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Evaluation of Cost Benefits to the SCDOT with Increased RAP-RAS Usage

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16. Abstract

Over 90% of U.S. highways and roads are constructed with hot mix asphalt (HMA) and as this infrastructure ages, these highways and roads must be maintained and rehabilitated. The 1970s marked the beginning of the widespread use of reclaimed asphalt pavement (RAP) in asphalt pavements in the United States. However, in early years, many state Department of Transportations (DOTs) used only a low percentage of RAP materials in their hot mix asphalt (HMA) mixtures. One major reason for this was that the mixtures containing high RAP contents could result in increased "blue smoke" emissions from plants since the RAP materials were fed directly into the path of hot gasses. However, with the modern design of new plants, this is no longer a major concern. There were three major objectives for this research project. The first was to analyze the cost benefits to the Department from the past utilization of RAP, RAS, and RAP/RAS in various mixtures around the state. The second objective was to develop a proposed pay schedule for aged binder versus virgin binder in the form of a draft specification. The third was to predict the potential cost savings to SCDOT from the use of the proposed alternate pay schedule. The researchers mined data from three different databases (Site Manager, Job-Mix-Formula (JMF) Log, and each individual JMF form per project) in order to generate the necessary information to complete project objectives.

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Disclaimer

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Table of Contents

List of Figures

Chapter 1 – Introduction

The 1970s marked the beginning of the widespread use of reclaimed asphalt pavement (RAP) in asphalt pavements in the United States. In addition, in the 1980s, some field trials with high RAP contents were constructed and evaluated. However, in early years, many state Department of Transportations (DOTs) used only a low percentage of RAP materials in their hot mix asphalt (HMA) mixtures. One major reason for this was that the mixtures containing high RAP contents could result in increased “blue smoke” emissions from plants since the RAP materials were fed directly into the path of hot gasses. It is important to note that with the modern design of new plants, this is no longer a major concern. Also, based on many years of field experience, the industry has developed very effective techniques to introduce the proper proportion of RAP into the HMA mixtures.

Over 90% of U.S. highways and roads are constructed with hot mix asphalt (HMA) and as this infrastructure ages, these highways and roads must be maintained and rehabilitated. The Federal Highway Administration’s (FHWA) recycled materials policy states that:

> “The same materials used to build the original highway system can be re-used to repair, reconstruct, and maintain them. Where appropriate, recycling of aggregates and other highway construction materials makes sound economic, environmental, and engineering sense”.

There are four major asphalt production cost categories including materials, plant production, trucking, and field construction (lay down). In general, the materials are the most expensive category, in many cases up to about 70% of the cost to produce HMA mixtures (Figure 1). The binder in any mix is the most expensive material. Therefore, the use of RAP in the intermediate and surface layers of flexible pavements replacing a portion of the binder is the most cost effective methods of constructing the nation’s pavements.

When the Superpave mix design procedure was initially implemented around the country in the 1990s, it did not include a method for incorporating RAP. Therefore, many state DOTs were reluctant to allow contractors to use RAP in Superpave mixes until the researchers and engineers began to develop procedures to account for the recycled material. The National Cooperative Highway Research Program (NCHRP) project 9-12 accomplished this goal to some extent. These guidelines for RAP content were relatively conservative; however, guidelines for RAP percentages have gradually been increased due to the efforts of agencies such as the Federal Highway Administration (FHWA) and the National Center for Asphalt Technology (NCAT), which have conducted research in this area (e.g., NCHRP project 9-46).

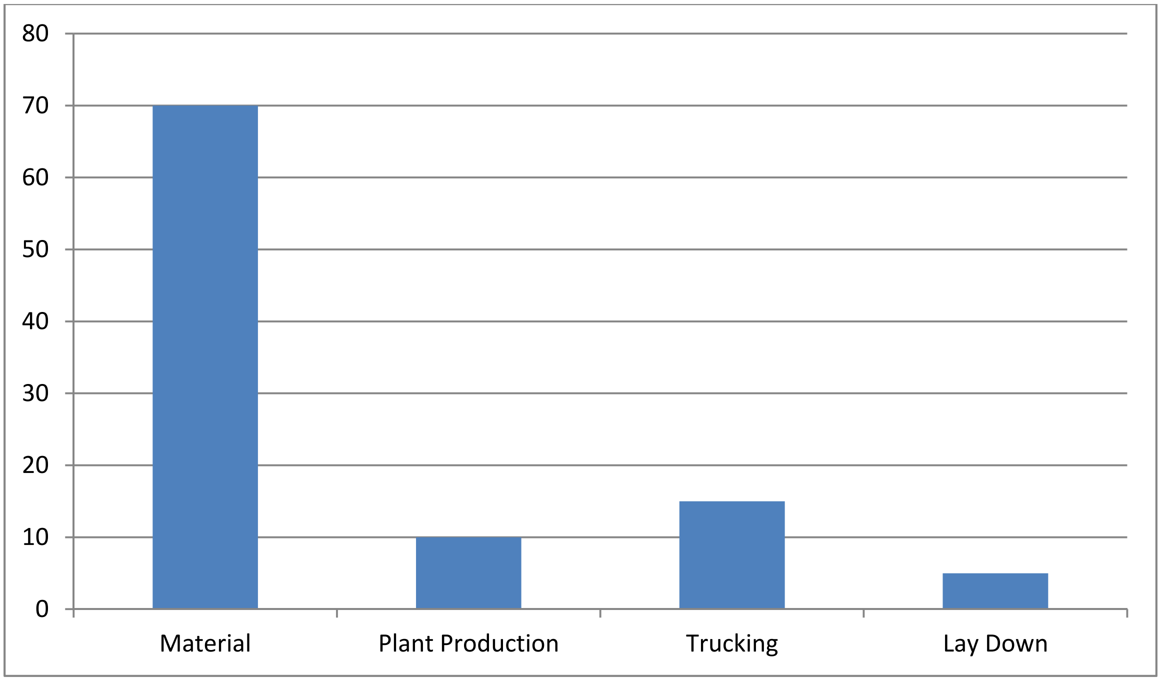


Figure 1-1: Production Cost Categories (%) for a Typical Construction Project

These days, the asphalt paving industry has been recognized as the number one recycler in the country by using approximately 56 million and 62 million tons of RAP in 2009 and 2010, respectively. This equates to over 3 million tons (19 million barrels) of reclaimed asphalt binder being used in new mixtures. It has been reported by the National Asphalt Pavement Association (NAPA) that approximately 96% of contractors are using RAP in their mixtures around the country.

Many state DOTs, including SCDOT, have been investigating the use of high percentages of RAP in their mixtures for many years. Actually, SCDOT is known to be one of the national leaders in the utilization of high percentages of RAP in intermediate and surface mixtures. There are many benefits of using RAP in various mixture types including: a) conservation of resources (e.g., aggregate and binder); b) life-cycle cost savings; c) environmental issues (e.g., conserving landfill space, etc.); and d) quality performance. Recently, with the utilization of warm mix asphalt (WMA) in various mixtures, there has been increased interest in using higher percentages of RAP. Some initial findings indicate that warm mix reduces the amount of initial oxidation in the virgin liquid binder so that it interacts more readily with the RAP binder. After the increase of petroleum prices; therefore an increase in binder cost, in 2008, many DOTs and the paving industry recommitted themselves to the utilization of higher percentages of RAP.

Another recycled product that has been used in many parts of the country is recycled asphalt shingles (RAS). SCDOT developed specifications many years ago regarding the utilization of RAS in some of their mixtures. RAS materials generally consist of asphalt binder, quality aggregates and fiber. In 2009 and 2010, FHWA contracted with NAPA for a survey of implementation/adoption of three key areas: RAP, RAS and warm mix asphalt (WMA). The survey concluded that there was a 57% increase in usage of RAS, manufacturer's waste and tear-offs (from 702,000 to 1.10 million tons) from 2009 to 2010. If an asphalt binder content of 20% for shingles is assumed, this would translate to 220,000 tons of asphalt binder conserved annually in the USA.

Today, 12 states allow the use of manufacturers' shingle waste in hot mix asphalt mixtures. In addition, 10 states allow the use of manufacturers' waste or roofing tear-offs in their mixtures. In the United States, an estimated 10 million tons of tear-off waste and 1 million tons of manufacturer waste are produced each year. It is estimated that approximately 1.8 million tons of asphalt binder could be conserved if all these could be incorporated into asphalt paving mixtures.

Some of the benefits of using RAS include the following: a) partial virgin binder replacement; b) partial fine aggregate replacement; c) improved rut resistance; and d) reduced landfilling of a valuable resource. There are many key barriers to the utilization of RAS, including supply, asbestos, processing, handling, storage, lack of specifications, and in some cases, lack of data on the performance of pavements utilizing RAS.

For this research project, the cost savings from the use of RAP and RAS in South Carolina (SC) pavements were investigated and determined. In addition, the economic effects of using increased amounts of RAP/RAS in SC's asphalt mixes were examined. Finally, a proposed pay schedule separating virgin binder from aged binder was developed that could potentially optimize SCDOT's cost savings when utilizing RAP and RAS materials.

Study Objectives

There were three main objectives for this research project. The first was to analyze the cost benefits to the Department from the past utilization of RAP, RAS, and RAP/RAS in various mixtures around the state. The second objective was to develop a proposed pay schedule for aged binder versus virgin binder in the form of a draft specification. The third was to predict the potential cost savings to SCDOT from the use of the proposed alternate pay schedule. The specific tasks to complete these objectives included the following:

1. Conducting an extensive literature review regarding the payment for RAP, RAS, and RAP/RAS mixtures around the country and their cost benefits to various agencies.
2. Conducting a nationwide survey of various State DOTs and other agencies to determine the extent of RAP/RAS usage with additional follow-ups with various Southeastern states (i.e. FL, GA, TN, AL, and NC).
3. Evaluating different cost calculations and pay items for each state agency responding to the survey.
4. Determining the percentage of SC asphalt mixes actually containing RAP/RAS from SCDOT's project records.
5. Conducting an analysis of prices to estimate past cost savings to SCDOT and to compare prices between the Districts based on SCDOT's data from various projects, including hot mix and warm mix asphalt mixtures.
6. Developing a draft specification for payment of RAP, RAS, and RAP/RAS mixtures that considers aged binder.

7. Developing a method of estimating the percent price reduction based on an increase in RAP/RAS content using both the existing pay schedule and the proposed pay schedule.
8. Analyzing SCDOT's current data collection system to determine if any changes/modifications will be needed to better track future cost savings associated with the use of RAP, RAS, and RAP/RAS in HMA mixtures.

Chapter 2 - Literature Review

National RAP Usage

One of the most recognized national industry surveys on RAP usage is conducted annually by the National Asphalt Pavement Association. Information Series 138, *Annual Asphalt Pavement Industry Survey on Recycled Materials and Warm Mix Asphalt Usage 2009-2012* stated that the number of states averaging more than 20 percent RAP in HMA/WMA mixes increased steadily from nine states in 2009 to 20 states in 2012. In addition, the national average percentage of RAP used in mixes has increased from about 19 percent in 2011 to about 20 percent in 2012. Table 2-1 shows the average percentages of RAP used in mixes in each state between 2009 and 2013. It is important to note that the survey does not consider the effects of different grades and sources of binders on the performance of various mixes (PG 58-34 vs PG 64-22). In addition, since the literature review contains materials from several years ago, some of the cost data does not reflect the actual cost of materials used today.

Laboratory Research

Horton et al 2011 [1] stated that today a mixture containing 30 percent RAP by mass is considered a high RAP mix. In this study, 11 mixtures were studied with RAP contents ranging from 34 to 70 percent and shingle contents ranging from zero to three percent. Temperatures at the plant were monitored during production. The paving mixes were then analyzed in the laboratory and parameters including air void content, gradation, binder content, and extracted binder grade were determined. Performance testing including dynamic modulus was completed. Major findings from this study show that mixtures exceeding 60 percent RAP content required excessive heating of the virgin aggregate and RAP. This causes premature excessive oxidation of the asphalt binder. High temperatures in the drum increases metal wear. Mixtures with 50% RAP were achievable and had good characteristics in the laboratory and on the road.

Huang et al. 2011 [2] presented results from a laboratory study in which hot-mix asphalt (HMA) mixtures with No. 4 sieve screened reclaimed asphalt pavement (RAP) were characterized for their cracking resistance through laboratory performance testing. A typical surface mixture commonly used in the state of Tennessee was evaluated at 0, 10, 20, and 30% RAP contents. Two types of aggregate (limestone and gravel) and three types of asphalt binders (PG 64-22, PG 70-22, PG 76-22) were used in this study. Mixtures cracking resistance was evaluated through Superpave indirect tension (IDT), beam fatigue, and semicircular bending (SCB) tests. The results from this study indicated that the inclusion of RAP generally increased stiffness and indirect tensile strength, however, if generally compromised cracking resistance for the mixtures studied. Mixture properties changed significantly at 30% RAP content as compared to those with 10 and 20% RAP. Field projects validated the findings of the study.

Table 2-1: NAPA RAP Report, % RAP per Mix by State

State	2009	2010	2011	2012	2013
Alabama	19%	25%	21%	22%	24%

Alaska	5%	3%	13%	8%	--
Arizona	13%	5%	11%	14%	13%
California	10%	19%	9%	16%	11%
Colorado	19%	19%	24%	29%	27%
Connecticut	15%	17%	13%	21%	NR
Delaware	20%	20%	N/R	28%	NR
Florida	24%	24%	30%	27%	31%
Georgia	19%	22%	23%	23%	23%
Hawaii	10%	9%	11%	14%	NR
Idaho	6%	10%	23%	28%	28%
Illinois	18%	20%	16%	30%	22%
Indiana	23%	24%	26%	23%	27%
Iowa	12%	17%	14%	15%	18%
Kansas	18%	20%	20%	20%	23%
Kentucky	9%	9%	9%	10%	15%
Louisiana	18%	18%	18%	19%	18%
Maine	13%	14%	15%	15%	18%
Maryland	19%	21%	24%	22%	23%
Massachusetts	14%	14%	11%	16%	18%
Michigan	27%	30%	36%	34%	32%
Minnesota	16%	19%	22%	20%	21%
Mississippi	16%	17%	18%	19%	18%
Missouri	12%	12%	19%	19%	20%
Montana	7%	8%	8%	10%	11%
Nebraska	NR	NR	30%	22%	29%
Nevada	6%	7%	10%	11%	14%

New Hampshire	15%	18%	21%	19%	19%
New Jersey	4%	17%	17%	16%	19%
New Mexico	NR	NR	20%	NR	NR
New York	10%	11%	16%	13%	13%
North Carolina	20%	22%	24%	15%	25%
North Dakota	NR	NR	11%	NR	NR
Ohio	23%	24%	23%	23%	28%
Oklahoma	12%	13%	18%	12%	15%
Oregon	26%	25%	24%	24%	25%
Pennsylvania	13%	13%	16%	16%	15%
Puerto Rico	0%	0%	2%	20%	NR
Rhode Island	11%	11%	8%	2%	NR
South Carolina	17%	20%	22%	24%	23%
South Dakota	12%	6%	18%	20%	NR
Tennessee	20%	17%	14%	20%	17%
Texas	11%	10%	13%	16%	14%
Utah	19%	21%	25%	19%	24%
Vermont	21%	20%	17%	23%	NR
Virginia	21%	28%	26%	26%	27%
Washington	18%	16%	16%	15%	19%
West Virginia	10%	11%	11%	12%	12%
Wisconsin	15%	15%	16%	14%	15%
Wyoming	6%	5%	1%	2%	NR

As the use of reclaimed asphalt pavement (RAP) in asphalt concrete mixture increases, it is important to understand how the addition of asphalt binder that has already been aged affects the overall properties and performance of the mixture. Tarbox et al. 2012 [3] evaluated four plant-produced mixtures containing 0%, 20% , 30%, and 40% RAP, which were aged long-term in an oven in the laboratory to three levels. The dynamic modulus was measured for each aging level and compared with un-aged values to determine whether there was a statistical difference. It was found that as RAP content increased, aging had less effect on stiffness; this finding was quantified with areas under the dynamic modulus curves and aging ratios. The greatest differences were observed at the high-temperature and low-frequency ranges. The study also showed that the slope of relaxation modulus was less affected by aging as RAP content increased. The Global Aging System (GAS) was used to predict the change in dynamic modulus over time with the virgin aggregate properties. The method over-predicted the measured changes in stiffness. The GAS was also used to predict how many months of service life were simulated for each mix by long-term aging. It was found that as RAP content increased, hot-mix asphalt mixes including RAP stiffened at a slower rate that virgin mixes.

Al-Qadi et al. 2012 [4] conducted research to characterize the performance of hot-mix asphalt (HMA) with high amounts of RAP and to identify any special considerations that must be met to utilize these higher RAP contents. Two material sources from two districts were used to prepare either 3/4-in nominal maximum aggregate size (NMAS) N90 binder mix designs. The mix designs included a control mix with 0% RAP and three HMA's with 30%, 40%, and 50% RAP for each district. A base asphalt binder (PG 64-22) was used in the mix design process; a single-bumped grade binder (PG 58-22) and a double-bumped grade (PG 58-28) were also used to prepare specimens for performance testing. The tests conducted on the HMAs were moisture susceptibility, flow number, complex modulus, beam fatigue, semi-circular bending, and wheel tracking. All tested HMAs with RAP performed equal to or better than the mixture prepared with virgin aggregate. The study found that HMAs with high RAP content (up to 50%) can be designed with desired volumetrics. RAP fractionation proved to be very effective. Using a softer asphalt binder grade was found to improve the properties of HMA mixtures with 30% RAP content and above.

Hossain et. al. 2013 [5] studied the effect of increasing RAP percentage and using fractionated RAP (FRAP) in HMA mixture on moisture resistance, rutting, and fatigue cracking were evaluated. Mixtures with five different RAP and FRAP contents (20%, 30%, and 40% RAP, and 30% FRAP and 40% FRAP) were studied. The Hamburg Wheel Tacking Device (HWTD) Test (TEX-242-F), Kansas Standard Test Method KT-56vor modified Lottman Test, and Dyanmic Modulus Test (AASHTO TP: 62-03) were used to predict moisture damage, rutting potential and fatigue cracking resistance of the mixes. HMA specimens were prepared based on Superpave HMA mix design criteria for 12.5mm (1/2 inch) Nominal Maximum Aggregate Size (NMAS) and compacted using the Superpave gyratory compactor. Results of these tests showed that although mixture performance the laboratory tests decline as the percentage of RAP increased in the mix, even mixtures with 40% RAP passed the minimum requirements in commonly used tests. When RAP is compared with FRAP, FRAP does not seem to improve performance of the HMA mixtures. This was largely confirmed by statistical analysis. Mixtures with RAP performed more or less the same as or better than the mixtures with FRAP.

Shu et al. 2010 [6] utilized the semi-circular bending (SCB) test to evaluate the effect of reclaimed asphalt pavement (RAP) on the cracking resistance of asphalt mixtures. Two types of SCB tests, the tensile strength and the fracture test, were conducted on a gravel mixture containing four percentages of RAP. The results show that RAP generally increased the SCB tensile strength but significantly decreased the post-failure tenacity of asphalt mixtures. RAP also decreased the J-integral of asphalt mixture and therefore it's cracking resistance. Both short-term and long-term aged asphalt mixtures exhibited similar trend in evaluating the effect of RAP.

Kowalski et al. 2010 [7] found that RAP is currently a widely-used material for the construction of asphalt pavements. However, in regions with aggregate prone to polishing, RAP is not commonly allowed in mainline surface courses for high volume roadways because of friction performance concerns. The initial part of the study described here included a comparison of RAPs collected from six different sources (mix plant stockpiles) in Indiana. It was shown that the field-collected RAP's exhibited fairly consistent properties in terms of their gradations and binder contents. In the second part of the study, low friction aggregate (limestone) was used to produce a "worst case scenario" RAP for evaluation of its influence on frictional characteristics of two types of hot mix asphalt mixtures: (a) dense graded asphalt (DGA) and (b) stone matrix asphalt (SMA). The DGA and SMA mixtures were produced with various amounts of this laboratory-produced "worst case scenario" RAP. The RAP was blended with two types of highly friction resistant aggregates: steel slag and air cooled blast furnace slag. Overall, the results suggest that for the materials and mixtures studied, the maximum amount (threshold level) of RAP that can be used in surface mixes without detrimental effect of their frictional properties was about 30%. That threshold level was not dependent on the type of aggregate present in RAP.

Shannon et al. 2013 [8] examined the effects that different methods of stockpile fractionation have on volumetric mix design properties for high-RAP surface mixes, with the goal of meeting all specified criteria for standard hot-mix asphalt (HMA) mix designs. To determine the distribution of fine aggregates and binder in RAP stockpile, RAP materials were divided by each sieve size. The composition of RAP materials retained on each sieve was analyzed to determine the optimum fractionation method. Fractionation methods were designed to separate the stockpile at a specified sieve size to control the amount of fine RAP materials which contain higher amounts of fine aggregates and dust contents. These fine RAP materials were used in reduced proportions or completely eliminated, thereby decreasing the amount of fine aggregate material introduced to the mix. Mix designs were performed using RAP materials from three different stockpiles and two fractionation methods (e.g., +#4 and -#4) with high-RAP contents up to 40% by virgin binder replacement. By using an optimum fractionation method, a mix with 40% RAP was successfully designed while meeting all Superpave criteria and asphalt film thickness requirement by controlling the dust content from RAP stockpiles.

West et al. 2013 [9] conducted research to (1) develop a mix design and evaluation procedure that provides satisfactory long-term performance for asphalt mixtures containing high reclaimed asphalt pavement (RAP) contents – in the range of 25 to 50% or greater – and (2) propose changes to existing American Association of State Highway and Transportation Officials (AASHTO) standards to adapt them to the design of high RAP content mixtures. The project team conducted a comprehensive laboratory experiment to answer basic questions about preparing and characterizing RAP materials for mix designs. A series of mix designs was then prepared with materials from four different parts of the United States with different RAP contents and different virgin binders. Those mix designs were evaluated against standard Superpave criteria and a set of performance-related tests to further assess the mix designs for their susceptibility to common forms of distress, such as fatigue cracking, low-temperature cracking, and moisture damage.

A concurrent effort developed a set of best practices for RAP management in field production and construction from information obtained through a literature review, surveys of current practices in the industry, discussions with numerous contractor quality control personnel, and analysis of contractor stockpile QC data from across the United States. The research found that only minor, though important, revisions to the current AASHTO standards for asphalt mix design, AASHTO R 35 (Superpave Volumetric Mix Design) were needed to adapt them for the successful design of high RAP content mixtures. As expected high RAP contents substantially increased the dynamic modulus of the asphalt mixtures as well as their rutting resistance as measured by the flow number test. Tensile strength ratios of high RAP content mixtures as measured by AASHTO 283 were comparable to those of control specimens with RAP, indicating similar moisture damage susceptibilities. As might be expected, compared to control specimens without RAP, the high RAP content mixtures generally had lower fracture energy at test temperatures used to evaluate susceptibility to fatigue and low-temperature cracking. This finding suggests that careful attention should be given to the selection of the performance grade of the virgin binder used in high RAP content mixtures to minimize any long-term risk of cracking distress.

Dennerman et al. [10] presented the findings from the first year of a three year Austroads study which aims to maximize the re-use of reclaimed asphalt pavement (RAP) in new asphalt product. The objective of the first year of the study was to improve the methodology for the characterization of RAP binders and the design of the binder blend in asphalt mixes containing RAP. The experimental work showed that the Dynamic Shear Rheometer (DSR) can be used to obtain viscosity parameters similar to the Shell sliding plate viscosity at 45 C and the capillary viscosity at 60 C. The DSR results are also more repeatable than the results of the Shell sliding-plate test, which has conventionally been a more common test used in Australia for the characterization of RAP binder. The results show that for the RAP sources under study, a blend of C170 with 10 percent to 20 percent RAP results in a viscosity equivalent to that of a C320, as generally accepted in current practice. The DSR based methodology used in this study provides a practical, consistent and cost-effective method to characterize RAP binder blends. As successfully demonstrated in this study, the viscosity results from the DSR tests can be used to design RAP binder blends to the desired viscosity.

Fatigue/HMA Additives

Hill et al. 2013 [11] studied the low temperature properties of RAP and virgin BMB (Bio-modified Binder) mixtures to determine if these mixtures exhibit improved low temperature performance as compared to conventional hot-mix asphalt. Disk-Shaped Compact Tension (DCT), Superpave Indirect Tension, and Acoustic Emission (AE) tests were employed to characterize low temperature properties of the asphalt mixtures. BMB mixtures exhibited a higher DCT fracture energies as compared to HMA for all RAP levels. In addition, BMB mixture fracture energy displayed a reduced dependence on RAP content, as the difference in average fracture energy between BMB and HMA mixtures increased with higher RAP contents.

Furthermore, BMB mixtures displayed consistently higher creep compliance which indicates that these mixtures can alleviate thermal stresses more easily than HMA. A recently developed acoustic emission testing procedure clearly indicated the effects of BMB as well as RAP in the mixture. The overall trends identified through AE testing were consistent with the findings from the DCT and ID(T) tests. In addition, AE results suggested a fundamental change in the behavior of the BMB RAP mixture relative to the HMA RAP mixture, e.g. a rejuvenating effect. In general, it was observed that BMB RAP mixtures exhibited superior low temperature cracking behavior as compared to HMA mixtures. It is important to note that the SC DOT does not use BMB mixtures at this point.

You et al. 2011 [12] evaluated the low-temperature performance of innovative materials gaining interest in the asphalt pavement industry which included warm mix asphalt (WMA), recycled asphalt shingles (RAS), reclaimed asphalt pavement (RAP), and bioasphalt. The materials are used as modifiers in typical HMA to enhance low-temperature field performances. Sasobit compounds at 0.5, 1.0, and 1.5% by weight of performance grade (PG) 52-34 asphalt binder were used to design the WMA. Five and 10% of RAS were also added to the PG 52-34 asphalt binder. 50% RAP combined with 50% of the base PG 58-28 binder, and 100% RAP extracted from the PG 58-28 HMA, were prepared and tested. The results showed that the ABCD method can be used alongside or as a confirmation test for the bending beam rheometer (BBR) in evaluating the low-temperature cracking resistance behavior of asphalt binders. It was also found that adding WMA additives beyond a certain percentage could potentially reduce the low-temperature cracking performance of asphalt binders. Also, swine waster bioasphalt can enhance low-temperature asphalt binder performance.

Mohammad et al. 2013 [13] conducted laboratory research investigating high RAP mixes with crumb rubber additives. Five mixtures were contained in the study. The control mixture was a typical PG 76-22 styrene-butadiene-styrene and no RAP. The second mixture utilized 15% RAP and PG 76-22 SBS binder. The third mixture contained no RAP, 30 mesh crumb rubber (CR) additives blended (wet process) with a PG 64-22 binder. The final mixture utilized 100% RAP with CR additives. Laboratory mixture characterization included Dynamic Modulus (E*) and Flow Number (FN) tests with the Asphalt Mixture Performance Tester, Semi-Circular Bend test, Dissipated Creep Strain Energy test, and the Modified Lottman test. In addition, Loaded Wheel Tracking (LWT) test was performed. Results indicate that the addition of CR additives as a dry feed to carry rejuvenating agents is promising. Mixtures containing high RAP content and CR additives exhibited similar performance as conventional mixture with PG 76-22 SBS binder.

Mohammad et al. 2011 [14] evaluated the use of crumb rubber (CR) from waste tires and engineered additives as a rejuvenator to high reclaimed asphalt pavement (RAP) content asphalt mixtures. Six asphalt mixtures were prepared by mixing aggregate blends with four asphalt binders, an unmodified asphalt binder classified as performance grade (PG) 64-22, two polymer-modified binders classified as PG 70-22 and PG 76-22, and a PG 76-22 crumb-rubber-modified-binder. The RAP content was varied from 0-40% and crumb-rubber additives were blended with the unmodified binder by using wet and dry processes. Hot-mix asphalt (HMA) mixture testing included an evaluation of rutting susceptibility, moisture resistance, and resistance to cracking using the flow number test, the loaded-wheel tracking test, the dynamic modulus test, the modified Lottman test, the dissipated creep strain energy test, and the semi-circular bending test.

Results of the experimental program indicated that the addition of CR additives rejuvenated the blended asphalt binder for the HMA mixture with high RAP content. The use of high RAP content with crumb rubber as a rejuvenator in preparation of HMA is expected to provide adequate moisture resistance and superior rutting resistance as compared to conventional mixtures. However, because of the hardening properties of the mix prepared with high RAP content, the fracture and cracking resistance of the produced mixture was reduced compared with polymer-modified mixes.

Rashwan et. al. 2012 [15] evaluated the performance of three commonly used warm mix technologies: Advera, Evotherm J1 and Sasobit were examined in comparison to a control hot mix asphalt (HMA) with respect to dynamic modulus and permanent deformation (flow number). Each mixture was developed using a performance grade 64-22 binder and two types of aggregates: limestone or quartzite. In addition, this study evaluated whether WMA additives enable the production of high RAP content (30%) mixtures with comparable performance to HMA. Warm mix asphalt mixtures were prepared at 120 C and compacted at 110 C showed no concerns regarding workability or compactability even in mixtures incorporating 30% RAP. Dynamic modulus and flow number tests were conducted to assess the stiffness and permanent deformation resistance, respectively. The performance data suggests that there is a significant difference in the performance of HMA mixtures and the three WMA technologies investigated. Dynamic modulus data of WMA mixtures were consistently lower as compared to HMA. The incorporation of RAP increased the dynamic modulus of all mixtures but the HMA mixtures were still higher than the WMA mixtures. Finally, the rutting resistance of WMA mixtures was considerably lower compared to HMA mixes via flow number testing.

Austerman et al. 2009 [16] studied the influence of the dose of two Warm Mix Asphalt (WMA) additives (Advera and Sasobit) on the binder properties and mixture properties in terms of workability, cracking susceptibility, and moisture susceptibility. Two Superpave mixtures, a 12.5 mm with 10 percent reclaimed asphalt pavement (RAP) and a 19.0 mm with 25 RAP, were used for this study. Binder testing showed that the addition of Sasobit at any dosage tested changed the performance grade of the binder and decreased the binder viscosity. The addition of Advera at the dosage tested did not change the performance grade of the binder and only marginally changed the viscosity of the binder viscosity. Workability testing of the mixtures showed that both WMA additives improved the workability of the mixtures at any dosage tested. Moisture susceptibility testing showed that the WMA additives tested at any dosage increased the moisture susceptibility of the mixtures. Cracking susceptibility testing showed the addition of Advera increased the cracking resistance of the mixtures at any dosage tested, whereas the addition of Sasobit only increased the cracking resistance of the mixture at a dose of 1.5 percent.

Mogawer et al. 2013 [17] examined if asphalt pavement rejuvenators can offset the stiffness attributed by the hardened binder from reclaimed asphalt pavement (RAP) and reclaimed asphalt shingles (RAS) in mixtures that incorporate high RAP and RAS content with adverse impact on the performance of the mixtures. Overall, the results showed that asphalt rejuvenators can mitigate the stiffness of the resultant binder. The cracking characteristics of the mixture were improved by the addition of the rejuvenators. However, the rutting and moisture susceptibility were adversely impacted at the dosage and the testing conditions used. Also the tests results at

4C generally showed that there was blending of the rejuvenated and virgin binder, however, no conclusion could be made at the higher temperatures.

Huang et al. 2013 [18] conducted a study of two RTFO-aged asphalt and their blends with 15 and 50 percent of extracted reclaimed asphalt pavement (RAP) binders to investigate the effect of RAP content and properties on the long-term aging characteristics of asphalt binders. This paper presented the influence of RAP binders on the rheological properties of fresh binders in terms of their aging characteristics. The results from the rheological analysis of aged blended binders indicate that the aging characteristics of blended binders are dependent on fresh asphalt binders. The results show the crossover frequency decreases as RAP concentrations increase and the rheological index increases as RAP concentration increases. The pattern for the stiffness increase as a function of aging times for RAP blended binders is similar to that of and typical chemical aging kinetic model, where the stiffness increases substantially initially and then levels off at longer aging times. The results demonstrate that there is a linear relationship between the logarithm of G* and phase angle for RAP blended binders at all aging times and RAP contents, regardless of asphalt and RAP sources.

Vahidi et al. 2013 [19] studied the addition of Ground Tire Rubber (GTR) and Treated GTR which were added to binder and to high RAP content mixtures. Rutting performance of the binders were evaluated by conducting the Multiple Stress Creep Recovery test. Fatigue performance was evaluated by the Linear Amplitude Sweep test. The degree of separation was measured by the conducting the Cigar Tube Test. Also, the effect of the suspension agent on the degree of separation was determined. GTR and Treated GTR significantly improved the rutting and fatigue performance of the asphalt binders. The suspension agent successfully decreased the degree of separation between the rubber particles and binder. GTR was introduced into the binder and the resulting rubberized binder was used to design a 9.5 mm Superpave mixture. The Treated GTR was directly added to the mixture. Treated GTR mixtures were mixed and compacted at lower temperatures compared to GTR mixtures. The dynamic modulus was determined using the Asphalt Mixture Performance Tester, reflective cracking performance was evaluated by the Thermal Stress Restrained Specimen Test, and rutting and moisture susceptibility was evaluated using the Hamberg Wheel Tracking Device. GTR and Treated GTR made the mixtures slightly more prone to reflective cracking, but improved their resistance to rutting, moisture susceptibility, and low temperature cracking.

Putman et al. 2012 [20] conducted research for the South Carolina Department of Transportation investigating WMA technologies and high Reclaimed Asphalt Pavement mixtures. The researchers concluded the following:

<u>Warm Mix Asphalt:</u>

1) The WMA additive Evotherm, did not have a significant effect of the properties of the virgin binders (PG 58-22, PG 64-22, and PG 76-22) included in this study.
2) The use of WMA technologies included in this study (Evotherm and foaming) did not have a significant impact on the optimum binder content determined from the asphalt mix designs. Therefore, a WMA mix can be designed using the same binder content as an equivalent HMA mixture. This has also been concluded by others (Bonaquist 2011).

The mixing and compaction temperatures for all WMA mixtures used in this portion of the study were 50 degrees F lower than the HMA mix counterparts.

3) The WMA technologies generally decreased the indirect tensile strength of the mixtures compared to the HMA mixtures, but all of the mixtures exceeded the minimum allowable wet ITS value of 65 psi.
4) The Evotherm additive had a compactibility enhancing effect on the mixtures compared to the other mixes.
5) The rutting resistance of mixtures made with the WMA technologies was aggregate source dependent. The WMA mixes exhibited similar rut depths as the HMA mixes for one aggregate, while the WMA mixes had higher rut depths than the HMA mixes for the other.
6) The effects of the WMA technologies on the resilient modulus were also aggregate specific. The foamed WMA mixtures generally had higher resilient modulus values for one aggregate source and the Evotherm WMA mixes generally had higher values for the other aggregate.

<u>Reclaimed Asphalt Pavement:</u>

1) The addition of RAP binder to virgin binders had a stiffening effect on each of the binders, and the trend was linear with respect to the RAB binder content. When the high PG failure temperatures were plotted against RAP content, the slopes of the curves for the two PG 64-22 binders were nearly identical indicating that the RAP binder increased the stiffness of the composite binders in a similar fashion regardless of the virgin binder source. It should be noted, however, that only two binder sources were used in this study. The replacement of the PG 64-22 binder with a softer grade PG 58-22 resulted in an approximately 4-5 degree C reduction of the upper PG failure temperature, and the slope of this curve was steeper.
2) The effects of RAP content on mix design properties are aggregate-, binder-, and RAP-specific, meaning that the mixture must be designed for each combination of materials to understand the effect of a particular RAP source on mix properties. The reason for this is the variable nature of RAP materials, namely the RAP binder properties and the gradation of the RAP. In this research, the addition of higher RAP contents resulted in finer mixes, which required higher binder content to ensure that the dust-to-binder ratio was kept within the specified range. While this practice would increase the cost of the asphalt mix, it is possible to adjust the virgin fine aggregate contents to control the dust-to-binder ratio without increasing the binder content and the cost of the mix.
3) As the RAP content is increased, the mixing and compaction temperatures of the mixtures also increased to ensure adequate mixing and compaction of the mix. This will increase the cost of the total mix since more energy is needed to produce the mixture.
4) The RAP content did not have a distinct effect on the indirect tensile strength of the mixtures as the effect appears to be aggregate of RAP specific. When PG 58-22 binder was substituted for the PG 64-22 for the 40 and 50% mixtures, the ITS values did decrease, but the decrease was not detrimental. All of the mixtures had a wet ITS well above the minimum specified value of 65 psi.
5) Susceptibility of the RAP mixtures to moisture induced damage was not an issue with the mixtures evaluated in this study as all of the mixes exhibited a TSR of greater than 85%.

However, the mixtures with 0% RAP generally had higher TSR values than the RAP mixes. Additionally, no evidence of visible stripping was observed in any specimens.

6) The rutting resistance of the mixes improved with the addition of RAP, but not necessarily with increasing RAP contents. The use of PG 58-22 binder in place of PG 64-22 binder in high RAP mixes (40 and 50% RAP) resulted in higher rut depths, but the rut depths were still significantly lower than the virgin mixes.
7) An increase in RAP content generally increased the resilient modulus of the asphalt mixtures. The substitution of PG 58-22 for the PG 64-22 binder for the higher RAP mixes reduced the resilient modulus.

<u>Mixtures made with WMA and RAP:</u>

1) The Evotherm WMA additive generally reduced the stiffness of the composite binders as indicated by the reduction in the upper PG failure temperature. The effect was more pronounced as the RAP content increased for the RTFO aged binders. It should be noted that the Evotherm composite binders were conditioned at a lower RTFO temperature (135 C) compared to the HMA binders (163 C), but this change was made to simulate the difference in actual production temperatures.
2) The WMA technologies had no significant effect on the mix design properties indicating that the optimal binder content used for HMA mixes could also be used for identical WMA mixes. However, it would be advantageous to conduct the mix design for the WMA mixes and have field verifications.
3) There was no distinct effect of WMA technology on the indirect tensile strength of the mixtures made with RAP and the results appeared to be aggregate specific. For mixtures made with aggregate source B, the Evotherm WMA mixtures had 3 out of 10 mixtures that had TSR values below 85% and for the aggregate C mixtures, the foamed WMA mixes had 2 out of 10 mixes with TSR values below 85%. The lowest TSR value recorded in the study was 78% and there were no visible signs of stripping for any of the mixes. Additionally, all of the wet ITS values were well above the minimum value of 65 psi.
4) WMA technologies may improve the compactibility of asphalt mixture at WMA temperatures when RAP is added, but the effect was significant for only one of the two RAP sources included in this study. This effect was quantified using the number of gyrations of the Superpave gyratory compactor to achieve the desired height and density of ITS specimens in the lab, which has not been correlated to field compaction.
5) The effect of WMA technology on the rutting resistance of mixtures containing RAP was dependent on the aggregate source, RAP properties, and binder source. No significant trend was noticed across all mixtures. However, as the RAP content increased, the rut depth of WMA and HMA mixtures generally decreased.
6) The resilient modulus of WMA mixtures containing RAP generally followed a similar tread as for HMA mixtures – the resilient modulus increased as the RAP content increased. Additionally, the WMA mixtures generally had similar or lower resilient modulus values than the HMA mixtures for a given RAP content with a few exceptions.

Degree of Blending (DOB)

Williams et al. 2013 [21] states that there has been a lack of understanding about how the binder from recycled asphalt pavement (RAP) contributes to the overall mix. Viewpoints range from assuming that it does not blend at all (i.e. RAP in the mix acts as a black rock) to 100 % blending of the virgin and recycled binders. The degree of blending (DOB) is defined as the percentage of RAP binder that is effectively mobilized in the mix (Coffey et al. 2013 [22]). Most state agencies assume full blending of RAP binder and aggregate particles, which is an assumption that may lead to under asphalting or a relatively stiffer mix (Coffey et al. 2013 [22], Al-Qadi 2007 [23]). Several studies have shown the contribution of RAP binder is somewhere in between these two assumptions by examining the rheology of the resulting asphalt binder (Stephens et al. 2001 [24]; Huang et al. 2005 [25]).

Coffey et al. [22] studied the impact of degree of blending between virgin and reclaimed asphalt binder (25% RAP- 3 sources) on predicted pavement performance using mechanistic-empirical pavement design guide. Dynamic modulus tests were conducted on each RAP source with two conditions: full blending and a calculated "Actual" degree of blending (DOB). For the full blending samples, it was assumed that all of the RAP was mobilized in the mix, and the virgin asphalt binder was offset accordingly. The "Actual" DOB samples were mixed after a DOB was determined. MEPDG Level 1 analysis was conducted using typical structures, climate, and traffic conditions for the state of New Jersey. Also, rutting and fatigue cracking performance between the two DOBs were compared for each of the RAP sources. The results indicate that DOB has a negligible effect on fatigue and rutting performance for the three RAP sources tested, all of which had high actual DOB's, greater than 85%. Therefore, for RAP with such high DOB values, full blending assumption would be cost effective and would not compromise the pavement performance.

Ozer et al., 2009 [26] investigated the reclaimed asphalt pavement (RAP) effect on hot-mix asphalt (HMA) volumetric and mechanical properties. An experimental program, including tests for measuring mixture complex moduli and fracture energy, was conducted. Six different mixture designs were prepared with varying percentages of RAP material (0, 20, and 40%) and two different material sources from Illinois. Because RAP binder is believed to be the only factor contributing to stiffness changes in the mixture, it is essential to determine RAP's binder contribution: in other words "working RAP binder", which affects the HMA stiffness and the mixing and compaction process. Control specimens and actual practice specimens were also prepared to serve as reference mixes. Control specimens included RAP materials (binder and aggregate) recovered using the Rotovapor method and virgin materials. Control specimens were designed to simulate the presence of varying proportions of working RAP binder in a RAP mixture.

Actual practice specimens were a combination of RAP and virgin materials (binder and aggregate). A complex modulus test was conducted on HMA to quantify the impact of the change in binder stiffness. The study found that the optimum job mix formula (JMF) asphalt content of the virgin HMA and HMA containing RAP is similar. The current assumption of 100% working binder does not need to be modified from a mix design point of view. The effect of aggregate selective absorption of binder on virgin and RAP materials was manifested in the results of the complex modulus tests. In addition, fracture energy tests were conducted to investigate the impact of RAP materials on HMA susceptibility to low-temperature cracking. The study concluded that using RAP materials may increase the potential for low-temperature cracking.

Doyle et al. 2010 [27] stated that it is important to understand the fundamental behavior of Reclaimed Asphalt Pavement (RAP) because more viscous materials had lesser amounts of reusable bitumen. The work presented in this paper shows that very high RAP WMA is feasible, though multiple advancements are needed prior to widespread use.

Binder Grade Adjustments with High RAP Content HMA Mixes

Most highway agencies have decades of experience with hot mix asphalt (HMA) containing low to moderate percentages of reclaimed asphalt pavement (RAP) because the general perception that RAP mixtures may be more susceptible to various modes of cracking. As the RAP proportion increases there is the potential for an increase in mixture stiffness and decrease in resistance to cracking. Willis et al, 2013 [28] proposed two options for increasing the durability of RAP mixtures. These include increasing the amount of virgin binder in the asphalt mixture or decrease the performance grade of the virgin binder. To assess these options, 0, 25, and 50 percent RAP mixtures at optimum asphalt content were designed using a standard PG 67-22 virgin asphalt binder. These mixtures were tested to evaluate surface cracking, reflection cracking, and rutting using the energy ratio (ER), overlay tester (OT), and asphalt pavement analyzer (APA), respectively. These tests were also conducted on the RAP mixtures with .25% and .50% higher asphalt contents and at the optimum asphalt content using a softer virgin binder. Additionally, the linear amplitude sweep (LAS) methodology was used to access the fatigue properties of the blended binders. The results show to improve cracking resistance increase the amount of virgin asphalt by 0.1 percent for every 10 percent of RAP binder in the mixture up to 30 percent RAP binder. When RAP binder exceeds 30 percent, a softer grade of asphalt binder should be used to increase the mixture's resistance to cracking. All mixtures should be assessed for rutting susceptibility.

Daniel et al. 2010 [29] conducted research for the New Hampshire Department of Transportation (NHDOT) in corporation with three local paving contractors is presented. Plant-produced hot-mix asphalt (HMA) mixtures containing reclaimed asphalt pavement (RAP) percentages from 0 to 25 percent were obtained from seven different batch plants. Twenty-eight mixtures were sampled and sent to the binder testing laboratories at NHDOT and Pike Industries, Inc. The virgin binders were also sampled and also tested. Binders were extracted and recovered from all of the mixtures and were tested to determine performance grade (PG) binder grade and critical cracking temperature. The effect of the RAP at various percentages on binder properties was evaluated. High-end PGs were found to remain the same or increase only one binder grade for the mixtures tested. Low-end PGs also remained the same or bumped only one grade, and the critical cracking temperature changed by only a few degrees for the mixtures examined in the study. In general, in South Carolina, batch plants are not used to produce asphalt mixtures.

Zhou et al. 2013 [30] presented the latest work on RAP/RAS mix design and performance analysis including field performance of a variety of RAP/RAS test sections around Texas, and the proposed RAP/RAS mix design and performance evaluation system for project-specific service conditions. RAP/RAS mixes can have better or similar performance than virgin mixes if they are well designed with balancing both rutting/moisture damage and cracking requirements. Cracking performance of RAP/RAS mixes is influenced by many factors, such as traffic, climate, existing pavement conditions for asphalt overlays, and pavement structure and layer thickness. It is obvious that a single cracking requirement does not apply to asphalt overlay applications. Instead a project-specific service conditions based mix design system should be developed. Based on the relationship between Overlay Test (OT) cycles and fracture properties (A and n) established user this study, a balanced RAP/RAS mix design and performance evaluation system for project-specific service conditions is proposed, and it includes a balance mix design procedure and a performance evaluation system in which the Hamberg wheel tracking test and associated criteria are used to control rutting/moisture damage and the OT, and the required OT cycles determined from S-TxACOL cracking prediction with consideration for climate, traffic, pavement structure and existing pavement conditions. Additionally, the impacts of soft binder on engineering properties of RAP/RAS in terms of dynamic modulus, HWTT rut depth, and OT cycles are investigated. The test results clearly indicated that the use of soft and modified asphalt binder (i.e., PG xx-28, PG xx-34) can effectively improve cracking resistance of RAP/RAS mixes without sacrificing much rutting/moisture damage resistance. Dynamic modulus is not a good indicator of cracking resistance of RAP/RAS mixes. Researchers highly recommend that the proposed RAP/RAS mix design and performance evaluation system for project-specific service be implemented statewide.

Field Performance Studies

On the National Center for Asphalt Technology (NCAT) Test Track in Alabama where accelerated loading tests are run on various asphalt mixtures, high RAP pavements have turned in some excellent rutting results [Brown - Better Roads 2010 [31]. Generally, the results show that the mixtures containing more RAP produce less rutting. NCAT's West explains that as RAP percentages increase, the binder stiffness also increases. And stiffer binders are more resistant to rutting. For example, less than 9 million equivalent single axle loadings (ESALs) on a 20% RAP mixture using a PG 76-22 binder showed a rut depth of 8.6 millimeters. By contrast, a 45% RAP mixture with PG 76-22 binder showed only 0.5mm of rut depth after 9 million ESALs.

West does, however, express some concern with cracking of high-RAP mixtures. Field performance results on cracking tend to vary, he says. In some cases the virgin mixes have performed better than RAP mixes and in others, the mixes with RAP have performed better than virgin mixes in terms of cracking. "A properly selected virgin binder can mitigate issues with cracking," West says.

Copeland et al 2010 [32]reported that in December 2007, a portion of State Route 11 in Deland, Florida, was milled and repaved with 45% reclaimed asphalt pavement (RAP). These high RAP mixes were produced at lower than normal hot-mix temperatures and with foamed warm-mix asphalt (WMA) technology. This project was the first large production in which the Florida Department of Transportation (DOT) allowed the use of high RAP in combination with WMA. FHWA, in cooperation with Florida DOT and the National Center for Asphalt Technology, was on site for production and placement of the high RAP-WMA. Plant-produced mix was collected by FHWA for performance testing evaluation. Two mixes were produced: a high RAP-hot-mix asphalt (HMA) control mix and a high RAP-WMA mix. Performance tests conducted by FHWA included performance grade (PG) determination of binders, dynamic modulus, and flow number.

PG results of the binders indicate that the high RAP-WMA mix is softer that the high RAP-HMA control mix. This is further confirmed by flow number results, where the high RAP-WMA mix had a lower flow number that the high RAP-HMA control mix did. Dynamic modulus results indicate that the high RAP-WMA mix is slightly softer that the high RAP-HMA control mix, especially at intermediate temperatures. Comparison of measured dynamic modulus results with those predicted using the Hirsh and Witczak models confirm that complete blending occurred in the high RAP-HMA control mix. However, incomplete mixing of RAP and virgin binders may have occurred in the high RAP-WMA mix.

Hajj et al. 2011 [33]investigated pavement sections with 15% RAP, 50% RAP with and without virgin binder grade change and a conventional hot-mix without RAP were built side-by-side in 2009 on Provincial Trunk Highway 8 from Gimli to Hnausa in Manitboa, Canada. During construction, field-produced mixtures and raw materials were sampled for further evaluation. The raw materials were used to reproduce the various mixtures in the laboratory. This paper presents the results of an extensive laboratory evaluation of the field- and laboratory-produced mixtures to moisture damage and thermal cracking resistance. The moisture damage was evaluated using the dynamic modulus test at multiple freeze-thaw cycles. The thermal cracking resistance of the mixtures was also evaluated at multiple freeze-thaw cycles using the thermal stress restrained specimen test (TSRST). Overall, HMA mixtures with 50% RAP resulted in acceptable resistance to moisture damage and thermal cracking. The use of multiple freeze-thaw cycles provided better indication of the mixture resistance to moisture damage. Overall the properties of the laboratory-produced mixtures in terms of moisture damage and thermal cracking resistance can be used to ensure quality field-produced mixtures.

In 2009, hot-mix asphalt pavement sections containing 0%, 15%, and 50% recycled asphalt pavement (RAP) were built in a collaborative effect between Manitoba infrastructure and Transportation and the Asphalt Research Consortium (Hajj et al – 2012 [34]). Two types of 50% RAP mixtures were evaluated: one with no grade change in asphalt binder (PG 58-28) from mixtures with lower RAP content and one with a grade change in asphalt binder (PG 52-34). The following methodologies were used to determine the effective binder properties of the evaluated field-produced mixtures: grading of the recovered binders, blending chart process, mortar procedure, and back calculation of binder properties from the measured dynamic modulus of mixtures with Hirsh model and the modified Huet-Sayegh model. Overall, good correlations were observed between the estimated critical temperatures from the blending chart process and the measured ones from the recovered asphalt binders. Of the various evaluated methods, the mortar procedure provided promising results when used to estimate the mixture binder properties at critical temperatures. The findings from the mortar procedure were consistent with the mixtures' resistance to thermal cracking and their current field performance. The procedure indicated that a partial blending was occurring between the virgin and RAP binders of the evaluated mixtures. Although some difficulties arose with the use of the Hirsch model, the back calculated binder shear moduli were reasonable. The modified Huet-Sayegh model requires further evaluation to access the true relationship between the characteristic times of binders and mixtures.

Clark et al 2012 [35] evaluated a trial project comparing two different high Reclaimed Asphalt Pavement (RAP) mixtures placed in 2009 on Route 10 near Albright's Corner, New Brunswick.

The project compared traditional grade-bumped Hot Mix Asphalt (HMA) using PG 52-34 virgin asphalt to a section using a combination of Hypertherm Warm Mix Asphalt (WMA) and conventional PG 58-28 binder. Results of the as-produced extracted binder samples showed that the WMA technology adequately softening the PG 58-28 binder in the high RAP mixture to perform as well or better than the traditional grade-bumped mixture in all performance measures including Thermal Stress Restrained Specimen Testing (TSRST). Laboratory and non-destructive testing after two full years of service shows continued evidence that the WMA produced mixture continues to remain softer than the conventional mixture and retains superior in situ properties.

The most frequent application of recycling materials in pavements is the reuse of reclaimed asphalt pavement (RAP) to produce recycled hot-mix asphalt (HMA). When designed properly, RAP mixes have demonstrated quality comparable to virgin HMAs in laboratory tests. Despite all the information available about the quality of RAP mixes, obstacles still prevent their more frequent used in pavement engineering. Carvalho et. al. 2010 [36] investigated Short- and long-term field performance of RAP mixes compared with virgin HMA overlays used in flexible pavements. Data from 18 Specific Pavement Studies-5 (SPS-5) sites from the Long-Term Pavement Performance program located across the United States and Canada were used. Performance data were collected during periods ranging from 8 to 17 years. Repeated measures analysis of variance was the statistical analysis tool chosen, pairing distress measurements with survey dates to compare performance and response. The results suggest that in the majority of scenarios RAP mixes have performance statistically equivalent to virgin HMA mixes. The statistical equivalency of deflections suggests that RAP overlays can provide structural improvement equivalent to virgin HMA overlays.

Bennert et al. 2013 [37]an extensive coring and forensic study was conducted to characterize the material properties of the Virgin and 30% Reclaimed Asphalt Pavement (RAP) asphalt mixtures utilized on the project. Along with field cores, raw materials (i.e. – aggregates, binder, and loose mix) were procured from FHWA-LTPP Materials Reference Library. Visual distress surveys from the LTPP database were collected and utilized to compare the mixture performance to the general field performance. Overall, the field performance indicated that both the virgin and 30% RAP sections initiated cracking within 1 to 3 years of each other, depending on the section evaluated. However, once cracking had been initiated, the 30% RAP sections cracked at a faster rate that the Virgin sections resulting in higher crack counts, even though the 30% RAP section was using a softer binder than the virgin section (i.e. AC-10 vs. AC-20). The Overlay Tester, Disk Shaped Compact Tension (DC(T)), and Low Temperature IDT and Creep Compliance were used to characterize intermediate and low temperature cracking properties of the mixtures. Asphalt binder characterization included PG grading, master stiffness curves, and Linear Amplitude Sweep (LAS) testing to characterize the stiffness and fatigue properties of the asphalt binders. The material testing program showed that the mixture test results matched the observed field cracking performance better than the asphalt binder testing conducted on the extracted and recovered asphalt binders. The Overlay Tester and DC(T) tests appeared to be the most sensitive to the cracking performance differences between the Virgin and 30% RAP mixtures, while the LAS test appeared to rank the fatigue performance of the 30% RAP mixture better than the Virgin mixture, which contradicted the observed field performance.

Li et al. 2013 [38] characterized RAP materials milled from the upper layer of three accelerated pavement test lanes that were exposed to climatic conditions over a number of years where the original binder and aggregate properties are known from the time of construction. The aggregate and binder in the RAP were extracted using both the solvents and ignition oven and compared to construction data to quantify the changes in measured properties. Three mixes containing 0%, 20%, and 40% RAP taken from one lane were then designed using virgin asphalt and aggregate materials from the same original source. The three mixes were tested for the dynamic modulus and cyclic direct tension fatigue to investigate the effect of RAP content on the mixture performance with a high degree of control over the volumetric characteristics of the mix designs. Both solvent and ignition oven extraction resulted in a decrease in the aggregate specific gravity and increase in the absorption compared to original values known during construction. Binder content and gradation from solvent and ignition oven extraction were similar for the two unmodified asphalt RAP sources, but the RAP SBS modified asphalt exhibited closer values to the other Two RAP materials using the ignition oven but did not with solvent. Mixes with 20% and 40% RAP could be satisfactorily designed to match the 0% RAP volumetrics. The dynamic modulus fatigue tests showed increasing stiffness, decreasing phase angle and decreasing fatigue resistance with increasing RAP.

Solanki et al. 2013 [39] explored the potential of using high reclaimed asphalt pavement (RAP) content with hot mix asphalt (HMA) in base and surface courses. A total of four Superpave mixes containing different percentages of RAP namely, 25% RAP and 40% RAP for S3 base courses and 0% RAP and 10% RAP for S4 surface courses were designed, constructed, and tested. The mechanistic characteristics of mixes were evaluated by conducting creep compliance, dynamic modulus, Hamburg rut, and 4-point beam fatigue tests. The creep compliance results showed a reduction in compliance of the mix due to increase in the RAP content. The dynamic modulus results illustrated that the asphalt mix containing a higher amount of RAP has higher dynamic modulus values. The increase in RAP content reduced rutting susceptibility and improved moisture damage potential of both S3 and S4 sections.

<u>Cost Analysis</u>

Brown (Better Roads – 2010 [31]) stated that since 2007, about half the states (24), have increased the allowable percentages of RAP in their asphalt pavements saving states significant dollars. To mill, haul and process RAP costs only a fraction of the cost of virgin mixtures. So RAP allows contractors to produce a lower cost hot mix and pass along the savings to owner agencies.

David Newcomb, vice-president of research and technology for the National Asphalt Pavement Association (NAPA), has indicated that more RAP is used in order to guard against future fluctuations in the price of asphalt binder. In addition, he has indicated that RAP is more environmental friendly and the results of research have indicated that the performance of mixtures containing RAP is satisfactory. RAP can be added directly to hot-mix asphalt at the mixing plant in amounts ranging from 10 percent to 50 percent of more by weight of the mix. "Properly designed and constructed, pavements with RAP will last as long as or longer than roadways built with virgin materials", indicted Kent Hansen, director of engineering for NAPA.

Total cost of milling RAP from a project, hauling it to an asphalt plant, and crushing and screening is typically between $6 and $10 per ton, says Randy West, director of the National Center for Asphalt Technology (NCAT) at Auburn University in Alabama. Virgin Aggregate costs range from $10 to $25 ton, depending on the region of the country. In 2008, virgin asphalt prices in 2008 jumped from about $350 to $899 per ton. In 2009, liquid binder stabilized at around $410 per ton.

For example, a virgin mix (5% binder but no RAP) with $15-per-ton aggregate and $410-per-ton asphalt binder costs about $34.75 per ton for hot mix materials. (The material cost is .95 x $15 + .05 x $410 = $34.75). By contrast, with a mixture of 5 percent asphalt binder and 20 percent RAP that costs $8 per ton to process, the materials for the RAP mix cost about $29 per ton – more than a 16% savings over the $34-per-ton virgin mixture. As RAP content and virgin binder costs increase, so do the savings.

