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Investigation of Synergistic Effects of Warm Mix Asphalt and High Fractionated Reclaimed Asphalt for Safe, Environmentally Sustainable Highway

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16. Abstract

To increase RAP materials by up to 75% by binder replacement, a fractionation method was applied to the RAP stockpile by discarding RAP materials passing No. 16 sieve. This fractionation method was effective in improving volumetric properties of the HMA mixture with high RAP contents. The mix designs were then performed for both HMA and WMA with varying fractionated RAP amounts accounting for a replacement of 20, 30, 40, 50 and 75% of the mixture's optimum asphalt binder content. All mix designs met the Iowa DOT mix design requirements except the one with 75% RAP materials by binder replacement due to the excessive amount of dust content. Hamburg Wheel Tracking (HWT) test was used to evaluate the rutting and moisture susceptibility of both HMA and WMA mixtures with varying RAP amounts. Overall, HMA mixtures performed better than WMA mixtures and the mixes with higher RAP amounts performed better except the mix with 30% RAP materials by binder replacement. Both HMA and WMA mixes with 75% RAP materials by binder replacement (90% by weight replacement) performed the best by exhibiting very little deformation ranging between 2 and 4 mm after 20,000 repetitions.

In order to evaluate the performance of WMA mixtures in the field, test sections were constructed in Iowa and Ohio. The average densities of the HMA and WMA test sections in Iowa were 94.3% and 93.9%, respectively, and those of the HMA and WMA test sections in Ohio were 94.6% and 95.2%, respectively. Significantly less emission and smoke were observed during construction of WMA mixtures, which confirmed the environmental benefits of using WMA technologies while meeting both Iowa and Ohio DOT's density requirements. Both HMA and WMA mixes from Iowa met Hamburg testing requirement by exhibiting very little deformation of 3 mm and 5 mm, respectively, after 20,000 repetitions. HMA mix from Ohio met Hamburg testing requirement by exhibiting very little deformation of 4 mm after 20,000 repetitions whereas WMA mix exhibited 15 mm deformation after 20,000 repetitions.

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Table of Contents

List of Figures

List of Tables

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Abstract

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. Various fractionation methods were designed and applied to the RAP stockpile for up to 75.0% RAP binder replacement. The component analysis of the RAP stockpile identified the distribution of aggregates and binder associated with RAP materials retained on each sieve. It is concluded that the fractionation methods were effective in improving volumetric properties of the HMA mixture with a high RAP content. Next, Warm Mix Asphalt (WMA) additive was used to improve the volumetric properties of high-RAP content mixtures. Different combinations of mix designs were established to evaluate the performance of the WMA technology compared to the conventional Hot Mix Asphalt (HMA) mixtures. Hamburg Wheel Tracking (HWT) test was used to evaluate the performance of the designed mixtures. All HMA mixtures passed the Hamburg Wheel test. However, only the WMA mixtures with 50% RAP or more passed the Hamburg Wheel test. Hamburg Wheel test results showed that HAM mixtures had better rutting resistance than WMA mixtures.

In order to evaluate the performance of WMA mixtures in the field, test sections were constructed in in Iowa City, Iowa and Lancaster, Ohio and field densities of WMA mixtures met Iowa DOT and ODOT specifications, respectively. Significantly less emission and smoke were observed during construction of WMA mixtures, which confirmed the environmental benefits of using WMA technologies. Based on the HWT test results of field mixtures, WMA mixtures exhibited similar rutting and moisture damage resistance compared to HMA mixtures in Iowa whereas they exhibited less rutting and moisture damage resistance compared to HMA mixtures in Ohio.

Chapter 1 Introduction

1.1 Background

Reclaimed Asphalt Pavement (RAP) has been used widely in the U.S. and is the world's most recycled product. The 2007 average national usage rate of RAP in HMA was estimated to be 12% and NAPA set a goal to double the national average RAP content from 12% to 24% in five years (1). A recent FHWA report stated, "Average RAP use is estimated at 12% in HMA…it is unknown why over half of the country uses less than 20 percent RAP in HMA" (2). The most difficult aspect of high-RAP mix design in Iowa is meeting the volumetric mix design criteria due to the large amount of fine aggregate material introduced to the HMA mix by the RAP materials (3). The Iowa DOT currently limits the maximum RAP use for the surface course to 15%. 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). Iowa and Minnesota have an additional specification for the volumetric mix design criteria of HMA mix designs, the Asphalt Film Thickness (AFT). The dust content increases the combined aggregate surface area which leads to problems meeting the film thickness requirement for high-RAP content mixtures (5). The film thickness requirement is intended to ensure sufficient asphalt binder coating of the aggregate structure; however, this AFT criterion also has the effect of limiting the RAP content that can be used in the mixture due to the increased dust content of the RAP materials.

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 (6). Beeson et al. (7) recommended 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. 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 (8). In a 2009 survey conducted by NCDOT, 9 State DOT's reported requiring fractionation and Wisconsin is reported to allow an increase of 5 percent binder replacement for surface mixes if fractionation is used (2).

The main objective of this research is to investigate the synergistic effect of Warm Mix Asphalt (WMA) and high reclaimed asphalt pavement (High RAP) contents for their mix designs and rutting potential using Hamburg Wheel Tracking (HWT) test. First, the optimum fractionation method was identified to separate the stockpile at predetermined sizes to isolate RAP materials within the stockpile that contained higher amounts of fine aggregate. Second, mix designs were performed with varying RAP contents accounting for a replacement of up to 75% of the total mixture's asphalt binder. Third, the HWT test was performed on the mixtures with varying amounts of RAP materials up to 75% by a binder replacement. Finally, the WMA mixtures were implemented in the field and the field samples were then subjected to the HWT test.

1.2 RAP Material Composition Analysis

RAP materials were obtained from stockpiles at a local, eastern-Iowa contractor's asphalt plant facility. Each stockpile was unique with respect to the combination of the original pavement's source, the recycling methods used and the recycled material's properties. A detailed analysis was conducted on RAP materials to investigate the material composition.

The RAP material used in this research (referred to herein as Stockpile C) consists of highway millings from Interstate 80 in eastern Iowa that were stockpiled at the contractor's asphalt plant. Millings were obtained at a high speed and a shallow depth from the surface, resulting in a small amount of dust content of 10.7%. The RAP materials met the criteria for Iowa DOT's 'Classified RAP'. Figure 1.1 shows the gradation of recovered aggregates from Stockpile C versus gradation of recovered aggregates from Stockpile A that were acquired at a slower speed and reaching deeper into the pavement down to 13 inches. As can be seen from Figure 1, Stockpile C is coarser than the Stockpile A due to the significantly less amounts of minus No. 200 materials. Therefore, for this research, the RAP materials from the Stockpile C were used.

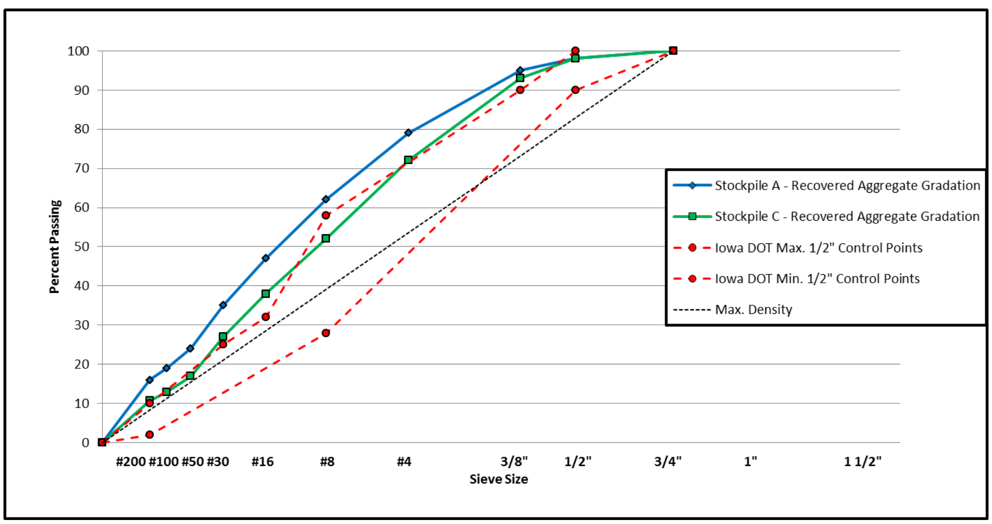

Figure 1.1 Recovered aggregate gradation vs. ½" mix size – Stockpile A & C

Table 1.1 summarizes the aggregate gradation of RAP materials from Stockpile C that were retained on each sieve based on the burn-off oven test result. For example, the first row in Table 1.1. represents the aggregate gradation of RAP materials retained on the 1.5-inch sieve.

For example, the extracted binder, the percentage and the dust content (minus No. 200) of RAP materials retained on the 1.5-inch sieve were 4.66%, 4.15% and 3.30%, respectively, whereas those of RAP materials retained on No. 200 sieve were 9.74%, 0.98%, 4.37%. Although the RAP materials retained on the No. 200 sieve is only 0.98% of the total stockpile compared to 4.15% for RAP materials retained on 1.5-inc sieve, it includes 9.74% of the total extracted binder and 4.37% of the total dust content that is significantly higher than those from the RAP materials retained on 1.5-inch sieve. As shown in Table 1.1, Stockpile C was split on No. 4 resulting in 60% coarse and 40% fine aggregates.

1.3 Design of Fractionation Methods

The composition analysis of a stockpile confirmed that a significant aggregate degradation has occurred during the milling and crushing process. The excessive amounts of fine aggregates produced from milling and crushing process pose a challenge in meeting Superpave criteria such as the combined aggregate gradation, dust-binder ratio and film thickness. Therefore, the first step in this research is to identify a RAP stockpile fractionation method that would help meet the Superpave criterion with high RAP contents. The following two methods named ‘Fractionated RAP’ and ‘Optimum FRAP’ were designed to produce the acceptable high-RAP mix design that would meet the Superpave criteria with a minimum disposal of fine RAP materials.

Table 1.1 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”	0.0	3.9	4.7	27.5	20.1	13.9	9.6	7.6	3.8	1.4	7.6	**4.66**	**4.15**	**3.30**
1”	0.0	5.5	5.7	27.7	18.8	12.8	8.7	7.6	3.8	1.4	8.0	**4.78**	**5.54**	**4.61**
¾”	1.1	1.1	10.0	6.2	27.6	16.2	10.9	8.3	7.8	3.7	7.2	**4.61**	**6.41**	**4.79**
½”	---	20.8	10.6	20.8	13.6	9.6	7.0	6.2	3.3	1.2	7.0	**4.09**	**12.68**	**9.26**
3/8”	---	---	39.81	21.9	10.2	7.2	5.2	5.0	2.7	1.0	5.7	**3.62**	**8.62**	**5.11**
No. 4	---	---	---	56.1	15.8	7.2	5.4	5.3	2.8	1.0	5.4	**3.66**	**22.18**	**14.91**
No. 8	---	---	---	---	65.2	12.0	5.5	5.7	3.1	1.1	7.5	**4.43**	**15.56**	**12.13**
No. 16	---	---	---	---	---	61.7	13.6	7.4	3.9	1.6	11.8	**5.55**	**10.38**	**12.82**
No. 30	---	---	---	---	---	---	60.8	14.9	5.0	1.9	17.4	**6.72**	**6.12**	**11.13**
No. 50	---	---	---	---	---	---	---	67.2	7.4	2.5	23.0	**7.98**	**4.35**	**10.45**
No. 100	---	---	---	---	---	---	---	---	64.2	7.5	28.3	**9.34**	**2.08**	**6.15**
No. 200	---	---	---	---	---	---	---	---	---	57.2	42.8	**9.74**	**0.98**	**4.37**
Coarse RAP	0	5	10	34	16	10	7	6	4	1.4	6.7	**4.02**	**59.6%**	**42.0%**
Fine RAP	0	0	0	0	26	21	15	14	7	3.2	13.8	**5.86**	**40.4%**	**58.0%**

1.3.1 Fractionated RAP' Method

This fractionation method directly targets the Fine RAP particles by physically removing the smallest of these materials from the original stockpile. The removal sieve size was determined based on the analysis of the recovered aggregate gradation of RAP materials retained on each sieve size as discussed above. For Stockpile C, in order to meet the gradation requirement for Superpave mix design, RAP materials passing No. 16 were discarded. Although this would discard 14.5% of the stockpile, as shown in Table 1.2, a significantly higher amount of fine aggregates would be removed.

1.3.2 'Optimum FRAP' Method

The second fractionation method splits the original RAP stockpile into two separate Coarse and Fine Fractionated RAP (FRAP) stockpiles. The new 'Coarse FRAP' and 'Fine FRAP' stockpiles are to be re-proportioned to limit the percentage of Fine FRAP included in the mix. Based on the component analysis of RAP materials retained on each sieve, for Stockpile C, the 3/8" sieve size was chosen. Table 1.3 shows that, as expected, the Fine FRAP stockpiles have significantly higher proportion of fine aggregates than the Coarse FRAP materials. To achieve the desired gradation properties, the following Coarse FRAP proportions were adopted:

- Optimum FRAP of Stockpile C – Coarse RAP proportion was increased from 34.7% to 50%. The large increase in Coarse FRAP percentage included in the total RAP material resulted in higher amounts of material being 'discarded' from the original stockpile C (30.6%).

Table 1.2 Fine aggregate reduction of 'fractionated RAP' method

RAP Stockpile Analysis	Fine Aggregate Composition – (% Retained)				Fine Agg. % of Total
	No. 50	No. 100	No. 200	Pan	
Original Stockpile C	10.0	4.0	2.3	10.7	**27.0%**
Fractionated RAP-C	6.4	3.2	1.2	7.6	**18.4%**
Fine Agg. % Reduction	-36.0%	-20.0%	-47.8%	-29.0%	**-31.9%**

Table 1.3 Recovered aggregate composition of coarse and fine FRAP stockpiles

RAP Stockpile	Recovered Aggregate Composition – (% Retained)										% of Original
	1/2"	3/8"	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200	Pan	
Coarse FRAP-C	11.9	13.5	23.4	15.2	10.3	7.0	6.9	3.4	1.2	7.3	**34.7%**
Fine FRAP-C	0.0	0.0	20.5	22.1	15.3	11.5	10.2	5.3	2.2	13.1	**65.3%**

1.4 Summary of Fractionation Methods

The 'Fractionated RAP' method removes all of RAP material passing the No. 16 sieve size from the stockpile C. This method resulted in significant fine aggregate reduction and minimal material discarded from each original stockpile. The 'Optimum FRAP' method splits each original RAP stockpile C at the 3/8" sieve size to produce a 'Coarse FRAP' stockpile (RAP materials retained a specified sieve) and a 'Fine FRAP' stockpile (RAP materials passing a specified sieve). The percentage of 'Coarse FRAP' was increased to bring the combined aggregate gradation to the middle of the fine aggregate gradation control points. Mix designs were performed for high-RAP content mixtures using RAP materials included as the 'Original RAP' method, the 'Fractionated RAP' method and the 'Optimum FRAP' method. Results of these mix designs were then compared to determine the effects of the fractionation methods on the volumetric properties of high-RAP mix designs.

1.5 High-RAP Mix Design

Currently, the maximum amount of RAP material currently allowed in the surface course by the Iowa DOT is limited to 30% of the virgin binder replacement by Classified RAP materials (4). In order to evaluate the fractionations methods for mixtures with high RAP content High-RAP mix designs were created for inclusion of 40% RAP material (measured by amount of virgin binder replaced) from each original RAP stockpile as well as the fractionated RAP stockpiles ('Fractionated RAP' and 'Optimum FRAP').

1.5.1 Mix Design Procedure

The Iowa DOT's 'Method of Design of Hot Mix Asphalt Mixes' (7) describes the process of aggregate and binder selection, material preparation and HMA mixture batching, curing and testing. The performance grade of the virgin binder was reduced by one temperature classification to PG 58-28, as required by the Iowa DOT for greater than 20% virgin binder replacement by RAP (4, 7). To achieve the target asphalt content of each sample, for a given amount of virgin asphalt replacement, the Iowa DOT's SHADES spreadsheet program was modified to determine the weights of materials to be added to the trial mixtures.

1.5.2 High-RAP Content Mix Design Results

Mix designs were performed for the HMA 300K ESAL 1/2" surface mixture (7). All mix designs contained RAP material that accounted for 40% replacement of the total mixture's binder content. These mix designs were then evaluated based on their compliance with the Iowa DOT's mix design criteria.

Table 1.4 summarizes the volumetric properties for each high-RAP mix design (40% binder replacement for each fractionation method) for RAP materials from Stockpile C. The fractionation methods were effective in decreasing the combined surface area resulting in the higher film thickness. Stockpile C contained 10.7% dust content. As can be seen from Table 1.4, the ‘Fractionated RAP’ method resulted in significant reduction in surface area and an increase in optimum asphalt content meeting all mix design criteria. The Optimum FRAP-C mixture improved the volumetric criteria over the Traditional-C mixture; however, they were not significant enough to meet the mix design criteria.

1.5.3 High-RAP Mix Design Summary

To meet Iowa DOT’s mix design criteria, fraction methods (‘Fractionated RAP’ and ‘Optimum FRAP’) were developed for High-RAP mixes with 40% replacement of the mixture’s virgin binder. Comparison of the results from these High-RAP mix designs showed that the volumetric properties are highly dependent on the material composition of the original RAP stockpile. For Stockpile C, the only ‘Fractionated RAP’ method met Iowa DOT’s mix design criteria. Throughout this research, the RAP materials from Stockpile C using the “Fractionation RAP method” have been used.

