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Optimizing Percentages of Asphalt Content Extracted from Mixes Containing RAP and/or RAS

Eslam Deef-Allah [a*≡] and Magdy Abdelrahman [b#]

[a] *Department of Civil, Architectural and Environmental Engineering, Missouri University of Science and Technology, Rolla, MO-65401, U.S.A.*
[b] *Missouri Asphalt Pavement Association (MAPA), Department of Civil, Architectural and Environmental Engineering, Missouri University of Science and Technology, Rolla, MO-65401, U.S.A.*

Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

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ABSTRACT

Extracting asphalt binders (ABs) from mixes including recycled asphalt shingles and/or reclaimed asphalt pavement (RAP) needs more investigation. The most popular way for extracting ABs from mixes is centrifuge extraction. The fine materials (dust) extracted with the effluent were quantified using ashing and centrifuge mineral matter determination methods (MMDMs). MMDM could underestimate the extracted asphalt content (EAC)% by overestimating dust amounts. As a result, the actual asphalt content% values were compared to the EAC% values utilizing ashing and centrifuge MMDMs. The EAC% values using the centrifuge MMDM showed more accurate values when compared to the EAC% values using the ashing MMDM. The fabrication techniques used in the field, lab, and plant mixes and the additives used in these mixes altered the interaction processes between virgin asphalt binders (VABs) and RAP binders. More interactions occurred in the plant mixes due to reheating these mixes prior to compaction in the lab. Thus, the EAC% values from plant mixes were higher than the EAC% values from the same mixes obtained from the field. The interactions between the RAP binder and the VAB were boosted by Evoflex that increased the EAC% values.

Keywords: Extraction; centrifuge extractor; asphalt content; ashing; interactions; ANOVA.

[≡] *Ph.D. Candidate;*
[#] *Endowed Professor;*
**Corresponding author: Email: emddkc@mst.edu;*

ACRONYMS

AAACMMDMS	*: Average Ashing and Centrifuge Mineral Matter Determination Methods*
AAC	*: Actual Asphalt Content*
AB	*: Asphalt Binder*
ABR	*: Asphalt Binder Replacement*
AC	*: Asphalt Content*
AMMDM	*: Ashing Mineral Matter Determination Method*
ANOVA	*: Analysis Of Variance*
CMMDM	*: Centrifuge Mineral Matter Determination Method*
CRM	*: Crumb Rubber Modifier*
EAB	*: Extracted Asphalt Binder*
EAC	*: Extracted Asphalt Content*
ECR	*: Engineered Crumb Rubber*
JMF	*: Job Mix Formula*
MMDM Method	*: Mineral Matter Determination*
NMAS	*: Nominal Maximum Aggregate Size*
PG	*: Performance Grade*
RAP	*: Reclaimed Asphalt Pavement*
RAS	*: Recycled Asphalt Shingles*
TCE	*: Trichloroethylene*
VAB	*: Virgin Asphalt Binder*

1. INTRODUCTION

In the 1970s, the oil embargo and rising crude oil costs led to asphalt pavement recycling. As a result, the supply of asphalt was limited. Contractors screened mixes comprising 80 percent reclaimed asphalt pavement (RAP) during that time [1–3]. When oil prices plummeted, the percentage of RAP in asphalt mixes lowered to 20 percent. This tendency persisted throughout Superpave's development [1–3]. RAP consists of valuable materials, aggregate and asphalt binder (AB) that have been scraped and processed from pavement [3–8]. Recycled asphalt shingles (RAS) were utilized in asphaltic mixes in the 1980s [1, 2]. Oil prices climbed again in the mid-to-late 2000s, increasing demand for RAP and RAS to cut total costs [1, 2]. The usage of RAP or RAS in the asphalt mixes is growing in the United States due to essential components that make them more suitable for use [9]. The use of RAP/RAS in asphalt mixes also has additional advantages, such as lowering the demand for natural resources, lowering pollutants during the production stage, and lowering the quantity of waste disposed of in landfills [10, 11].

ABs may be extracted from asphaltic mixes using a variety of ways. Because of its simplicity and usage at room temperature, the centrifuge extraction method is the most prevalent method for extracting ABs from mixes with solvents [12–16]. If characterizing extracted asphalt binders (EABs) is required, the centrifuge extraction approach is utilized. One of the major disadvantages of this approach is that it leaves about 4% of the overall binder with the aggregate [12, 15, 17]. During the extraction process, the solvents are utilized to dissolve the ABs, and mineral matter (dust) is released along with the dissolved ABs. A filterless centrifuge is then used to extract the mineral matter. The ABs are recovered using a distillation procedure accomplished by a rotary evaporator (rotavap) after the mineral matter is removed from the extracted solvent [18, 19]. This method of recovery has been in use since the 1970s [20]; however, the rotavap's overheating would increase the recovered ABs' stiffness [21–23]. Additionally, the stiffness of the ABs may be reduced if there is any remaining solvent in the recovered ABs. It was discovered that even 0.5 percent of the solvent left in the recovered ABs might result in a viscosity reduction of 50 percent [23]. The existence of trichloroethylene (TCE) in the recovered AB with a proportion of 0.9 percent by weight resulted in a 6℃ drop in the ring and ball softening point, according to Nösler et al. [24].

Rodezno and Julian [12] evaluated the effects of several extraction procedures on the characteristics of EABs: centrifuge, ignition, automated utilizing the asphalt analyzer, and reflux. Eight mixes were examined, which included RAP/RAS or none. The experimental program was made possible by the participation of several Wisconsin laboratories to assess within-lab and between-lab variability. For mixes containing a virgin asphalt binder (VAB), the average difference between the percentages of the actual asphalt content (AAC) and extracted asphalt content (EAC) was 0.21 percent, and may reach 0.38 percent for mixes with a high percentage of RAP/RAS, recycled binder percentage of 30-35 percent, according to the centrifuge extraction method. Using RAP/RAS in asphaltic mixes had little impact on within-lab or between-lab variability. Because the average differences between the percentages of AAC and EAC were 0.05 percent and 0.17 percent, respectively, the ignition and asphalt analyzer extraction techniques were the most accurate. When it comes to EAB characterization, the ignition approach isn't an option. There was no dramatic change in the performance grade (PG) characterization of EABs irrespective of the extraction technique or solvent used—toluene, TCE, or n-propyl bromide [9]. Nonetheless, another study [25] found that the characteristics of EABs employing the three types of solvents listed above differed.

The influence of the extraction procedure on the AB content was examined by Piérard et al. [26]. ABs treated with ethyl vinyl acetate or styrene butadiene styrene were extracted from fresh, short-term aged, and compacted mixes produced in the lab. Two types of aggregates and two sources of ABs were employed. To separate binders from mixes, different solvents were used: toluene, dichloromethane, and TCE. Regardless of the solvent used, the average extracted percentage of the AB was 6.3 ± 0.2 percent, which was less than the AAC% (6.6 percent). Because the intensities of the released polymer's peaks were identical for the modified binder used in the creation of mixes and the recovered one, Fourier transform infrared data demonstrated that drops in the AB content were not associated with decreases in the polymer content. There was no discernible influence of aggregate type and/or compaction procedure on the EAC%. The percentage of EAB from short-term aged mixes varied depending on the ABs and solvent's types.

The impact of the extraction method via reflux on the EAC's percentage from lab and field asphalt mixes including crumb rubber modifier (CRM) was investigated by Sirin and Tia [27]. The AAC% of CRM-modified mixes was 6.34 percent, with a CRM percentage of 0.76 percent, for a total of 7.1 percent asphalt and CRM content by weight. In addition, typical mixes containing only 6.34 percent AB were investigated. The EAC% was found to be lower than the AAC% for both modified and unmodified mixes. The average not extracted percentage of AB and CRM in CRM modified mixes was determined to be 0.86 percent. An average not extracted AB percentage of 0.25 percent was detected in typical mixes. Thus, out of a CRM percentage of 0.76 percent by weight of the mix, the average percentage of CRM that remained in the reflux was 0.61 percent (0.86 percent − 0.25 percent). This demonstrated that including recycled materials in asphalt mixes, such as CRM, made the extraction of ABs from these mixes more challenging.