Hansen et al. 2013 [40] conducted a survey to quantify the use of RAP, RAS, and WMA produced by the asphalt pavement industry. Survey results show significant growth in the use of RAP, RAS, and WMA technologies from 2009 to 2011. The asphalt industry remains the country's number one recycler by recycling asphalt pavements at a rate of over 99 percent and almost all (98 percent) contractors/branches reported using RAP in 2011. The amount of RAP used in asphalt mixtures has increased by 19 percent, from 56 million tons in 2009 to 66 million tons in 2011. Assuming 5 percent liquid asphalt in RAP, this represents over 3.3 million tons (19 million barrels) of asphalt binder conserved. The estimated savings, at $600 per ton for asphalt binder, is $1.98 billion. Use of RAS (both manufacturer's scrap and post-consumer shingles) increased 70 percent from 2009 to 1.2 million tons in 2011. Assuming a conservative asphalt content of 20 percent for the RAS, this represents 380,000 tons (2.2 million barrels) of asphalt binder conserved. The estimated savings, at $600 per ton for asphalt binder, is $228 million.

Dr. J. Don Brock, president of Astec Industries (Harrington – Public Roads 2005 [41]) explains RAP economics by offering an example of a contractor in Daytona Beach, Fl, where rock cost was $19 per ton and liquid asphalt was an additional $12 per ton. Staying within specifications enabled use of a maximum of 20 percent of un-sized RAP in the mix. Mixes containing sized RAP enabled the contractor to increase the amount of recycled material to 45 percent and still stay within specifications. For this company, which sells approximately 400,000 tons of product annually, the $7 difference per short ton resulted in $2.8 million in savings (Recycled Roadways, Vol 68: No. 4 – Public Roads).]

Dale Rand, P.E., director of the flexible pavements branch at the Texas Department of Transportation in *For Construction Pros.com "Recognizing RAP for What it's Worth-2013* [42]*"* estimates savings of up to $10 per ton of hot mix are possible by using 20% RAP and figuring the cost of virgin binder at $678 per ton. "Last year was a down year for new asphalt tonnage in the state of Texas; contractors placed 5 million tons of hot mix. If we placed 5 million tons, at $10 per ton savings, that $50 million of savings in a bad year," says Rand.

Working with soft aggregates and milling 2 inches deep, a Roadtec RX 700 (half-lane machine) cost $340 per hour to operate. It can produce 334 tons per hour of RAP, for a milling cost of $1.02 per ton. If the aggregate is harder and labor costs more, the milling cost per ton of RAP goes to $1.45 [42]. If one assumes a virgin mix cost of $40 per ton of materials, and it costs

$4.02 per ton to mill and truck RAP, that means the RAP is worth $35.98 per ton, or $36. The RX 900 can mill 2,672 tons of RAP per eight-hour day. At $36 per ton, that's $96,192 worth of RAP per day. An RX 900 costs $517 per hour to own and operate, or $517,000 per year (1,000 hours of operation). The payback for this operation will be just 5.37 days (e.g., $517,000/$96,192).

A study completed in 1997 by the FHWA explains that some of the benefits of RAP are more than just cost savings. RAP saves room in landfills, transportation costs, and can be a better option under bridges and adjacent to guardrails where conventional overlays can be problematic (FHWA 1997- [43]). The same report by the FHWA explains two approaches to determining the cost of using RAP; the material costs and the construction cost approaches. The material costs approach estimates the savings that can be achieved by using recycled material instead of virgin material. For example, consider $5 per ton and $120 per ton as average costs of aggregate and liquid asphalt in 1997, respectively. The cost of a virgin mix with 6 percent asphalt comes out to be $11.90 per ton. If the contractor used a half-lane milling machine and hauled the RAP back to the HMA plant, the total cost for RAP would have been $3.70 per ton, considering $1.70 per ton for machine and labor milling, and $2.00 per ton for trucking costs. Hence, the savings compared to using virgin aggregate material would have been $8.20 per ton. All cost analysis tables are available in the 1997 FHWA report entitled *Pavement Recycling Guidelines for State and Local Governments.*

Financial considerations are a significant part of decisions regarding the use of RAP. Several States have conducted studies to determine if the use of RAP in Hot Plant Mixes is cost effective and the results have been overwhelming. The Florida DOT estimates $224 million in savings from the use of RAP since 1979, the equivalent to two-thirds of their annual resurfacing budget (Andreen et. al 2012 – [44]). A Minnesota study estimated 18% savings if 40% RAP were used in HMA production (Horvath 2003- [45]). The Indiana DOT conducted a cost-benefit analysis of a research project [Designing Superpave Mixes with Locally Reclaimed Asphalt Pavement] as part of an independent review of the cost-effectiveness of the DOT's research program. According to the conservative estimate of the cost-effectiveness review, Indiana DOT's saving in materials were nearly $330,000 per year when adding only 5 percent RAP to more than 5 million tons of base and intermediate mixes – although RAP contents of 15 to 20 percent are more typical. The review did not assess the environmental benefits of reusing RAP. The study yielded a conservative benefit-to-cost ratio of 220:1 for Indiana in material cost savings alone.

Andreen et al. 2012 [44] conducted cost analysis based on two materials; an asphalt pavement with RAP used in the mix (RHPM) and hot plant mix pavement (HPM). The 2010 WYDOT Average Bid Prices were used in the cost analysis portion of this study. RAP was used at a rate of 15% for the RHPM mixtures. A savings of $40.87 per ton of RAP was saved by implementing a 15% RAP mix, meaning the value of RAP in HMA is $40.87/ton. The savings would increase by using a greater amount of RPA in the HPM.

Lee et al. 2012 [45] used the Pavement Life-cycle Assessment Tool for Environmental and Economic Effects (PaLATE) and energy consumption data provided by local hot mix asphalt plants to confirm the benefits of energy savings and CO_2 reduction derived from using Reclaimed Asphalt Pavement (RAP). According to the results of the analysis, producing 30% RAP mixture has only 84% of energy consumption and 80% of CO_2 emission of a virgin hot mix asphalt mixture. The reduction of energy consumption and CO_2 emission is mainly due the reuse of asphalt concrete. Although there are some studies that claim that mixtures containing RAP do not perform as well as virgin mixtures, as long as the life of RAP pavement can achieve over 80% of the new mixture's life, there will be positive benefits on reduced energy consumption and CO_2 reduction from a life cycle approach. Using RAP in pavement mixture is indeed a feasible and potential way to make pavement construction greener.

Brown stated in *Hot Mix Asphalt Technology* [46] that the use of recycled asphalt shingles can save $2 to $3 per ton of asphalt compared to virgin mixes. The North Carolina Department of Transportation (NCDOT) allows for 20 percent of the total binder in an asphalt mixture to come from any combination of recycled asphalt pavement (RAP) and asphalt shingles. A typical mix used in North Carolina contains 12 percent RAP and 3 percent shingles. Cost savings comes not only from the reclaimed binder but also from the fact that mixes made with recycled shingles are more easily compacted which allows contractors to spend less time on rolling to attain the required density.

<u>Recycled Asphalt Shingles (RAS)</u>

Cascione et al. 2011 [47] investigated the impacts of post-consumer recycled asphalt shingles (RAS) on the performance of hot mix asphalt (HMA) and its compatibility with fractionated recycled asphalt pavement (RAP). In the summer of 2009, a field demonstration project was conducted by the Illinois Toll way Authority on Interstate Highway I-90. Eight mix designs containing zero and five percent RAS and varying percentages of FRAP were developed and placed in the pavement shoulder. Production and laboratory samples of the mixes were obtained for dynamic modulus testing, beam fatigue testing, fracture energy tests, binder extraction, and subsequent characterization. From the dynamic modulus testing, master curves were constructed to determine how the behavior of the asphalt materials containing RAS differed from the behavior of the asphalt materials not containing RAS when varying percentages of FRAP were part of the mix designs. From the extracted binders, a suite of Superpave tests was conducted at different temperatures and frequencies to build master curves for analyzing how the addition of RAS binder affected the rheological properties of the mix binder blend. Fracture energy testing was conducted using the disk-shaped compact tension test to estimate thermal cracking potential. Laboratory test results indicate that the mixes containing five percent RAS with less than 40% recycled materials exhibit an increased resistance to permanent deformation while maintaining satisfactory performance in fatigue and low-temperature cracking. It is thought that the fibers in the RAS materials likely contribute to the performance of the mixtures, since the mix performance test results did not follow the trend of low temperature binder performance grade increase with the addition of recycled materials.

Fowlow et al. (2011) [48] compared the laboratory performance of four Hot Mix Asphalt (HMA) mixes: one contained only Reclaimed Asphalt Pavement (RAP), and three mixes contained different Reclaimed Asphalt Shingle (RAS) products. Superpave mixture designs resulted in higher asphalt contents and VMA values for the RAS mixtures compared to the RAP mixture. Testing included the determination of PG grade, shear modulus and phase angle, creep stiffness and slope values, and critical cracking temperatures for binder recovered from the HMA mixtures. Mixture testing included complex modulus and Thermal Stress Restrained Specimen Tensile Strength tests on all four mixtures and fatigue testing on two mixtures. The Hirsh model was used to back calculate the binder shear modulus, values for binder modulus and phase angle were used to determine the effective high temperature PG grade of the mixtures. The binder testing indicates that the RAS mixtures are stiffer than the RAP mix at high temperatures and would perform better with respect to low temperature cracking. The mixture testing shows that all four mixtures have similar low temperature performance, but the RAP mix is stiffer and has poorer fatigue resistance at intermediate temperatures than the RAS mixtures.

Hall et al. 2010 [49]reported that approximately 1,000,000 tons of shingles are added to landfills in the United States each year, and these shingles typically contain a significant portion of asphalt binder. Because of the rising cost of asphalt binder, which is the most expensive component of asphalt pavements, the resource could be tapped as an environmentally friendly way to reduce the necessary amount of virgin binder in asphalt pavement mixtures. Recently, a number of states have been involved in the evaluation and implementation of Recycled Asphalt Shingles (RAS) as an efficient means for reducing paving costs and wisely using a product that would otherwise be considered a waste material. Most states limit the use of RAS to 5% manufacturer scrap shingles, although some states allow the inclusion of tear-off (post-consumer) shingles. The state of Missouri has been a leader in the RAS field, allowing up to 7% RAS (including tear-offs), and has reported 20-25% reductions in asphalt binder requirements, as well as overall savings of $3 to $5 per ton of asphalt. Many states have performed RAS trial projects, and have reported favorable results. In most cases, the sections containing shingles show similar or better performance than the control sections. The primary concerns for RAS mixes are the processing of the shingles, the quality and consistency of the material when added to the mix, appropriate limits for mix design, and the potential adverse effects resulting from any hardening of the asphalt binder that may have occurred in the RAS product. Some states have expressed significant concerns of asbestos contamination, although testing has shown this threat to be minimal.

Ozar et al. 2013 [50] evaluated the effect of high asphalt binder replacement for a low N-design asphalt mixture including RAP and RAS on performance indicators such as permanent deformation, fracture, and fatigue potentials, and stiffness. A developed experimental program included complex modulus, fracture, overlay reflective cracking resistance, wheel track pavement deformations, and push-pull fatigue tests. The asphalt binder replacement (combinations of RAS and RAP asphalt binder) levels in the mix were in a range of 43 to 64%. Permanent deformation resistance of the mixtures was improved in the presence of RAS. Fracture tests at low temperature did not reveal any significant difference between the specimens prepared at varying percentages of binder replacement. Fatigue potential of mixtures increased with increasing RAS and asphalt binder replacement. The specimens prepared with 2.5% RAS and PG 46-34 showed the best fatigue performance. The impact of binder bumping was highlighted by the results of all tests. The improvement in fatigue life and fracture energy was noticeable when the asphalt binder type was changed from PG 58-28 to PG 46-34 at the highest asphalt binder replacement level. The results showed that complex modulus test results can provide crucial information about the mix viscoelastic properties such as relaxation potential and long-term stiffness that can be used, along with fracture tests, to evaluate mix brittleness at relatively high asphalt binder replacement levels.

Chapter 3 - Experimental Design

National Survey on RAP/RAS Usage

In order to gain an understanding of the overall activities around the country regarding the utilization of RAP and RAS, the researchers decided to conduct a national survey. Initially, an extensive literature review was conducted. The focus of the literature review was RAP/RAS research and other RAP/RAS surveys conducted in the recent past. Areas of particular interest included long-term performance studies and economic impact studies as related to RAP/RAS.

Based on this review of literature and objectives presented in the proposal, researchers presented a draft survey to the RAP/RAS Steering Committee. The draft survey included many more questions than a normal survey would contain. This was intentionally done in order to present various options for the desired information to be included in the final survey. After several meetings of the RAP/RAS Steering Committee and electronic correspondence, the final questions for the survey were approved by the Steering Committee. The survey was then forwarded to the other state DOT's around the country using SCDOT's internal communication system (AASHTO Subcommittee on Materials Group – Merrill Zwanka is SCDOT's representative). The survey questions and results are included in Table 10-1 in Appendix A.

After compiling and reviewing results from the initial survey it was apparent that some surveys were amenable to follow-up questions. The follow-up questions were forwarded via email to the respondents of the initial survey. The follow up questions and the responses are presented in Table 10-2 in Appendix A.

Analysis of SCDOT Project Data as Related to RAP Usage and Economic Benefits

SCDOT's internal Site Manager Construction Management System was the source of all project data used in this research. Job-Mix-Formula (JMF) Logs and individual SCDOT JMF Forms were obtained from the SCDOT Office of Materials Research. Each JMF includes the information about the mix composition and mix volumetrics for each mix per type per project. RAP Percentage, Optimal Binder Content, and % Binder in RAP/RAS for each mix per project were obtained from the various JMF forms.

Initially, researchers were informed by SCDOT personnel about the information contained within Site Manager over the course of several meetings and email correspondence. Several repetitions of data queries were sent back and forth until a final version was selected by researchers. SCDOT personnel were most helpful during this repetitive process.

Researchers selected data for calendar years 2008-2013 to be analyzed in detail. The reason 2008 was selected as the cut-off year for analysis is that a major change in how mixes were designated was adopted by SCDOT in 2008. In addition, SCDOT has made significant advances in RAP percentages allowed in various mixes over this time. Researchers felt this time period would be more relevant and meaningful to current RAP policies than data before this time period.

To meet objectives outlined in the proposal, various categories of data per project were selected. These included File Number, Project ID, District, County, Year - YYYY, Year-Month - YYMM, Year-Month-Day - YYMMDD, ITEM ID, Material Code, Material Description, Bid Quantity, Contract Quantity, Paid Quantity and Unit Cost. Projects with zero quantities paid were deleted. Researchers deemed there was no value in tracking mixes that did not contribute to the population of data. Projects less than 2,500 tons were deleted as well. It was believed that small quantities could potentially skew the data due to higher unit costs typically associated with low tonnage projects.

Mixes that do not contain RAP per SCDOT specifications were not analyzed (OGFC Mixes and Preventive Maintenance Thin Lift Mixes). Mixes that were analyzed over the 2008-2013 time period included: Surface A, B, C, CM, D, and E mixes; Intermediate A, B, and C mixes; Base A and B mixes; and Shoulder Widening mixes.

Researchers determined that multiple indices would be needed in order to estimate RAP/RAS economic value over the 2008-2013 evaluated time period. Binder costs in particular can vary widely depending upon supply and demand issues and therefore is tracked by SCDOT on a monthly basis for payment purposes to contractors. Therefore, it seemed reasonable to select the SCDOT Monthly binder index for RAP/RAS estimation purposes. YYMMDD per project per mix type was used to select the appropriate monthly SCDOT binder index. Early in the analysis of the data there were two indices per month. Later in the data only one monthly index is used by SCDOT. These changes are reflected in the data.

An aggregate index was more difficult to determine. There are no published indices with regards to aggregates. Prices are much less turbulent than binder prices due to the natural resource being locally available and abundant in most cases. However, researchers wanted to take into account inflation associated with this period of time. Aggregate industry institutions and aggregate suppliers were contacted in seeking advice on best methods and any information they may provide. Written information was impossible to come by due to Anti-Trust concerns. Therefore, the simple indices chosen were based off verbal conversations with various aggregate producers individually. Researchers used \$15 per aggregate ton beginning in 2008. A 2.5% increase was applied for each successive year until 2013. The \$15 per aggregate ton represents the combined mix cost of several sizes of aggregate and an average \$5 per ton haul cost to the asphalt plant.

The Site Manager Project Data was first sorted by File Number, YYMMDD, and Material Description, which divided the data down to various mixes used per project per SCDOT payment period. The File Number was then located in the Job-Mix-Formula Log which designated the various SCDOT JMF mix design forms for each mix type for that project. Then each SCDOT JMF form for each mix type was reviewed and the percentage of RAP used, % Asphalt Binder Contained in RAP, and the Optimal Binder Content for each mix was recorded. From this mined data in combination with the Binder Indices and Aggregate Indices selected, all other calculations needed to meet objectives were obtained. These calculated values include % Aged Binder, % Virgin Binder, Quantity of Aged Binder from RAP on Payment Date, Value of RAP Binder on Payment Date Based on SCDOT Asphalt Binder Index, Quantity of RAP Aggregate on Payment Date, Value of RAP Aggregate on Payment Date, Total Value of RAP, Total Quantity of Binder in Tons, Total Mix Cost Paid, and Total Mix Unit Cost. The value for total % Asphalt Binder in the mix on the payment date for each mix was assumed to be the same as the target binder content (Optimal Binder Content) on the JMF form for each particular mix. Likewise, the value for % Asphalt Binder Contained in RAP on the payment date for each mix was assumed to be the same as the % Asphalt Binder Contained in RAP on the JMF form for each particular mix. These assumptions were made because that data is not currently collected by SCDOT for mixture line item payments. The following are the formulas used for each of these calculated values.

- % Aged Binder =
$$\frac{\frac{\%\,Binder\ in\ RAP\ from\ JMF\ form}{100} \times \%RAP\ from\ JMF\ form}{Optimal\ Binder\ Content\ from\ JMF\ form} \times 100$$
- % Virgin Binder = $100 - \%\,Aged\ Binder$
- Quantity of Aged Binder =
$$\frac{\%\,Aged\ Binder}{100} \times \frac{Optimal\ Binder\ Content\ from\ JMF\ form}{100} \times Pd.\,Mix\ Qty.$$
- Value of RAP Binder = $Quantity\ of\ Aged\ Binder \times Binder\ Index\ on\ Pymt.\,Date$
- Quantity of RAP Aggregate =
$$\frac{\%\,RAP\ from\ JMF\ form}{100} \times Paid\ Mix\ Quanity$$
- Value of RAP Aggregate = $Quantity\ of\ RAP\ Agg. \times Agg.\,Index\ on\ Pymt.\,Date$
- Total Value of RAP = $Value\ of\ RAP\ Binder + Value\ of\ RAP\ Aggregate$
- Total Binder Quantity in Tons =
$$\frac{Optimal\ Binder\ Content\ from\ JMF\ form}{100} \times Pd.\,Mix\ Qty.$$
- Total Mix Cost Paid (including mix and binder) =
$(Pd.\,Mix\ Qty. \times Unit\ Price) + (Total\ Binder\ Qty. \times Binder\ Index\ on\ Pymt.\,Date)$
- Total Mix Unit Cost =
$$\frac{Total\ Mix\ Cost\ Paid}{Paid\ Mix\ Quantity}$$
- Theoretical Total Cost of Virgin Mix (including mix and binder) =
$$Total\ Mix\ Cost\ Paid + Total\ Value\ of\ RAP$$
- Theoretical Unit Cost of Virgin Mix (including mix and binder) =
$$\frac{Theoretical\ Total\ Cost\ of\ Virgin\ Mix}{Paid\ Mix\ Quantity}$$
- Estimated Savings =
$$Theoretical\ Total\ Cost\ of\ Virgin\ Mix - Total\ Mix\ Cost\ Paid$$
- Estimated % Savings =
$$\frac{Estimated\ Savings}{Total\ Mix\ Cost\ Paid} \times 100$$

A sample of the final culled data that was used in the analysis phase of this project is shown in Table 10-3 in Appendix B.

<u>Development of Cost Model</u>

The main objective of this portion of the study was to compare the upper quantiles of the unit cost between two groups of asphalt pavement mixes containing different percentages of aged binder. It is hypothesized that the data with greater than 30 percent of aged binder (translating to less amounts of virgin asphalt binder) would have upper quantile unit cost values and cost risk that are significantly less compared to mixes that contained less than ten percent of aged binder in the mix (greater amounts of virgin binder).

For this study, comparing the upper quantiles of unit cost between the two aged binder groups was accomplished by using the methodology outlined by Wilcox. This method uses a percentile bootstrap of the quantiles to determine if there is a statistically significant difference between two independent groups for a given quantile level. This method was chosen for two reasons. The first reason is that it uses the Harrell-Davis estimator to estimate the qth quantile. This estimator of the sample quantile is beneficial for comparisons involving cost data because it is distribution free and can efficiently estimate quantiles for light and heavy tailed distributions that are symmetric or asymmetric. Another advantage of the Harrell-Davis quantile estimator is that it uses a weighted average of all the order statistics of the sample data in the estimation of the qth quantile and performs well when there are tied values. The second reason the method proposed by Wilcox was used is that it allows for unequal sample sizes between the two groups in the comparison. The method also provides good control of the Type I error probability and power when comparing $q \geq 0.75$.

Let Y be a random variable having a beta distribution with shape parameters $a = (n + 1)q$ and $b = (n +1)(1 - q)$.

$$W_i = P\left(\frac{i-1}{n} \leq Y \leq \frac{i}{n}\right)$$

The Harrell-Davis (6) estimate of the qth quantile is

$$\hat{\theta}_q = \sum_{i=1}^{n} W_i X_{(i)}$$

The method proposed by Wilcox et al. (7) to compare quantiles between two independent data sets is outlined below. The null hypothesis of the test is $H_0: \theta_{q1} = \theta_{q2}$. Let X_{ij} be a random sample from the jth group, where $i = 1, 2, \ldots, n_j$. From the sample data in the jth group, a bootstrap sample (of size n_j) is produced by resampling with replacement and the Harrell-Davis estimate of the qth quantile, $\hat{\theta}_j^*$, is calculated from the bootstrap sample. Let $d_j^* = \hat{\theta}_1^* - \hat{\theta}_2^*$, the difference between the qth quantile estimates of the two groups. This process is repeated B times. Let A denote the number of times $d^* < 0$ and let C be the number of times $d^* = 0$. By letting

$$\hat{p}^* = \frac{A + 0.5C}{B}$$

a generalized p-value can be calculated by $2min(\hat{p}^*, 1 - \hat{p}^*)$. Because multiple tests are conducted between the two groups (one for each quantile of interest), a critical p-value is calculated using a technique formulated by Hochberg, an improvement on the Bonferroni method used to control the probability of Type I errors (8). For the difference between the qth quantile estimates of the two groups to be significant, the calculated p-value must not exceed the critical p-value. Confidence intervals for the difference between the two quantiles are calculated by letting $l = \alpha B/2$ (rounded to the nearest integer) and by letting $u = B - l$. By arranging the calculated difference between a given qth quantile between the two groups in ascending order of magnitude, the $1 - \alpha$ confidence interval for $\theta_1 - \theta_2$ is estimated by $\left(d^*_{(l+1}, d^*_{(u)}\right)$. The qcomhd function within the WRS package in R was used to run the analysis.

Chapter 4 – Survey

A national survey was conducted and the results are shown in Appendix A (Table 10-1 and Table 10-2). Several related topics were addressed in this survey and some of the questions asked including the following: tons of hot mix asphalt (HMA) and/or warm mix asphalt (WMA) used in 2012; tons of RAP and RAS used in HMA mixtures; tons of RAP and RAS in WMA mixtures; % of RAP based on total weight of mix; % of RAP based on aged binder based on total binder weight; higher percentages of RAP in WMA mixtures; utilizing a methodology to calculate the cost savings by using RAP and or RAS; intermediate and base mixes containing RAP and RAS; traffic information; any additives used in the mixes; and many other questions. Nineteen states responded to the survey sent out by SC DOT Materials Research Office.

The amount of HMA and WMA mixtures placed in 2012 varied from over 350,000 tons (Connecticut) to almost 4.7 million tons (Florida) of HMA and/or WMA mixtures. The results indicated that most states allow RAP and many allow RAS in their mixtures. Approximately 70% of the responded indicated that the maximum %RAP by weight of the mix is used to specify the required amount of RAP in HMA mixtures. Over 30% indicated that they specify the aged binder, by total weight of the binder, as the maximum %RAP in mixtures (Figure 4-1). Some of the states also indicated the utilization of other methods.

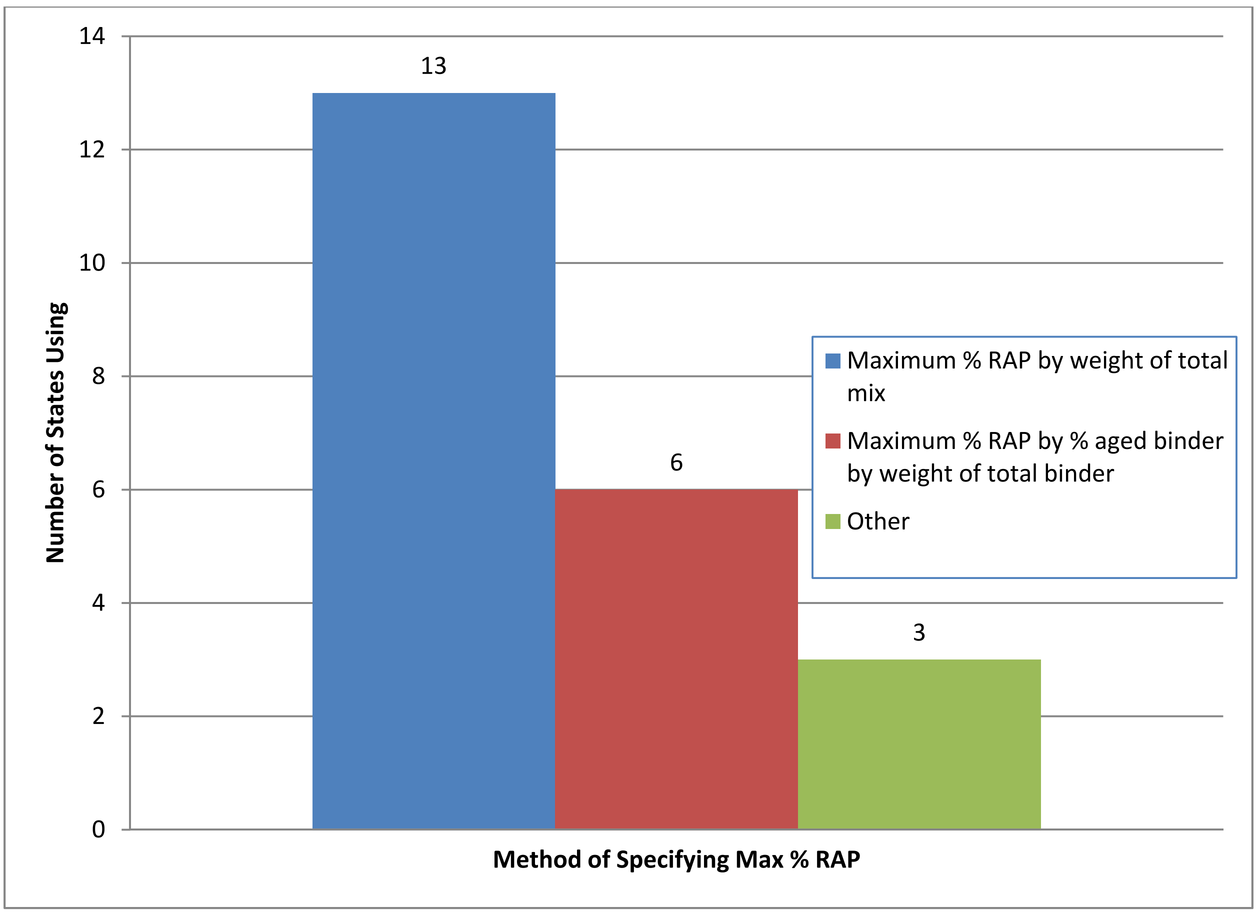


Figure 4-1: Number of States Using the Method of Specifying Maximum %RAP

Figure 4-2 shows that approximately 90% of states responded indicated that they allow higher percentages of RAP in their mixes when using warm mix additives (WMA). In addition, Figure 4-3 indicates that about 70% of the states, responding to the survey, allow the use of RAS in their HMAs.

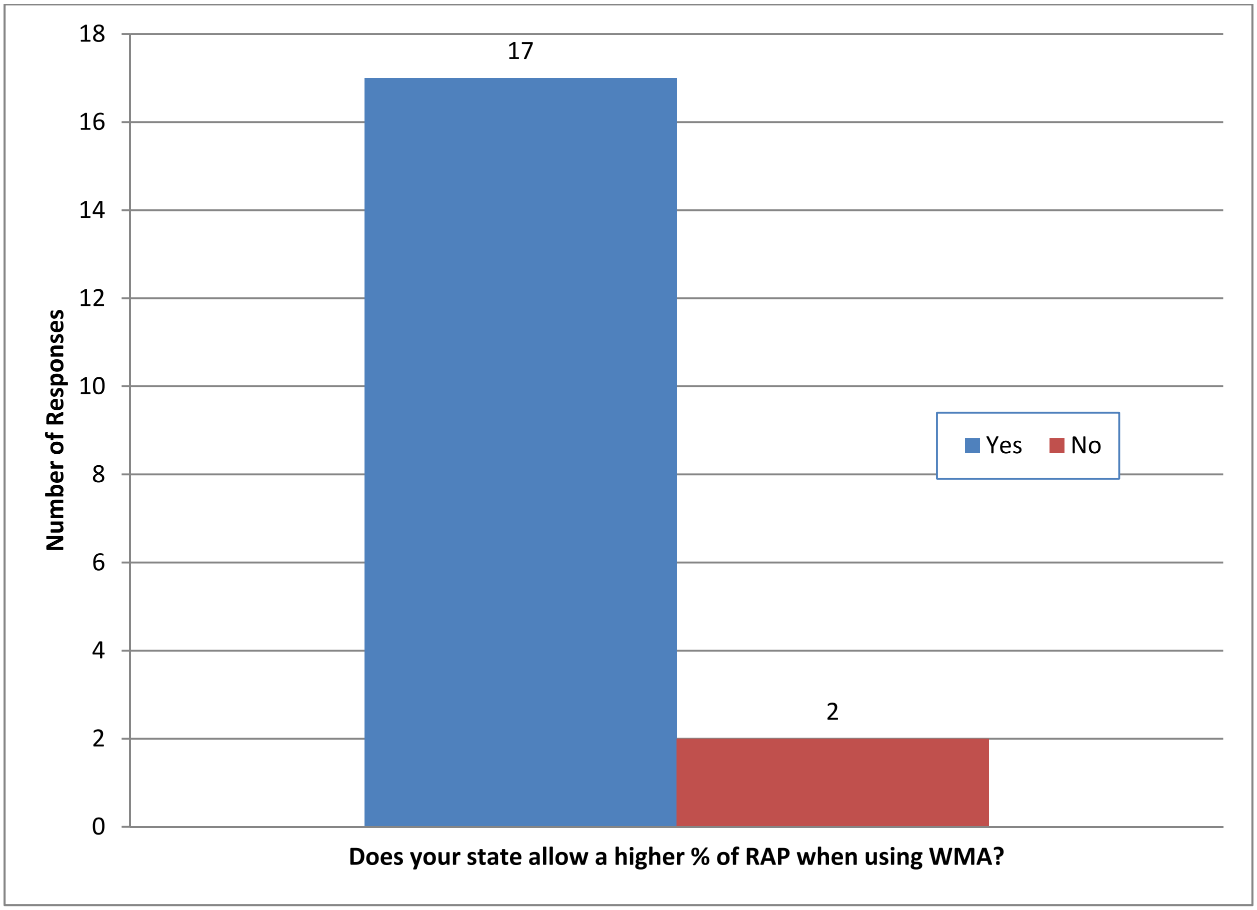


Figure 4-2: Number of States Using High Percentages of RAP in Mixtures Containing WMA

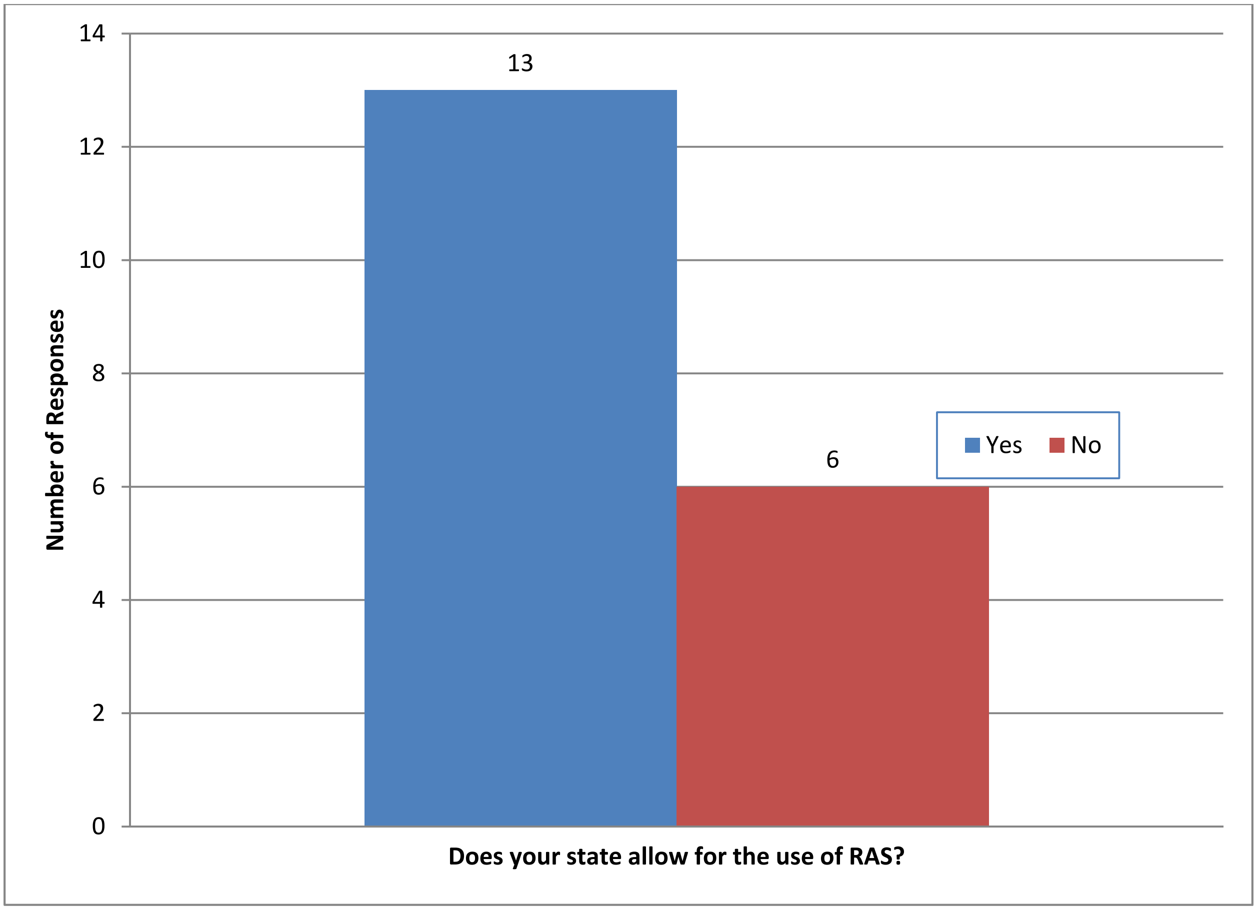


Figure 4-3: Number of States Utilizing RAS in Their Mixtures

Over 60% of the responders indicated that they allow the use of RAP and RAS in the same mix (Figure 4-4). However, only 15% of the states indicated that they have a method to estimate the cost savings for the mixtures containing RAP or RAS (Figure 4-5). Approximately 75% of states indicated that they calculate the aged binder contents in their mixes (Figure 4-6). Only one state (5%) has a separate pay schedule (Nebraska Department of Roads) for the virgin and aged binders (Figure 4-7). Figure 4-8 shows that over 63% of states responding to the survey indicated that they require softer binder with the mixes using higher percentages of RAP or RAS (>30%).

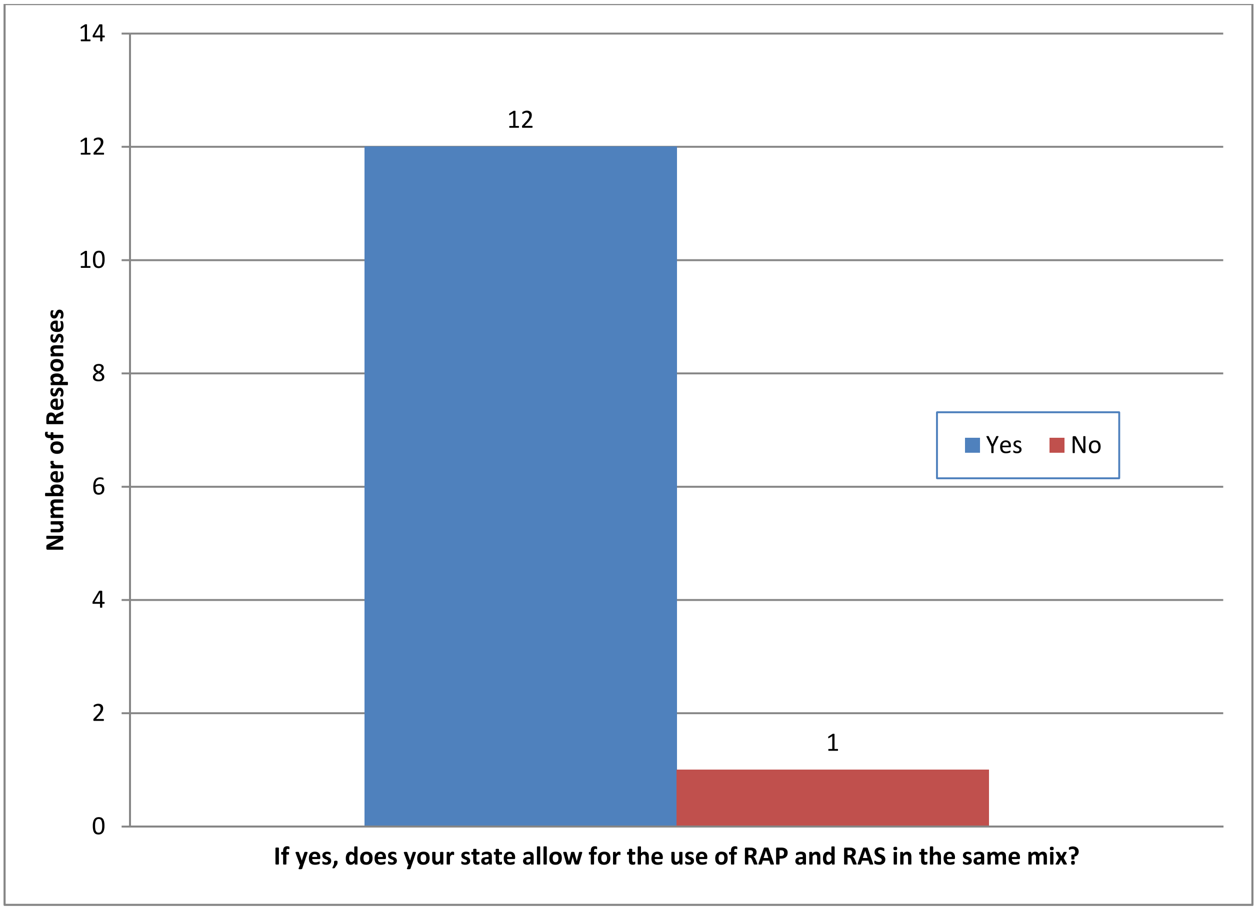


Figure 4-4: Number of States Allowing Use of RAP and RAS in the Same Mix

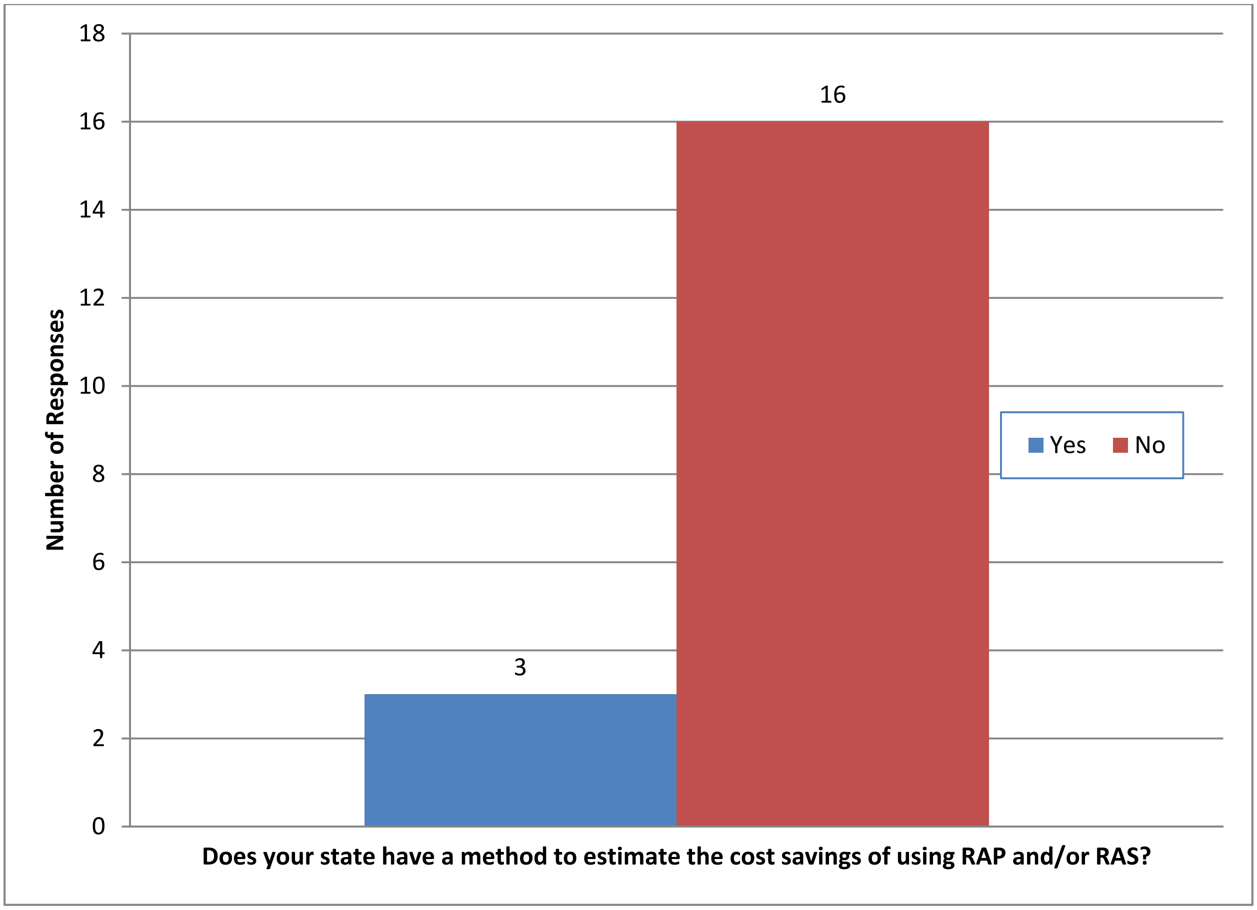


Figure 4-5: States Having a Method to Estimate Cost Savings of Using RAP and/or RAS

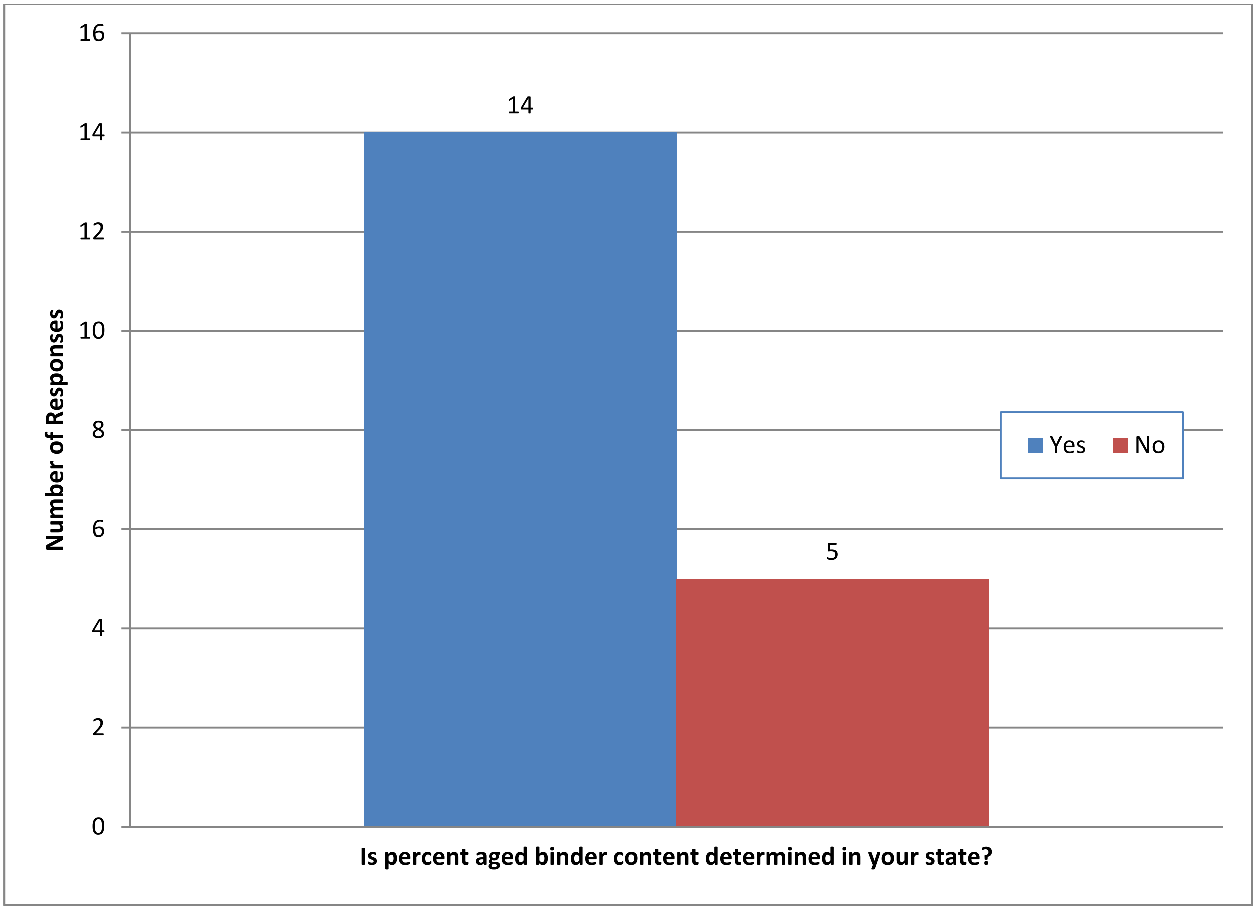


Figure 4-6: States that Determine Aged Binder Content

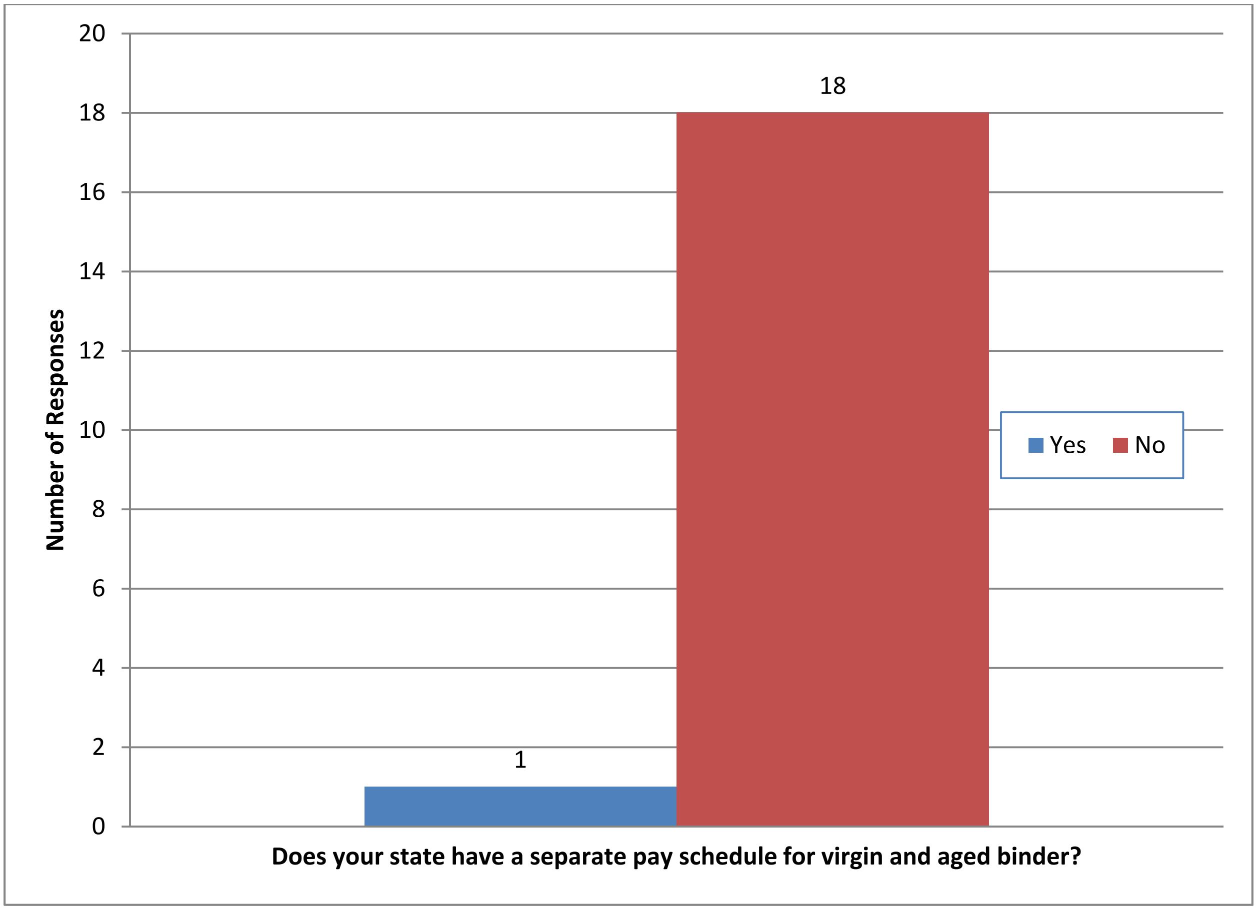


Figure 4-7: States Having a Separate Pay Schedule for Virgin and Aged Binder

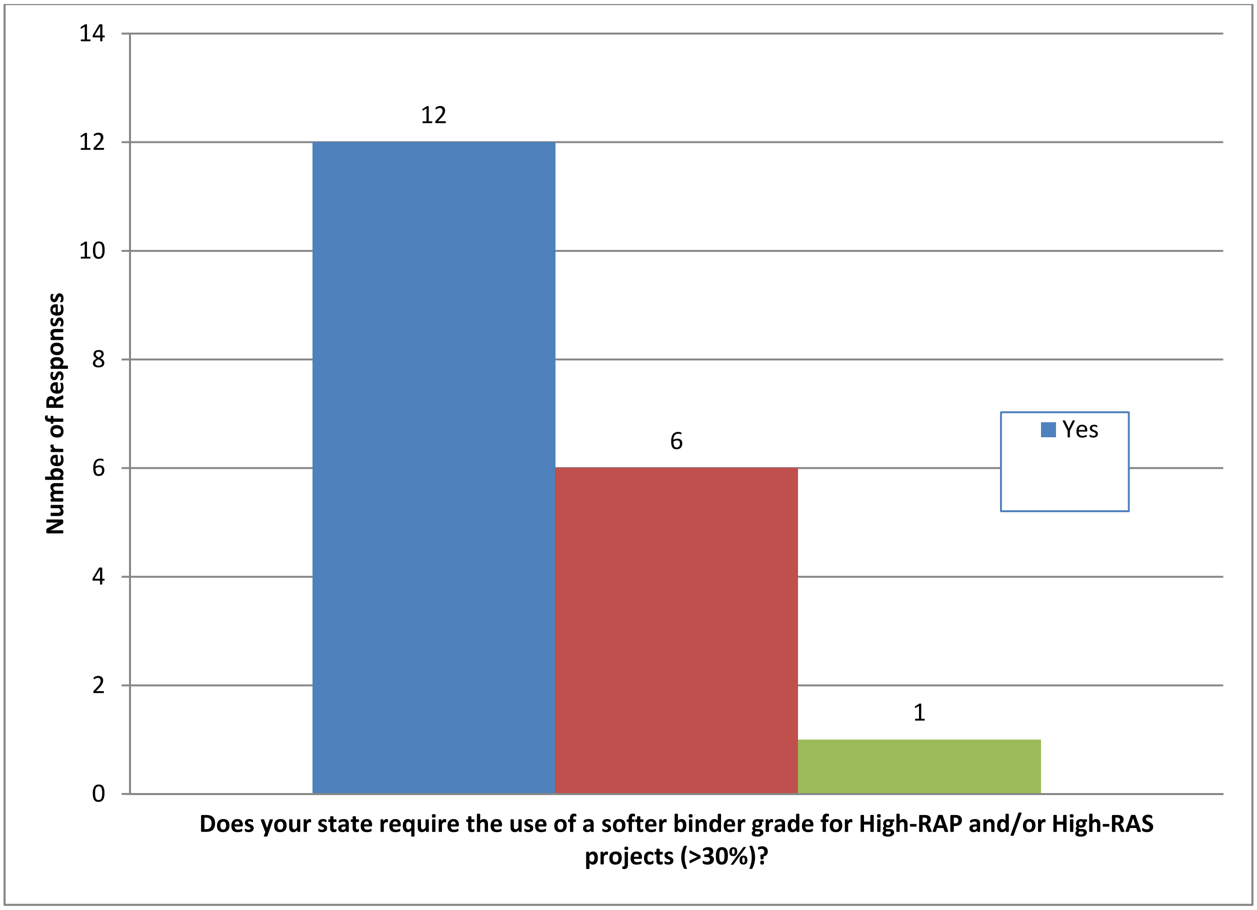


Figure 4-8: States Requiring the Use of a Softer Binder Grade with High-RAP and/or High-RAS Projects (>30%)

A follow-up survey was conducted for several states: Illinois, Kansas, Maryland, and Michigan. The survey was conducted to gather more information regarding the utilization of high percentages of RAP in the HMA mixtures. In addition, the performance issues of these mixtures were investigated. The utilization of softer grade binders in these mixes was also investigated.

Illinois DOT officials indicated that the upper limits are commonly employed. "While the threshold for grade bumping down to a softer asphalt binder grade is set at 20%, the economic threshold for contractors' usage is around 31%. There is not enough cost savings below 31% to offset the additional cost associated with the softer asphalt binder grade." This is due to the grade of binders used for mixtures containing more than 20% RAP (e.g., PG 58-28).

Kansas DOT officials indicated that on many preservation jobs where millings from the project are used as the RAP source, there is a capping of the RAP at 25%. However, if millings are not available from the project and permissive RAP is allowed, the cap is lowered to 15%. The blending charts are used on some of the projects where plenty of millings are available to establish the allowable percentage of RAP that can be used in the mix. The grade of the RAP binder and the virgin binder are input into the blending chart, and it establishes the allowable percentage of RAP by assuming complete blending of the binders. The specification is set up for target binder grades of PG64-22 or PG70-22. The PG64-22 target only has a requirement for the low end blended grade and PG70-22 has it for both the high end and low end (low end grade establishes maximum percentage of RAP and high end grade establishes minimum percentage of RAP).

The Kansas DOT officials also indicated that the contractors generally like the blending chart projects as it often allows them to add more than the conventional 25% RAP to the mix. In some cases, mixes with up to 50% RAP and even higher levels of binder replacement are used. In most instances, the contractors have been able to meet volumetric requirements on these high RAP mixtures without fractionating; however, in some cases, they noticed some bag house problems as they struggled to meet DOT's dust to binder requirement of 1.2. The specification allows RAS in any mix that is allowed to have RAP; however, the RAP is capped at 10% and the RAS at 5%.

Maryland officials indicated that they allow up to 20% in surface, with up to 15% in polymer-modified surface mixes and mixes requiring high-polish-resistant aggregate, and up to 25% in base courses. The contractors can get approved for higher amounts if they do the additional testing and develop blending charts and follow TP-62 for plant mixing capability analysis. This type of specification has been in effect for several years, and the DOT has not seen any negative effects such as fatigue cracking.

Michigan DOT officials indicated that the contractors are allowed to use up to 17% with no change in binder. However, the DOT allows larger amounts with adjustments to the binder. The 17% was selected based on national research and national best practices.

Chapter 5 - Results

Overall RAP Usage in South Carolina

Based on the averages attained within the National Asphalt Pavement Association's (NAPA) *Annual Asphalt Pavement Industry Survey on Recycled Materials and Warm Mix Asphalt Usage 2009-2012* mentioned in the literature review, it appears that the RAP allowances/usages by SCDOT per mix are above national averages for this time period. Table 5-1 indicates that the average percent RAP used in South Carolina is on par with, and in some cases above, what neighboring southeastern states are using at this current time. It should be noted that NAPA's national survey reported that South Carolina had average percentages of RAP in their mixes of 17, 20, 22 and 24 from 2009 to 2012. As shown in Figure 5-1, the data from this project indicated that average percentages of RAP in all South Carolina mixes from 2009 to 2012 were 18.06, 19.48, 21.58 and 20.46, respectively. The national survey was based on survey results collected by NAPA. The data from the research was based on actual quantities paid and subsequent calculations from information from mix design data. The close proximity of values would indicate that both methodologies are fairly consistent.