Table 1.4 Volumetric mix design result comparison - 40% RAP (binder replaced)

RAP Method	**Stockpile C**		
RAP Design	**Trad.**	**Frac.**	**Opt.**
Air Voids (P_a)	3.5%	3.5%	3.5%
Optimum AC	4.22%	5.18%	4.87%
ADD AC	2.53%	3.11%	2.92%
RAP Weight	42.2%	47.9%	42.0%
Asphalt Content of RAP Material	4.00%	4.33%	4.65%
Volumetrics @ Optimum AC	**4.22%**	**5.18%**	**4.87%**
Agg. Sp. Gr. (G_{sb})	2.644	2.645	2.644
Effective Sp. Gr. (G_{se})	2.675	2.677	2.702
Max. Sp. Gr. (G_{mm})	2.508	2.474	2.505
Bulk Sp. Gr. (G_{mb})	2.420	2.388	2.418
Binder Abs. (P_{ba}, %)	0.45	0.48	0.84
Effective Binder (P_{be}, %)	3.79	4.73	4.08
Agg. Surface Area (m^2/kg)	5.91	5.04	5.66
Mix Design Criteria	**40% Trad-C**	**40% Frac-C**	**40% Opt-C**
VMA (%)	12.3	14.4	13.0
VFA (%)	71.6	75.7	73.1
Dust Content (Minus No. 200)	7.0	5.9	6.8
Film Thickness (μm)	6.4	9.4	7.2
Dust – Binder Ratio	1.9	1.3	1.7

Chapter 2 Mix Design and Hamburg Wheel Tracking Test of WMA mixtures with Fractionated RAP Materials

2.1 Introduction

It was found in the previous task that, in order to meet Superpave mix design requirements, it would be necessary to fractionate RAP materials. Thus, the fractionated RAP materials from I-80 rehabilitation project were used to produce laboratory specimens for the mix design and the HWT test. A total of ten mixtures were designed: five WMA mixtures using LEADCAP additive and five HMA mixtures as a control mixture with varying amounts of fractionated RAP materials of 20, 30, 40, 50 and 75% by a binder replacement. The laboratory mixtures were designed for a traffic level of 0.3 million ESAL per Iowa DOT mix design requirements and NCHRP 691 Report for WMA mix design.

2.2 Virgin Aggregate & RAP Material Properties

The Limestone virgin aggregates of four different stockpiles collected from River Products quarry along with varying amounts of fractionated RAP from I-80 rehabilitation project were used for designing the mix with ½ inch nominal maximum size. As discussed earlier, RAP materials passing the No 16 sieve were removed from the RAP stockpile. The Virgin aggregate properties, RAP material properties and the combined gradations for each of five different amounts of RAP materials by a binder replacement of 20, 30, 40, 50 and 75% are summarized in Tables 2.1 through 2.5, respectively, and the combined gradations are plotted on the 0.45 power gradation chart in Figures 2.1 through 2.5, respectively.

Table 2.1 Combined aggregate gradation and mixture properties with 20% RAP content

Mix Design Info.		*Virgin Aggregate Properties*						*RAP Properties*					
Project Name	High-RAP	**Virgin Agg. Batch Mix**		**G_{sb}**	**ABS, %**	**G_{sa}**	**RAP (% Binder Replaced)**	**RAP ID**	**% of RAP**	**G_{sb}**	**ABS, %**	**G_{sa}**	**% AC**
Traffic ESAL	300,000	**Sand**	**7.0%**	2.634	0.47	2.667	**20.0%**	**Frac. ≥ #16**	**100.0%**	2.650	1.190	2.736	4.33
Mix Size	1/2"	**Man. Sand**	**13.0%**	2.649	0.84	2.709	**RAP (% Total Mix Weight)**		**0.0%**	0.000	0.000	0.000	0.00
Layer	Surface	**1/2" to Dust**	**65.0%**	2.638	0.98	2.708	**24.3%**	**Combined RAP Mix**		**2.650**	**1.190**	**2.736**	**4.33**
Virgin Binder	PG 64-22	**3/8" Chips**	**15.0%**	2.642	1.04	2.717	**RAP (% Dry Aggregate Weight)**	**Combined Mixture Properties**		**G_{sb}**	**ABS, %**	**G_{sa}**	**% AC**
WMA Additive	LEADCAP 7-1	**Combined Virgin Mix**		**2.640**	**0.900**	**2.707**	**23.5%**			**2.642**	**0.955**	**2.713**	**5.25**

Virgin Aggregate Batch Mix and RAP Material Combined Gradation

Sieve Size		Stockpile and percentage passing				Virgin Agg.	RAP Aggregate Gradation		Recovered	**Comb. Grad.**	Design Spec, 12.5 mm	
ID	mm	**Sand**	**Man. Sand**	**1/2" to Dust**	**3/8" Chips**	Batch Mix	**Frac. ≥ #16**	**0**	Agg. Blend	**w/RAP @ P_{bi}**	Min.	Max.
3/4 in	19.0	100.0	100.0	100.0	100.0	100.0	100	0	100.0	**100.0**	**100.0**	**100.0**
1/2 in	12.5	100.0	100.0	95.0	100.0	96.8	96.5	0.0	96.5	**96.7**	**90.0**	**100.0**
3/8 in	9.5	100.0	100.0	80.0	97.0	86.6	91.1	0.0	91.1	**87.6**	**-**	**90.0**
#4	4.75	95.0	98.0	29.0	42.0	44.5	62.6	0.0	62.6	**48.8**	**-**	**-**
#8	2.36	90.0	76.0	10.0	10.0	24.2	40.7	0.0	40.7	**28.1**	**28.0**	**58.0**
#16	1.18	79.0	43.0	8.0	9.0	17.7	25.9	0.0	25.9	**19.6**	**-**	**-**
#30	0.6	53.0	20.0	7.0	8.0	12.1	18.4	0.0	18.4	**13.6**	**-**	**-**
#50	0.3	16.0	8.3	6.5	7.5	7.5	12.0	0.0	12.0	**8.6**	**-**	**-**
#100	0.15	2.0	2.8	6.0	7.0	5.5	8.8	0.0	8.8	**6.2**	**-**	**-**
#200	0.075	1.0	2.5	5.0	5.5	4.5	7.6	0.0	7.6	**5.2**	**2.0**	**10.0**
% Total weight of mixture		**5.3%**	**9.8%**	**49.2%**	**11.4%**	**Surf. Area**	**24.3%**	**0.0%**	**Surf. Area**	**Surf. Area**	Total	
% dry aggregate weight		**5.4%**	**9.9%**	**49.7%**	**11.5%**	**4.00**	**23.5%**	**0.0%**	**6.22**	**4.52**	**OK**	

Table 2.2 Combined aggregate gradation and mixture properties with 30% RAP content

Mix Design Info.				*Virgin Aggregate Properties*						*RAP Properties*			
Project Name	High-RAP	**Virgin Agg. Batch Mix**		**G_{sb}**	**ABS, %**	**G_{sa}**	**RAP (% Binder Replaced)**	**RAP ID**	**% of RAP**	**G_{sb}**	**ABS, %**	**G_{sa}**	**% AC**
Traffic ESAL	300,000	**Sand**	**7.0%**	2.634	0.47	2.667	**30.0%**	**Frac. ≥ #16**	**100.0%**	2.650	1.190	2.736	4.33
Mix Size	1/2"	**Man. Sand**	**13.0%**	2.649	0.84	2.709	**RAP (% Dry Mix Weight)**		**0.0%**	0.000	0.000	0.000	0.00
Layer	Surface	**1/2" to Dust**	**65.0%**	2.638	0.98	2.708	**37.7%**	**Combined RAP Mix**		**2.650**	**1.190**	**2.736**	**4.33**
Virgin Binder	PG 58-28	**3/8" Chips**	**15.0%**	2.642	1.04	2.717	**RAP (% Total Aggregate)**	**Combined Mixture Properties**		**G_{sb}**	**ABS, %**	**G_{sa}**	**% AC**
WMA Additive	LEADCAP 7-1	**Combined Virgin Mix**		**2.640**	**0.900**	**2.707**	**36.6%**			**2.643**	**0.988**	**2.717**	**5.42**

Virgin Aggregate Batch Mix and RAP Material Combined Gradation

Sieve Size		Stockpile and percentage passing				Virgin Agg.	RAP Aggregate Gradation		Recovered	**Comb. Grad.**	Design Spec, 12.5 mm	
ID	mm	**Sand**	**Man. Sand**	**1/2" to Dust**	**3/8" Chips**	Batch Mix	**Frac. ≥ #16**	**0**	Agg. Blend	**w/RAP @ P_{bi}**	Min.	Max.
3/4 in	19.0	100.0	100.0	100.0	100.0	100.0	100	0	100.0	**100.0**	**100.0**	**100.0**
1/2 in	12.5	100.0	100.0	95.0	100.0	96.8	96.5	0.0	96.5	**96.6**	**90.0**	**100.0**
3/8 in	9.5	100.0	100.0	80.0	97.0	86.6	91.1	0.0	91.1	**88.2**	-	**90.0**
#4	4.75	95.0	98.0	29.0	42.0	44.5	62.6	0.0	62.6	**51.2**	-	-
#8	2.36	90.0	76.0	10.0	10.0	24.2	40.7	0.0	40.7	**30.2**	**28.0**	**58.0**
#16	1.18	79.0	43.0	8.0	9.0	17.7	25.9	0.0	25.9	**20.7**	-	-
#30	0.6	53.0	20.0	7.0	8.0	12.1	18.4	0.0	18.4	**14.4**	-	-
#50	0.3	16.0	8.3	6.5	7.5	7.5	12.0	0.0	12.0	**9.2**	-	-
#100	0.15	2.0	2.8	6.0	7.0	5.5	8.8	0.0	8.8	**6.7**	-	-
#200	0.075	1.0	2.5	5.0	5.5	4.5	7.6	0.0	7.6	**5.6**	**2.0**	**10.0**
% dry weight of mixture		**4.4%**	**8.1%**	**40.5%**	**9.4%**	**Surf. Area**	**37.7%**	**0.0%**	**Surf. Area**	**Surf. Area**	Total	
% of total aggregate		**4.4%**	**8.2%**	**41.2%**	**9.5%**	**4.00**	**36.6%**	**0.0%**	**6.22**	**4.82**	**OK**	

Table 2.3 Combined aggregate gradation and mixture properties with 40% RAP content

Mix Design Info.		*Virgin Aggregate Properties*						*RAP Properties*					
Project Name	High-RAP	**Virgin Agg. Batch Mix**		**G_{sb}**	**ABS, %**	**G_{sa}**	**RAP (% Binder Replaced)**	**RAP ID**	**% of RAP**	**G_{sb}**	**ABS, %**	**G_{sa}**	**% AC**
Traffic ESAL	300,000	**Sand**	**7.0%**	2.634	0.47	2.667	**40.0%**	**Frac. ≥ #16**	**100.0%**	2.650	1.190	2.736	4.33
Mix Size	1/2"	**Man. Sand**	**13.0%**	2.649	0.84	2.709	**RAP (% Dry Mix Weight)**		**0.0%**	0.000	0.000	0.000	0.00
Layer	Surface	**1/2" to Dust**	**65.0%**	2.638	0.98	2.708	**48.2%**	**Combined RAP Mix**		**2.650**	**1.190**	**2.736**	**4.33**
Virgin Binder	PG 58-28	**3/8" Chips**	**15.0%**	2.642	1.04	2.717	**RAP (% Total Aggregate)**	**Combined Mixture Properties**		**G_{sb}**	**ABS, %**	**G_{sa}**	**% AC**
WMA Additive	LEADCAP 7-1	**Combined Virgin Mix**		**2.640**	**0.900**	**2.707**	**47.1%**			**2.645**	**1.017**	**2.720**	**5.20**

Virgin Aggregate Batch Mix and RAP Material Combined Gradation

Sieve Size		Stockpile and percentage passing				Virgin Agg.	RAP Aggregate Gradation		Recovered	**Comb. Grad.**	Design Spec, 12.5 mm	
ID	mm	**Sand**	**Man. Sand**	**1/2" to Dust**	**3/8" Chips**	Batch Mix	**Frac. ≥ #16**	**0**	Agg. Blend	**w/RAP @ P_{bi}**	Min.	Max.
3/4 in	19.0	100.0	100.0	100.0	100.0	100.0	100	0	100.0	**100.0**	**100.0**	**100.0**
1/2 in	12.5	100.0	100.0	95.0	100.0	96.8	96.5	0.0	96.5	**96.6**	**90.0**	**100.0**
3/8 in	9.5	100.0	100.0	80.0	97.0	86.6	91.1	0.0	91.1	**88.7**	-	**90.0**
#4	4.75	95.0	98.0	29.0	42.0	44.5	62.6	0.0	62.6	**53.0**	-	-
#8	2.36	90.0	76.0	10.0	10.0	24.2	40.7	0.0	40.7	**31.9**	**28.0**	**58.0**
#16	1.18	79.0	43.0	8.0	9.0	17.7	25.9	0.0	25.9	**21.5**	-	-
#30	0.6	53.0	20.0	7.0	8.0	12.1	18.4	0.0	18.4	**15.0**	-	-
#50	0.3	16.0	8.3	6.5	7.5	7.5	12.0	0.0	12.0	**9.7**	-	-
#100	0.15	2.0	2.8	6.0	7.0	5.5	8.8	0.0	8.8	**7.0**	-	-
#200	0.075	1.0	2.5	5.0	5.5	4.5	7.6	0.0	7.6	**5.9**	**2.0**	**10.0**
% dry weight of mixture		**3.6%**	**6.7%**	**33.7%**	**7.8%**	**Surf. Area**	**48.2%**	**0.0%**	**Surf. Area**	**Surf. Area**	Total	
% of total aggregate		**3.7%**	**6.9%**	**34.4%**	**7.9%**	**4.00**	**47.1%**	**0.0%**	**6.22**	**5.05**	**OK**	

Table 2.4 Combined aggregate gradation and mixture properties with 50% RAP content

Mix Design Info.		***Virgin Aggregate Properties***						***RAP Properties***					
Project Name	High-RAP	**Virgin Agg. Batch Mix**		**G_{sb}**	**ABS, %**	**G_{sa}**	**RAP (% Binder Replaced)**	**RAP ID**	**% of RAP**	**G_{sb}**	**ABS, %**	**G_{sa}**	**% AC**
Traffic ESAL	300,000	**Sand**	**7.0%**	2.634	0.47	2.667	**50.0%**	**Frac. ≥ #16**	**100.0%**	2.650	1.190	2.736	4.33
Mix Size	1/2"	**Man. Sand**	**13.0%**	2.649	0.84	2.709	**RAP (% Dry Mix Weight)**		**0.0%**	0.000	0.000	0.000	0.00
Layer	Surface	**1/2" to Dust**	**65.0%**	2.638	0.98	2.708	**60.8%**	**Combined RAP Mix**		**2.650**	**1.190**	**2.736**	**4.33**
Virgin Binder	PG 58-28	**3/8" Chips**	**15.0%**	2.642	1.04	2.717	**RAP (% Total Aggregate)**	**Combined Mixture Properties**		**G_{sb}**	**ABS, %**	**G_{sa}**	**% AC**
WMA Additive	LEADCAP 7-1	**Combined Virgin Mix**		**2.640**	**0.900**	**2.707**	**59.7%**			**2.646**	**1.053**	**2.724**	**5.25**

Virgin Aggregate Batch Mix and RAP Material Combined Gradation

Sieve Size		Stockpile and percentage passing				Virgin Agg.	RAP Aggregate Gradation		Recovered	**Comb. Grad.**	Design Spec, 12.5 mm	
ID	mm	**Sand**	**Man. Sand**	**1/2" to Dust**	**3/8" Chips**	Batch Mix	**Frac. ≥ #16**	**0**	Agg. Blend	**w/RAP @ P_{bi}**	Min.	Max.
3/4 in	19.0	100.0	100.0	100.0	100.0	100.0	100	0	100.0	**100.0**	**100.0**	**100.0**
1/2 in	12.5	100.0	100.0	95.0	100.0	96.8	96.5	0.0	96.5	**96.6**	**90.0**	**100.0**
3/8 in	9.5	100.0	100.0	80.0	97.0	86.6	91.1	0.0	91.1	**89.3**	**-**	**90.0**
#4	4.75	95.0	98.0	29.0	42.0	44.5	62.6	0.0	62.6	**55.3**	**-**	**-**
#8	2.36	90.0	76.0	10.0	10.0	24.2	40.7	0.0	40.7	**34.0**	**28.0**	**58.0**
#16	1.18	79.0	43.0	8.0	9.0	17.7	25.9	0.0	25.9	**22.6**	**-**	**-**
#30	0.6	53.0	20.0	7.0	8.0	12.1	18.4	0.0	18.4	**15.9**	**-**	**-**
#50	0.3	16.0	8.3	6.5	7.5	7.5	12.0	0.0	12.0	**10.2**	**-**	**-**
#100	0.15	2.0	2.8	6.0	7.0	5.5	8.8	0.0	8.8	**7.4**	**-**	**-**
#200	0.075	1.0	2.5	5.0	5.5	4.5	7.6	0.0	7.6	**6.3**	**2.0**	**10.0**
% dry weight of mixture		**2.7%**	**5.1%**	**25.5%**	**5.9%**	**Surf. Area**	**60.8%**	**0.0%**	**Surf. Area**	**Surf. Area**	Total	
% of total aggregate		**2.8%**	**5.2%**	**26.2%**	**6.0%**	**4.00**	**59.7%**	**0.0%**	**6.22**	**5.33**	**OK**	

