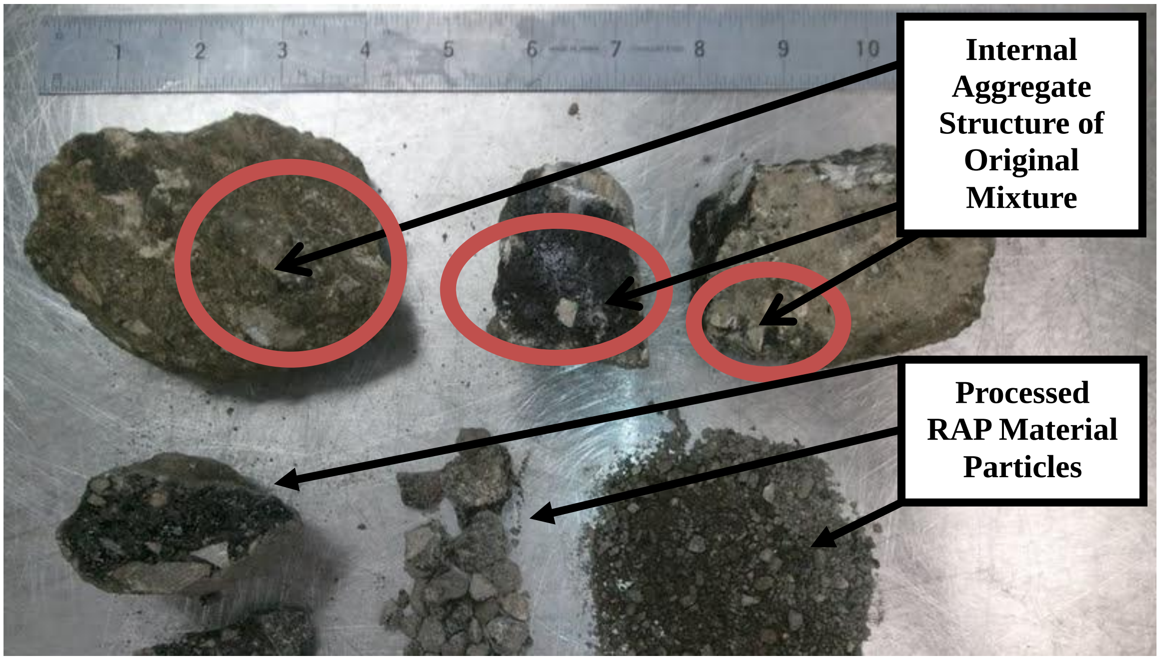

Figure 2.1 Recycled Asphalt Pavement Material Composition

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 DOTs 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.

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 2.1 Iowa DOT RAP Stockpile Categorization Criteria & Allowable Usage

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

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

Table 2.2 DOT Standards and Specifications for RAP Usage in Midwestern States

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

Table 2.2 (cont.) DOT Standards and Specifications for RAP Usage in Midwestern States

State	Maximum RAP % in Surface	Binder Grade Change	Volumetric Mix Design Criteria
Illinois(8)	▪ No specified max. for High & Low ESAL Mixes ▪ Engineer can adjust quantity based on test results ▪ Only ‘Homogeneous’ or ‘Conglomerate’ allowed	▪ RAP > 15% may require softer binder as determined by engineer ▪ RAP not allowed with polymer-modified binder	▪ % Pass #200 – Max 6% or 8% (High/Low ESAL) ▪ Dust/Binder – Max 1.0 @ design ▪ VMA – Min. 14.0% (1/2” mix); VFA – 65-75%
Indiana(9)	▪ Max 15% RAP (3% RAS) by weight for surface course mixtures with ESAL ≥ 3 million ▪ Max 25% RAP (5% RAS) 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% ▪ Film Thickness – Min. 8.5 µm
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%

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’s requirement for high-ESAL mixtures) (8; 9; 18). However, the increased processing required to achieve a smaller top size will increase the dust content (minus No. 200 material) of the RAP leading to 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$^{\text{TM}}$ recycling plant used by many local contractors (shown in fig. 2.2) utilizes a horizontal impact crusher to break apart the RAP materials that are fed into the system (see fig. 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.

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).

Figure 2.2 Recycled Asphalt Pavement Processing Equipment - Astec Prosizer™

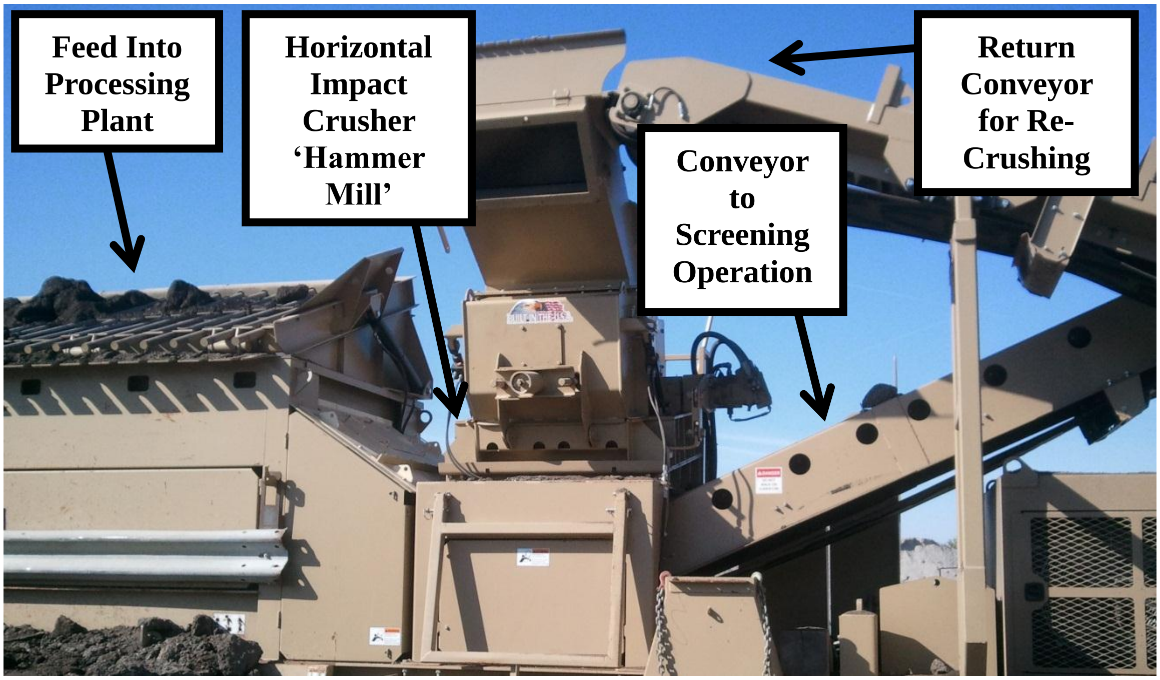

Figure 2.3 RAP Processing Equipment - Hammer Mill Crusher

2.3 High-RAP Mix Design Requirements

The maximum RAP percentage allowed in surface course mixtures is 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 ESALs.

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’s 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, voids in mineral aggregates, voids filled with asphalt); 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 states of Iowa and Minnesota have 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's 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's 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's 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 1990s 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 occurred during the removal and processing operations (3). The chemical binder extraction and aggregate testing results are attached in Appendix A.

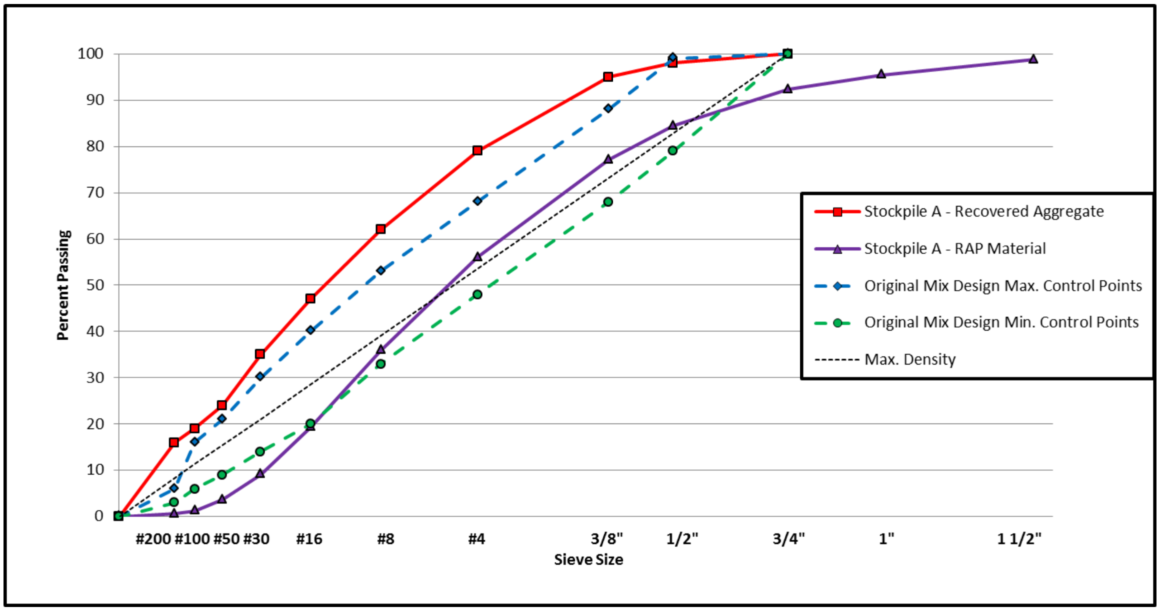

Figure 3.1 Recovered Aggregate & RAP Material Gradation Comparison - Stockpile A

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. RAP gradation analysis results are summarized in Appendix B. As expected, the RAP materials exhibited a coarser gradation because each RAP particle contains a range of aggregate sizes still held together by the asphalt binder; however, after binder extraction these particles are separated to show the extremely fine aggregate structure seen in figure 3.1. It was necessary to develop a relationship between the gradation of the stockpiled RAP materials and that of the recovered aggregates. The Stockpile A RAP material was separated by sieve sizes ranging from 1½" down to No. 200 and an ignition-oven binder burn-off test was conducted on the sample of each RAP material size. Next, a gradation analysis was done on the recovered aggregates from each RAP-size sample.

Table 3.1 shows a summary of the material composition of each RAP particle size (i.e. recovered aggregate composition and binder content) as well as the distribution of those RAP material sizes in the overall stockpile. Figure 3.2 shows that the recovered aggregate gradation after chemical binder extraction (as seen in fig. 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 considered 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 largest 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 contribute 41% of the total dust content due to the fact that these materials contain a higher portion of minus No. 200 material and make up a significant portion of the RAP stockpile.

The RAP-size categories established for Stockpile A show a successfully developed relationship between the size of the RAP particle and the proportion of fine aggregate contained in that material. Fractionation of the 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. The Fine RAP category represents over half of the total stockpile, where the No. 16 and No. 30 RAP sizes have the largest asphalt contents 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.