Table 5-1: Results from NAPA's 2009-2012 National Survey on RAP Usage

State	2009	2010	2011	2012	2013
Alabama	19%	25%	21%	22%	24
Alaska	5%	3%	13%	8%	--
Arizona	13%	5%	11%	14%	13
California	10%	19%	9%	16%	11
Colorado	19%	19%	24%	29%	27
Connecticut	15%	17%	13%	21%	NR
Delaware	20%	20%	N/R	28%	NR
Florida	24%	24%	30%	27%	31
Georgia	19%	22%	23%	23%	23
Hawaii	10%	9%	11%	14%	NR
Idaho	6%	10%	23%	28%	28
Illinois	18%	20%	16%	30%	22
Indiana	23%	24%	26%	23%	27
Iowa	12%	17%	14%	15%	18

Kansas	18%	20%	20%	20%	23
Kentucky	9%	9%	9%	10%	15
Louisiana	18%	18%	18%	19%	18
Maine	13%	14%	15%	15%	18
Maryland	19%	21%	24%	22%	23
Massachusetts	14%	14%	11%	16%	18
Michigan	27%	30%	36%	34%	32
Minnesota	16%	19%	22%	20%	21
Mississippi	16%	17%	18%	19%	18
Missouri	12%	12%	19%	19%	20
Montana	7%	8%	8%	10%	11
Nebraska	NR	NR	30%	22%	29
Nevada	6%	7%	10%	11%	14
New Hampshire	15%	18%	21%	19%	19
New Jersey	4%	17%	17%	16%	19
New Mexico	NR	NR	20%	NR	NR
New York	10%	11%	16%	13%	13
North Carolina	20%	22%	24%	15%	25
North Dakota	NR	NR	11%	NR	NR
Ohio	23%	24%	23%	23%	28
Oklahoma	12%	13%	18%	12%	15
Oregon	26%	25%	24%	24%	25
Pennsylvania	13%	13%	16%	16%	15
Puerto Rico	0%	0%	2%	20%	NR
Rhode Island	11%	11%	8%	2%	NR
South Carolina	17%	20%	22%	24%	23

South Dakota	12%	6%	18%	20%	NR
Tennessee	20%	17%	14%	20%	17
Texas	11%	10%	13%	16%	14
Utah	19%	21%	25%	19%	24
Vermont	21%	20%	17%	23%	NR
Virginia	21%	28%	26%	26%	27
Washington	18%	16%	16%	15%	19
West Virginia	10%	11%	11%	12%	12
Wisconsin	15%	15%	16%	14%	15
Wyoming	6%	5%	1%	2%	NR

Average RAP Percentage per District per Year

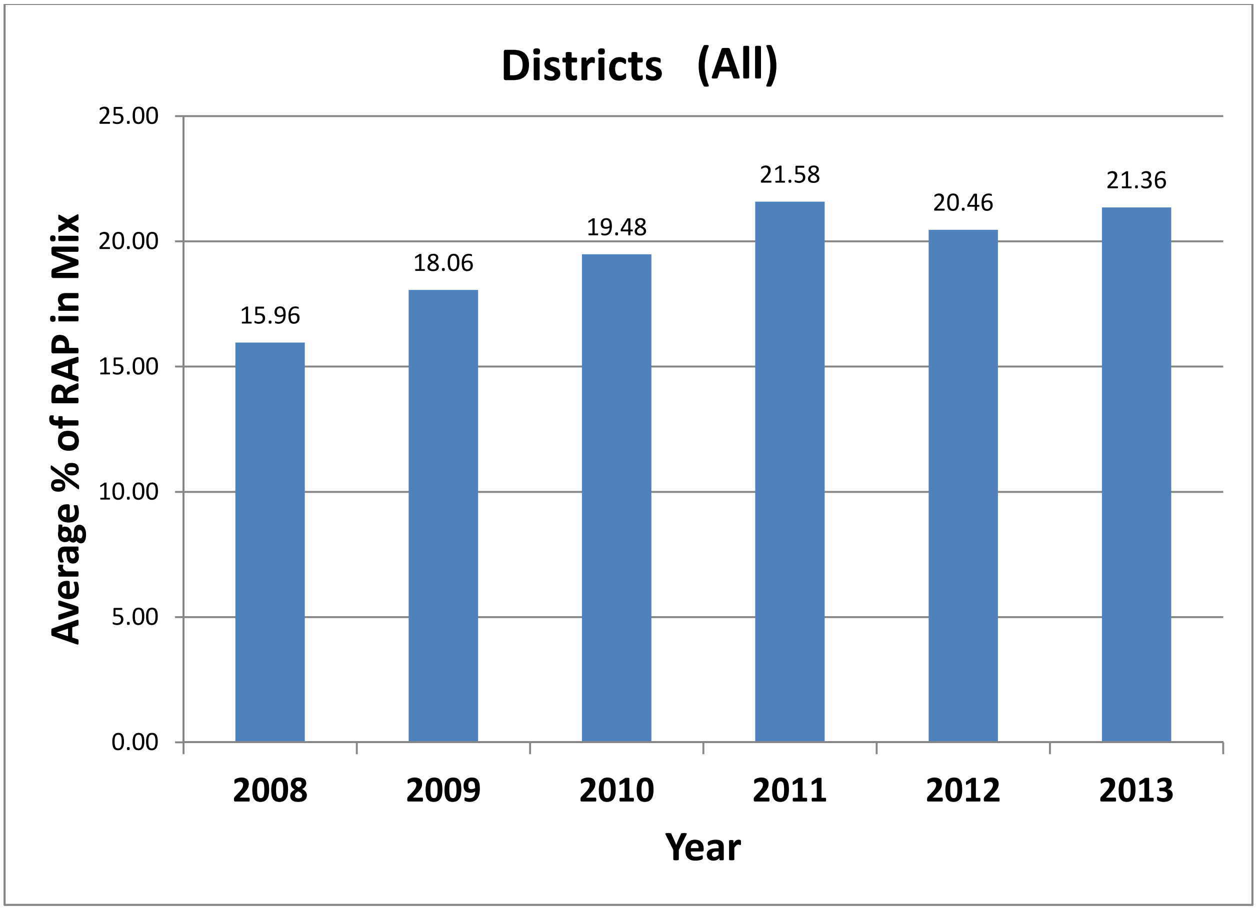


Figure 5-1: Average % RAP used in SC per Year (All SCDOT Engineering Districts Combined)

One objective of this research was to determine the average percent RAP used for all mix types per SCDOT Engineering District. For this analysis, all mix types were combined and averaged per SCDOT District/per year. It should be noted that differences of average percent RAP per mix have many variables that can affect comparisons between Districts. The average percent RAP per mix could be a function of the type of projects that were completed in each District. For example an urban District with more interstate work may exhibit a lower percentage of RAP used per mix than a rural District that may have utilized lower-volume mixes that allow for the use of higher RAP percentages. On the other hand, RAP supply may be limited in some rural areas causing a lower percentage of RAP to be utilized in those Districts.

As shown in Figure 5-1, the average percentage of RAP per mix for all 7 Districts in 2008 was 15.96. This same figure shows that the average percent RAP per mix for all 7 Districts combined steadily increased almost 2% per year between 2008 and 2011. The use of RAP in Years 2008, 2009, and 2010 were significantly different (lower) than all other years at the α = 0.05 level (Appendix C, Table 10-4). The trend then flattened out in 2012 and 2013 with averages of 20.46 and 21.36, respectively. Years 2011, 2012, and 2013 had the highest percent RAP used and were not significantly different from each other at the α = 0.05 level (Appendix C,

Table 10-4). This would indicate that contractors have found a comfort level within the tolerances of current SCDOT specifications balancing RAP percentages allowed per mix, production capabilities, and available RAP.

Figure 5-2 shows SCDOT District comparisons by SCDOT District per year (2008-2013). Table 10-5 through Table 10-17 in Appendix C show statistical comparisons between SCDOT Districts for each year studied (2008-2013). District 6 had the highest average percent RAP used per district (Figure 5-3) and was significantly different than all other SCDOT Districts studied from 2008-2013 (Appendix C, Table 10-18). SCDOT's Districts 1, 4, and 7 were the next highest and were significantly different from all other SCDOT Districts at the $\alpha = 0.05$ significance level (Appendix C, Table 10-18). SCDOT's Districts 2, 3, and 5 had the lowest RAP percentages used per district and were significantly different than all other SCDOT Districts at the $\alpha = 0.05$ level (Appendix C, Table 10-18). Districts 6 and 7 have limited aggregate sources, which may explain the use of higher RAP in these areas.

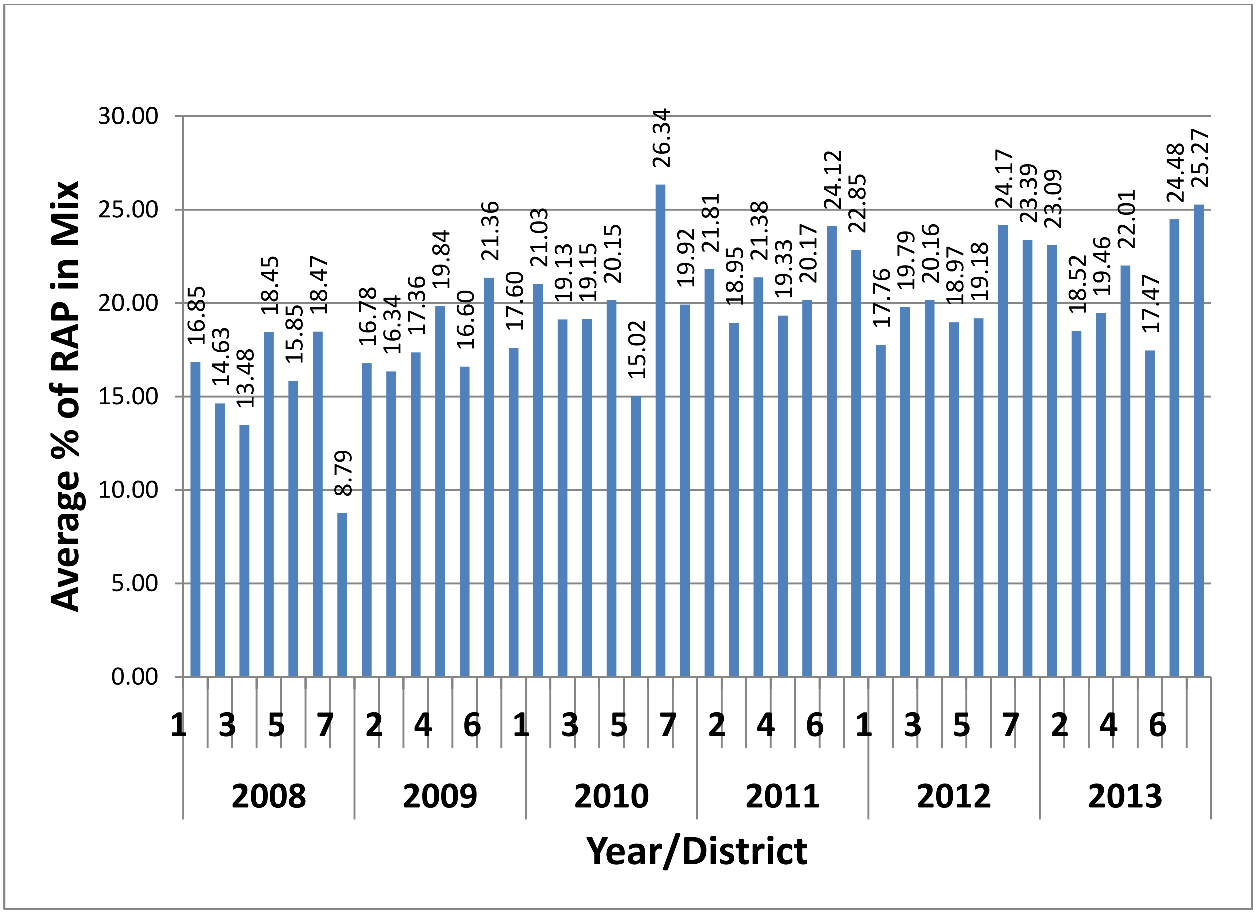


Figure 5-2: Average Percentages of RAP in all Mixes per SCDOT Engineering District per Year

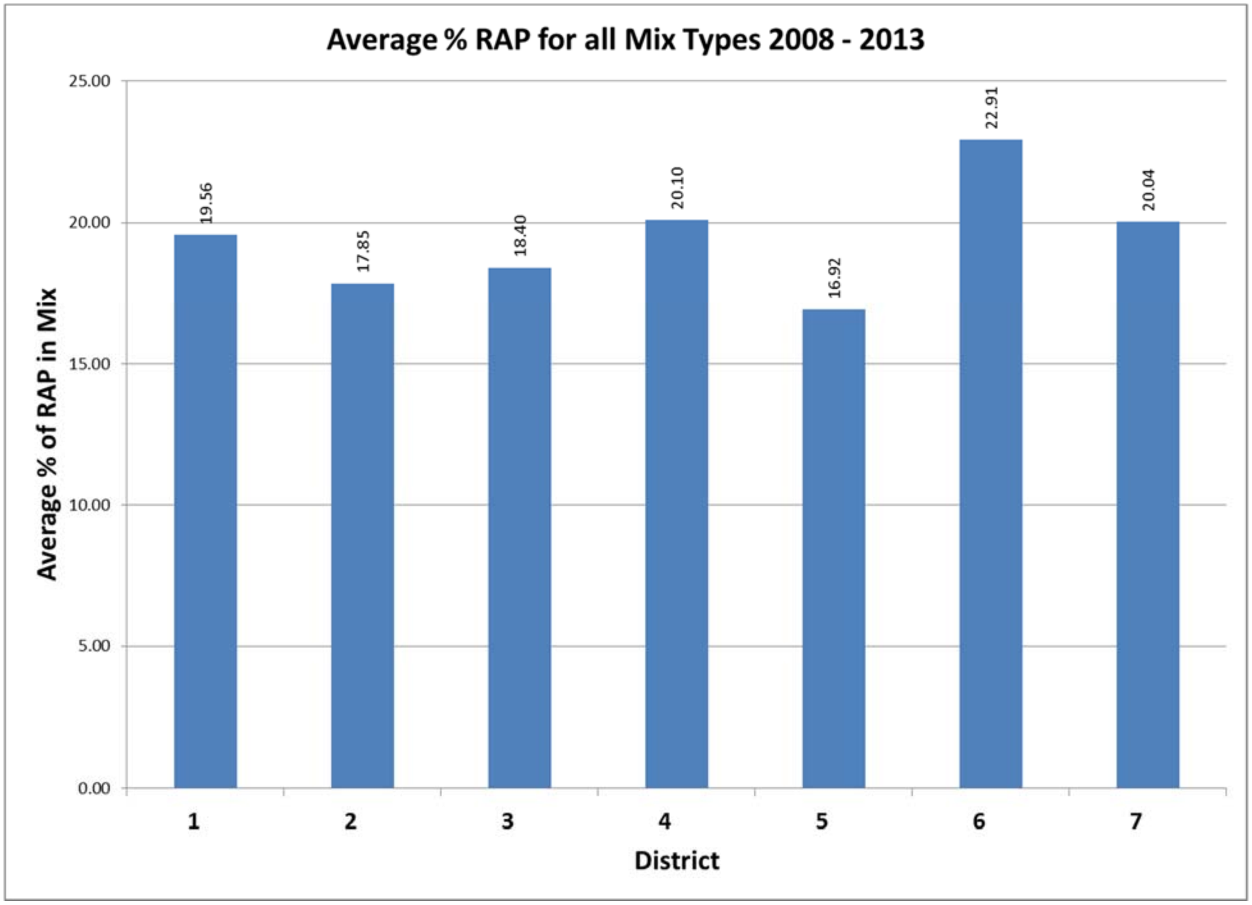


Figure 5-3: Average Percentages of RAP in all Mixes per SCDOT Engineering District 2008 - 2013

Average RAP Percentage per Mix Type per District per Year

Another objective of this research was to determine RAP percentages per mix type per SCDOT Engineering District. RAP percentages per mix type were averaged per District for the years 2008-2013. Table 5-2 contains these averages, standard deviations, and RAP allowed per SCDOT specifications from SC-M-407, while Figure 5-4 through Figure 5-16 represent this data graphically.

It should be noted that allowable RAP percentages were increased from the previous version of SC-M-407 in June 2011. Generally speaking, RAP percentages were increased approximately 5% per mix type from the previous version. Therefore, one could expect the data to be skewed toward lower percentages used for all mixes compared to actual RAP percentages used from June 2011 going forward provided that these percentages are physically achievable. Prior to 2011, less RAP and RAS were permitted in the SC DOT's mixtures.

Table 5-2: Average RAP % per Mix Type for all Districts 2008-2013

Mix Type	Average % RAP	Std. Deviation	RAP Allowed SCDOT–M-407 - (06/11) (non-Fractionated)	RAP Allowed SCDOT-M-407- (06/11) (Fractionated)
Shoulder Widening	28.75	3.117	50	50
Base A	24.04	5.200	30	35
Base B	21.69	4.441	30	35
Base C	15.00	12.91	-	35
Intermediate A	13.80	9.96	-	15
Intermediate B	15.50	3.11 2	20	30
Intermediate C	18.98	2.178	25	35
Surface A	8.09	2.753	-	15
Surface B	15.73	2.07	15	25
Surface C	19.12	2.944	20	30
Surface CM	18.19	1.707	20	30
Surface D	18.29	4.42	20	30
Surface E	18.77	5.97	-	30

HMA Shoulder Widening Course

As shown in Table 5-2, the average RAP percentage for HMA Shoulder Widening Course was 28.75% from 2008-2013. SCDOT specifications allow percentages of up to 50% RAP in this type of mixture. There are a number of reasons why this average percentage of RAP contained in HMA Shoulder Widening Mix is not closer to the SCDOT maximum allowable RAP percentage of 50% including: a) contractors that have chosen not to use RAP, b) RAP availability in rural areas, c) contractor capabilities (non-fractionated RAP vs. Fractionated RAP), and d) control of mix volumetrics. In addition, most asphalt plants currently in use in South Carolina cannot consistently produce RAP mixes at higher percentages. When using higher RAP percentages, bag house issues as well as superheating RAP may provide difficulties for some configurations of asphalt plants. However, it should be noted that some asphalt plants in South Carolina do have the capability of producing mixes containing high RAP percentages.

Figure 5-4 shows the average percent RAP used in HMA Shoulder Widening Course per District between 2008 and 2013. District 6 had the highest average percent RAP used and was significantly different at the α = 0.05 level than all other SCDOT Districts except District 7 (Appendix C, Table 10-19). Districts 1, 3, 4, and 7 were the next highest average percent RAP used and were not significantly different from each other at the α = 0.05 level (Appendix C, Table 10-19). Districts 2 and 5 had the lowest average percent RAP used in HMA Shoulder Widening Course.

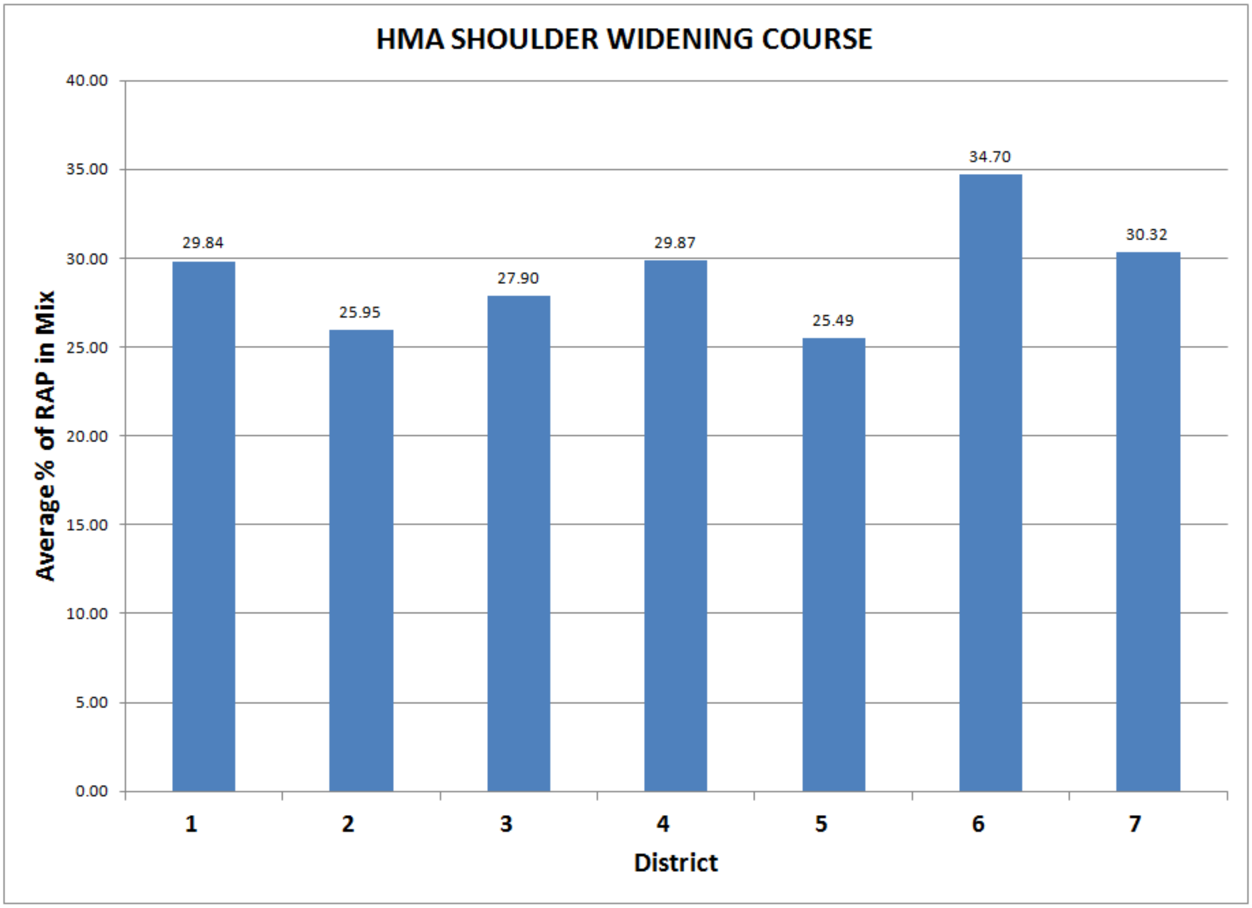


Figure 5-4: HMA Shoulder Widening Course Average Percent RAP Per District from 2008-2013

HMA Base Course Type A

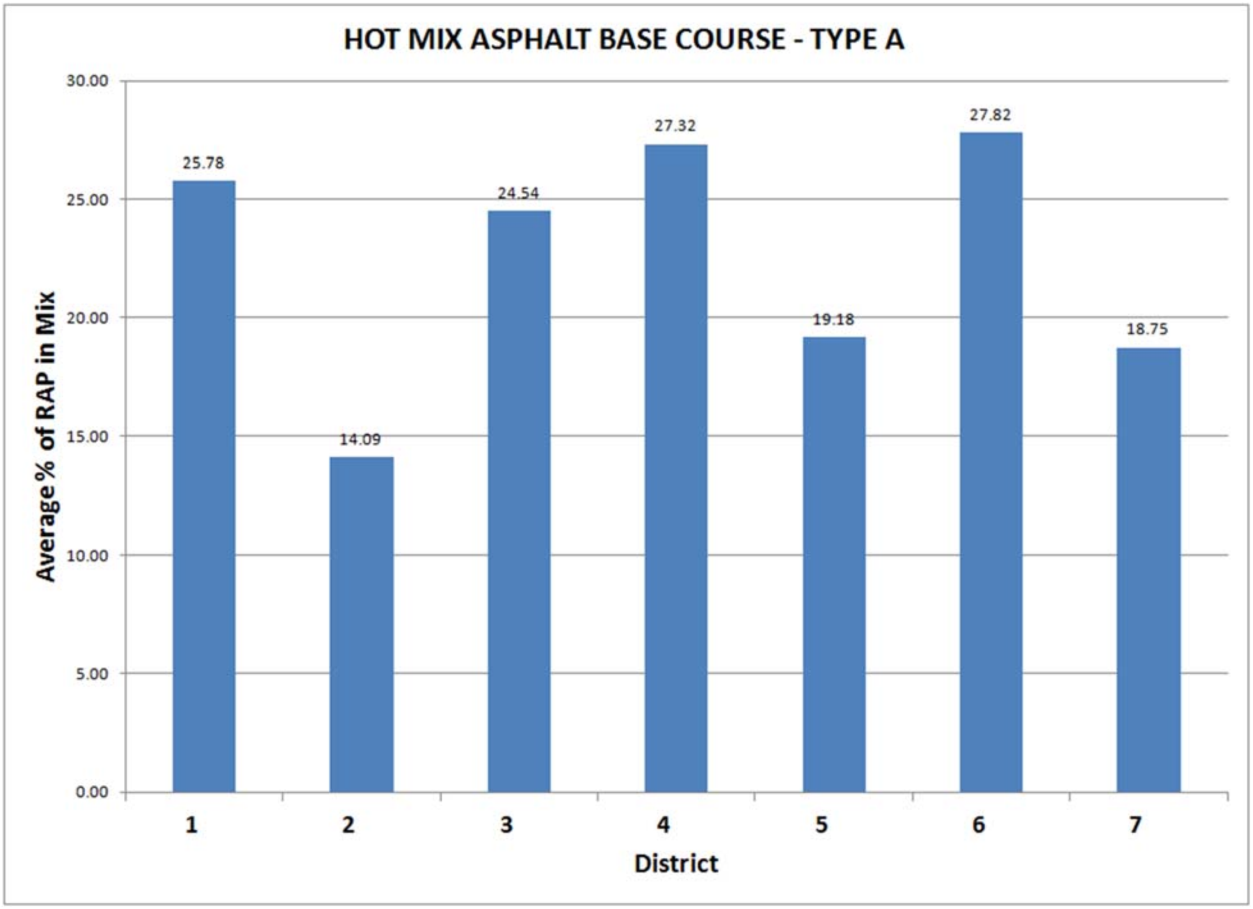


Figure 5-5: HMA Base Course Type A Average Percent RAP per District from 2008-2013

As shown in Table 5-2, the average percentage of RAP used in HMA Base Course Type A was 24.04% from 2008-2013. SCDOT specifications allow the use of up to 35% RAP in this type of mixture. As discussed previously, the reasons why the average percentage of RAP utilized is not closer to the SCDOT maximum allowable RAP percentage could include many factors.

Figure 5-5 shows the average percent RAP used in HMA Base Course Type A per District between 2008 and 2013. Districts 1, 3, 4, and 6 had the highest average percent RAP used in HMA Base Course A from years 2008-2013 and were statically equivalent to each other at the $\alpha = 0.05$ level (Appendix C, Table 10-20). Districts 2, 5, and 7 had the lowest average percent RAP used in HMA Base Coure A from years 2008-2013 and were statistically equivalent to each other at the $\alpha = 0.05$ level (Appendix C, Table 10-20).

HMA Base Course Type B

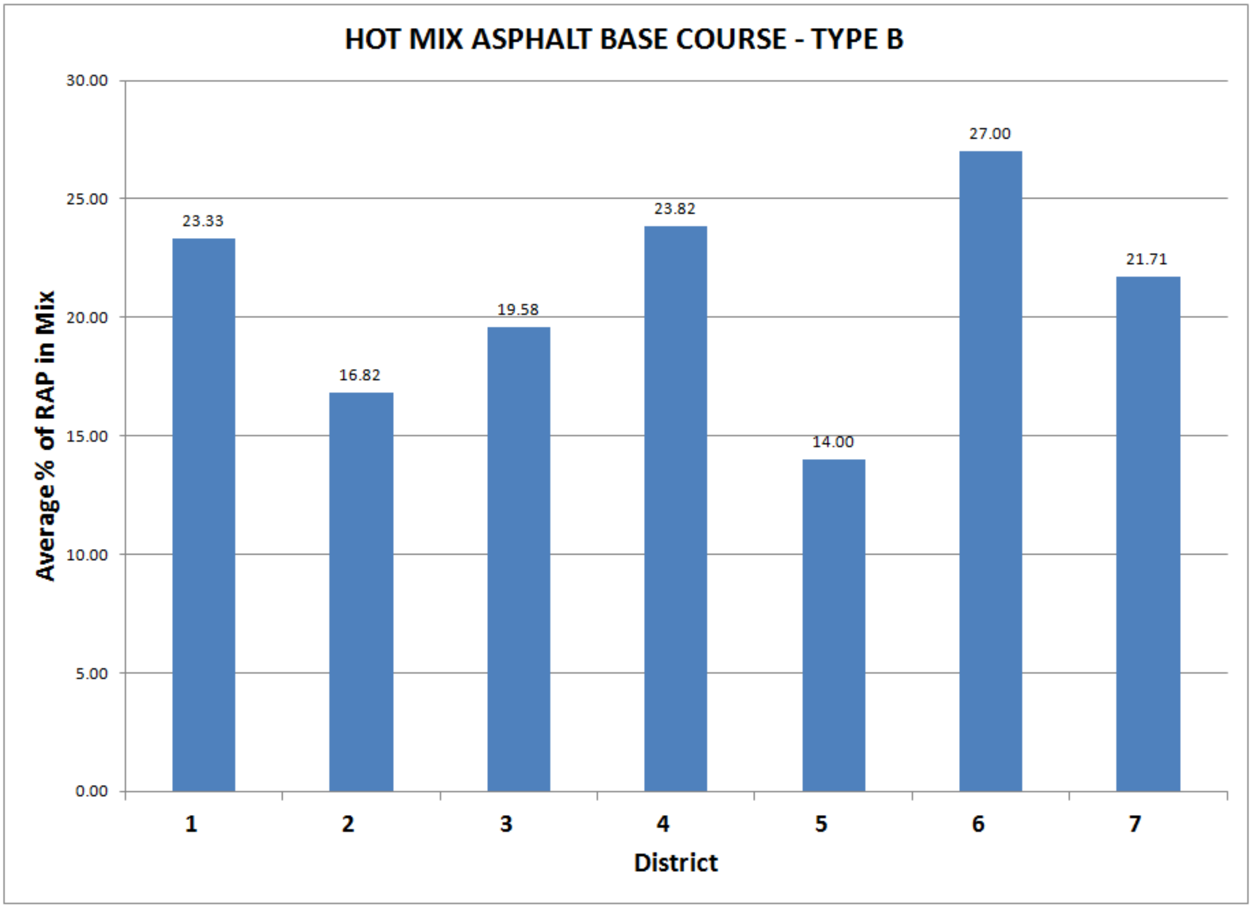


Figure 5-6: HMA Base Course Type B Average Percent RAP per District from 2008-2013

As shown in Table 5-2, the average percentage of RAP used in HMA Base Course Type B was 21.69% from 2008-2013. SCDOT specifications allow the use of up to 35% RAP in this type of mixture. Figure 5-6 shows the average percent RAP used in HMA Base Course Type B per District between 2008 and 2013. SCDOT Districts 1, 3, 4, 6, and 7 had the highest average percent RAP used in Base Course Type B between 2008-2013 and were statistically equivalent to each other at the $\alpha = 0.05$ level (Appendix C, Table 10-21). District 2 and 5 had the lowest average percent RAP used in Base Course Type B between 2008-2013 and were statistically equivalent to each other at the $\alpha = 0.05$ level (Appendix C, Table 10-21).

HMA Base Course Type C

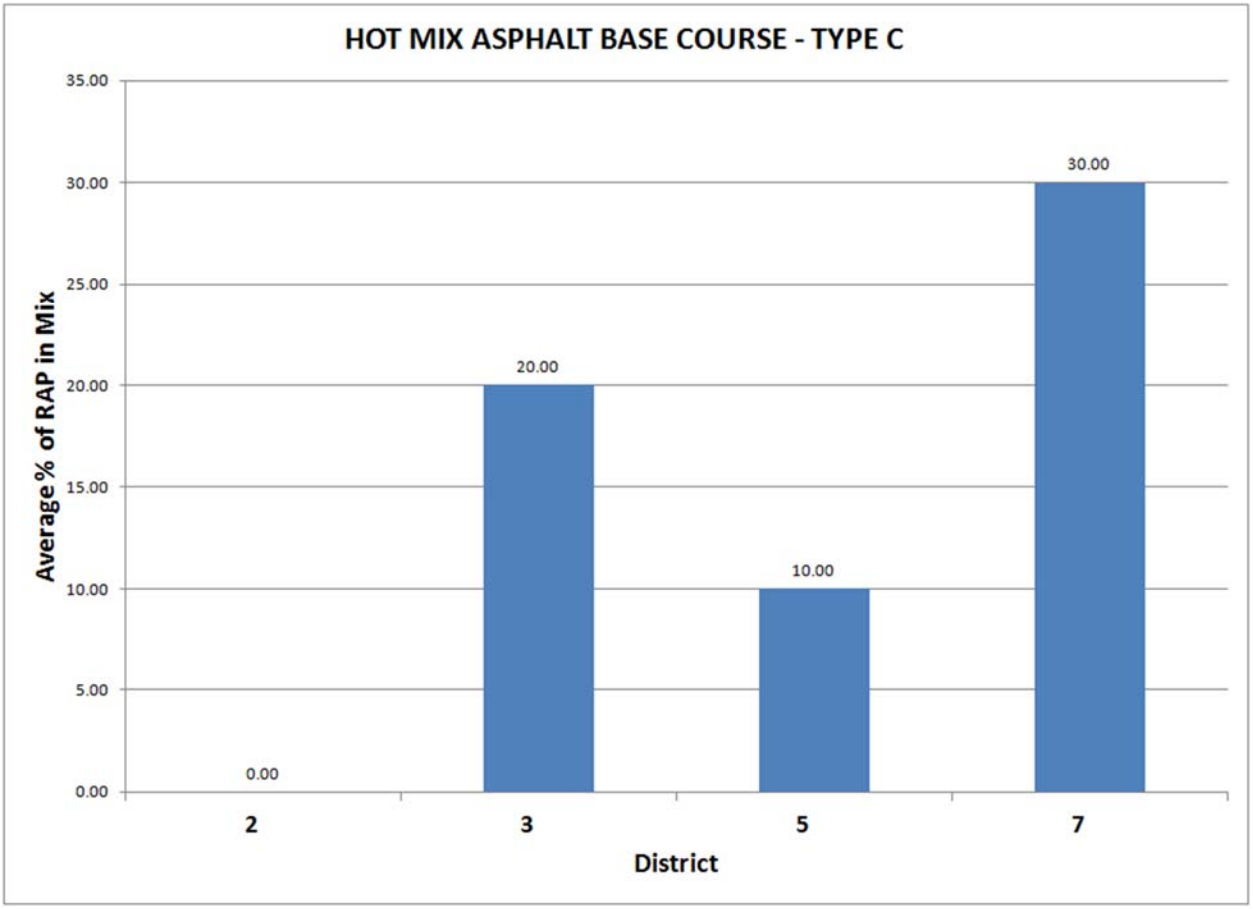


Figure 5-7: HMA Base Course Type C Average Percent RAP per District from 2008-2013

As shown in Table 5-2, the average percentage of RAP used in HMA Base Course Type C was 15.00% from 2008-2013. SCDOT specifications allow the use of up to 35% RAP in this type of mixture. It should be noted that only fractionated RAP can be used in this type of mix due to the fineness of the gradation tolerances. Figure 5-7 shows the average percent RAP used in HMA Base Course Type C per District between 2008 and 2013. Not all Districts utilized this mix type during this time period. There was not sufficient data available to run a statistical analysis on this set of data.

HMA Intermediate Course Type A

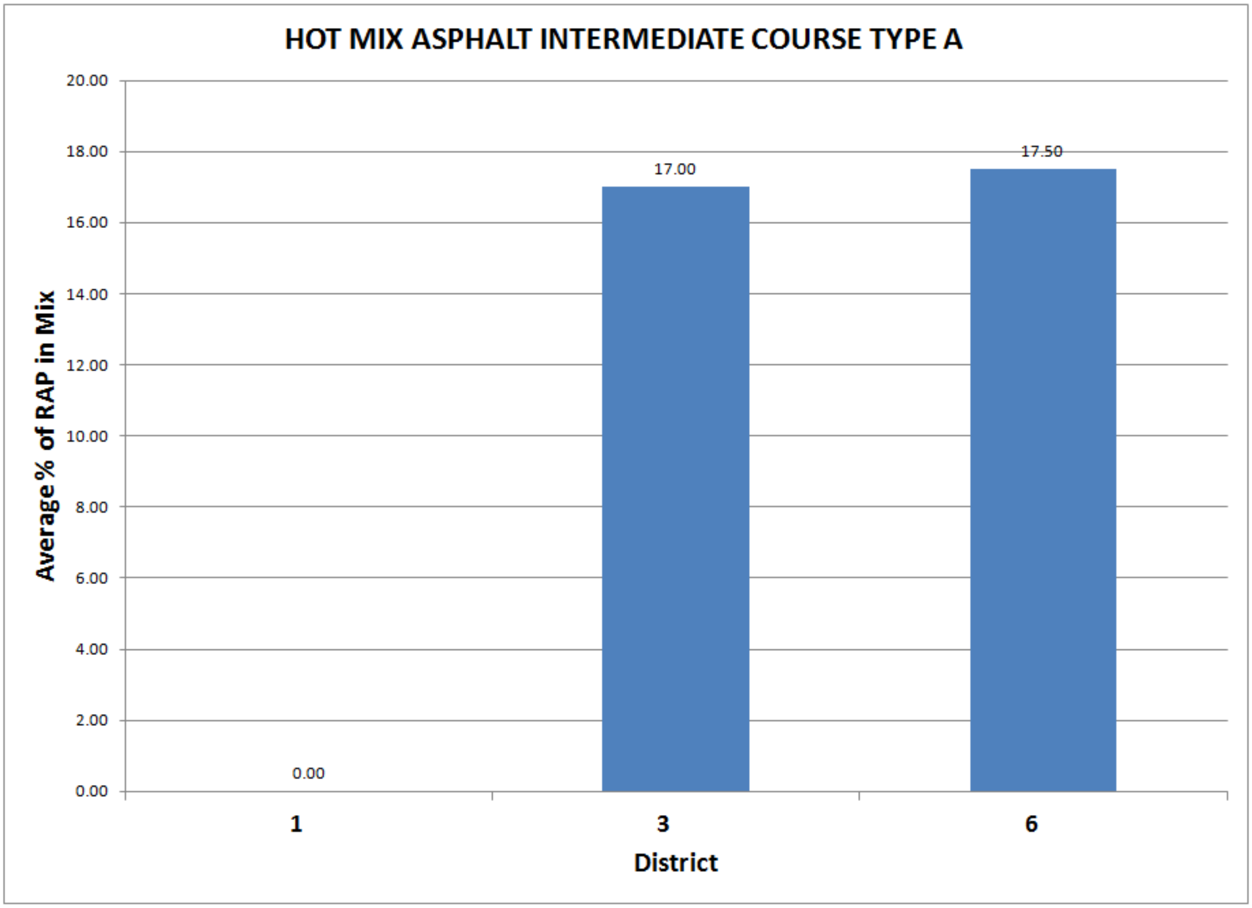


Figure 5-8: HMA Intermediate Course Type A Average Percent RAP per District from 2008-2013

As shown in Table 5-2, the average percentage of RAP used in HMA Intermediate Course Type A was 13.80% from 2008-2013. SCDOT specifications allow the use of up to 15% RAP in this type of mixture. This average percent RAP used in the Intermediate Type A mixes is close to the 15% allowed. This mix is typically used on large interstate projects where more planning and competition may drive contractors to maximize RAP percentages in order to be competitive in the low-bid process. Also, utilizing RAP in percentages less than 20% is more controllable from a volumetric standpoint than mixtures containing higher percentages of RAP. More contractors have the capability to utilize RAP at these more conservative percentages. Figure 5-8 shows the average percent RAP used in HMA Intermediate Course Type A per District between 2008 and 2013. Not all Districts utilized this mix type during this time period. There was not sufficient data available to run a statistical analysis on this set of data.

HMA Intermediate Course Type B

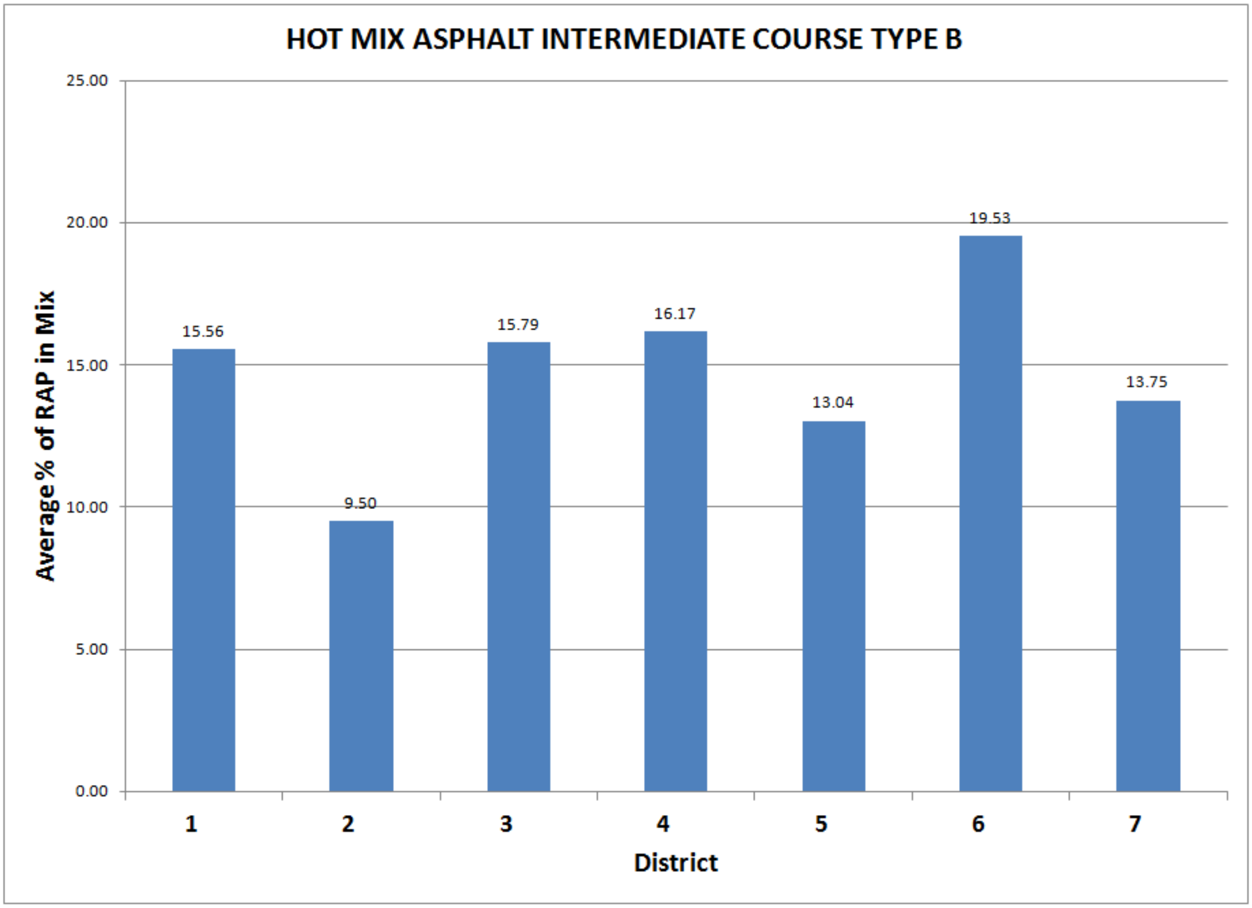


Figure 5-9: HMA Intermediate Course Type B Average Percent RAP Per District from 2008-2013

As shown in Table 5-2, the average percentage of RAP used in HMA Intermediate Course Type B was 15.50% from 2008-2013 while SCDOT specifications allow the use of up to 30% RAP in this type of mixture. The maximum allowable RAP percentage for this type of mixture was only 20% until July 2011 when it increased to 30%. Therefore, the data may be skewed to a lower overall percentage of RAP than is currently in use.

Figure 5-9 shows the average percent RAP used in HMA Intermediate Course Type B per District between 2008 and 2013. District 6 has the highest average percent RAP used in Intermediate Course B and is significantly different at the $\alpha = 0.05$ level from all other Districts (Appendix C, Table 10-22). Districts 1, 3, 4, 5, and 7 have the next highest average percent RAP used in HMA Intermediate Course Type B mixes and are statistically equivalent at the $\alpha = 0.05$ level. Districts 2 and 5 had the lowest average percent RAP used in HMA Intermediate Course Type B mixes and are statistically equivalent at the $\alpha = 0.05$ level (Appendix C, Table 10-22).

HMA Intermediate Course Type C

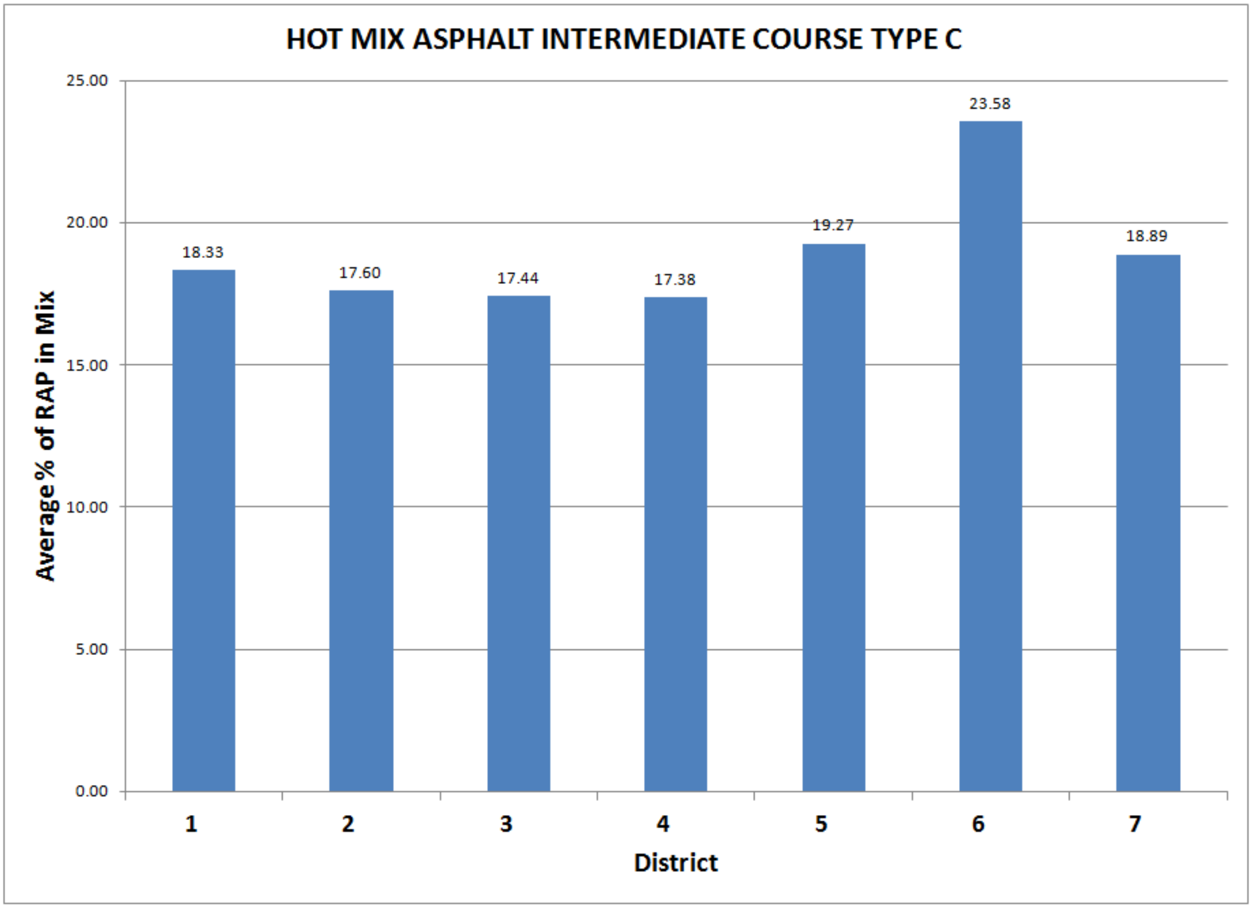


Figure 5-10: HMA Intermediate Course Type C Average Percent RAP per District from 2008-2013

As shown in Table 5-2, the average percentage of RAP used in HMA Intermediate Course Type C was 18.98% from 2008-2013 (SCDOT specifications: up to 35% RAP) The maximum allowable RAP percentage for this type of mixture was only 30% until July 2011 when it increased to 35%. Therefore, the data may be skewed to a lower overall percentage of RAP than is currently in use.

Figure 5-10 shows the average percent RAP used in HMA Intermediate Course Type C per District between 2008 and 2013. District 6 has the highest average percent RAP used for HMA Intermediate Course Type C from 2008-2103 and was significantly different at the $\alpha = 0.05$ level from all other Districts (Appendix C, Table 10-23). The percentages of RAP used, in HMA Intermediate Course Type C mixtures, in Districts 1, 2, 3, 4, 5, and 7 were statistically equivalent across these Districts (Appendix C, Table 10-23).

HMA Surface Course Type A

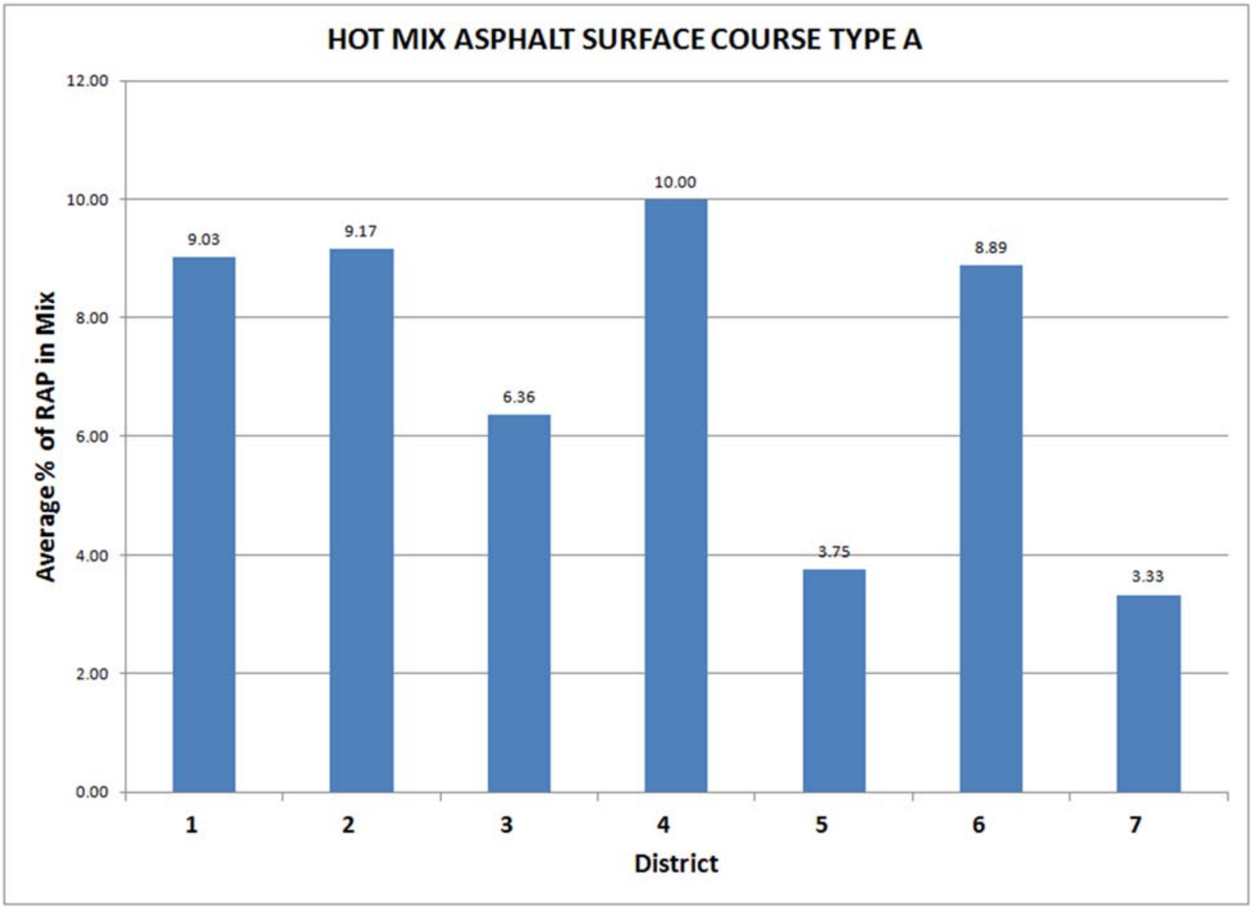


Figure 5-11: HMA Surface Course Type A Average Percent RAP per District from 2008-2013

As shown in Table 5-2, the average percentage of RAP used in HMA Surface Course Type A was 8.09% from 2008-2013 (SCDOT specifications: up to 15% RAP) However, it should be noted that the maximum allowable RAP percentage for this type of mixture was only 10% until July 2011 when it increased to 15%, so the data may be skewed to a lower overall percentage of RAP than is currently in use. In addition, only fractionated RAP can be used in this mix type, which would limit its use to those contractors with the capability of handling fractionated RAP. In addition, PG 76-22 is used in all Surface Type A mixtures instead of PG 64-22.

Figure 5-11 shows the average percent RAP used in HMA Surface Course Type A per District between 2008 and 2013. Districts 1, 2, 4, and 6 have the highest average percent RAP used in HMA Surface Course Type A from 2008-2013 and are statistically equivalent to each other (Appendix C, Table 10-24). Districts 5 and 6 had the lowest average percent RAP used in HMA Type A from 2008-2013 and are statistically equivalent to each other at the $\alpha = 0.05$ level (Appendix C, Table 10-24).

HMA Surface Course Type B

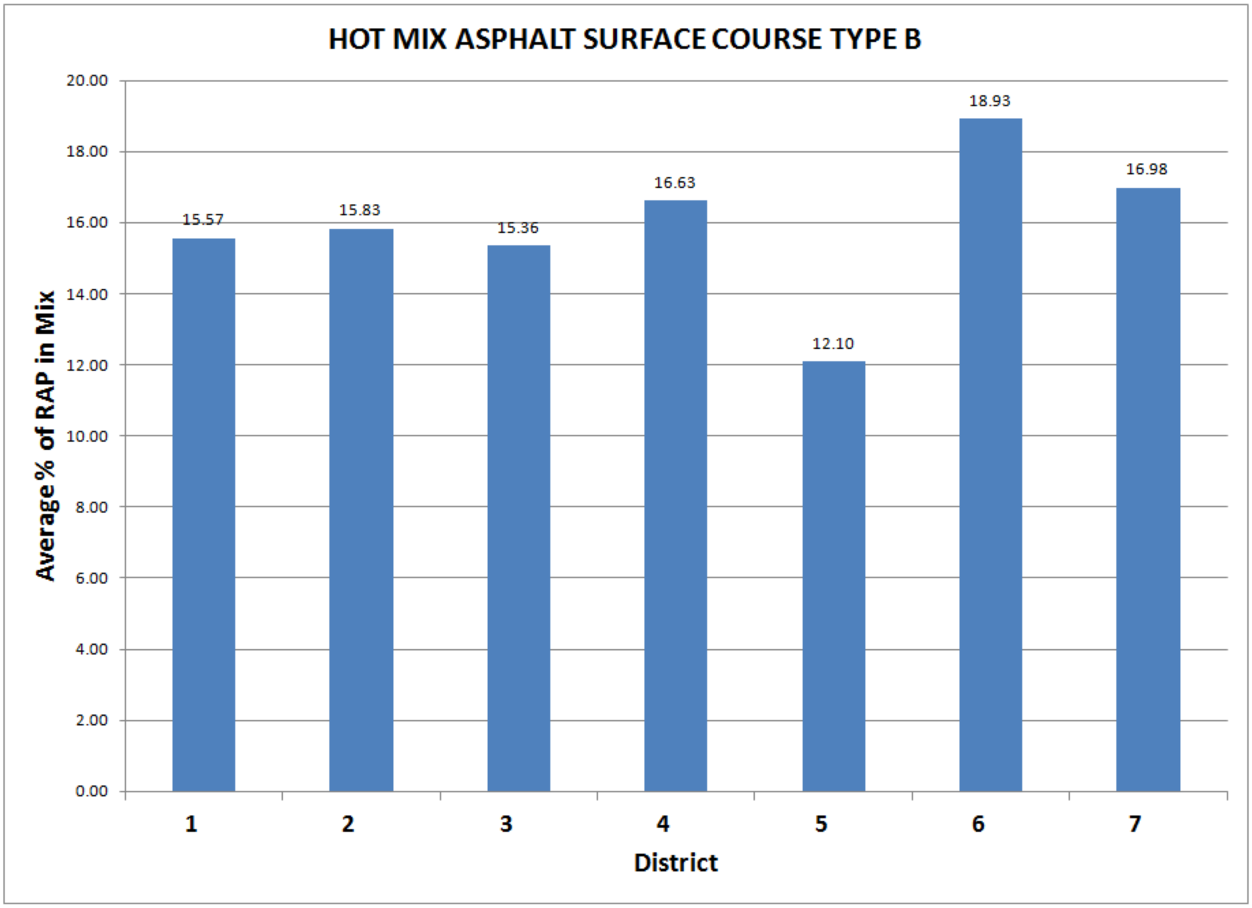


Figure 5-12: HMA Surface Course Type B Average Percent RAP Per District from 2008-2013

As shown in Table 5-2, the average percentage of RAP used in HMA Surface Course Type B was 15.73% from 2008-2013 (SCDOT specifications: up to 25% RAP) Figure 5-12 shows the average percent RAP used in HMA Surface Course Type B per District between 2008 and 2013. District 6 had the highest average percent RAP used in HMA Surface Course Type B from 2008-2013 and was significantly different from all other Districts (Appendix C, Table 10-25). Districts 1, 2, 3, 4, and 7 average percent RAP used in HMA Surface Course Type B from 2008-2013 were statistically equivalent at the $\alpha = 0.05$ level (Table B-22). District 5 had the lowest average percent RAP used in HMA Surface Course Type B from 2008-2013 and was statistically different than all other Districts (Appendix C, Table 10-25).