Table 2.5 Combined aggregate gradation and mixture properties with 75% RAP content

Mix Design Info.		*Virgin Aggregate Properties*						*RAP Properties*					
Project Name	High-RAP	**Virgin Agg. Batch Mix**		**G_{sb}**	**ABS, %**	**G_{sa}**	**RAP (% Binder Replaced)**	**RAP ID**	**% of RAP**	**G_{sb}**	**ABS, %**	**G_{sa}**	**% AC**
Traffic ESAL	300,000	**Sand**	**7.0%**	2.634	0.47	2.667	**75.0%**	**Frac. ≥ #16**	**100.0%**	2.650	1.190	2.736	4.33
Mix Size	1/2"	**Man. Sand**	**13.0%**	2.649	0.84	2.709	**RAP (% Total Mix Weight)**		**0.0%**	0.000	0.000	0.000	0.00
Layer	Surface	**1/2" to Dust**	**65.0%**	2.638	0.98	2.708	**90.3%**	**Combined RAP Mix**		**2.650**	**1.190**	**2.736**	**4.33**
Virgin Binder	PG 58-28	**3/8" Chips**	**15.0%**	2.642	1.04	2.717	**RAP (% Dry Aggregate Weight)**	**Combined Mixture Properties**		**G_{sb}**	**ABS, %**	**G_{sa}**	**% AC**
WMA Additive	LEADCAP 7-1	**Combined Virgin Mix**		**2.640**	**0.900**	**2.707**	**89.9%**			**2.649**	**1.152**	**2.733**	**5.20**

Virgin Aggregate Batch Mix and RAP Material Combined Gradation

Sieve Size		Stockpile and percentage passing				Virgin Agg.	RAP Aggregate Gradation		Recovered	**Comb. Grad.**	Design Spec, 12.5 mm	
ID	mm	**Sand**	**Man. Sand**	**1/2" to Dust**	**3/8" Chips**	Batch Mix	**Frac. ≥ #16**	**0**	Agg. Blend	**w/RAP @ P_{bi}**	min	max
3/4 in	19.0	100.0	100.0	100.0	100.0	100.0	100	0	100.0	**100.0**	**100.0**	**100.0**
1/2 in	12.5	100.0	100.0	95.0	100.0	96.8	96.5	0.0	96.5	**96.5**	**90.0**	**100.0**
3/8 in	9.5	100.0	100.0	80.0	97.0	86.6	91.1	0.0	91.1	**90.7**	-	**90.0**
#4	4.75	95.0	98.0	29.0	42.0	44.5	62.6	0.0	62.6	**60.8**	-	-
#8	2.36	90.0	76.0	10.0	10.0	24.2	40.7	0.0	40.7	**39.0**	**28.0**	**58.0**
#16	1.18	79.0	43.0	8.0	9.0	17.7	25.9	0.0	25.9	**25.0**	-	-
#30	0.6	53.0	20.0	7.0	8.0	12.1	18.4	0.0	18.4	**17.8**	-	-
#50	0.3	16.0	8.3	6.5	7.5	7.5	12.0	0.0	12.0	**11.6**	-	-
#100	0.15	2.0	2.8	6.0	7.0	5.5	8.8	0.0	8.8	**8.5**	-	-
#200	0.075	1.0	2.5	5.0	5.5	4.5	7.6	0.0	7.6	**7.3**	**2.0**	**10.0**
% Total weight of mixture		**0.7%**	**1.3%**	**6.3%**	**1.5%**	**Surf. Area**	**90.3%**	**0.0%**	**Surf. Area**	**Surf. Area**	Total	
% dry aggregate weight		**0.7%**	**1.3%**	**6.6%**	**1.5%**	**4.00**	**89.9%**	**0.0%**	**6.22**	**6.00**	**OK**	

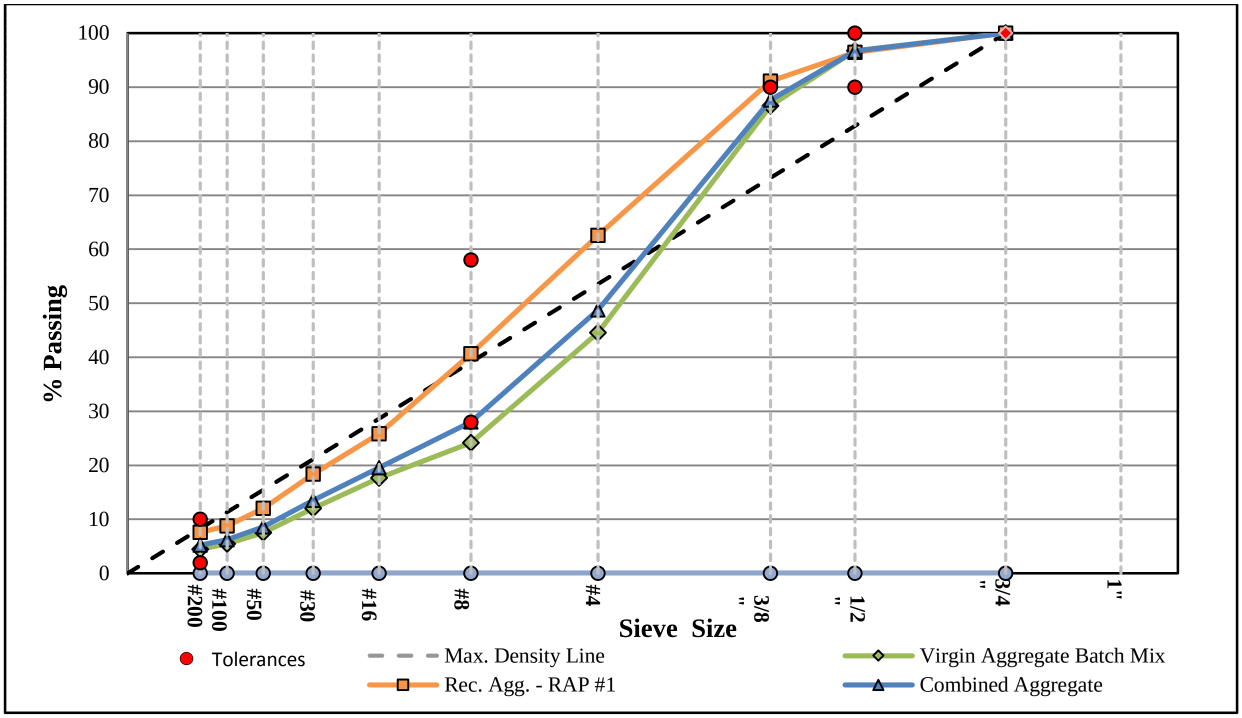

Figure 2.1 Combined aggregate gradation chart for mixtures with 20% RAP

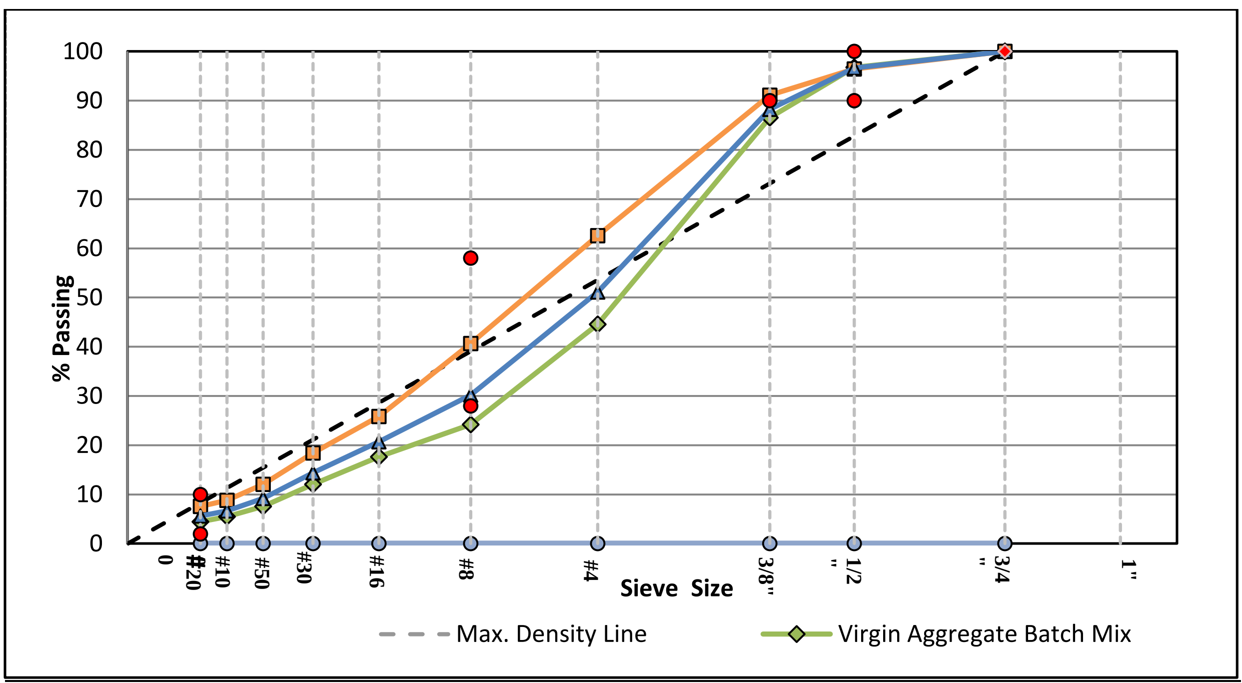

Figure 2.2 Combined aggregate gradation chart for mixtures with 30% RAP

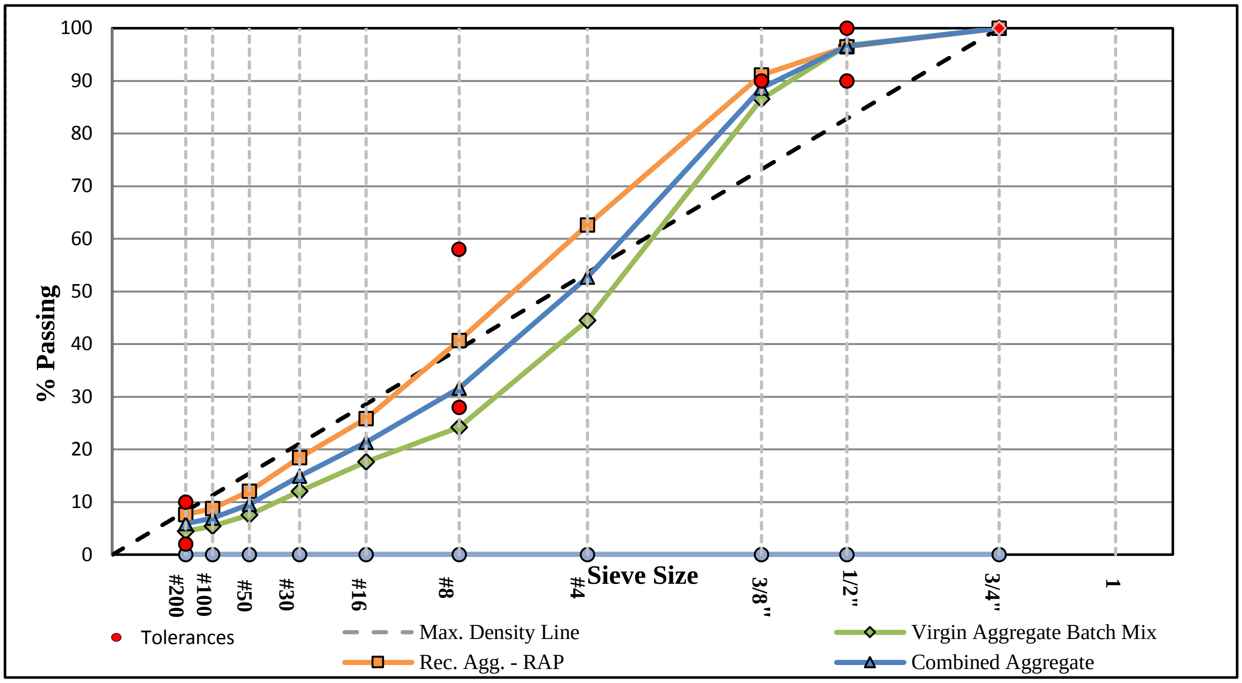

Figure 2.3 Combined aggregate gradation chart for mixtures with 40% RAP

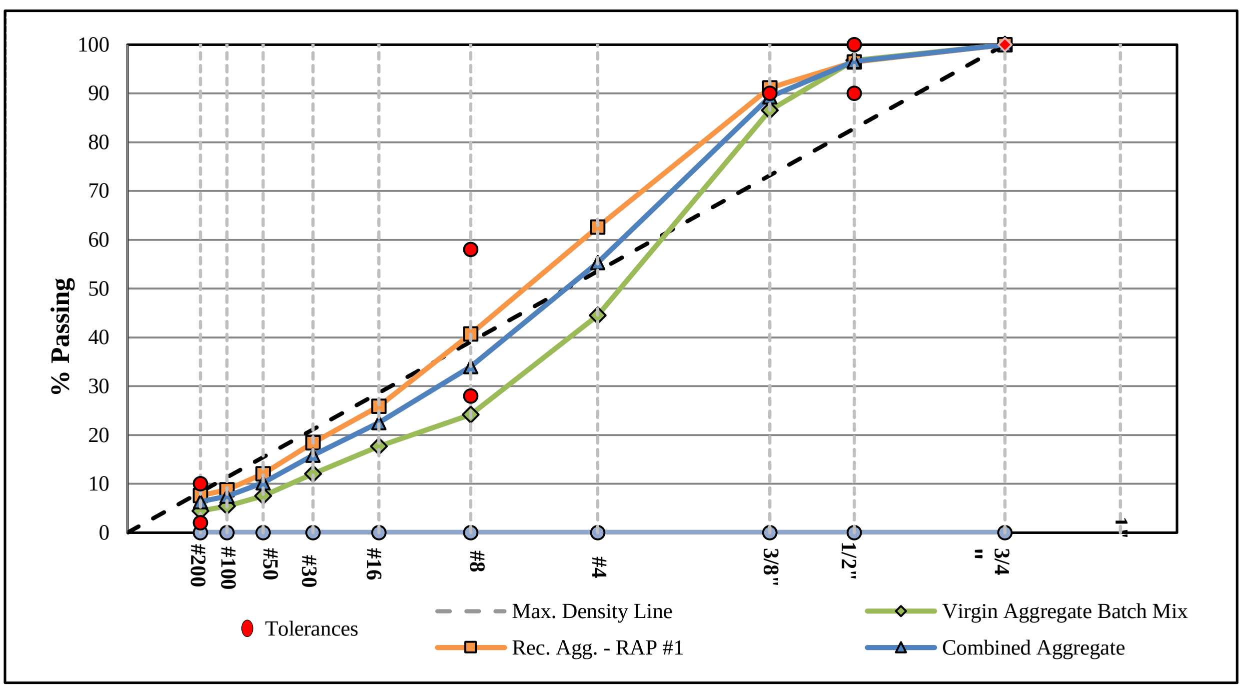

Figure 2.4 Combined aggregate gradation chart for mixtures with 50% RAP

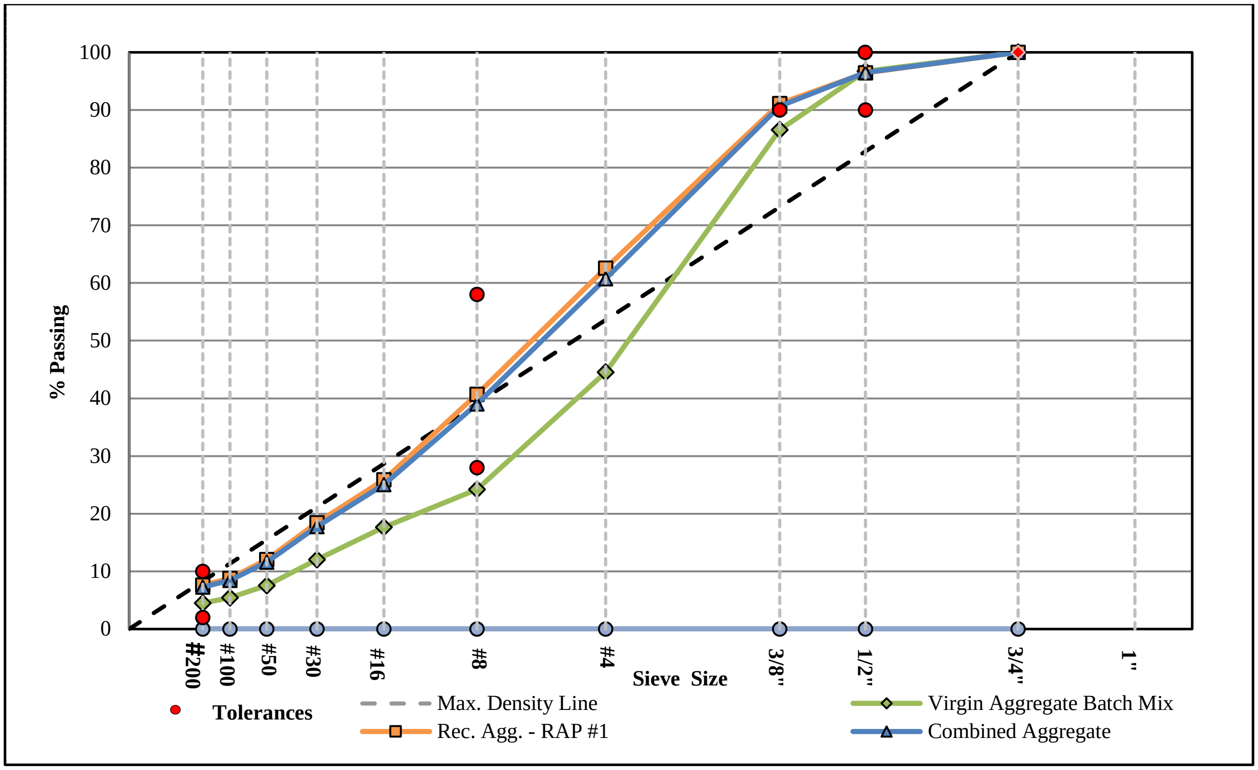

Figure 2.5 Combined aggregate gradation chart for mixtures with 75% RAP

As can be seen from these tables, due to the less amount of binder available from the RAP materials than the optimum binder content, the percentage of RAP materials by weight were significantly higher than the percentage by binder replacement. For example, as shown in Table 5, the 75% replacement by binder content was equivalent to 90% replacement by weight. As shown in Figures 2.1 through 2.5, all combined gradations met the Superpave gradation requirements.

