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Determining Percentage of Recycled Asphalt Pavement in Asphalt Mixtures

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Drum mix plants are the primary hot-mix asphalt (HMA) production plants for most Kansas Department of Transportation (KDOT) projects. In drum mix plants, a totalizer controls the input rate of virgin aggregates and recycled asphalt pavement (RAP). In current practice, the RAP percentage is determined by the input rate shown on the totalizer. However, KDOT conducted a detailed analysis of data from one project and found that the estimated amount of RAP based on the asphalt cement mass-balance method was higher than the designed RAP content. The study for this report included visits to several plants and the collection of plant operation and total production data to calculate the RAP percentage. Furthermore, a Monte-Carlo approach was followed to estimate RAP quantity based on RAP binder content, and actual plant input and output data verified the calculations. This report proposes test guidelines for RAP and reclaimed asphalt shingle percentages.

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PREFACE

The Kansas Department of Transportation's (KDOT) Kansas Transportation Research and New-Developments (K-TRAN) Research Program funded this research project. It is an ongoing, cooperative and comprehensive research program addressing transportation needs of the state of Kansas utilizing academic and research resources from KDOT, Kansas State University and the University of Kansas. Transportation professionals in KDOT and the universities jointly develop the projects included in the research program.

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Abstract

Drum mix plants are the primary hot-mix asphalt (HMA) production plants for most Kansas Department of Transportation (KDOT) projects. In drum mix plants, a totalizer controls the input rate of virgin aggregates and recycled asphalt pavement (RAP). In current practice, the RAP percentage is determined by the input rate shown on the totalizer. However, KDOT conducted a detailed analysis of data from one project and found that the estimated amount of RAP based on the asphalt cement mass-balance method was higher than the designed/Job Mix Formula RAP content. The study for this report included visits to several plants and the collection of plant operation and total production data to calculate the RAP percentage. Furthermore, a Monte-Carlo approach was followed to estimate RAP quantity based on RAP binder content, and actual plant input and output data verified the calculations. This report proposes test guidelines for RAP and reclaimed asphalt shingle percentages.

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Chapter 1: Introduction

1.1 Background

Drum mix plants, the primary hot-mix asphalt (HMA) production plants for most Kansas Department of Transportation (KDOT) projects, use belts to feed virgin aggregates and reclaimed asphalt pavement (RAP) into a drum for HMA production. At the beginning of each project, the belts are calibrated to control the aggregate and RAP quantities during mixing. Based on the totalizer input, a specific amount of virgin binder is then pumped from a storage tank (NAPA & APWA, 2000). Although current specifications require the use of a totalizer to determine the percentage of RAP in HMA, an asphalt cement mass-balance method identified discrepancies in amount of RAP fed into the drum for various projects when compared to the totalizer method. KDOT conducted a detailed analysis of one project and found that the amount of RAP backcalculated from the total mass of mixture and virgin binder content was higher than the designated RAP content, highlighting the need for data investigation and verification of multiple projects.

1.2 Objective

The objective of this study was to investigate the discrepancies between calculated and actual RAP contents in HMA produced in the drum mix plants. The study collected actual feed/input data from plant production and then compared the data to the calculated results.

1.3 Report Outline

This report is divided into four chapters. Chapter 1 states the background and objective of the research. Chapter 2 describes the literature review. Chapter 3 outlines the plant investigation. Chapter 4 presents the results and analysis, and Chapter 5 summarizes the conclusions and presents the recommendations based on this study.

Chapter 2: Literature Review

An HMA plant aims to produce a homogeneous asphalt mixture by blending aggregate and asphalt binder at an elevated temperature. Batch and drum mix HMA plants are currently used in the United States. Batch plants produce small, precise batches of HMA mixture until total tonnage is reached, while drum mix plants continuously manufacture HMA mixtures without interruption.

2.1 Batch Plants

A batch plant includes a cold-feed system, asphalt cement system, aggregate dryer, mixing tower, and emission-control system (NAPA & APWA, 2000). The major components of a batch plant are shown in Figure 2.1. The aggregates used in mixing are placed into individual cold-feed bins and output with a designed proportion. The gathering conveyor under the cold-feed bins transports aggregates to a charging conveyor and then to the dryer. After the drying operation, a bulk elevator transports the aggregates to the top of the mixing tower and discharges them into various hot storage bins as they pass through vibration screens. A weigh hopper weighs the aggregates discharged from the hot bins to ensure the correct aggregate proportion. At the same time, a proper amount of asphalt cement (per Job Mix Formula, JMF) is pumped into a bucket above the pugmill. If RAP is used in the mixture, it is stored in a separate cold bin and added via either the bottom of the bulk elevator, the hot bins, or the weigh hopper, which is most common. The aggregates are then dropped into the pugmill and mixed for a short period, discharging asphalt cement into the pugmill. The mixing process is finished in a short period of time. After mixing, the mixture is discharged from the bottom of the mixing tower into the mixing vehicle or conveyor that moves the mixture to a silo (NAPA & APWA, 2000).

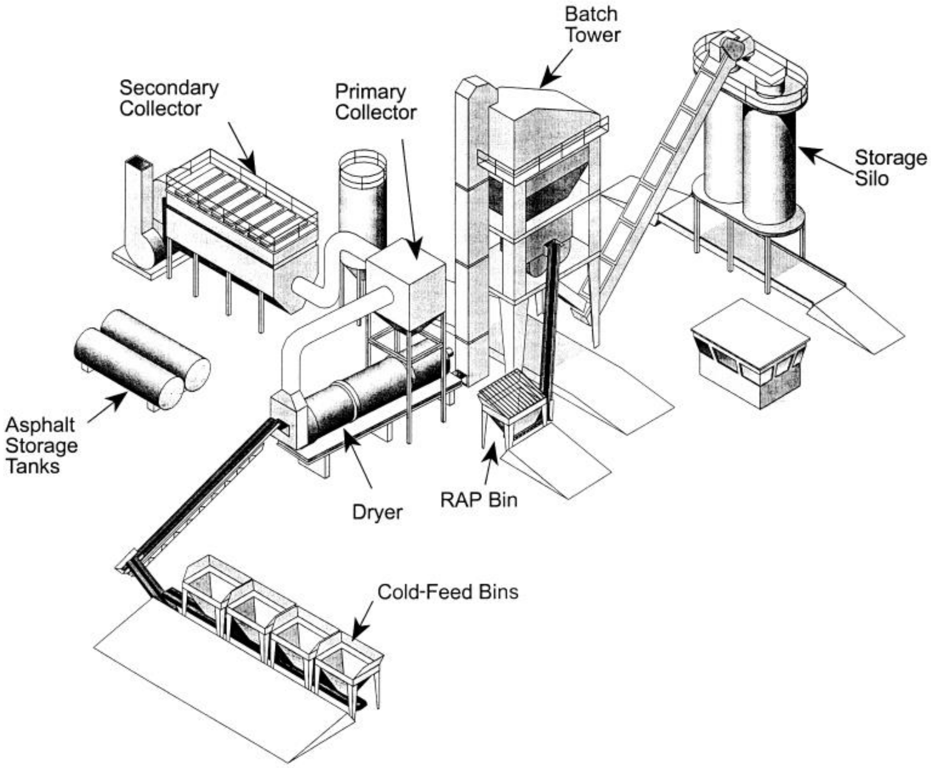


Figure 2.1: Major Components of a Batch Plant
Source: NAPA & APWA (2000)

2.2 Drum Mix Plants

Drum mix plants are typically either parallel-flow or counter-flow; KDOT typically utilizes both types. Parallel-flow and counter-flow plants have similar mixing procedures and significant components, including a cold-feed system, an asphalt cement supply system, a drum mixer, and surge or storage silos. A diagram of a drum mix plant is shown in Figure 2.2.