HMA Surface Course Type C

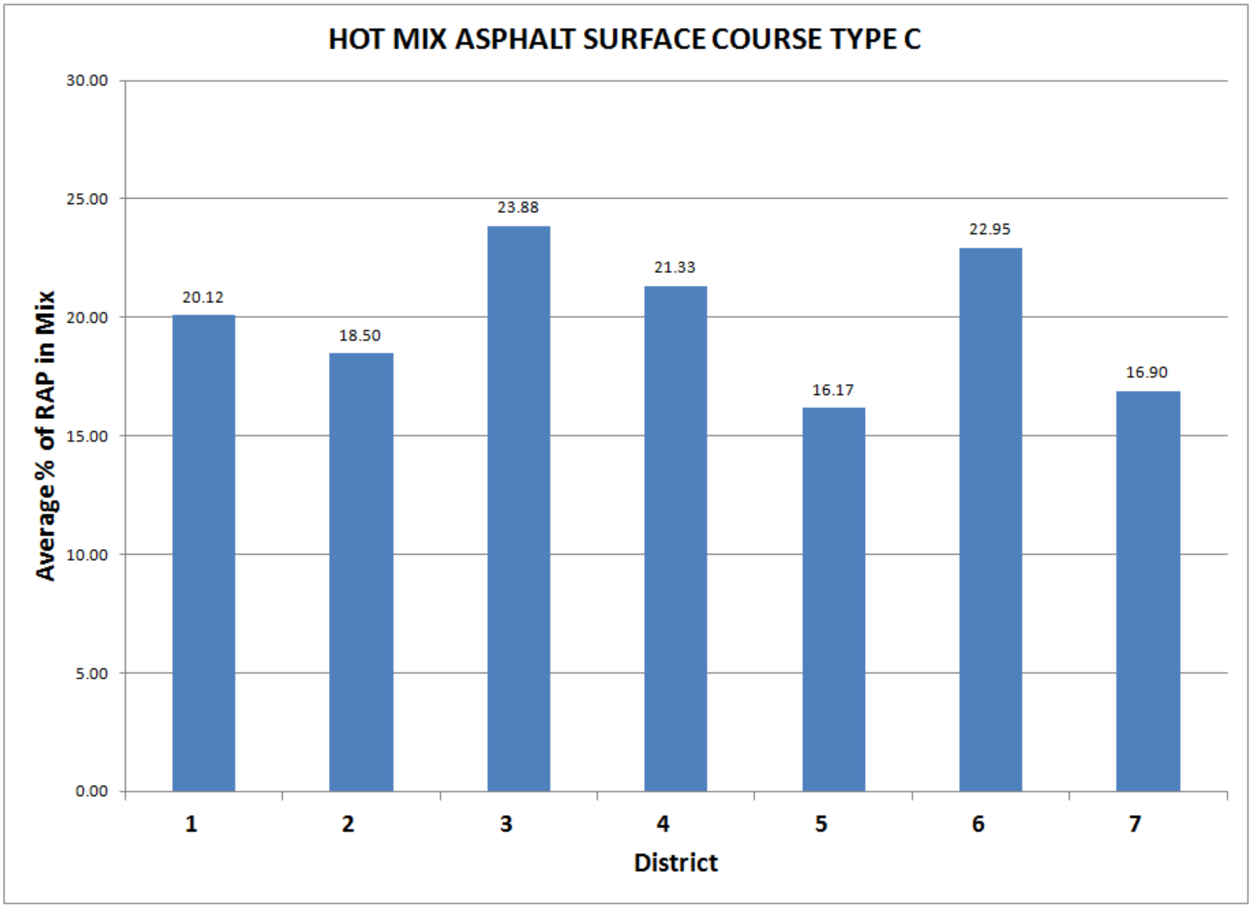


Figure 5-13: HMA Surface Course Type C Average Percent RAP per District from 2008-2013

The average percentage of RAP used in HMA Surface Course Type C was 19.12% from 2008-2013 (Table 5-2). SCDOT specifications allow the use of up to 30% RAP in this type of mixture. Figure 5-13 shows the average percent RAP used in HMA Surface Course Type C per District between 2008 and 2013. Districts 3, 4, and 6 had the highest average percent RAP used in HMA Surface Course Type C mixes from 2008-2013 and are statistically equivalent at the $\alpha = 0.05$ level (Appendix C, Table 10-26). Districts 5 and 7 had the low average percent RAP used in HMA Surface Course Type C per District between 2008-2013 and were statistically equivalent at the $\alpha = 0.05$ level (Appendix C, Table 10-26).

HMA Surface Course Type CM

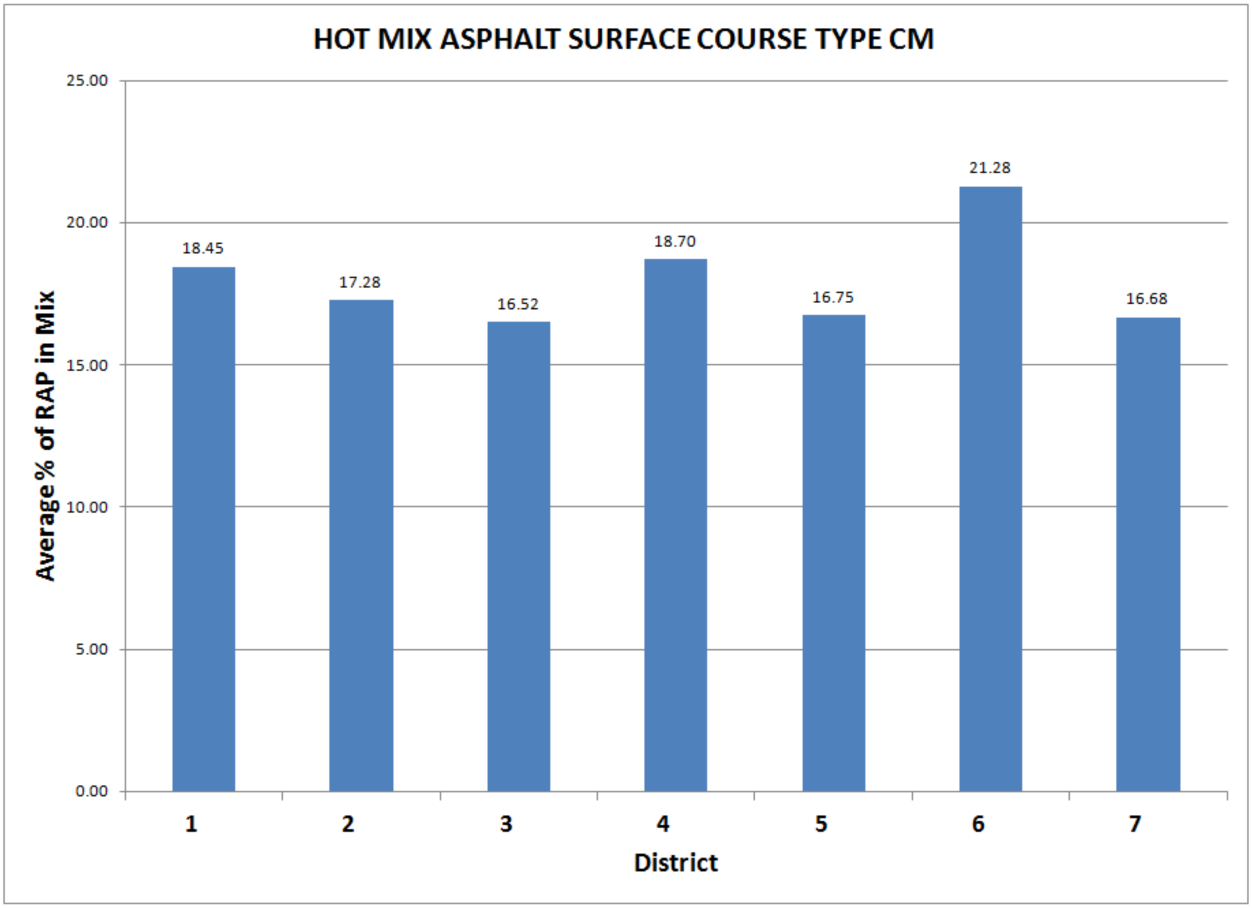


Figure 5-14: HMA Surface Course Type CM Average Percent RAP Per District from 2008-2013

As shown in Table 5-2, the average percentage of RAP used in HMA Surface Course Type CM was 18.19% from 2008-2013 (SCDOT specifications: up to 30% RAP). Figure 5-14 shows the average percent RAP used in HMA Surface Course Type CM per District between 2008 and 2013. District 6 has the highest average percent RAP used in HMA Surface Course Type CM from 2008-2013 and was significantly different than all other Districts at the $\alpha = 0.05$ level (Appendix C, Table 10-27). District 3 had the lowest average percent RAP used in HMA Surface Course Type CM from 2008-2013 but was statistically equivalent to all other Districts except Districts 4 and 6 (Appendix C, Table 10-27).

HMA Surface Course Type D

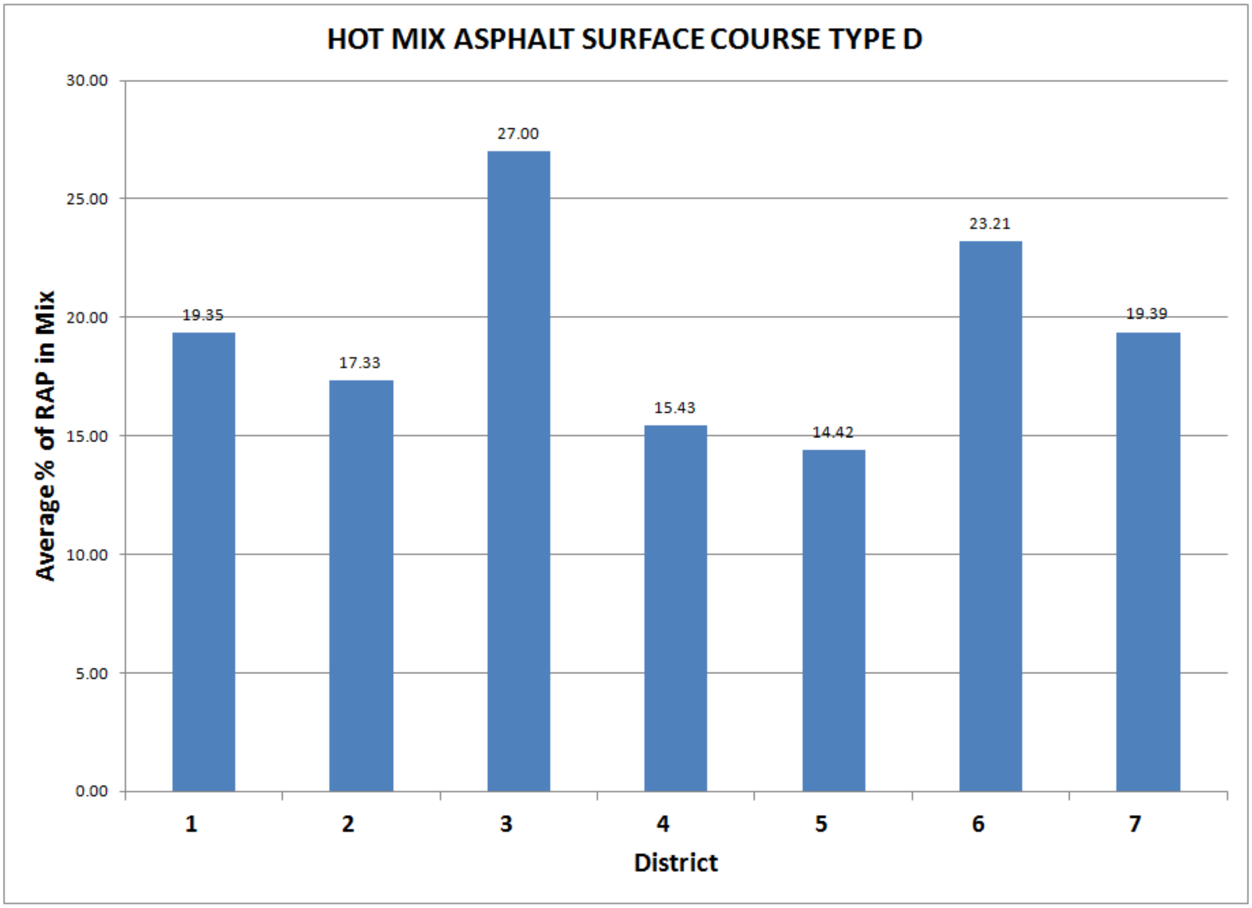


Figure 5-15: HMA Surface Course Type D Average Percent RAP per District from 2008-2013

The average percentage of RAP used in HMA Surface Course Type D was 18.29% from 2008-2013 (Table 5-2) and the allowable percent RAP use is up to 30% RAP. Figure 5-15 shows the average percent RAP used in HMA Surface Course Type D per District between 2008 and 2013. District 3 had the highest average percent RAP used in HMA Surface Course Type D from 2008-2013. However, it must be noted that sample size for this District was small (n=2). District 6 was the next highest and was significantly different than all other Districts at the $\alpha = 0.05$ level (Appendix C, Table 10-28). Districts 2, 4, and 5 had the lowest average percent Rap used in HMA Surface Course Type D mixes and were statistically equivalent at the $\alpha = 0.05$ level (Appendix C, Table 10-28)

HMA Surface Course Type E

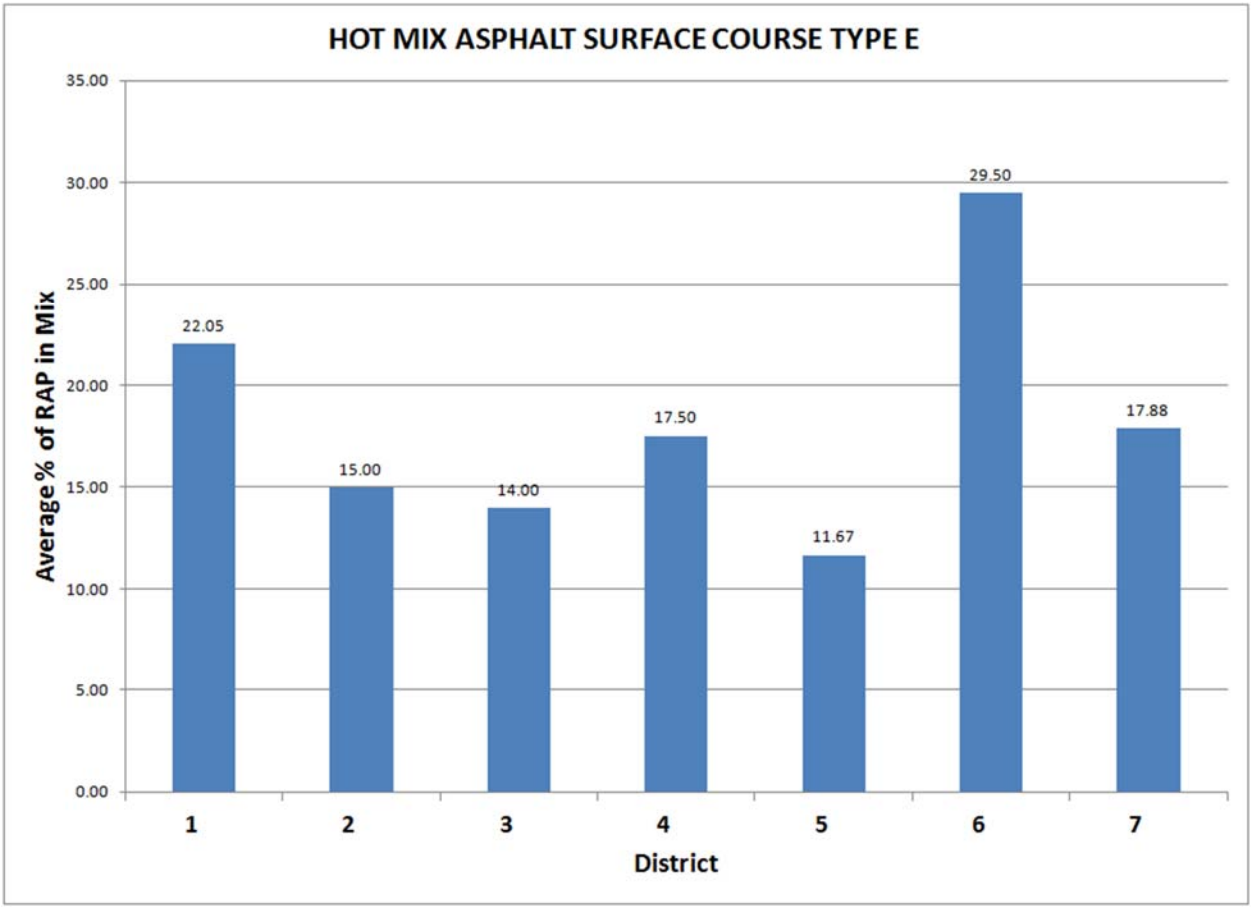


Figure 5-16: HMA Surface Course Type E Average Percent RAP per District from 2008-2013

As shown in Table 5-2, the average percentage of RAP used in HMA Surface Course Type E was 18.77% from 2008-2013 (SCDOT specifications: up to 30%). It should be noted that only fractionated RAP can be used in HMA Surface Course Type E due to the fineness of the overall mix. Figure 5-16 shows the average percent RAP used in HMA Surface Course Type E per District between 2008 and 2013. District 6 had the highest average percent RAP used in HMA Surface Course Type E mixes from 2008-2013 and was significantly different than all other mixes (Appendix C, Table 10-29). Districts 2, 3, 4, 5, and 7 had the lowest average percent RAP used in HMA Surface Course Type E mixes and were statistically equivalent to each other at the $\alpha = 0.05$ level (Appendix C, Table 10-29).

Average Percentage of Mixes Containing RAP per District and per County

Another objective of this research was to determine the percentage of mixes utilizing RAP per mix type per SCDOT Engineering District and per South Carolina County. Data for the following SCDOT mixes were analyzed: HMA Shoulder Widening Course; Base Courses A, B, and C; Intermediate Courses A, B, and C; and Surface Courses A, B, C, CM, D, and E. It should be noted that if a mix design on an approved SCDOT JMF Mix Design Form contained RAP, it was assumed that the RAP mix was indeed used on the project. This assumption is based on the financial incentive that contractors themselves have when using RAP mixes. This assumption was also agreed on by the SCDOT's Asphalt Materials Engineer. No statistical analysis was performed on mixes containing RAP due to the obvious differences in the data when plotted.

Figure 5-17 indicates that HMA Shoulder Widening Course mixes contained RAP in 100% of the time in Districts 1, 3, 4, and 6. The remaining SCDOT Districts (2, 5, and 7) all utilized RAP in HMA Shoulder Widening Course mixes over 90% of the time. Figure 5-18 shows the percentage of mixes containing RAP that were utilized in each County between 2008 and 2013. Five South Carolina counties did not have a project that contained SCDOT HMA Shoulder Widening Course mix during the years included in this data (2008 – 2013). In 38 out of the 41 remaining counties, RAP was utilized in 100% of HMA Shoulder Widening Course mixes. In the remaining three counties (2, 19, and 23), RAP was utilized in HMA Shoulder Widening Course mixes over 77% of the time.

HMA Shoulder Widening Course

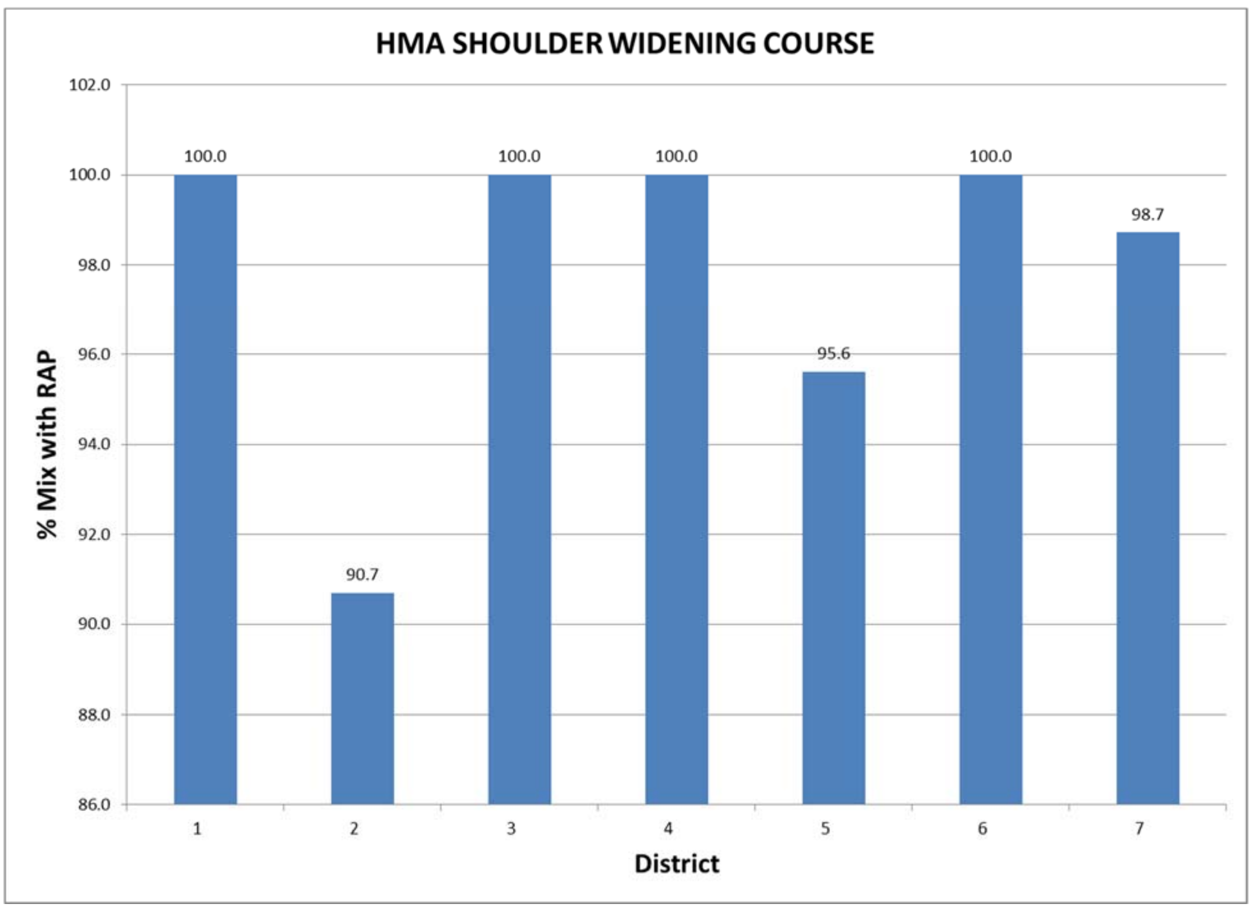


Figure 5-17: SCDOT HMA Shoulder Widening Course, % of Mixes containing RAP per District

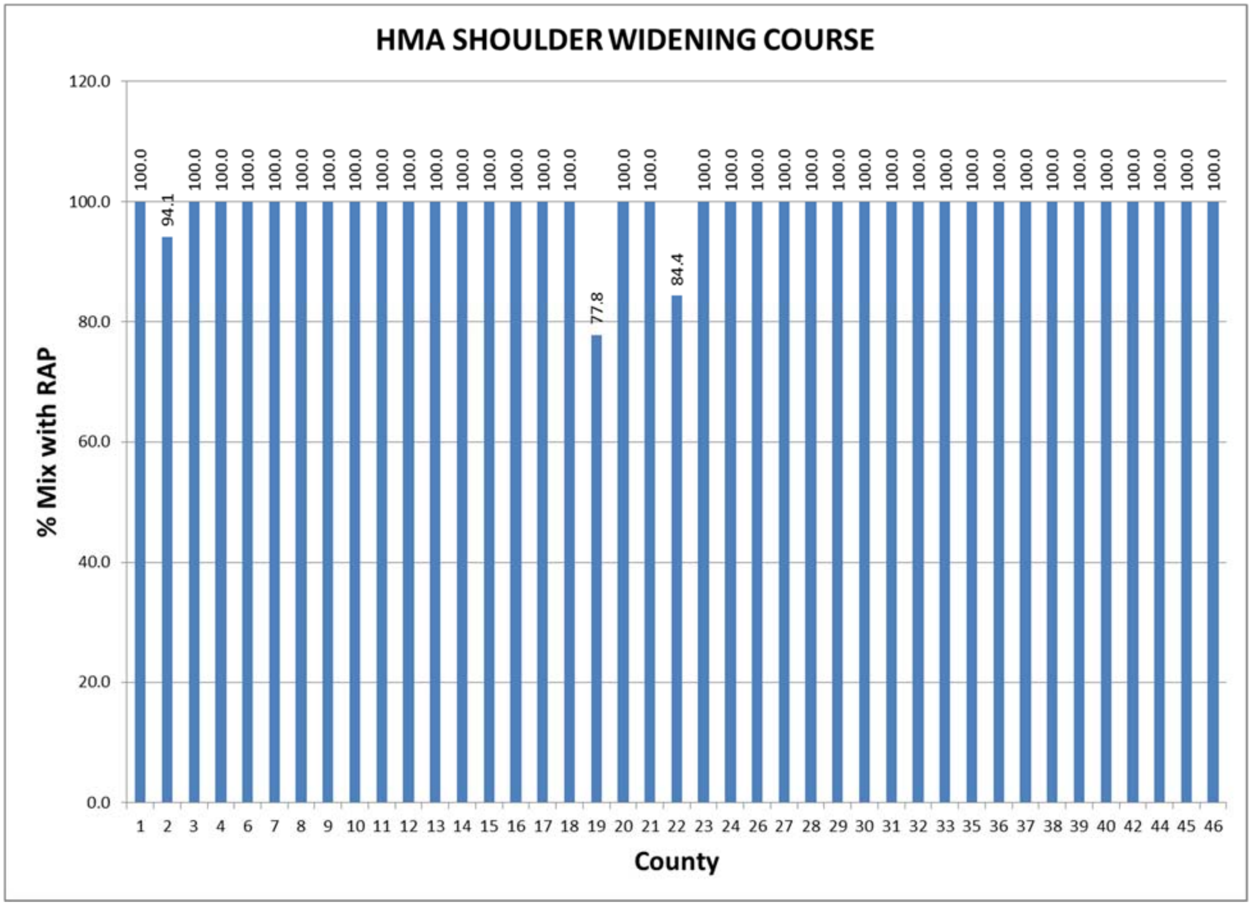


Figure 5-18: SCDOT HMA Shoulder Widening Course, % of Mixes containing RAP per County

Figure 5-19 indicates that HMA Base Course Type A mixes contained RAP 100% of the time in Districts 1, 3, 4, 6 and 7. The remaining SCDOT Districts (2 and 5) all utilized RAP in HMA Base Course Type A mixes over 90% of the time. Figure 5-20 shows the percentage of mixes containing RAP that were utilized in each County between 2008 and 2013. Fifteen South Carolina counties did not have a project that contained Hot Mix Asphalt Base Course Type A mix during the years included in this data (2008 – 2013). In 27 out of the 31 remaining counties, RAP was utilized in 100% of HMA Base Course Type A mixes. In three of the four remaining counties (22, 24, and 29), RAP was utilized in HMA Base Course Type A mixes over 75% of the time. One county did not utilize any RAP in its HMA Base Course Type A mixes.

HMA Base Course Type A

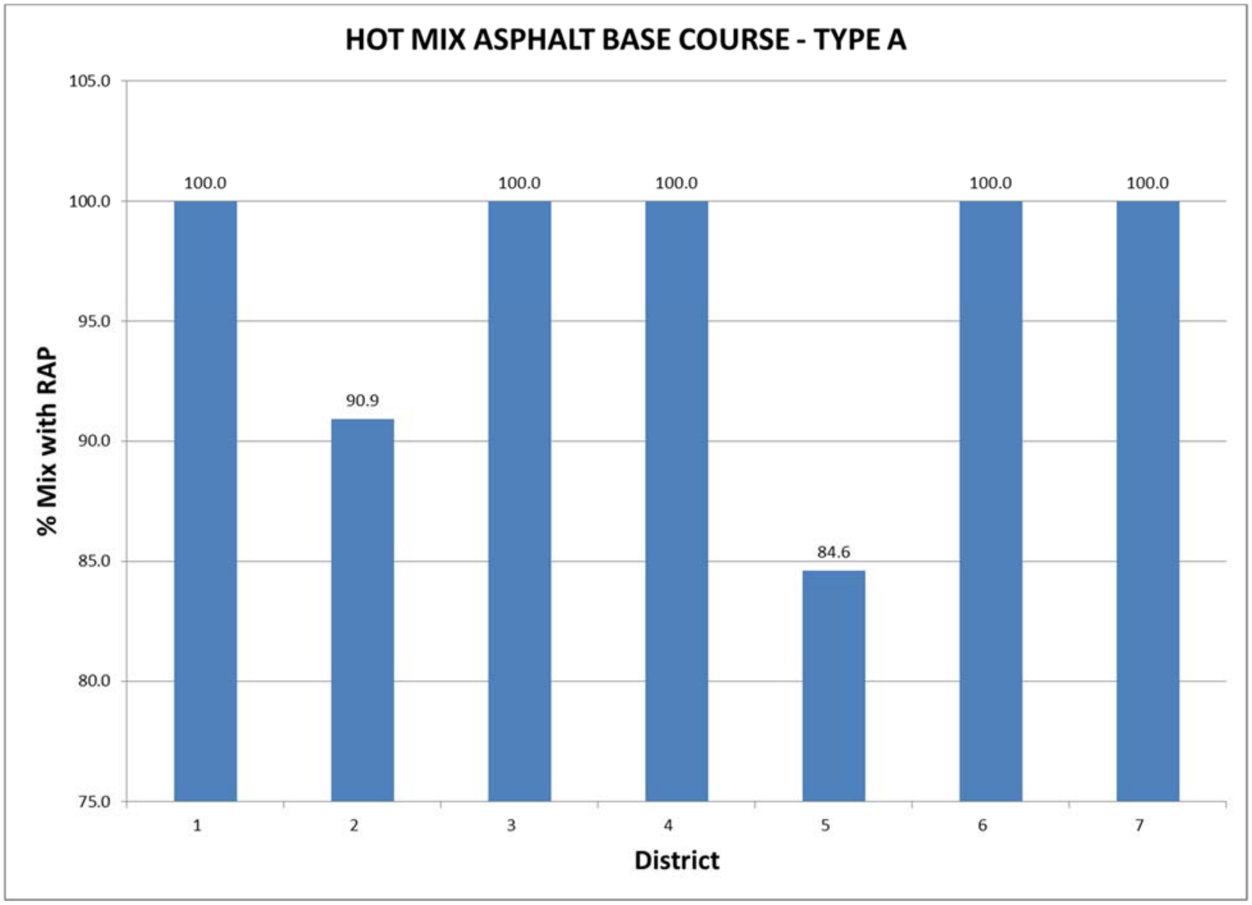


Figure 5-19: SCDOT Hot Mix Asphalt Base Course Type A, % Mix with RAP per District

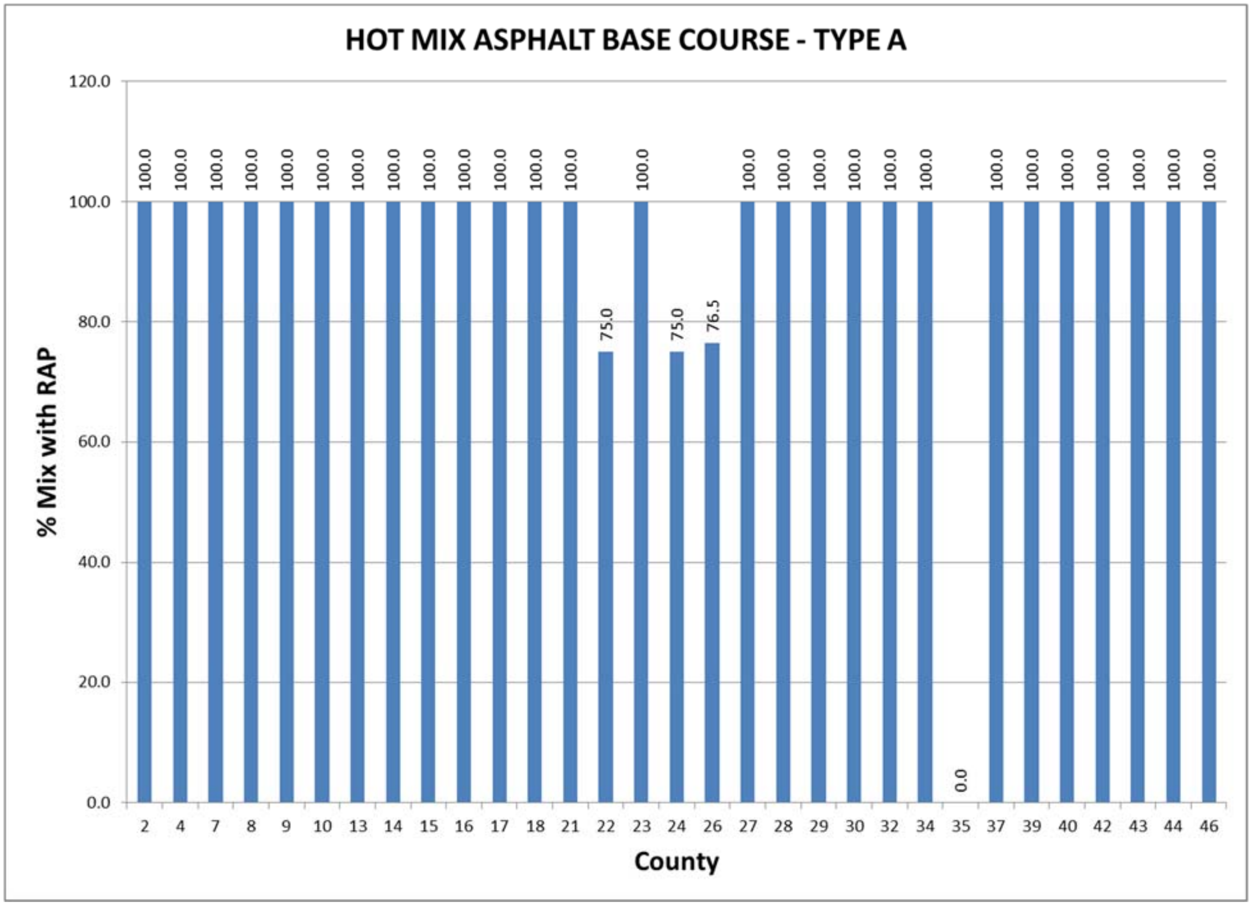


Figure 5-20: SCDOT Hot Mix Asphalt Base Course Type A, % Mix with RAP per County

Figure 5-22 indicates that HMA Base Course Type B mixes contained RAP 100% of the time in Districts 1, 3, 4, and 6. The remaining SCDOT Districts (2, 5, and 7) utilized RAP in HMA Base Course Type B mixes between 66.7% and 85.7% of the time. Figure 5-24 shows the percentage of mixes containing RAP that were utilized in each County between 2008 and 2013. Eleven South Carolina counties did not have a project that contained HMA Base Course Type B mix during the years included in this data (2008 – 2013). In 31 out of the 35 remaining counties, RAP was utilized in 100% of HMA Base Course Type B mixes. Of the remaining four counties, in HMA Base Course Type B mixes, RAP was utilized 75% of the time in one county (2), 28.6% of the time in another county (26), and 50% of the time in the remaining two counties (30 and 41).

HMA Base Course Type B

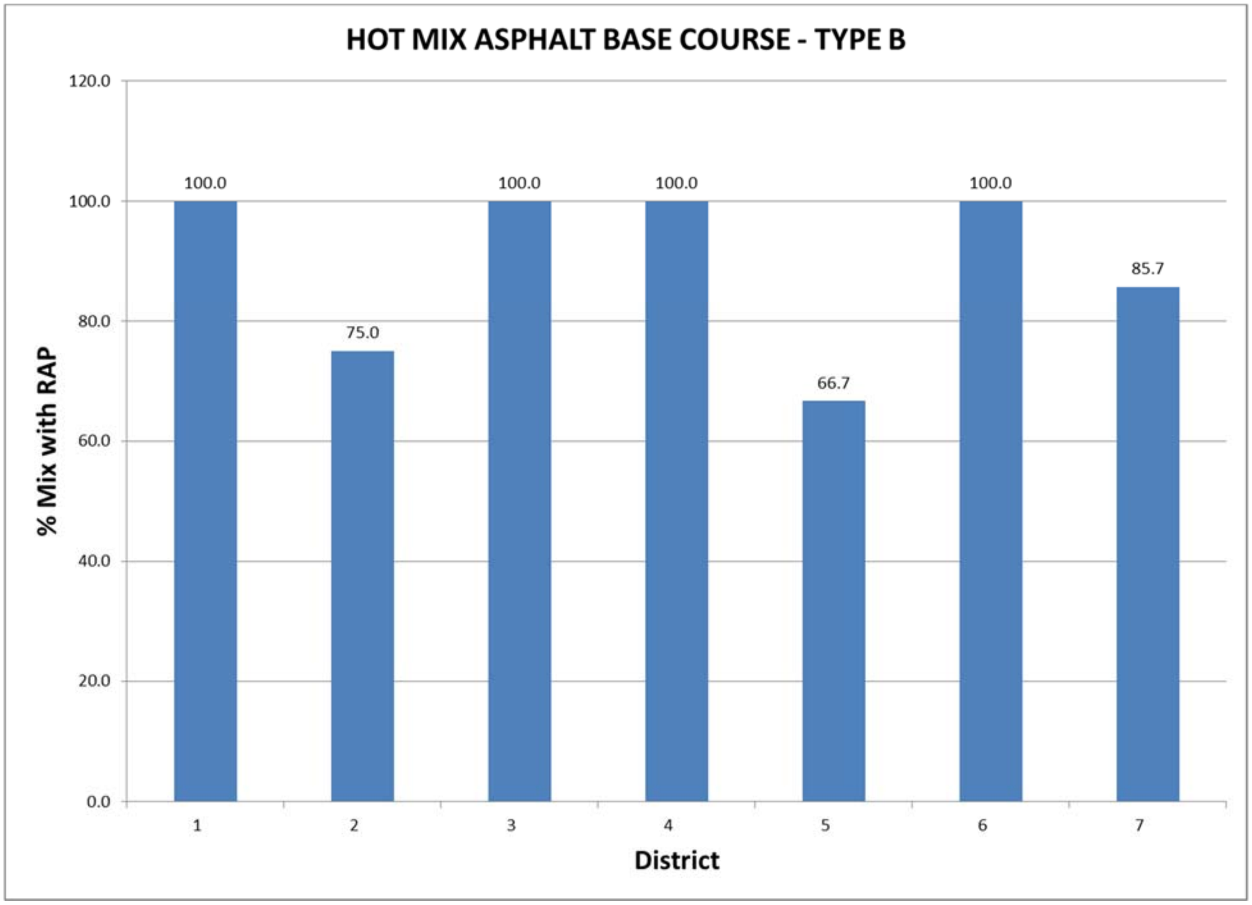


Figure 5-21: SCDOT Hot Mix Asphalt Base Course Type B, % Mix with RAP per District

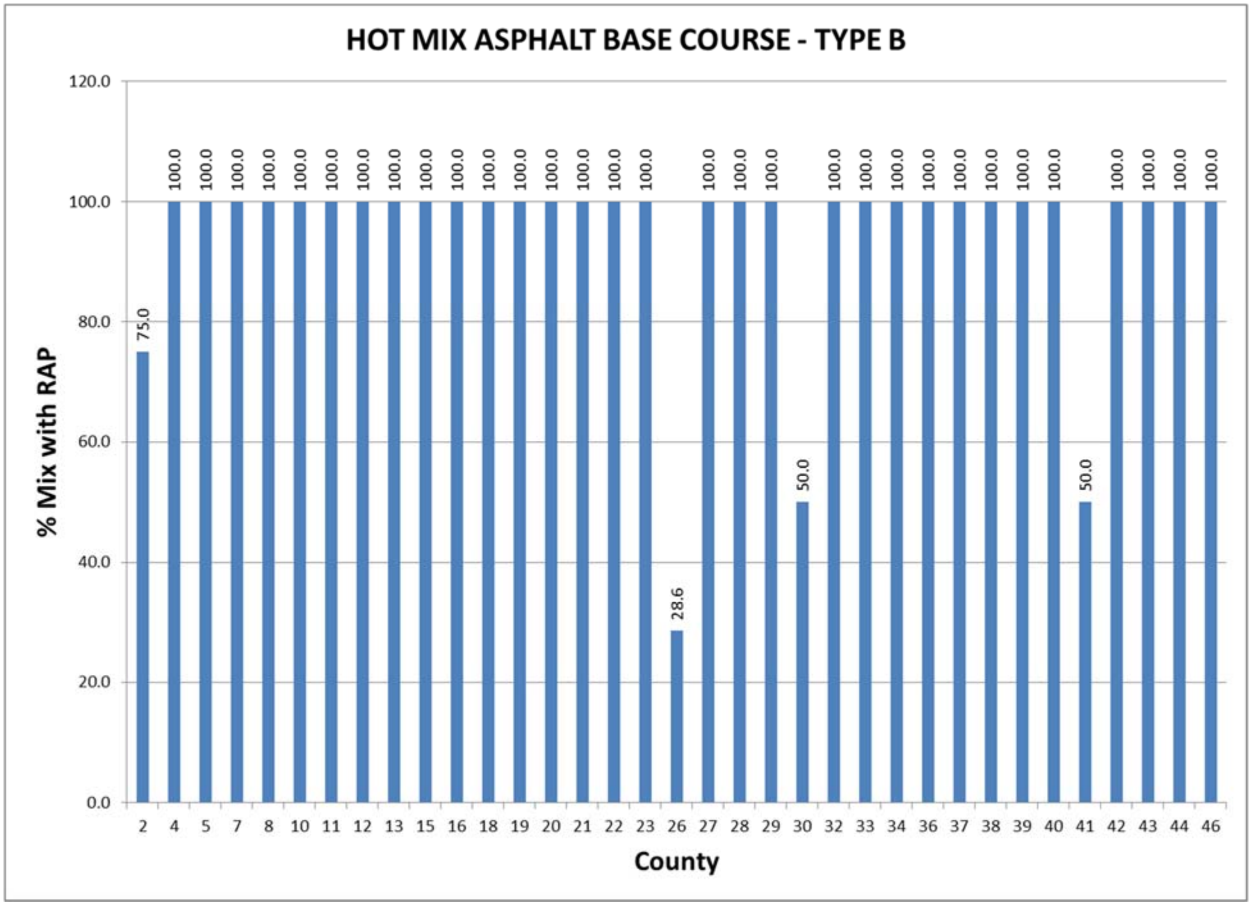


Figure 5-22: SCDOT Hot Mix Asphalt Base Course Type B, % Mix with RAP per County

It should be noted that HMA Base Course Type C had very limited use across the state during the time period examined in this study (2008 – 2013). It was only utilized in four counties, which were each located in a different District. Figure 5-23 indicates that HMA Base Course Type C mixes contained RAP 100% of the time in Districts 3, 5, and 7. Although District 2 utilized HMA Base Course Type C during the years examined, none of those mixes contained any RAP. Districts 1, 4, and 6 did not have any projects utilizing HMA Base Course Type C. Figure 5-24 shows the percentage of mixes containing RAP that were utilized in each County between 2008 and 2013. Three of the four South Carolina counties (9, 22 and 23) that utilized HMA Base Course Type C during this time used mixes containing RAP 100% of the time. The other county (30) that utilized HMA Base Course Type C during this time did not use any RAP in these mixes. None of the other 42 counties utilized HMA Base Course Type C mixtures during the years examined in this study. HMA Base Course Type C is a specialty mix; therefore, its limited use is not unexpected.

HMA Base Course Type C

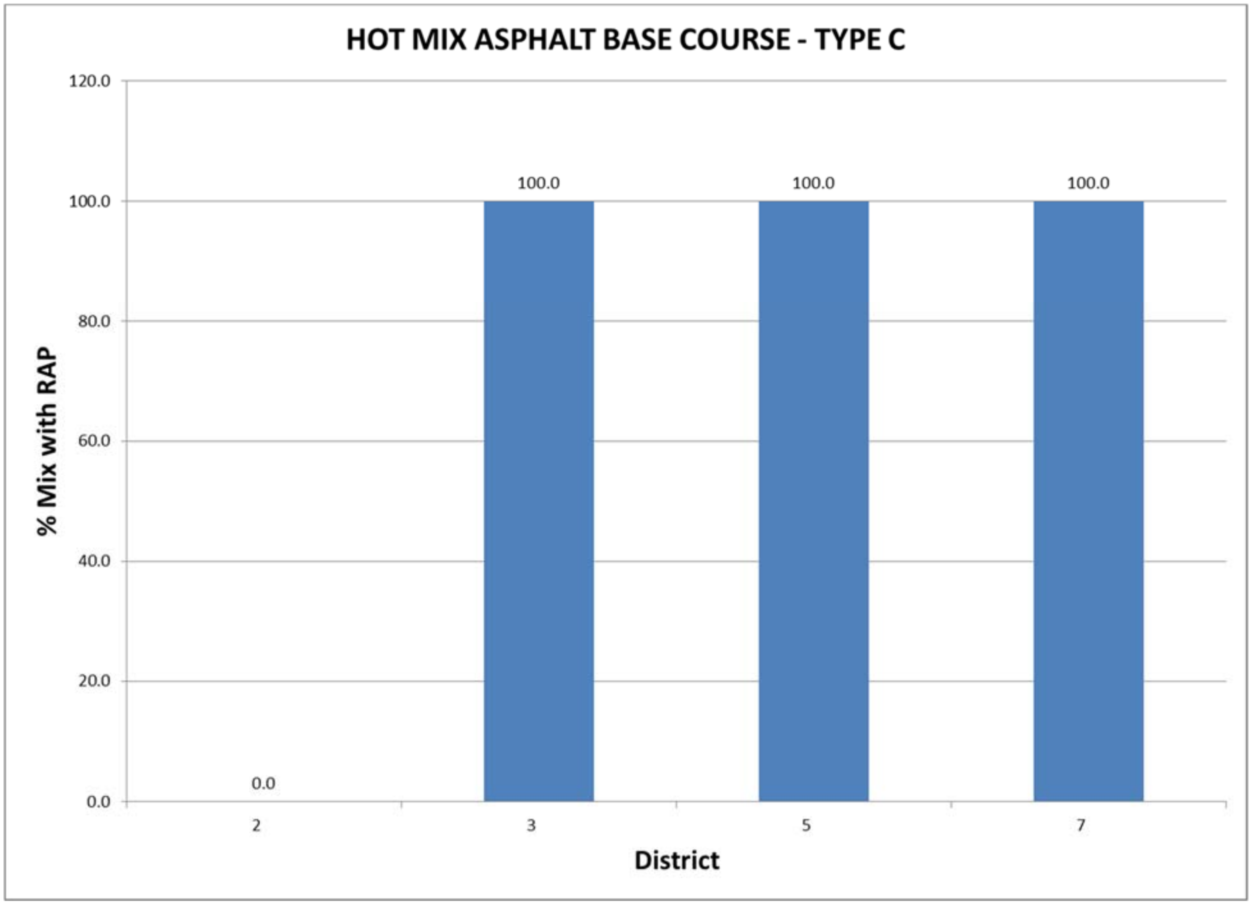


Figure 5-23: SCDOT Hot Mix Asphalt Base Course Type C, % Mix with RAP per District

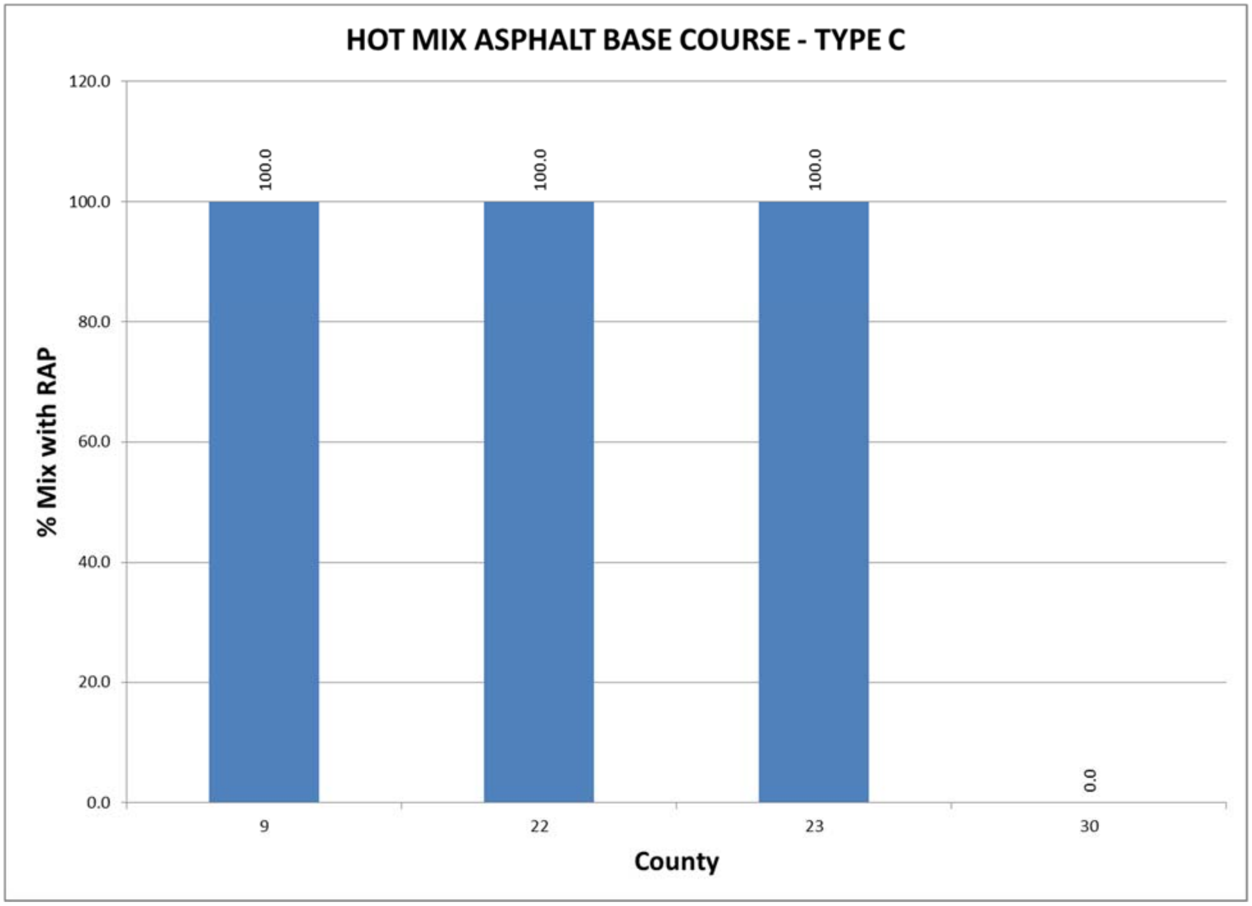


Figure 5-24: SCDOT Hot Mix Asphalt Base Course Type C, % Mix with RAP per County

It should be noted that HMA Intermediate Course Type A had very limited use across the state during the time period examined in this study (2008 – 2013). It was only utilized in five counties distributed across three Districts. Figure 5-25 indicates that HMA Intermediate Course Type A mixes containing RAP 100% of the time in Districts 3 and 6. Although District 1 utilized HMA Intermediate Course Type A during the years examined, none of those mixes contained any RAP. Districts 2, 4, 5, and 7 did not have any projects utilizing HMA Intermediate Course Type A. Figure 5-26 shows the percentage of mixes containing RAP that were utilized in each County between 2008 and 2013. Four of the five South Carolina counties (8, 10, 23 and 39) that utilized HMA Intermediate Course Type A during this time used mixes containing RAP 100% of the time. The other county (40) that utilized HMA Intermediate Course Type A during this time did not use any RAP in these mixes. None of the other 41 counties utilized HMA Intermediate Course Type A mixtures during the years examined in this study. HMA Intermediate Course Type A is a specialty mix that is polymer modified. Due to the cost of polymer modification and SCDOT preference for Intermediate Type B and Intermediate Type C in the design of mixes, limited use is not unexpected.

HMA Intermediate Course Type A

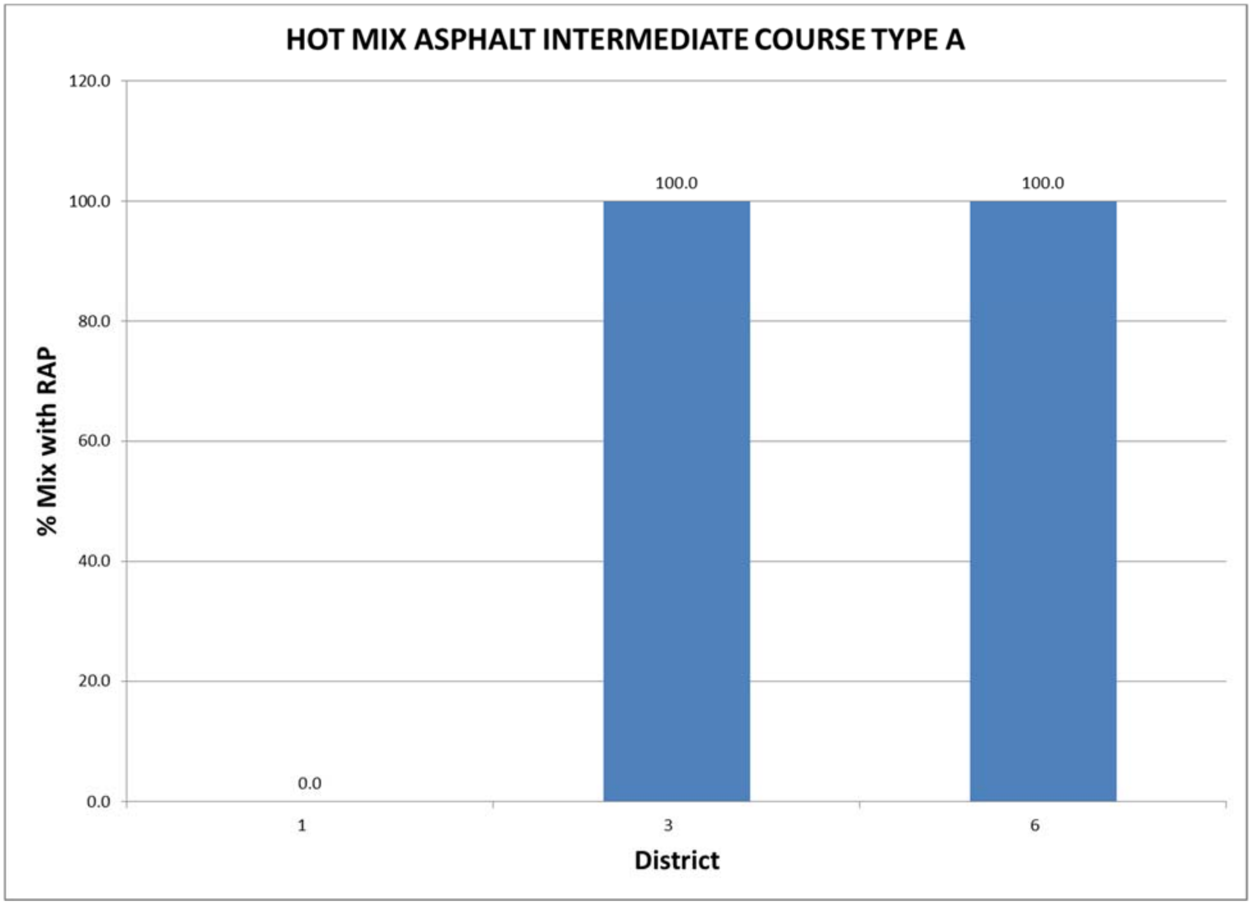


Figure 5-25: SCDOT Hot Mix Asphalt Intermediate Course Type A, % Mix with RAP per County

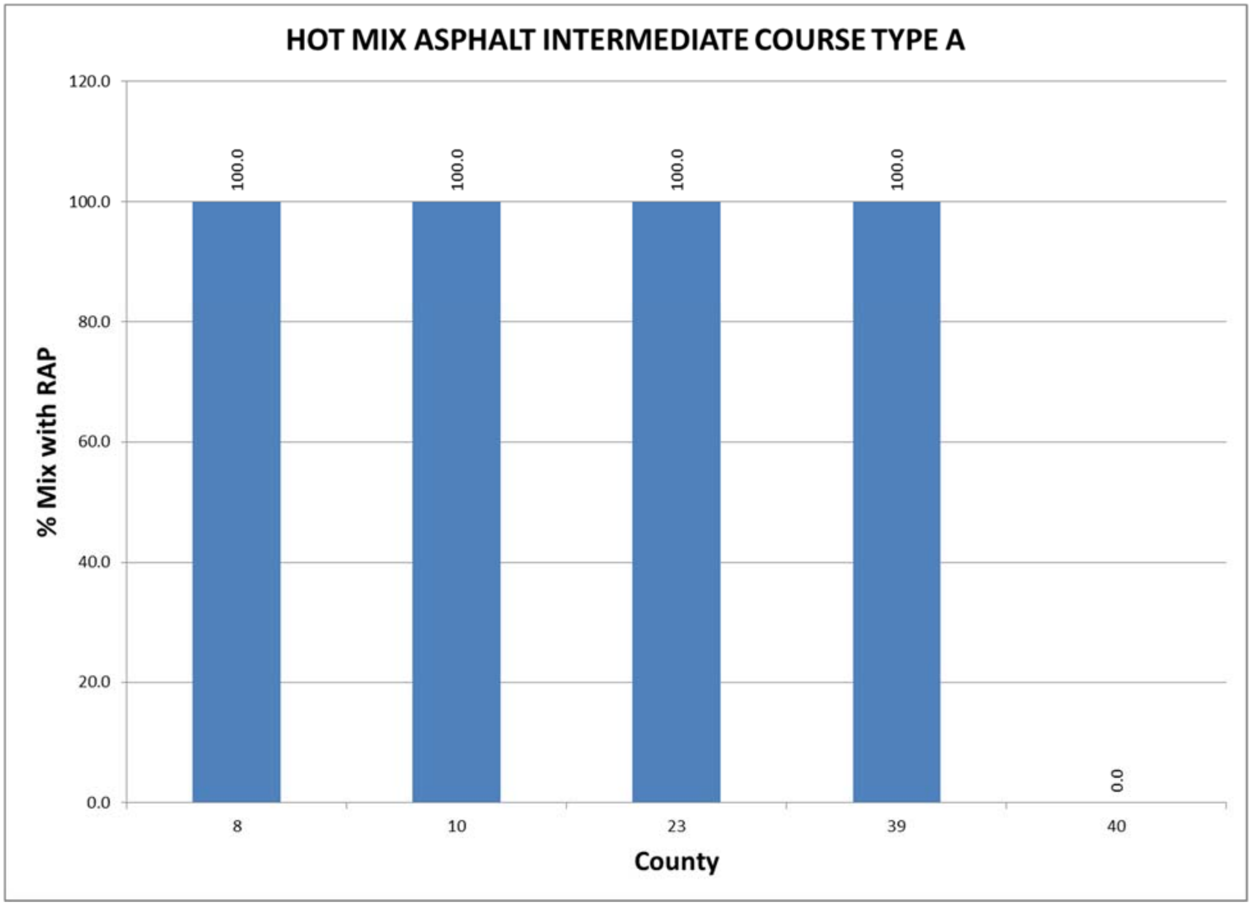


Figure 5-26: SCDOT Hot Mix Asphalt Intermediate Course Type A, % Mix with RAP per County

Figure 5-27 indicates that HMA Intermediate Course Type B mixes contained RAP 100% of the time in Districts 1, 3, and 4. The remaining SCDOT Districts (2, 5, 6 and 7) utilized RAP in HMA Intermediate Course Type B mixes more than 72% of the time. Figure 5-28 shows the percentage of mixes containing RAP that were utilized in each County between 2008 and 2013. Eighteen South Carolina counties did not have a project that contained HMA Intermediate Course Type B mix during the years included in this study (2008 – 2013). In 23 out of the 28 remaining counties, RAP was utilized in 100% of HMA Intermediate Course Type B mixes. Of the remaining five counties, four (2, 10, 22, and 26) utilized RAP in at least 70% of their HMA Intermediate Course Type B mixes, while one county (24) only utilized RAP in 25% of its HMA Intermediate Course Type B mixes.