Table 3.1 Sieve-Size-Separated RAP Material Composition Analysis - Stockpile A

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

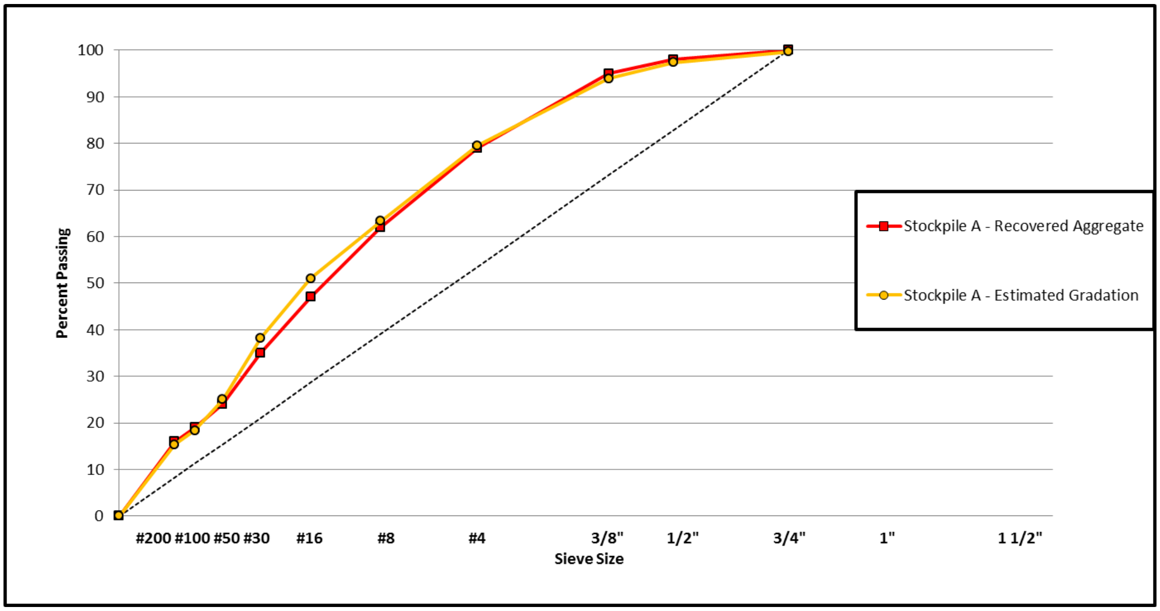

Figure 3.2 Recovered Aggregate Gradation vs. Estimated Gradation - Stockpile A

3.2 Composition Analysis of Certified RAP from Airport

The second RAP stockpile used in the study (referred to herein as Stockpile B) is composed primarily of millings from the same eastern Iowa airport runway as the Classified RAP material of Stockpile A. However, while the material was stockpiled at the contractor's facility there were small amounts of another RAP material added to the stockpile. As a result, the stockpile underwent further quality control testing to become 'Certified RAP' (see Appendix A for DOT extraction testing report). Figure 3.3 shows the recovered aggregate gradation for the Certified RAP of Stockpile B, the original airport runway mix design gradation range and the recovered aggregate gradation for the Stockpile A Classified RAP material (makes up an overwhelming majority of Stockpile 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 a reduced amount of fine aggregate material, as is evident by the downward shift of the gradation curve with respect to Stockpile A. The gradation curve was 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.

The results of the composition analysis for the Stockpile B Certified RAP materials are shown 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.

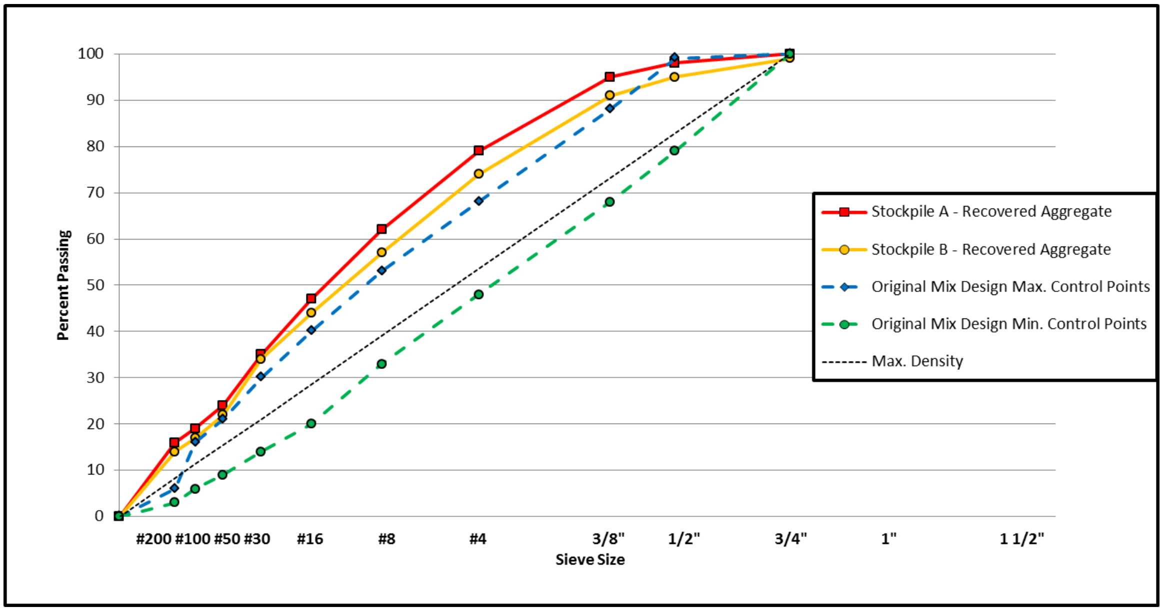

Figure 3.3 Recovered Aggregate Gradation vs. Original Mix Design - Stockpile A & B

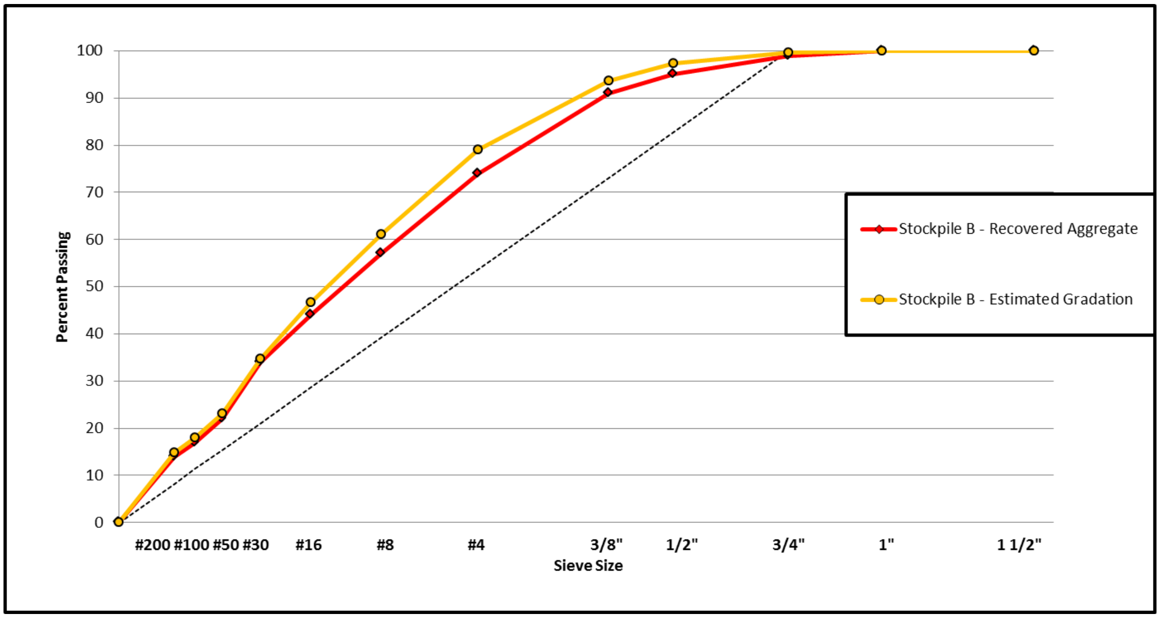

Figure 3.4 Recovered Aggregate Gradation vs. Estimated Gradation - Stockpile B

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

These RAP materials continue to show that the recovered aggregate composition of the very fine material sizes from each Coarse RAP material is much lower than the Fine RAP material sizes. 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, the No.16 and No.30 size RAP materials have the two largest asphalt contents of Stockpile B; and the No. 8 and No. 16 size RAP materials are again the main sources of the total dust content.

Comparing tables 3.1 and 3.2 shows that the distribution of RAP sizes within Stockpile A and B is different, even though the RAP materials are from the same runway millings source. Stockpile B contains a lower percentage of Fine RAP material (50% compared to 56% of Stockpile A) and also has a coarser recovered aggregate gradation than Stockpile A (fig. 3.3). Therefore, decreasing the amount of Fine RAP material in the stockpile results in the recovered aggregate gradation being controlled more by the aggregate distribution of the larger Coarse RAP that have lower dust contents.

The material composition of the larger RAP pieces more closely reflect the properties of the original mix design because they have not been as heavily 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 gradation range for the original runway mix design. The recovered aggregate gradations of the Coarse RAP materials is much more representative of the original mix design gradation than the entire RAP stockpile. Increasing the amount of Coarse RAP materials added to the HMA mixture will result in a reduction of fine aggregate contributed by the RAP.

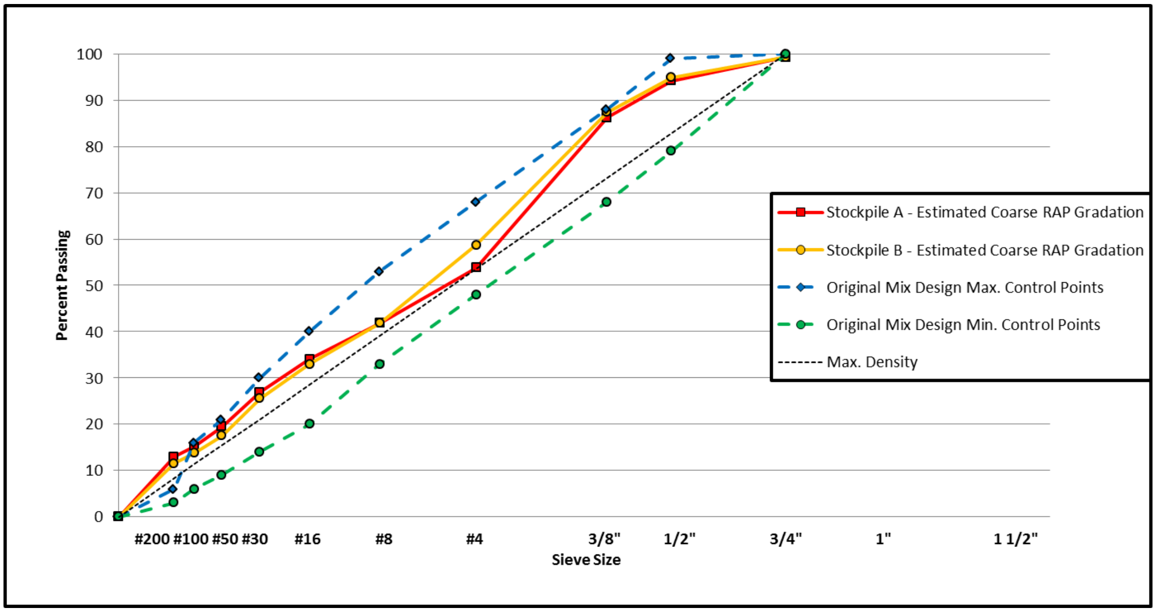

Figure 3.5 Estimated Coarse RAP Gradation vs. Original Mix Design - Stockpile A & B

3.3 Composition Analysis of Certified RAP from Unknown Source

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) (see Appendix A for DOT extraction testing report). Figure 3.6 shows the recovered aggregate gradation for the Certified RAP of Stockpile C compared to Stockpiles A and B. The Certified RAP material of Stockpile C showed the best recovered aggregate gradation with 10% dust content. The significant downward shift in the gradation curve means that there is much less fine aggregate material contained in this RAP stockpile.