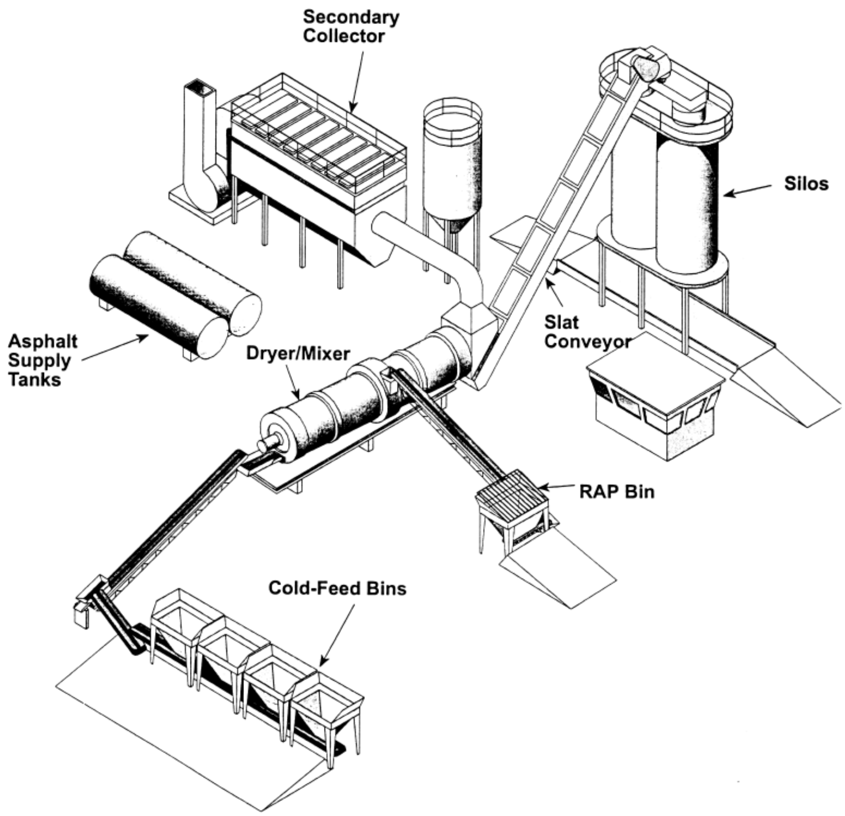


Figure 2.2: Major Components of a Drum Mix Plant
Source: NAPA & APWA (2000)

2.2.1 Parallel-Flow Drum Mix Plants

In parallel-flow drum mix plants, cold-feed bins typically are used to introduce aggregates into the mixing process, and the size of the gate and the speed of the feeder belt beneath the bin are used to control the proportion of the material. A gathering conveyor under the cold-feed bins gathers all the aggregates and delivers them to a charging conveyor via passage through a scalping screen. The charging conveyor then transports the aggregates into the drum mixer. The charging conveyor typically contains a weighbridge and a sensor (Figure 2.3) to control the amount of aggregate needed in the mix. The weighbridge under the conveyor belt measures the weight of the aggregate passing over the weigh idler, which is attached to the load cell. The charging conveyor operates at a constant speed that is recorded with a belt sensor. The totalizer combines the information gathered from the two devices to determine the actual wet weight of the aggregates in tons per hour. The moisture information of the aggregates must be manually input into the control system to convert the wet weight to dry weight so that the proper amount of asphalt cement per

JMF is calculated. The control system screen of a drum mix plant investigated in this research is presented in Figure 2.4.

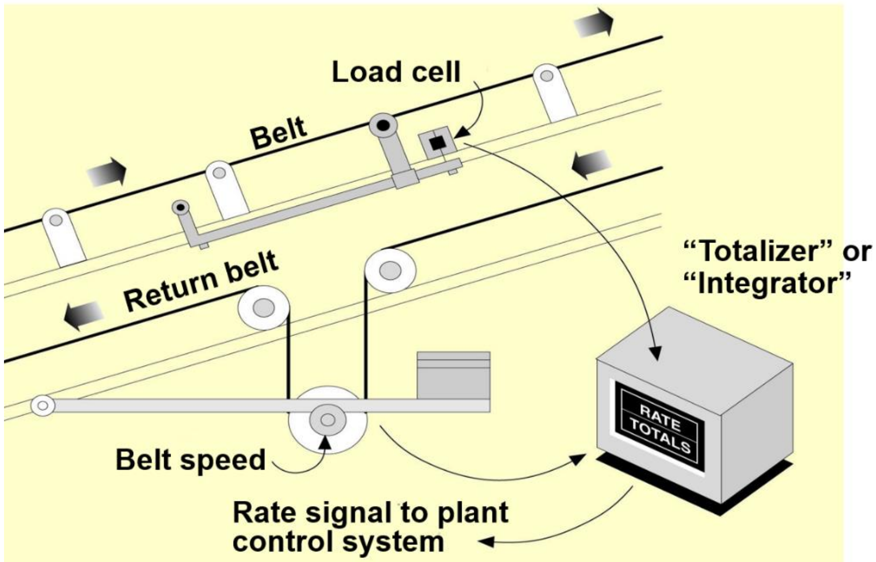


Figure 2.3: Weighbridge System
Source: NAPA & APWA (2000)

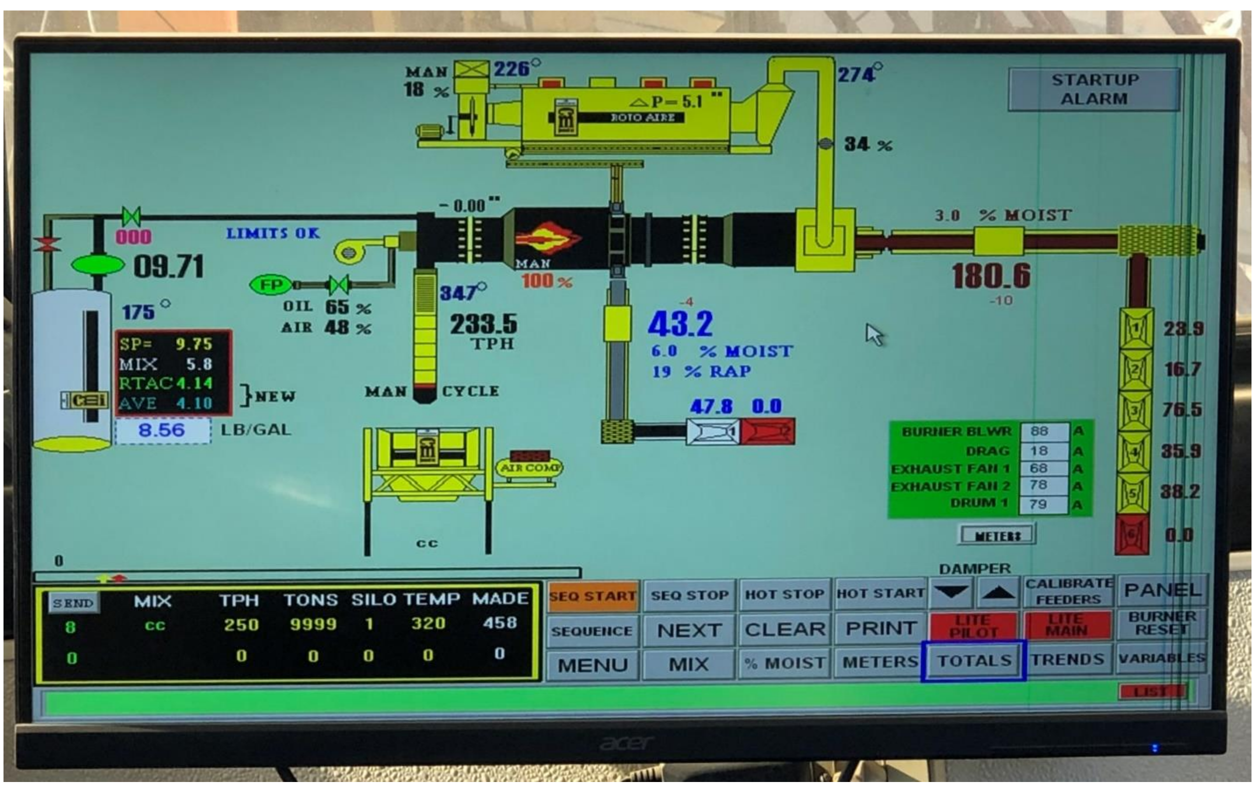


Figure 2.4: Sample Control System of Drum Mix Plant
Photo Courtesy: APAC (2021)