HMA Intermediate Course Type B

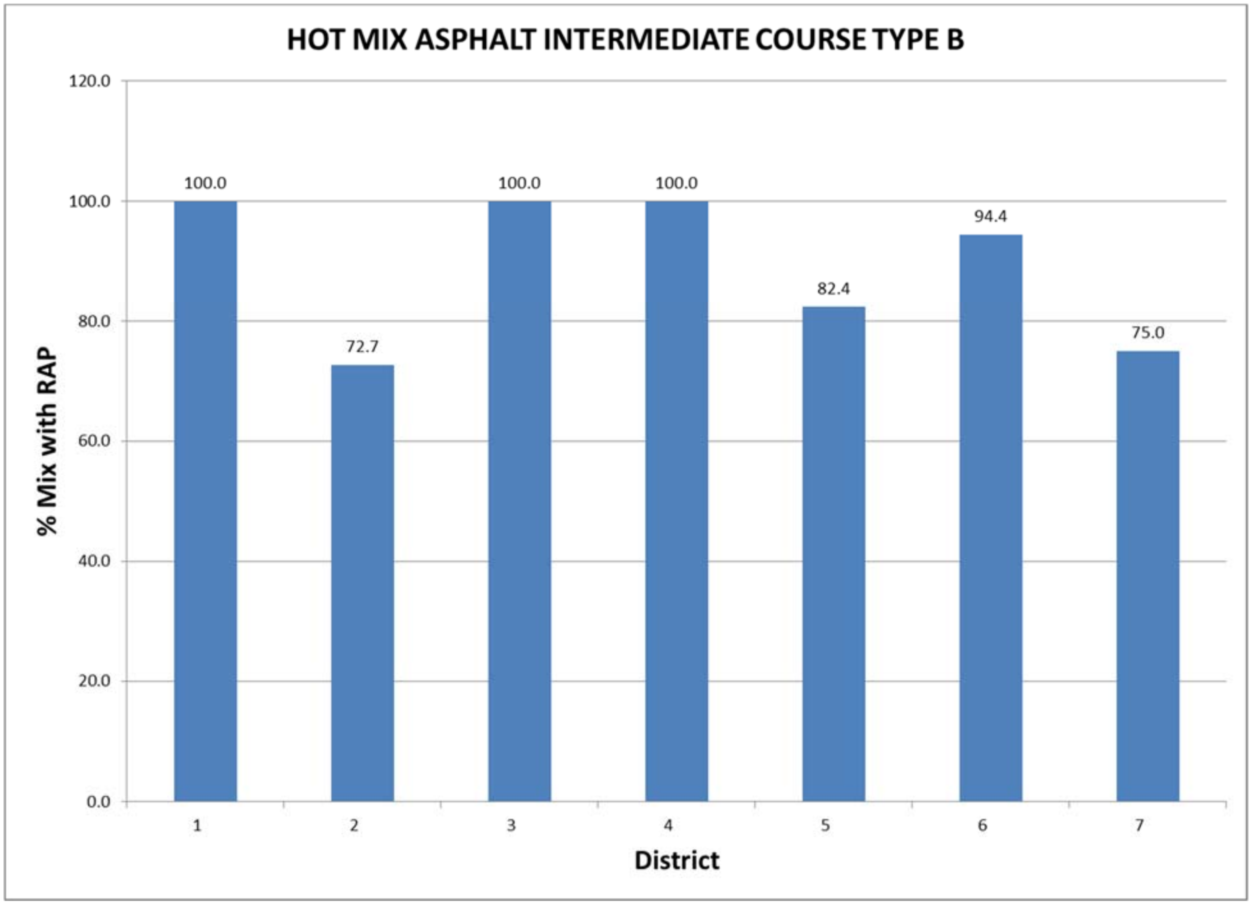


Figure 5-27: SCDOT Hot Mix Asphalt Intermediate Course Type B, % Mix with RAP per District

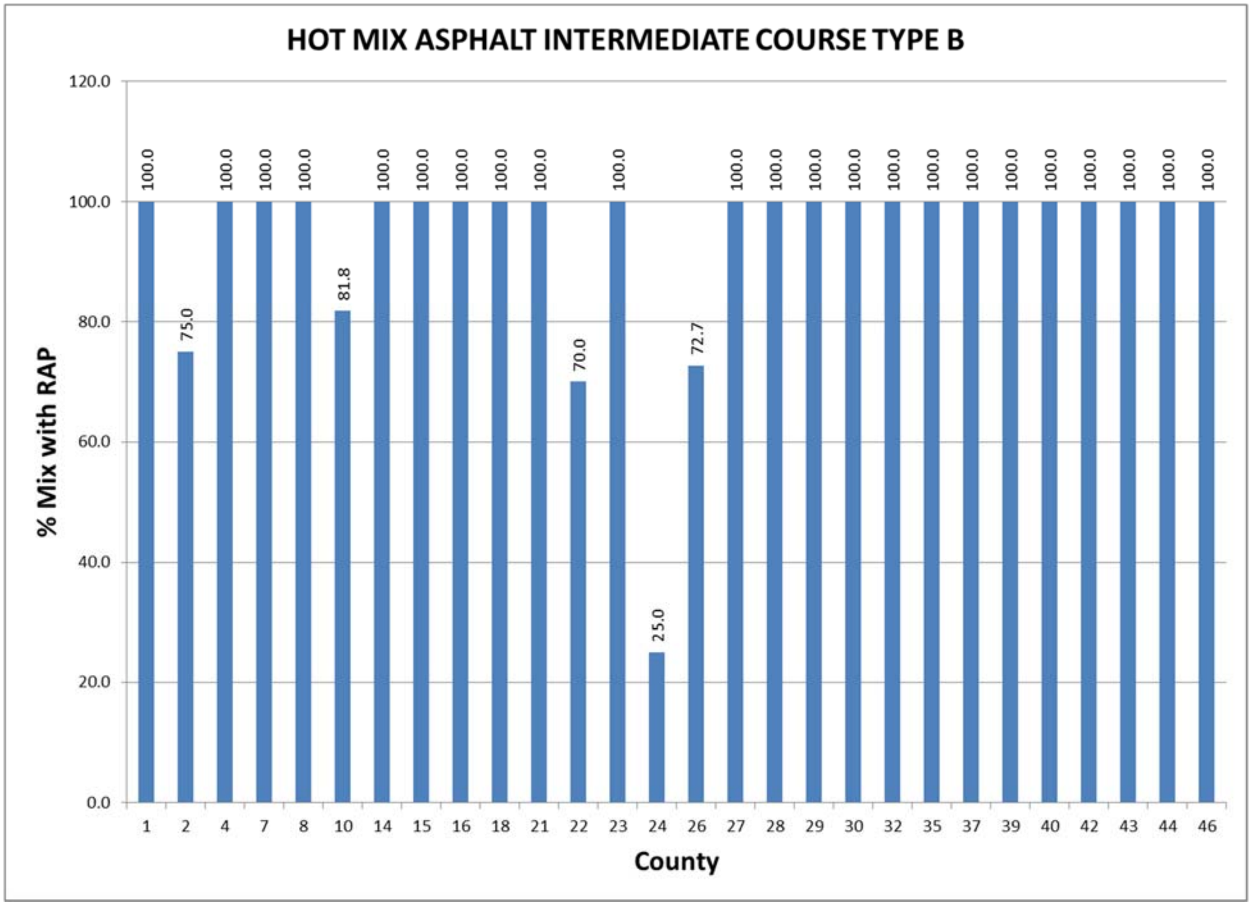


Figure 5-28: SCDOT Hot Mix Asphalt Intermediate Course Type B, % Mix with RAP per County

Figure 5-29 indicates that HMA Intermediate Course Type C mixes contained RAP 100% of the time in Districts 3, 6, and 7. The remaining SCDOT Districts (1, 2, 4 and 5) all utilized RAP in HMA Intermediate Course Type C mixes more than 94% of the time. Figure 5-30 shows the percentage of mixes containing RAP that were utilized in each County between 2008 and 2013. Five South Carolina counties did not have a project that contained HMA Intermediate Course Type C mix during the years studied in this data (2008 – 2013). In 35 out of the 41 remaining counties, RAP was utilized in 100% of HMA Intermediate Course Type C mixes. All of the remaining six counties (2, 10, 22, 24 and 26) utilized RAP between 80% and 96% of the time in their HMA Intermediate Course Type C mixes.

HMA Intermediate Course Type C

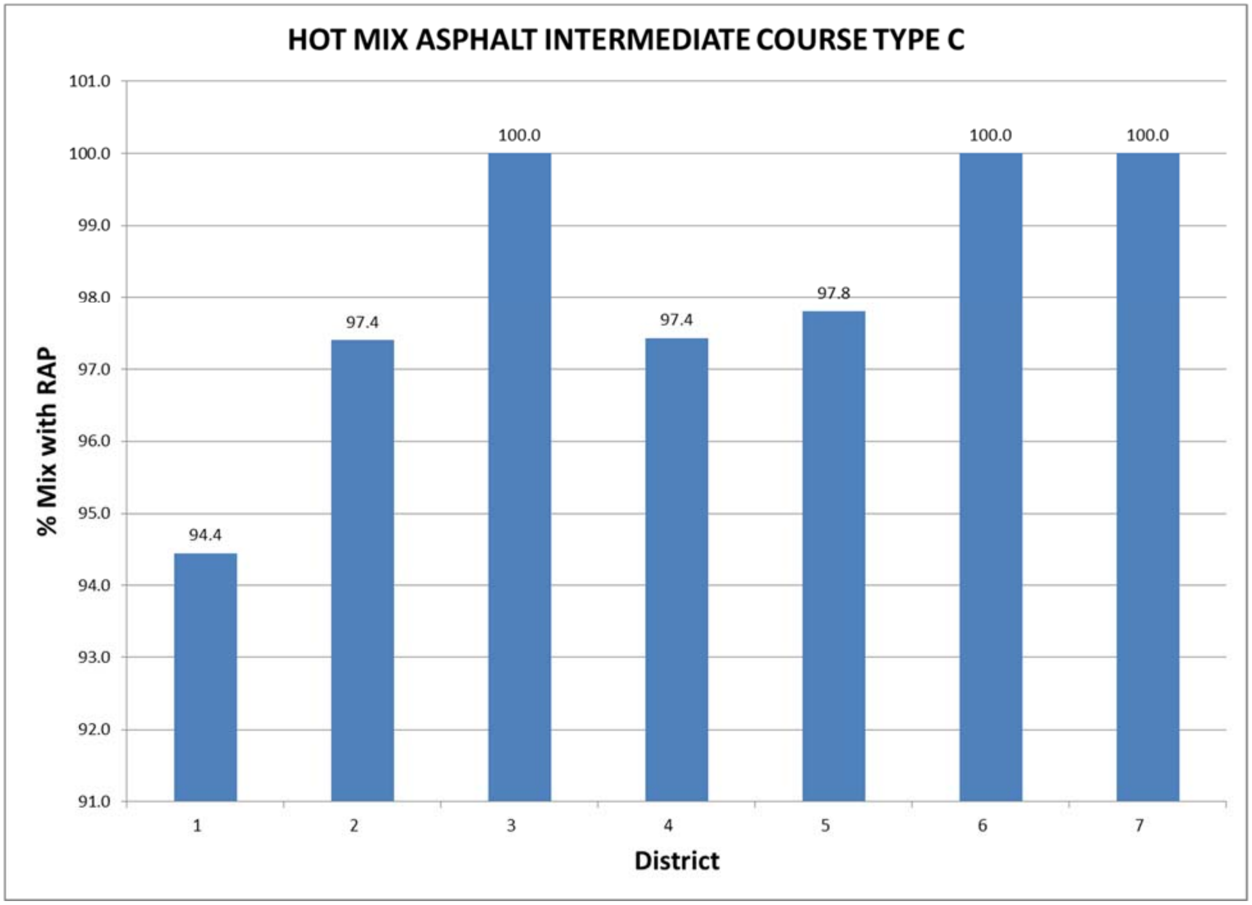


Figure 5-29: SCDOT Hot Mix Asphalt Intermediate Course Type C, % Mix with RAP per District

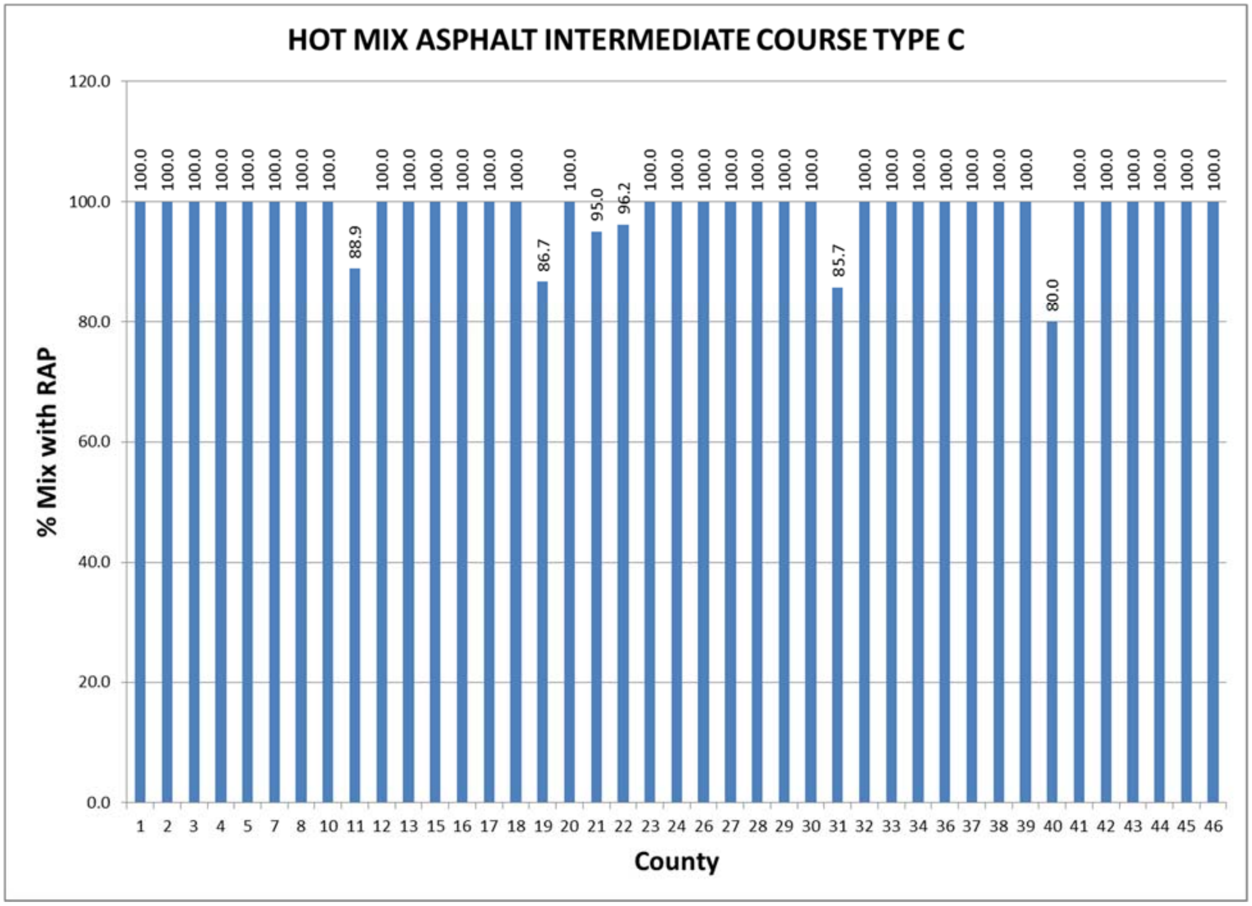


Figure 5-30: SCDOT Hot Mix Asphalt Intermediate Course Type C, % Mix with RAP per County

Figure 5-31 indicates that HMA Surface Course Type A mixes contained RAP 100% of the time in District 4. Three of the remaining SCDOT Districts (1, 2 and 6) utilized RAP in HMA Surface Course Type A mixes over 88.9% of the time. District 3 utilized RAP in 63.6% of its HMA Surface Course Type A mixes, while the remaining two Districts (5 and 7) only utilized RAP in 33.3% of their HMA Surface Course Type A mixes. Figure 5-32 shows the percentage of mixes containing RAP that were utilized in each County between 2008 and 2013. Twenty-one South Carolina counties did not have a project that contained HMA Surface Course Type A mix during the 2008-2013 time period. In 15 out of the 25 remaining counties, RAP was utilized in 100% of HMA Surface Course Type A mixes. In four of the ten remaining counties (7, 30, 32 and 42), RAP was utilized in HMA Surface Course Type A mixes over 78% of the time. Two of the remaining counties (21 and 23) utilized RAP in 50% of their HMA Surface Course Type A mixes, while one county (16) only utilized RAP in 33.3% of its HMA Surface Course Type A mixes. In addition, the last four counties (2, 14, 17 and 22) did not utilize any RAP in their HMA Surface Course Type A mixes.

HMA Surface Course Type A

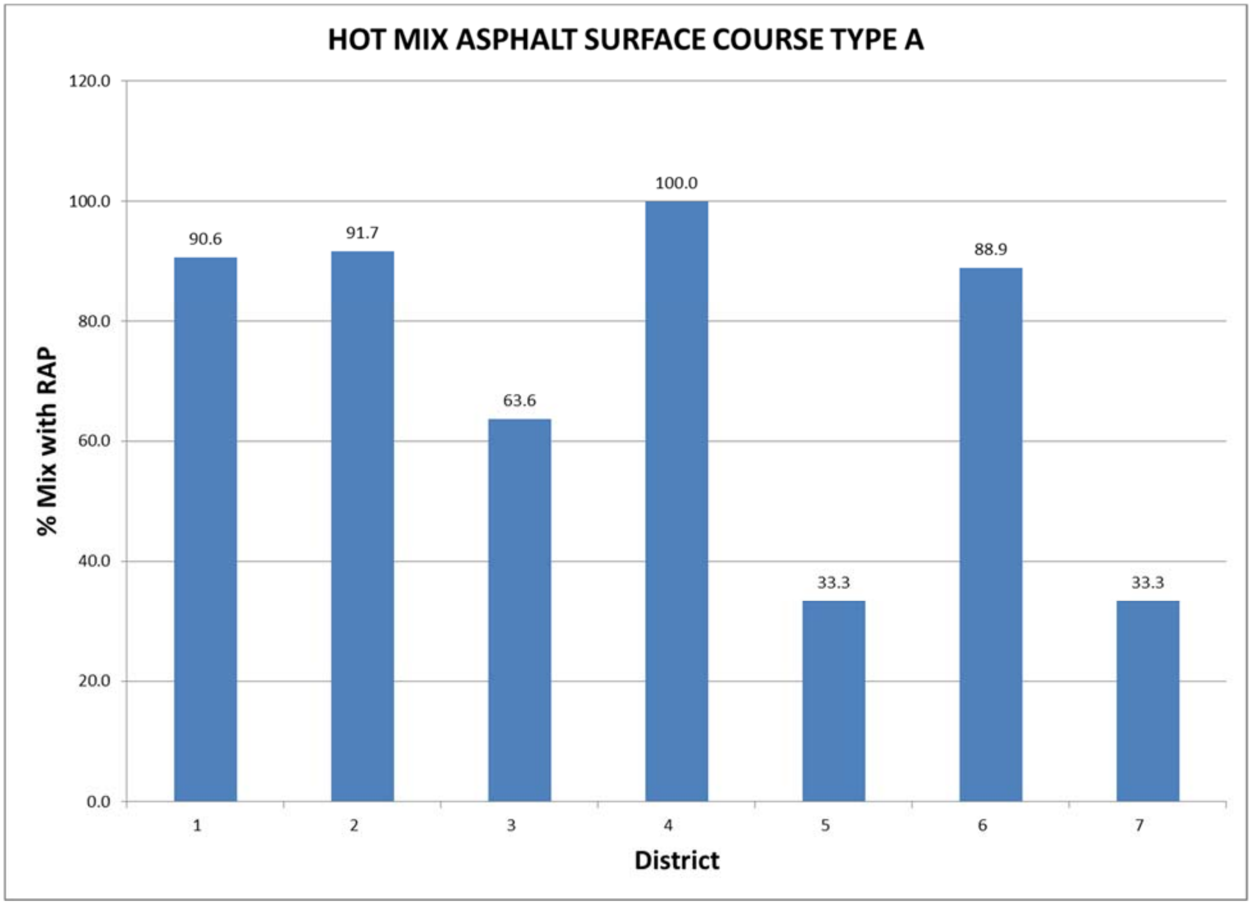


Figure 5-31: SCDOT Hot Mix Asphalt Surface Course Type A, % Mix with RAP per District

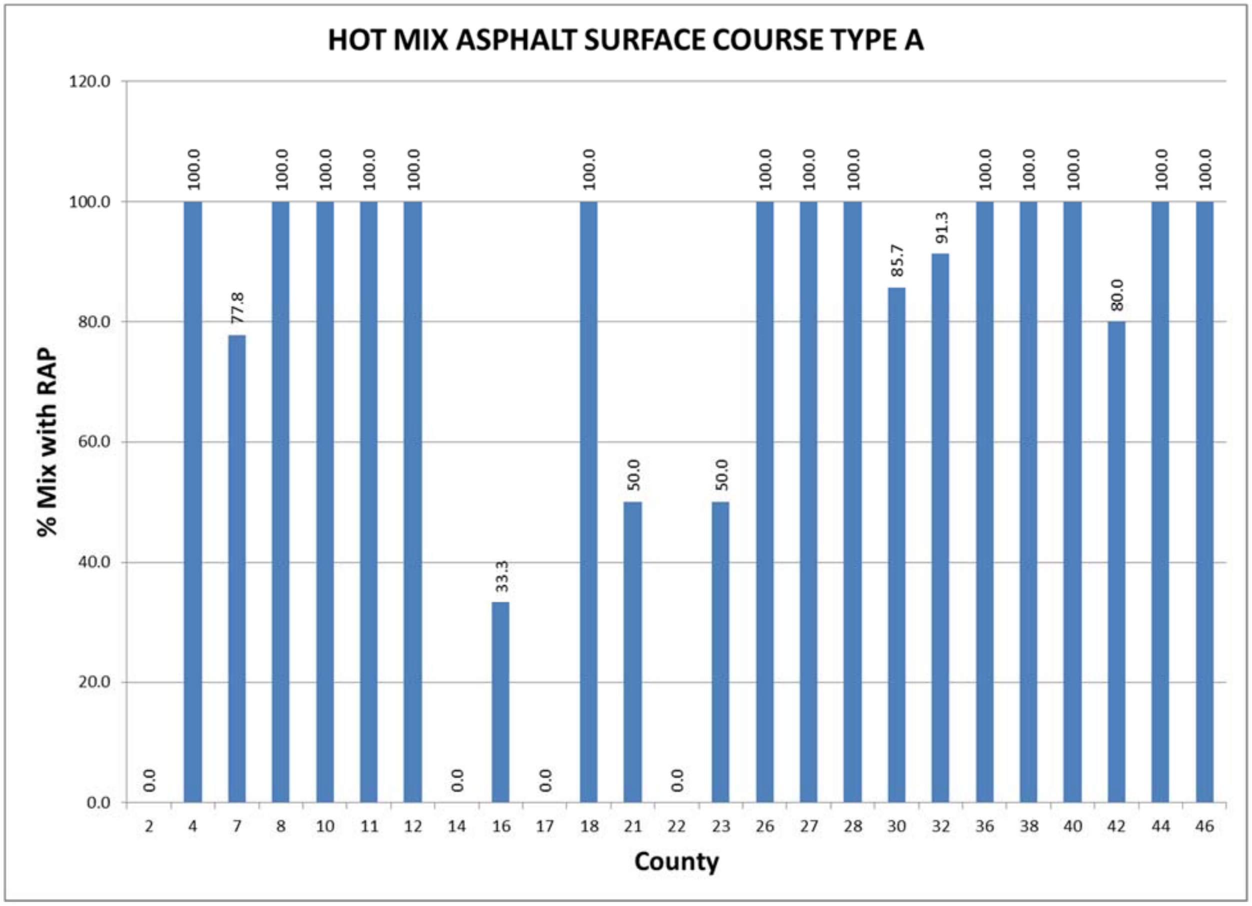


Figure 5-32: SCDOT Hot Mix Asphalt Surface Course Type A, % Mix with RAP per County

Figure 5-33 indicates that HMA Surface Course Type B mixes contained RAP 100% of the time in Districts 3 and 4. All of the remaining SCDOT Districts (1, 2, 5, 6 and 7) utilized RAP in HMA Surface Course Type B mixes over 85% of the time. Figure 5-34 shows the percentage of mixes containing RAP that were utilized in each County between 2008 and 2013. Five South Carolina counties did not have a project that contained HMA Surface Course Type B mix during the years included in this data (2008 – 2013). In 24 out of the 41 remaining counties, RAP was utilized in 100% of HMA Surface Course Type B mixes. In 12 of the 17 remaining counties, RAP was utilized in HMA Surface Course Type B mixes over 75% of the time. Two of the other remaining counties (14 and 17) utilized RAP in 66.7% and 42.9% of their HMA Surface Course Type B mixes, respectively. The remaining two counties (5 and 6) did not utilize any RAP in their HMA Surface Course Type B mixes.

HMA Surface Course Type B

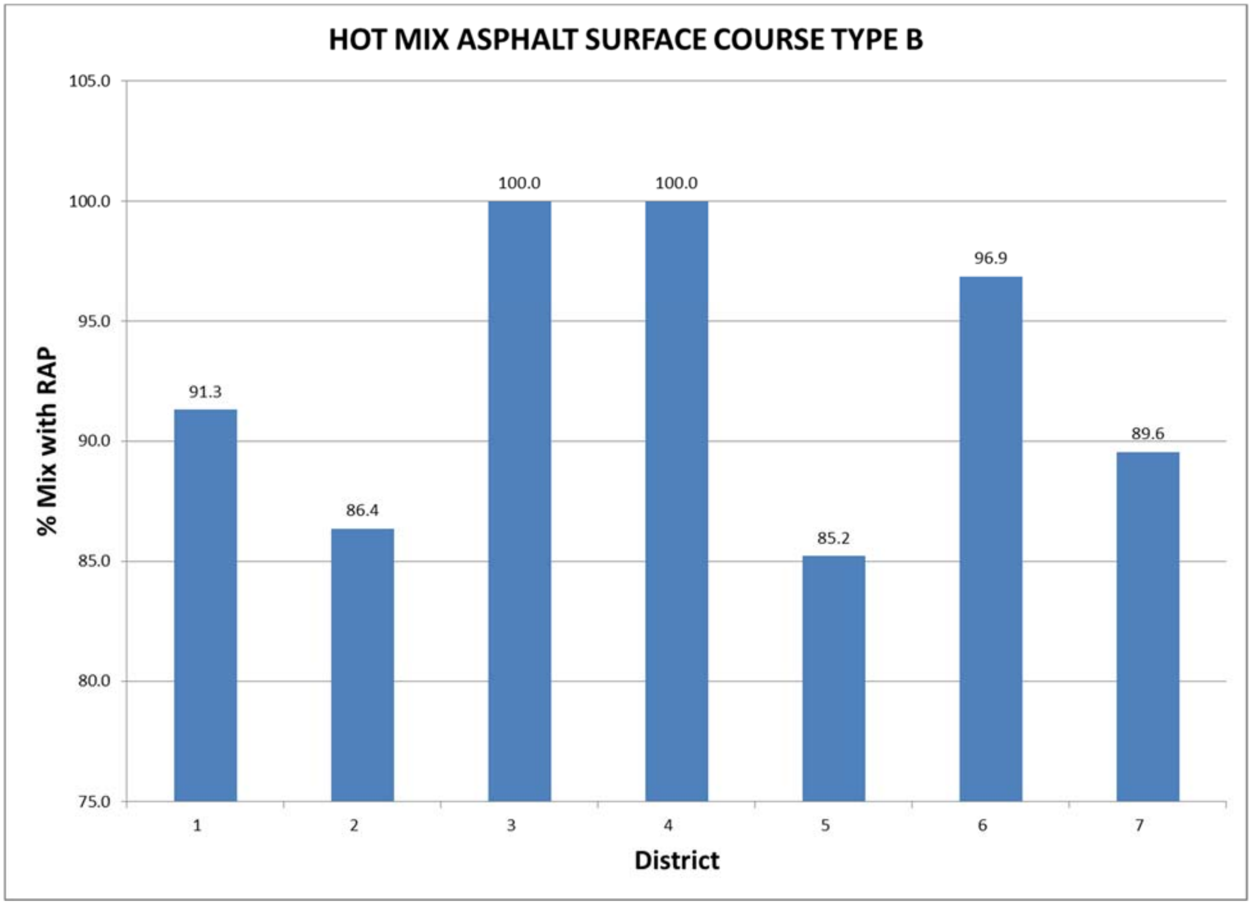


Figure 5-33: SCDOT Hot Mix Asphalt Surface Course Type B, % Mix with RAP per District

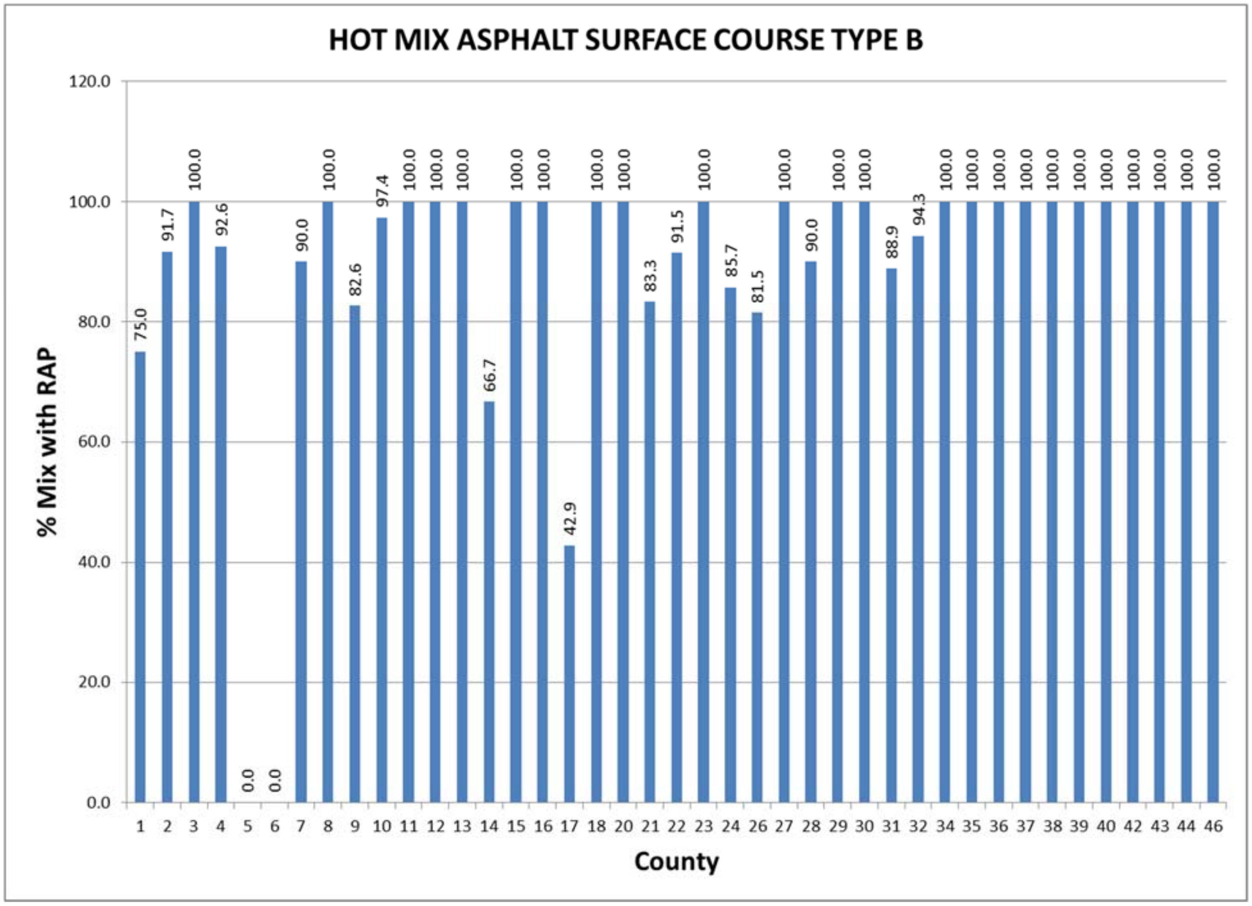


Figure 5-34: SCDOT Hot Mix Asphalt Surface Course Type B, % Mix with RAP per County

Figure 5-35 indicates that HMA Surface Course Type C mixes contained RAP 100% of the time in Districts 4 and 6. Four of the remaining SCDOT Districts (1, 2, 3 and 5) utilized RAP in HMA Surface Course Type C mixes more than 94% of the time. District 7 utilized RAP in 76.1% of its HMA Surface Course Type C mixes. Figure 5-36 shows the percentage of mixes containing RAP that were utilized in each County between 2008 and 2013. Three South Carolina counties did not have a project that contained HMA Surface Course Type C mix during the years included in this data (2008 – 2013). In 34 out of the 43 remaining counties, RAP was utilized in 100% of HMA Surface Course Type C mixes. Of the HMA Surface Course Type C mixes in the remaining counties, five counties (3, 19, 22, 23 and 40) utilized RAP at least 89% of the time, one county (26) utilized RAP 76% of the time, and two counties (9 and 38) utilized RAP 50% of the time.

HMA Surface Course Type C

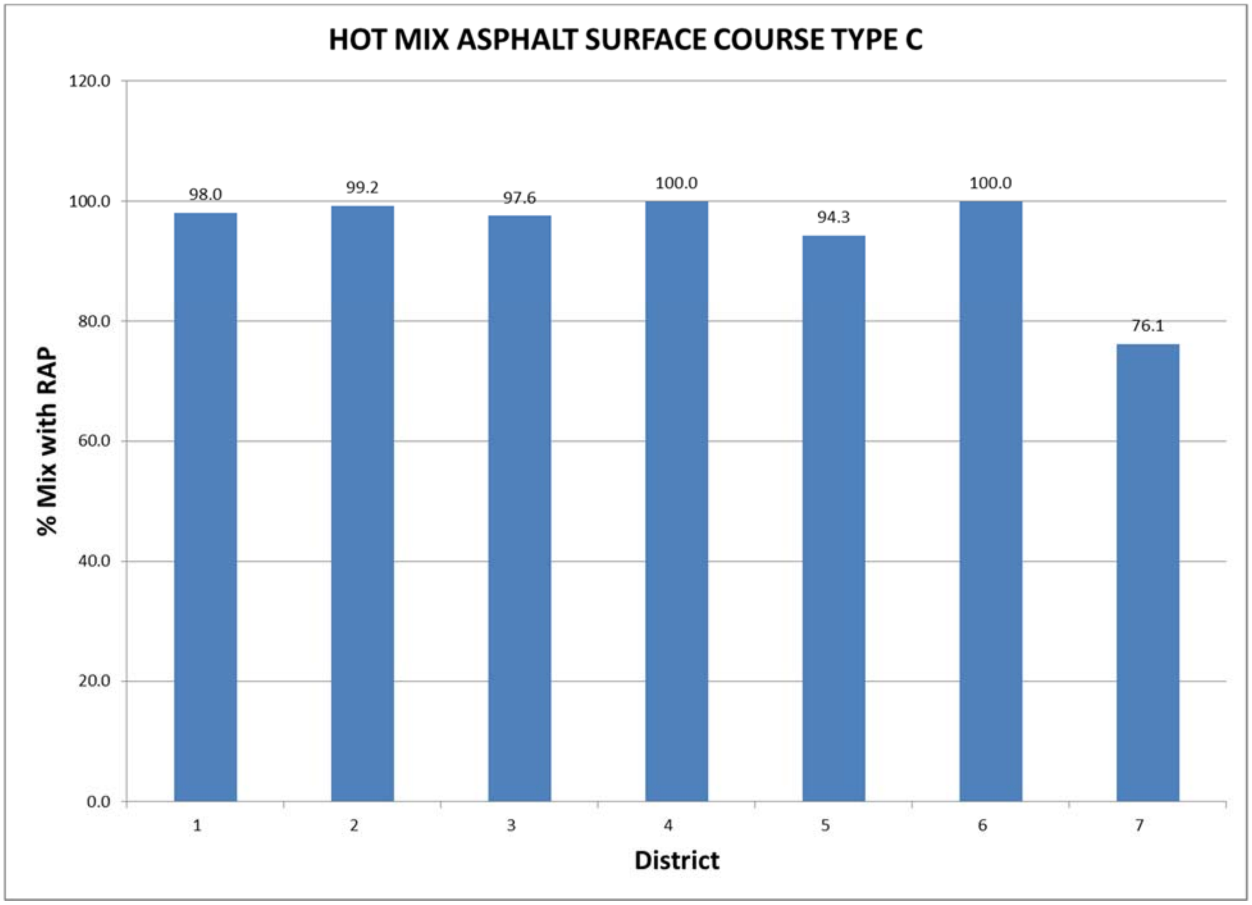


Figure 5-35: SCDOT Hot Mix Asphalt Surface Course Type C, % Mix with RAP per District

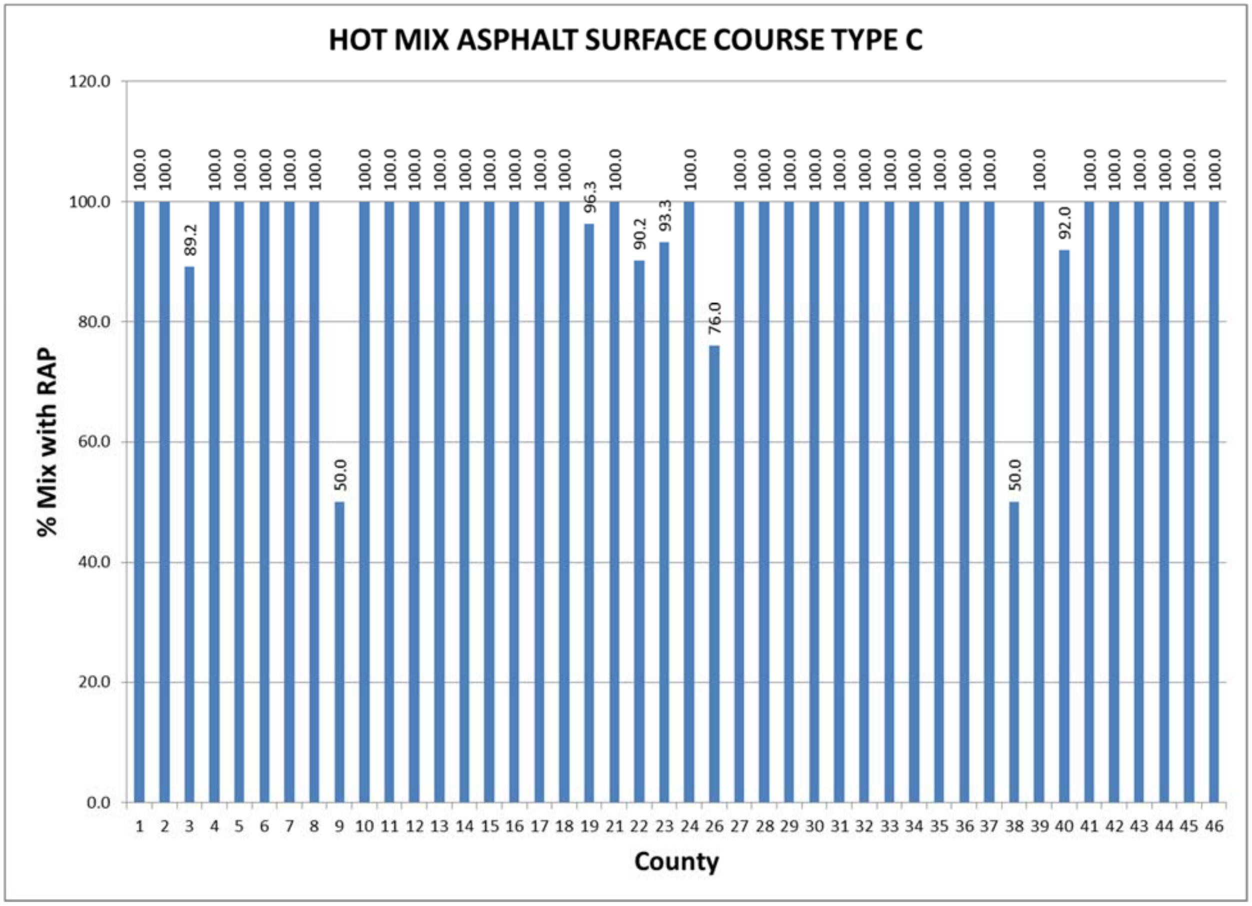


Figure 5-36: SCDOT Hot Mix Asphalt Surface Course Type C, % Mix with RAP per County

Figure 5-37 indicates that HMA Surface Course Type CM mixes contained RAP 100% of the time in Districts 1, 4 and 6. All of the remaining SCDOT Districts (2, 3, 5 and 7) utilized RAP in HMA Surface Course Type CM mixes over 90% of the time. Figure 5-38 shows the percentage of mixes containing RAP that were utilized in each County between 2008 and 2013. Eight South Carolina counties did not have any projects that contained HMA Surface Course Type CM mixes during the years included in this data (2008 – 2013). In 31 out of the 38 remaining counties, RAP was utilized in 100% of HMA Surface Course Type CM mixes. In 5 of the 7 remaining counties, RAP was utilized in HMA Surface Course Type CM mixes over 71% of the time. One other county (24) utilized RAP in 50% of its HMA Surface Course Type CM mixes, and the last remaining county (6) did not utilize any RAP in its HMA Surface Course Type CM mixes.

HMA Surface Course Type CM

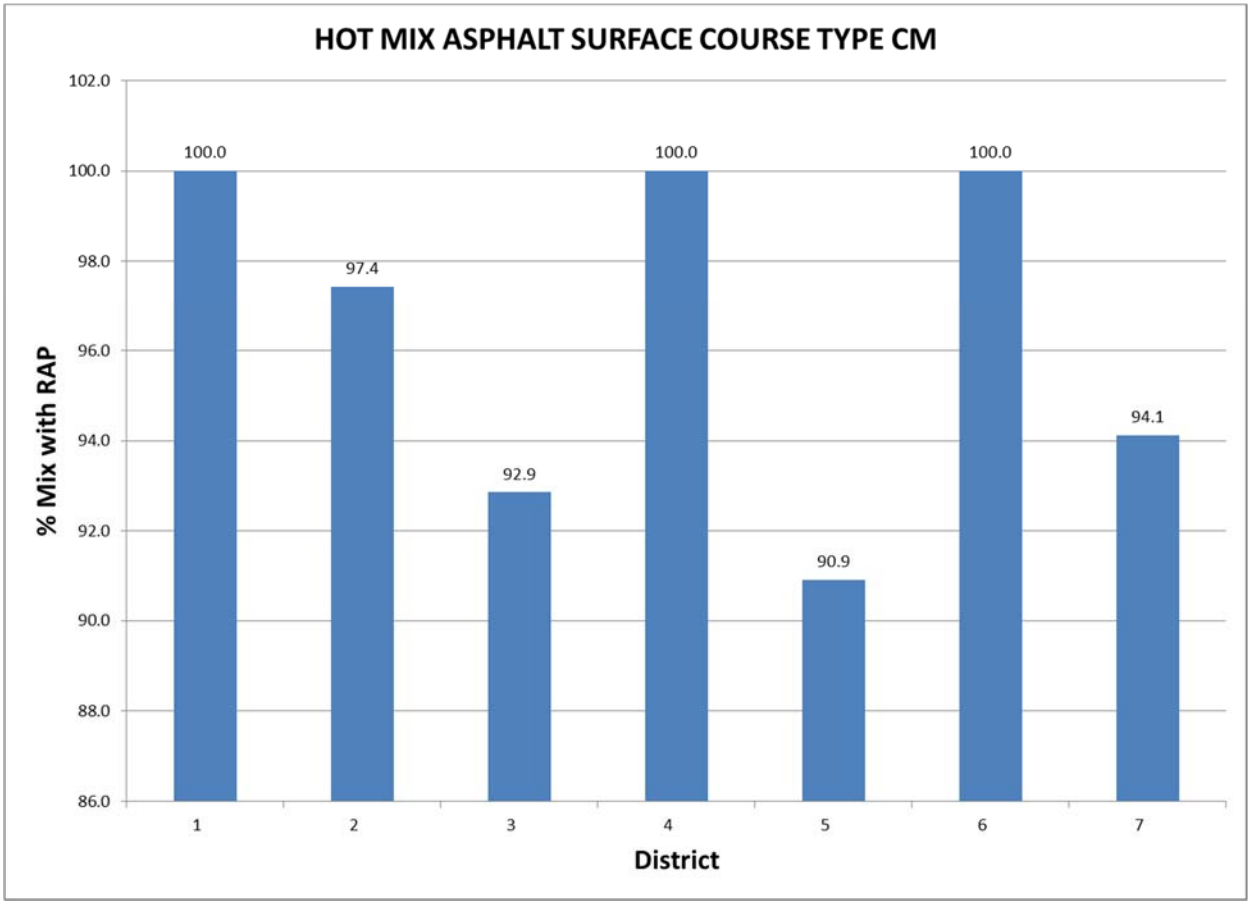


Figure 5-37: SCDOT Hot Mix Surface Course Type CM, % Mix with RAP per District

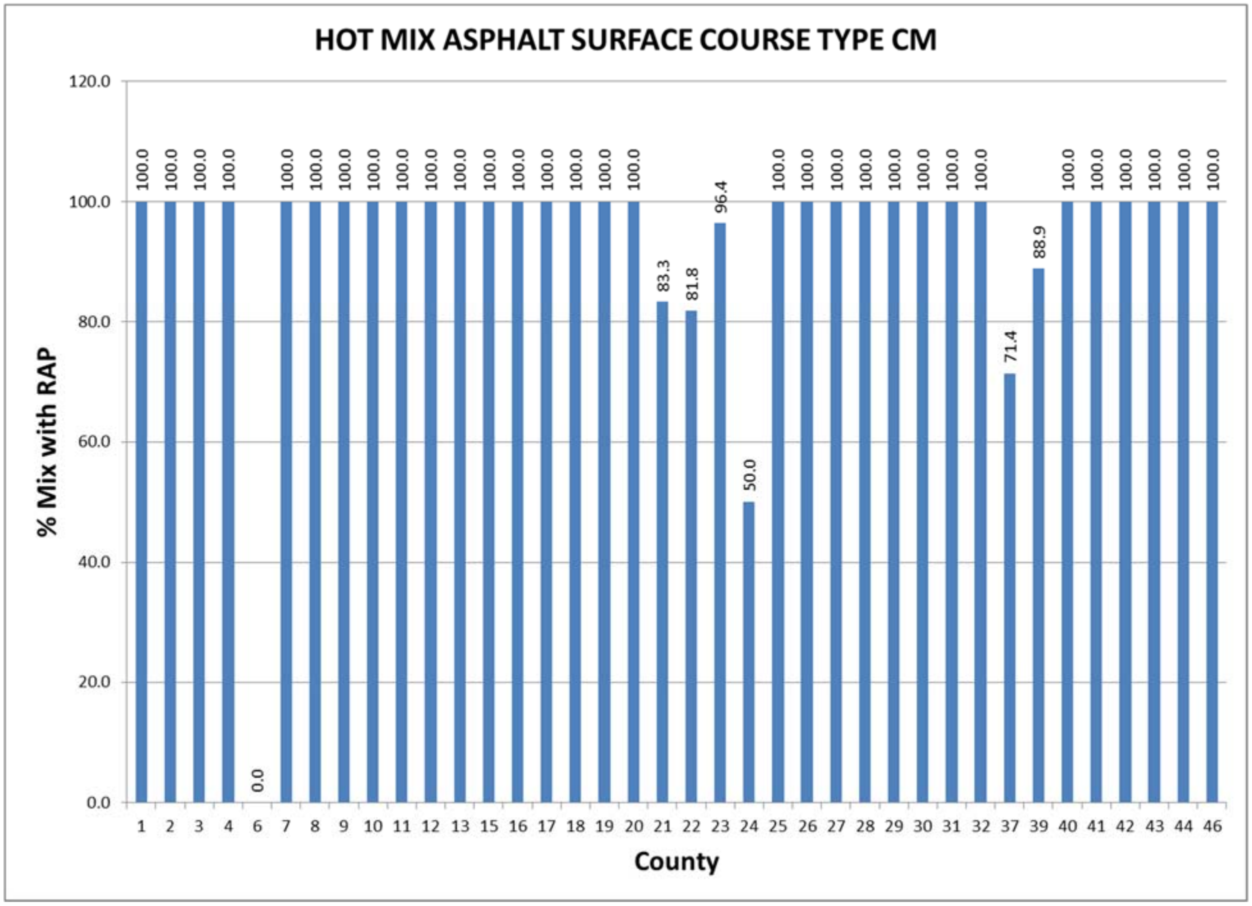


Figure 5-38: SCDOT Hot Mix Surface Course Type CM, % Mix with RAP per County

Figure 5-39 indicates that HMA Surface Course Type D mixes contained RAP 100% of the time in Districts 3, 4 and 6. All of the remaining SCDOT Districts (1, 2, 5 and 7) utilized RAP in HMA Surface Course Type D mixes more than 88% of the time. Figure 5-40 shows the percentage of mixes containing RAP that were utilized in each County between 2008 and 2013. Four South Carolina counties did not have a project that contained HMA Surface Course Type D mix during the years included in this data (2008 – 2013). In 36 out of the 42 remaining counties, RAP was utilized in 100% of HMA Surface Course Type D mixes. Of the HMA Surface Course Type D mixes in the remaining seven counties, four counties (9, 16, 21 and 28) utilized RAP at least 79% of the time, one county (22) utilized RAP 72.7% of the time, one county (33) utilized RAP 66.7% of the time, and one county (36) utilized RAP 60% of the time.

HMA Surface Course Type D

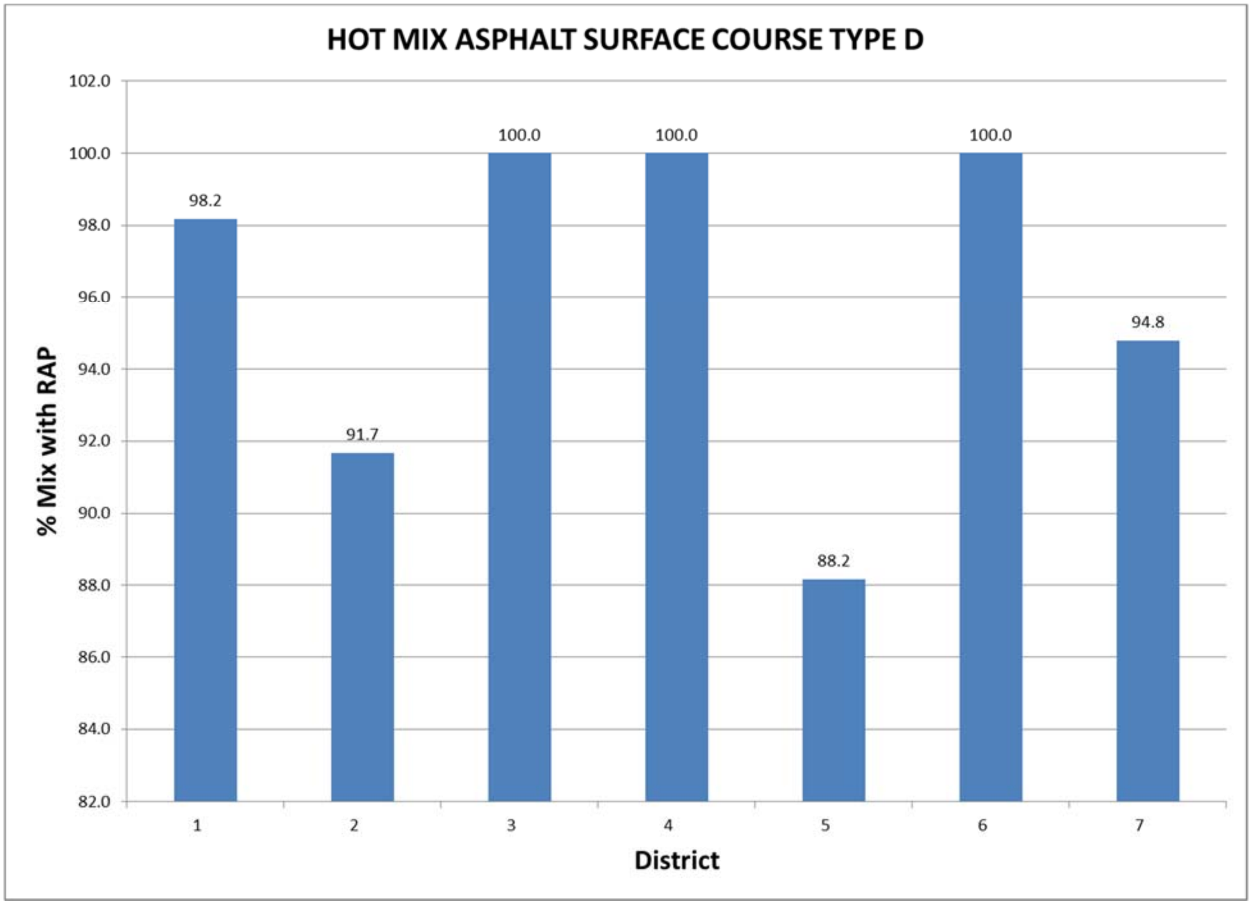


Figure 5-39: SCDOT Hot Mix Surface Course Type D, % Mix with RAP per District

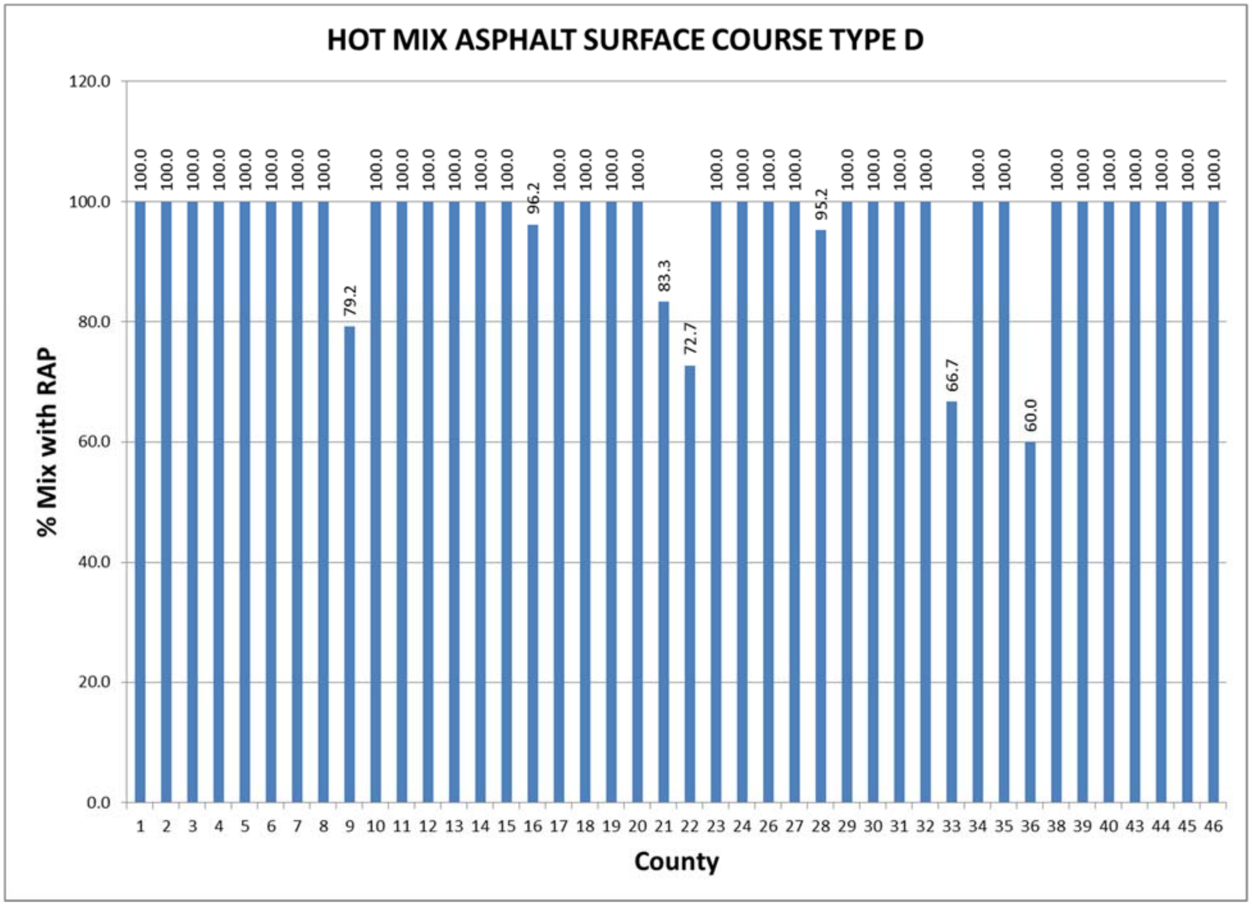


Figure 5-40: SCDOT Hot Mix Surface Course Type D, % Mix with RAP per County

Figure 5-41 indicates that HMA Surface Course Type E mixes contained RAP 100% of the time in District 6. Of the HMA Surface Course Type E mixes in the remaining SCDOT Districts, Districts 1 and 4 utilized RAP over 95% of the time, District 7 utilized RAP over 81% of the time, Districts 2 and 3 utilized RAP over 71% of the time, and District 5 utilized RAP 62.5% of the time. Figure 5-42 shows the percentage of mixes containing RAP that were utilized in each County between 2008 and 2013. Seventeen South Carolina counties did not have a project that contained HMA Surface Course Type E mix during the years included in this data (2008 – 2013). In 17 out of the 29 remaining counties, RAP was utilized in 100% of HMA Surface Course Type E mixes. In HMA Surface Course Type E mixes in the remaining counties, four counties (20, 29, 42, and 46) utilized RAP over 80% of the time, one county (4) utilized RAP 60% of the time, four counties (2, 16, 23 and 26) utilized RAP 50% of the time, and one county (14) utilized RAP 33.3% of the time. The remaining two counties (22 and 40) did not utilize any RAP in their HMA Surface Course Type E mixes.