2.3 Asphalt Binder

The target performance grade (PG) for the binder used for all mixtures is PG 64-22 and Iowa DOT requires lowering the high temperature grade by one level for the HMA mixture that includes more than 20% RAP materials. Therefore, two asphalt binder types were evaluated in this study: PG64-22 for mixtures with RAP content up to 20% by binder replacement and PG 58-28 for mixtures with RAP content more than 20% by binder replacement. As recommended by the Flint Hills Resources, HMA mixing and compaction temperatures for the PG 64-22 binder were determined as 311° F (155°C) and 293° F (145°C), respectively, and those for the PG58-28 binder were determined as 300° F (150°C), and 275° F (135°C), respectively.

2.4 Mix Design

As summarized in Table 2.6, mixing and compaction temperatures for HMA laboratory samples were determined following the Iowa DOT RAP mix design procedure. Mix design properties for both HMA and WMA mixtures with different RAP amounts of 20, 30, 40, 50 and 75% by binder replacement are summarized in Tables 2.7 through 2.11. As it can be seen from these tables, all HMA and WMA mixtures met the Iowa DOT mix design requirements except the mixtures with 75% RAP by binder replacement, which did not meet VMA, dust/binder ratio and film thickness.

Table 2.6 Mixing and compaction temperatures for laboratory specimens

Binder Type	Mixture	RAP Heat-Up		Binder Temp.	Mixing Temp.	Comp. Temp.
PG 58-28	HMA	Max. 2 hours	300º F (150º C)	300º F (150º C)	300º F (150º C)	285º F (140º C)
PG 58-28	WMA	Max. 2 hours	275º F (135º C)	300º F (150º C)	275º F (135º C)	250º F (125º C)
PG 64-22	HMA	Max. 2 hours	300º F (150º C)	300º F (150º C)	300º F (150º C)	285º F (140º C)
PG 64-22	WMA	Max. 2 hours	275º F (135º C)	300º F (150º C)	275º F (135º C)	250º F (125º C)

Table 2.7 Mix design summary for mixtures with 20% RAP

Mix Design Properties	HMA	LEADCAP 7-1	Mix Design Criteria
Target Air Voids	3.67%	3.10%	3.5 ± 0.5
Optimum Binder Content (%)	5.25	5.25	----
Virgin Asphalt Binder Content (ADD AC %)	4.20	4.20	----
Virgin Aggregate Content (% Dry Mix Weight)	76%	76%	----
RAP Content (% Dry Mix Weight)	0.24	0.24	----
RAP Content (% Total Aggregate)	0.23	0.23	----
Aggregate Bulk Specific Gravity (G_{sb})	2.642	2.642	----
Aggregate Effective Specific Gravity (G_{se})	2.669	2.664	----
Aggregate Apparent Specific Gravity (G_{sa})	2.713	2.713	----
Aggregate Water Absorption (%)	0.955	0.955	----
Asphalt Binder Bulk Specific Gravity (G_b)	1.043	1.043	----
Bulk Specific Gravity at Optimum AC (G_{mb})	2.376	2.386	----
Maximum Theoretical Specific Gravity (G_{mm})	2.467	2.463	----
Percent Binder Absorption (P_{ba} %)	0.40	0.32	----
Percent Effective Binder (P_{be} %)	4.87	4.95	----
Comb. Agg. Surface Area (m^2/ Kg.)	4.52	4.52	----
Comb. Agg. Dust Content ($P_{0.075}$ %)	5.20	5.20	Maximum 10%
%G_{mm} at N_{ini} (7 gyrations)	84.54	84.27	≤ 92.0%
%G_{mm} at N_{des} (68 gyrations)	96.33%	96.90%	96.5% ± 0.5
%G_{mm} at N_{max} (104 gyrations)	97.80	97.98	≤ 98.0%
Voids in Mineral Aggregate (VMA, %)	14.78	14.42	Minimum 14%
Voids Filled with Asphalt (VFA, %)	75.15	78.52	70% - 80%
Dust to Binder Ratio ($P_{0.075}$/P_{be})	1.07	1.05	0.6 - 1.4
Film Thickness (μm)	10.77	10.94	8.0 - 13 μm

Table 2.8 Mix design summary for mixtures with 30% RAP

Mix Design Properties	*HMA*	*LEADCAP 7-1*	*Mix Design Criteria*
Target Air Voids	3.99%	3.81%	----
Optimum Binder Content (%)	5.20	5.20	----
Virgin Asphalt Binder Content (ADD AC %)	3.64	3.64	----
Virgin Aggregate Content (% Dry Mix Weight)	64%	64%	----
RAP Content (% Dry Mix Weight)	0.4	0.4	----
RAP Content (% Total Aggregate)	0.4	0.4	----
Aggregate Bulk Specific Gravity (G_{sb})	2.643	2.643	----
Aggregate Effective Specific Gravity (G_{se})	2.677	2.666	----
Aggregate Apparent Specific Gravity (G_{sa})	2.717	2.717	----
Aggregate Water Absorption (%)	0.984	0.984	----
Asphalt Binder Bulk Specific Gravity (G_b)	1.036	1.036	----
Bulk Specific Gravity at Optimum AC (G_{mb})	2.375	2.370	----
Maximum Theoretical Specific Gravity (G_{mm})	2.473	2.464	----
Percent Binder Absorption (P_{ba} %)	0.50	0.33	----
Percent Effective Binder (P_{be} %)	4.73	4.89	----
Comb. Agg. Surface Area (m^2/ Kg.)	4.78	4.78	----
Comb. Agg. Dust Content ($P_{0.075}$ %)	5.57	5.57	Maximum 10%
%G_{mm} at N_{ini} (7 gyrations)	84.59	84.51	≤ 92.0%
%G_{mm} at N_{des} (68 gyrations)	96.01	96.19	96.5% ± 0.5
%G_{mm} at N_{max} (104 gyrations)	97.47	97.77	≤ 98.0%
Voids in Mineral Aggregate (VMA, %)	14.84	15.00	Minimum 14%
Voids Filled with Asphalt (VFA, %)	73.08	74.58	70% - 80%
Dust to Binder Ratio ($P_{0.075}$/P_{be})	1.18	1.14	0.6 - 1.4
Film Thickness (µm)	9.89	10.22	8.0 - 13 µm

Table 2.9 Mix design summary for mixtures with 40% RAP

Mix Design Properties	HMA	LEADCAP 7-1	Mix Design Criteria
Target Air Voids	3.45%	3.5%	3.5 ± 0.5
Optimum Binder Content (%)	5.30	5.10	----
Virgin Asphalt Binder Content (ADD AC %)	3.18	3.06	----
Virgin Aggregate Content (% Dry Mix Weight)	51.7	53.2	----
RAP Content (% Dry Mix Weight)	49.3	46.8	----
RAP Content (% Total Aggregate)	48.2	45.7	----
Aggregate Bulk Specific Gravity (G_{sb})	2.645	2.645	----
Aggregate Effective Specific Gravity (G_{se})	2.687	2.682	----
Aggregate Apparent Specific Gravity (G_{sa})	2.720	2.720	----
Aggregate Water Absorption (%)	1.017	1.017	----
Asphalt Binder Bulk Specific Gravity (G_b)	1.036	1.036	----
Bulk Specific Gravity at Optimum AC (G_{mb})	2.390	2.395	----
Maximum Theoretical Specific Gravity (G_{mm})	2.477	2.481	----
Percent Binder Absorption (P_{ba} %)	0.62	0.54	----
Percent Effective Binder (P_{be} %)	4.75	4.55	----
Comb. Agg. Surface Area (m^2/ Kg.)	5.07	5.03	----
Comb. Agg. Dust Content ($P_{0.075}$ %)	5.97	5.91	Maximum 10%
%G_{mm} at N_{ini} (7 gyrations)	86.83	82.12	≤ 92.0%
%G_{mm} at N_{des} (68 gyrations)	96.55	96.5	96.5% ± 0.5
%G_{mm} at N_{max} (104 gyrations)	98.00	97.67	≤ 98.0%
Voids in Mineral Aggregate (VMA, %)	14.5	14.00	Minimum 14%
Voids Filled with Asphalt (VFA, %)	75.8	75.00	70% - 80%
Dust to Binder Ratio ($P_{0.075}/P_{be}$)	1.26	1.3	0.6 - 1.4
Film Thickness (μm)	9.36	9.07	8.0 - 13 μm

Table 2.10 Mix designs summary for mixtures with 50% RAP

Mix Design Properties	HMA	LEADCAP 7-1	Mix Design Criteria
Target Air Voids	3.36%	3.03%	3.5 ± 0.5
Optimum Binder Content (%)	5.20	5.20	----
Virgin Asphalt Binder Content (ADD AC %)	2.60	2.60	----
Virgin Aggregate Content (% Dry Mix Weight)	40%	40%	----
RAP Content (% Dry Mix Weight)	0.60	0.60	----
RAP Content (% Total Aggregate)	0.59	0.59	----
Aggregate Bulk Specific Gravity (G_{sb})	2.646	2.646	----
Aggregate Effective Specific Gravity (G_{se})	2.706	2.681	----
Aggregate Apparent Specific Gravity (G_{sa})	2.724	2.724	----
Aggregate Water Absorption (%)	1.052	1.052	----
Asphalt Binder Bulk Specific Gravity (G_b)	1.036	1.036	----
Bulk Specific Gravity at Optimum AC (G_{mb})	2.412	2.401	----
Maximum Theoretical Specific Gravity (G_{mm})	2.496	2.476	----
Percent Binder Absorption (P_{ba} %)	0.87	0.51	----
Percent Effective Binder (P_{be} %)	4.38	4.72	----
Comb. Agg. Surface Area (m^2/ Kg.)	5.32	5.32	----
Comb. Agg. Dust Content ($P_{0.075}$ %)	6.32	6.32	Maximum 10%
%G_{mm} at N_{ini} (7 gyrations)	86.05	83.41	≤ 92.0%
%G_{mm} at N_{des} (68 gyrations)	96.64	96.97	96.5% ± 0.5
%G_{mm} at N_{max} (104 gyrations)	97.66	97.96	≤ 98.0%
Voids in Mineral Aggregate (VMA, %)	13.56	13.96	Minimum 14%
Voids Filled with Asphalt (VFA, %)	75.19	78.31	70% - 80%
Dust to Binder Ratio ($P_{0.075}/P_{be}$)	1.44	1.34	0.6 - 1.4
Film Thickness (µm)	8.24	8.87	8.0 - 13 µm

Table 2.11 Mix designs summary for mixtures with 75% RAP

Mix Design Properties	HMA	LEADCAP 7-1	Mix Design Criteria
Target Air Voids	3.11%	3.33%	3.5 ± 0.5
Optimum Binder Content (%)	5.20	5.10	----
Virgin Asphalt Binder Content (ADD AC %)	1.30	1.28	----
Virgin Aggregate Content (% Dry Mix Weight)	10%	11%	----
RAP Content (% Dry Mix Weight)	0.90	0.89	----
RAP Content (% Total Aggregate)	0.90	0.88	----
Aggregate Bulk Specific Gravity (G_{sb})	2.649	2.649	----
Aggregate Effective Specific Gravity (G_{se})	2.725	2.724	----
Aggregate Apparent Specific Gravity (G_{sa})	2.733	2.732	----
Aggregate Water Absorption (%)	1.152	1.146	----
Asphalt Binder Bulk Specific Gravity (G_b)	1.036	1.036	----
Bulk Specific Gravity at Optimum AC (G_{mb})	2.434	2.431	----
Maximum Theoretical Specific Gravity (G_{mm})	2.512	2.515	----
Percent Binder Absorption (P_{ba} %)	1.09	1.08	----
Percent Effective Binder (P_{be} %)	4.16	4.08	----
Comb. Agg. Surface Area (m^2/ Kg.)	6.00	5.96	----
Comb. Agg. Dust Content ($P_{0.075}$ %)	7.28	7.22	Maximum 10%
%G_{mm} at N_{ini} (7 gyrations)	84.67	82.48	≤ 92.0%
%G_{mm} at N_{des} (68 gyrations)	96.89	96.67	96.5% ± 0.5
%G_{mm} at N_{max} (104 gyrations)	97.98	97.49	≤ 98.0%
Voids in Mineral Aggregate (VMA, %)	12.89	12.90	Minimum 14%
Voids Filled with Asphalt (VFA, %)	75.90	74.19	70% - 80%
Dust to Binder Ratio ($P_{0.075}/P_{be}$)	1.75	1.77	0.6 - 1.4
Film Thickness (µm)	6.94	6.84	- 13 µm

2.5 Hamburg Wheel Tracking (HWT) Device

The Hamburg Wheel Tracking (HWT) device applies a constant load of 685 N through a steel wheel with a diameter of 203.5 mm and a width of 47.0 mm. The test is run in a water bath that is heated to 50 °C after the test specimens are conditioned for 30 minutes. Figure 2.6 shows the HWT device and the test specimens. The test is completed when the wheel has passed over the specimens 20,000 times for 6.5 hours or when the rut depth exceeds 20 mm. NCHRP Report 691 recommends the temperatures for short-term and performance aging of WMA mixtures. For short-term aging, two hours at the compaction temperature is recommended for both WMA and HMA mixtures. For performance aging, four hours at the compaction temperature is recommended for HMA and two hours at compaction temperature followed by16 hours at 60°C (140°F) is recommended for WMA.

The Hamburg Wheel Tracking Device measures rut depth throughout the test and reports four properties: 1) post-compaction consolidation, 2) creep slope, 3) stripping inflection point, and 4) stripping slope. The post-compaction consolidation occurs at around 1,000 wheel passes that is normally caused by the densification of the mixture. The creep slope is used to measure the rutting susceptibility of the mixture that measures the permanent deformation caused by the wheel passes. The higher creep slope indicates the lower rutting resistance of the mixture. The stripping inflection point (SIP) and the stripping slope are used to identify the wheel pass when the specimen is damaged due to moisture. The higher number of passes to SIP indicates the higher resistance to moisture damage and the higher stripping slope value indicates the lower rutting resistance during moisture damage of the mixture. In general, a mixture with a stripping inflection point less than 10,000 passes is considered as moisture susceptible.

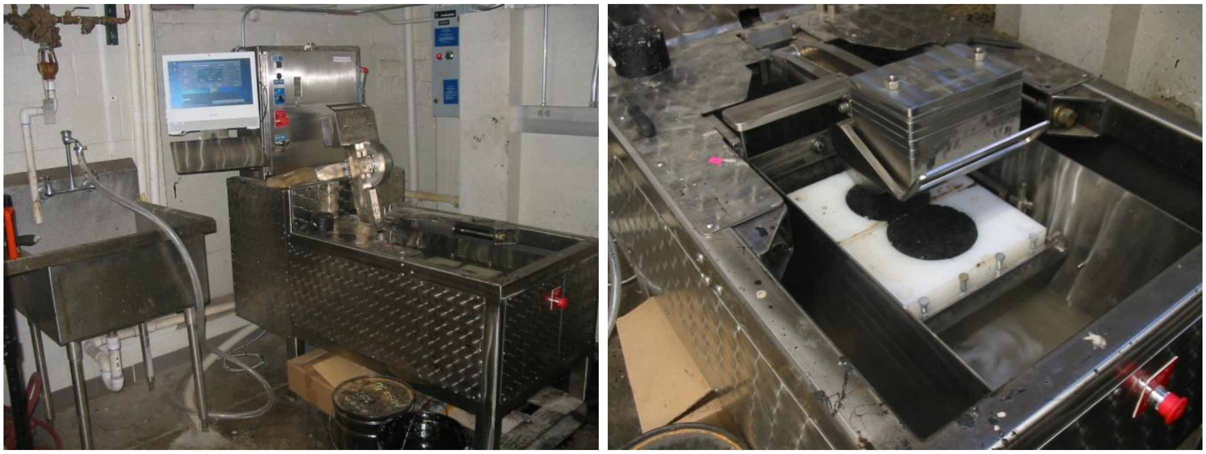

Figure 2.6 Hamburg wheel tracking device (left) and specimens ready for testing (right)

The HWT test was performed on both laboratory WMA and HMA specimens with a target air void content of 7.0 ± 2.0 %. Specimens were compacted with a height of 60 mm to fit the mold for the Hamburg Wheel Tracking device. As shown in Figure 2.7, 7.5 mm of material was removed from one side of the specimen so that they fit together in the specimen tray.