In a drum mix plant, the burner is located at the upper end of the drum, and the aggregates are introduced into the drum through an inclined chute or a slinger conveyor. The inclined chute above the burner transports the aggregates by gravity. The slinger conveyor below the burner throws the aggregate into the drum with sufficient belt speed (Roberts et al., 1991; NAPA & APWA, 2000). As the aggregates travel into the drum, the moisture is removed and heated. If recycled materials are used, such as RAP and reclaimed asphalt shingles (RAS), they are delivered from a separate cold-feed bin with its conveyor system. Recycled materials are fed into the drum from a collar in the middle of the drum to prevent overheating. Once the virgin aggregates and reclaimed materials move to the discharge end of the drum, asphalt cement is pumped from the storage tank, fed through a meter, and injected into the aggregates, which are then coated with a binder while tumbling in the drum. The mixture then moves to the lower end of the drum and transits into a conveyor device. The conveyor, such as a drag slat conveyor or belt elevator, carries the HMA mixture into a storage silo, and the silo delivers the mixtures into haul vehicles in batches. The weight of each batch is weighed via silo scales, platform scales, or truck scales (NAPA & APWA, 2000).

2.2.2 Counter-Flow Drum Mix Plants

The operation process of counter-flow drum mix plants is like parallel-flow drum mix plants except for mixing. In the parallel-flow drum, the aggregates and hot air flow in the same direction through the drum, while in the counter-flow drum, the aggregates and hot gases flow in opposite directions. In double-barrel counter-flow drums the drying and mixing processes occur in separate barrels. The aggregates are introduced into the drum from the upper end and dried and heated via the burner at the lower end. The dried and heated aggregates are then discharged downward into the outer barrel to mix with the asphalt cement. If applicable, RAP is added to the external drum. However, this mixing unit is not commonly used since the external drum does not rotate (NAPA & APWA, 2000). The most common counter-flow drum in Kansas is the conventional counter-flow drum, which contains a burner inside the drum near the lower end; the aggregates enter the drum from the upper end. The drum portion in front of the flame is the drying zone. The dried and heated aggregates then move down to the mixing zone behind the burner and mix with asphalt cement. If applicable, RAP is introduced into the mixing zone behind the burner to avoid high temperature and further aging of RAP.

2.2.3 Calibration

Calibration is required to ensure accurate production of the HMA mixture for all drum mix plants. The plant should be calibrated prior to the start of production of new HMA mixtures and whenever the portable plant is relocated, the plant has shut down for a relatively long time, the supply system for the ingredient proportions is broken, or the material changes (AASHTO, 2017a; Kennedy et al., 1986). Calibration procedures require running some aggregates on the charging conveyor and recording the weight that passes over the weigh idler. Instead of delivering the aggregates into the drum mixer, a truck is used to collect all aggregates and weights. KDOT requires belt-scale accuracy within 2% of the material weight (KDOT, 2015). If the tolerance is exceeded, the weighbridge should be adjusted following the manufacturer's guide so that two consecutive tests are within tolerance. The cold-feed bins should be calibrated by determining the flow of aggregates with different gate openings and different belt speeds. The gate openings should be calibrated above, at, and below the estimated plant production rate. To calibrate the belt speed, 20%, 50%, and 80% of the maximum feeder belt speed are selected (NAPA & APWA, 2000; Kennedy et al., 1986). The contractors typically set up the gate opening based on experience and then calibrate the speed of the feeder belt bracket to match the anticipated production rates. The drum mix plant's asphalt cement pump and meter system must be calibrated to ensure the correct amount of asphalt binder is injected into the mix. An empty and clean distributor truck is required to carry the binder and pump it back to the storage tank. After pumping the needed amount of asphalt cement, the weight of the distributor truck is taken over a certified scale, and the net weight is calculated. The plant console catches the reading of the metering system and calculates the weight. These two values should be within the required tolerance, typically 2% in Kansas (KDOT, 2015).

2.3 Reclaimed Materials in HMA Mixture Production

Using recycled materials such as RAP and RAS in asphalt pavement construction can decrease the demand for new materials such as virgin binder and aggregates, which can consequently lower material costs and preserve natural resources. Williams et al. (2022) stated that approximately 94.6 million tons of RAP and 630,000 tons of RAS were used in asphalt mixtures in 2021. RAP usage replaced 4.7 million tons of asphalt binder and more than 89 million tons of aggregate, resulting in a $3.4 billion savings (Williams et al., 2022). During the construction season of 2021, the use of RAS reduced the need for 126,000 tons of asphalt binder and 315,000 tons of aggregate, saving over $69 million (Williams et al., 2022).

2.3.1 Reclaimed Asphalt Pavement

FHWA defines RAP as “removed or reprocessed pavement materials that contain asphalt binder and aggregates during resurfacing, rehabilitation, or reconstruction operations” (Copeland, 2011). Although a total of 1,915 asphalt pavements were initially recycled, standard use of RAP did not become a practice until crude oil prices increased significantly due to the Arab oil embargo in 1973 (West, 2015; Copeland, 2011). In the United States, RAP is a valuable alternative to virgin materials and is recycled more than any materials (Williams et al., 2022). More than 95% of RAP returned to produce new pavements, while the remaining 5% were used as unbound aggregate bases or subbases (Chesner et al., 1998; Williams et al., 2022).

RAP is collected from milling and full-depth pavement removal, as well as occasional plant waste during production. Asphalt milling is a process of pavement rehabilitation that typically removes rutting from the surface to produce a smooth, even surface for repaving. In comparison, full-depth pavement demolition breaks down the entire pavement into chunks with heavy equipment and then crushes it into manageable sizes for reuse. Plant waste is usually stored in a separate stockpile or added to the unprocessed RAP stockpile for future processing (Copeland, 2011).

Although the use of an HMA mixture with RAP has many advantages, recycled materials often demonstrate decreased durability, specifically due to the aged asphalt binder from RAP. Most states allow 0% to 30% recycled materials in HMA mixtures. Studies have shown that, in mixtures containing up to 20% RAP, aged binders do not significantly influence the blended binder properties (Kennedy et al., 1998). However, increased percentages of RAP could dramatically affect the performance of the blended binder (Al-Qadi et al., 2007). According to the AASHTO

Superpave mix design specification (AASHTO M 323-17, 2017), the level of the binder performance grade (PG) must be reduced by one when using more than 15% RAP. When adding more than 25% RAP, the virgin binder performance grade (PG) should be determined according to the properties of the RAP binder.

Daniel and Lachance (2005) found that a mixture with 15% RAP had increased stiffness but lower compliance, indicating that the mixture with RAP is more resistant to permanent deformation and less resistant to fatigue and thermal cracking. The 25% and 40% RAP mixtures had higher voids in mineral aggregate (VMA) and voids filled with asphalt (VFA), making the mixture soft, decreasing the dynamic modulus, and increasing creep compliance.