HMA Surface Course Type E

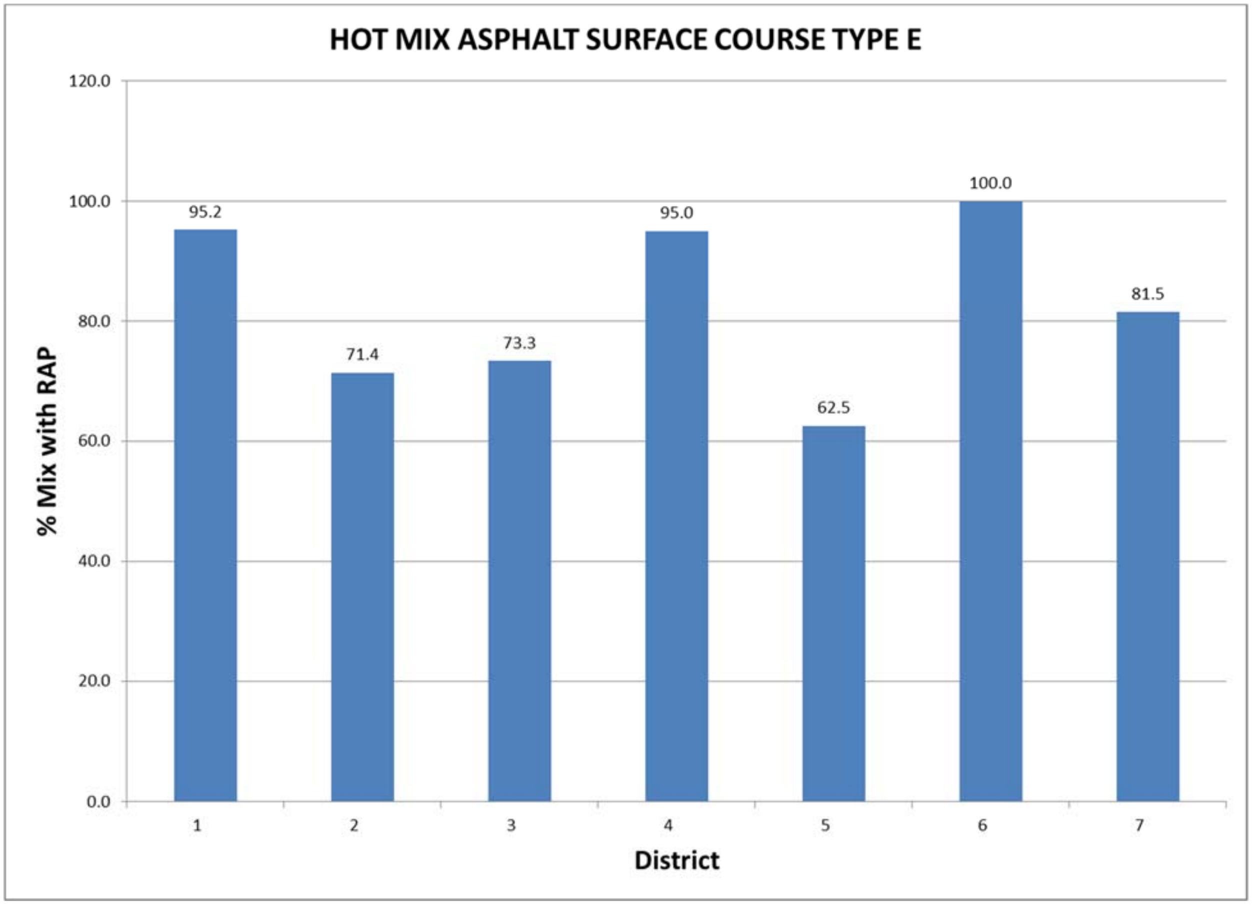


Figure 5-41: SCDOT Hot Mix Surface Course Type E, % Mix with RAP per District

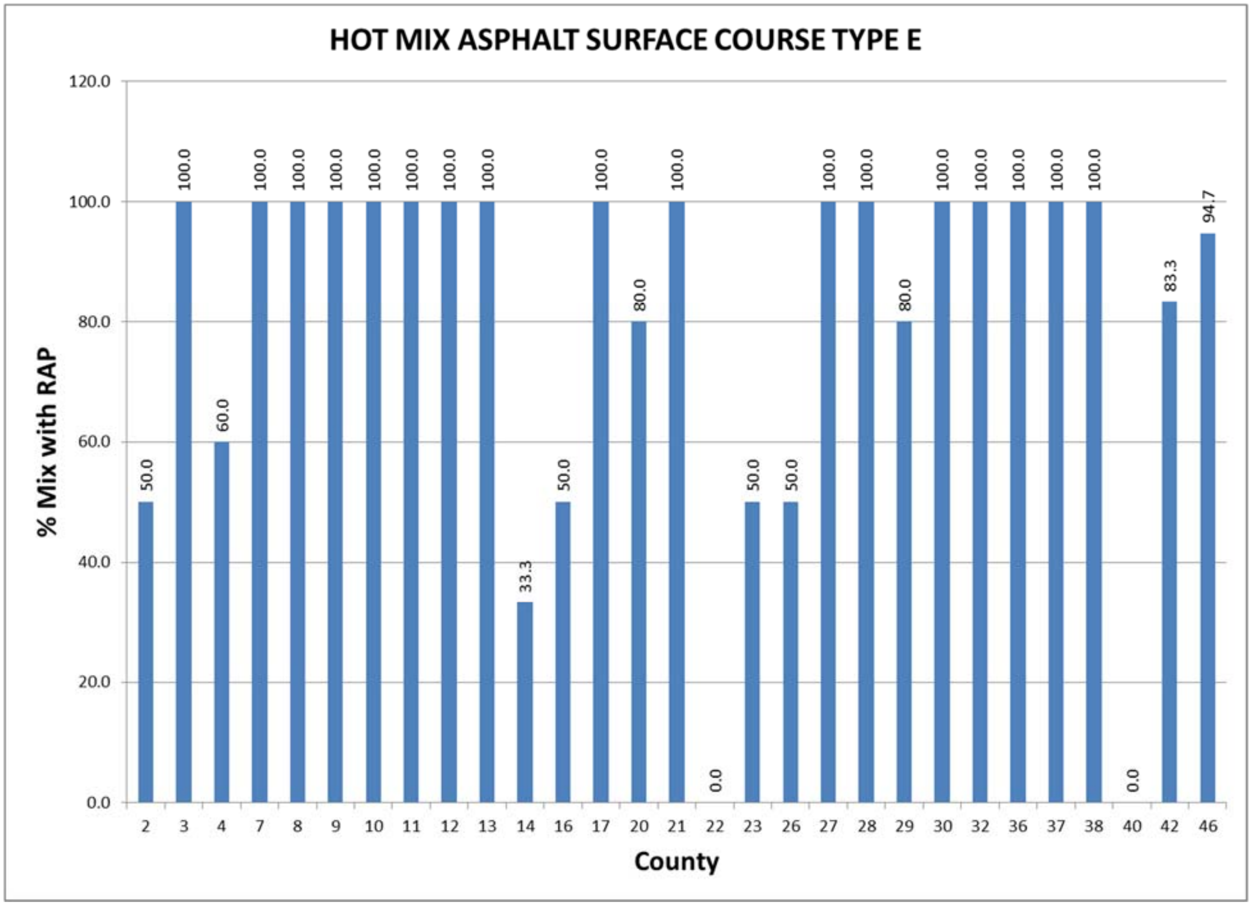


Figure 5-42: SCDOT Hot Mix Surface Course Type E, % Mix with RAP per County

Average Unit Cost Per Mix Per District and Per County

Another objective of this research was to compare unit costs per mix type between SCDOT Engineering Districts and between South Carolina Counties. The following is a breakdown of that data by mix type for 2008-2013. Virgin and RAP mix prices are combined for this portion of the analysis. It should be noted that for all graphs, if there is not a data point for either a county and/or a District, it simply means that the particular mix in question was not used in that location during the time period studied. It should also be noted that unit mix costs can be affected by a wide variety of factors including project size, project location (urban vs. rural, night vs. day), transportation costs, mix application rate, time period placed, and overall market conditions just to name a few. For this portion of the study, all data points for mixes with less than 2,500 tons on a particular project were eliminated from the data. This deletion was approved by the Steering Committee for this project in an attempt to isolate the prices for mainline paving only in order to hopefully reduce the effect of small project size on unit prices.

HMA Shoulder Widening Course

Error! Reference source not found. represents the graphical presentation of unit cost per District of HMA Shoulder Widening Course mixes from 2008-2013. Figure 5-44 represents the graphical presentation of unit cost per County of HMA Shoulder Widening Course mixes from 2008-2013.

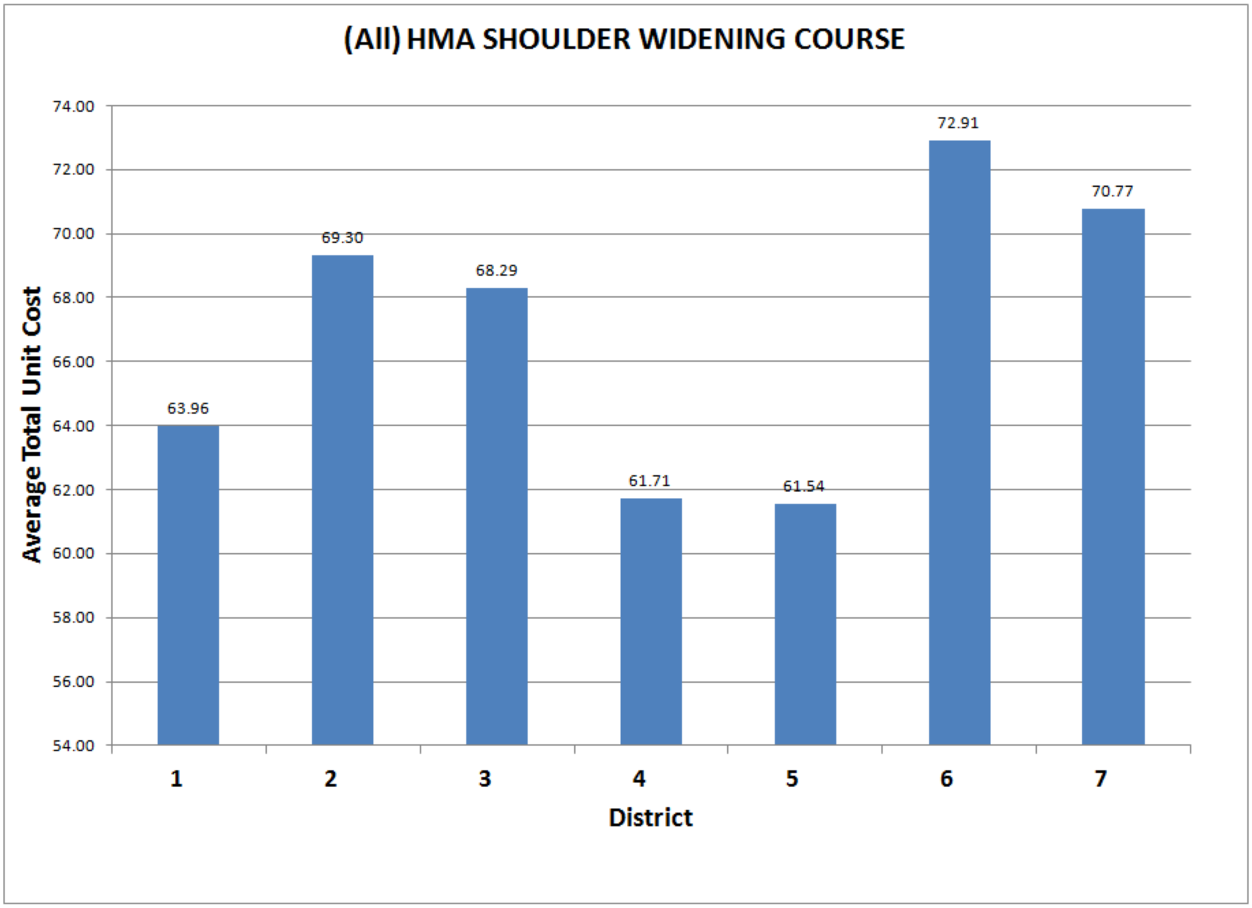


Figure 5-43: HMA Shoulder Widening Course Average Unit Cost per SCDOT District from 2008-2013

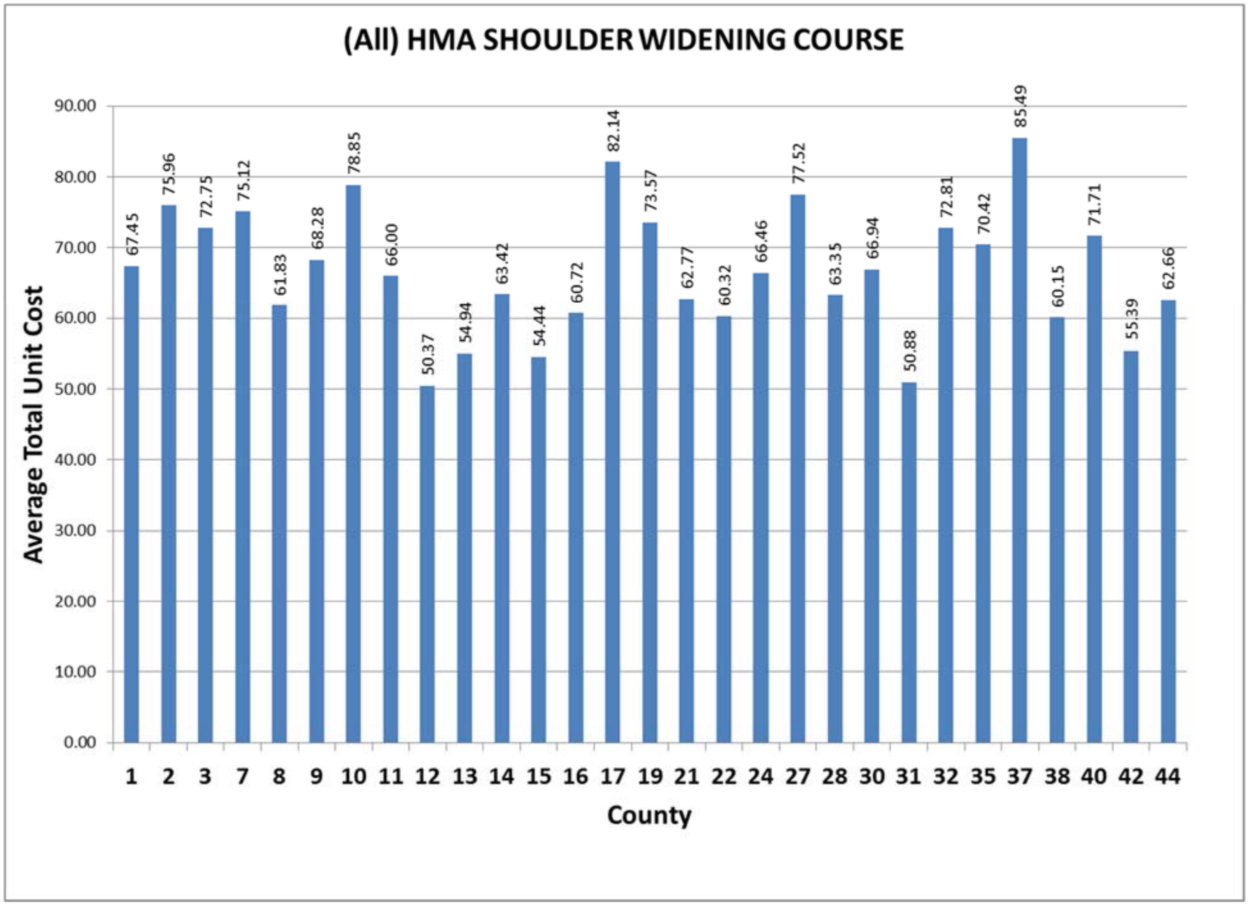


Figure 5-44: HMA Shoulder Widening Course Average Unit Cost per SC County from 2008-2013

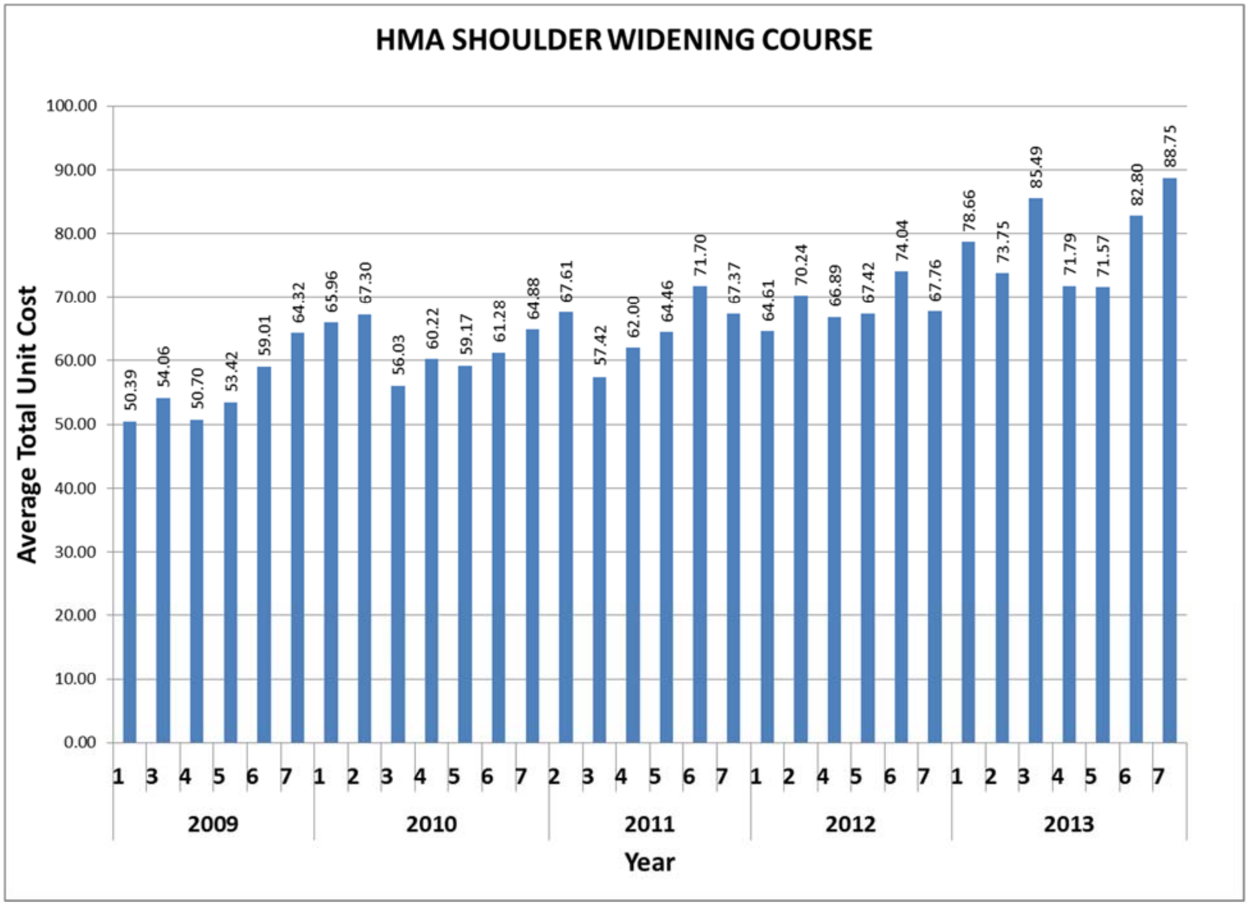


Figure 5-45: HMA Shoulder Widening Course Average Unit Cost Per SCDOT District per Year from 2008-2013

Figure 5-43 indicates that SCDOT Districts 6 and 7 had the highest unit cost for HMA Shoulder Widening Mix from 2008-2013 at $72.91 and $70.77, respectively. However, Districts 3, 4, 6 and 7 were significantly equivalent at the $\alpha = 0.05$ level (Appendix C, Table 10-30). Districts 4 and 5 had the lowest unit cost for HMA Shoulder Widening Mix from 2008-2013 at $61.71 and $61.54, respectively, and were significantly different from all other Districts except District 2 at the $\alpha = 0.05$ level (Appendix C, Table 10-30). The average unit cost of HMA Shoulder Widening Mix from 2008-2013 was $65.75 with a standard deviation of $4.529 per District.

Figure 5-44 indicates that SCDOT designated counties, 17 and 37 had the highest unit cost for HMA Shoulder Widening mix from 2008-2013 at $82.14 and $85.49 respectively. SCDOT designated counties 12 and 31 had the lowest unit cost for HMA Shoulder Widening Mix from 2008-2013 at $50.37 and $50.88 respectively. The average unit cost of HMA Shoulder Widening Mix from 2008-2013 was $65.75 with a standard deviation of $9.075 per county. No statistical analysis was performed due to limited amount of data available per data point (HMA Shoulder Widening per County).

Figure 5-45 indicated that a general increase in prices per year for HMA Shoulder Widening Course took place. Unit costs for HMA Shoulder Widening mix averaged $55.84 in 2009 and increased incrementally to an average of $78.54 in 2013. This gradual increase is mostly likely due to inflationary pressures and/or trends in the SCDOT Asphalt Binder Index. No statistical analysis was performed due to limited amount of data available per data point (County/District/Year).

HMA Base Course Type A

Figure 5-46 represents the graphical presentation of unit cost per SCDOT District of HMA Base Course Type A mixes from 2008-2013. Figure 5-47 represents the graphical presentation of unit cost per SC county of HMA Base Course Type A mixes from 2008-2013.

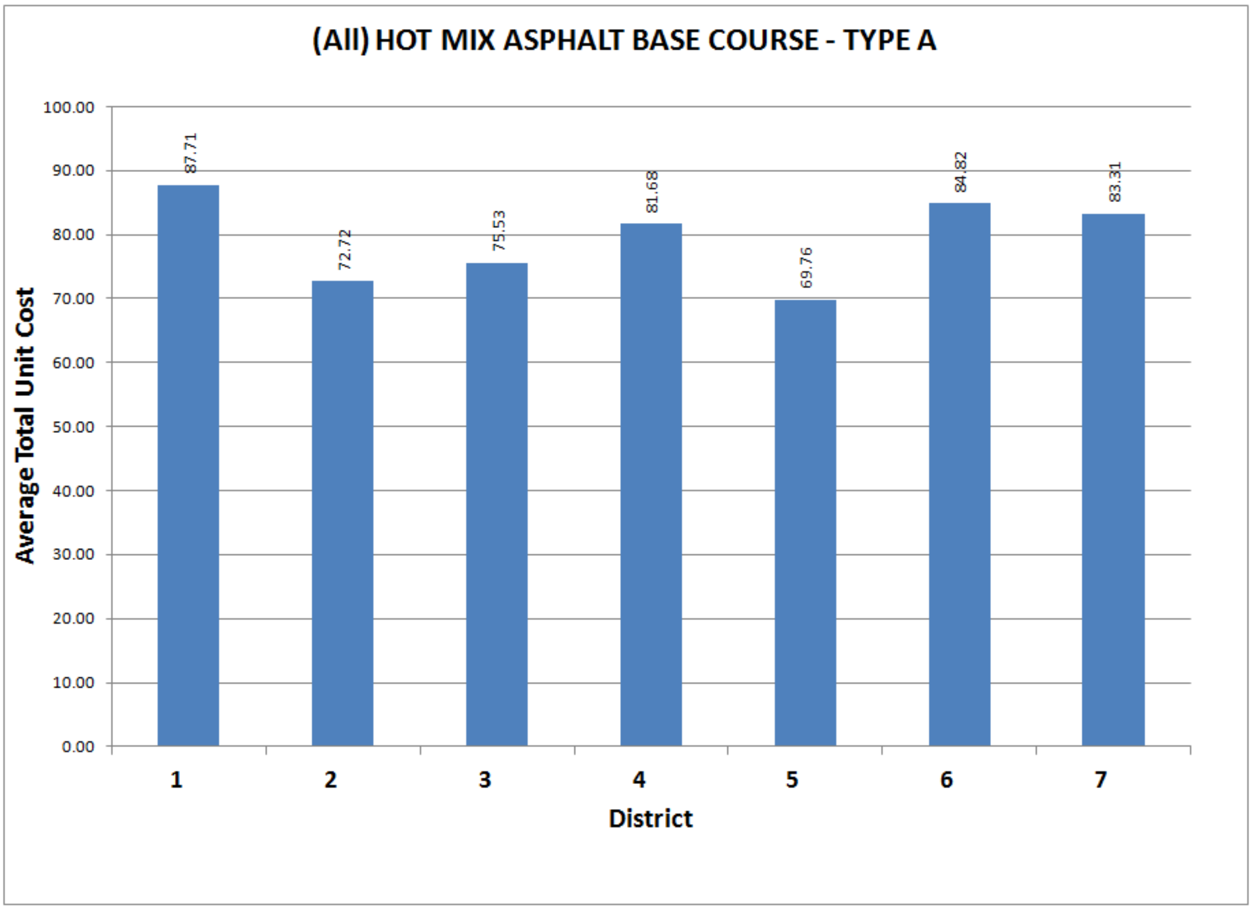


Figure 5-46: HMA Base Course Type A Average Unit Cost Per SCDOT District from 2008-2013

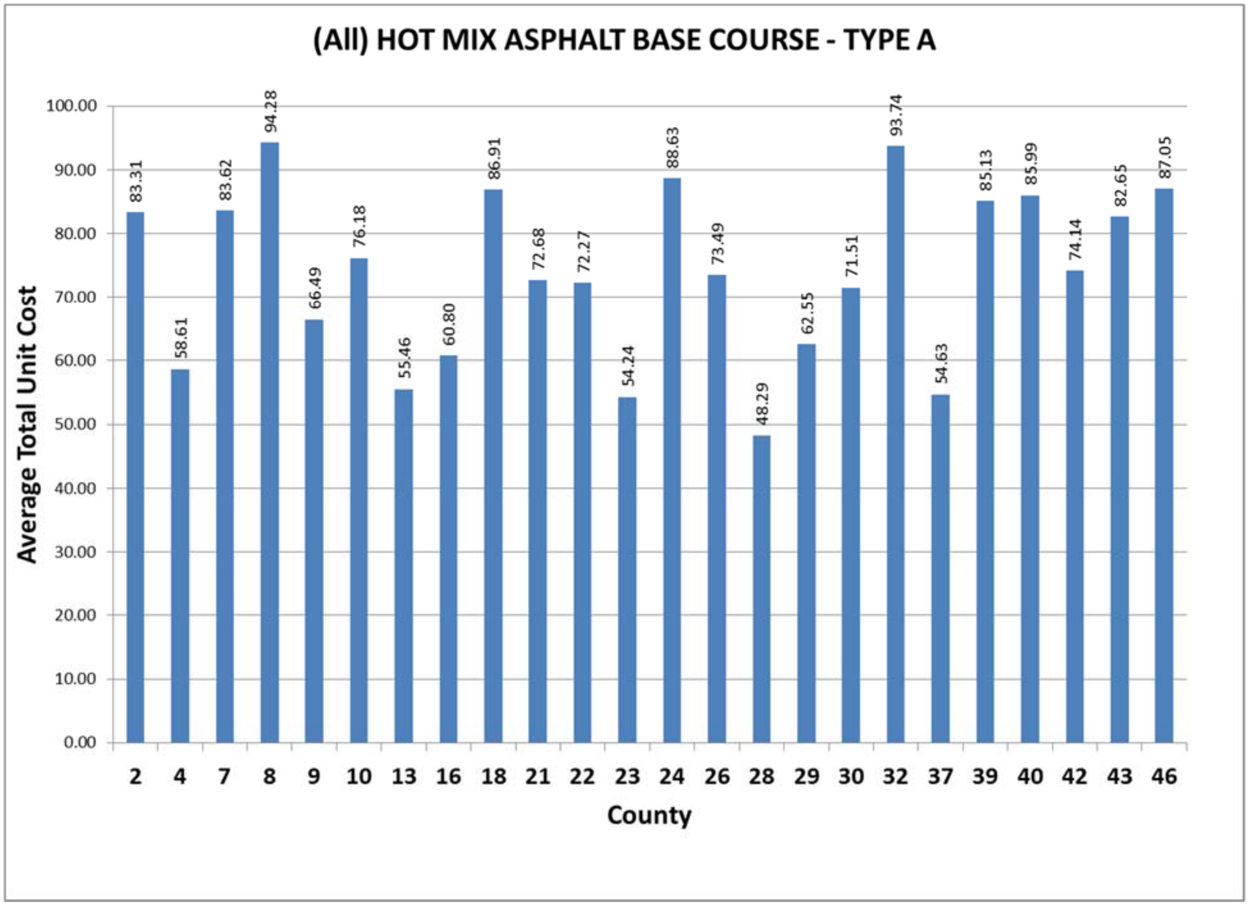


Figure 5-47: HMA Base Course Type A Average Unit Cost Per SC County from 2008-2013

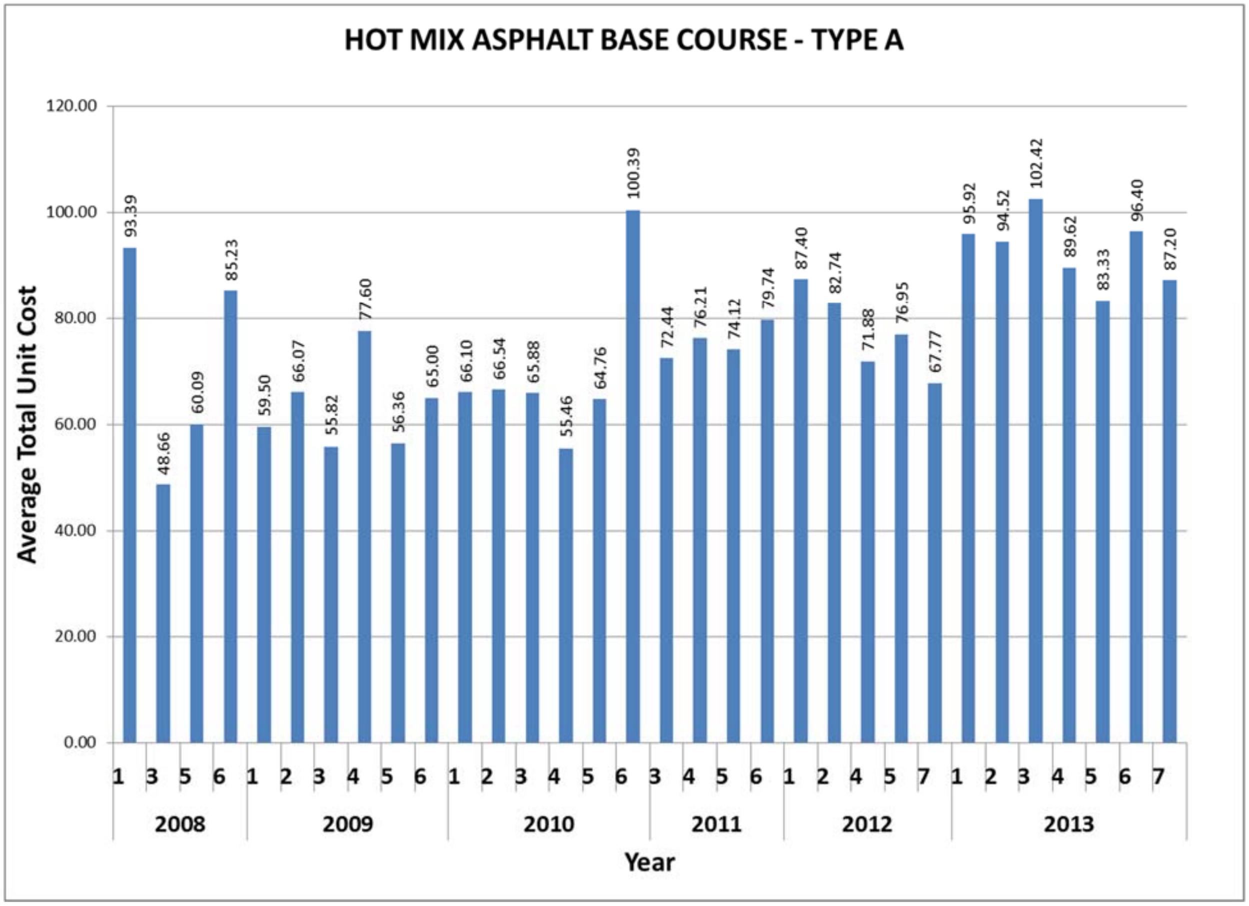


Figure 5-48: HMA Base Course Type A Unit Cost Per SCDOT District per Year from 2008-2013

Figure 5-46 indicates that SCDOT District 1 and 6 had the highest unit cost for HMA Base Course Type A mix from 2008-2013 at $87.71 and $84.82 respectively. District 2 and 5 had the lowest unit cost for HMA Base Course Type A mix from 2008-2013 at $72.77 and $69.76 respectively. District 1 and 5 were significantly different at the $\alpha = .05$ level (Appendix C, Table 10-31). All other combinations of Districts were significantly equivalent (Appendix C, Table 10-31). The average unit cost of HMA Base Course Type A from 2008-2013 was $80.28 with a standard deviation of $6.678 per District.

Figure 5-47 indicates that SCDOT designated counties, 8 and 32 had the highest unit cost for HMA Base Course Type A mix from 2008-2013 at $94.28 and $93.74 respectively. SCDOT designated counties 23 and 28 had the lowest unit cost for HMA Base Course Type A from 2008-2013 at $54.24 and $48.29 respectively. The average unit cost of HMA Base Course Type A from 2008-2013 was $80.28 with a standard deviation of $13.912 per county. No statistical analysis was performed due to limited amount of data available per data point (HMA Base Course A per County).

Figure 5-48 shows that a general increase in prices per year per SCDOT District for HMA Base Course Type A took place. Unit costs for HMA Base Course Type A mix averaged $71.22 in 2008 and increased incrementally to an average of $92.81 in 2013. This gradual increase is most likely due to inflationary pressures and/or trends in the SCDOT Asphalt Binder Index. No statistical analysis was performed due to limited amount of data available per data point (County/District/Year).

HMA Base Course Type B

Figure 5-49 represents the graphical presentation of unit cost per SCDOT District of HMA Base Course Type B mixes from 2008-2013. Figure 5-50 represents the graphical presentation of unit cost per SC county of HMA Base Course Type B mixes from 2008-2013. Figure 5-51 represents the graphical presentation of unit cost per SCDOT District per year of HMA Base Course Type B from 2008-2013.

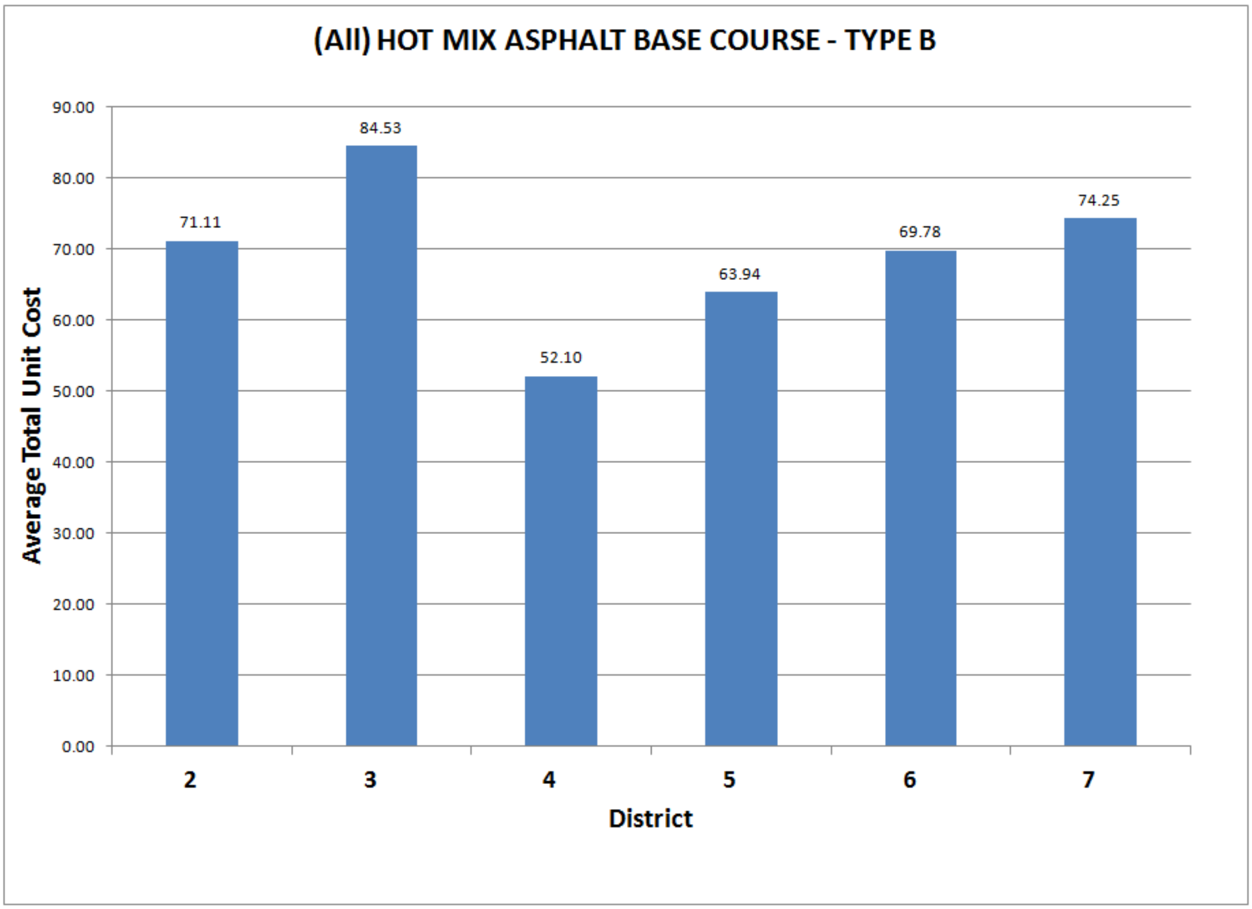


Figure 5-49: HMA Base Course Type B Average Unit Cost Per District from 2008-2013

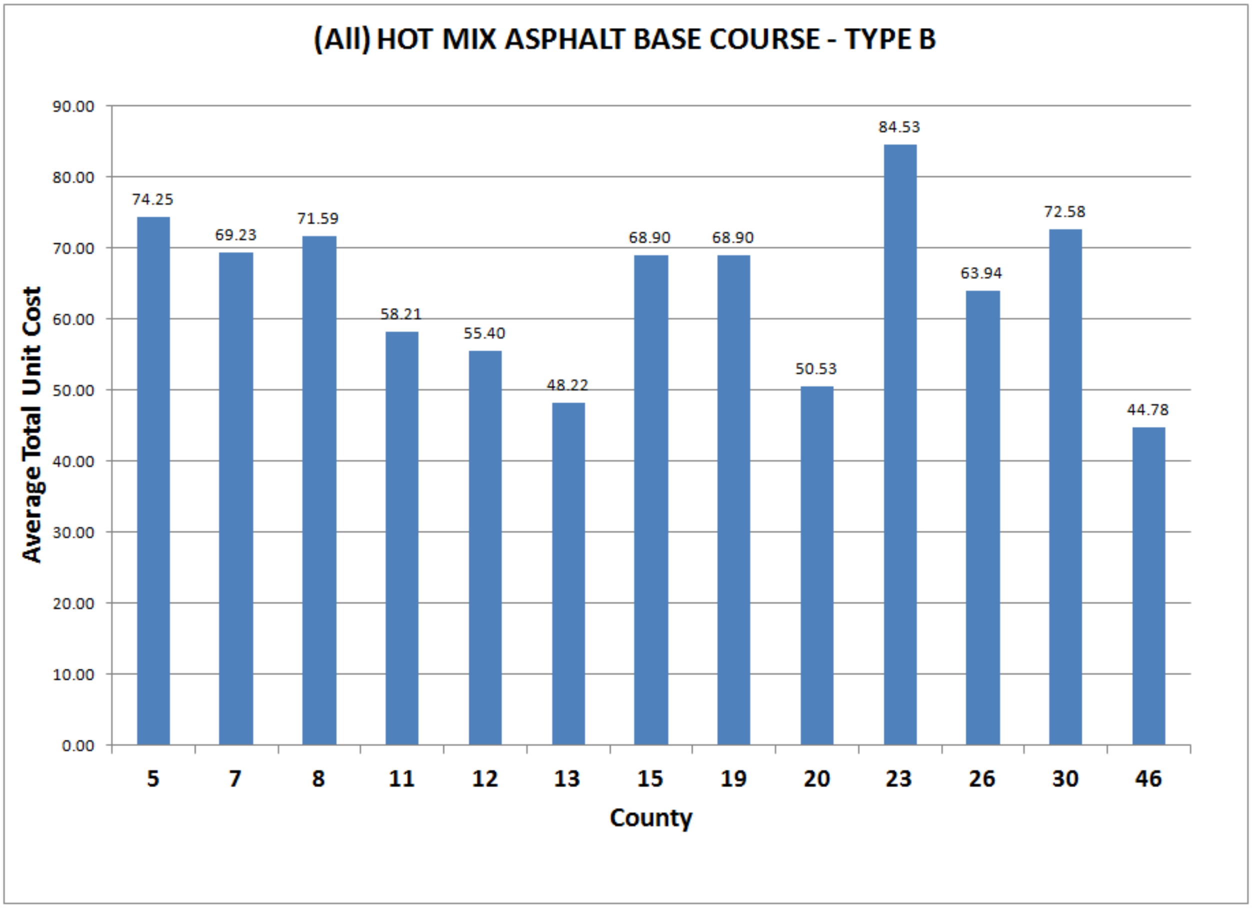


Figure 5-50: HMA Base Course Type B Average Unit Cost Per SC County from 2008-2013

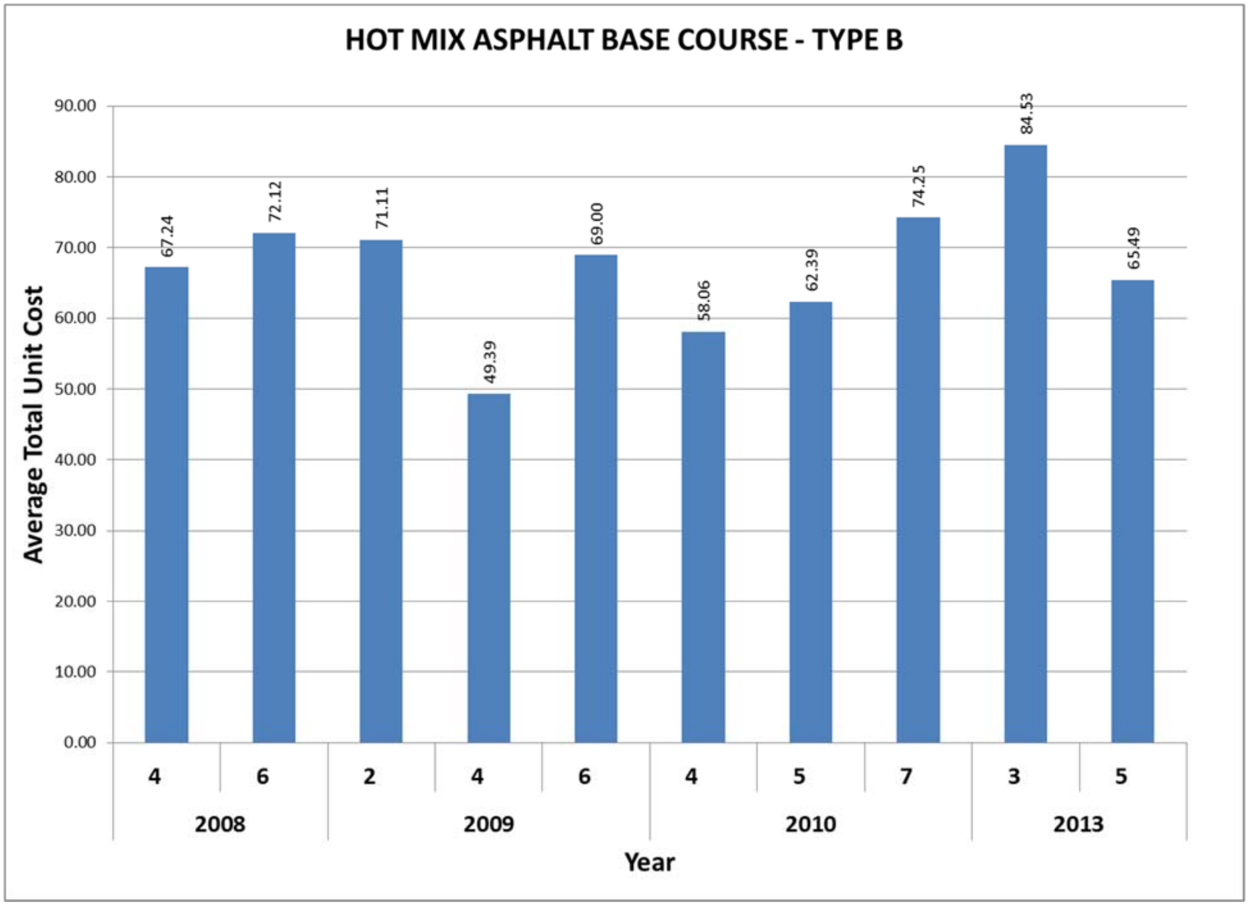


Figure 5-51: HMA Base Course Type B Unit Cost Per SCDOT District per Year from 2008-2013

Figure 5-49 indicates that District 3 and 7 had the highest unit cost for HMA Base Course Type B mix from 2008-2013 at $84.58 and $76.25 respectively. District 4 and 5 had the lowest unit cost for HMA Base Course Type B mix from 2008-2013 at $52.10 and $63.94, respectively. The average unit cost of HMA Base Course Type B from 2008-2013 was $63.30 with a standard deviation of $10.815 per District. No statistical analysis was performed due to limited data for this mix type.

Figure 5-50 indicates that SC counties 5 and 23 had the highest unit cost for HMA Base Course Type A mix from 2008-2013 at $74.25 and $84.53, respectively. However, counties 13 and 46 had the lowest unit cost for HMA Base Course Type B from 2008-2013 at $48.22 and $44.78, respectively. The average unit cost of HMA Base Course Type B from 2008-2013 was $63.30 with a standard deviation of $11.69 per county. No statistical analysis was performed due to limited data for this mix type.

There were no observable trends in the unit costs data per district/per year in Figure 5-51. No statistical analysis was performed due to limited data for this mix type.

HMA Base Course Type C

HMA Base Course Type C had very limited use statewide and was used only in SCDOT District 2. There were no observable trends to be reported with this mix. No statistical analysis was performed due to limited data for this mix type.

HMA Intermediate Course Type A

HMA Intermediate Course Type A had very limited use statewide and is used primarily on interstate projects. There were no projects where Intermediate A was placed in amounts greater than 2,500 tons during the years included in this project. As mentioned earlier, data points for mixes placed at less than 2,500 tons per project were not analyzed due to their potential to affect cost data. No statistical analysis was performed due to limited data for this mix type.

HMA Intermediate Course Type B

Figure 5-52 represents the graphical presentation of unit cost per SCDOT District of HMA Intermediate Course Type B mixes from 2008-2013. Figure 5-53 represents the graphical presentation of unit cost per County of HMA Intermediate Course Type B mixes from 2008-2013. Figure 5-54 represents the graphical presentation of unit cost per SCDOT District per year of HMA Intermediate Course Type B from 2008-2013.

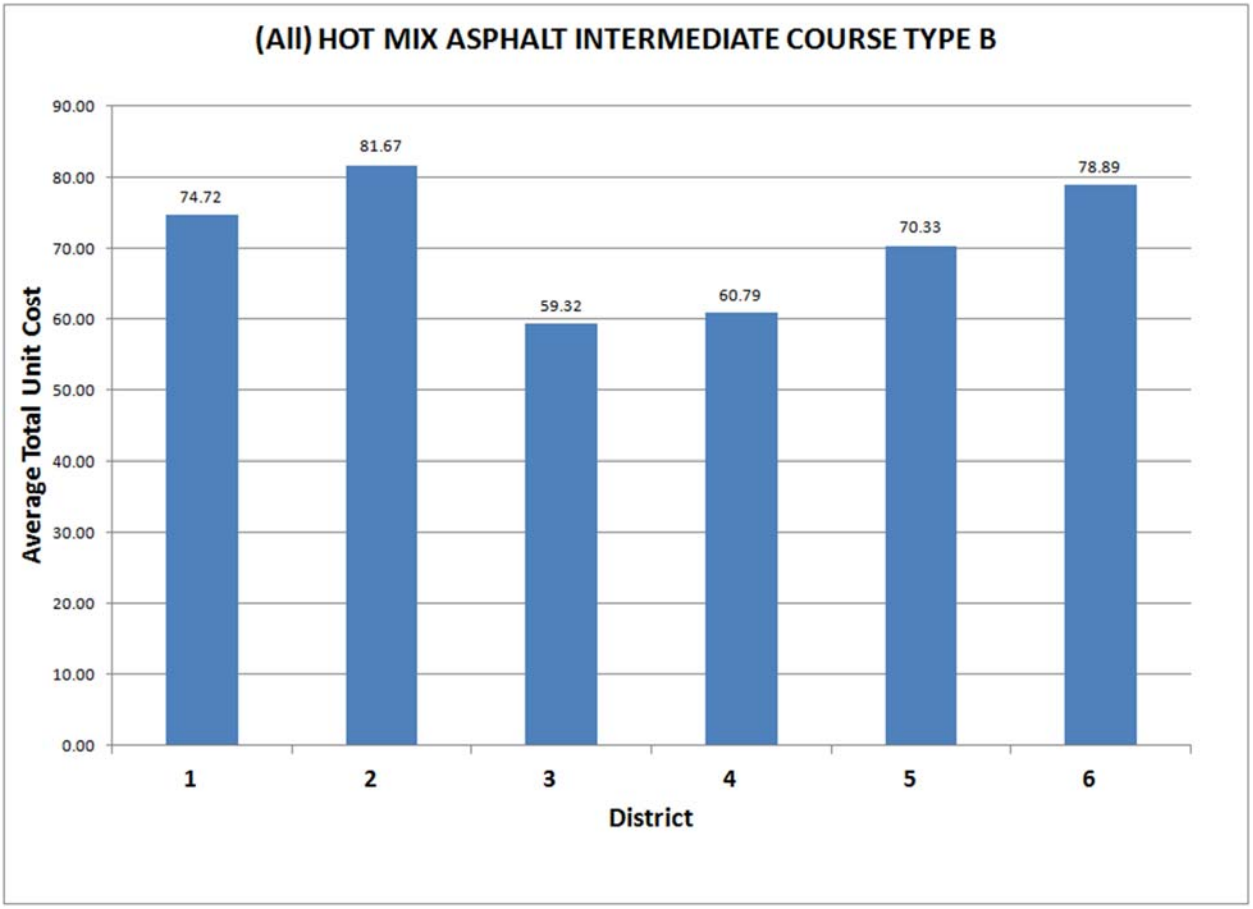


Figure 5-52: HMA Intermediate Course Type B Average Unit Cost Per SCDOT District from 2008-2013

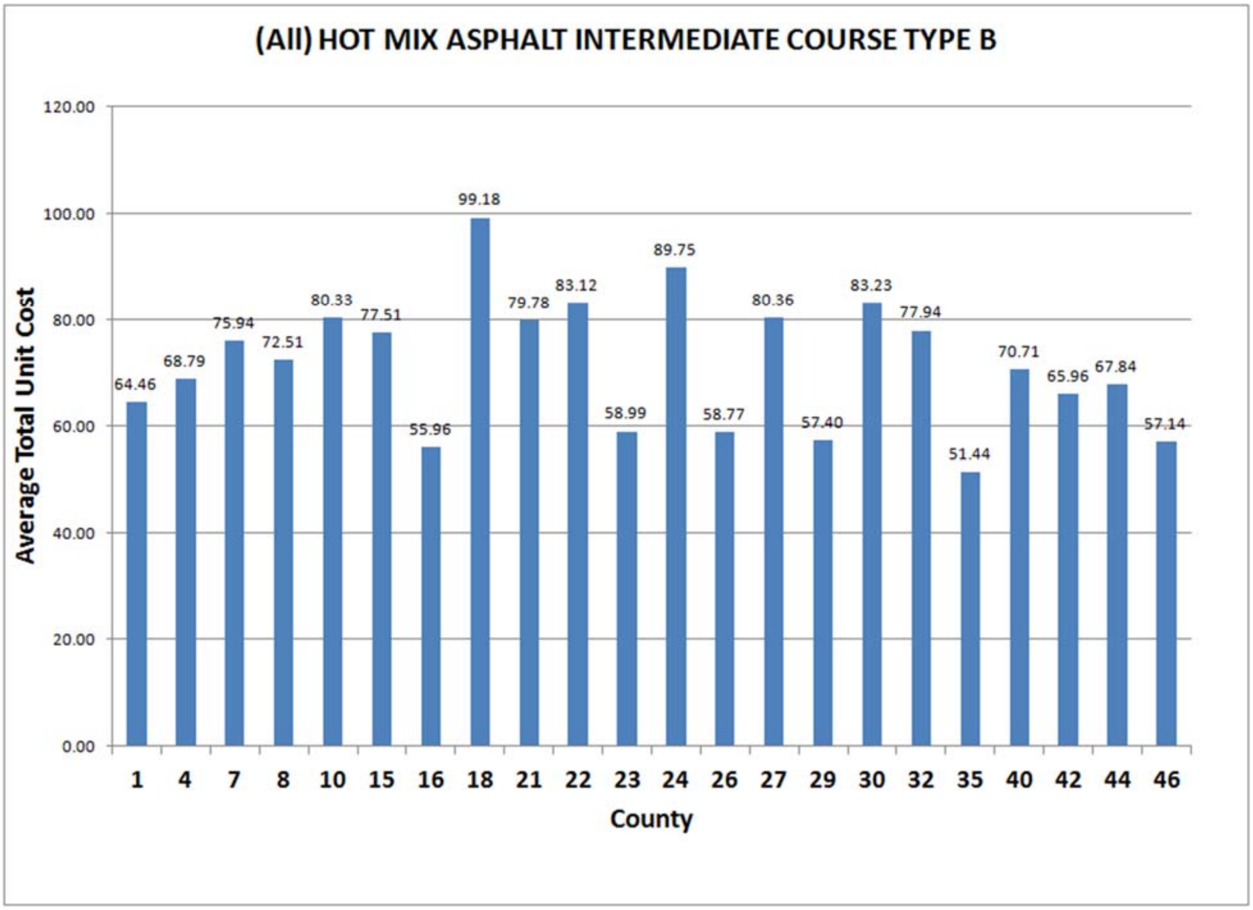


Figure 5-53: HMA Intermediate Course Type B Average Unit Cost Per SC County from 2008-2013

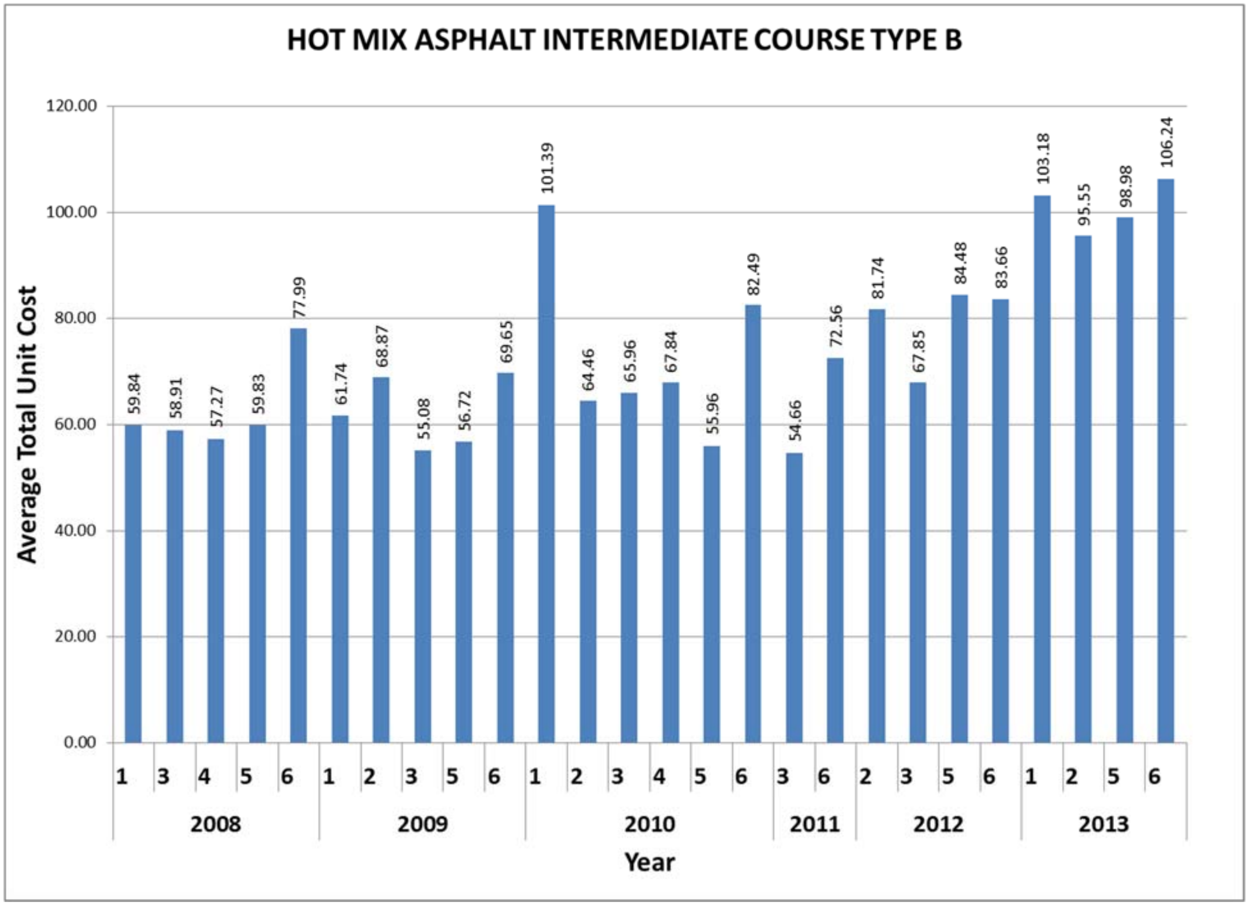


Figure 5-54: HMA Intermediate Course Type B Average Unit Cost Per SCDOT District per Year from 2008-2013

Figure 5-52 indicates that SCDOT Districts 2, 4, 5, and 6 had the highest unit cost for HMA Intermediate Course Type B from 2008-2013 and were significantly equivalent at the $\alpha = 0.05$ level (Appendix C, Table 10-32). SCDOT Districts 3 and 4 had the lowest unit cost for HMA Intermediate Course Type B from 2008-2013 at $59.32 and $60.79, respectively, and were significantly equivalent at the $\alpha = 0.01$ level (Appendix C, Table 10-32). The average unit cost of HMA Intermediate Course Type B from 2008-2013 was $72.84 with a standard deviation of $10.71 per SCDOT District.