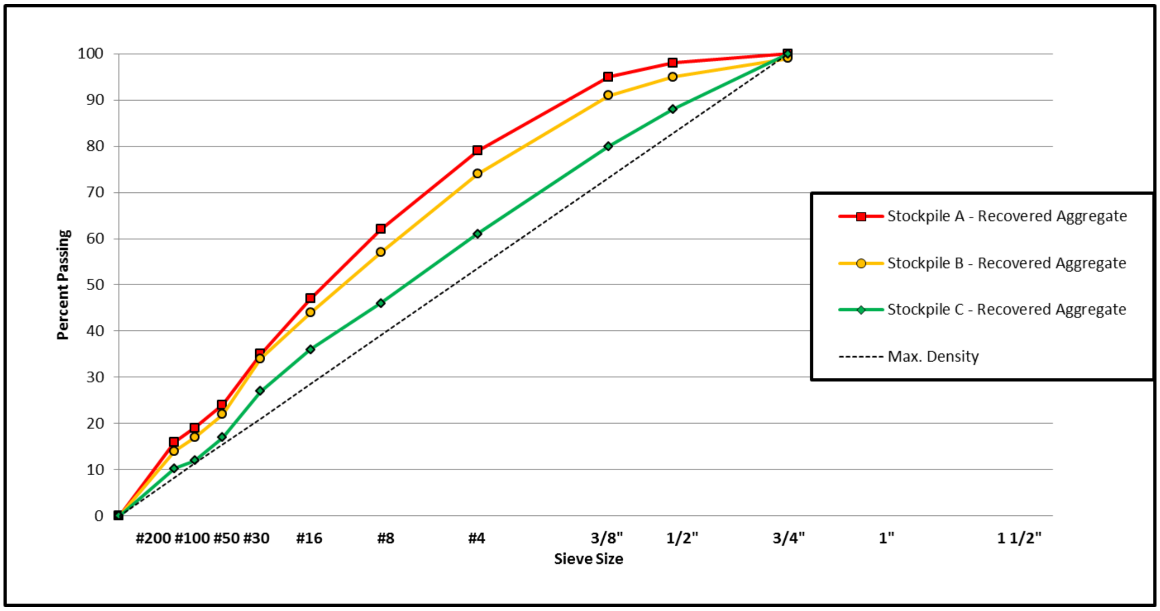

Figure 3.6 Recovered Aggregate Gradation Comparison - Stockpile A, B and C

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 Stockpiles A and B remains applicable for differentiation between the size of RAP material 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 Stockpiles 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 the 'Sieve-Size-Separated RAP Material Composition Analysis' that effectively showed that each RAP stockpile used in this study can be described in terms of its fine aggregate composition by the proportions of Coarse and Fine RAP material (split at the No. 4 sieve size) contained in that stockpile.

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

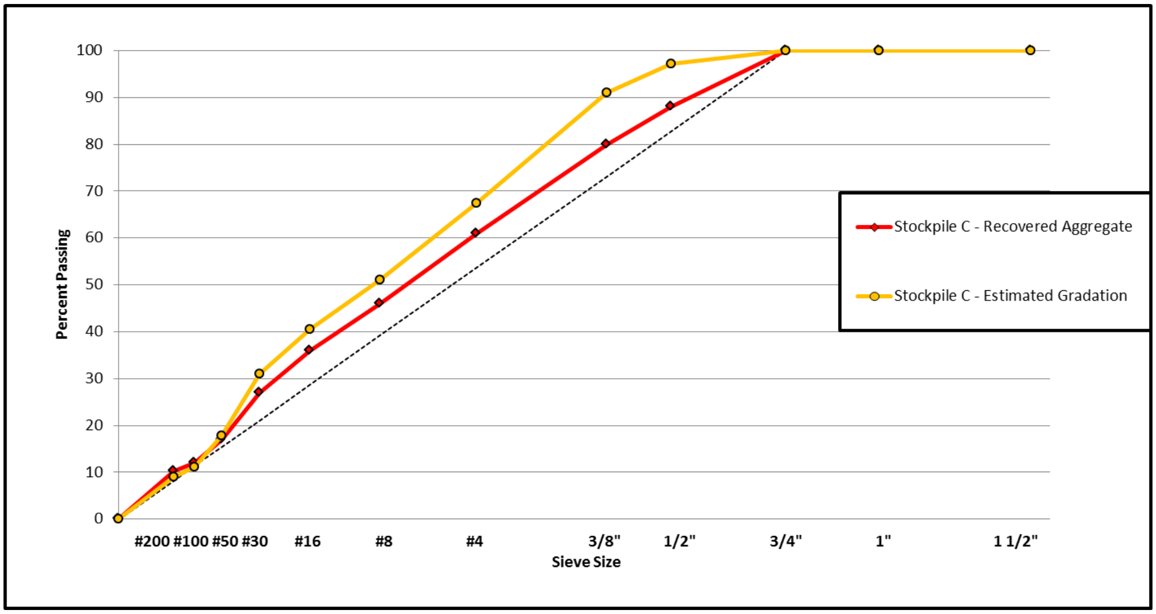

Figure 3.7 Recovered Aggregate Gradation vs. Estimated Gradation - Stockpile C

The Fine RAP materials make up only 35% of Stockpile C (compared to 56% of Stockpile A and 50% of Stockpile B) and the dust content is significantly lower than the other RAP materials. Figure 3.8 shows that the normalized composite gradation of the Coarse RAP from Stockpile C is very representative of a ½" mix size gradation because the recovered aggregate gradation is dominated by the properties of the Coarse RAP materials (65% of the stockpile). The high amount of Coarse RAP material in Stockpile C also suggests that this material may not have been processed as extensively.

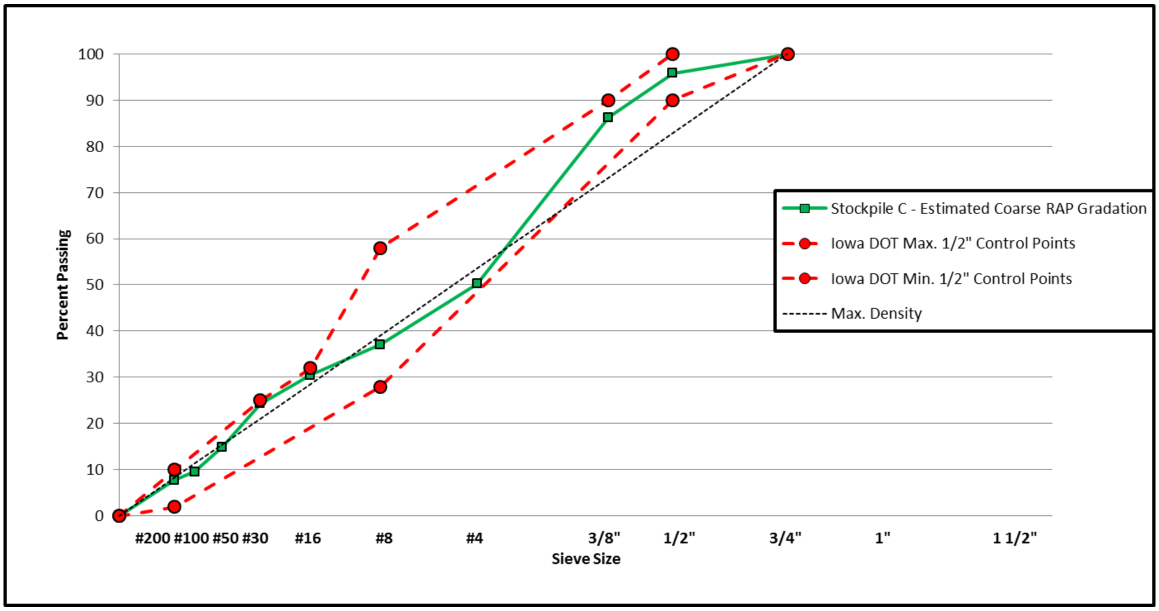

Figure 3.8 Estimated Coarse RAP Gradation vs. ½” Mix Size - Stockpile C

3.4 Summary of RAP Material Composition Analysis

The following three different RAP material stockpiles were analyzed:

1. Stockpile A – Classified RAP material solely from airport runway millings
2. Stockpile B – Certified RAP material primarily from airport runway millings
3. Stockpile C – Certified RAP from unknown combination of pavement millings

The RAP Material Composition Analysis was conducted on all three stockpiles. The Coarse RAP category was defined as RAP materials retained on a No. 4 sieve. The recovered fine aggregate distribution from each Coarse RAP size was very consistent and the dust content was lower than the overall stockpile. The Fine RAP category was defined as RAP materials that pass through a No. 4 sieve. The recovered aggregate distribution from each Fine RAP size was very highly variable and the dust contents were significantly higher than the Coarse RAP material. The Fine RAP materials exhibited higher recovered asphalt binder content.

The Coarse and Fine RAP aggregate distributions of the Stockpile A and B materials showed consistent patterns, as was expected for materials from the same source; therefore these stockpiles were 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. Stockpile B was 50% Fine RAP material (smaller than No. 4 sieve) resulting in a total dust content of 14%, while Stockpile A was 56% Fine RAP material resulting in a total dust content of 16%. Stockpile C contained a much higher percentage of Coarse RAP material (65% of the stockpile) and a much lower dust content of 10%.

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

The amount of dust created during the processing of the RAP depends on both the crushing system and the top size selected (18). Certain crushing operations will create excessive amounts of dust out of the RAP materials. Hammer mill impact crushers, like the one included on the Astec ProSizer^{TM}, 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 and then sampled and categorized separately. This change for the RAP processing operation would result in RAP stockpiles containing significantly higher proportions of Coarse RAP material. Also, an increase in the top size requirement could further improve the properties of these RAP stockpiles.

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 caused a 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. The purpose of RAP fractionation for this research was to create new stockpiles with reduced fine aggregate composition to mitigate the impact of this material on the high-RAP mix design.

For 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 were 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. The impacts of the Fine RAP material's reduction/removal should be addressed for these methods to be used in practice. First, the fractionation method should allow for the highest 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. These considerations led to the following two methods:

1. 'Fractionated RAP' method
2. 'Optimum FRAP' method

4.1 Analysis of 'Fractionated RAP' Method

The first fractionation method directly targets the Fine RAP materials by physically removing the smallest of these RAP sizes from the stockpile during the processing operation. The Astec Prosizer^{TM} processing equipment with a high-frequency vibration screening mechanism can be used to effectively separate the RAP materials 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 fig. 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.

Initial attempts with this fractionation method set the removal threshold at the No. 4 RAP size (i.e. all RAP material passing No. 4 sieve was removed from the original stockpile), which removed the entire Fine RAP category. When this threshold was applied to the Stockpile A Classified RAP a very significant amount of material was being removed from the original stockpile (56% passed No. 4 sieve). This was considered unacceptable for maintaining the amount of usable material; therefore, smaller RAP size removal thresholds were explored.