The use of recycled materials in asphalt mixes not only changes the performance of the EABs but also makes the extraction process more difficult. The major goal of this study was to use the centrifuge extraction procedure to maximize the EAC% from mixes including RAP and/or RAS. Various fabrication methods were used in field, plant, and lab mixes containing different VABs and different asphalt binder replacement (ABR) percentages by RAP/RAS. The objective of this study was achieved by comparing the EAC% using the centrifuge extraction process with the AAC%. The mineral matter determination method (MMDM) could underrate the EAC% [13]. Therefore, the effect of MMDM on the EAC% was evaluated. The interactions between VAB and RAP/RAS binder might be affected by different fabrication processes employed in field, plant, and lab mixes. Recycling agents (such as Evoflex) boosted the RAP binder's contribution in the mixes, resulting in more interactions between VAB and RAP binder [8]. Increasing these interactions could enhance the EAC% when compared to the AAC%, which was investigated in this study.

2. MATERIALS AND METHODS

2.1 Materials

2.1.1 Field mixes

In two batches, sixty field samples as cores were obtained from various routes: The first batch contained 38 cores (Fig. 1) and the second batch included 22 cores (Fig. 2(a)). Tables 1 and 2 provide more information on the first and second batch cores, respectively. The field cores presented in Table 1 were collected in 2016, and the field cores in Table 2 were sampled in 2019. The cores were sampled after two weeks of the pavement construction phase in 2016 for field cores taken from routes built in 2016. Different ABR percentages by RAP/RAS, as well as different additives, were used in the mixes. The additives' percentages in the job mix formula (JMF) were specified by the net weight of VAB. RAP and RAS were not present in some mixes (e.g., MO 94, US 54-7, and US 54-5). The total asphalt content (AC) % values in Tables 1 and 2 represent the AAC%, as defined by the JMF.

2.1.2 Plant mixes

Following Superpave, four asphalt mixes were produced, each of which was made in a drum-mix plant. Twelve plant mixes were sampled from behind the paver during the construction process; these plant mixes represented the four asphalt mixes. Plant mixes were reheated to 100 ± 5℃ in the lab before separation; they were then reheated to the temperature required for compaction, as specified in the JMF, and compacted using Superpave gyratory, as shown in Fig. 2(a). RAP or RAS were present in these mixtures. Table 3 provides more information on these mixes.

2.1.3 Lab mixes

Following Superpave, lab mixes (shown in Fig. 2(b)) were created using the same components as the US 54-6 and US 63-1 mixes. Different additives were utilized in lab mixes (e.g., Morelife, Evoflex, and Evotherm). Using a softer VAB in mixes including RAP is advised [28] to improve the workability characteristics. In lab mixes, a softer AB that has a PG of 46−34 was utilized to compare the effect of utilizing a soft AB in RAP mixes to mixes having the same ingredients but with a stiffer binder having a PG of 58−28. Rubber was added to RAP-based mixes to promote sustainability. In lab mixes, an engineered crumb rubber (ECR), a form of dry-process ground tire rubber, was utilized in three different percentages—5%, 10%, and 20% by the net weight of the total binder. ECR and AB were heated to 170℃ before being mixed for 30 minutes in a high-shear mixer at 3500 revolutions per minute. Following mixing of the binders or modified binders with the aggregates, the mixes were short-term aged in the oven for two hours at the compaction temperature—as mentioned in the JMF—before being compacted. A Superpave gyratory was used to compact the lab mixtures. Table 4 presents further information on the mixes. The route name (e.g., MO 13), section number (e.g., 1), and coding (e.g., F1) are represented by the codes for mixes.

Fig. 1. The first batch of field cores [5]

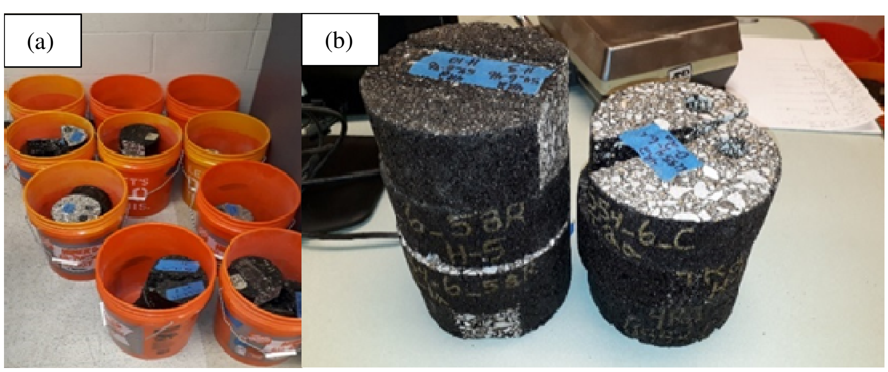

Fig. 2. (a) The second batch of field cores and plant mixes and (b) Lab mixes [5]

2.2 Methods

A centrifuge extractor, Fig. 3(a), was used to extract the binders from the mixes following ASTM D2172 / D2172M-17e1 [18]. The TCE solvent was utilized to remove the ABs from the mixes. The ashing technique was used to measure the quantity of mineral matter in the effluent by placing a representative sample of roughly 100 ml of effluent—EAB, TCE, and mineral matter—into an ignition dish. To better estimate the EAC%, the representative sample of the effluent was taken at least twice in two ignition dishes at a rate of 100 ml per dish. Using a filterless centrifuge (Fig. 3(b)), the quantity of mineral matter was removed and determined in the residual effluent. Figs. 3(c) and 3(d) show the mineral matter obtained using the ashing and centrifuge procedures, respectively. Hence, the ashing MMDM (AMMDM), centrifuge MMDM (CMMDM), and average ashing and centrifuge MMDMs (AAACMMDMs) were used to compute the EAC%.

3. RESULTS AND ANALYSIS

3.1 Plant Mixes

Fig. 4 shows the AAC% versus EAC% values for plant mixes utilizing different MMDMs. As shown in Fig. 4(a), only two samples had the same AAC% and EAC% utilizing AMMDM. Furthermore, the EAC% values for roughly 60% of the samples were lower than the AAC% values. This shows that the EAC% was underestimated by AMMDM. One-third of the samples had EAC% with the same values as the AAC% utilizing CMMDM (Fig. 4(b)). The EAC% using AAACMMDMs versus AAC% values are shown in Fig. 4(c). The JMFs have an acceptable tolerance on the AAC% that is normally in the range of ± 0.3% to ± 0.4% [12, 29]. The EAC% values using CMMDM had more accurate results when compared to the EAC% values by AMMDM or AAACMMDMs. This was inferred because 83.33% of the samples had EAC% values utilizing AMMDM or AAACMMDMs within the AAC% ± 0.3% (see Figs. 4(a) and 4(c)). However, using CMMDM, as indicated in Fig. 4(b), 91.67% of the samples had EAC% within the AAC% ± 0.3%.

The one-way analysis of variance (ANOVA) presented in Table 5 was calculated using JMP Pro software. The means of the EAC% values utilizing different MMDMs were compared to the mean of the AAC% values using an ANOVA. The means of AAC% and EAC% values by the different MMDMs did not differ significantly. This was concluded because the Prob > F (p-value) was higher than the significance level α (0.05).

Fig. 5 depicts the EAC per AAC values for plant mixes utilizing different MMDMs. The EAC% values by CMMDM were higher than the EAC% values utilizing AMMDM for almost 75% of plant mixes. Considering AAACMMDMs, the EAC per AAC values for mixes including RAP were between 91 and 109 percent, and for mixes containing RAS, between 98 and 105 percent. The EAC% values for RAS-containing mixes were more precise than the EAC% values for RAP-containing mixes due to the different interaction mechanisms between RAP binder and VAB compared to RAS binder and VAB, which needs further investigations.