Shu et al. (2008) found that mixtures containing RAP demonstrated increased tensile strength and decreased post-failure tenacity. The dissipated creep strain energy and energy ratio decreased, resulting in decreased fatigue life of HMA mixtures. Plateau values from the beam fatigue test showed that the inclusion of RAP would need more input energy for damage, thereby shortening the fatigue life.

Izaks et al. (2015) concluded that high RAP content decreases fatigue resistance and that an HMA mixture could be designed with up to 50% RAP since RAP has no significant effect on volumetric and mechanical properties. They determined that increasing the effective asphalt content of the recycled asphalt mixtures increases mixture durability and fatigue resistance.

Hong et al. (2010) analyzed the field data of several pavement sections in Texas with 35% RAP from 1991 to 2007. Overall, relatively satisfactory performance of the sections was observed during the monitoring period, although the area with 35% RAP had more cracking, lower rut depth, and similar roughness compared to the pavement without RAP. The researchers concluded that, with proper mix design, the performance of a pavement containing up to 35% RAP would be identical to that of pavements without RAP during an average pavement life span.

2.3.2 Reclaimed Asphalt Shingles (RAS)

RAS is typically derived from tear-offs of roofs and manufactured shingle waste. Three essential components comprise RAS: fibers, asphalt cement, and mineral granules. In the late 1980s, the first shingle recycling was established, and the investigation of HMA with RAS began

(Aschenbrener, 2018). Most RAS is used for paving projects. After grounding the shingles into particles, the large particles can be used for base stabilization, while the smaller particles are used in the surface course. AASHTO M350-22 (2022) is the current standard specification for RAS usage in asphalt mixtures. Due to the angular and hard granules in RAS, the VMA of the HMA with RAS has been shown to increase, indicating that the mixture is less susceptible to cracking (Willis & Turner, 2016). However, the asphalt binder in RAS is more aged, oxidized, much stiffer and more brittle than virgin binders, which likely decreases the mixture's cracking resistance (Stroup-Gardiner, 2016). Typically, 3%–5% RAS by weight or approximately 15%–20% binder replacement is used in asphalt mix design (Aschenbrener, 2018; Hand et al., 2021). State DOTs also have specific requirements for RAS use in combination with RAP.

2.3.3 Summary

Although some DOTs allow increased amounts of recycled materials in HMA mixtures, the effect of high percentages of recycled materials on long-term pavement performance is a significant concern. Therefore, consistency control of recycled materials during HMA processing and production in a drum mix plant is critical. An Asphalt Concrete (AC) mass-balanced method calculates the percentage of RAP and RAS with quality control (QC) and quality assurance (QA) data to verify the usage of recycled materials. Therefore, the process control is crucial in the production of HMA.

Chapter 3: Plant Investigation

Researchers for the current study visited four portable plants for projects on US-83, US-36, US-24, and K-23 in KDOT District Three; two mobile plants for projects on K-15 and I-135 in KDOT District Two; and one portable plant for a project on K-31 in District One.

3.1 Project and Superpave Mixture Data

Process control and quality assurance data on RAP contents were collected from the seven projects, and the mixture information of these projects is shown in Table 3.1.

Table 3.1: Study Project and Superpave HMA Data

Project No.	U083-020 KA 5662-01	U036-20 KA 5663-01	24-90 KA-5343-01	32 KA 5550-01	15-106 KA 5865-01	K031-099 KA 6316-01	I135-85 KA 6064-01
Route	US-83	US-36	US-24	K-32	K-15	K-31	I-135
%RAP	25	25	25	25	20	25	25
Target % AC	5.30	5.20	5.20	5.20	5.60	5.90	5.20
% AC by Mass of Mix	5.05	5.07	5.31	5.38	5.99	6.23	5.51
Bulk Specific Gravity of Aggregates	2.580	2.581	2.595	2.608	2.504	2.556	2.560
Theoretical Maximum Specific Gravity	2.433	2.426	2.426	2.417	2.344	2.406	2.409
Bulk Specific Gravity of Mix	2.349	2.339	2.357	2.354	2.273	2.343	2.307
Eff. Specific Gravity of Aggregates	2.623	2.614	2.624	2.616	2.550	2.641	2.612
Absorbed % AC	0.66	0.51	0.44	0.12	0.74	1.29	0.80
Effective % AC	4.42	4.59	4.89	5.27	5.29	5.02	4.75
% VMA	13.6	14.0	14.0	14.6	14.7	14.0	14.8
% Air Voids	3.45	3.59	2.84	2.61	3.03	2.62	4.23
% VFA	74	74	80	82	79	82	72
Dust/Binder Ratio	1.1	1.0	0.9	0.8	0.7	1.1	1.0

3.2 Totalizer Data

The plant operation data was obtained periodically for up to three days from seven projects. Flow rates, such as the feed rate of the virgin aggregates and RAP from the totalizer, were collected every 10 to 15 minutes of mix production. Plant calibration was observed on the first day of the project beginning. Virgin aggregate and RAP weights were measured by the weighbridge, and after correcting for moisture, dry weight was continuously calculated by the system. This information was recorded for this project every 30 minutes. These weight values were used to calculate the RAP percentage in the HMA mixture, which is the percentage of the aggregate blend, including virgin aggregate and RAP, not a portion of the entire mixture. RAP percentage calculation results are shown in Table 3.2, along with the job mix formula (JMF) RAP percentage of each project.

Table 3.2: RAP Percentage Calculated from Totalizer Data

Project No.	District No.	JMF RAP Content	Plant Operation Data							
			Feed Rate				Totalizer			
			Mean RAP Quantity	Std. Dev.	COV	No. of Data Points	Mean RAP Quantity	Std. Dev.	COV	No. of Data Points
U083-020 KA 5662-01	3	25%	23.7%	0.007	2.9%	45	23.7%	0.001	0.5%	17
U036-20 KA 5663-01	3	25%	23.5%	0.008	3.3%	52	24.0%	0.006	2.6%	24
24-90 KA-5343-01	3	25%	22.7%	0.010	4.3%	78	23.4%	0.006	2.6%	23
32 KA 5550-01	3	25%	23.5%	0.009	4.0%	78	23.0%	0.011	4.6%	25
15-106 KA 5865-01	2	20%	19.8%	0.008	3.8%	86	19.9%	0.008	3.8%	25
K031-099 KA 6316-01	1	25%	24.3%	0.005	2.0%	73	24.2%	0.002	1.0%	22
I135-85 KA 6064-01	2	25%	25.0%	0.006	2.5%	85	24.5%	0.009	3.5%	19

As shown in the table, the totalized RAP percentage did not exceed the maximum RAP level in JMF, and the RAP percentages determined by the totalizer were consistent with the target feed rates. The low coefficients of variation of the rate data indicate precise process control.

3.3 AC Mass-Balance Method

This study also utilized an AC mass-balance method to calculate the percentage of RAP in the HMA mixture. Knowledge of the mixture's AC content, typically determined via QC testing, is necessary to calculate volumetric properties to determine the mixture's suitability. This study utilized Kansas test method KT-57: Determination of Asphalt Content and Gradation of Hot-Mix Asphalt Concrete by the Ignition Method (2022) to determine the AC content of the HMA mixture and RAP. Added virgin AC and AC from the added RAP amount constitute the total binder content of the mix. Therefore, the theoretical AC content of an HMA mixture at the maximum allowable RAP percentage was calculated by

$$P_{b\ MixTheo.} = (AC + \%RAP_{Max} * P_{b\ RAP} * (Q_{Mix} - AC)) / Q_{Mix}$$

Equation 3.1

Where:

$P_{b\ MixTheo.}$ = theoretical AC content of the HMA mixture;

AC = virgin AC and additives (ton);

$\%RAP_{Max}$ = maximum RAP percentage of JMF allowed in the mixture, expressed as decimal (i.e., 25% = 0.25);

$P_{b\ RAP}$ = AC content of RAP based on the average QC/QA test results; and

Q_{Mix} = total quantity of mix produced.