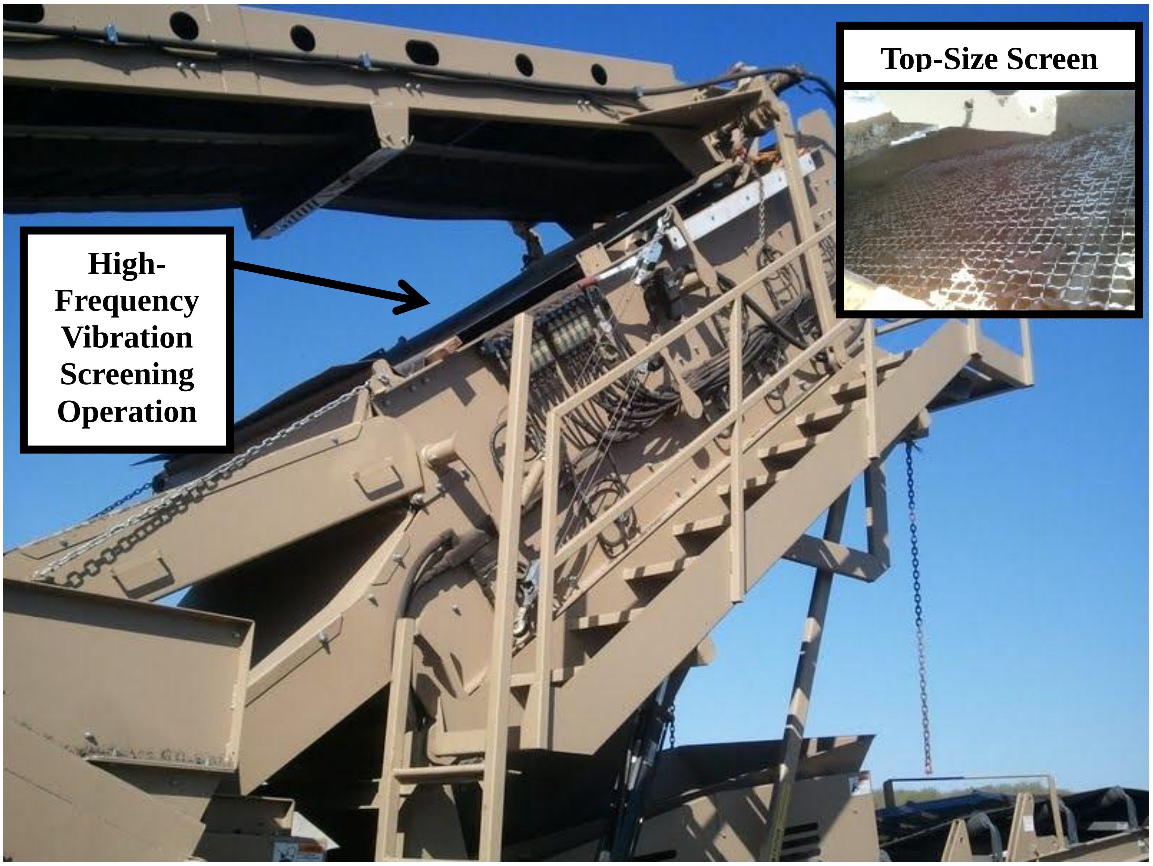

Figure 4.1 High-Frequency, Stacked-Screening Operation for Fine RAP Removal

Removal of all RAP materials smaller than the No. 16 sieve removed 19% from the stockpile; however, the No. 30-size RAP material (10% of stockpile's material) contains the second-highest asphalt content of Stockpile A. 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.

In order to determine the effectiveness of fine aggregate reduction, an ignition-oven binder burn-off was conducted on a sample from the lab-produced, Fractionated RAP 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 by a 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.

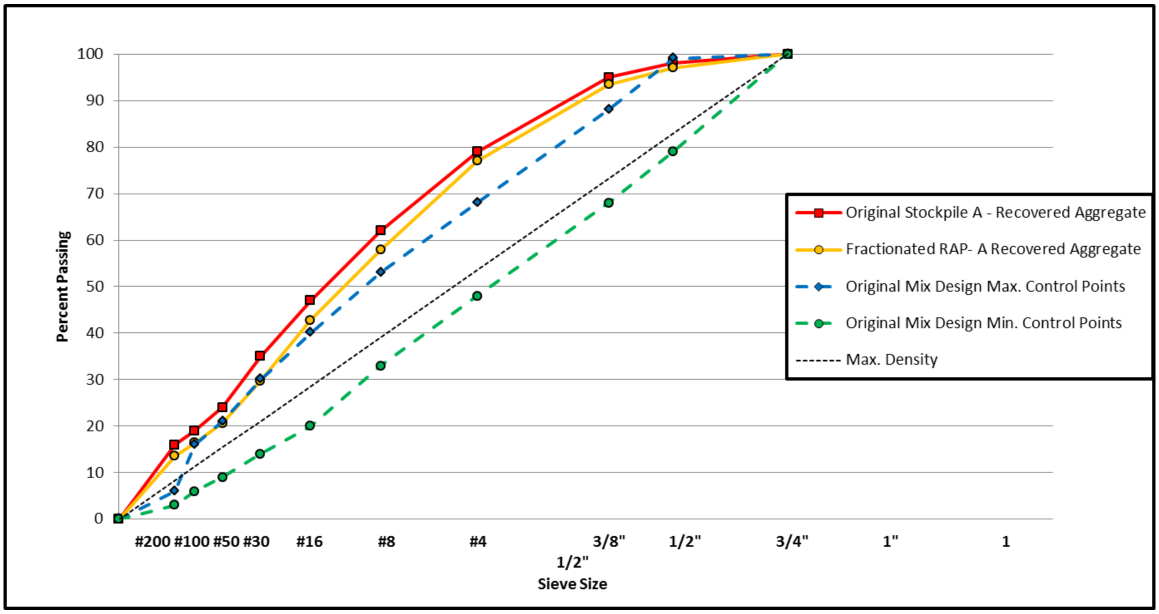

Figure 4.2 Gradation Improvement of 'Fractionated RAP' Method - Stockpile A

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 Stockpiles B and C for comparing the impact that the ‘Fractionated RAP’ method would have 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) observed from 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)**				**% of Stockpile**
	No. 50	**No. 100**	**No. 200**	**Pan**	
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)**				**% of Stockpile**
	No. 50	**No. 100**	**No. 200**	**Pan**	
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 Fractionated RAP-B and Fractionated RAP-C stockpiles contained less fine aggregates and dust contents 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 exhibited slight increases in the amount of No. 50, No. 100 and No. 200 aggregate materials, but the very large dust content reduction was still achieved. 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, 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 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 meeting the specified mix design criteria. The effect of the Fractionated RAP method 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 Analysis of 'Optimum FRAP' Method

The second fractionation method followed more traditional practices by splitting the original RAP material into two separate stockpiles during processing (see fig. 4.3). 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. This method more effectively targeted the No. 8 and No. 16 RAP sizes which were the main contributers to the overall dust content.

Figure 4.3 RAP Fractionation into Coarse FRAP (right) and Fine FRAP (left)

An ignition-oven binder burn-off was conducted on a sample from the lab-produced, Coarse and Fine FRAP stockpiles to determine the asphalt content of each 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 and Fine FRAP materials from Stockpile A, B and C. The Fine RAP category has a significantly higher proportion of very fine aggregate than the Coarse RAP materials. The dust contents of all the Coarse FRAP materials are much lower than their respective original stockpile, and the Coarse FRAP-A and Coarse FRAP-C materials meet the maximum gradation control point of 10% passing the No. 200 screen.

Table 4.4 Recovered Aggregate Composition of Coarse and Fine FRAP Stockpiles

RAP Stockpile	Recovered Aggregate Composition – (% Retained)										% of Stockpile
	1/2”	**3/8”**	**No. 4**	**No. 8**	**No. 16**	**No. 30**	**No. 50**	**No. 100**	**No. 200**	**Pan**	
Coarse FRAP-A	5.5	8.5	32.6	13.9	9.0	7.6	8.1	3.6	2.1	9.1	**44.0%**
Fine FRAP-A	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%**

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 a very similar pattern to the estimated Coarse RAP composite gradation. A summary of the testing results from the ignition-oven binder burn-off and recovered aggregate gradation analyses are summarized in Appendix C.

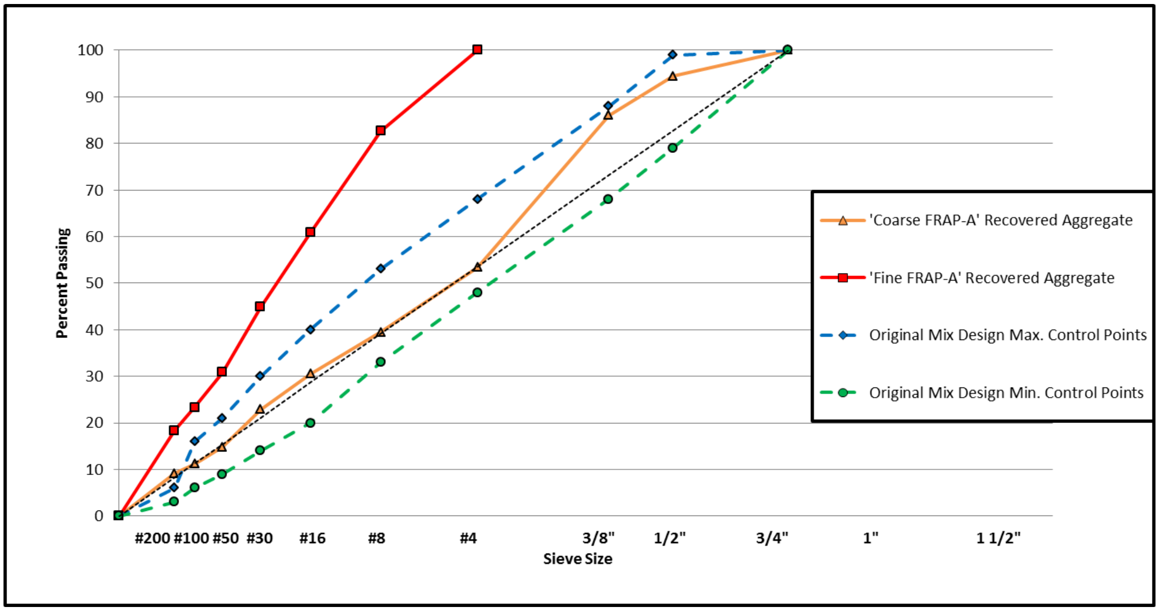

Figure 4.4 Gradation Comparison of Coarse FRAP and Fine FRAP - Stockpile A

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

4.3 Summary of Fractionation Methods

The purpose of these RAP fractionation methods was to create new stockpiles with reduced fine aggregate composition. The Fine RAP materials (RAP material smaller than No. 4 sieve size) were targeted for removal due to their increased composition of very fine aggregate material.

The 'Fractionated RAP' method removes all of RAP material smaller than the No. 30 sieve size from the stockpile during the processing operation. 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). During the mix design process the percentages of ‘Coarse FRAP’ material used in the total amount of RAP added to the mixture was higher than the amount naturally present in the original stockpile. 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 mixes.

Chapter 5 High-RAP Content Mix Design Procedure

The Iowa DOT's "Method of Design of Hot Mix Asphalt Mixes" (7) procedure describes the entire process of aggregate and binder selection, material preparation and HMA mixture batching, curing and testing. Typically the SHADES spreadsheet 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 from Materials IM 501 (see Appendix E) to account for the binder and aggregate contributed by the RAP (19). The problem with using the SHADES program for this research was that the percent of RAP material input into the system was taken as the percentage of dry material weight of the total mixture ($\%RAP_{weight}$), rather than the percentage of virgin binder replacement ($\%RAP_{binder}$). The program then calculates the necessary amount of virgin binder to add to the mixture ($AC_{(add)}$), in addition to the binder contributed by the asphalt content of the RAP material ($P_{b(RAP)}$), to achieve the target asphalt content of the mixture ($AC_{(total)}$) as shown below:

$$AC_{(add)} = \frac{\left(AC_{(total)} * 100\right) - \left(\%RAP_{weight} * P_{b(RAP)}\right)}{100 - \left(\%RAP_{weight} * P_{b(RAP)} * 0.01\right)} \tag{5.1}$$

Example:

$$= \frac{(5.50 * 100) - (50.0 * 5.00)}{100 - (50.0 * 5.00 * 0.01)} = 3.08\%\ ADD\ AC$$

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

5.1 Mix Design Modification for Binder Replacement Method

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

$$\%RAP_{weight} = \frac{\left(AC_{(total)} - AC_{(add)}\right)}{\left(P_{b(RAP)} * 0.01\right) - \left(AC_{(add)} * P_{b(RAP)} * 0.0001\right)} \tag{5.2}$$

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

$$\begin{gathered} AC_{(total)} - AC_{(add)} = AC_{(RAP)} = AC_{(total)} * \%RAP_{binder} * 0.01 \\ AC_{(add)} = AC_{(total)} * (1 - \%RAP_{binder} * 0.01) \end{gathered} \tag{5.3}$$

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

$$\%RAP_{weight} = \frac{\left(AC_{(total)} * \%RAP_{binder}\right)}{\left(P_{b(RAP)}\right) - \left(P_{b(RAP)} * AC_{(total)} * (1 - \%RAP_{binder} * 0.01) * 0.01\right)} \tag{5.4}$$

Example:

$$= \frac{(5.50 * 50)}{(5.00) - \left[5.00 * 5.50 * \left(1 - (50 * 0.01)\right) * 0.01\right]} = 56.6\% \; RAP_{weight}$$

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

This equation and other formulae in IM 501 (Appendix E) can be used to determine the weights of virgin and RAP material to be included in high-RAP trial mixtures during the mix design process when the RAP % by binder replacement method is desired.