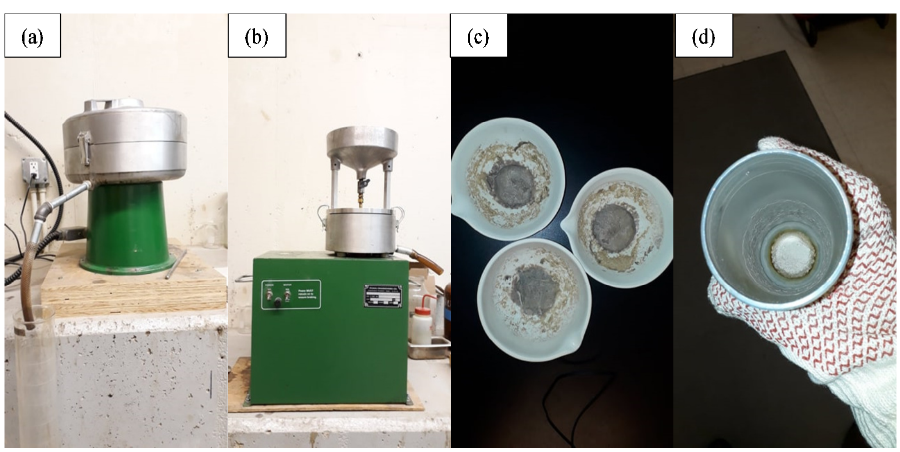

Fig. 3. (a) Centrifuge extractor, (b) Filterless centrifuge, (c) Mineral matter in ignition dishes, and (d) Mineral matter in centrifuge metal cup [5]

Table 1. Details of the first batch of field cores [5]

#	Code	PG of VAB	Virgin AC[a] (%)	Total AC (%)	ABR by RAP–RAS (%)	NMAS[b] (mm)	Const.[c] Year	Additives
1	MO 13-1-F1	64–22H	4.4	5.7	17–0	9.5	2016	0.5%[1]
2	MO 13-1-F2							
3	MO 13-1-F3							
4	US 54-6-F1	58–28	3.6	5.1	31–0	12.5	2016	1%[1]
5	US 54-6-F2							
6	US 54-6-F3							
7	US 54-1-F1	58–28	3.6	5.2	0–33	12.5	2016	2.5%[2], 3.5%[3], and 1.5%[1]
8	US 54-1-F2							
9	US 54-1-F3							
10	US 63-1-F1	58–28	3.4	5.1	35–0	12.5	2016	0.5%[4] and 1.75%[5]
11	US 63-1-F2							
12	US 63-1-F3							
13	US 63-2-F1	64–22	4.1	5.6	20–10	12.5	2008	1.5%[6] and 0.5%[7]
14	US 63-2-F2							
15	US 63-2-F3							
16	US 54-3-F1	58–28	3.6	5.2	18–15	12.5	2016	1%[1]
17	US 54-3-F2							
18	US 54-3-F3							
19	US 54-5-F1	64–22H	5.4	5.4	0–0	12.5	2016	1%[1]
20	US 54-5-F2							
21	US 54-4-F1	64–22H	3.2	4.8	35–0	12.5	2016	3%[3] and 1%[1]
22	US 54-4-F2							
23	US 54-4-F3							
24	US 54-2-F1	58–28	3.6	5.3	33–0	12.5	2016	1%[1]
25	US 54-2-F2							
26	US 54-2-F3							
27	US 50-1-F1	64–22	3.8	5.0	25–0	12.5	2011	1.5%[6] and 1%[7]
28	US 50-1-F2							
29	US 50-1-F3							
30	MO 52-1-F1	64–22	3.7	4.8	0–34	12.5	2010	1.5%[6] and 0.8%[7]
31	MO 52-1-F2							
32	MO 52-1-F3							
33	US 54-7-F1	64–22	6.2	6.2	0–0	12.5	2003	0.25%[8]
34	US 54-7-F2							

#	Code	PG of VAB	Virgin AC[a] (%)	Total AC (%)	ABR by RAP–RAS (%)	NMAS[b] (mm)	Const.[c] Year	Additives
35	US 54-7-F3							
36	US 54-8-F1	70–22	5.1	5.6	9–0	12.5	2006	0.5%[7]
37	US 54-8-F2							
38	US 54-8-F3							

[a] AC: Asphalt content, [b] NMAS: Nominal maximum aggregate size, and [c] Const.: Construction; [1] Morelife T280 and [2] IPC70 are anti-stripping agents. [3] PC 2106 and [4] Evotherm are warm-mix additives. [5] Evoflex CA is a rejuvenator; [6] Bag house fines. [7] AD-here HP Plus and [8]LOF 65-00LS1 are anti-stripping agents

Table 2. Information on the second batch of field cores [5]

#	Code	PG of VAB	Total AC (%)	ABR by RAP–RAS (%)	NMAS (mm)	Date of Most Recently Overlay
1	MO 151-F1	64–22	4.7	16–15	12.5	2014
2	MO 151-F2					
3	MO 151-F3					
4	MO 151-F4					
5	MO 151-F5					
6	US 61 N-F1	64–22H	5.3	30–0	9.5	2013
7	US 61 N-F2					
8	US 61 N-F3					
9	US 54-F1	70–22	5.7	12–0	12.5	2010
10	US 54-F2					
11	US 54-F3					
12	MO 6-F1	58–28	5.9	30–0	4.75	2015
13	MO 6-F2					
14	MO 6-F3					
15	MO 6-F4					
16	MO 6-F5					
17	MO 94-F1	64–22	5.6	0–0	12.5	2005
18	MO 94-F2					
19	MO 94-F3					
20	US 36-F1	64–22	5.1	25–0	12.5	2011
21	US 36-F2					
22	US 36-F3					

Table 3. Plant mixes' information [5]

#	Code	PG of VAB	Virgin AC (%)	Total AC (%)	ABR by RAP–RAS (%)	NMAS (mm)	Const. Year	Additives
1	MO 13-1-P1	64–22H	4.4	5.7	17–0	9.5	2016	0.5%[1]
2	MO 13-1-P2							
3	MO 13-1-P3							
4	US 54-6-P1	58–28	3.6	5.1	31–0	12.5	2016	1%[1]
5	US 54-6-P2							
6	US54-6-P3							
7	US 54-1-P1	58–28	3.6	5.2	0–33	12.5	2016	2.5%[2], 3.5%[3], and 1.5%[1]
8	US 54-1-P2							
9	US 54-1-P3							
10	US 63-1-P1	58–28	3.4	5.1	35–0	12.5	2016	0.5%[4] and 1.75%[5]
11	US 63-1-P2							
12	US 63-1-P3							

[1] Morelife T280 and [2] IPC70 are anti-stripping agents. [3] PC 2106 [4] Evotherm are warm-mix additives; [5] Evoflex CA is a rejuvenator.