If QC/QA data is available for the HMA mixture and RAP and the quantities of produced HMA mixture and virgin AC are known, then the theoretical %RAP can be calculated by

$$\%RAP_{Theo.} = ((Q_{Mix} * P_{b\ Mix}) - AC) / (P_{b\ RAP} * (Q_{Mix} - AC))$$

Equation 3.2

Where:

$\%RAP_{Theo.}$ = theoretical %RAP; and

$P_{b\ Mix}$ = average AC content of the HMA mixture based on the average QC/QA testing values.

The QC/QA data from the HMA mixture and RAP and the total quantity of HMA mixture and virgin AC were collected from the contractor and KDOT after construction. Table 3.3 shows the back-calculation results of the RAP percentages compared to the totalizer results.

Table 3.3: RAP Percentage Comparison

Project No.	District No.	JMF RAP Content	Mean RAP Quantity		
			AC Mass-Balance Data	Plant Operation Data	
				Feed Rate	Totalizer
U083-020 KA 5662-01	3	25%	28.6%	23.7%	23.7%
U036-20 KA 5663-01	3	25%	27.6%	23.5%	24.0%
24-90 KA-5343-01	3	25%	26.6%	22.7%	23.4%
32 KA 5550-01	3	25%	26.7%	23.5%	23.0%
15-106 KA 5865-01	2	20%	18.4%	19.8%	19.9%
K031-099 KA 6316-01	1	25%	25.6%	24.3%	24.2%
I135-85 KA 6064-01	2	25%	29.7%	25.0%	24.5%

Significant differences between the AC mass-balance method results and the totalizer method results from the five projects were highly concerning to KDOT. For example, for the QC/QA data from Project 32 KA 5550-01, RAP AC contents from the contractor and KDOT differed significantly. The average values of the RAP AC content and calculated RAP percentages from Project 32 KA 5550-01 are shown in Table 3.4.

Table 3.4: RAP and AC Content from Project 32 KA 5550-01

32 KA 5550-01	JMF	Total	KDOT	Contractor
Average RAP AC Content		6.5%	7.8%	5.8%
RAP Content	25%	26.7 %	22.1%	29.8%

As shown in the table, KDOT QA data showed a high AC RAP content (7.8%), resulting in a decreased RAP percentage that was the maximum RAP percentage required by contract documents. The contractor's QC results for the AC content of RAP were 5.8%, which increased the RAP percentage, proving that the AC content of RAP significantly impacted the RAP percentage. To further investigate the influence of AC contents in RAP and HMA mixtures, burn-off tests were done in the laboratory at Kansas State University, and the RAP AC results from KDOT and the contractor were compared.

3.4 Burn-Off Tests

Two other projects (K-31 and I-135) were also visited later as follow up in this study. Plant operation data were obtained, and RAP and HMA mixtures were collected to conduct burn-off tests according to KDOT test method KT-57 (2022). The HMA mixtures were randomly collected behind the paver, and the RAP samples were collected via the outlet on the RAP belt conveyer. A total of 1,500 grams of HMA mixtures and 2,000 grams of RAP samples were collected for the burn-off tests. The test samples were preheated under 110 ± 5 °C to dry to a constant mass and to ensure all the particles could be spread evenly on the basket. After cooling the samples to room temperature, the mass of the sample and basket were recorded. The initial sample weight was calculated from the mass of the sample and basket minus the mass of the empty basket. The sample was put into the ignition oven at a temperature of 500 °C. The sample was burned until it was free of asphalt and then removed from the furnace to cool to room temperature. The weight was re-recorded, and the total weight of the aggregate after ignition was calculated. The following equation was used to calculate the asphalt content of the sample:

$$AC\% = \left[\frac{(W_S - W_A)}{W_S} * 100\right] - C_F$$

Equation 3.3

Where:

AC% = measured (corrected) asphalt content percent by mass of the sample;

WA = total mass of aggregate remaining after ignition;

W_S = total mass of the sample prior to ignition; and

C_F = calibration factor, percent of mass of the HMA sample.

Table 3.5 presents the burn-off test results compared to the QC and QA results obtained from KDOT and the contractor.

Table 3.5: AC Content from Burn-Off Tests

AC (%)	Project No.			
	K031-099 KA 6316-01		I135-85 KA 6064-0135	
	HMA	RAP	HMA	RAP
JMF	5.90%	-	5.40%	-
QC	6.00%	7.03%	5.38%	5.66%*
QA	6.07%	7.52%	5.38%	6.11%
KSU Lab	6.12%	6.57%	5.45%	5.57%

*in mix design submittal

As shown in Table 3.5, no significant differences between the asphalt binder contents were observed for both projects' HMA mixtures. However, the test results of RAP asphalt content from multiple labs showed differences. That, in turn, affected the calculated RAP contents from the AC mass-balance method. The RAP percentage calculation results based on QC, QA, and laboratory results are shown in Table 3.6, along with the RAP content obtained from plant operation data.

Table 3.6: RAP Percentages Based on QC, QA, and Laboratory Burn-Off Test Results

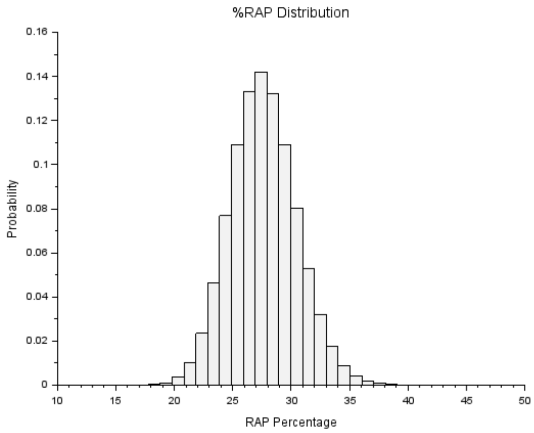
Project No.	District No.	JMF	Mean RAP Quantity				
			AC Mass-Balance Data			Plant Operation Data	
			QC	QA	KSU Lab	Feed Rate	Totalizer
K031-099 KA 6316-01	2	25%	25.8%	24.1%	27.6%	24.3%	24.2%
I135-85 KA 6064-0135	2	25%	31.4%	29.1%	32.0%	25.0%	24.5%

Chapter 4: Data Analysis

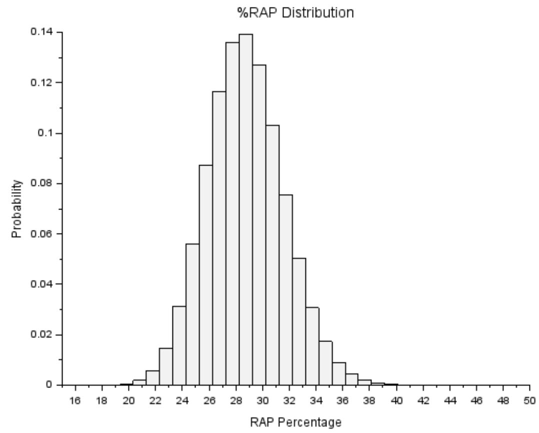
4.1 Monte Carlo Simulation

The Monte Carlo simulation is a statistical method to predict the probability of output with random variables and repeated random sampling. In other words, the method can quantitatively account for risk in forecasting and decision-making (Kroese et al., 2014). This study used Scilab for the Monte Carlo simulations to randomly generate binder content in RAP and HMA mixture to calculate the RAP percentage and generate the RAP percentage probability distribution. Scilab is a user-friendly scientific computation software that provides numerical computations and algorithms testing (Baudin, 2010).