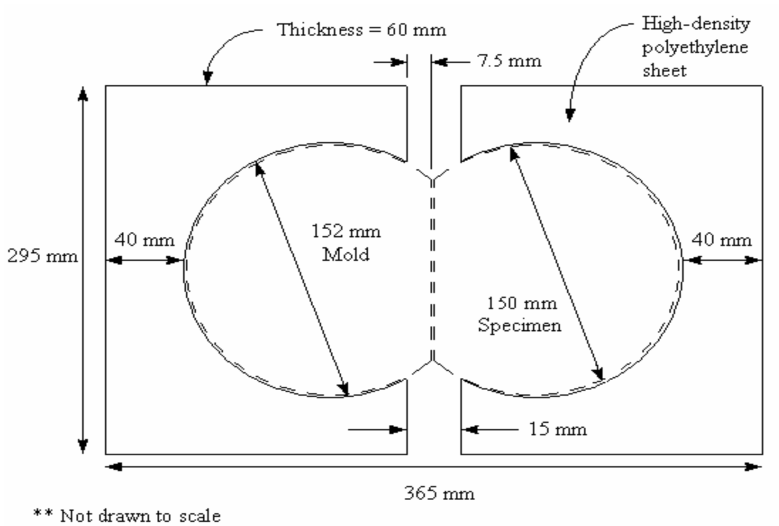

Figure 2.7 Dimensions of the specimen and the mold

2.6 Hamburg Wheel Tracking Test Results

All the HWT tests were run in a water bath that is heated to 50 °C after the test specimens are conditioned for 30 minutes. The test is automatically terminated at 20,000 wheel passes or at a maximum of 20 mm rut depth. The specimen fails the test when the maximum rut depth at any point of the specimen surface reaches 20 mm at passes less than less than 20,000.

2.6.1 Mixtures with 20% RAP by Binder Replacement

The HWT test results of HMA and WMA mixture including 20% RAP by binder replacement are summarized in Table 2.12 and plotted in Figure 2.8. All HMA specimens successfully passed the test with the average maximum rut depth of 14.33 mm. WMA mixtures didn’t pass the test and the average number of passes to failure (20 mm rut depth) was 8,675 passes. The average SIP values were 10,250 passes for HMA specimens and 4,375 for WMA specimens.

2.6.2 Mixtures with 30% RAP by Binder Replacement

The HWT test results of HMA and WMA mixtures including 30% RAP by binder replacement are summarized in Table 2.13 and plotted in Figure 2.9. All HMA specimens successfully passed the test with the average maximum rut depth of 16.2 mm. WMA mixtures didn’t pass the test and the average number of passes to failure (20 mm rut depth) was 11,450 passes. The average SIP values were 8,000 passes for HMA specimens and 6,250 for WMA specimens. It is interesting to note that the SIP value for HMA was lower but the SIP value for WMA was higher when the RAP amount was increased from 20% to 30% by binder replacement.

2.6.3 Mixtures with 40% RAP by Binder Replacement

The HWT test results of HMA and WMA mixture including 40% RAP are summarized in Table 2.14 and plotted in Figure 2.10. All HMA specimens successfully passed the test with the average maximum rut depth of 12.0 mm. WMA mixtures didn't pass the test, and the average number of passes to failure (20 mm rut depth) was 13,075 passes. The average SIP were 10,500 passes for HMA specimens, and 6,875 for WMA specimens. It should be noted that the SIP value for HMA was higher but the SIP value for WMA was similar when the RAP amount was increased from 30% to 40% by binder replacement.

2.6.4 Mixtures with 50% RAP by Binder Replacement

The HWT test results of HMA and WMA mixture including 50% RAP are summarized in Table 2.15 and plotted in Figure 2.11. Both HMA and WMA specimens successfully passed the test with the average maximum rut depths of 4.2 mm and 19.0 mm, respectively. The average SIP were 15,000 passes for HMA specimens, and 10,750 for WMA specimens. It should be noted that the SIP values for both HMA and WMA were significantly higher when the RAP amount was increased from 40% to 50% by binder replacement.

2.6.5 Mixtures with 75% RAP by Binder Replacement

The Hamburg Wheel Tracking Test results of HMA and WMA mixture including 50% RAP are summarized in Table 2.16 and plotted in Figure 2.12. Both HMA and WMA specimens successfully passed the test with the average maximum rut depths of 2.5 mm for HMA specimens and 3.8 mm for WMA specimens. The average SIP values of both HMA and WMA specimens were greater than 20,000 passes when 75% RAP materials by binder replacement (90% RAP materials by weight) were used.

Table 2.12 Hamburg wheel test results for mixtures including 20% RAP

20 % RAP-Mix Type	Test ID	Air Voids, %	Total Number of Passes	Inverse Creep Slope (Pass/mm)	Inverse Stripping Slope (Pass/mm)	SIP	Max. Rut Depth, mm
HMA	HMA 1	6.0	20000	2200	1837	11000	10.9
	HMA 2	6.1	20000	4211	856	9500	17.8
	Average	**6.0**	**20000**	**3205**	**1347**	**10250**	**14.3**
LEADCAP 7-1	L 1	6.1	8400	938	321	3750	20.0
	L 2	6.1	8950	1250	272	5000	20.0
	Average	**6.1**	**8675**	**1094**	**297**	**4375**	**20.0**

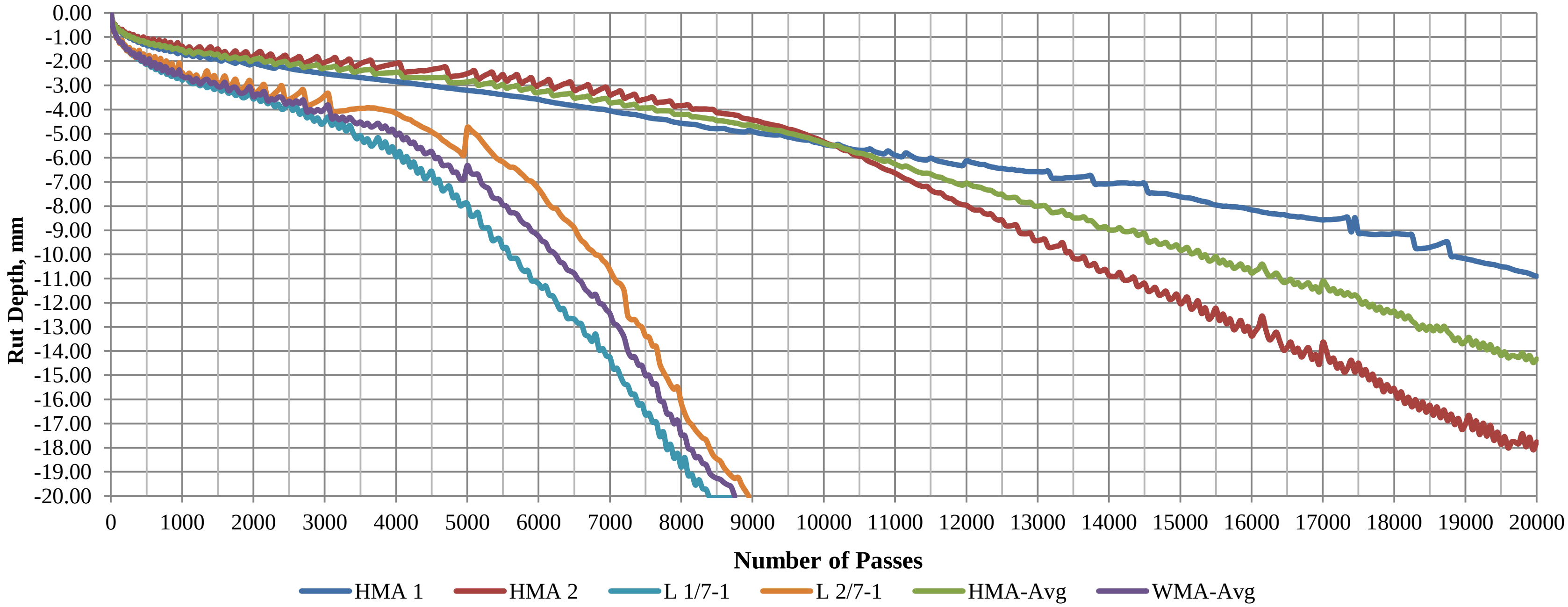

Figure 2.8 Hamburg wheel test results for mixtures including 20% RAP

Table 2.13 Hamburg wheel test results for mixtures including 30% RAP

30 % RAP-Mix Type	Test ID	Air Voids %	Total Number of Passes	Inverse Creep Slope (Pass/mm)	Inverse Stripping Slope (Pass/mm)	SIP	Max. Rut Depth, mm
HMA	HMA 1	6.4	20000	3200	1161	8000	14.3
	HMA 2	6.3	20000	3200	853	8000	18.1
	Average	**6.3**	**20000**	**3200**	**1007**	**8000**	**16.2**
LEADCAP 7-1	L 1	6.4	10650	1429	377	5000	20.0
	L 2	6.2	12250	1364	352	7500	20.0
	Average	**6.3**	**11450**	**1396**	**364**	**6250**	**20.0**

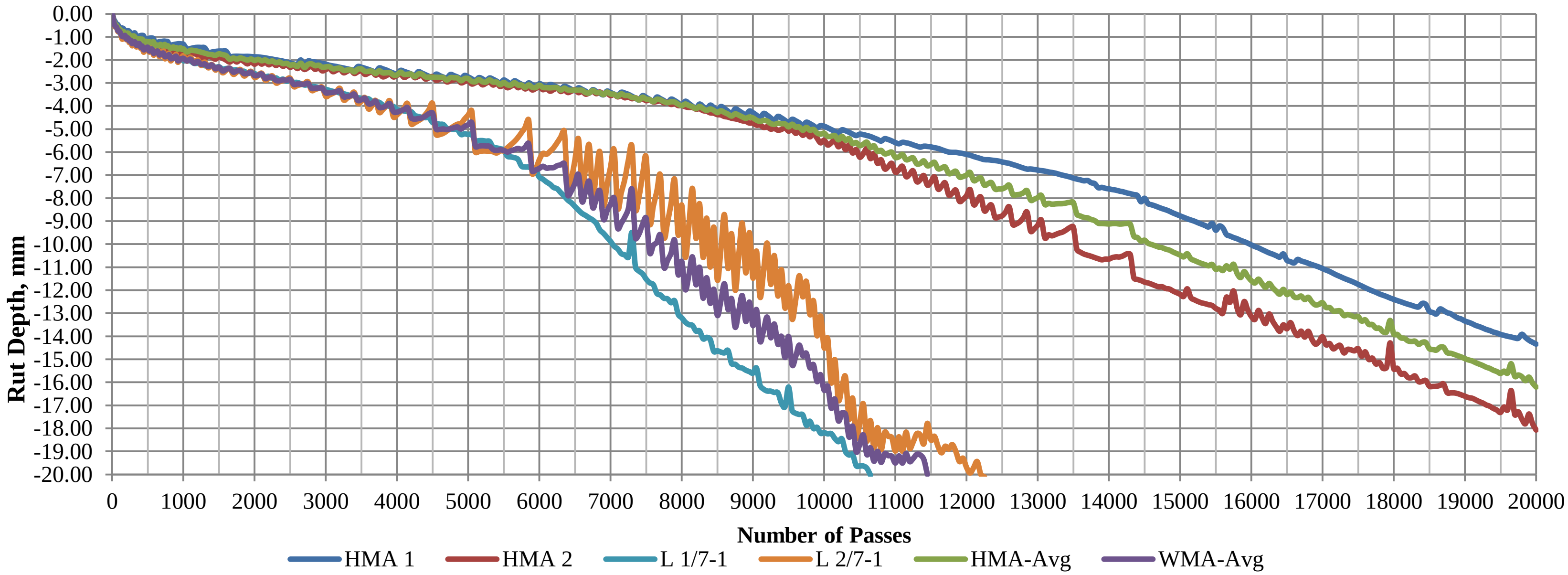

Figure 2.9 Hamburg wheel test results for mixtures including 30% RAP

Table 2.14 Hamburg wheel test results for mixtures including 40% RAP

40 % RAP-Mix Type	Test ID	Air Voids %	Total Number of Passes	Inverse Creep Slope (Pass/mm)	Inverse Stripping Slope (Pass/mm)	SIP	Max. Rut Depth, mm
HMA	HMA 1	6.7	20000	4400	1343	11000	9.7
	HMA 2	6.6	20000	1667	1274	10000	14.4
	Average	**6.6**	**20000**	**3033**	**1309**	**10500**	**12.0**
LEADCAP 7-1	L 1	6.8	14650	1938	468	7750	20.0
	L 2	7.35	11500	6.78	1304	407	6000
	Average	**7.06**	**13075**	**1621**	**438**	**6875**	**20.0**

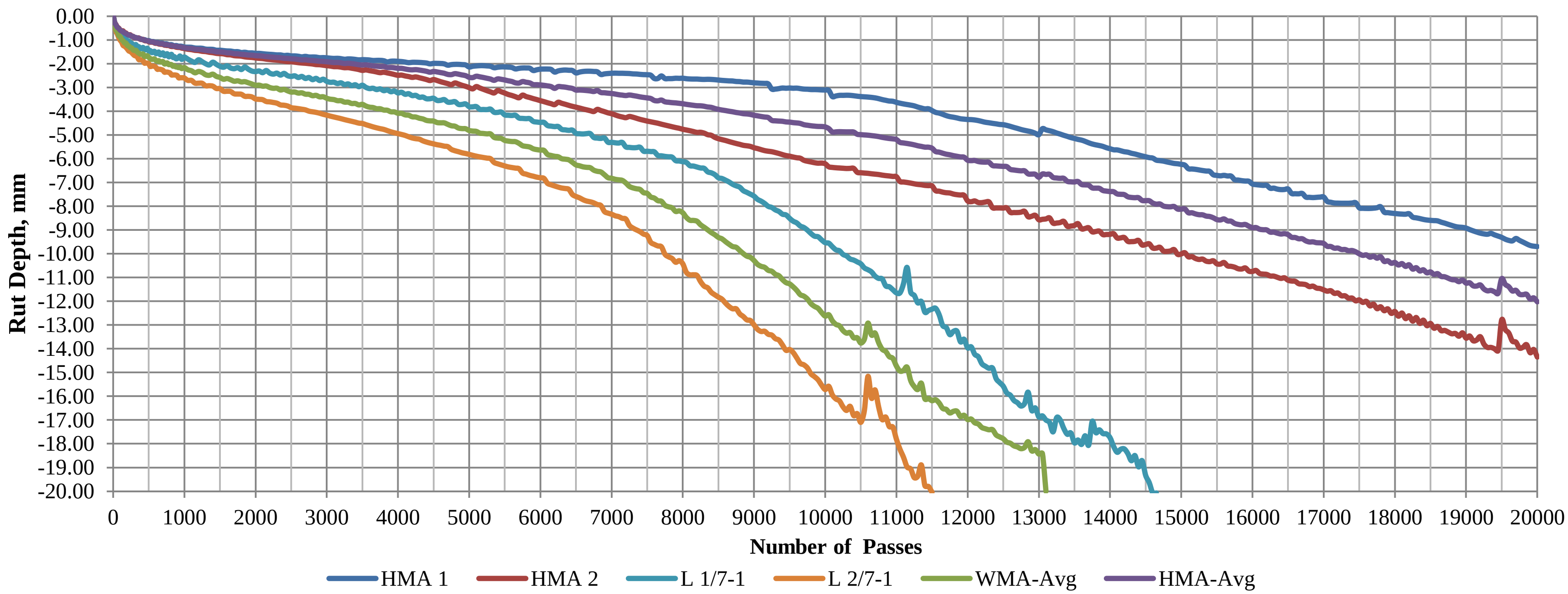

Figure 2.10 Hamburg wheel test results for mixtures including 40% RAP

Table 2.15 Hamburg wheel test results for mixtures including 50% RAP

50 % RAP-Mix Type	Test ID	Air Voids %	Total Number of Passes	Inverse Creep Slope (Pass/mm)	Inverse Stripping Slope (Pass/mm)	SIP	Max. Rut Depth, mm
HMA	HMA 1	6.6	20000	7500	4202	15000	3.7
	HMA 2	6.5	20000	5455	3226	15000	4.8
	Average	**6.5**	**20000**	**6477**	**3714**	**15000**	**4.2**
LEADCAP 7-1	L 1	6.2	20000	4500	509	13500	17.0
	L 2	6.1	20000	2462	765	8000	20.0
	Average	**6.2**	**20000**	**3481**	**637**	**10750**	**19.0**