5.2 Leftover Material from RAP Stockpile Fractionation

For the 'Optimum FRAP' method, the amount of material added from the 'Coarse FRAP' stockpile was increased (as a proportion of the total RAP weight added to the mixture) to improve the combined gradation. The criteria for this new proportion selection 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 No. 200)
2. The combined aggregate surface area and fine aggregate composition should be less than those of the original and 'Fractionated RAP' stockpile

The modified mix design spreadsheet program was used to determine these expected gradation properties for increasing the proportion of Coarse FRAP material in the total RAP weight added to the mixture. To achieve the desired combined gradation properties, the Coarse FRAP proportion for the Stockpile A material was increased to 75% of the total RAP weight added to the mixture for the 'Optimum FRAP-A' blend (the original stockpile was composed of 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 calculates the expected amount of leftover material (*%RAP*$_{unused}$), as a percentage of the original stockpile, based on the original proportion of Coarse and Fine RAP material and the new, increased Coarse FRAP percentage:

$$\%\,RAP_{unused} = \frac{(\%\,Coarse_{new} - \%\,Coarse_{orig}) * \left(1 + \frac{\%\,Fine_{orig}}{\%\,Coarse_{orig}}\right)}{1 + (\%\,Coarse_{new} - \%\,Coarse_{orig}) * \left(1 + \frac{\%\,Fine_{orig}}{\%\,Coarse_{orig}}\right)} * 100 \tag{5.5}$$

Example:

$$= \frac{(0.75 - 0.44) * \big(1 + (0.56/0.44)\big)}{1 + (0.75 - 0.44) * \big(1 + (0.56/0.44)\big)} * 100 = 41.3\%\ RAP_{unused}$$

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

In contrast to the Fractionated RAP method, the unused percentages are not removed from the new stockpile; but rather, the Fine FRAP stockpile materials are used less for the Optimum FRAP blend resulting in a build-up of this material. The analyses of the calculation of build-up material from each stockpile are summarized in Appendix E.

Chapter 6 Summary and Conclusions

While reclaimed asphalt pavement (RAP) materials are widely used around the country, their usage has been limited due to a difficulty in meeting the required volumetric properties for high-RAP content mixtures. The larger pieces of RAP exhibit a material composition very similar to the original mix design; however, these materials must be processed further to allow for sufficient blending with virgin materials in the asphalt plant. The current state of practice of RAP processing, where the original pavement is broken down with a crushing operation, produces an aggregate structure that is no longer representative of the original pavement's mix design.

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. In order 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 change the gradations of RAP stockpiles before they are included in the mixture to help produce high-RAP content mix designs that meet all specified volumetric criteria.

The analysis of three different RAP stockpiles used in this study revealed that each processed RAP material could be separated into two categories: Coarse RAP and Fine RAP, 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 (retained on the No. 4 sieve size) contained lower amounts of fine aggregate material and dust content than the Fine RAP materials (passing the No. 4 sieve 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 added to the mixture, were effective in reducing the fine aggregate composition of the new stockpile.

This research project successfully completed the following tasks:

1. Performed a detailed analysis of the composition of the stockpiled RAP materials
2. Designed two effective fractionation methods for RAP materials to reduce fine aggregate composition
3. Developed a modified mix design procedure to account for binder replacement of RAP materials

6.1 Findings

Findings from the research project are summarized below:

1. Coarse RAP materials (retained on the No. 4 sieve) contain lower proportions of fine aggregate material (dust content)
2. Their material composition is much more representative of the original pavement's mix design
3. Increased presence of Coarse RAP material in the original stockpile resulted in lower fine aggregate composition of the recovered aggregate
4. Fractionation methods designed to increase the amount of Coarse RAP material in the new stockpile are effective in reducing the fine aggregate composition of the RAP material and decreasing the aggregate surface area of the HMA mixture

6.2 Recommendations

To increase the amount of RAP materials in the HMA mixtures, the following recommendations are proposed:

1. The top-size requirement for stockpiled RAP materials should be increased in order to reduce the amount of processing done to the pavement millings and allow for the RAP materials to better maintain the gradation 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 should be divided into Coarse RAP and Fine RAP categories by splitting at the No. 4 sieve size to allow for increased use of Coarse RAP materials
4. A detailed gradation analysis of the stockpiled RAP materials should be performed to identify the amount of fine RAP material in the stockpile and the amount expected to be discarded after application of fractionation methods

6.3 Future Research

A further characterization of high-RAP content HMA surface mixtures should be performed by measuring the dynamic modulus, flow numbers, beam fatigue and semi-circular bending. A field-constructible mix design should be developed using local, batch-mixed aggregates combined with high-RAP material milled from Interstate-80 in eastern Iowa. These materials should be used to construct field test sections with up to 50% RAP by binder replacement using the 300,000 ESAL ½” surface mix design.

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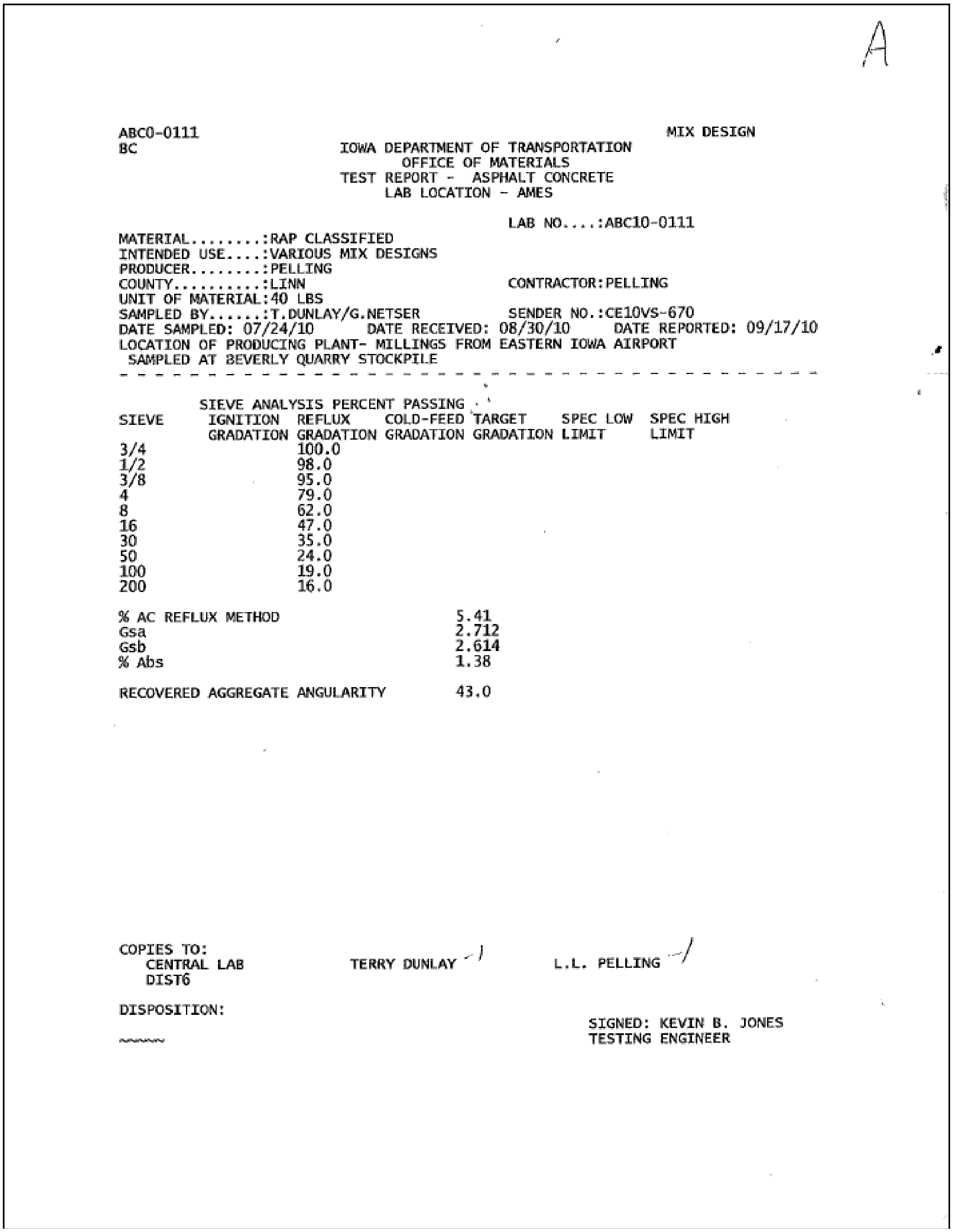
Appendix A Iowa DOT Stockpile Categorization Reports



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				

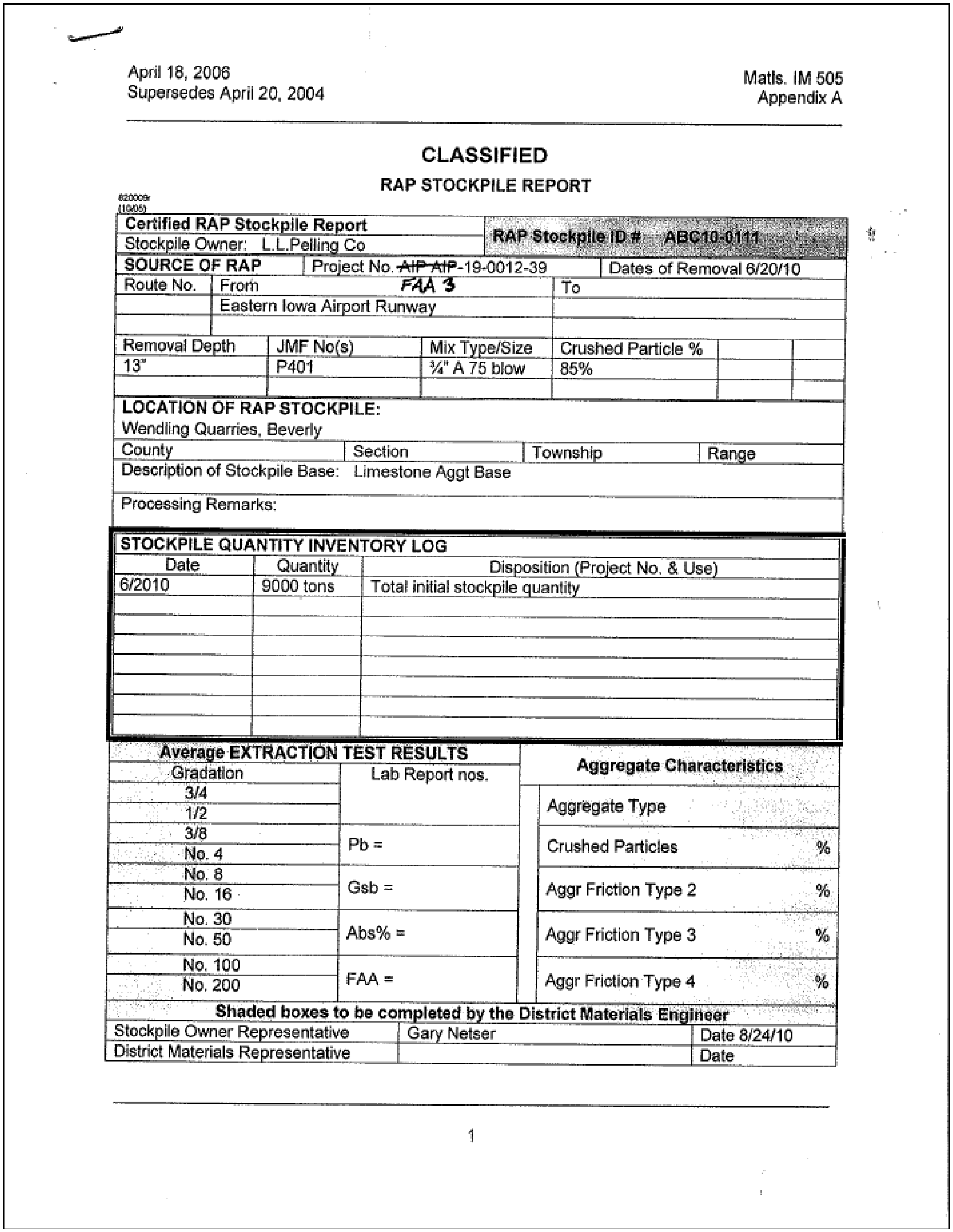
% AC REFLUX METHOD	5.41
Gsa	2.712
Gsb	2.614
% Abs	1.38
RECOVERED AGGREGATE ANGULARITY	43.0