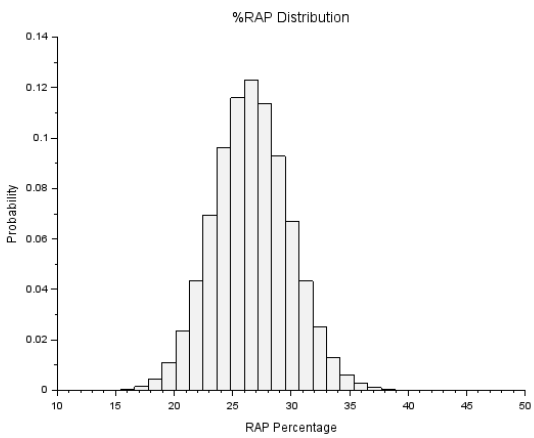
To start a Monte Carlo simulation, a functional equation was created in the software to determine the RAP percentage (Equation 3.2), and then the input parameters were defined in the software. The total quantity of HMA mixture produced and the total AC usage were considered constant values. Two variables, binder content in RAP and HMA mixture, were randomly generated with specified mean and standard deviation following a normal distribution. The average values collected from each project's burn-off test results and standard deviation values were calculated and used as inputs in the software, as shown in Table 4.1. In addition, the multi-laboratory precision, which is 0.117%, from the Kansas test method KT-57 was also used and compared to the simulation results of the collected RAP asphalt content standard deviation. An extensive random data set was needed to perform the simulation because more data provided an anticipated input variation; thereby, providing a reliable indication of the outputs. In this study, 5,000,000 was the initial number for each variable to generate and obtain the RAP percentage. Histogram plots were also generated to show the RAP percentage distribution, as illustrated in Figures 4.1 and 4.2. The risks of RAP percentage exceeding the JMF value were also calculated and tabulated in Table 4.1.



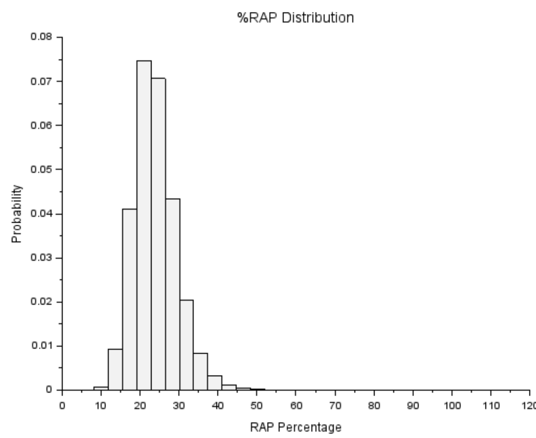
(a) Project U036-20 KA-5663-01



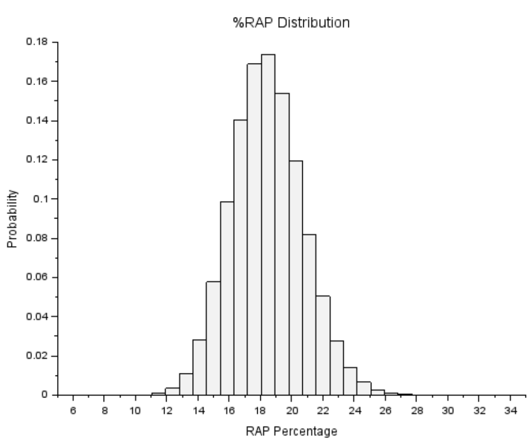
(b) Project U083-020 KA-5662-01



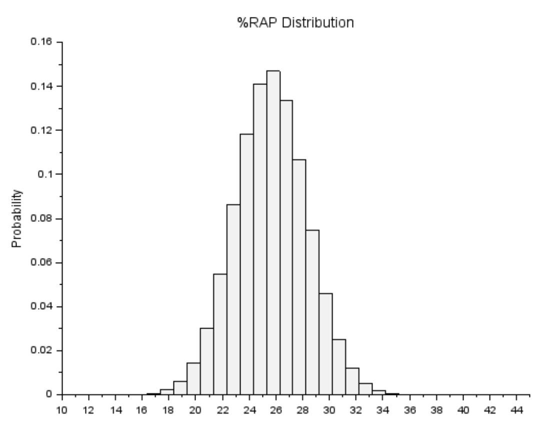
(c) Project U024-90 KA-5343-01



(d) Project 32 KA-5550-01

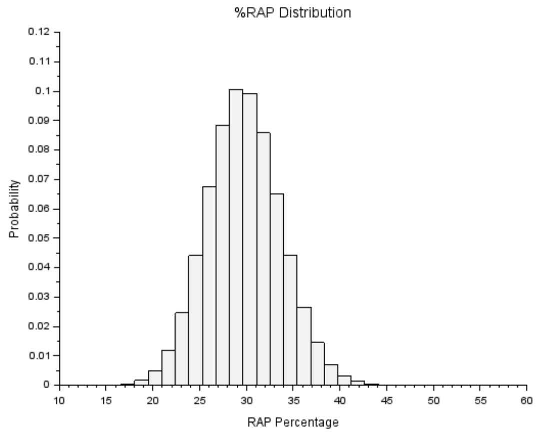


(e) Project K015-106 KA-5865-01



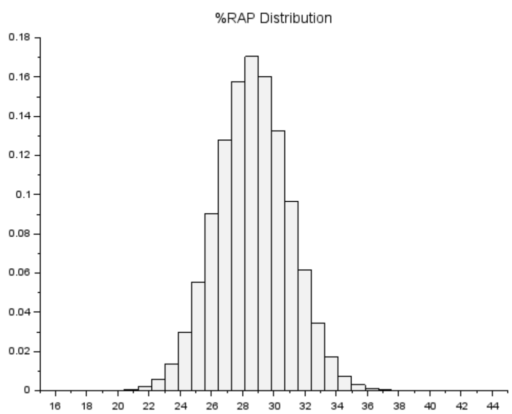
(f) Project K031-099 KA-6316-01

Figure 4.1 RAP Percentage Distribution based on Collected RAP AC Standard Deviation

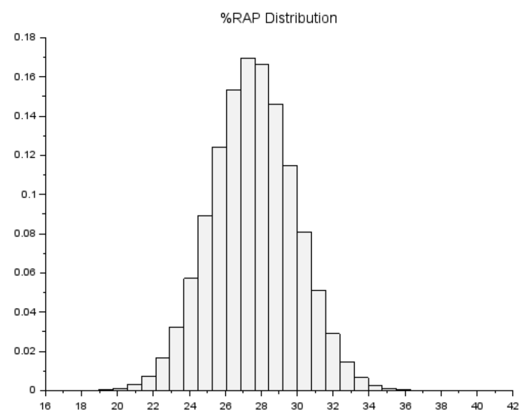


(g) Project I135-85 KA-6064-01

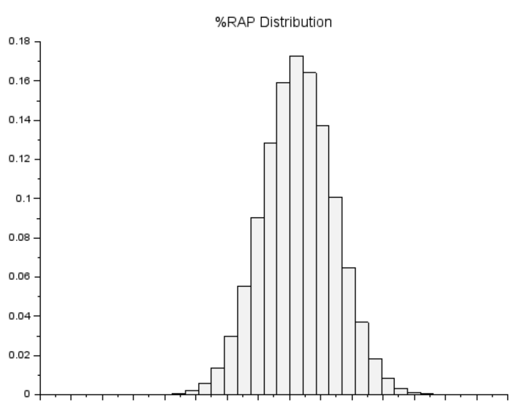
Figure 4.1 RAP Percentage Distribution based on Collected RAP AC Standard Deviation (Continued)