Table 4. Lab mixes' information [5]

#	Code	Virgin AC (%)	Total AC (%)	PG of VAB	ABR by RAP–RAS (%)	ECR[a] (%)	Additives
1	US 54-6-L1	3.6	5.1	58–28	31–0	0	
2	US 54-6-L2						
3	US 54-6-L3						
4	US 54-6-R[b]-L1						3%[1]
5	US 54-6-R-L2						
6	US 54-6-SB[c]-L1			46–34			
7	US 54-6-SB-L2						
8	US 54-6-SB-E5[d]-L1	3.7	5.2			5	
9	US 54-6-SB-E5-L2						
10	US 54-6-SB-E5-L3						
11	US 54-6-SB-E20[e]-L1	4.0	5.5			20	
12	US 54-6-SB-E20-L2						
13	US 63-1-R-L1	3.4	5.1	58–28	35–0		1.75%[1] and 0.5%[2]
14	US 63-1-R-L2						
15	US 63-1-R-L3						
16	US 63-1-SB-L1			46–34			
17	US 63-1-SB-L2						

#	Code	Virgin AC (%)	Total AC (%)	PG of VAB	ABR by RAP–RAS (%)	ECR[a] (%)	Additives
18	US 63-1-SB-L3						
19	US 63-1-SB-R-L1						1.75%[1] and 0.5%[2]
20	US 63-1-SB-R-L2						
21	US 63-1-SB-R-L3						
22	US 63-1-SB-E10-L1	3.6	5.3			10	
23	US 63-1-SB-E10-L2						
24	US 63-1-SB-E20-L1	3.8	5.5			20	
25	US 63-1-SB-E20-L2						

[a] ECR is Engineered crumb rubber, [b] R is Rejuvenator, [c] SB is Soft binder, [d] E5 is 5% ECR, and [e] E20 is 20% ECR. [1] Evoflex CA is a rejuvenator.[2] Evotherm is a warm-mix additive.

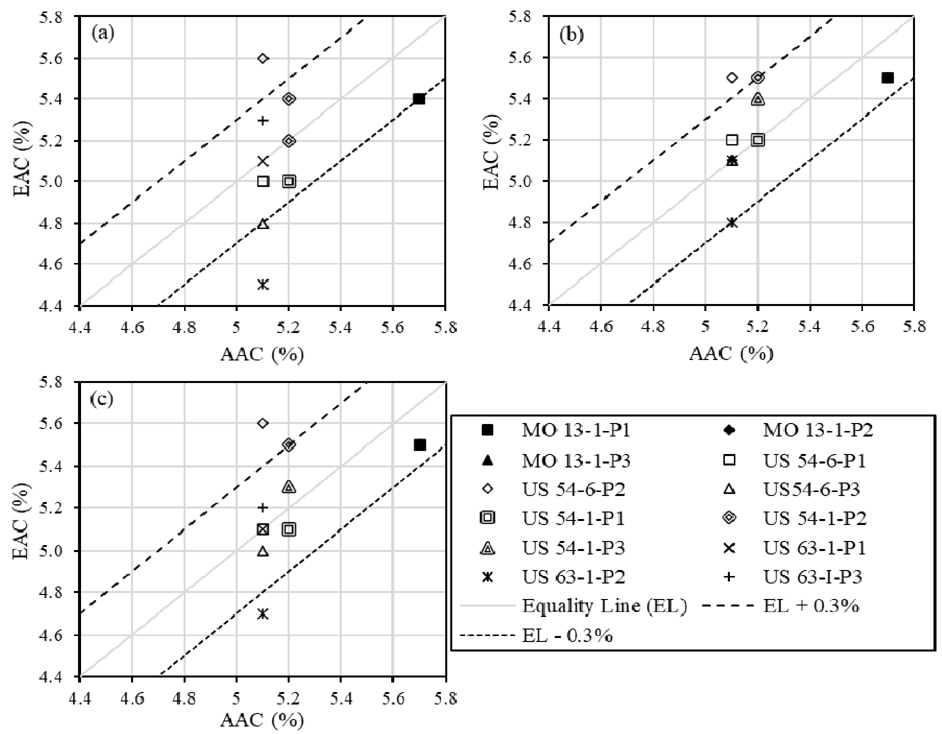

Fig. 4. AAC% versus EAC% values for plant mixes; (a) AMMDM, (b) CMMDM, and (c) AAACMMDMs

Table 5. ANOVA results: AAC% and EAC% values for plant mixes

Source	D.F.[a]	S.S.[b]	M.S.[c]	F Ratio	Prob > F
Method	3	0.089	0.030	0.406	0.749
Error	44	3.211	0.073		
C. Total	47	3.300			

[a] D.F.: Degrees of freedom, [b] S.S.: Sum of squares, [c] M.S.: Mean square

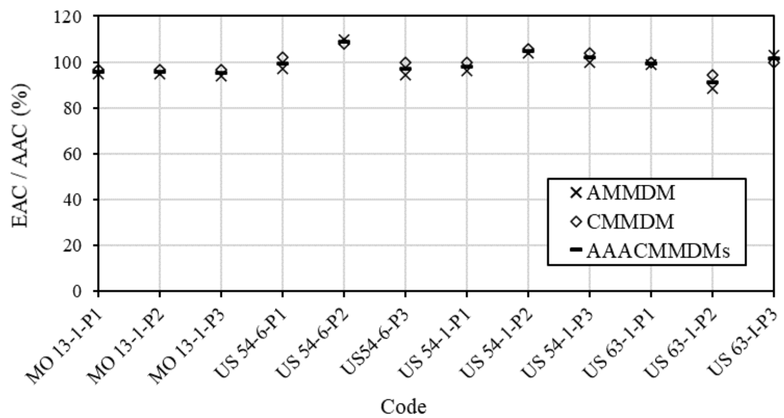

Fig. 5. EAC per AAC values for plant mixes

3.2 Field Mixes Constructed before 2016

Fig. 6 illustrates AAC% versus EAC% values using different MMDMs for field mixes constructed before 2016. RAP/RAS were present in mixes, whereas RAP/RAS were absent in others (e.g., MO 94 and US 54-7). The AAC% values were between 4.7% and 6.2%. The EAC% values by AMMDM ranged from 4.3% to 6.8%. By using CMMDM, the EAC% values ranged from 4.6% to 6.8%. Through using AAACMMDMs, the EAC% values ranged from 4.5% to 6.8%. The EAC% values using CMMDM or AAACMMDMs showed more accurate results than the EAC% values using AMMDM. This was concluded because 56.76% of the samples had EAC% using CMMDM within the AAC% ± 0.3% (note Fig. 6(b)), and 54.05% of the samples had EAC% using AAACMMDMs within the AAC% ± 0.3% (note Fig. 6(c)). Nevertheless, using AMMDM, as shown in Fig. 6(a), 48.65% of the samples presented EAC% within the AAC% ± 0.3%. As a result, the EAC% values were undervalued by AMMDM.

The ANOVA was used to identify the effect of MMDMs on the EAC%, as shown in Table 6. The Prob > F was found to be 0.869 that was higher than the α significance level (0.05). Hence, there was no discernible difference between the AAC% and EAC% values utilizing different MMDMs.

The EAC per AAC values for field mixes utilizing different MMDMs are presented in Fig. 7. For most samples—71% of the samples—the EAC values utilizing CMMDM per AAC values were higher than the EAC values by AMMDM per AAC values. For mixes containing RAP, the highest EAC per AAC values were recorded for the MO 6 mixes. These mixes were recently constructed in 2015 and contained VAB with a PG of 58−28, which was softer than VABs used in the other mixes. However, these mixes contained a high ABR percentage by RAP (30%). Therefore, using a soft VAB in the mixes facilitated the extraction process especially if those mixes contained a high percentage of RAP and/or RAS.

3.3 Field, Plant, and Lab Mixes

The AAC% and EAC% values using different MMDMs are presented in Fig. 8 for the US 54-6 mixes. These mixes contained 31% ABR percentage by RAP. For the US 54-6 mixes, the AAC% was 5.1%; even so, certain lab mixes contained AAC% of 5.2% or 5.5%. The EAC% values by AMMDM were between 4.4% and 6.0%, as shown in Fig. 8 (a). The EAC% values by CMMDM (Fig. 8(b)) were more precise, ranging between 4.8% and 5.6%. Fig. 8(c) illustrates the EAC% values utilizing the AAACMMDMs, which ranged from 4.7% to 5.8%. The EAC% values utilizing CMMDM or

AAACMMDMs yielded more accurate results than those of AMMDM. This was concluded because 94.44% of the samples had EAC% values using CMMDM within the AAC% ± 0.3% (see Fig. 8(b)), and 77.78% of the samples had EAC% values using AAACMMDMs within the AAC% ± 0.3% (note Fig. 8(c)). However, using AMMDM, as shown in Fig. 8(a), 66.67% of the samples showed EAC% values within the AAC% ± 0.3%. For more than 71% of the samples in Figs. 8(a) or 8(c), the EAC% values were lower than the AAC% values. Consequently, the EAC% values were underrated by AMMDM. The calculation of the mineral matter in the extracted effluent by the ashing procedure is based on a representative sample of the extracted effluent (e.g., 100 ml). Nonetheless, the total mineral matter in the extracted effluent is calculated by CMMDM, which is usually between 2000 and 6000 ml.