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

DISPOSITION:

SIGNED: KEVIN B. JONES
TESTING ENGINEER

Figure A.1 Iowa DOT Binder Extraction Testing Report – Stockpile A



April 18, 2006
Supersedes April 20, 2004

Matls. IM 505
Appendix A

CLASSIFIED

RAP STOCKPILE REPORT

820009r
(10/05)

Certified RAP Stockpile Report Stockpile Owner: L.L.Pelling Co	**RAP Stockpile ID # ABC10-0111**

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.
3/4	
1/2	
3/8	
No. 4	Pb =
No. 8	
No. 16	Gsb =
No. 30	
No. 50	Abs% =
No. 100	
No. 200	FAA =

Aggregate Characteristics

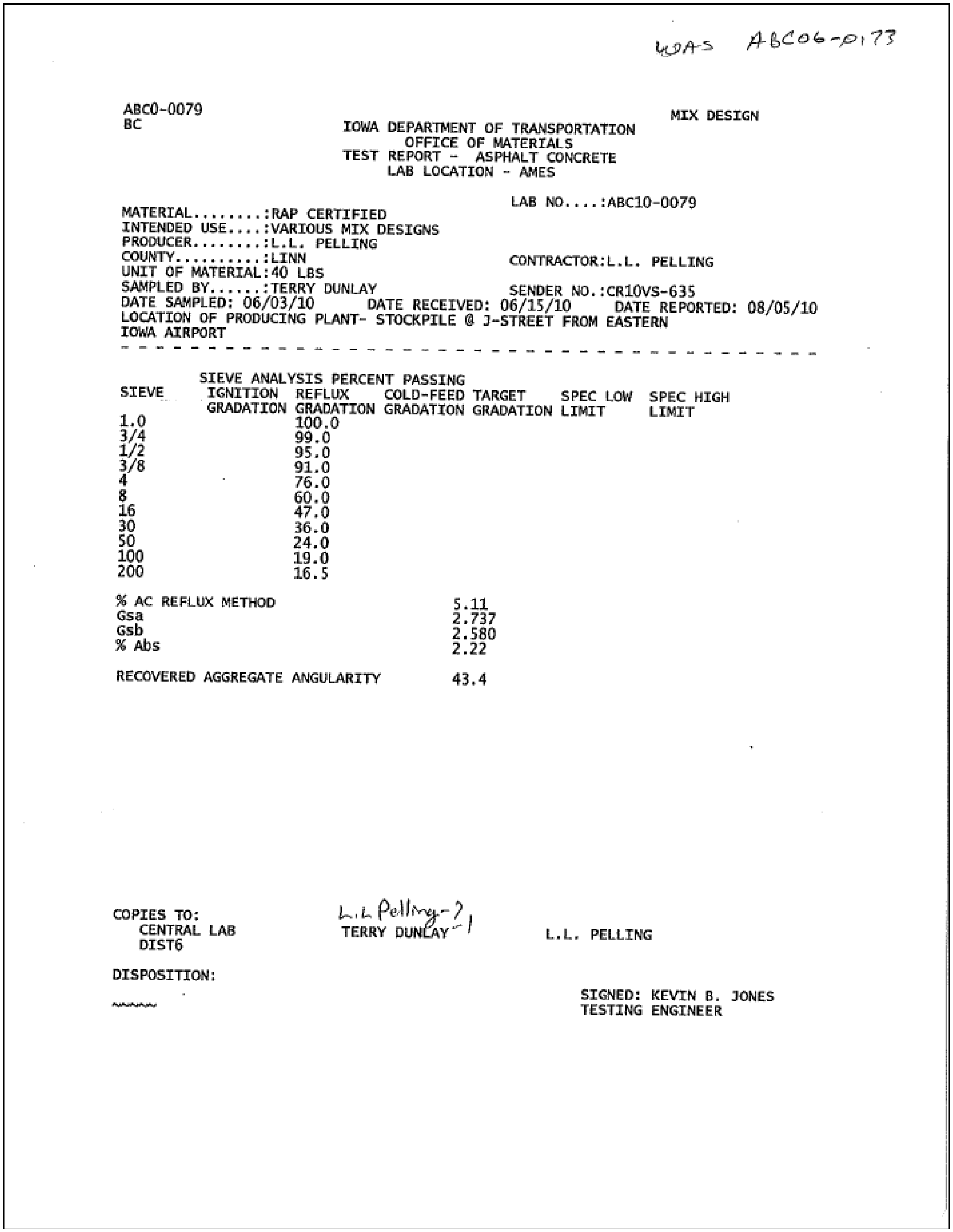
Aggregate Type	
Crushed Particles	%
Aggr Friction Type 2	%
Aggr Friction Type 3	%
Aggr Friction Type 4	%

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 A.2 LL Pelling RAP Stockpile Report – Stockpile A



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

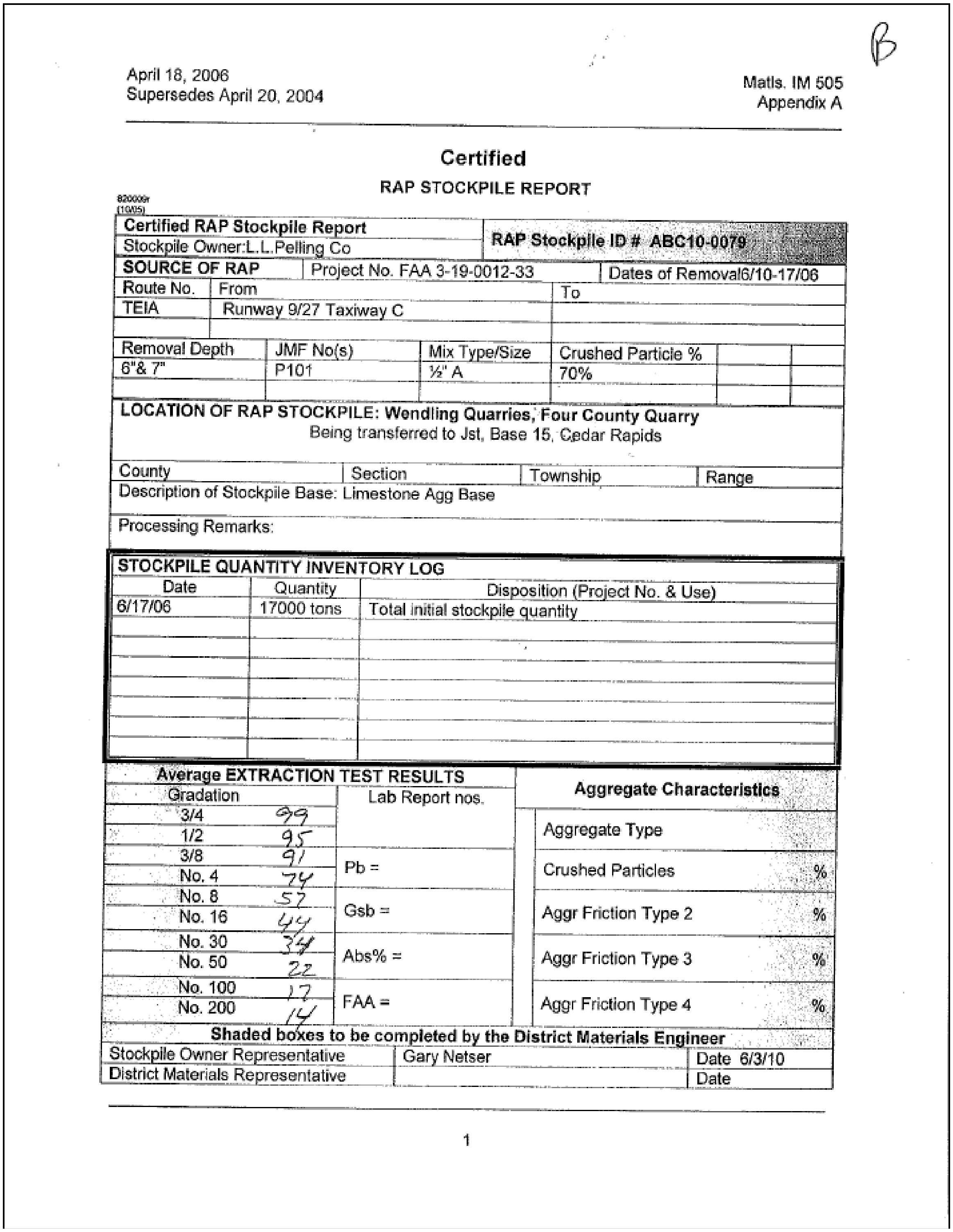
L.L Pelling-7
TERRY DUNLAY -1

L.L. PELLING

DISPOSITION:

SIGNED: KEVIN B. JONES
TESTING ENGINEER

Figure A.3 Iowa DOT Binder Extraction Testing Report – Stockpile B



B

April 18, 2006
Supersedes April 20, 2004

Matls. IM 505
Appendix A

Certified
RAP STOCKPILE REPORT

820009r
(10/05)

Certified RAP Stockpile Report
Stockpile Owner:L.L.Pelling Co
RAP Stockpile ID # ABC10-0079

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

Gradation		Lab Report nos.
3/4	99	
1/2	95	
3/8	91	Pb =
No. 4	74	
No. 8	57	Gsb =
No. 16	44	
No. 30	34	Abs% =
No. 50	22	
No. 100	17	FAA =
No. 200	14	