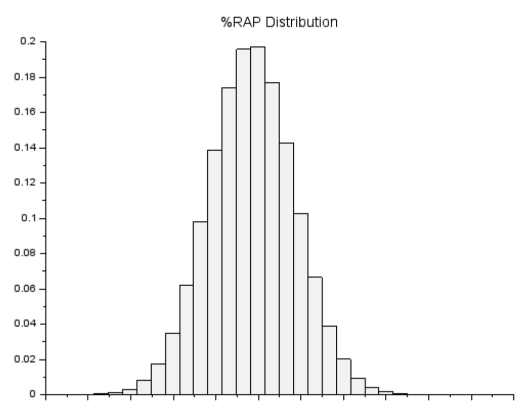
(a) Project U036-20 KA 5663-01



(b) Project U083-020 KA 5662-01

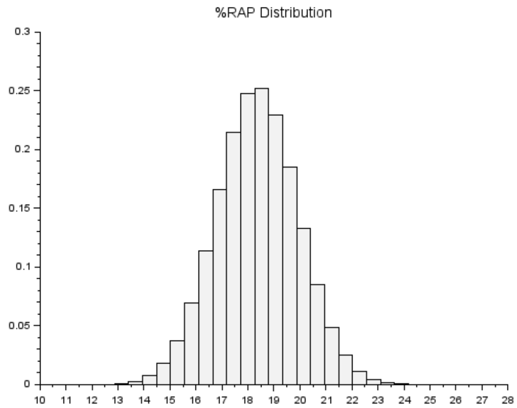


(c) Project 24-90 KA-5343-01

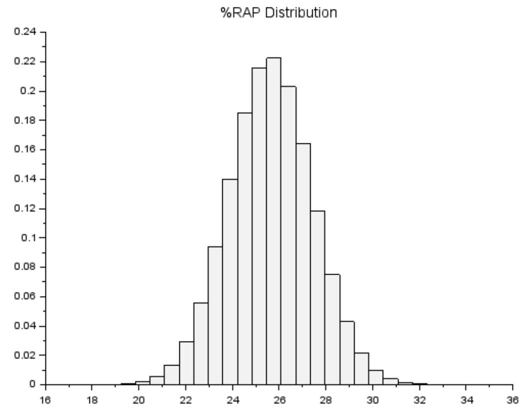


(d) Project 32 KA 5550-01

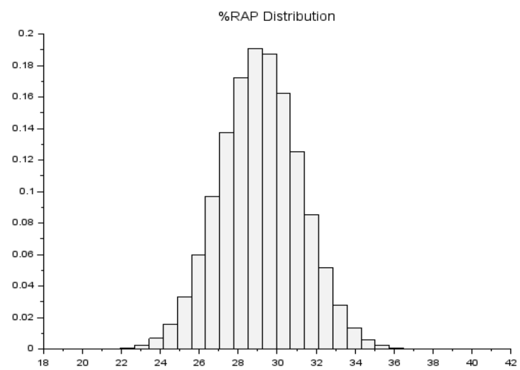
Figure 4.2: RAP Percentage Distribution based on KT-57 Multi Lab Precision



(e) Project 15-106 KA 5865-01



(f) Project K031-099 KA 6316-01



(g) Project I135-85 KA 6064-01

Figure 4.2: RAP Percentage Distribution based on KT-57 Multi Lab Precision (Continued)

Table 4.1: Risk of RAP Percentages over JMF

Project No.	Design HMA AC Content (%)	Average HMA AC Content (%)	Std. Dev.	No. of Data Points	Average RAP AC Content (%)	Std. Dev.	No. of Data Points	Risk* (%)	Risk** (%)
U083-020 KA-5662-01	5.30	5.26	0.001	45	5.41	0.003	11	91.0	94.2
U036-20 KA-5663-01	5.30	5.26	0.001	45	5.41	0.003	11	82.6	86.5
U024-90 KA-5343-01	5.20	5.19	0.002	32	5.47	0.002	8	68.7	75.3
32 KA-5550-01	5.20	5.31	0.002	35	6.48	0.010	8	37.5	19.9
K015-106 KA-5865-01	5.60	5.60	0.001	45	7.94	0.005	7	24.1	14.8
K031-099 KA-6316-01	5.90	6.02	0.002	68	7.07	0.002	14	59.1	63.6
I135-85 KA-6064-01	5.40	5.38	0.002	60	6.11	0.003	4	88.9	98.7

*Collected Data Std. Dev. Bias
** KT-57 Multi Lab Precision

Figures 4.1 and 4.2 show that most simulated RAP percentages followed a normal distribution except the simulation with collected data standard deviation of Project 32 KA-5550-01. The RAP percentage distribution chart of Project 32 KA-5550-01 with collected data standard deviation shifted to the left. As shown in Table 4.1, the standard deviation of collected data of Project 32 KA-5550-01 went up to 0.01 because of the vast difference between QC and QA burn-off results and the fewer data points. This higher standard deviation would cause some "outstanding" simulation results. However, the probabilities were extremely low, which is hard to see in the distribution chart.

The burn-off results for the HMA mixture were very close to, or the same as, the design/JMF binder content of the HMA mixture, and the standard deviation values of QC/QA data were very close to 0.00117, the expected precision. The standard deviation of RAP asphalt content ranged from 0.002 to 0.010 resulting from fewer data points collected. Therefore, the RAP binder content was shown to be the variable that most significantly affects the RAP percentage, thereby increasing the risk of exceeding the target RAP percentage.

Comparing the distribution charts with different standard deviations, the graphs with KT-57 standard precision had narrow ranges of the RAP percentage but higher probabilities, thereby increasing the risk. However, for projects 32 KA-5550-01 and K015-106 KA-5865-01, the risks with standard test precision decreased since the AC Mass-Balance results were within the target RAP percentage, and a lower standard deviation would further narrow down the possibility of exceeding the target value.

Chapter 5: Conclusions & Recommendations

5.1 Conclusions

This study investigated RAP percentage using the totalizer method in the HMA plant and the AC mass-balance method after production. The RAP percentage determined by the totalizer method was steady and did not exceed the designed percentage of RAP. However, a significant difference was observed between the AC mass-balance method results and the totalizer results. For example, the burn-off test results of binder content in RAP from the contractor and KDOT differed, which resulted in varying RAP percentages; a high RAP AC content resulted in a decreased percentage of RAP. Follow up investigations were made at two more plants to determine the effect of RAP asphalt content and burn-off tests were conducted on RAP and HMA mixtures collected from the projects. The burn-off test results from multiple labs showed significant differences, indicating that RAP AC content significantly influences the RAP content calculated based on the AC mass-balance method. The Monte Carlo analysis also supported this observation.

5.2 Recommendations

In current QC practices for RAP in Kansas, the contractor determines RAP AC content once during the first lot and then once per 1,000 tons of RAP. For QA, KDOT conducts one test during the first lot and one test per 4,000 tons of RAP (KDOT, 2015b; KDOT, 2022). However, the percentage of RAP usage in the projects (20%–25%) and the volume of HMA production on each project limits the testing frequency for the RAP AC content. Small sample sizes may increase variability and decrease precision in the RAP percentage analysis. Therefore, a higher frequency for testing the binder content of RAP is recommended to enlarge the population to reduce variability. Results from this study prompted the following suggestions:

- The test frequency for the RAP AC content should be the same as the HMA QC/QA test: one per sublot for the contractors and one per lot for KDOT (KDOT, 2015b; KDOT, 2022).
- Additional tests should be conducted during the RAP collection process: from milling every 1,000 tons, samples should be randomly selected from

truckloads daily, or random tests should be conducted for each RAP stockpile at the plant.