Figure 5-53 indicates that SCDOT designated counties 18 and 24 had the highest unit cost for HMA Intermediate Course Type B from 2008-2013 at $99.18 and $89.75, respectively. SCDOT designated counties 16 and 35 had the lowest unit cost for HMA Intermediate Course Type B from 2008-2013 at $55.96 and $51.44, respectively. The average unit cost of HMA Intermediate Course Type B from 2008-2013 was $72.84 with a standard deviation of $12.27 per county. Since there was limited data at various data point, no statistical analysis was performed on this set of data.

Figure 5-54 indicated that a general increase in prices per year for HMA Intermediate Course Type B took place. Unit costs for HMA Shoulder Widening mix averaged $66.20 in 2008 and increased incrementally to an average of $99.16 in 2013. This gradual increase is mostly likely due to inflationary pressures and/or trends in the SCDOT Asphalt Binder Index. There were no statistical analysis performed on this set of data due to limited data at various data points.

HMA Intermediate Course Type C

Figure 5-55 represents the graphical presentation of unit cost per SCDOT District of HMA Intermediate Course Type C mixes from 2008-2013. Figure 5-56 represents the graphical presentation of unit cost per SC county of HMA Intermediate Course Type C mixes from 2008-2013. Figure 5-57 represents the graphical presentation of unit cost per SCDOT District per year of HMA Intermediate Course Type C from 2008-2013.

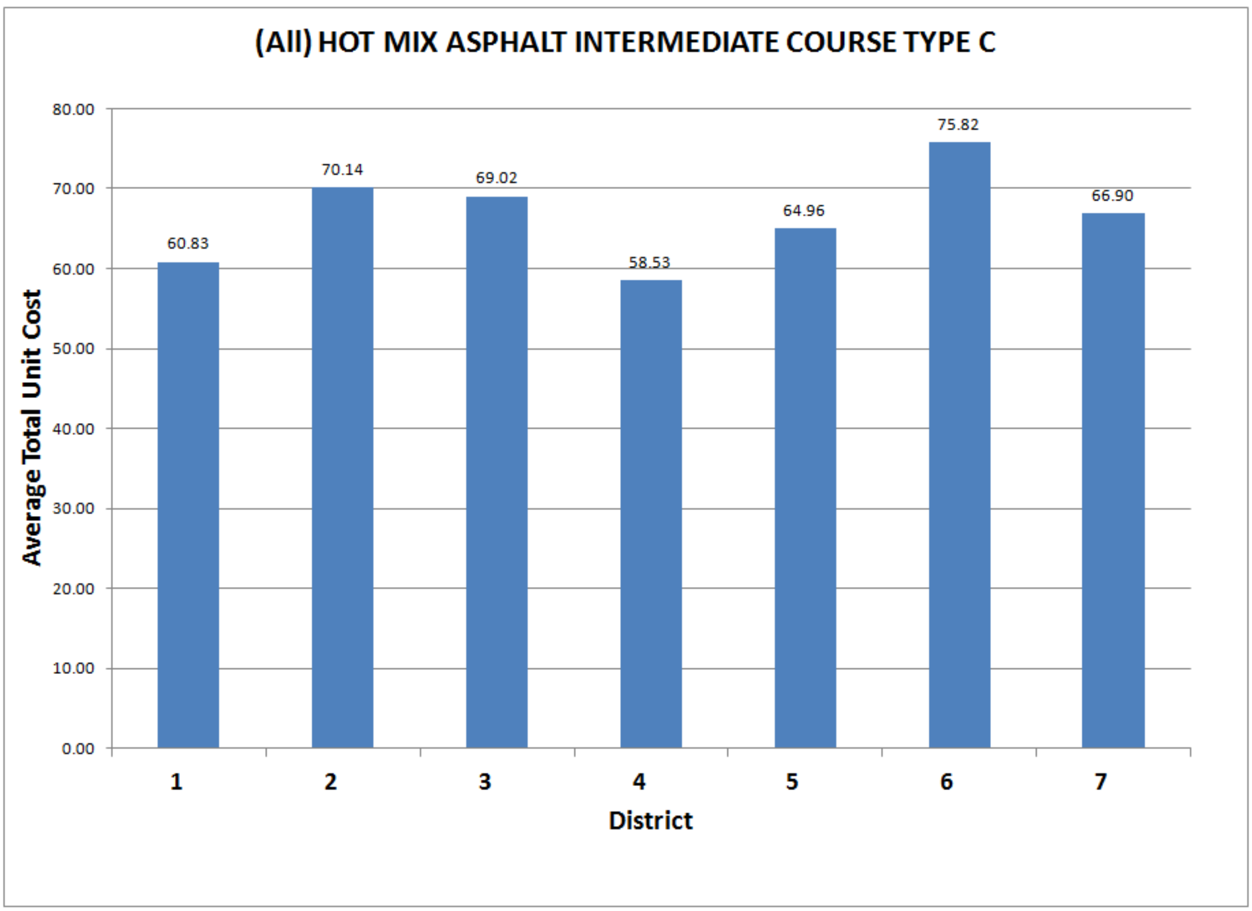


Figure 5-55: HMA Intermediate Course Type C Average Unit Cost Per SCDOT District from 2008-2013

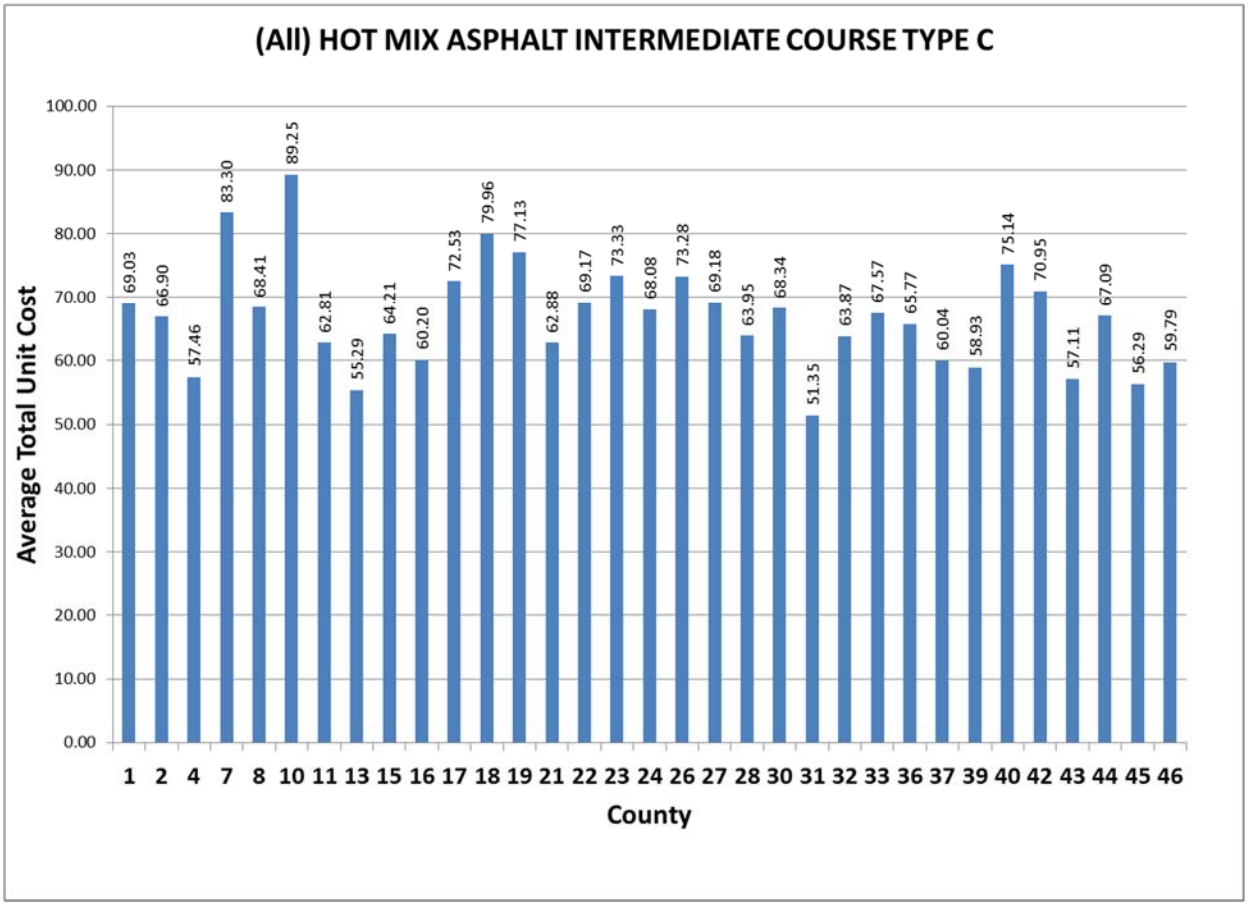


Figure 5-56: HMA Intermediate Course Type C Average Unit Cost Per SC County from 2008-2013

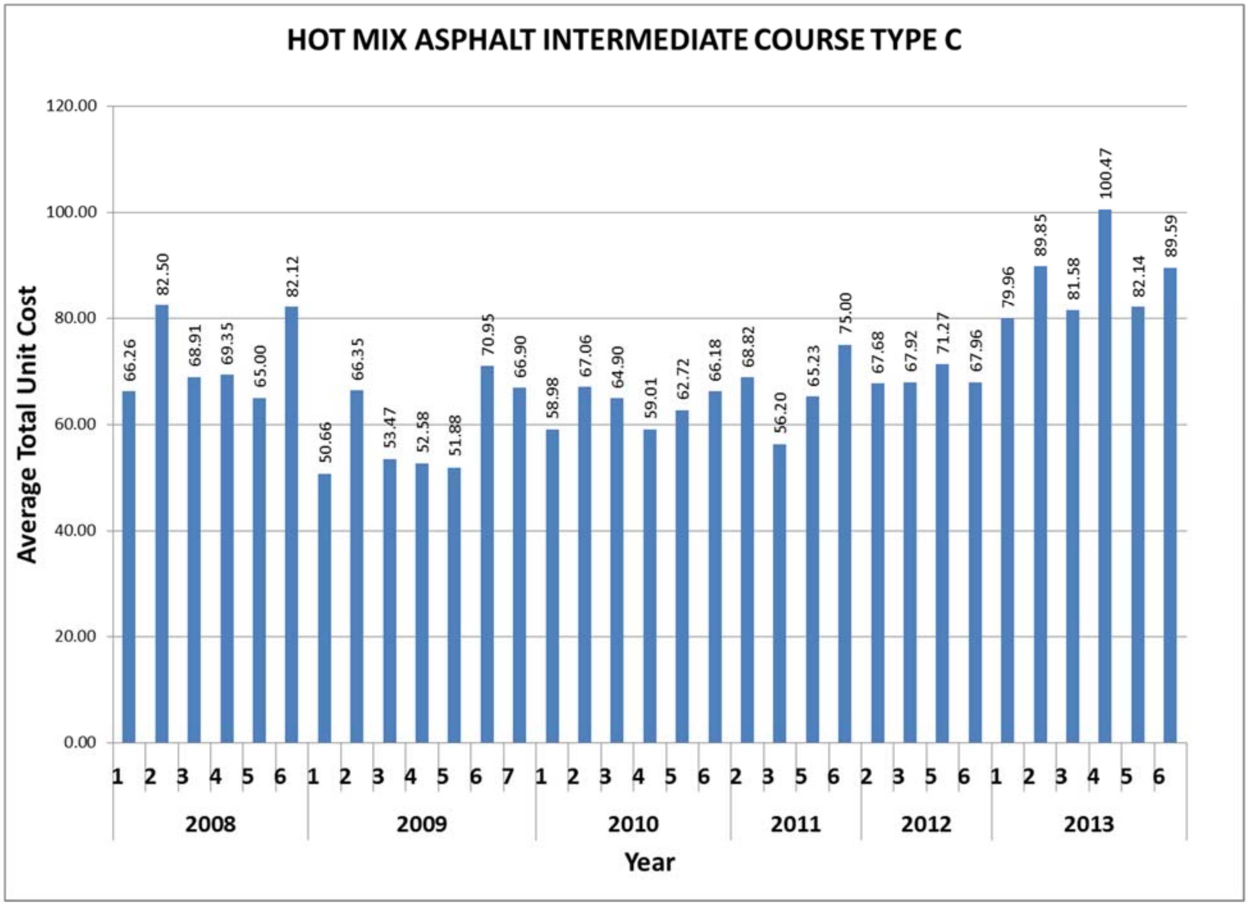


Figure 5-57: HMA Intermediate Course Type C Average Unit Cost Per SCDOT District per Year from 2008-2013

Figure 5-55 indicates that SCDOT District 6 had the highest unit cost for HMA Intermediate Course Type C from 2008-2013 at $75.82 and was significantly different at the $\alpha = 0.05$ level (Appendix C, Table 10-33). SCDOT Districts1, 3, 4, and 5 had the lowest unit cost for HMA Intermediate Course Type C from 2008-2013 and were significantly equivalent at the $\alpha = 0.05$ level (Appendix C, Table 10-33). The average unit cost of HMA Intermediate Course Type C from 2008-2013 was $68.04 with a standard deviation of $6.227 per District.

Figure 5-56 indicates that SCDOT designated counties 7 and 10 had the highest unit cost for HMA Intermediate Course Type C from 2008-2013 at $83.30 and $89.25, respectively. SCDOT designated counties 3 and 31 had the lowest unit cost for HMA Intermediate Course Type C from 2008-2013 at $55.29 and $51.35, respectively. The average unit cost of HMA Intermediate Course Type C from 2008-2013 was $68.04 with a standard deviation of $8.295 per county. There were no statistical analysis performed on this graph due to limited data at various data points.

Figure 5-57 indicates that a general increase in unit cost per year for HMA Intermediate Course Type C took place. Unit costs for HMA Intermediate Course Type C mix averaged $71.83 in

2008 and increased incrementally to an average of $83.76 in 2013. This gradual increase is mostly likely due to inflationary pressures and/or trends in the SCDOT Asphalt Binder Index. No statistical analysis was performed on this graph due to limited data at various data points.

HMA Surface Course Type A

Figure 5-58 represents the graphical presentation of unit cost per SCDOT District of HMA Surface Course Type A mixes from 2008-2013. Figure 5-59 represents the graphical presentation of unit cost per SC county of HMA Surface Course Type A mixes from 2008-2013. Figure 5-60 represents the graphical presentation of unit cost per SCDOT District per year of HMA Surface Course Type A from 2008-2013.

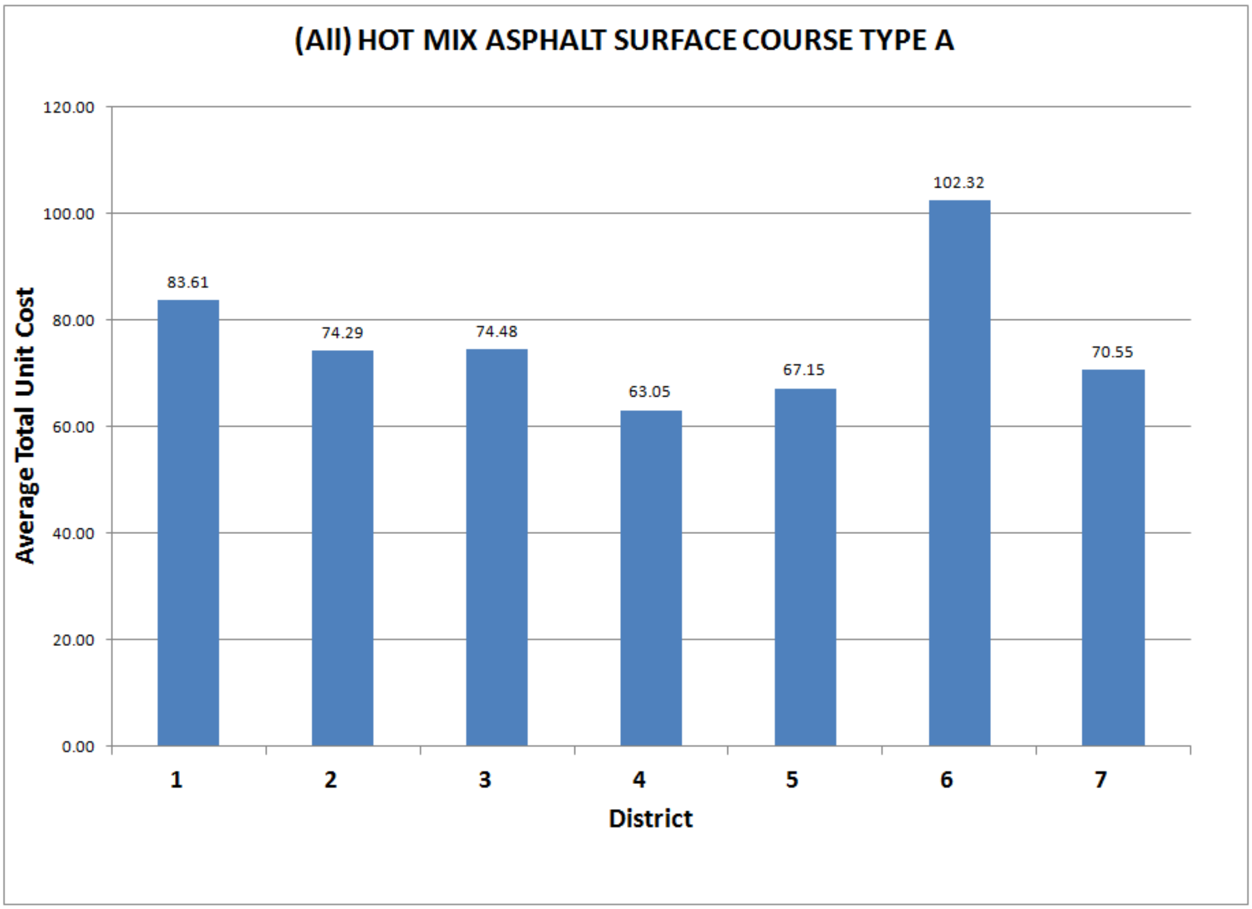


Figure 5-58: HMA Surface Course Type A Average Unit Cost Per SCDOT District from 2008-2013

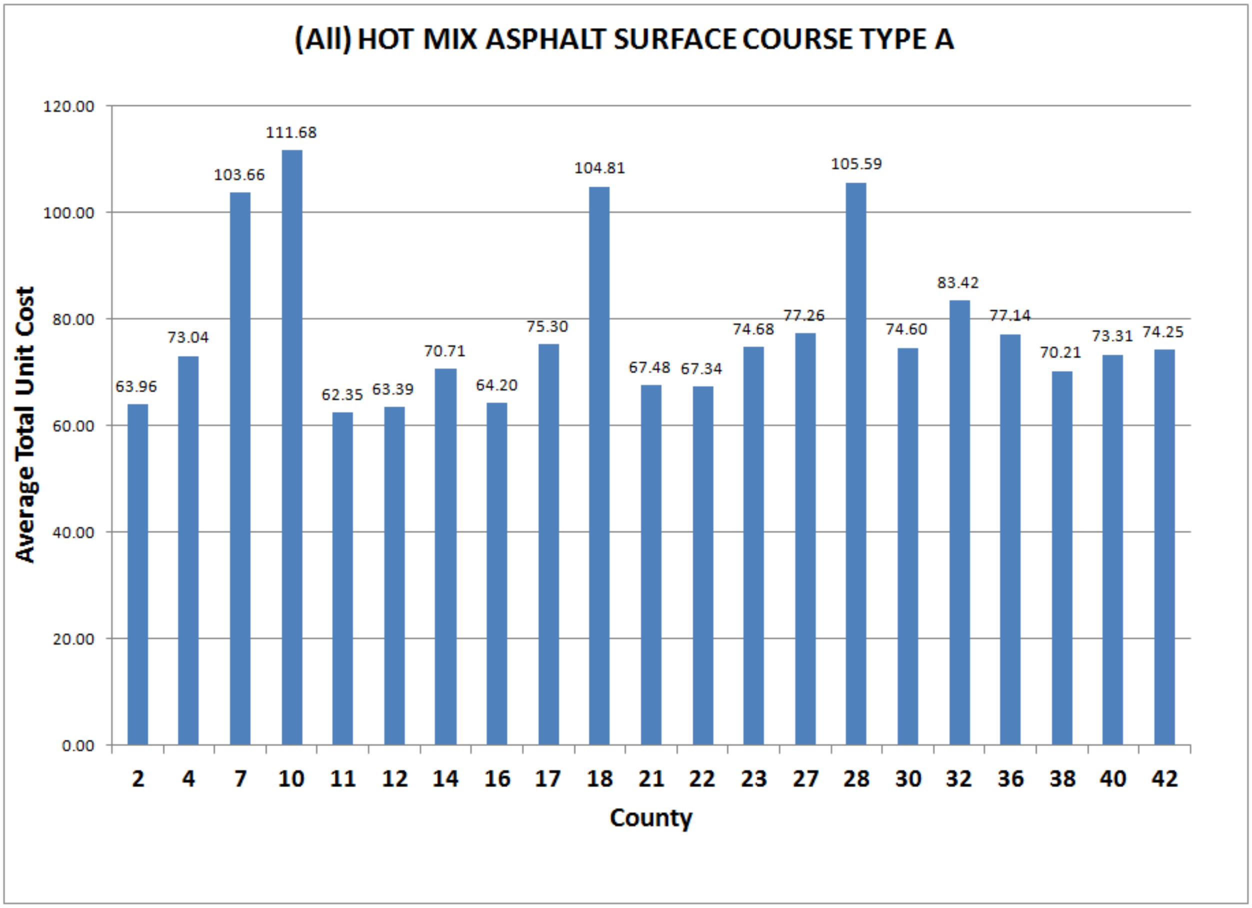


Figure 5-59: HMA Surface Course Type A Average Unit Cost Per SC County from 2008-2013

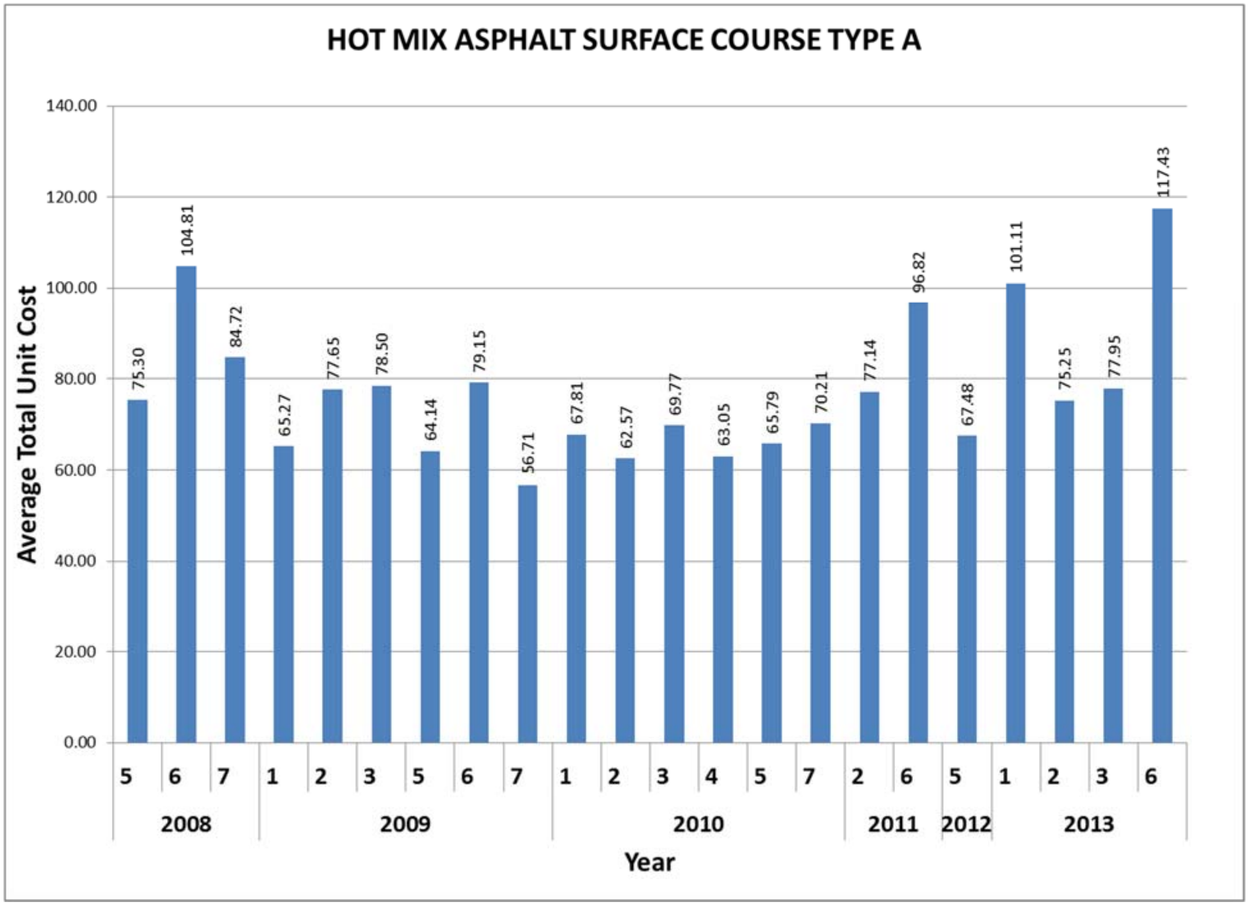


Figure 5-60: HMA Surface Course Type A Average Unit Cost Per SCDOT District per Year from 2008-2013

Figure 5-58 indicates that SCDOT District 6 had the highest unit cost for HMA Surface Course Type A from 2008-2013 at $102.33 and was significantly different at the $\alpha = 0.05$ level compared to all other Districts (Appendix C, Table 10-34). SCDOT Districts 4 and 5 had the lowest unit cost for HMA Surface Course Type A from 2008-2013 at $65.05 and $67.15, respectively and they were statistically equivalent at the $\alpha = 0.05$ level (Appendix C, Table 10-34). The average unit cost of HMA Surface Course Type A from 2008-2013 was $80.78 with a standard deviation of $6.22 per SCDOT District.

Figure 5-59 indicates that SCDOT designated counties 7 and 10 had the highest unit cost for HMA Surface Course Type A from 2008-2013 at $103.66 and $111.68, respectively. SCDOT designated counties 11 and 12 had the lowest unit cost for HMA Surface Course Type A from 2008-2013 at $62.35 and $63.39, respectively. The average unit cost of HMA Surface Course Type A from 2008-2013 was $80.78 with a standard deviation of $15.13 per county. No statistical analysis was performed on this graph due to limited data at various data points.

There were no general trends determined from Figure 5-60 which evaluated unit cost per year per SCDOT District for HMA Surface Course Type A. There was no statistical analysis performed on this data set due to limited data at various data points.

HMA Surface Course Type B

Figure 5-61 represents the graphical presentation of unit cost per SCDOT District of HMA Surface Course Type B mixes from 2008-2013. Figure 5-62 represents the graphical presentation of unit cost per SC county of HMA Surface Course Type B mixes from 2008-2013. Figure 5-63 represents the graphical presentation of unit cost per SCDOT District per year of HMA Surface Course Type B from 2008-2013.

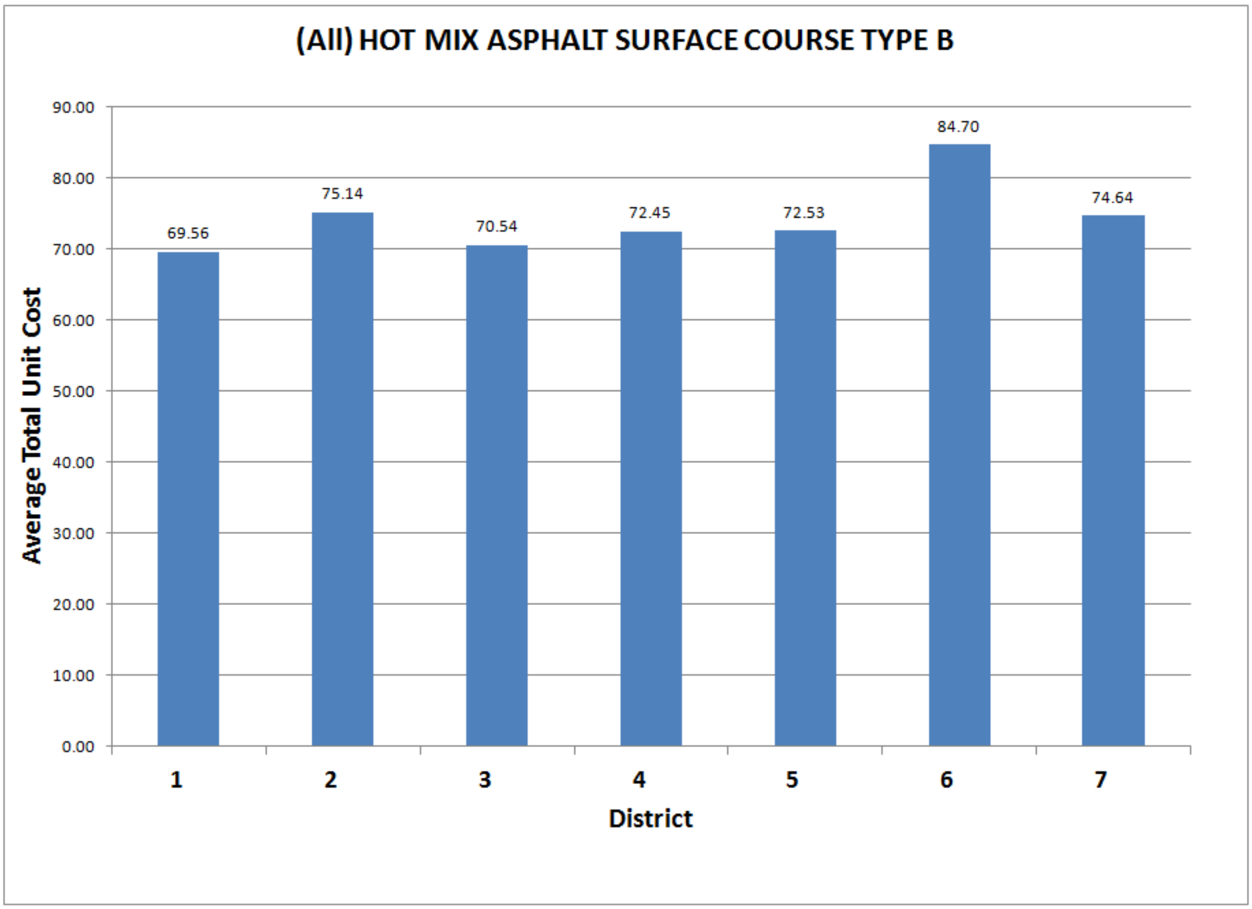


Figure 5-61: HMA Surface Course Type B Average Unit Cost Per SCDOT District from 2008-2013

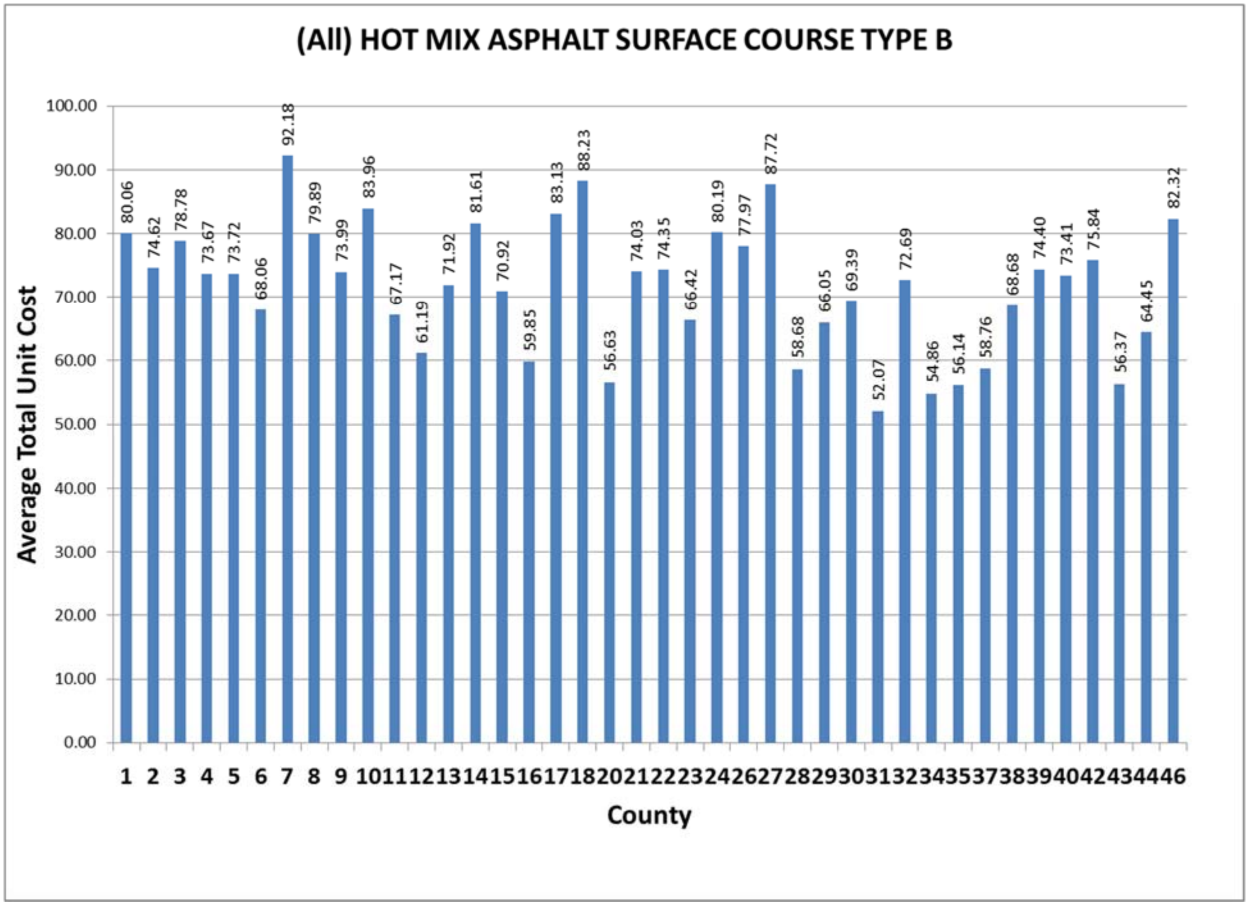


Figure 5-62: HMA Surface Course Type B Average Unit Cost Per SC County from 2008-2013

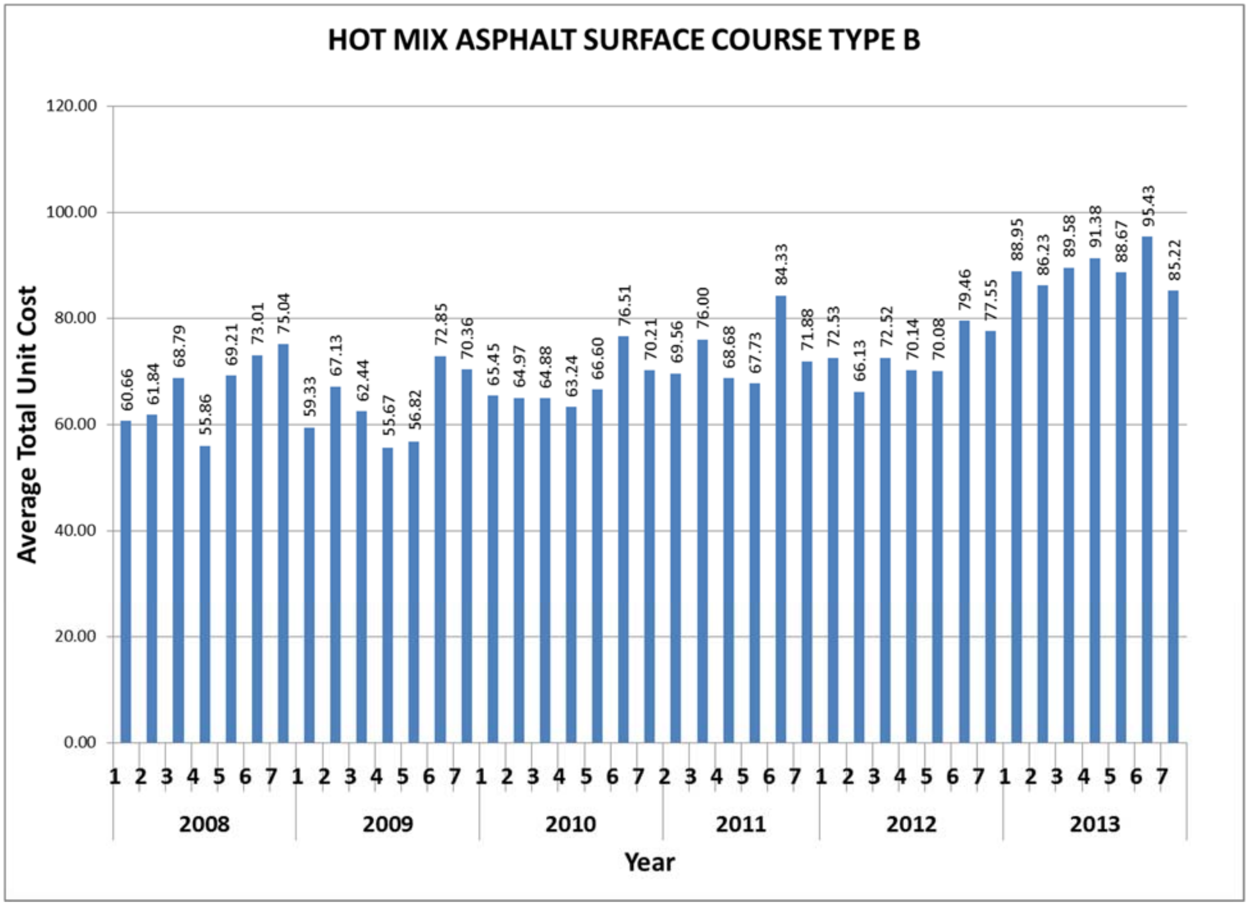


Figure 5-63: HMA Surface Course Type B Average Unit Cost Per SCDOT District per Year from 2008-2013

Figure 5-61 indicates that SCDOT and 6 had the highest unit cost for HMA Surface Course Type B from 2008-2013 at $84.70 and was significantly different from all other Districts (Appendix C, Table 10-35). SCDOT District 1 had the lowest unit cost for HMA Surface Course Type B from 2008-2013 at $69.56 and was significantly different that all Districts except District 7 (Appendix C, Table 10-35). The average unit cost of HMA Surface Course Type B from 2008-2013 was $74.57 with a standard deviation of $5.03 per SCDOT District.

Figure 5-62 indicates that SCDOT designated counties 7 and 18 had the highest unit cost for HMA Surface Course Type B from 2008-2013 at $92.18 and $88.23, respectively. SCDOT designated counties 31 and 34 had the lowest unit cost for HMA Surface Course Type B from 2008-2013 at $52.07 and $54.88, respectively. The average unit cost of HMA Surface Course Type B from 2008-2013 was $74.57 with a standard deviation of $10.03 per county.   No statistical analysis was performed on this graph due to limited data at various data points.

Figure 5-63 indicates that a general increase in unit cost per year for HMA Surface Course Type B took place. Unit costs for HMA Surface Course Type B mix averaged $67.25 in 2008 and increased incrementally to an average of $90.59 in 2013. This gradual increase is mostly likely due to inflationary pressures and/or trends in the SCDOT Asphalt Binder Index. No statistical analysis was performed on this graph due to limited data at various data points.

HMA Surface Course Type C

Figure 5-64 represents the graphical presentation of unit cost per SCDOT District of HMA Surface Course Type C mixes from 2008-2013. Figure 5-65 represents the graphical presentation of unit cost per SC county of HMA Surface Course Type C mixes from 2008-2013. Figure 5-66 represents the graphical presentation of unit cost per SCDOT District per year of HMA Surface Course Type C from 2008-2013.

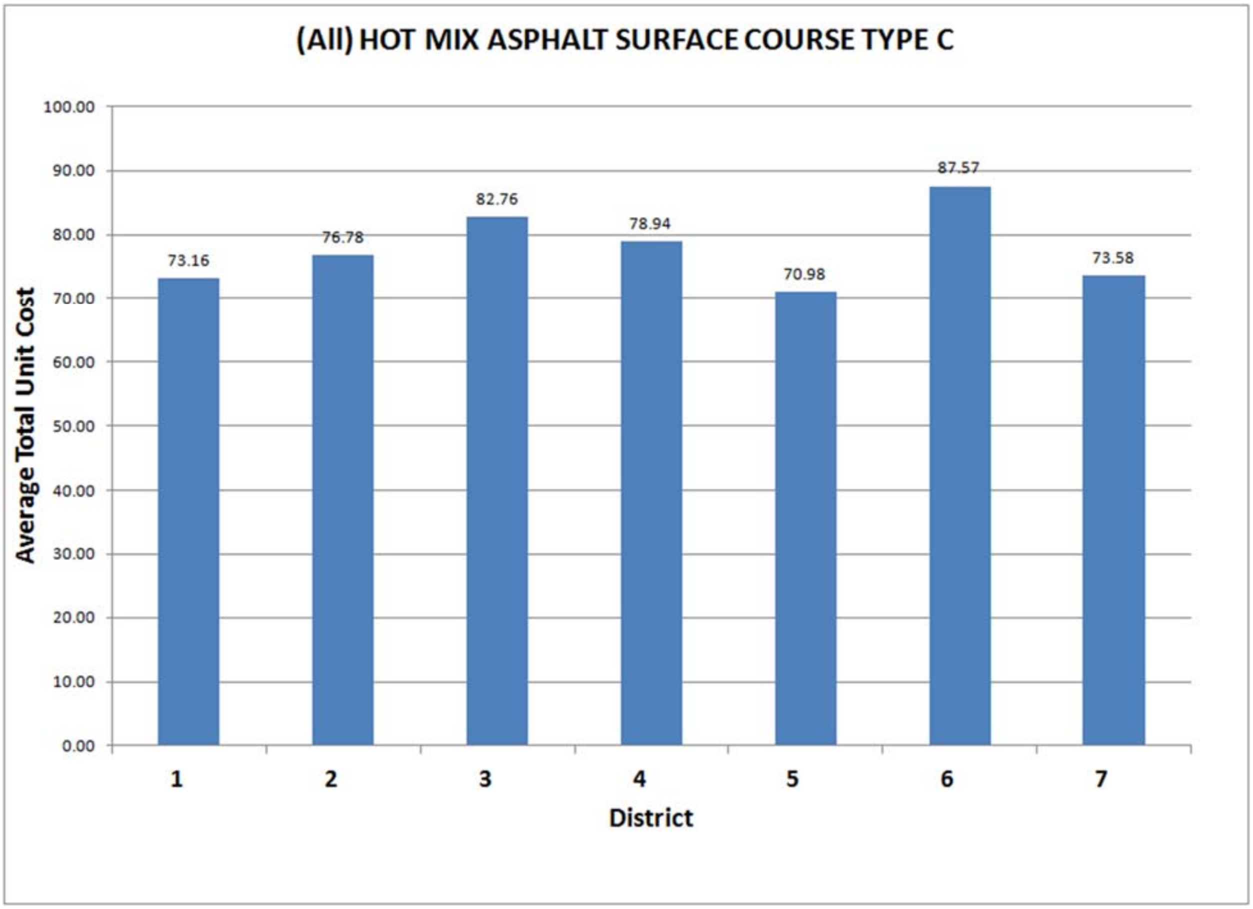


Figure 5-64: HMA Surface Course Type C Average Unit Cost Per SCDOT District from 2008-2013

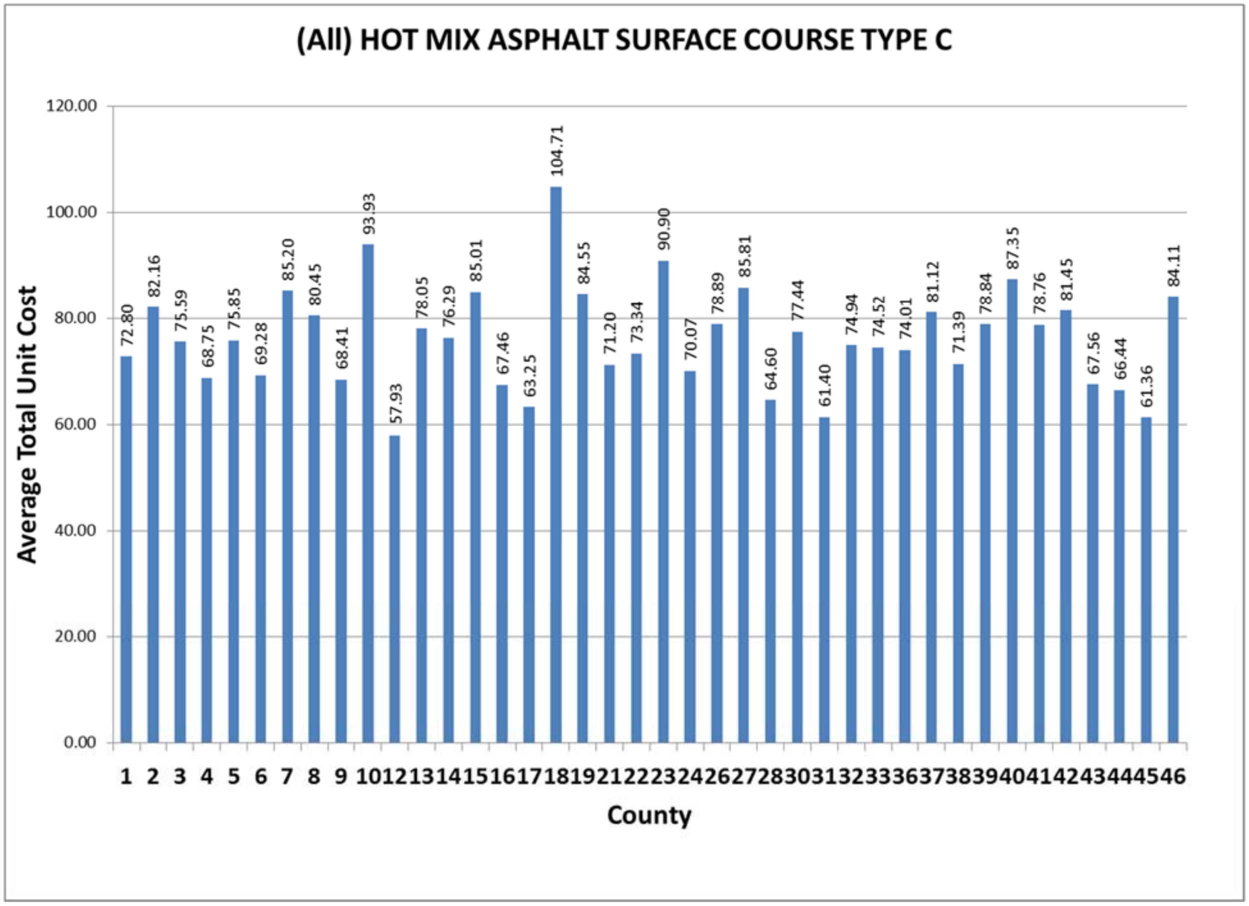


Figure 5-65: HMA Surface Course Type C Average Unit Cost Per SC County from 2008-2013

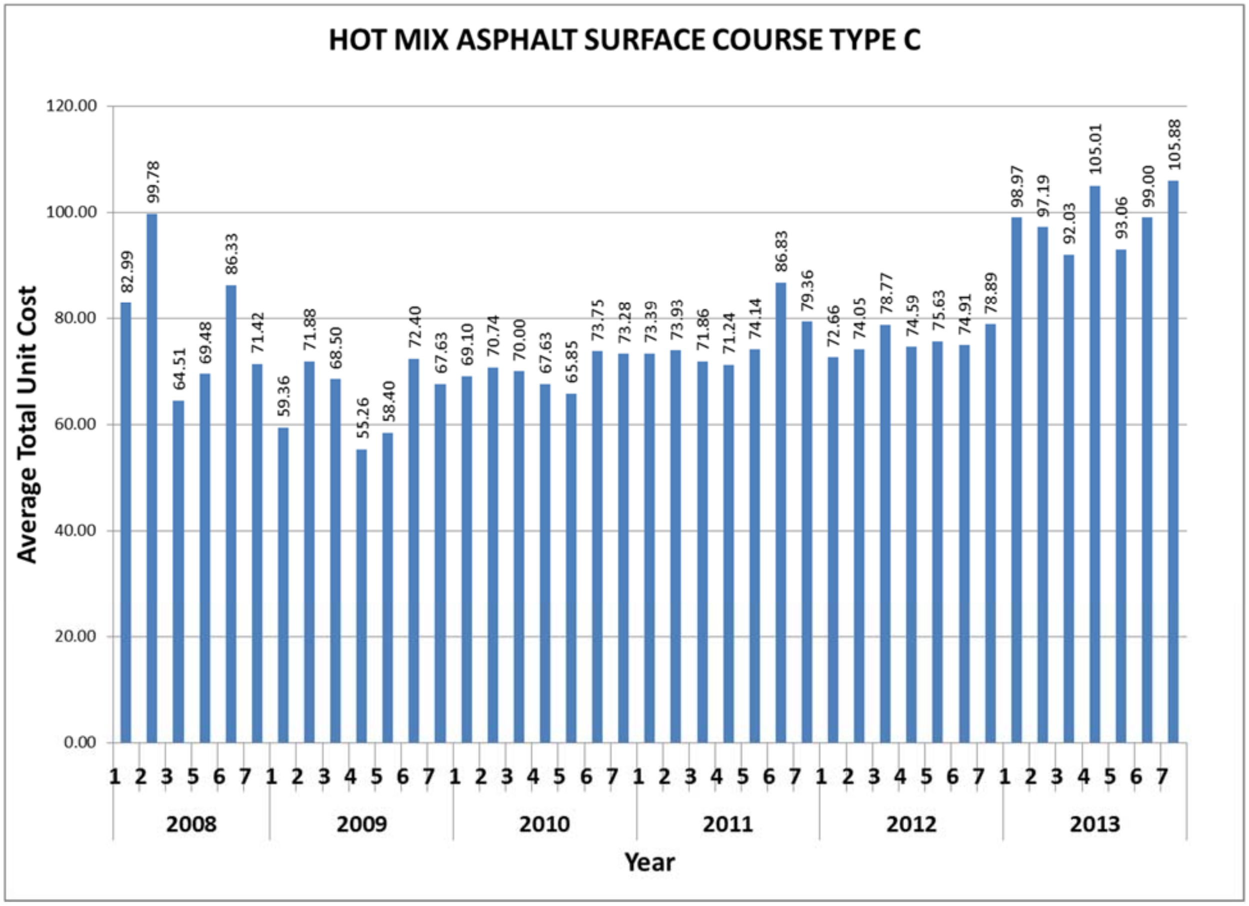


Figure 5-66: HMA Surface Course Type C Average Unit Cost Per SCDOT District per Year from 2008-2013

Figure 5-64 indicates that SCDOT District 6 had the highest unit cost for HMA Surface Course Type C from 2008-2013 at $87.57 However, Districts 3,4, and 6 were statistically equivalent at the $\alpha = 0.05$ level (Appendix C, Table 10-36). SCDOT Districts 1 and 5 had the lowest unit cost for HMA Surface Course Type C from 2008-2013 at $73.16 and $76.58, respectively, and were statistically equivalent at the $\alpha = 0.05$ level (Appendix C, Table 10-36). The average unit cost of HMA Surface Course Type C from 2008-2013 was $75.38 with a standard deviation of $5.89 per SCDOT District.

Figure 5-65 indicates that SCDOT designated counties 10 and 18 had the highest unit cost for HMA Surface Course Type C from 2008-2013 at $93.93 and $104.71, respectively. SCDOT designated counties 12 and 45 had the lowest unit cost for HMA Surface Course Type C from 2008-2013 at $57.93 and $61.36, respectively. The average unit cost of HMA Surface Course Type C from 2008-2013 was $75.38 with a standard deviation of $9.585 per county. No statistical analysis was performed on this graph due to limited data at various data points.

Figure 5-66 indicates that a general increase in unit cost per year for HMA Surface Course Type C took place. Unit costs for HMA Surface Course Type C mix averaged $78.77 in 2008 and increased incrementally to an average of $97.01 in 2013. This gradual increase is mostly likely due to inflationary pressures and/or trends in the SCDOT Asphalt Binder Index. No statistical analysis was performed on this graph due to limited data at various data points.

HMA Surface Course Type CM

Figure 5-67 represents the graphical presentation of unit cost per SCDOT District of HMA Surface Course Type CM mixes from 2008-2013. Figure 5-68 represents the graphical presentation of unit cost per SC county of HMA Surface Course Type CM mixes from 2008-2013. Figure 5-69 represents the graphical presentation of unit cost per SCDOT District per year of HMA Surface Course Type CM from 2008-2013.