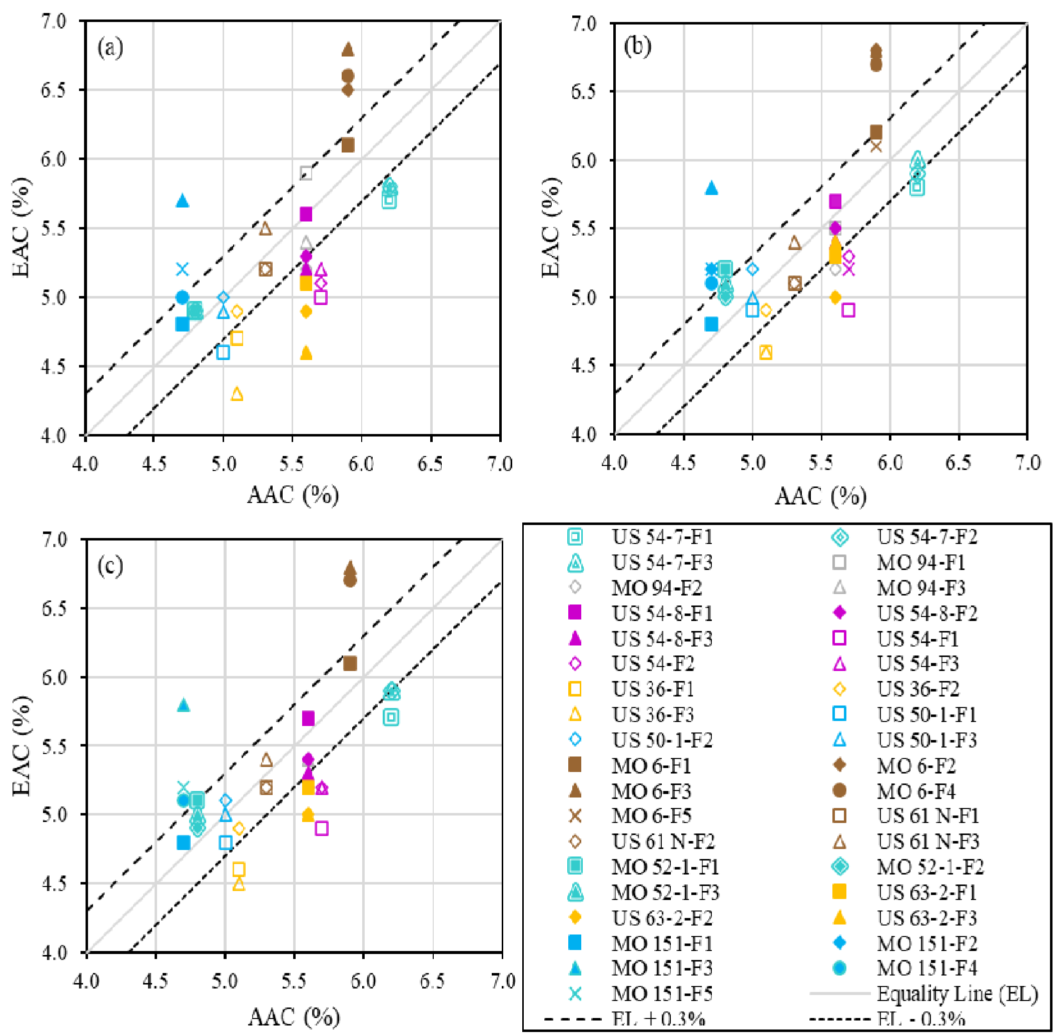

Fig. 6. AAC% versus EAC% values for field mixes constructed before 2016; (a) AMMDM, (b) CMMDM, and (c) AAACMMDMs

Table 6. ANOVA results: AAC% and EAC% values for field mixes constructed before 2016

Source	D.F.	S.S.	M.S.	F Ratio	Prob > F
Method	3	0.213	0.071	0.239	0.869
Error	144	42.829	0.297		
C. Total	147	43.042			

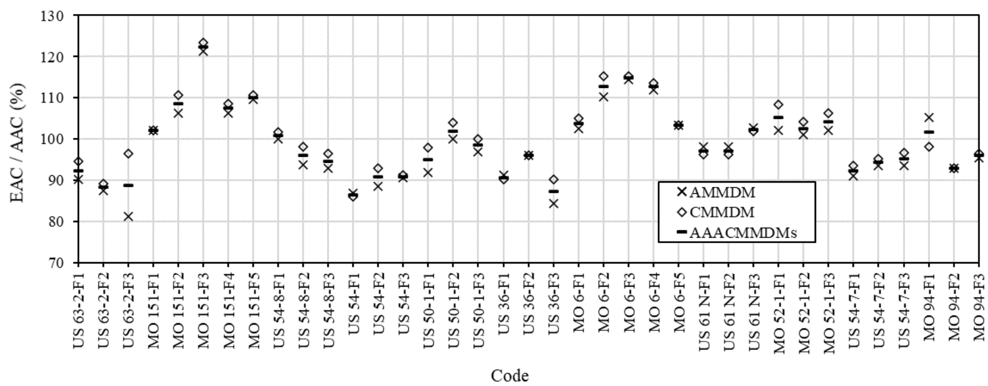

Fig. 7. EAC per AAC values for field mixes constructed before 2016

The AAC% versus EAC% values by different MMDMs for the US 63-1 mixes are depicted in Fig. 9. These mixes contained 35% ABR percentages by RAP. The AAC% for these mixes was 5.1%; however, certain lab mixes contained AAC% of 5.3% and 5.5%. By using AMMDM, the EAC% values ranged from 4.5% to 6.0% (Fig. 9(a)). The EAC% values by CMMDM (Fig. 9(b)) were more precise, with values ranging from 4.7% to 5.8%. Employing AAACMMDMs, Fig. 9(c) yielded EAC% values ranging from 4.6% to 5.9%. The EAC% values using CMMDM illustrated more accurate results than the EAC% values using AMMDM or AAACMMDMs. This was deduced because 68.42% of the samples had EAC% values using AMMDM or AAACMMDMs within the AAC% ± 0.3%, as presented in Figs. 9(a) and 9(c). Nonetheless, using CMMDM, as indicated in Fig. 9(b), 89.47% of the samples had EAC% values within the AAC% ± 0.3%.

Using ANOVA, the means of the EAC% values using different MMDMs were compared to the mean of the AAC% values to clearly understand the effect of MMDMs on the EAC% values, as presented in Table 7. The Prob > F is 0.383 that was higher than the 0.05 level of significance. When comparing the means of the EAC% values utilizing different MMDMs to the mean of the AAC% values, no significant differences were discovered.

Using different MMDMs, Fig. 10 shows the EAC per AAC values for the US 54-6 mixes. The EAC per AAC values ranged from 85% to 110%. The EAC% values by CMMDM were higher than those of AMMDM. Furthermore, the US 54-6 plant mixes had the highest EAC per AAC values. Because the plant mixtures were reheated in the lab before compaction, there were more interactions between VAB and RAP binder. The EAC% values rose as a result of these interactions.