Aggregate Characteristics

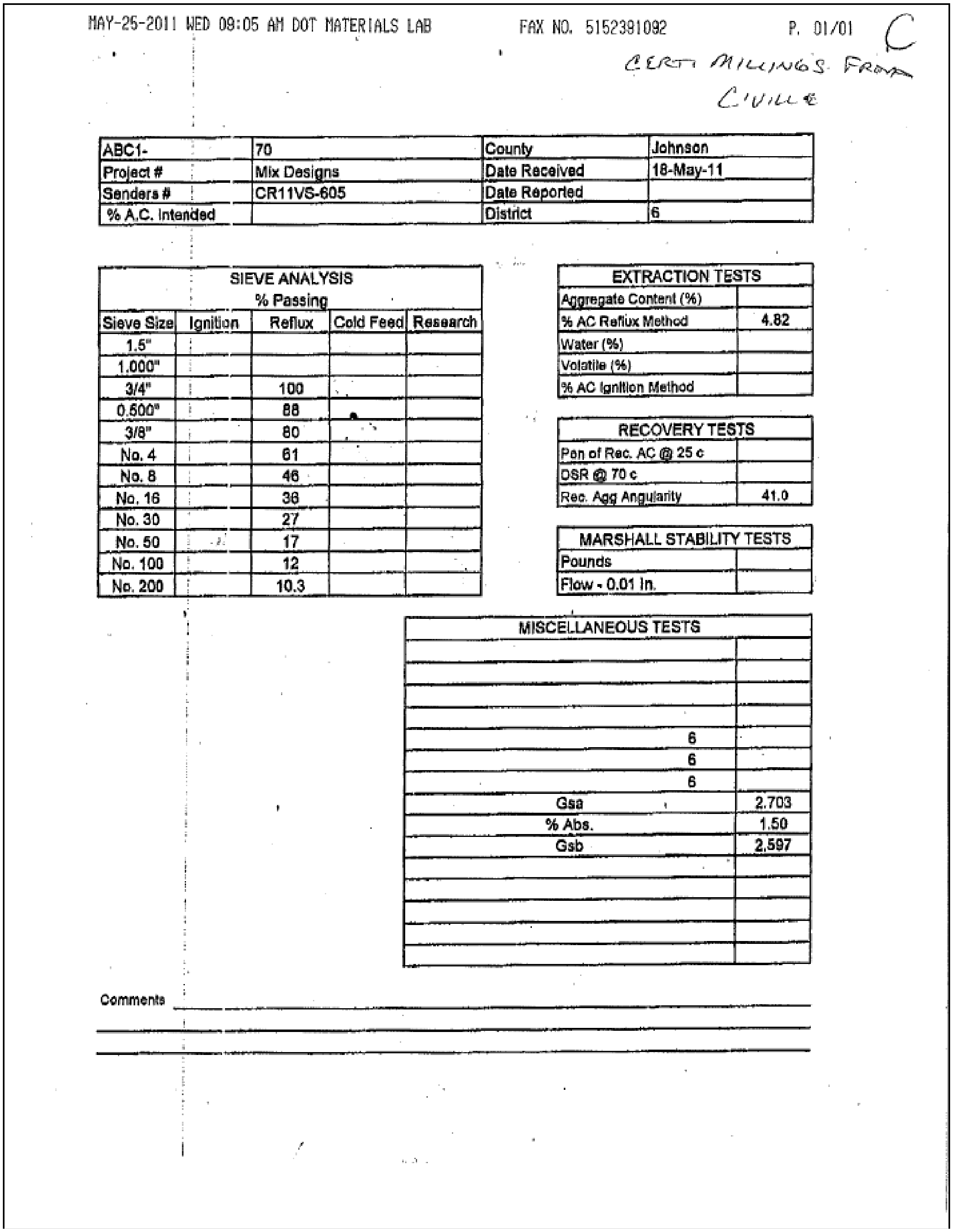
Aggregate Type	
Crushed Particles	%
Aggr Friction Type 2	%
Aggr Friction Type 3	%
Aggr Friction Type 4	%

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 A.4 LL Pelling RAP Stockpile Report – Stockpile B



MAY-25-2011 WED 09:05 AM DOT MATERIALS LAB FAX NO. 5152391092 P. 01/01

C

CERTI MILLINGS FROM
C'VILLE

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 A.5 Iowa DOT Binder Extraction Testing Report – Stockpile C

Appendix B RAP Stockpile Gradation Analysis

Table B.1 RAP Gradation Sampling - Stockpile A (Classified Millings from Eastern Iowa Airport)

		Sample 1		Sample 2		Sample 3		Sample 4		Sample 5	
Sieve Size		Retained Mass (grams)	Percent Retained (%)	Retained Mass (grams)	Percent Retained (%)	Retained Mass (grams)	Percent Retained (%)	Retained Mass (grams)	Percent Retained (%)	Retained Mass (grams)	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

		Sample 6		Sample 7		Sample 8		**Summary of 8 Samples @ 5,000 grams each**			
Sieve Size		Retained Mass (grams)	Percent Retained (%)	Retained Mass (grams)	Percent Retained (%)	Retained Mass (grams)	Percent Retained (%)	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 B.2 RAP Gradation Sampling - Stockpile B (Certified Millings from Eastern Iowa Airport)

		Sample 1		Sample 2		Sample 3		Sample 4		Sample 5	
Sieve Size		Retained Mass (grams)	Percent Retained (%)	Retained Mass (grams)	Percent Retained (%)	Retained Mass (grams)	Percent Retained (%)	Retained Mass (grams)	Percent Retained (%)	Retained Mass (grams)	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

		Sample 6		Sample 7		Sample 8		**Summary of 8 Samples @ 5,000 grams each**			
Sieve Size		Retained Mass (grams)	Percent Retained (%)	Retained Mass (grams)	Percent Retained (%)	Retained Mass (grams)	Percent Retained (%)	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 B.3 RAP Gradation Sampling - Stockpile C (Certified Millings from Unknown Sources)

		Sample 1		Sample 2		Sample 3		Sample 4		Sample 5	
Sieve Size		Retained Mass (grams)	Percent Retained (%)	Retained Mass (grams)	Percent Retained (%)	Retained Mass (grams)	Percent Retained (%)	Retained Mass (grams)	Percent Retained (%)	Retained Mass (grams)	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

		Sample 6		Sample 7		Sample 8		Summary of 8 Samples @ 5,000 grams each			
Sieve Size		Retained Mass (grams)	Percent Retained (%)	Retained Mass (grams)	Percent Retained (%)	Retained Mass (grams)	Percent Retained (%)	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				

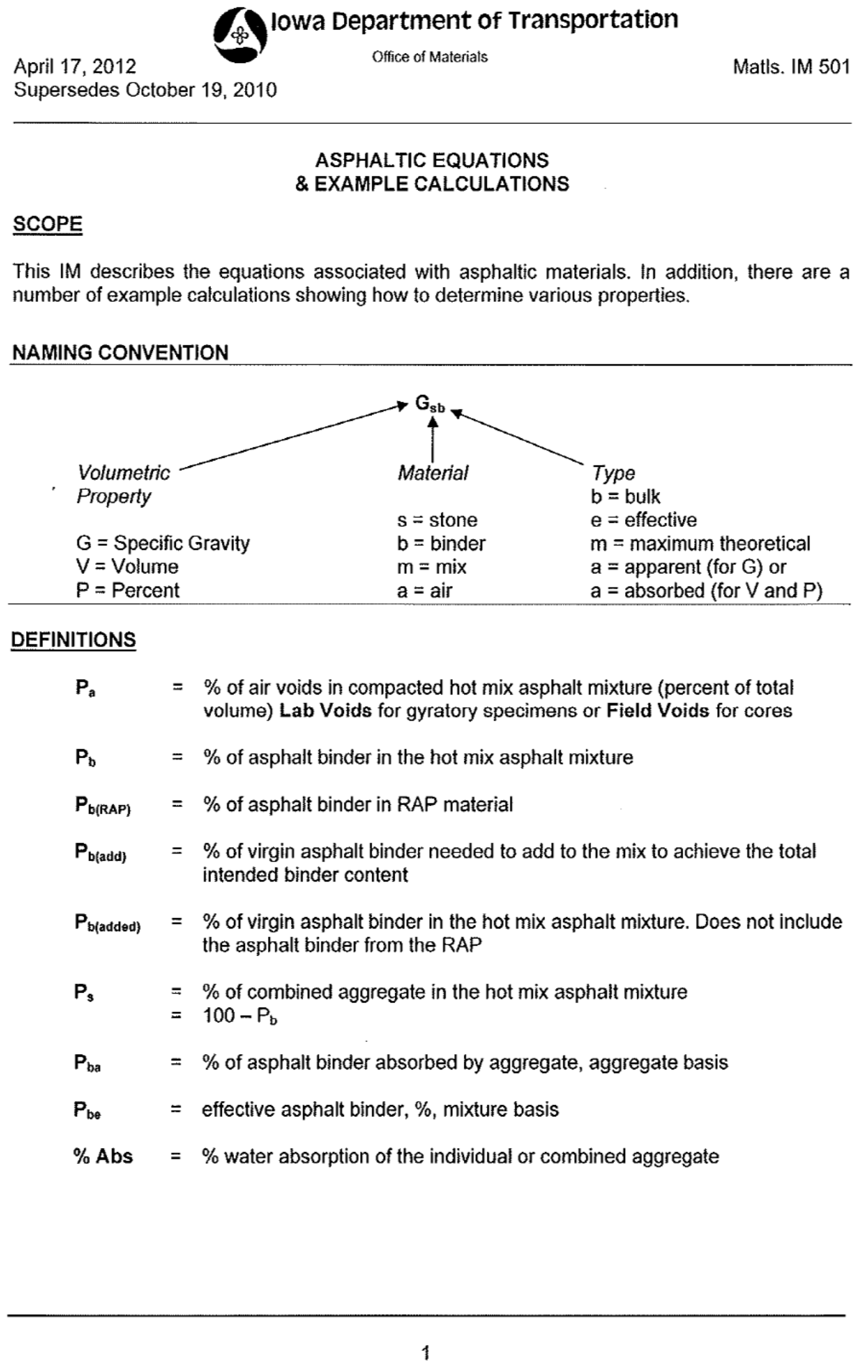
Appendix C Fractionated RAP Stockpile Properties

Table C.1 Recovered Aggregate Gradation and Asphalt Content of All 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 Volumetric Equations and RAP Formulas



Iowa Department of Transportation

Office of Materials

April 17, 2012
Supersedes October 19, 2010

Matls. IM 501

ASPHALTIC EQUATIONS
& EXAMPLE CALCULATIONS

SCOPE

This IM describes the equations associated with asphaltic materials. In addition, there are a number of example calculations showing how to determine various properties.

NAMING CONVENTION

G_{sb}

Volumetric Property

G = Specific Gravity
V = Volume
P = Percent

Material

s = stone
b = binder
m = mix
a = air

Type

b = bulk
e = effective
m = maximum theoretical
a = apparent (for G) or
a = absorbed (for V and P)

DEFINITIONS

P_a = % of air voids in compacted hot mix asphalt mixture (percent of total volume) **Lab Voids** for gyratory specimens or **Field Voids** for cores

P_b = % of asphalt binder in the hot mix asphalt mixture

$P_{b(RAP)}$ = % of asphalt binder in RAP material

$P_{b(add)}$ = % of virgin asphalt binder needed to add to the mix to achieve the total intended binder content

$P_{b(added)}$ = % of virgin asphalt binder in the hot mix asphalt mixture. Does not include the asphalt binder from the RAP

P_s = % of combined aggregate in the hot mix asphalt mixture
= $100 - P_b$

P_{ba} = % of asphalt binder absorbed by aggregate, aggregate basis

P_{be} = effective asphalt binder, %, mixture basis

% Abs = % water absorption of the individual or combined aggregate

ABS = fraction of water absorption of the individual or combined aggregate
= % Abs/100
ABS is always used in the calculations rather than % Abs.

G_{sa} = apparent specific gravity of the aggregate

G_{se} = effective specific gravity of the combined aggregate

G_{sb} = bulk specific gravity of the aggregate (dry basis)

$G_{sb(SSD)}$ = bulk specific gravity of the aggregate (SSD basis)
Used for Portland Cement Concrete **NOT ASPHALT!!!**

G_b = specific gravity of the asphalt binder at 25°C (77°F)

G_{mm} = maximum specific gravity of the hot mix asphalt mixture. Often referred to as the Rice specific gravity, solid specific gravity or solid density.

G_{mb} = bulk specific gravity of compacted hot mix asphalt mixture

$G_{mb(measured)}$ = G_{mb} of gyratory specimen as determined from test procedure in IM 321

$G_{mb(corrected)}$ = corrected G_{mb} of gyratory specimen at N_{des}, also called **Lab Density**.
$G_{mb(corrected)}$ and $G_{mb(measured)}$ will be the same when compacting to N_{des} so no correction is necessary.

$G_{mb(field\ core)}$ = bulk specific gravity of pavement cores (also $G_{mb(field)}$ or **Field Density**)

VMA = % voids in mineral aggregate, (percent of bulk volume), compacted mix

V_t = design target air voids, %

VFA = % voids filled with asphalt binder

N_{ini} = Number of gyrations used to measure initial compaction.

N_{des} = Number of gyrations used to measure design compaction. G_{mb} for Lab Density is determined at N_{des}.

N_{max} = Number of gyrations used to measure maximum compaction.

N_x = Level of compaction, where x is the number of gyrations.