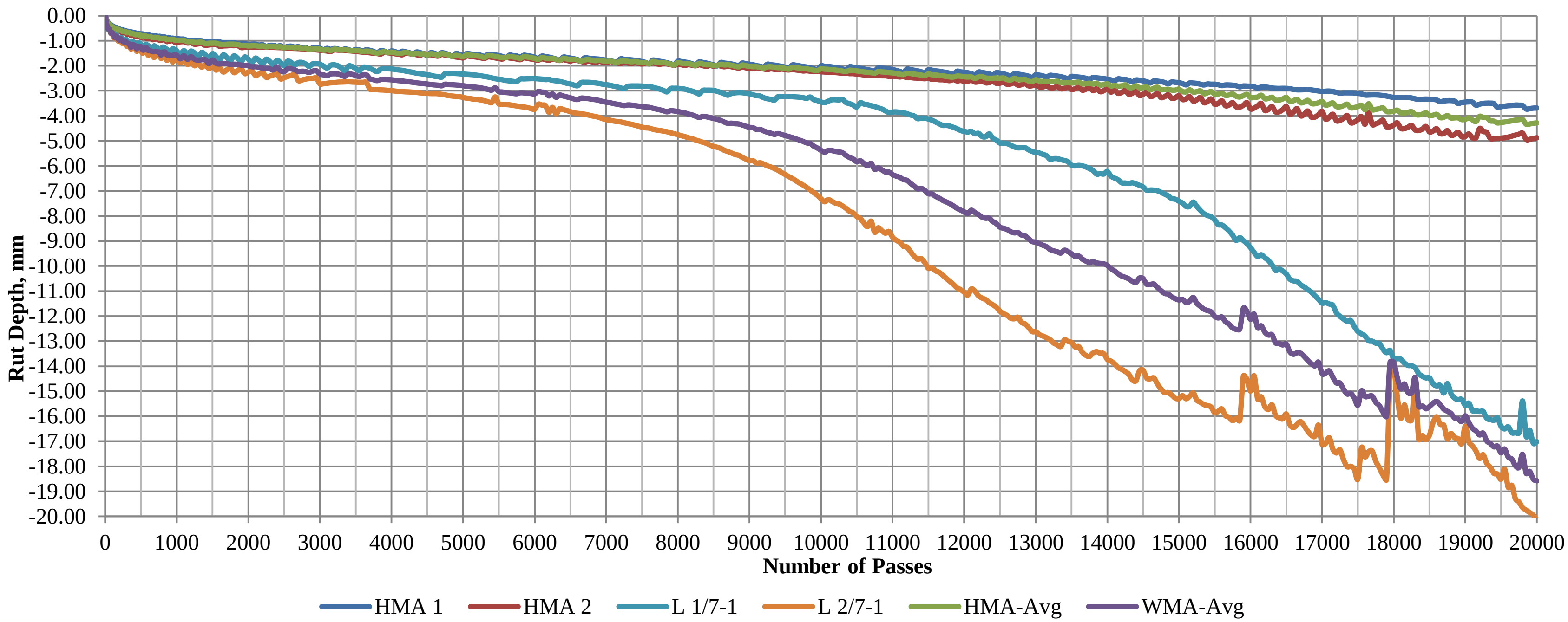

Figure 2.11 Hamburg wheel test results for mixtures including 50% RAP

Table 2.16 Hamburg wheel test results for mixtures including 75% RAP

75 % RAP-Mix Type	Test ID	Air Voids %	Total Number of Passes	Inverse Creep Slope (Pass/mm)	Inverse Stripping Slope (Pass/mm)	SIP	Max. Rut Depth, mm
HMA	HMA 1	6.2	20000	8929	N/A	>20000	2.7
	HMA 2	6.1	20000	10870	N/A	>20000	2.3
	Avg	**6.1**	**20000**	**9899**	**N/A**	**>20000**	**2.5**
LEADCAP 7-1	L 1	6.5	20000	5970	N/A	>20000	3.9
	L 2	6.2	20000	6309	N/A	>20000	3.7
	Avg	**6.3**	**20000**	**6140**	**N/A**	**>20000**	**3.8**

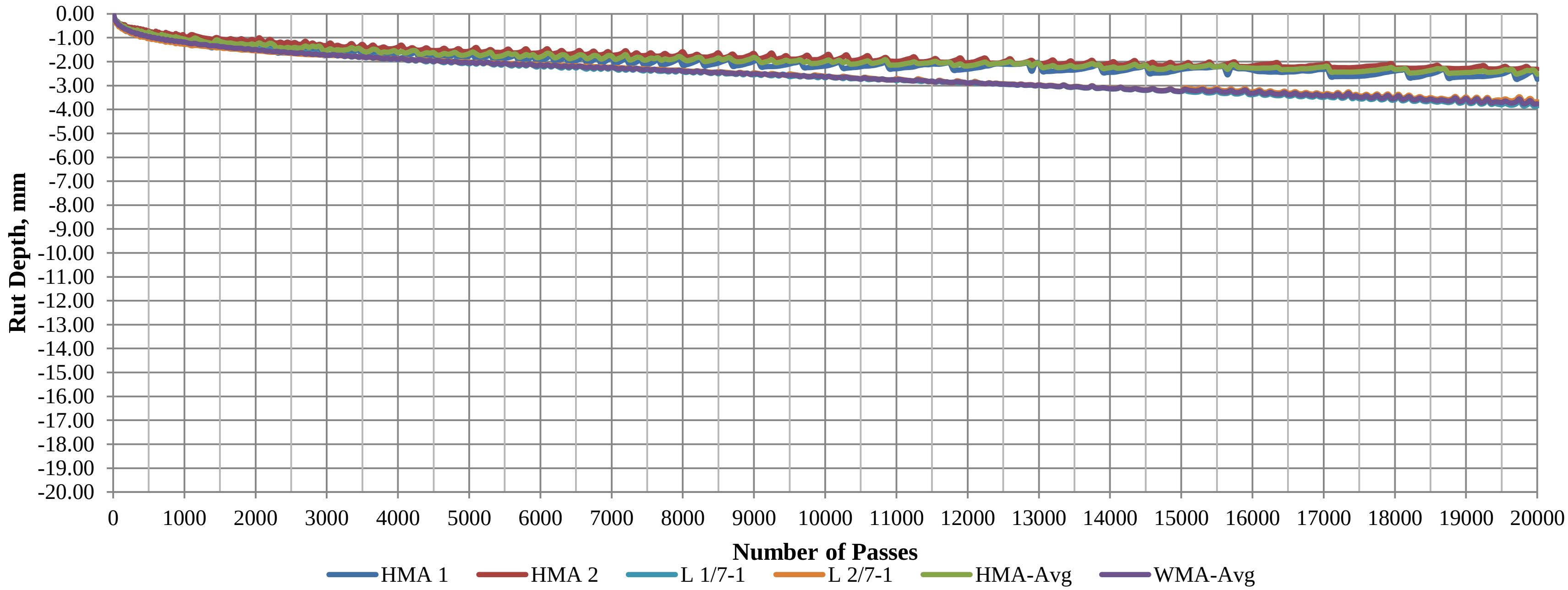

Figure 2.12 Hamburg wheel test results for mixtures including 75% RAP

Chapter 3 Field Implementation of WMA Mixtures with RAP Materials

3.1 State Highway 6 in Iowa

Two test sections were constructed for the field evaluation study; one HMA section with approximately 0.3 mile long, and one WMA section with approximately 0.5 mile long. The two test sections consisted of surface layer with a thickness of 1.5 inch. The HMA mix was placed on the inside lane and the WMA mix was placed on the outside lane. As shown in Figure 3.1, the test sections are located on the west bound of Highway 6 started from south of Lakeside drive towards the downtown of Iowa City, Iowa. The two mixtures were used for comparison: HMA as a control mixture and WMA mixture prepared using LEADCAP additive. The mixtures were designed according to Superpave mix design procedure for a traffic level of 10 million ESALs per Iowa DOT mix design requirements and NCHRP 691 report “Mix Design Practices for Warm Mix Asphalt”. The mixtures used limestone virgin aggregate and 30% fractionated RAP by binder replacement. The LEADCAP technology used for this research effort was RAPCAP (liquid).

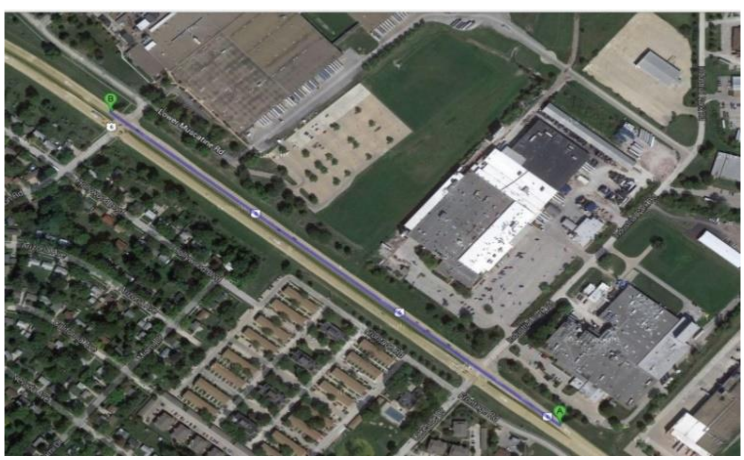

Figure 3.1 Iowa project location (from A to B)

3.1.1 Virgin Aggregate and RAP Material Properties

The aggregate gradation for this project was designed with ½ inch nominal maximum size using 6 different stockpiles collected from River Products Quarry in Coralville, Iowa. All virgin aggregate properties met Iowa DOT specifications. Table 3.1 shows the combined aggregate gradation information for the designed mixes and Figure 3.2 shows a plot of gradation on the 0.45 power gradation chart. The Fractionated RAP from I-80 Interstate Highway was used for building the test sections. In order to meet the mix design requirements, all RAP materials smaller than the 5/16-inch size from the RAP stockpile were removed.

3.1.2 Asphalt Binder

The target performance grade (PG) for the binder used for all mixtures was PG70-22. Iowa DOT requires lowering the PG for the binder used with any mixture includes more 20% RAP by one grade level. Therefore, asphalt binder with PG64-28 was used for the constructed test sections. The asphalt binder properties were evaluated according to AASHTO M320 standard. The selected asphalt binder met all specifications as shown in Table 3.1. Asphalt mixing temperature for the PG 64-28 was determined as 155° C (311° F), as recommended by the binder supplier company.

Table 3.1 Combined aggregate gradation and properties for Iowa project mixtures (source: LL Pelling)

Material	% in Mix	Producer & Location	Type (A or B)	Friction Type	G_{sb}	%Abs
Sand	11.0%	Williams/S&G Materials Inc.	A	4	2.634	0.47
TAT4 Man. sand	14.0%	Klein/River Products Co	A	4	2.649	0.84
3/4" A	11.0%	Klein/River Products Co	A	4	2.652	0.86
3/8" slag	14.0%	Montpelier/Blackheart Slag	A	2	3.709	1.20
3/8 W. chips	12.0%	Columbus Junction/River Products Co	A	4	2.583	3.23
Classified RAP	38.0%	38% ABC13-0119 (3.38 % AC)	A	2	2.662	1.30

Individual Aggregates Sieve Analysis - % Passing (Target)											
Material	1"	3/4"	1/2"	3/8"	#4	#8	#16	#30	#50	#100	#200
Sand	100	100	100	100	95	90	79	53	16	2.0	1.0
TAT4 Man. sand	100	100	100	100	98	76	43	20	8.3	2.8	2.5
3/4" A	100	100	55	19	4.0	3.0	3.0	2.5	2.5	2.0	2.0
3/8" slag	100	100	100	100	31	1.8	1.6	1.5	1.5	1.4	1.0
3/8 W. chips	100	100	100	95	50	15	4.0	2.7	2.6	2.5	2.3
Classified RAP	100	100	93	80	51	36	27	20	14	10	8.8

Preliminary Job Mix Formula Target Gradation											
Upper Tolerance	100	100	99	90	61	42		21			6.4
Comb Grading	**100**	**100**	**92**	**83**	**54**	**37**	**26**	**17**	**9.0**	**5.1**	**4.4**
Lower Tolerance	100	100	85	76	47	32		13			2.4
S. A. sq. m/kg	Total	4.47		+0.41	0.22	0.30	0.43	0.49	0.55	0.62	1.44

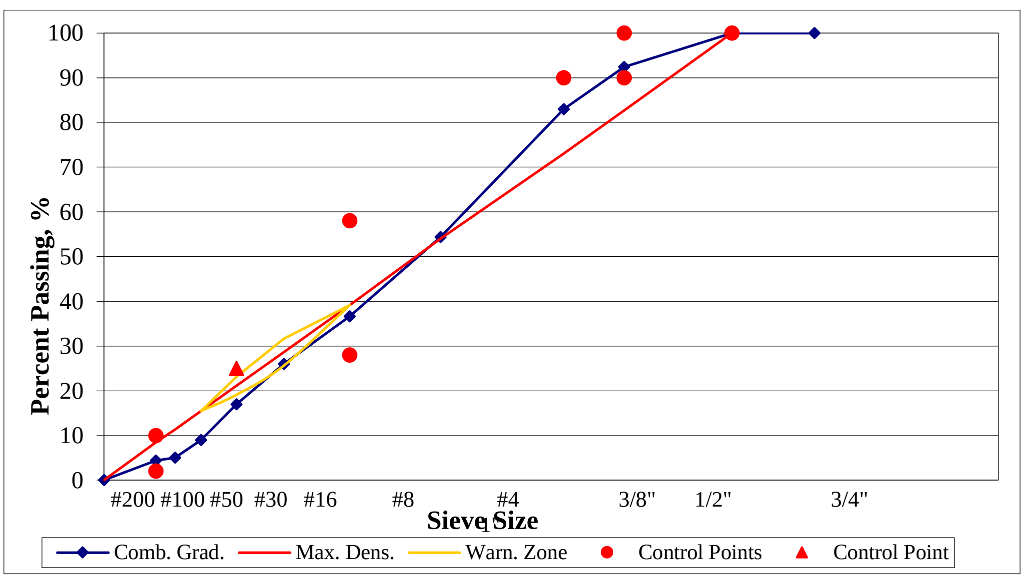

Figure 3.2 Combined aggregate gradation chart for Iowa project mixtures

Table 3.2 Asphalt binder PG64-28 test results (source: BM&S Co.)

ORIGINAL BINDER				
Test Method			**Test Results**	**Specifications**
Flash Point, ASTM D92-05a/AASHTO T48-04			250+	230ºC Min.
Rotational Vis @ 135C, ASTM D4402/AASHTO T316-04			1.062	3.000 Pa-s Max.
DSR (Dynamic Shear Rheometer), AASHTO T315-05				
Test Temperature, ºC	G*, kPa	Phase Angle, δ, degrees	**G*/sinδ, kPa**	
64	2.281	72.02	2.015	1.000 kPa Min.
Fail Temperature			72.25	report, ºC
Density (Pycnometer) ASTM D70-03/AASHTO T228-04			n/a	Report
RTFO (ROLLING THIN FILM OVEN)				
Mass Loss, ASTM D2872-04/AASHTO T240-03			-0.74%	1.000% Max.
DSR (Dynamic Shear Rheometer), AASHTO T315-05				
Test Temperature, ºC	G*, kPa	Phase Angle, δ, degrees	**G*/sinδ, kPa**	
64	4.868	65.77	5.396	2.200 kPa min
Fail Temperature			N/A	report, ºC
PAV (PRESSURE AGING VESSEL), 100C				
DSR (Dynamic Shear Rheometer), AASHTO T315-05				
Test Temperature, ºC	G*, kPa	Phase Angle, δ, degrees	**G*/sinδ, kPa**	
22	5858	40.41	3797	5000 kPa Max.
BBR (Bending Beam Rheometer), ASTM D6648-01/AASHTO T313-05				
Test Temperature, ºC				
-18	Stiffness, MPa		199.5	300 MPa Max.
	m-value		0.319	0.300 Min.
This binder meets the qualifications of a PG 64-28				

3.1.3 Mix Design

Mixing and compaction temperatures for the two mixtures were established following Iowa DOT RAP mix design procedure and they are summarized in Table 3.3. The mix design for the HMA with 30% RAP materials by binder replacement is summarized in Table 3.4. The mix design met all requirements except VMA and the optimum binder content was relatively low (4.33%). Since 30% of the optimum binder content (4.33%) is to be provided by the binder from the RAP materials, only 3.1% virgin asphalt was added.