The EAC per AAC values for the US 54-6 lab mixes utilizing different MMDMs are shown in Fig. 11. The ratio of EAC to AAC ranged from 88% to 110%. For most samples, more than 83 percent of the samples, CMMDM exhibited more EAC% values than those of AMMDM. Increasing the EAC per AAC values by utilizing a 3% Evoflex highlighted Evoflex's involvement in boosting the contribution of recycled materials in the mixes. The interactions between the RAP binder and VAB were improved as a result of this contribution. The same results were observed with a softer VAB (PG 46−34); there were smaller variations in the EAC per AAC values using different MMDMs. Thus, using a softer VAB by decreasing the high PG of the VAB by two grades and the low PG by one grade caused the EAC% to increase by 2% from the AAC%.

Using different MMDMs, Fig. 12 illustrates the EAC per AAC values for the US 63-1 mixes. The ratio of EAC to AAC ranged from 88% to 112%. Most samples (78%) showed that the EAC% values by CMMDM were higher than those of AMMDM. For plant and lab mixes, the highest EAC per AAC values were reported. When compared to interactions in the field mixes, more interactions between RAP binder and VAB existed in plant and lab mixes. The fabrication mechanism used in lab mixes and reheating plant mixes to the compaction temperature in the lab increased the interactions between VAB and RAP binder [8], which increased the compatibility of VAB and RAP binder and thus resulted in higher EAC% values compared to those extracted from field mixes. Fig. 13 depicts the EAC per AAC values for the US 63-1 lab mixes utilizing different MMDMs. The EAC per AAC values ranged from 95% to 112%. For 70% of the samples, CMMDM exhibited higher EAC% values than those of AMMDM.

For lab mixes containing ECR, a portion of the rubber particles remained with the aggregate, while the second portion melted in the AB, and the third portion was retrieved with the effluent. The ECR particles that remained with the aggregate and were retrieved with the effluent are shown in Fig. 14. During the sieve analysis, the first ECR portion was seen with the aggregate particles (Fig. 14(c)). The second ECR portion that melted in the AB was responsible for improving the stiffness and elasticity of the EABs [8]. After the filterless centrifuge procedure, the third ECR portion was discovered in the metal cup with the mineral matter (Fig. 14(b)).

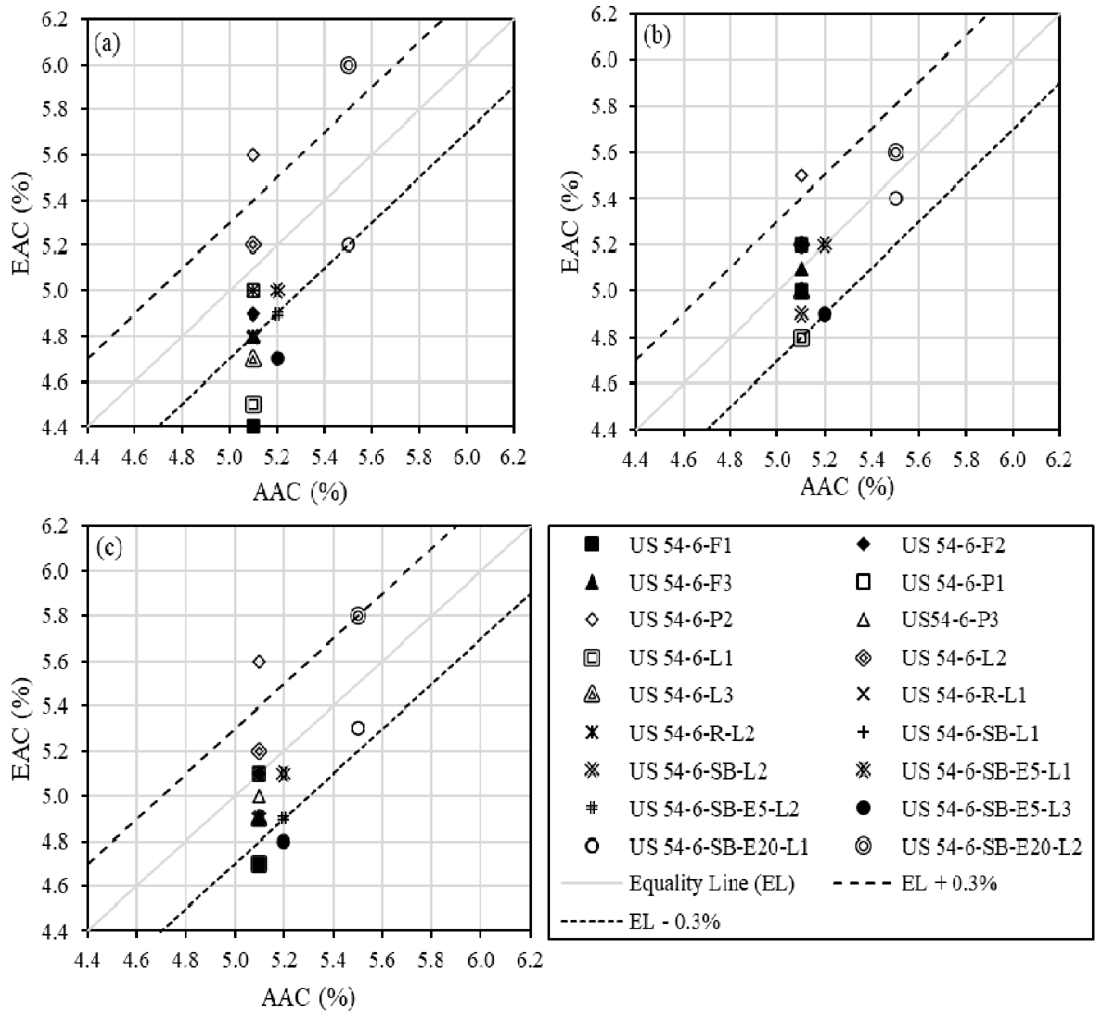

Fig. 8. AAC% versus EAC% values for the US 54-6 mixes; (a) AMMDM; (b) CMMDM, and (c) AAACMMDMs

Table 7. ANOVA results: AAC% and EAC% values for the US 54-6 and US 63-1 mixes

Source	D.F.	S.S.	M.S.	F Ratio	Prob > F
Method	3	0.294	0.098	1.025	0.383
Error	144	13.774	0.096		
C. Total	147	14.068			