R = temperature correction multiplier obtained from IM 350 Table 2 App. A

d_t = density of water at test temperature, g/cc

h_{max} = the height of the specimen at N_{max}, mm

h_{des} = the height of the specimen at N_{des}, mm

h_x = the height of the specimen at any gyration level N_x, mm

C_x = percent of compaction expressed as a percentage of G_{mm}
Where x is the number of gyrations (this is normally N_{ini} or N_{max})

S = slope of the compaction curve

FT = Film Thickness, microns

SA = Surface Area, m^2/kg

F/B = Filler/Bitumen Ratio also called Fines/Bitumen Ratio

σ_{n-1} = Sample Standard Deviation

$\bar{x}$ = sample average

FORMULAS

All calculations shown have been rounded for ease of presentation. Normally calculations will involve maintaining more significant figures throughout the intermediate calculations and only rounding the final result. The values generated by the software specified by the DOT will be the accepted results for reporting purposes.

All specific gravity calculations will be reported to 3 decimal places. Binder content is reported to 2 decimal places. Percent voids, VMA and VFA are reported to 1 decimal place.

Unless noted as otherwise, the following information is given to perform the calculations. Any additional needed information will be provided with the sample calculation.

$P_b = 5.75\%$

$P_s = 100 - 5.75 = 94.25\%$

% Abs = 1.39

ABS = 1.39/100 = 0.0139

$G_b = 1.031$

% minus #200 (75 µm) sieve = 5.0%

$G_{sa} = 2.667$

$G_{se} = 2.659$

$G_{sb} = 2.572$

$G_{sb(SSD)} = 2.608$

$G_{mm} = 2.438$

$G_{mb\ (field)} = 2.215$

$G_{mb\ (measured)} = 2.310$

$G_{mb\ (corrected)} = 2.273$

% RAP = 10.0%

$P_{b(RAP)} = 5.00\%$

VOLUMETRIC EQUATIONS

To convert the specific gravity of asphalt binder from one temperature to another, the following two equations are used.

G_b (at 60°F)

$$= \frac{G_b\ (\text{at } 77^\circ \text{F})}{0.9961} \qquad = \frac{1.031}{0.9961} = 1.035$$

G_b (at 77°F)

$$= 0.9961 \times G_b\ (\text{at } 60^\circ\text{F}) \qquad = 0.9961 \times (1.035) = 1.031$$

% Abs

$$= \frac{W_a + W_b - W_c}{W_c} \text{ x } 100$$

$$= \frac{1315.7 + 690.3 - 2000.0}{2000.0} \text{x} 100 = 0.30\%$$

Where:

W_a = Saturated-Surface-Dry (SSD) weight of coarse portion, 1315.7 g
W_b = Saturated-Surface-Dry (SSD) weight of fine portion, 690.3 g
W_c = Combined dry weight of coarse and fine portion, 2000.0 g

% Abs$_{\text{(combined)}}$

$$= [\%\ \text{Abs}_1 \times (P_{s1})] + [\%\ \text{Abs}_2 \times (P_{s2})] + [\%\ \text{Abs}_3 \times (P_{s3})] + \ldots$$

$$= 0.67(0.50) + 1.23(0.05) + 2.21(0.45) = 1.39\%$$

Where:

% Abs_1 = 0.67% P_{s1} = 50%
% Abs_2 = 1.23% P_{s2} = 5%
% Abs_3 = 2.21% P_{s3} = 45%

G_{sa}

$$= \frac{W \times R}{W + W_1 - W_2} \qquad = \frac{(2000.0)(1.0000)}{2000.0 + 6048.0 - 7298.1} = 2.667$$

Where:

W = Weight of dry sample, 2000.0 g
W_1 = Sample weight of pycnometer filled with water at test temperature, 6048.0 g
W_2 = Sample weight of pycnometer filled with water and sample, 7298.1 g
R = Multiplier to correct temperature to 77°F = 1.0000 @ 77°F

G_{sb}

$$= \frac{G_{sa}}{1 + (\text{ABS}) \times (G_{sa})} \qquad = \frac{2.667}{1 + (0.0139)(2.667)} = 2.572$$

$G_{sb\ (combined)}$

$$= \frac{100}{\frac{P_{s1}}{G_{sb1}} + \frac{P_{s2}}{G_{sb2}} + \frac{P_{s3}}{G_{sb3}} + ..} \qquad = \frac{100}{\frac{50.0}{2.657} + \frac{5.0}{2.642} + \frac{45.0}{2.640}} = 2.649$$

Where:

$P_{s1} = 50.0\%$ $\qquad$ $G_{sb1} = 2.657$
$P_{s2} = 5.0\%$ $\qquad$ $G_{sb2} = 2.642$
$P_{s3} = 45.0\%$ $\qquad$ $G_{sb3} = 2.640$

G_{se}

$$= \frac{P_s}{\frac{100}{G_{mm}} - \frac{P_b}{G_b}} \qquad = \frac{100 - 5.75}{\frac{100}{2.438} - \frac{5.75}{1.031}} = 2.659$$

G_{mm}

$$= \frac{W \times R}{W + W_1 - W_2} \qquad = \frac{(2020.0)(1.0000)}{2020.0 + 6048.0 - 7239.5} = 2.438$$

Where:

W = Sample weight of sample, 2020.0 g
W_1 = Sample weight of pycnometer filled w/water at test temperature, 6048.0 g
W_2 = Sample weight of pycnometer filled w/water and sample, 7239.5 g
R = Multiplier to correct temperature to 77°F = 1.0000 @ 77°F

To correct the density of water to 77°F the R multiplier is used. The value of R is given in the tables in IM's 350 and 380 for temperatures from 60 to 130°F. R is calculated as follows:

R

$$= \frac{d_t}{0.99707} \qquad = \frac{0.99707}{0.99707} = 1.0000$$

Where: $\qquad$ d_t = density of water at temperature t = 0.99707 g/cc at 77°F.

G_{mb} $\quad$ (or $G_{mb\ (measured)}$)

$$= \frac{W_1}{W_3 - W_2} \qquad = \frac{4800.0}{4805.6 - 2727.7} = 2.310$$

Where:

W_1 = Sample Dry weight, 4800.0 g
W_2 = Sample weight in water, 2727.7 g
W_3 = Sample weight in air, SSD, 4805.6 g

P_a $\quad$ (lab voids)

$$= \frac{G_{mm} - G_{mb}}{G_{mm}} \times 100 \qquad = \frac{2.438 - 2.310}{2.438} \times 100 = 5.3\%$$

%G$_{mm}$	(field core)	$= \frac{G_{mb(\text{field core})}}{G_{mm(\text{lot avg.})}} \times 100$	$= \frac{2.215}{2.438} \times 100 = 90.9\%$
P$_a$	(field voids)	$= 100 - \%G_{mm}$	$= 100 - 90.9 = 9.1\%$
VMA		$= 100 - \left[\frac{G_{mb} \times P_s}{G_{sb}}\right]$	$= 100 - \frac{(2.310)(94.25)}{2.572} = 15.4\%$
VFA		$= \frac{VMA - P_a}{VMA} \times 100$	$= \frac{15.4 - 5.3}{15.4} \times 100 = 65.6\%$
P$_{ba}$		$= \frac{(G_{se} - G_{sb})}{(G_{se} \times G_{sb})} \times G_b \times 100$	$= \frac{2.659 - 2.572}{(2.659)(2572)} \times 1.031 \times 100 = 1.31\%$
P$_{be}$		$= P_b - \left[\frac{P_{ba} \times P_s}{100}\right]$	$= 5.75 - \frac{(1.31)(94.25)}{100} = 4.52\%$
F/B	(fines/bitumen)	$= \frac{\text{Total \% of minus \#200 material}}{P_{be}}$	$= \frac{5.00}{4.52} = 1.11$

Where: Total % of minus #200 (75 µm) includes both virgin aggregate and RAP when used.

RAP FORMULAS

To determine the percent of asphalt binder to add to a mix containing RAP (**$P_{b(add)}$**) to achieve the total intended P_b shown on the JMF (this the value to which the plant controls are set):

$$\mathbf{P_{b(add)}} = \frac{[(100) \times (\text{total intended } P_b)] - [(\%\,\text{RAP}) \times (P_{b(RAP)})]}{100 - [(\%\,\text{RAP}) \times (P_{b(RAP)}) \times (0.01)]}$$

$$= \frac{(100)(5.75) - (10.0)(5.00)}{100 - (10.0)(5.00)(0.01)} = 5.28\%$$

To determine the percent of aggregate contributed by the RAP in the total aggregate blend:

$$\mathbf{\%\,RAP_{(aggregate)}} = \frac{(\%\,\text{RAP}) \times [1.00 - (P_{b(RAP)} \times 0.01)]}{\%\,\text{virgin agg.} + [(\%\,\text{RAP}) \times (1.00 - (P_{b(RAP)} \times 0.01))]} \text{ x } 100$$

$$= \frac{(10.0)(1.00 - (5.00)(0.01))}{90.0 + (10.0)(1.00 - (5.00)(0.01))} \text{ x } 100 = 9.55\%$$

To determine the actual percent virgin aggregate in the total aggregate blend containing RAP:

$$\mathbf{\%\,virgin\ agg.} = \frac{\%\,\text{virgin agg.}}{\%\,\text{virgin agg.} + [(\%\,\text{RAP}) \times (1.00 - (P_{b(RAP)} \times 0.01))]} \text{ x } 100$$

$$= \frac{90.0}{90.0 + (10.0)(1.00 - (5.00)(0.01))} \text{ x } 100 = 90.45\%$$

To determine the total percent asphalt binder in a mix containing RAP:

$$\mathbf{Total\ P_b} = P_{b(added)} + [(\%\,\text{RAP}) \times (P_{b(RAP)}) \times (0.01)] - [(P_{b(added)}) \times (\%\,\text{RAP}) \times (P_{b(RAP)}) \times (0.0001)]$$

$$= 5.28 + (10.0)(5.00)(0.01) - (5.28)(10.0)(5.00)(0.0001) = 5.75\%$$

Where: $P_{b(added)}$ is the actual percent of virgin asphalt binder added to the mix from the tank stick, flow meter or batch weights - **not the $P_{b(add)}$ determined above which is the original determination on the JMF.**

$$FM_{Type2} = \frac{[600 - (62 + 50 + 37 + 26 + 17 + 6.9)]}{100} \times 0.35 = 1.40$$

FILM THICKNESS EXAMPLE:

SIEVE ANALYSIS % PASSING													
Sieve	in. (mm)	1 (25.0)	3/4 (19.0)	1/2 (12.5)	3/8 (9.5)	#4 (4.75)	#8 (2.36)	#16 (1.18)	#30 (0.600)	#50 (0.300)	#100 (0.150)	#200 (0.075)	
Combined Grading		100	100	95	86	68	47	38	26	10	5.4	3.9	
Surface Area Coefficient						0.0041	0.0082	0.0164	0.0287	0.0614	0.1229	0.3277	TOTAL
Surface Area	(m^2/kg)	0.41				0.28	0.39	0.62	0.75	0.61	0.66	1.28	5.00

The surface area (**SA**) is found by taking the % Passing times the Surface Area Coefficient. The Surface Area for the material above the #4 sieve is a constant 0.41. The total surface area is found by adding all of the individual surface area values.

SA (for each sieve) $= (\% \text{ Passing}) \times (\text{Surface Area Coefficient})$

$= (38)(0.0164) = 0.62$ (for the #16 sieve above)

Where: The Surface Area Coefficients are constants.

FT (Film Thickness) $= \frac{P_{be}}{SA} \times 10$ $= \frac{4.52}{5.00} \times 10 = 9.0$

Appendix E Optimum FRAP Proportion Selection

Table E.1 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 E.2 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 E.3 Optimum FRAP Proportion Selection – Stockpile C

	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	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

	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			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%

											% 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	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

	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			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%

											% 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	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

	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			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%

											% 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	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%