Table 3.3 Mixing and compaction temperatures for IA project mixtures

Binder Type	Mixture	Binder Temp.	Mixing Temp.	Comp. Temp.
PG 64-28	HMA	300° F (150° C)	300° F (150° C)	285° F (140° C)
PG 64-28	WMA	300° F (150° C)	275° F (135° C)	250° F (125° C)

Table 3.4 Mix design summary for IA project mixtures (source: LL Pelling)

Asphalt Binder Source and Grade:	Bituminous Materials & Supply (Tama, IA)					
Adjust grade to PG 64-28	Gyratory Data					
% Asphalt Binder	3.9	**4.33**	4.6	4.9		Number of Gyrations
Gmb @ N-Des.	2.491	**2.501**	2.508	2.529		N-Initial
Max. Sp.Gr. (Gmm)	2.625	**2.606**	2.594	2.585		8
% Gmm @ N- Initial	86.7	**87.9**	88.6	89.2		N-Design
%Gmm @ N-Max		**96.5**				96
% Air Voids	5.1	**4**	3.3	2.2		N-Max
% VMA	13.1	**13.2**	13.2	12.7	**OUT**	152
% VFA	61.2	**69.7**	74.9	83		Gsb for Angularity Method A
Film Thickness	7.43	**8.43**	9.08	9.62		2.646
Filler Bit. Ratio	1.33	**1.17**	1.08	1.02		
Gse	2.801	**2.8**	2.799	2.803		Pba / %Abs Ratio
Pbe	3.32	**3.77**	4.06	4.3		0.46
Pba	0.6	**0.59**	0.57	0.63		
% New Asphalt Binder	67.9	**71.3**	73	74.7		Slope of Compaction Curve
Combined Gb @ 25°C	1.0296	**1.0296**	1.0296	1.0296		13.6
						Mix Check

Aggregate Type Used	A		Combined	From RAM	Excellent
G_{sb}	2.756	% Friction Type 4 (+4)	62.6	24	Pb Range Check
G_{sa}	2.859	Or Better	89.1	29	1
% Water Abs	1.31	% Friction Type 3 (+4)	0	0	RAM Check
S.A. m^2 / Kg.	4.47	Or Better	26.5	5	OK
Angularity-method A	43	% Friction Type 2 (+4)	26.5	5	
% Flat & Elongated	0.6	% Friction Type 2 (-4)	9	0.9	Specification Check
Sand Equivalent	91	Type 2 Fineness Modulus	2.4	1.6	OUT Does Not Comply
Virgin G_b @ 25°C	1.0294	% Crushed	83	31.6	

Disposition : An asphalt content of 4.30% is recommended to start this project.
Data shown in 4.33% Column is interpolated from test data.
The % ADD AC to start project is 3.10%

3.1.4 Field Compaction and Mat Densities

The construction of the HMA, and WMA test sections started at 7 pm on the 8th and the 9th of September, 2013 respectively. The construction process went very well in terms of field compaction. As shown in Figure 3.3, the HMA mixture produced more emission and smoke than the WMA mixture that produced little smoke or emission. Figure 3.4 shows pictures of the test sections after construction is completed.

Figure 3.3 HMA (left) and WMA (right) emissions during construction

Figure 3.4 Test sections after compaction

The target air voids during construction was 5.0 to 6.0%. A total number of 6 cores were collected from each test section to measure the filed densities of the test sections. The average densities of the HMA and WMA test sections were 94.3%, and 93.9%, respectively. Tables 3.5 and 3.6 show the density data for HMA and WMA, respectively.

Table 3.5 Density data for HMA test section (source: LL Pelling)

COMPACTED MAT_HMA TEST SECTION										
Core	Station	CL Reference	W1 Dry (g)	W2 in H20 (g)	W3 Wet (g)	Diff.	G_{mb}	% of G_{mm}	P_a (%)	Thickness (in.)
1	234+65	3.0 S\W Pass	819.5	479.5	820.0	340.5	2.407	92.3	7.7	1.63
2	229+88	4.6 S\W Pass	867.8	516.5	868.3	351.8	2.467	94.6	5.4	1.75
3	229+33	8.0 S\W Pass	814.9	487.5	815.1	327.6	2.487	95.3	4.7	1.50
4	216+40	7.6 S\W Pass	715.3	422.9	715.9	293.0	2.441	93.6	6.4	1.50
5	213+89	1.0 S\W Pass	701.3	417.2	701.9	284.7	2.463	94.4	5.6	1.25
6	209+39	7.2 S\W Pass	650.4	389.9	650.8	260.9	2.493	95.6	4.4	1.25
Course Placed:			Surface (Travel Lane)				Thickness QI:		0.96	
Intended Lift Thickness:			1.50				Avg. Mat Density:		2.460	
Date Placed:			09/08/13				Avg. % of G_{mm}:		94.300	
Test Date/By:			09/08/13				Avg. % Field Voids:		5.70	

Table 3.6 Density data for WMA test section (source: LL Pelling)

COMPACTED MAT_WMA TEST SECTION										
Core	Station	CL Reference	W1 Dry (g)	W2 in H20 (g)	W3 Wet (g)	Diff.	G_{mb}	% of G_{mm}	P_a (%)	Thickness (in.)
1	268+00	6.9 S\W Drv	767.2	460.5	776.7	316.2	2.426	92.9	7.1	1.50
2	262+74	9.6 S\W Drv	836.4	496.2	837.0	340.8	2.454	94.0	6.0	1.75
3	260+65	9.8 S\W Drv	793.0	468.2	793.7	325.5	2.436	93.3	6.7	1.63
4	256+63	1.0 S\W Drv	791.0	471.6	791.6	320.0	2.472	94.6	5.4	1.50
5	250+69	2.6 S\W Drv	772.8	460.5	773.4	312.9	2.470	94.6	5.4	1.50
6	244+98	7.6 S\W Drv	832.3	494.2	832.8	338.6	2.458	94.1	5.9	1.75
Course Placed:			Surface (Travel Lane)				Thickness QI:		2.42	
Intended Lift Thickness:			1.50				Avg. Mat Density:		2.453	
Date Placed:			09/09/13				Avg. % of G_{mm}:		93.917	
Test Date/By:			09/09/13				Avg. % Field Voids:		6.08	

3.1.5 Hamburg Wheel Tracking Test

Hamburg Wheel Tracking (HWT) test was performed on both laboratory-compacted field specimens. Loose mix samples were collect from the asphalt plant and the HWT test specimens were fabricated in the asphalt research laboratory at the University of Iowa. The specimens had a target air void content of 7.0 ± 2.0 % following the AASHTO T 324 Standards for “Hamburg Wheel-Track Testing of Compacted Hot Mix Asphalt (HMA)”. Specimens were compacted with approximate height of 60 mm to fit the mold for the HWT device. 7.5 mm of material was removed from one side of the specimen so that they fit together in the specimen tray. The Hamburg Wheel Tracking Test results of HMA and WMA mixture are summarized in Table 3.7 and plotted in Figure 3.5. As it can be seen from the test results in Figure 3.5, both HMA and WMA specimens successfully passed the test with average maximum rut depths of 3.0 mm for HMA specimens and 4.9 mm for WMA specimens. The average SIP were greater than 20,000 passes for both HMA and WMA specimens. It can be concluded that both HMA and WMA mixtures exhibited high resistance to rutting and moisture damage.

Table 3.7 Hamburg wheel test results for IA test sections

Mix Type	Test ID	Air Voids %	Total Number of Passes	Inverse Creep Slope (Pass/mm)	Inverse Stripping Slope (Pass/mm)	SIP	Max. Rut Depth, mm
HMA	**HMA 1**	**6.93%**	**20000**	**13072**	**N/A**	**>20000**	**2.8**
	HMA 2	**6.75%**	**20000**	**9699**	**N/A**	**>20000**	**3.3**
	Average	**6.84%**	**20000**	**11386**	**N/A**	**>20000**	**3.0**
WMA/ RAPCAP	**L 1**	**6.50%**	**20000**	**7117**	**N/A**	**>20000**	**4.1**
	L 2	**6.70%**	**20000**	**4376**	**N/A**	**>20000**	**5.7**
	Average	**6.60%**	**20000**	**5747**	**N/A**	**>20000**	**4.9**

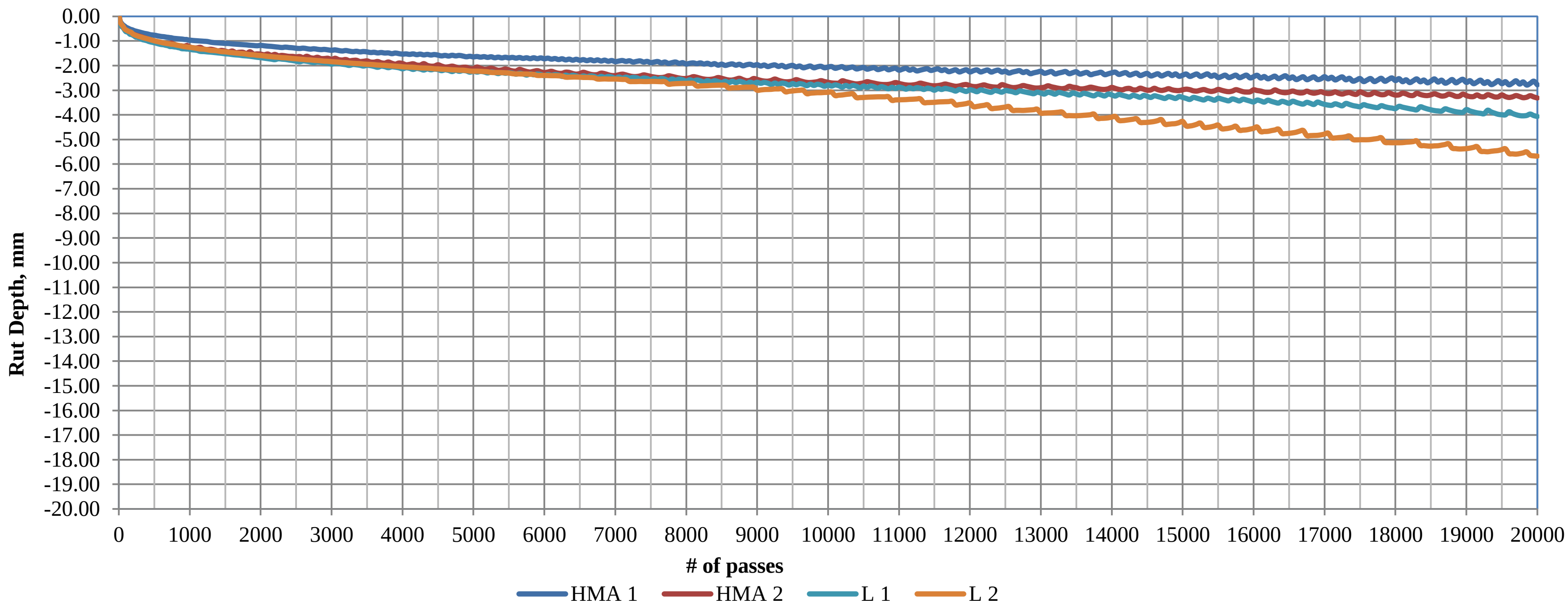

Figure 3.5 Hamburg wheel test results for IA test sections

3.2 State Highway 158 in Ohio

The WMA project is located on State Highway 158 at the milepost of 75.5 in Lancaster, Ohio. The WMA test section starts from mile post 75.5 to mile post 85.5 with a total length of 1 mile. The HMA mixtures were applied at the section adjacent to the WMA test section at mile post 85.5. A 3.0-inch asphalt layer was constructed that consisted of two layers; the intermediate layer with a thickness of 1.75 inch and the surface layer with a thickness of 1.25 inch.

The two mixtures designed for this research study were: HMA as a control mixture and WMA mixture prepared using LEADCAP additive. The mixtures were designed according to Marshall mix design procedure following Ohio DOT mix design specifications and NCHRP 691 report “Mix Design Practices for Warm Mix Asphalt”. The mixtures used a blend of limestone and gravel aggregates and 25% RAP materials by weight for an intermediate layer and 20 % RAP by weight for a surface layer.

3.2.1 Aggregate properties

Intermediate Layer: The aggregate gradation for the intermediate layer was designed with 3/4 inch nominal maximum size using 5 different stockpiles collected from the Shelly Company Quarry in Lancaster, Ohio. All virgin aggregate properties met Iowa DOT mix design requirements. The combined aggregate gradation is summarized in Table 3.8 and plotted on a 0.45 power gradation chart in Figure 3.6.

Table 3.8 Aggregate gradation and properties for intermediate layer mixtures (ODOT)

Sieve Size		Stockpile and percentage passing						Design Spec, NMAS 1 inch	
ID	mm	Limestone	Limestone /Gravel	Natural Sand	Limestone Sand	RAP	Combined Gradation	Min.	Max.
1 in	25	100.0	100.0	100.0	100.0	100.0	100	95	100
3/4 in	19	83.0	100.0	100.0	100.0	100.0	94	85	100
1/2 in	12.5	38.0	100.0	100.0	100.0	98.0	79	65	85
3/8 in	9.5	20.0	90.0	100.0	100.0	89.3	70	-	-
#4	4.75	5.0	17.0	99.0	94.0	65.0	49	35	60
#8	2.36	4.0	3.0	87.0	66.0	48.5	37	25	48
#16	1.18	4.0	3.0	68.0	40.0	35.5	27	16	36
#30	0.6	4.0	3.0	47.0	26.0	26.5	19	12	30
#50	0.3	4.0	3.0	16.0	17.0	16.5	11	5	18
#100	0.15	4.0	2.0	4.0	10.0	11.8	7	2	10
#200	0.075	2.5	2.0	3.0	5.7	9.2	5	-	-
% of Each stockpile		33.0%	12.0%	15.0%	15.0%	25.0%	100.0%	Check Total	

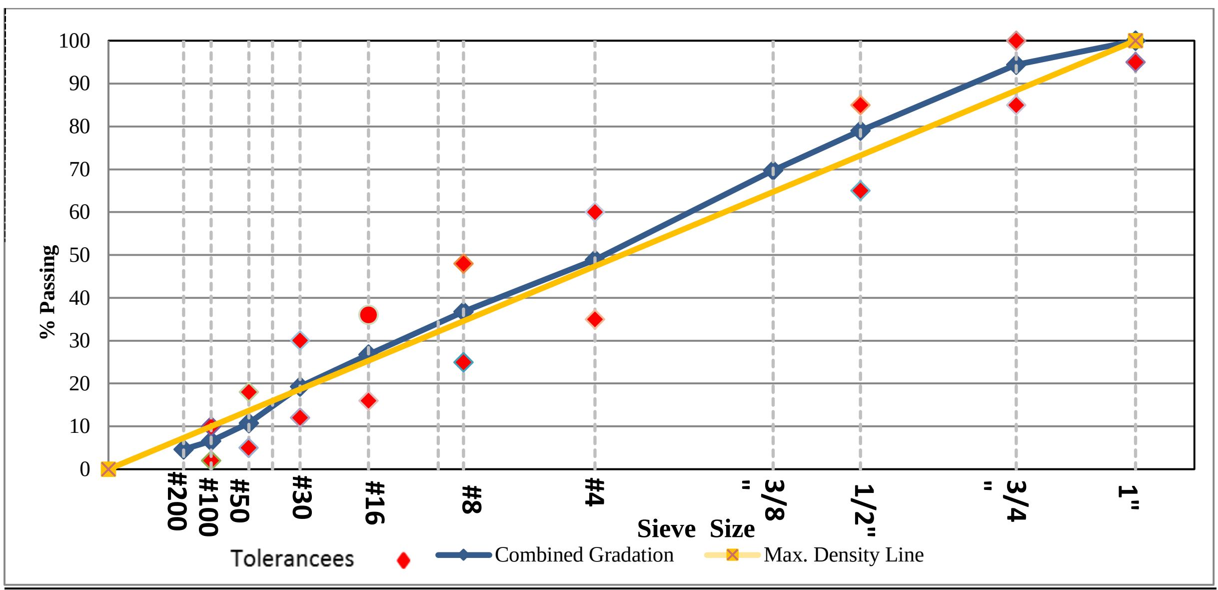

Figure 3.6 Combined aggregate gradation chart for intermediate layer mixtures (ODOT)

Surface Layer: The aggregate gradation for the surface layer was designed with 1/2 inch nominal maximum size using 4 different stockpiles collected from the Shelly Company Quarry in Lancaster, Ohio. All virgin aggregate properties met Iowa DOT mix design requirements. The combined aggregate gradation is summarized in Table 3.9 and plotted on a 0.45 power gradation chart in Figure 3.7.