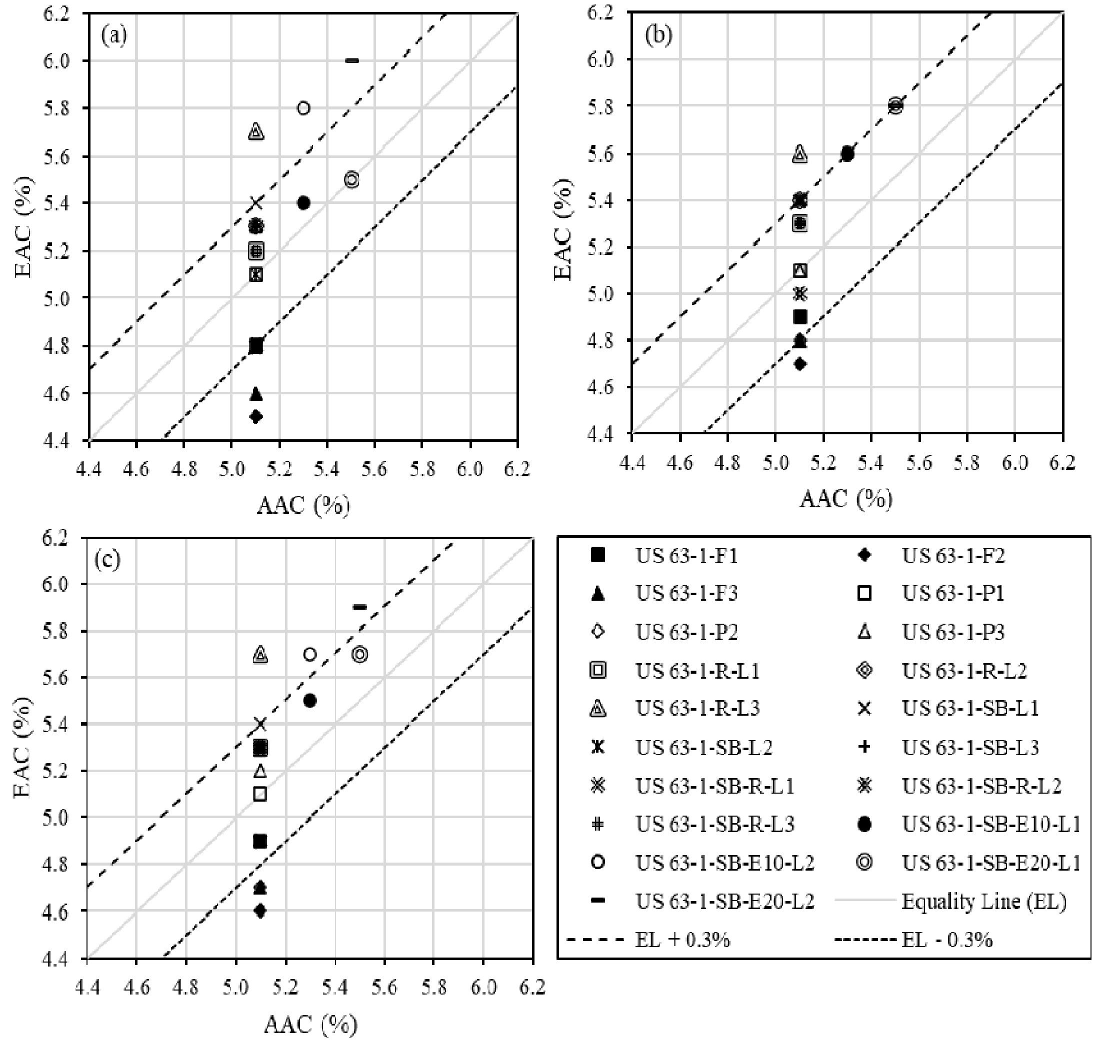

Fig. 9. AAC% versus EAC% values for the US 63-1 mixes; (a) AMMDM, (b) CMMDM, and (c) AAACMMDMs