- RAP fractionation after collection should also be considered. The RAP is usually fractionated into two or more stockpiles and divided into coarse and fine fractions. Fractionating RAP should reduce segregation during RAP transport with conveyors and increase control over the asphalt cement content and RAP aggregate gradation (Bateman, 2009).
- NCHRP project 09-69, Verifying Quantities of Materials Used in Asphalt Mixtures at Production Facilities, is currently being conducted to recommend procedures to verify quantities of various materials used in asphalt mixtures at production facilities and prepare guidelines for their application. Thus, broader guidelines are expected to verify quantities not only for RAP and RAS but also for additives such as latex, ground tire rubber, warm-mix additives, anti-strip additives, fibers, and mineral fillers.

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Appendix A

A.1 Plant Totalizer Data Collection of Project 15-106 KA 5865-01

Table A.1: Feed Rate Data

Day 1			Day 2			Day 3		
Feed Rate (tph)		RAP%	Feed Rate (tph)		RAP%	Feed Rate (tph)		RAP%
Virgin Aggregate	RAP		Virgin Aggregate	RAP		Virgin Aggregate	RAP	
143.1	35.6	19.9%	142.4	33.3	19.0%	144	34.2	19.2%
159.5	42.2	20.9%	140	33.6	19.4%	142.4	36.7	20.5%
169.2	45.2	21.1%	143.4	32.9	18.7%	154.8	39.4	20.3%
171.4	37.6	18.0%	155.1	35.1	18.5%	157.7	37	19.0%
177.6	40.7	18.6%	153.2	38.9	20.2%	150.8	39.5	20.8%
177.3	45	20.2%	149.4	38.1	20.3%	154.3	39.8	20.5%
177.1	44.3	20.0%	153.3	37.8	19.8%	146.1	40	21.5%
177.7	44.3	20.0%	149.7	36.4	19.6%	152.9	39.8	20.7%
178.3	45.5	20.3%	148.9	37.9	20.3%	153.3	39.1	20.3%
176.7	43.9	19.9%	137.7	37.7	21.5%	154.9	39	20.1%
183.2	45.8	20.0%	149.6	38.2	20.3%	155	38.5	19.9%
183.7	44.7	19.6%	154.4	38.4	19.9%	154.4	39.4	20.3%
178.6	42.5	19.2%	156.8	38	19.5%	171.4	42.1	19.7%
178.7	45.4	20.3%	150.7	41.2	21.5%	177	44.3	20.0%
179.5	43.7	19.6%	170.8	40.3	19.1%	178.1	44.9	20.1%
178.6	39.7	18.2%	166	39.6	19.3%	180.6	43.2	19.3%
180	42.9	19.2%	167.3	44.3	20.9%	175.5	44.3	20.2%
174.9	41.6	19.2%	169.8	42.3	19.9%	175.9	44.2	20.1%
177.4	44.8	20.2%	153.1	41.1	21.2%	179.2	42.5	19.2%
178.9	41.2	18.7%	158.8	41.5	20.7%	177.6	41.8	19.1%
180	42.4	19.1%	166.8	39	19.0%	175.6	42.5	19.5%
Average		**19.6%**	164.6	41	19.9%	19.9%	43.5	19.6%
			167.6	39.8	19.2%	177.4	44.3	20.0%
			167.4	40.8	19.6%	179.1	43.5	19.5%
			153.1	41.8	21.4%	178.2	42.2	19.1%
			171.5	41.7	19.6%	182	42.5	18.9%
			168.9	41.3	19.6%	176.5	40.7	18.7%
			171.3	42	19.7%	178.7	42.4	19.2%
			166.9	41.7	20.0%	177.8	42.7	19.4%
			169.1	40.5	19.3%	176.2	41.1	18.9%
			171.1	42	19.7%	**Average**		**19.8%**
			167.9	42.1	20.0%			
			166.6	44.8	21.2%			
			169.2	43.1	20.3%			
			167.2	43.2	20.5%			
			Average		**20.0%**			
Average of 3 Days RAP%: 19.8%								

For feed rate data, $\text{RAP\%} = \frac{\text{RAP feed rate}}{\text{Virgin Aggregate feed rate} + \text{RAP feed rate}} * 100$

Table A.2: Scale Weight Data

Day 1					Day 2					Day 3				
Scale Weight (tons)				RAP%	Scale Weight (tons)				RAP%	Scale Weight (tons)				RAP%
Virgin Aggregate Scale	RAP Scale	Weight Difference of Virgin Aggregate	Weight Difference of RAP		Virgin Aggregate Scale	RAP Scale	Weight Difference of Virgin Aggregate	Weight Difference of RAP		Virgin Aggregate Scale	RAP Scale	Weight Difference of Virgin Aggregate	Weight Difference of RAP	
106.57	18.94				49.00	8.88				115.25	25.44			
187.13	38.35	80.56	19.41	19.4%	133.31	28.86	84.31	19.98	19.2%	200.35	47.06	85.1	21.62	20.3%
255.84	55.71	68.71	17.36	20.2%	207.11	47.25	73.8	18.39	19.9%	212.92	50.27	12.57	3.21	20.3%
344.92	77.39	89.08	21.68	19.6%	243.84	56.77	36.73	9.52	20.6%	305.28	73.24	92.36	22.97	19.9%
398.84	90.95	53.92	13.56	20.1%	332.55	79.07	88.71	22.3	20.1%	378.83	91.51	73.55	18.27	19.9%
427.21	97.8	28.37	6.85	19.4%	372.62	89.07	40.07	10.00	20.0%	428.95	103.92	50.12	12.41	19.8%
450.83	103.44	23.62	5.64	19.3%	477.34	114.4	104.72	25.33	19.5%	499.68	121.02	70.73	17.1	19.5%
469.63	107.89	18.8	4.45	19.1%	541.00	130.06	63.66	15.66	19.7%	552.71	134	53.03	12.98	19.7%
480.65	111.18	11.02	3.29	23.0%	590.44	142.15	49.44	12.09	19.6%	635.19	153.73	82.48	19.73	19.3%
Average				**20.0%**	615.51	148.54	25.07	6.39	20.3%	**Average**				**19.8%**
					Average				**19.9%**					
Average of 3 Days RAP%: 19.9%														

When calculating RAP% with scale weights, the difference between two weight measurements are used. During the plant warm-up process, the aggregates and RAP that pass through the weighbridge before mixing may be recorded. The use of weight difference between two measurements increases accuracy, so $\text{RAP\%} = \frac{\text{Weight Difference of RAP}}{\text{Weight Difference of Aggregate+Weight Difference of RAP}}$

Appendix B

B.1 Sample Scilab Code for Monte Carlo Simulation

```
clear
//x1 = Binder percentage in HMA Mixture
//x2 = Binder percentage in RAP
Q=33658.52 //Total HMA produced
AC=1414.79 //Tatal Binder usage

function[RAPpercent]=RAP(x1,x2,Q,AC)
   RAPpercent=100.*(x1.*Q-AC)/(x2.*(Q-AC))
endfunction

N=5000000
x1=grand(N,1,'nor',0.0560,0.00117)
x2=grand(N,1,'nor',0.0794,0.00117)

SuccessPointCount=0;
FailPointCount=0;

Results=[]
out=[]

for i=1:N
   if RAP(x1(i),x2(i),Q,AC)<20
      SuccessPointCount=SuccessPointCount+1;
   else
      FailPointCount=FailPointCount+1;
   end
      [RAPpercent]=RAP(x1(i),x2(i),Q,AC)
      Results=[Results;RAPpercent]
      out=[out,Results]
      Results=[]
end

I=100*FailPointCount./N
disp(I/1000)

histplot(30,out(1,:))
title("%RAP Distribution")
```

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