Table 3.9 Aggregate gradation and properties for surface layer mixtures (ODOT)

Sieve Size		Stockpile and percentage passing					Design Spec, NMAS 1/2 inch	
ID	mm	Limestone /Gravel	Natural Sand	Limestone Sand	RAP	Combined Gradation	Min.	Max.
1 in	25	100.0	100.0	100.0	100.0	100	100	100
3/4 in	19	100.0	100.0	100.0	100.0	100	100	100
1/2 in	12.5	100.0	100.0	100.0	98.0	100	100	100
3/8 in	9.5	92.0	100.0	100.0	89.5	94	90	100
#4	4.75	20.0	99.0	94.0	65.3	55	45	57
#8	2.36	3.0	87.0	66.0	49.0	38	30	45
#16	1.18	3.0	68.0	40.0	35.8	28	17	35
#30	0.6	3.0	47.0	26.0	26.8	20	12	15
#50	0.3	3.0	16.0	17.0	16.8	10	5	18
#100	0.15	2.0	4.0	10.0	12.0	5	2	10
#200	0.075	2.0	3.0	5.7	9.3	4		
% of Each stockpile		47.0%	23.0%	10.0%	20.0%	100.0%	Check Total	

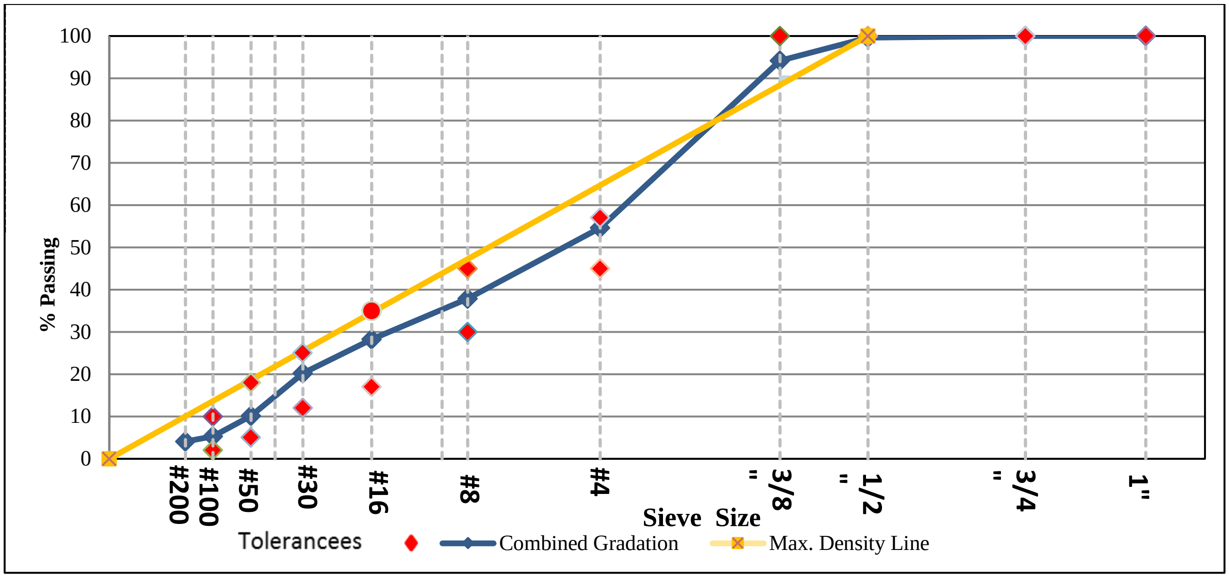

Figure 3.7 Combined aggregate gradation chart for surface layer mixtures (ODOT)

3.2.2 Asphalt Binder

The asphalt binder used for the intermediate layer was PG 64-22. Asphalt mixing temperature for the PG 64-22 was determined as 155° C (311° F), as recommended by the binder supplier company. The asphalt binder used for the surface layer was PG 70-22M. Asphalt mixing temperature for the PG 70-22M was determined as 160° C (320° F), as recommended by the binder supplier company.

3.2.3 Field Compaction and Mat Densities

Intermediate Layer: The construction of the HMA and WMA test sections started at 7 am on the 27th of August, 2013. Figure 3.8 shows pictures of the test sections during construction. The WMA mixtures showed better workability during construction, which resulted in less compaction effort than the compaction effort needed for HMA mixture. The target field air voids during compaction was 6.0%. The nuclear gauge method was used to measure the mat densities during construction. Three cores were extracted and used to calibrate the nuclear gauge. Four to Six different locations per mile were selected to measure the densities of the asphalt mat. The average densities of the HMA and WMA test sections were 94.6%, and 95.3% respectively. Table 3.10 shows the density data for both HMA and WMA test sections.

Surface Layer: The construction of the HMA and WMA test sections started at 7 am on 14th and 16th of September, 2013 respectively. Three cores were extracted and used to calibrate the nuclear gauge. Four to Six different locations per mile were selected to measure the densities of the asphalt mat. The average densities of the HMA and WMA test sections were 94.6%, and 95.2% respectively. Table 3.11 shows the density data for HMA and WMA test sections.

Figure 3.8 The construction process of the intermediate layer

Table 3.10 Density data of HMA and WMA test sections for intermediate layer (ODOT)

8/27/13/ LEADCAP	Gauge Reading (Contractor QC)		
Longitudinal Location	Transverse Location	Actual Gauge Reading, pcf	% Density
334100 NB	L	143.5	93.7
324100 NB	C	146.1	95.4
314100 NB	R	146	95.9
304100 NB	L	147	96
294100 NB	C	146.4	95.6
ODOT QA Tests	Pcfs L C R Ave	% Density	ODOT Initials
334100 NB	143.5 143.3 140.3 142.4	93.0	
290100 NB	146.2 146.3 143.0 145.2	94.8	
8/27/13/ HMA	Gauge Reading (Contractor QC)		
Longitudinal Location	Transverse Location	Actual Gauge Reading, pcf	% Density
376100 NB	L	141.8	95.6
366100 NB	C	142.6	94.1
356100 NB	R	140.9	95
346100 NB	L	141.8	93.6
ODOT QA Tests	Pcfs L C R Ave	% Density	ODOT Initials
356100 NB	144.7 149.1 140.9 144.9	95.6	
346100 NB	141.8 144.7 141.7 142.7	94.2	

Table 3.11 Density data of HMA and WMA test sections for surface layer (ODOT)

9/16/13/ LEADCAP	Gauge Reading (Contractor QC)		
Longitudinal Location	Transverse Location	Actual Gauge Reading, pcf	% Density
336100 NB	L	143.2	95.7
326100 NB	C	144.3	96.5
316100 NB	R	140.9	94.2
306100 NB	L	140.1	93.7
296100 NB	C	143.5	95.9
286100 NB	R	142	94.9
ODOT QA Tests	Pcfs L C R Ave	% Density	ODOT Initials
326100 NB	139.2 144.3 140.9 141.5	94.6	
306100 NB	141.7 144.4 141.6 142.6	95.3	
9/14/13/ HMA	Gauge Reading (Contractor QC)		
Longitudinal Location	Transverse Location	Actual Gauge Reading, pcf	% Density
376100 NB	L	141.8	95.6
366100 NB	C	142.6	94.1
356100 NB	R	140.9	95
346100 NB	L	141.8	93.6
ODOT QA Tests	Pcfs L C R Ave	% Density	ODOT Initials
356100 NB	144.7 149.1 140.9 144.9	95.6	
346100 NB	141.8 144.7 141.7 142.7	94.2	

3.2.4 Hamburg Wheel Tracking Test

Hamburg Wheel Tracking (HWT) test was performed on both laboratory WMA and HMA specimens. Loose mix samples were collect from The Shelly Company's mix plant located in Lancaster, Ohio. The HWT test specimens were fabricated in the asphalt research laboratory at the University of Iowa. The specimens had a target air void content of 7.0 ± 2.0 % per AASHTO T 324 Standards for "Hamburg Wheel-Track Testing of Compacted Hot Mix Asphalt (HMA)". Specimens were compacted with approximate height of 60 mm to fit the mold for the HWT device. 7.5 mm of material was removed from one side of the specimen so that they fit together in the specimen tray.

The Hamburg Wheel Tracking Test results of HMA and WMA mixture for the intermediate layer and the surface layer are summarized in Table 3.12 (plotted in Figure 3.8) and Table 3.13 (plotted in Figure 3.9), respectively.

As can be seen from the test results, both HMA and WMA specimens for both layers successfully passed the test. The maximum rut depths for the intermediate layer mixtures were 3.9 mm for HMA specimens with SIP greater than 20,000 passes and 14.9 mm for WMA specimens with average SIP of 8,250 passes. The maximum rut depths for the surface layer mixtures were 3.2 mm for HMA specimens with SIP greater than 20,000 passes and 7.9 mm for WMA specimens with average SIP of 12,375 passes. It can be concluded that HMA mixtures exhibited greater resistance to the rutting and moisture damage than the WMA mixtures.

Table 3.12 Hamburg wheel test results for intermediate layer test sections, OH project

Mix Type	Test ID	Air Voids %	Total Number of Passes	Inverse Creep Slope (Pass/mm)	Inverse Stripping Slope (Pass/mm)	SIP	Max. Rut Depth, mm
HMA	**HMA 1**	**5.72%**	**20000**	**8969**	**N/A**	**>20000**	**3.5**
	HMA 2	**5.56%**	**20000**	**8163**	**N/A**	**>20000**	**4.3**
	Average	**5.64%**	**20000**	**8566**	**N/A**	**>20000**	**3.9**
WMA/ LEADCAP	**L 1**	**6.10%**	**20000**	**1970**	**861**	**6500**	**16.6**
	L 2	**5.59%**	**20000**	**2500**	**1155**	**10000**	**13.2**
	Average	**5.85%**	**20000**	**2235**	**1008**	**8250**	**14.9**

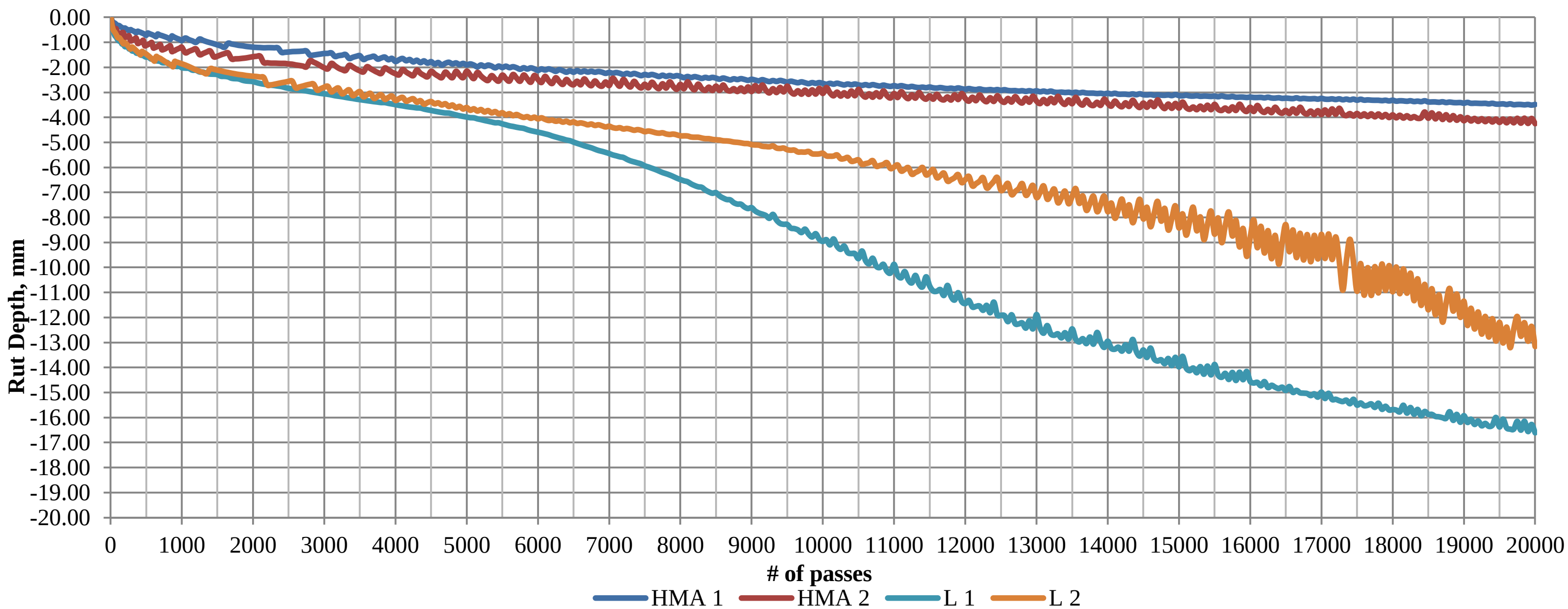

Figure 3.9 Hamburg wheel test results for intermediate layer test sections, OH project

Table 3.13 Hamburg wheel test results for surface layer test sections, OH project

Mix Type	Test ID	Air Voids %	Total Number of Passes	Inverse Creep Slope (Pass/mm)	Inverse Stripping Slope (Pass/mm)	SIP	Max. Rut Depth, mm
HMA	**HMA 1**	**6.79%**	**20000**	**11173**	**N/A**	**>20000**	**3.4**
	HMA 2	**6.80%**	**20000**	**12048**	**N/A**	**>20000**	**2.9**
	Average	**6.80%**	**20000**	**11611**	**N/A**	**>20000**	**3.2**
WMA/ LEADCAP	**L 1**	**6.53%**	**20000**	**4141**	**2395**	**13250**	**7.8**
	L 2	**6.43%**	**20000**	**3194**	**3295**	**11500**	**8.1**
	Average	**6.48%**	**20000**	**3668**	**2845**	**12375**	**7.9**

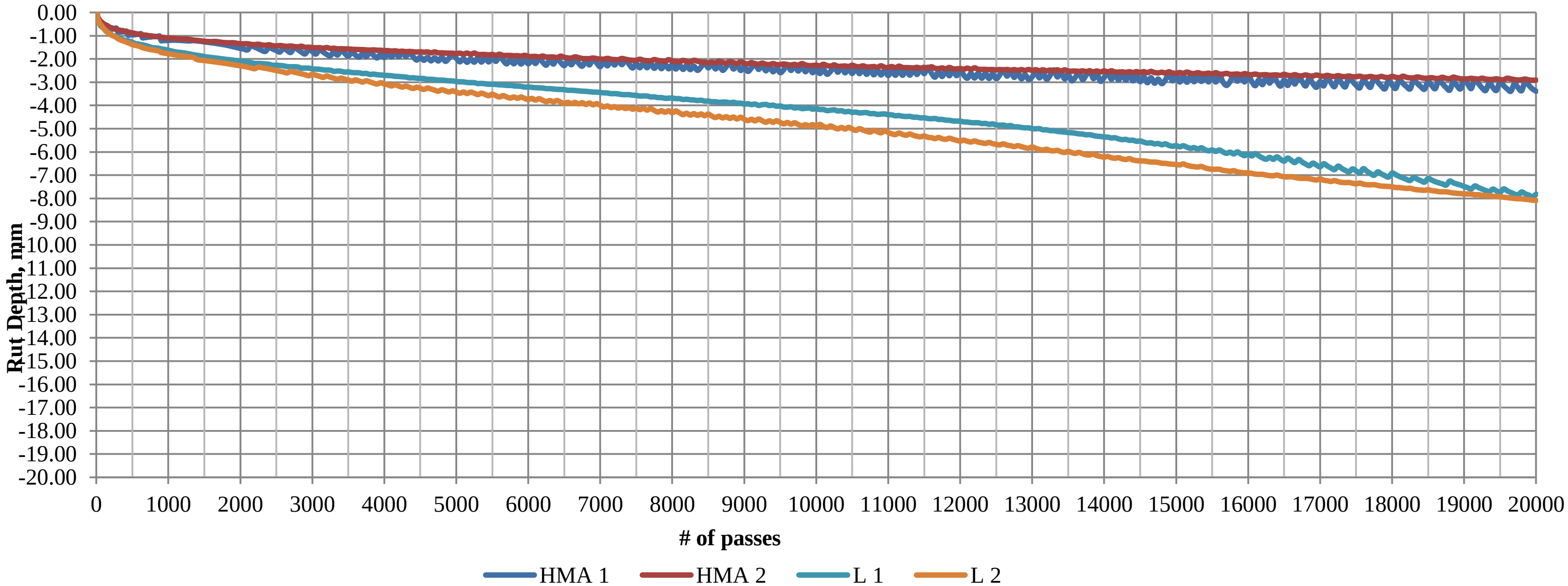

Figure 3.10 Hamburg wheel test results for surface layer test sections, OH project

Chapter 4 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 main objective of this research is to investigate the synergistic effect of Warm Mix Asphalt (WMA) and high RAP contents for their mix designs and rutting potential using Hamburg Wheel Tracking (HWT) test.

First, the component analysis of the RAP stockpile was performed to identify the distribution of aggregates and binder content associated with a different RAP material size retained on each sieve. This sieve-by-sieve analysis of different RAP stockpiles helped identify a critical sieve size to discard fine RAP materials in order to meet Superpave mix design requirements.

Second, to increase RAP materials by up to 75% by binder replacement, a fractionation method was applied to the RAP stockpile by discarding RAP materials passing No. 16 sieve. The mix designs were performed for both HMA and WMA with varying fractionated RAP contents accounting for a replacement of 20, 30, 40, 50 and 75% of the mixture's asphalt binder. All mix designs met the Iowa DOT mix design requirements except the one with 75% RAP materials by binder replacement due to the excessive amount of dust content. The optimum asphalt content ranged consistently between 5.1% and 5.20% for both HMA and WMA mixes for air voids of 3.5% and the 0.3 million ESAL design.

Third, the HWT test was performed on the mixtures with varying amounts of fractionated RAP materials of 20, 30, 40, 50 and 75% by a binder replacement. Overall, the HMA performed better than WMA for all mixes. The mixes with higher RAP amounts performed better except the mix with 30% RAP materials by binder replacement. Both HMA and WMA mixes with 75% RAP materials by binder replacement (90% by weight replacement) performed the best by exhibiting very little deformation ranging between 2 and 4 mm after 20,000 repetitions.

Finally, the WMA mix with 30% RAP materials by binder replacement and the WMA with 20% RAP materials by weight replacement were applied in the test sections in State Highway 6 in Iowa and State Highway 158 in Ohio, respectively. The average densities of the HMA and WMA test sections in Iowa were 94.3% and 93.9%, respectively, and those of the HMA and WMA test sections in Ohio were 94.6% and 95.2%, respectively. Significantly less emission and smoke were observed during construction of WMA mixtures, which confirmed the environmental benefits of using WMA technologies while meeting both Iowa and Ohio DOT's density requirements.

Both HMA and WMA mixes from State Highway 6 in Iowa met Hamburg testing requirement by exhibiting very little deformation of 3 mm and 5 mm, respectively, after 20,000 repetitions. HMA mix from State Highway 158 in Ohio met Hamburg testing requirement by exhibiting very little deformation of 4 mm after 20,000 repetitions whereas WMA mix exhibited 15 mm deformation after 20,000 repetitions.

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