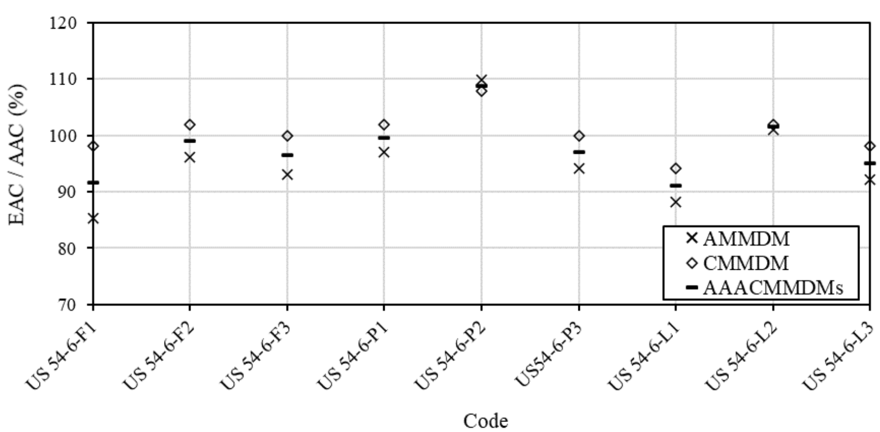

Fig. 10. EAC per AAC values for the US 54-6 mixes

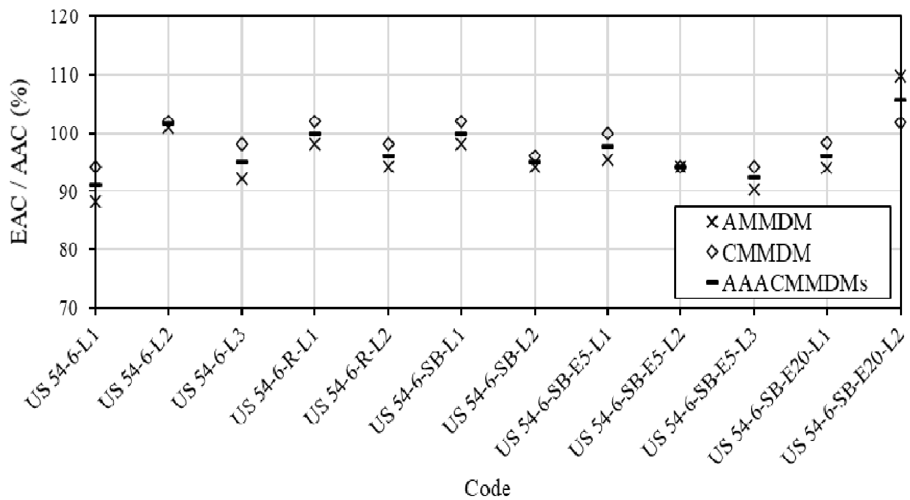

Fig. 11. EAC per AAC values for the US 54-6 lab mixes

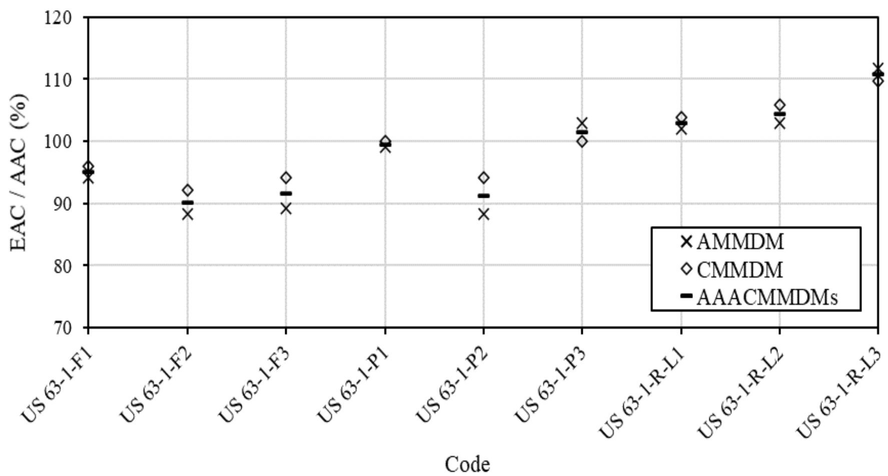

Fig. 12. EAC per AAC values for the US 63-1 mixes

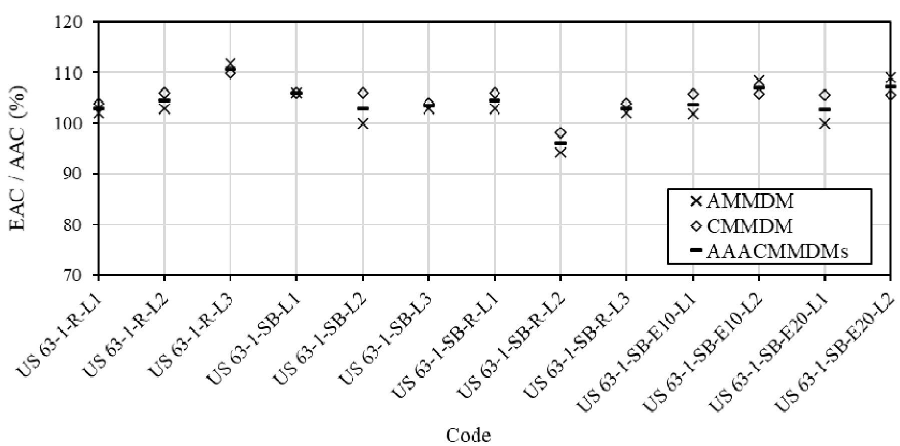

Fig. 13. EAC per AAC values for the US 63-1 lab mixes

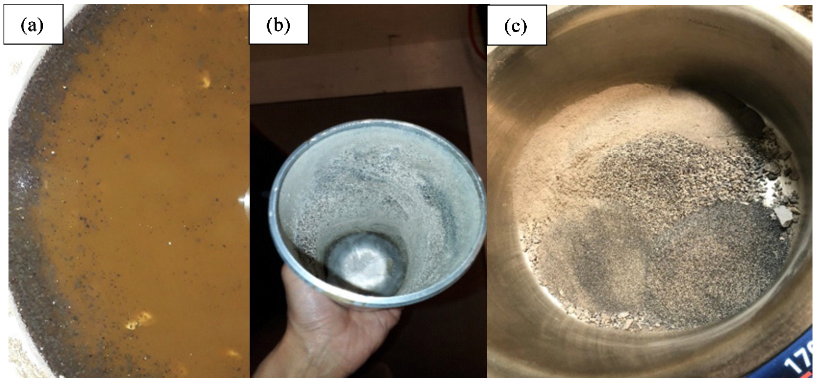

Fig. 14. The extracted ECR particles; (a) TCE-suspended ECR particles in the extractor bowl, (b) ECR particles extracted with the mineral matter after the filterless centrifuge process, and (c) ECR particles remained with the aggregate [5]

3.4 Field Mixes Constructed in 2016

Fig. 15 depicts the AAC% and EAC% values for field mixes constructed in 2016 using different MMDMs. The AAC% values ranged from 4.8% to 5.7%. The EAC% values utilizing AMMDM were determined to be between 4.4% and 5.3%, as shown in Fig. 15(a). The majority of samples (87%) had EAC% values that were lower than the AAC% values. As a result, the EAC% values were underestimated by AMMDM. The accuracy of the EAC% values was improved by utilizing CMMDM, as shown in Fig. 15(b). By using CMMDM, the EAC% values ranged from 4.7% to 5.6%. Hence, the EAC% values utilizing CMMDM were more accurate. As shown in Fig. 15(c), the EAC% values were computed using AAACMMDMs, the EAC% values ranged from 4.6% to 5.5%. To conclude, the EAC% values using CMMDM had more accurate results than the EAC% values using AMMDM or AAACMMDMs. This was deduced because 65.22% of the samples had EAC% using AMMDM within the AAC% ± 0.3%, and 78.26% of the samples had EAC% using AAACMMDMs within the AAC% ± 0.3%, as seen in Figs. 15(a) and 15(c). However, using CMMDM, as shown in Fig. 15(b), 91.30% of the samples had EAC% within the AAC% ± 0.3%.

The ANOVA results are shown in Table 8 to demonstrate the influence of different MMDMs on the EAC% values. The Prob > F was 0.0028 that was less than the 0.05 threshold of significance. When comparing the means of the EAC% values using different MMDMs to the mean of the AAC% values, there was a significant difference. The Tukey honestly significant difference (HSD) test was used to determine which MMDM had a significant difference. Table 9 shows the Tukey HSD test results for the connecting letters report. The levels that were not connected by the same letter differed greatly. When compared to the means of the AAC% or EAC% values using CMMDM, the mean of the EAC% values using AMMDM was significantly different.

Table 8. ANOVA results: AAC% and AAC% values for field mixes constructed in 2016

Source	D.F.	S.S.	M.S.	F Ratio	Prob > F
Method	3	0.978	0.326	5.067	0.0028
Error	88	5.661	0.064		
C. Total	91	6.639			

Table 9. Tukey HSD test results

Level			Mean
AAC%	A		5.22
EAC% by CMMDM	A		5.20
EAC% by AAACMMDMs	A	B	5.08
EAC% by AMMDM		B	4.96

Note: Significant differences exist between levels that are not connected by the same letter.

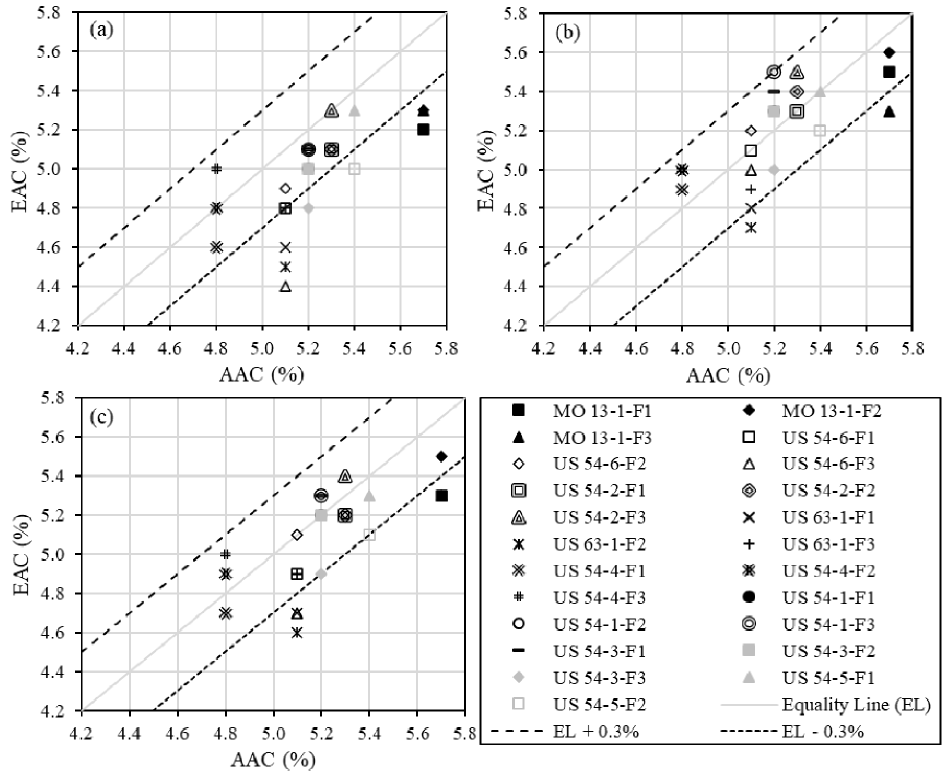

Fig. 15. AAC% versus AAC% values for field mixes constructed in 2016; (a) AMMDM, (b) CMMDM, and (c) AAACMMDMs

4. CONCLUSION

Asphalt binders were extracted from field, plant, and lab mixes containing reclaimed asphalt pavement (RAP) and/or recycled asphalt shingles. Extraction was performed using a centrifuge extractor, and the percentages of extracted asphalt content (EAC) were evaluated using two mineral matter determination methods (MMDMs). The EAC% values using ashing MMDM (AMMDM), centrifuge MMDM (CMMDM), and average ashing and centrifuge MMDMs were compared with the actual asphalt content (AAC)% values. The effect of the different fabrication methods used in the mixes on the EAC% values was analyzed. The effect of using a soft virgin asphalt binder (VAB) or Evoflex as a recycling agent on the EAC% values was explored. The following conclusions were reached as a result of this study:

1. In ASTM D2172 / D2172M-17e1, the procedures of the AMMDM recommend measuring ~ 100 ml in the ignition dish of the extracted effluent immediately after agitation, which could underrate the EAC%. Based on several trials carried out by the researchers, it was found that pouring the 100-ml representative sample in the ignition dish after three minutes of the agitation increased the accuracy of the EAC%.
2. Higher percentages of mixes had EAC% within the AAC% ± 0.3% using CMMDM compared to AMMDM. Therefore, CMMDM showed more accurate EAC% values than those of AMMDM.
3. As a result of adopting a softer VAB by lowering the high-performance grade (PG) by two grades and the low PG by one grade, the EAC% increased by 2% from the AAC%.
4. Reheating plant mixes in the lab to the compaction temperature increased the interactions between VAB and RAP binder, resulting in increased the EAC% values when compared to EAC% values from the same mixes collected from the field.
5. The use of Evoflex boosted the interactions between the RAP binder and VAB, which increased the EAC%.

DISCLAIMER

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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