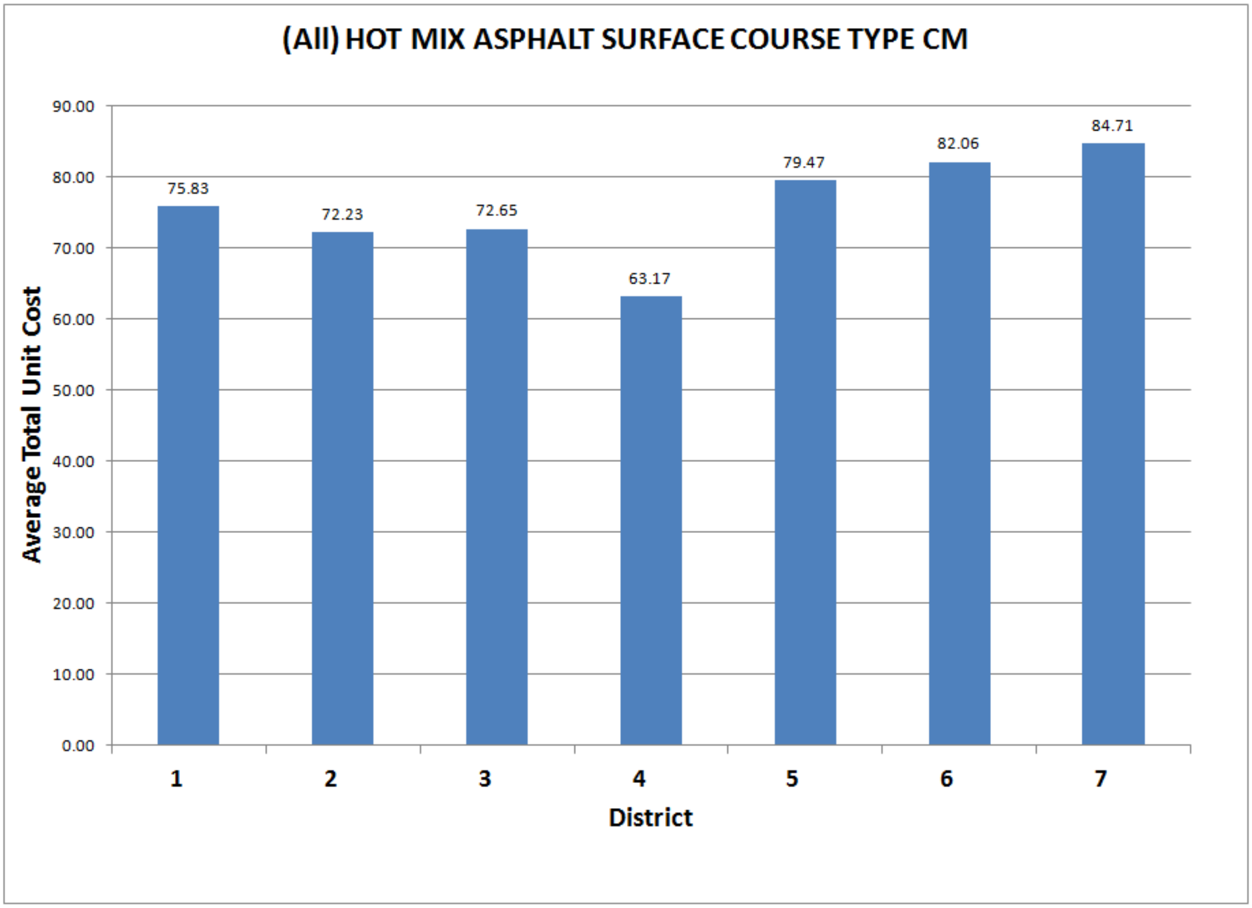


Figure 5-67: HMA Surface Course Type CM Average Unit Cost Per SCDOT District from 2008-2013

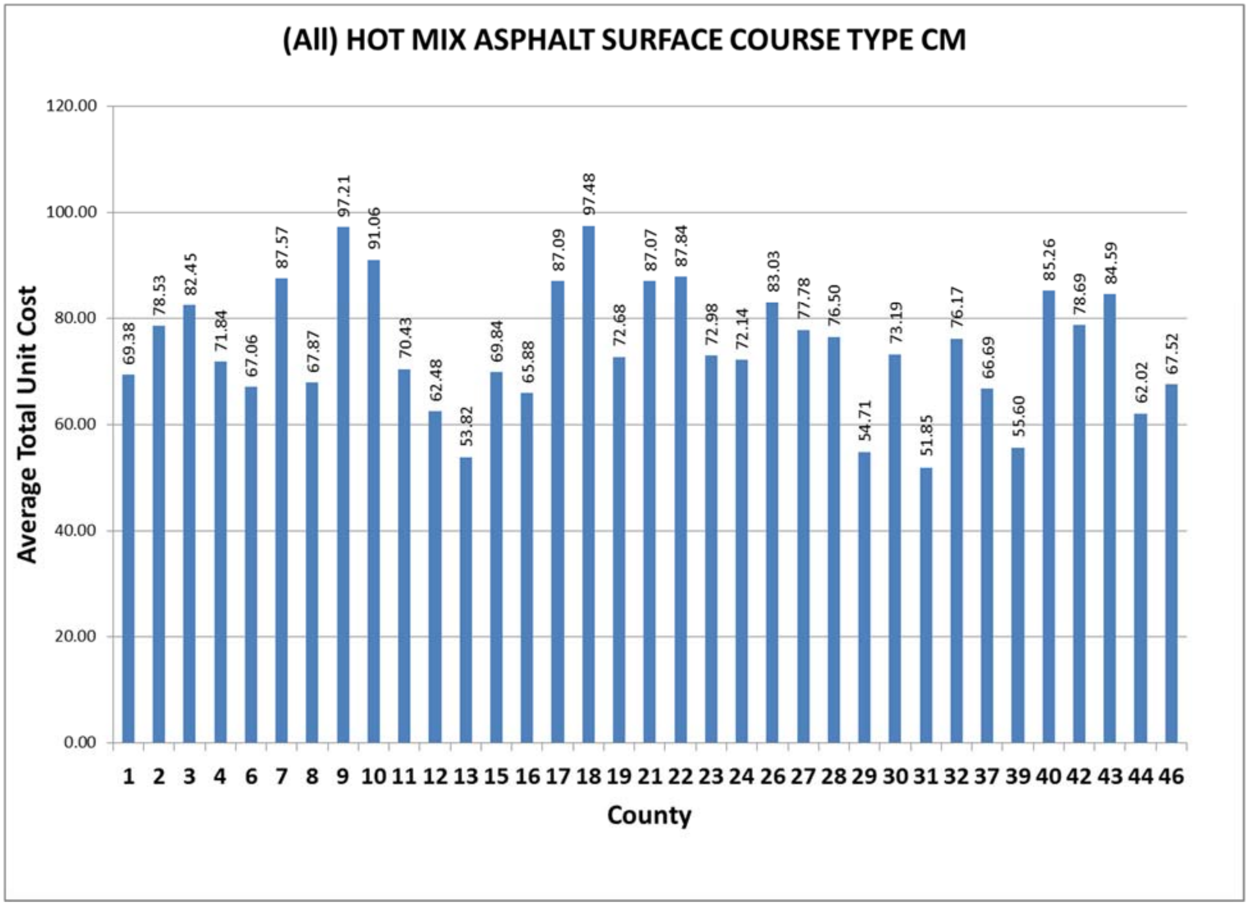


Figure 5-68: HMA Surface Course Type CM Average Unit Cost Per SC County from 2008-2013

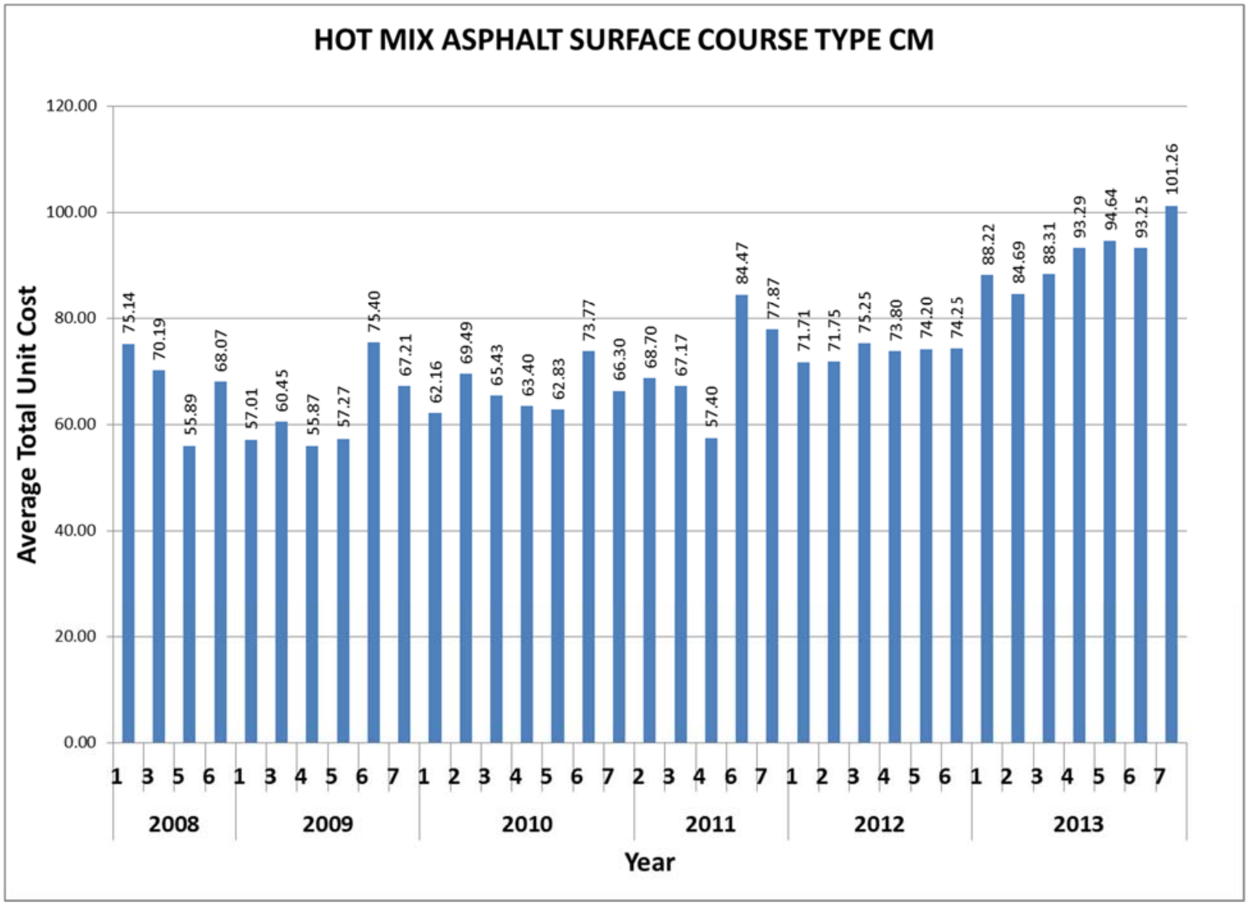


Figure 5-69: HMA Surface Course Type CM Average Unit Cost Per SCDOT District per Year from 2008-2013

Figure 5-67 indicates that SCDOT District 5, 6 and 7 had the highest unit cost for HMA Surface Course Type CM from 2008-2013 and statistically equivalent at the $\alpha = 0.05$ level (Appendix C, Table 10-37). SCDOT District 4 had the lowest unit cost for HMA Surface Course Type CM from 2008-2013 and was statistically different than all other Districts at the $\alpha = 0.05$ level (Appendix C, Table 10-37). The average unit cost of HMA Surface Course Type CM from 2008-2013 was $75.09 with a standard deviation of $7.24 per SCDOT District.

Figure 5-68 indicates that SCDOT designated counties 9 and 18 had the highest unit cost for HMA Surface Course Type CM from 2008-2013 at $97.31 and $97.48, respectively. SCDOT designated counties 13 and 31 had the lowest unit cost for HMA Surface Course Type CM from 2008-2013 at $51.85 and $53.82, respectively. The average unit cost of HMA Surface Course Type CM from 2008-2013 was $75.09 with a standard deviation of $11.82 per county. No statistical analysis was performed on this graph due to limited data at various data points.

Figure 5-69 indicates that a general increase in unit cost per year for HMA Surface Course Type CM took place. Unit costs for HMA Surface Course Type CM mix averaged $69.22 in 2008 and increased incrementally to an average of $91.84 in 2013. This gradual increase is mostly likely due to inflationary pressures and/or trends in the SCDOT Asphalt Binder Index. No statistical analysis was performed on this graph due to limited data at various data points.

HMA Surface Course Type D

Figure 5-70 represents the graphical presentation of unit cost per SCDOT District of HMA Surface Course Type D mixes from 2008-2013. Figure 5-71 represents the graphical presentation of unit cost per SC county of HMA Surface Course Type D mixes from 2008-2013. Figure 5-72 represents the graphical presentation of unit cost per SCDOT District per year of HMA Surface Course Type D from 2008-2013.

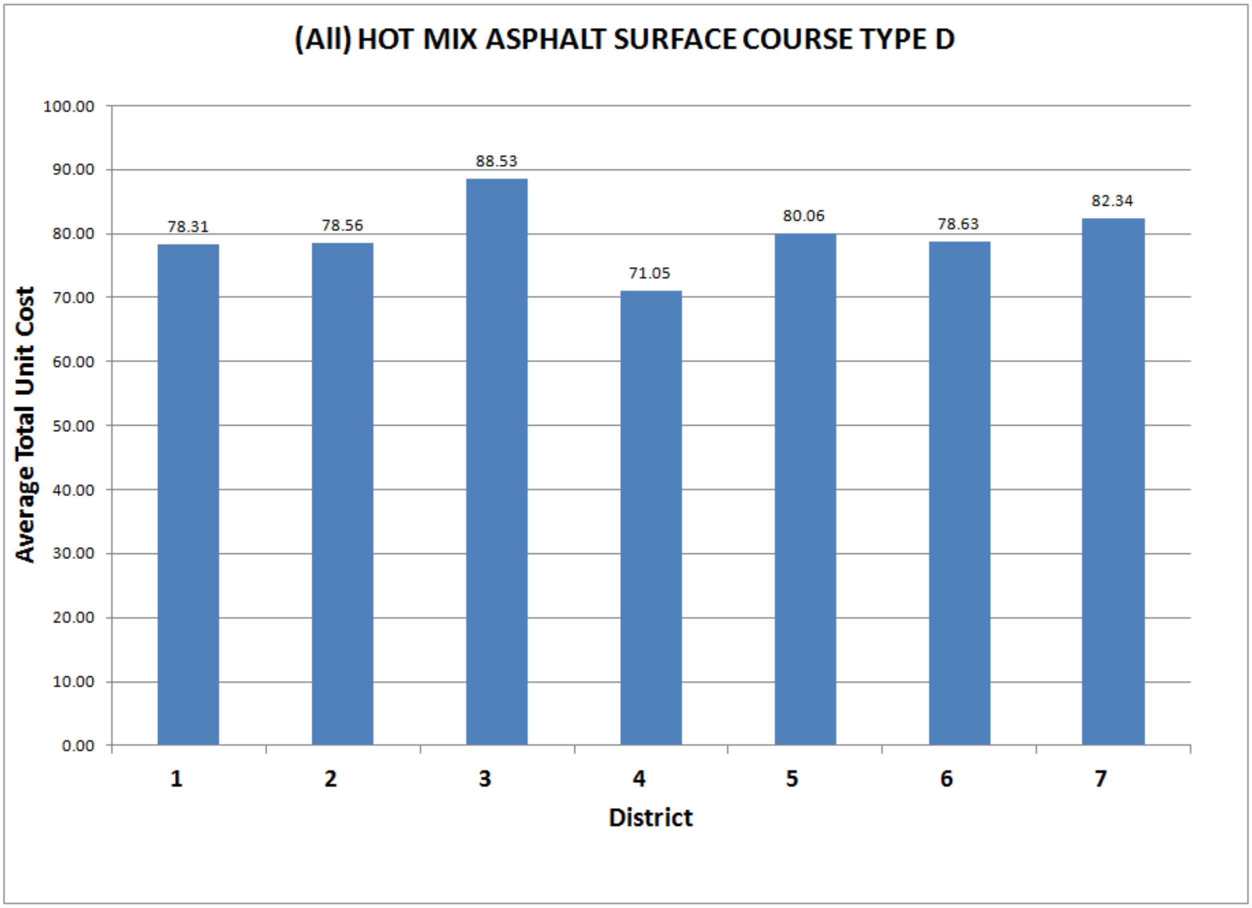


Figure 5-70: HMA Surface Course Type D Average Unit Cost Per SCDOT District from 2008-2013

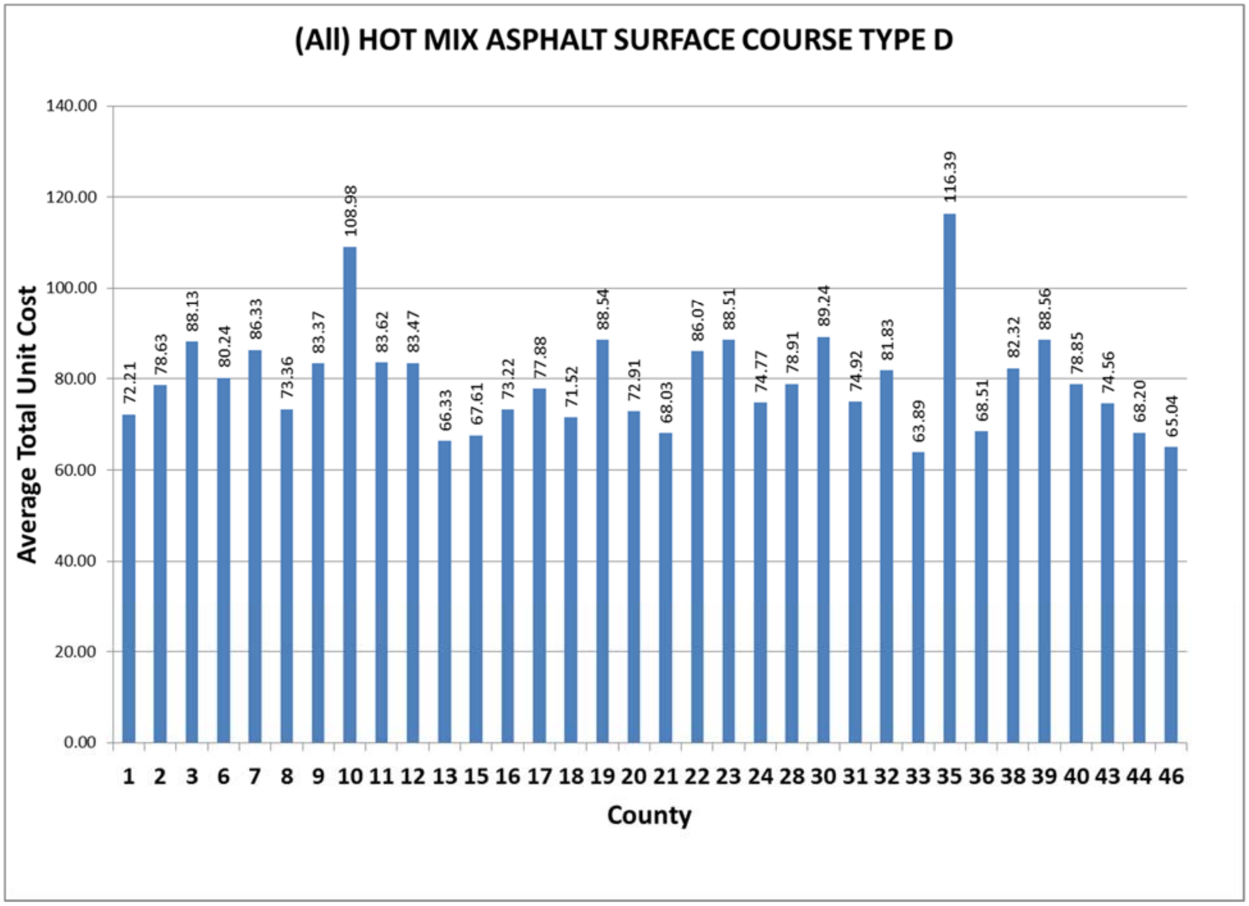


Figure 5-71: HMA Surface Course Type D Average Unit Cost Per SC County from 2008-2013

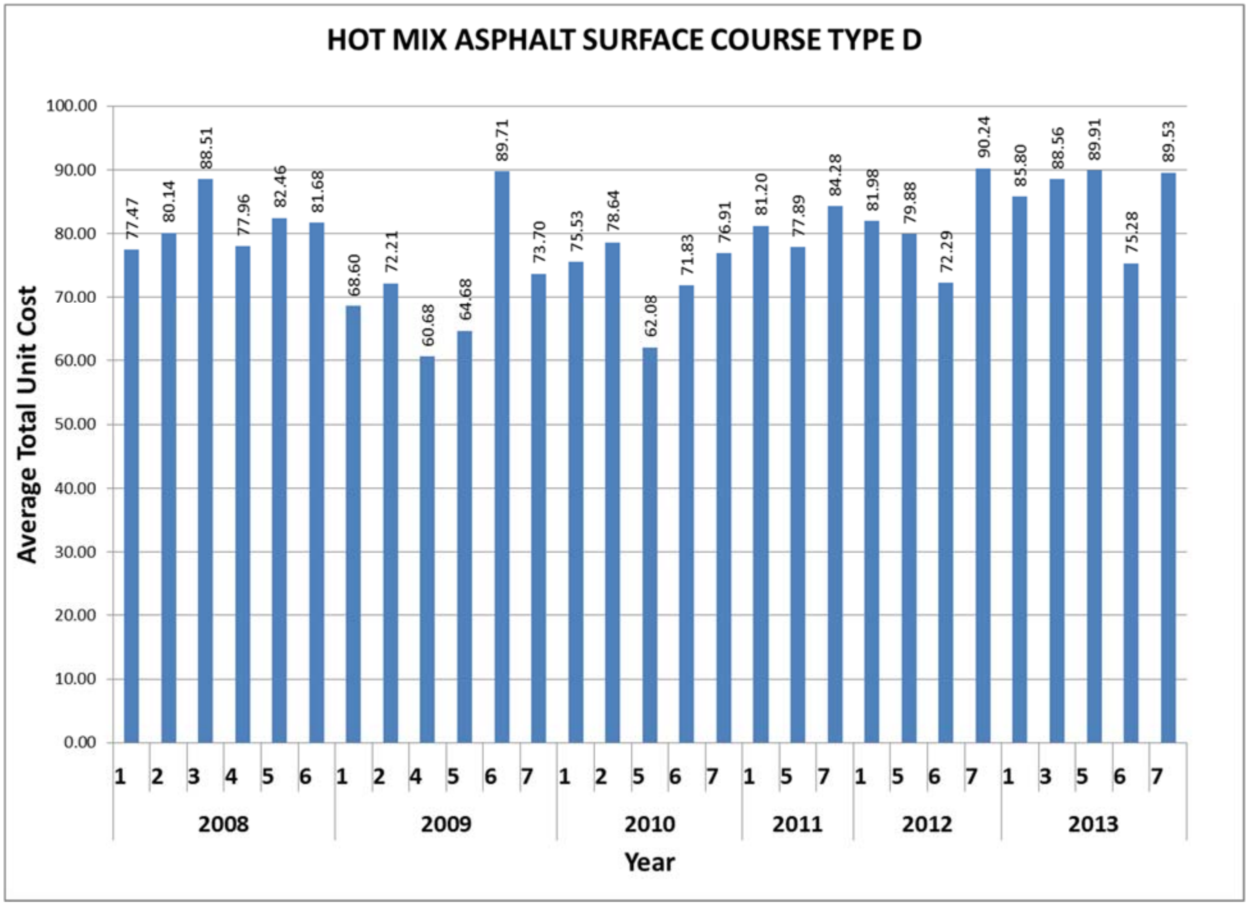


Figure 5-72: HMA Surface Course Type D Average Unit Cost Per SCDOT District per Year from 2008-2013

Figure 5-70 indicates that SCDOT District 3 had the highest unit cost for HMA Surface Course Type D from 2008-2013 at $88.53. However, the results for all Districts were significantly equivalent except District 4 (Appendix C, Table 10-38). SCDOT District 4 had the lowest unit cost for HMA Surface Course Type D from 2008-2013 at $71.05 . The average unit cost of HMA Surface Course Type D from 2008-2013 was $78.95 with a standard deviation of $5.23 per SCDOT District.

Figure 5-71 indicates that counties 10 and 35 had the highest unit cost for HMA Surface Course Type D from 2008-2013 at $106.98 and $116.39, respectively. In addition, counties 33 and 46 had the lowest unit cost for HMA Surface Course Type D from 2008-2013 at $63.89 and $65.04, respectively. The average unit cost of HMA Surface Course Type D from 2008-2013 was $78.95 with a standard deviation of $11.35 per county. No statistical analysis was performed on this graph due to limited data at various data points.

There were no trends observed in Figure 5-72 concerning unit cost per year for HMA Surface Course Type D. No statistical analysis was performed on this graph due to limited data at various data points.

HMA Surface Course Type E

Figure 5-73 represents the graphical presentation of unit cost per SCDOT District of HMA Surface Course Type E mixes from 2008-2013. Figure 5-74 represents the graphical presentation of unit cost per SC county of HMA Surface Course Type E mixes from 2008-2013. Figure 5-75 represents the graphical presentation of unit cost per SCDOT District per year of HMA Surface Course Type E from 2008-2013.

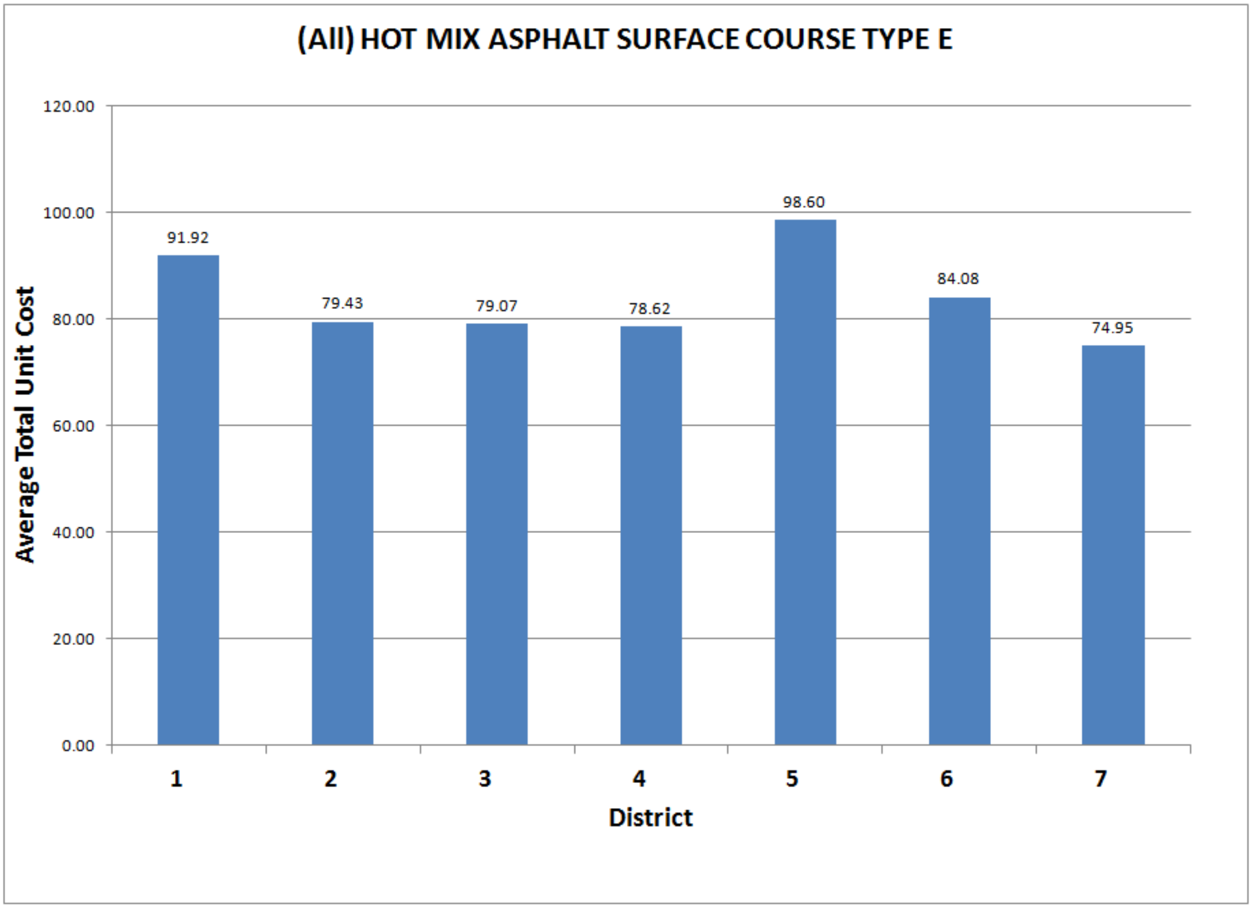


Figure 5-73: HMA Surface Course Type E Average Unit Cost Per SCDOT District from 2008-2013

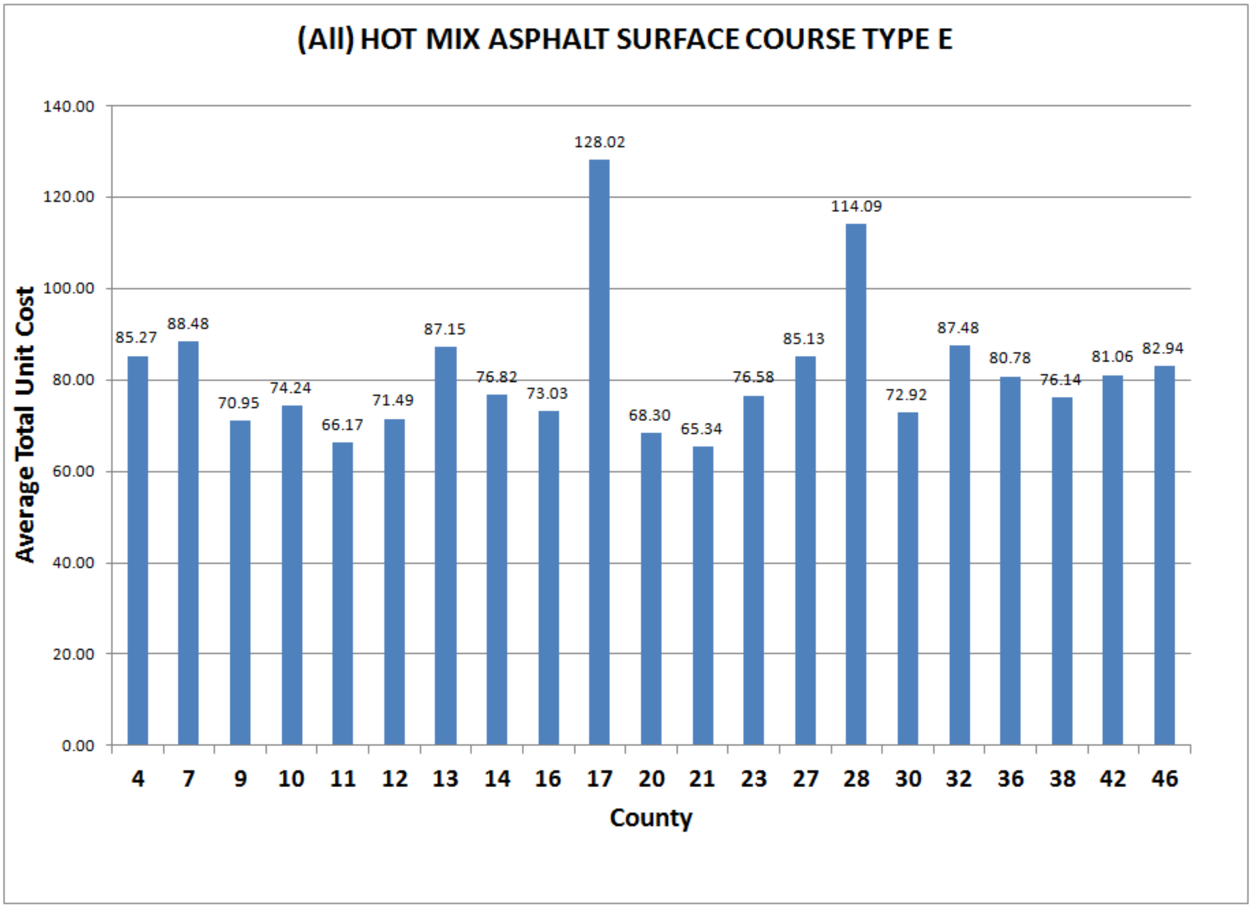


Figure 5-74: HMA Surface Course Type E Average Unit Cost Per SC County from 2008-2013

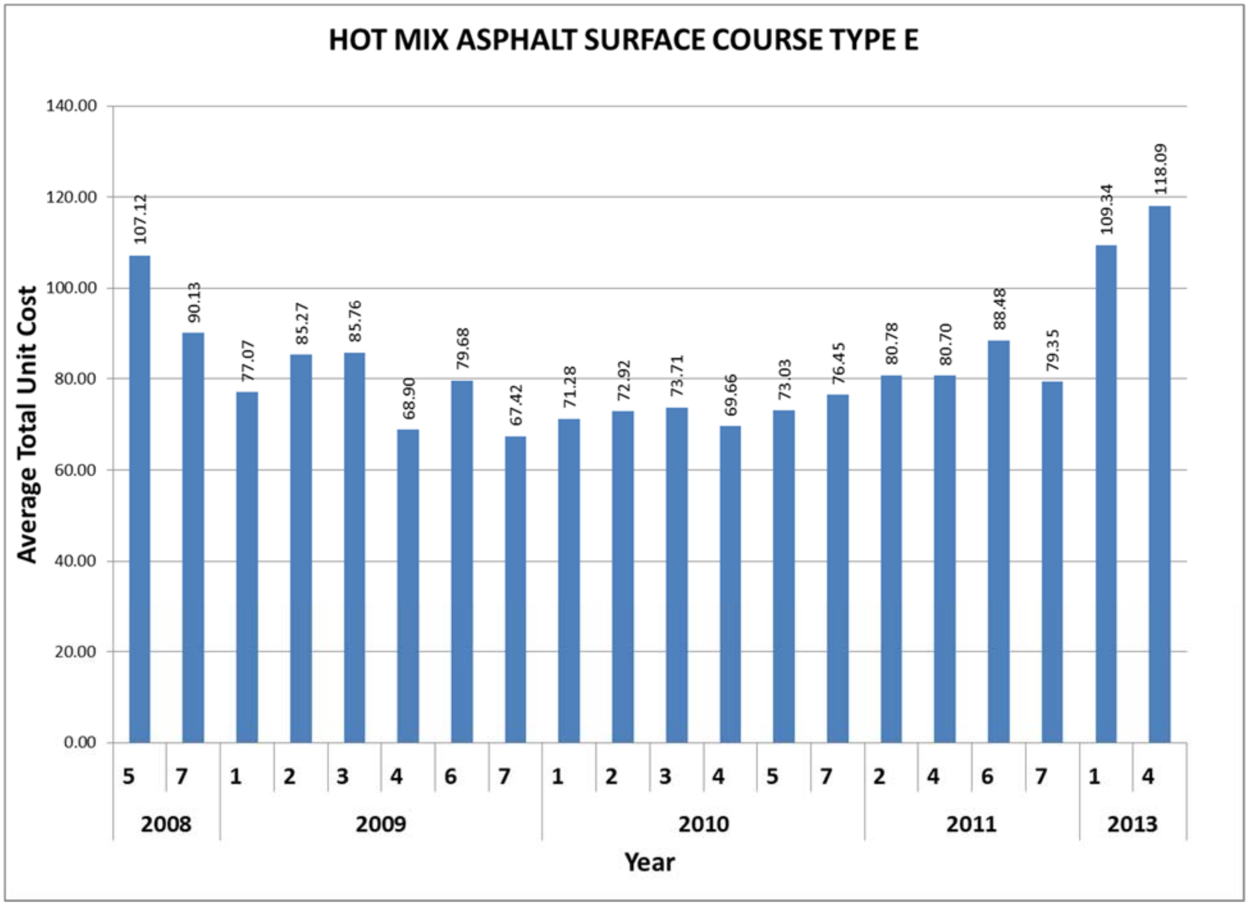


Figure 5-75: HMA Surface Course Type E Average Unit Cost Per SCDOT District per Year from 2008-2013

Figure 5-73 indicates that SCDOT Districts 1 and 5 had the highest unit cost for HMA Surface Course Type E from 2008-2013 at $91.92 and $98.60, respectively. SCDOT Districts 4 and 7 had the lowest unit cost for HMA Surface Course Type E from 2008-2013 at $78.62 and $74.95, respectively. The results indicated that Districts 1 and 7 were significantly different at the $\alpha = 0.05$ level (Appendix C, Table 10-39). The results of all other District combinations were significantly equivalent at the $\alpha = 0.01$ level (Appendix C, Table 10-39). The average unit cost of HMA Surface Course Type E from 2008-2013 was $83.92 with a standard deviation of $8.48 per SCDOT District.

Figure 5-74 indicates that counties 17 and 28 had the highest unit cost for HMA Surface Course Type E from 2008-2013 at $128.02 and $114.09, respectively. In addition, counties 11 and 21 had the lowest unit cost for HMA Surface Course Type E from 2008-2013 at $65.17 and $65.34, respectively. The average unit cost of HMA Surface Course Type E from 2008-2013 was $83.92 with a standard deviation of $15.05 per county. No statistical analysis was performed on this graph due to limited data at various data points.

There were no trends observed in Figure 5-75 concerning unit cost per year for HMA Surface Course Type E. No statistical analysis was performed on this graph due to limited data at various data points.

Cost Comparison of Average Unit Costs of RAP and Virgin Mixes per Year

Asphalt pavement unit cost data points from SCDOT's database for the years 2008 through 2013 were used in this study. It should be noted that unit mix costs can be affected by a wide variety of factors including project size, project location (urban vs. rural, night vs. day), transportation costs, mix application rate, time period placed, and overall market conditions just to name a few. For this portion of the study, all data points for mixes with less than 2,500 tons on a particular project were eliminated from the data. This deletion was approved by the Steering Committee for this project in an attempt to isolate the prices for mainline paving only in order to reduce the effect of small project size on unit prices.

For this section, the total mix unit cost including mix and asphalt binder was calculated using the actual mix unit price for each data point from Site Manager plus the respective calculated binder unit cost for each data point using the SCDOT monthly asphalt indices and the target asphalt binder content for each data point pulled from the associated SCDOT JMF form. In addition, the theoretical unit cost of virgin mix including mix and asphalt binder was calculated using the actual mix unit price for each data point from Site Manager; the respective calculated binder cost paid for each data point using the SCDOT monthly asphalt indices; the estimated value of aggregate each year gathered from the aggregate industry; and the target asphalt binder content, percentage of RAP used, and binder content of the RAP used for each data point pulled from the associated SCDOT JMF form. The following are the formulas used for each of these calculated values.

- % Aged Binder = $$\frac{\frac{\%\,Binder\ in\ RAP\ from\ JMF\ form}{100} \times \%RAP\ from\ JMF\ form}{Optimal\ Binder\ Content\ from\ JMF\ form}$$
- % Virgin Binder = $100 - \%\ Aged\ Binder$
- Quantity of Aged Binder = $$\frac{\%\,Aged\ Binder}{100} \times \frac{Optimal\ Binder\ Content\ from\ JMF\ form}{100} \times Pd.\,Mix\ Qty.$$
- Value of RAP Binder = $Quantity\ of\ Aged\ Binder \times Binder\ Index\ on\ Pymt.\,Date$
- Quantity of RAP Aggregate = $$\frac{\%\,RAP\ from\ JMF\ form}{100} \times Paid\ Mix\ Quanity$$
- Value of RAP Aggregate = $Quantity\ of\ RAP\ Agg. \times Agg.\,Index\ on\ Pymt.\,Date$
- Total Value of RAP = $Value\ of\ RAP\ Binder + Value\ of\ RAP\ Aggregate$
- Total Binder Quantity in Tons = $$\frac{Optimal\ Binder\ Content\ from\ JMF\ form}{100} \times Pd.\,Mix\ Qty.$$

- Total Mix Cost Paid (including mix and binder) = $(Pd.\,Mix\ Qty. \times Unit\ Price) + (Total\ Binder\ Qty. \times Binder\ Index\ on\ Pymt.\,Date)$
- Total Mix Unit Cost =
$$\frac{Total\ Mix\ Cost\ Paid}{Paid\ Mix\ Quantity}$$
- Theoretical Total Cost of Virgin Mix (including mix and binder) =
$$Total\ Mix\ Cost\ Paid + Total\ Value\ of\ RAP$$
- Theoretical Unit Cost of Virgin Mix (including mix and binder) =
$$\frac{Theoretical\ Total\ Cost\ of\ Virgin\ Mix}{Paid\ Mix\ Quantity}$$

The comparison of average total unit mix cost of RAP vs. theoretical virgin mixes per year for all mixture type, HMA shoulder widening course, Type A mix, and Type B mix are shown in Figure 5-76 to Figure 5-79, respectively.

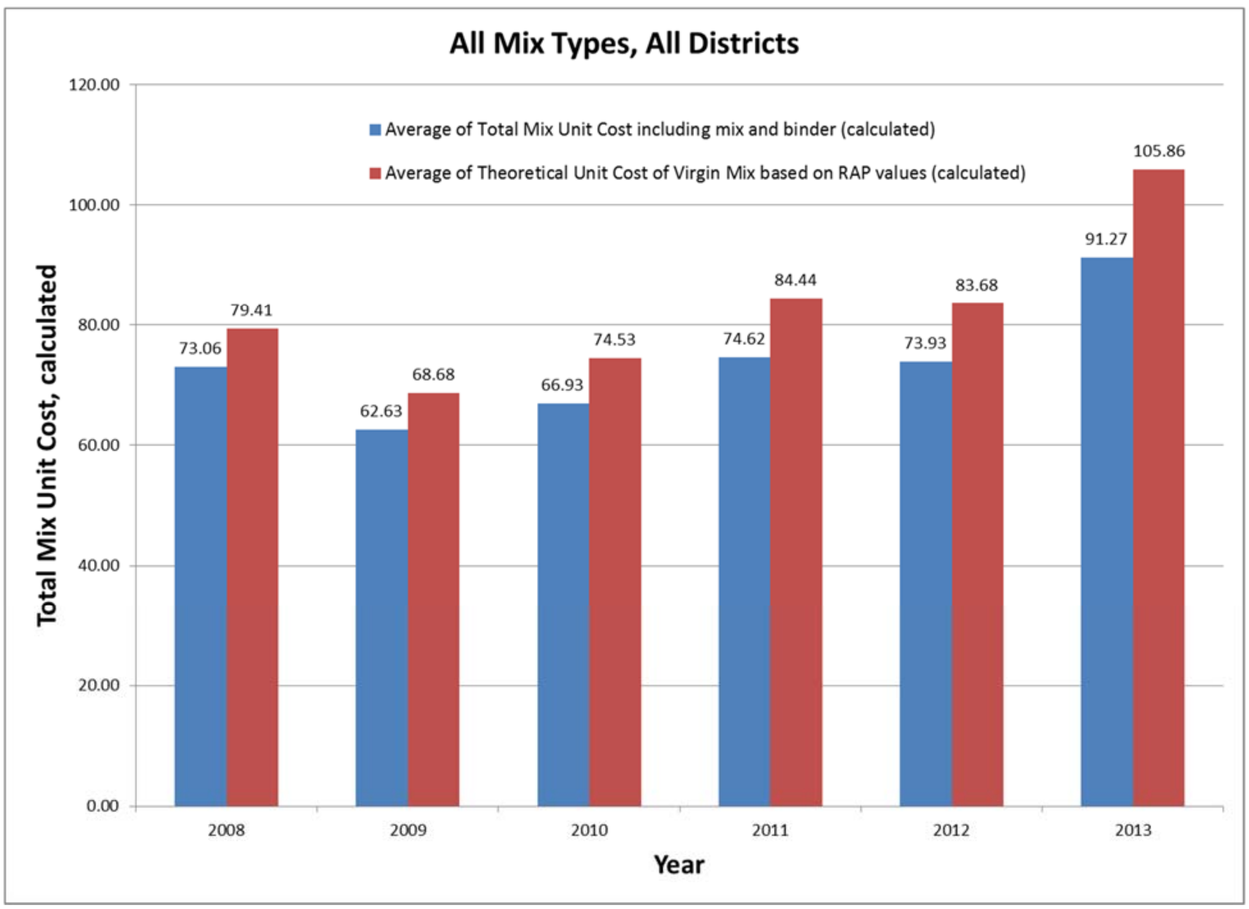


Figure 5-76: Comparison of Average Total Unit Mix Cost of RAP vs. Theoretical Virgin Mixes per Year

HMA Shoulder Widening Course

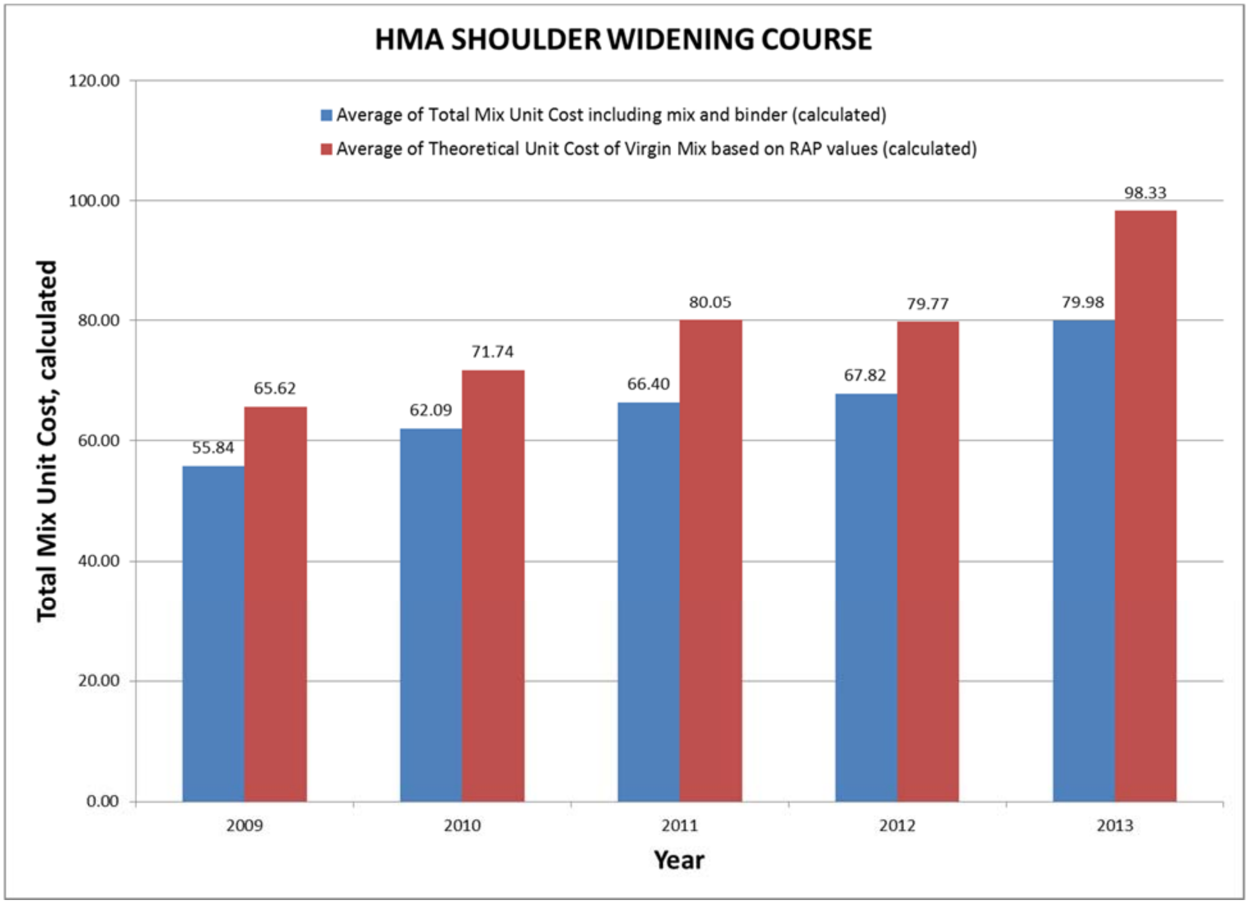


Figure 5-77: Comparison of Average Total Unit Mix Cost of RAP vs. Theoretical Virgin Mixes per Year for HMA Shoulder Widening Course

HMA Base Course Type A

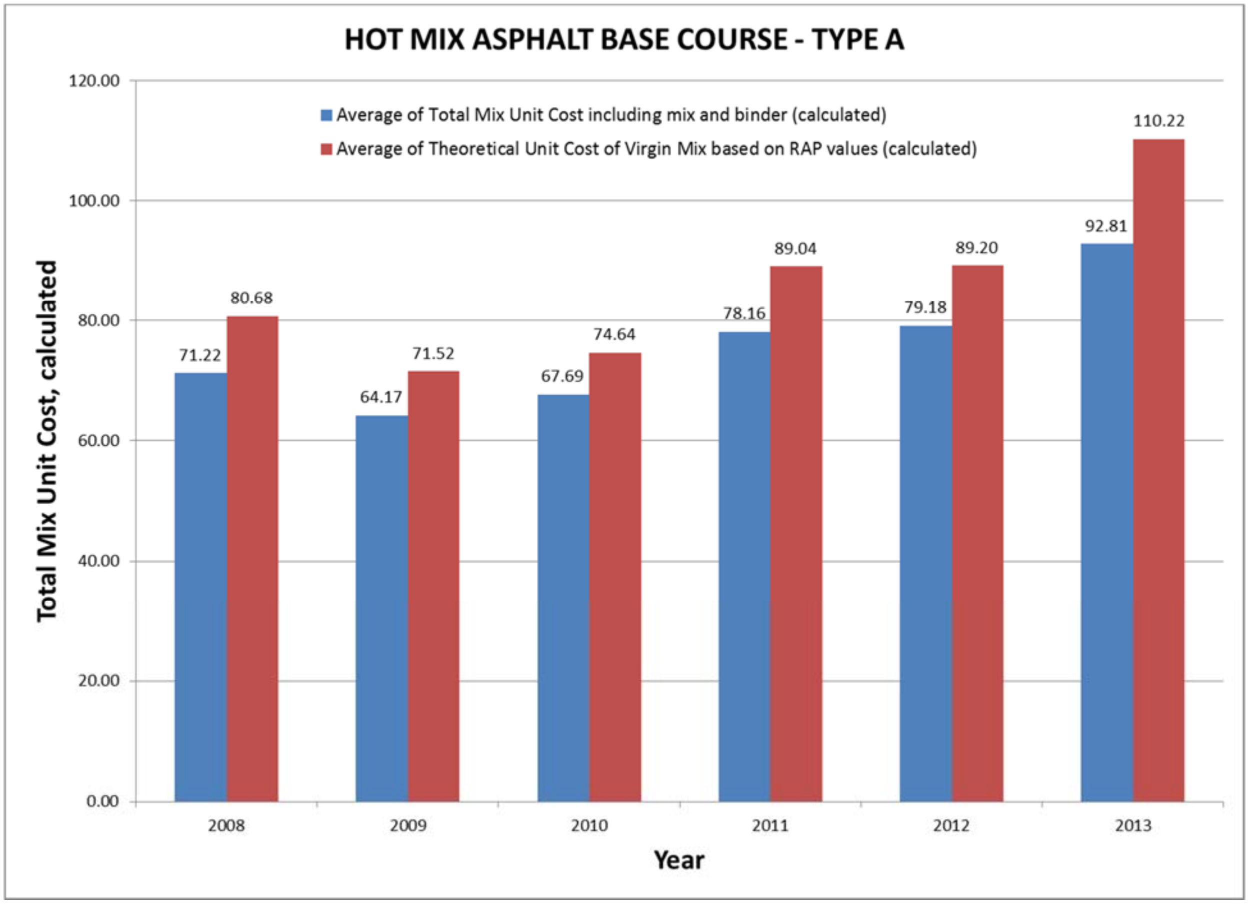


Figure 5-78: Comparison of Average Total Unit Mix Cost of RAP vs. Theoretical Virgin Mixes per Year for HMA Base Course Type A

HMA Base Course Type B

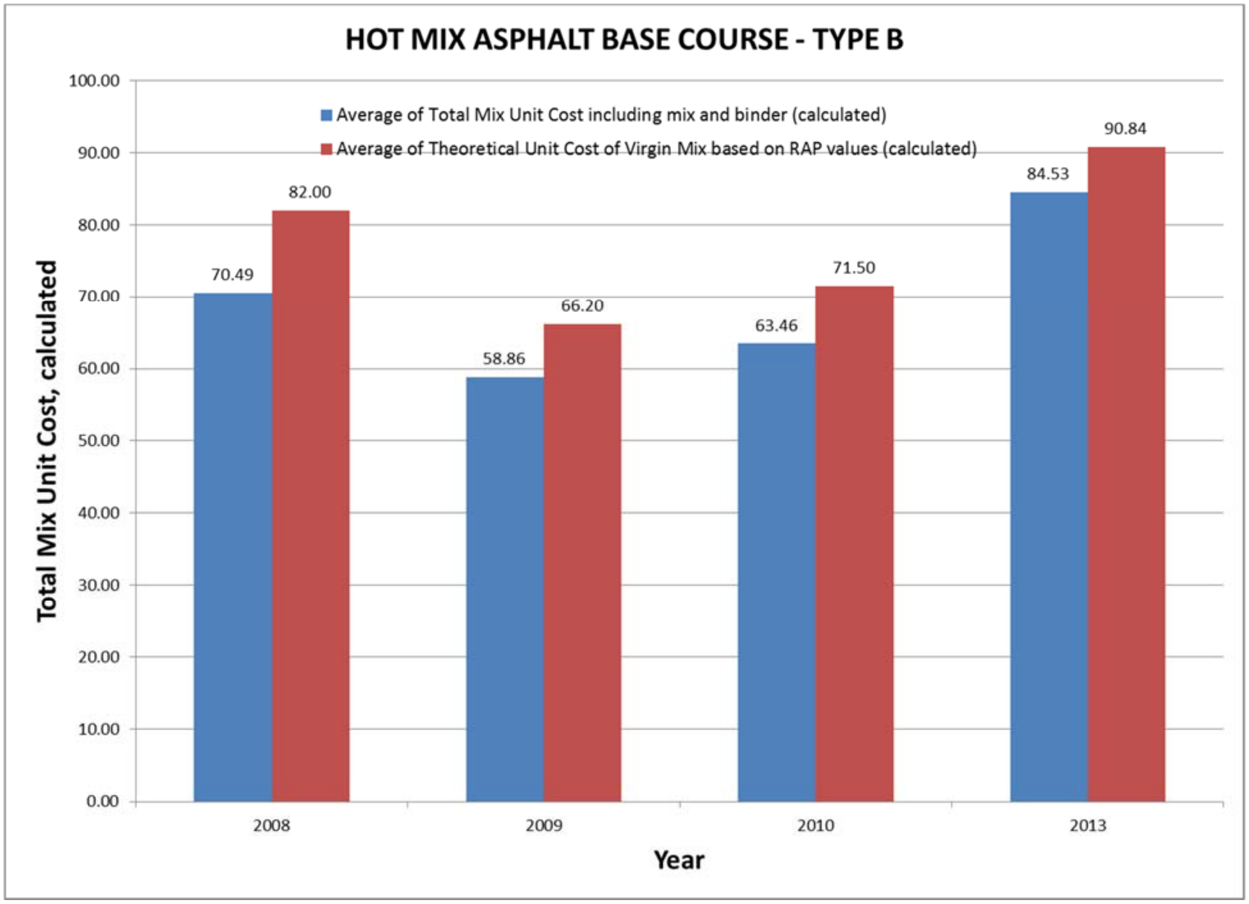


Figure 5-79: Comparison of Average Total Unit Mix Cost of RAP vs. Theoretical Virgin Mixes per Year for HMA Base Course Type B

HMA Base Course Type C

HMA Base Course Type C had very limited use statewide and was used only in SCDOT District 2.

HMA Intermediate Course Type A

HMA Intermediate Course Type A had very limited use statewide and is used primarily on interstate projects. There were no projects where Intermediate A was placed in amounts greater than 2,500 tons during the years included in this project. As mentioned earlier, data points for mixes placed at less than 2,500 tons per project were not analyzed due to their potential to affect the cost data. The results of comparison of average total unit mix cost of RAP vs. theoretical virgin mixes per year for all mixtures are shown in Figures 5-80 to 5-87.

HMA Intermediate Course Type B

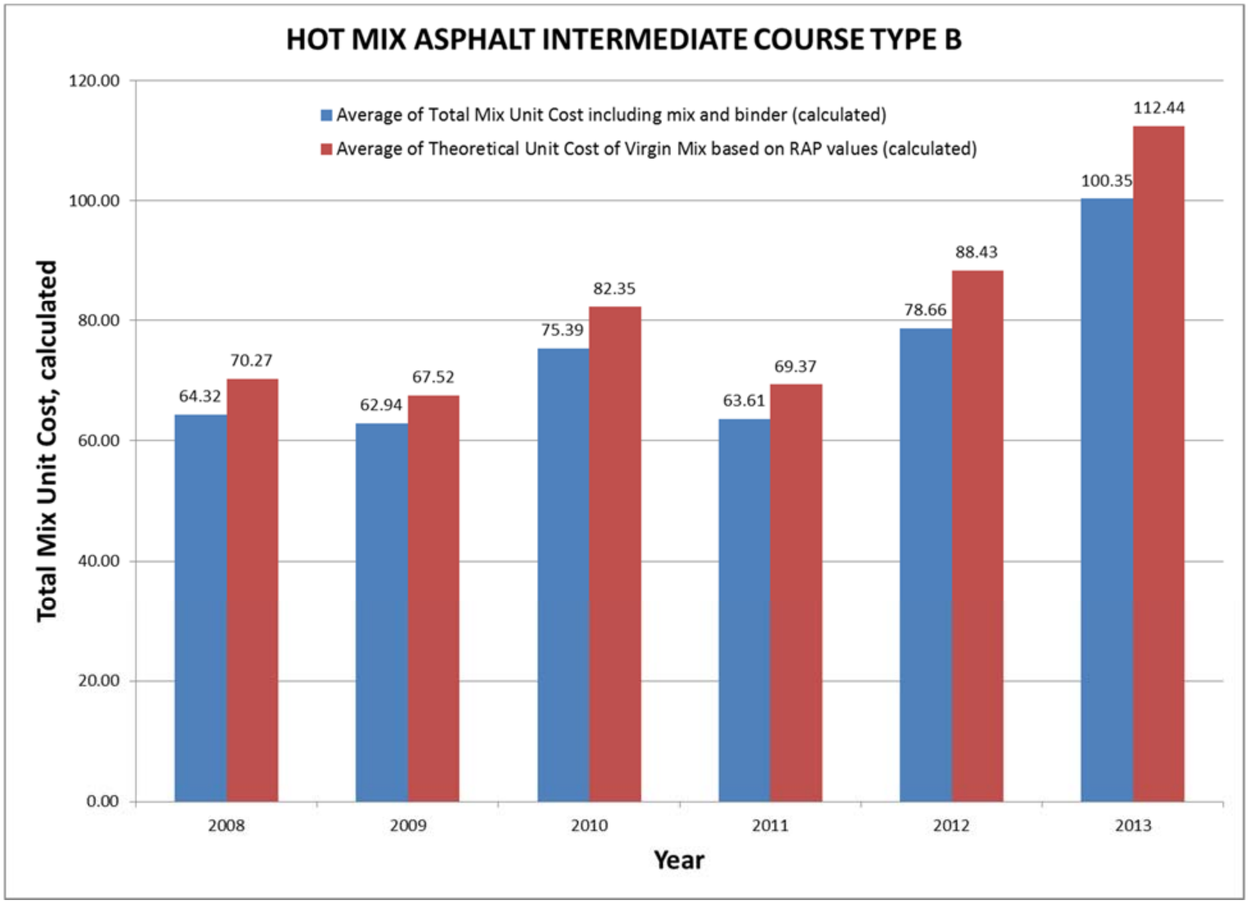


Figure 5-80: Comparison of Average Total Unit Mix Cost of RAP vs. Theoretical Virgin Mixes per Year for HMA Intermediate Course Type B

HMA Intermediate Course Type C

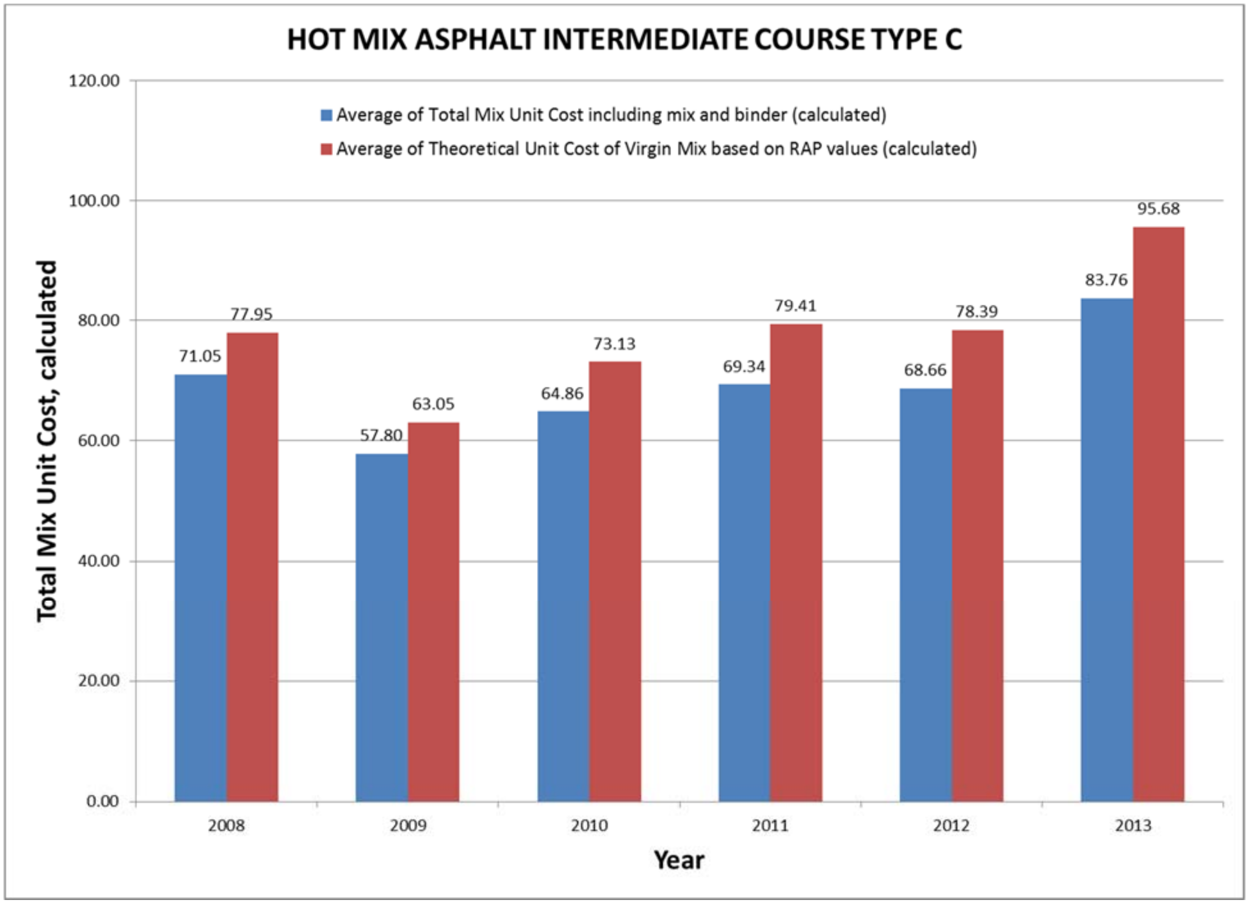


Figure 5-81: Comparison of Average Total Unit Mix Cost of RAP vs. Theoretical Virgin Mixes per Year for HMA Intermediate Course Type C

HMA Surface Course Type A

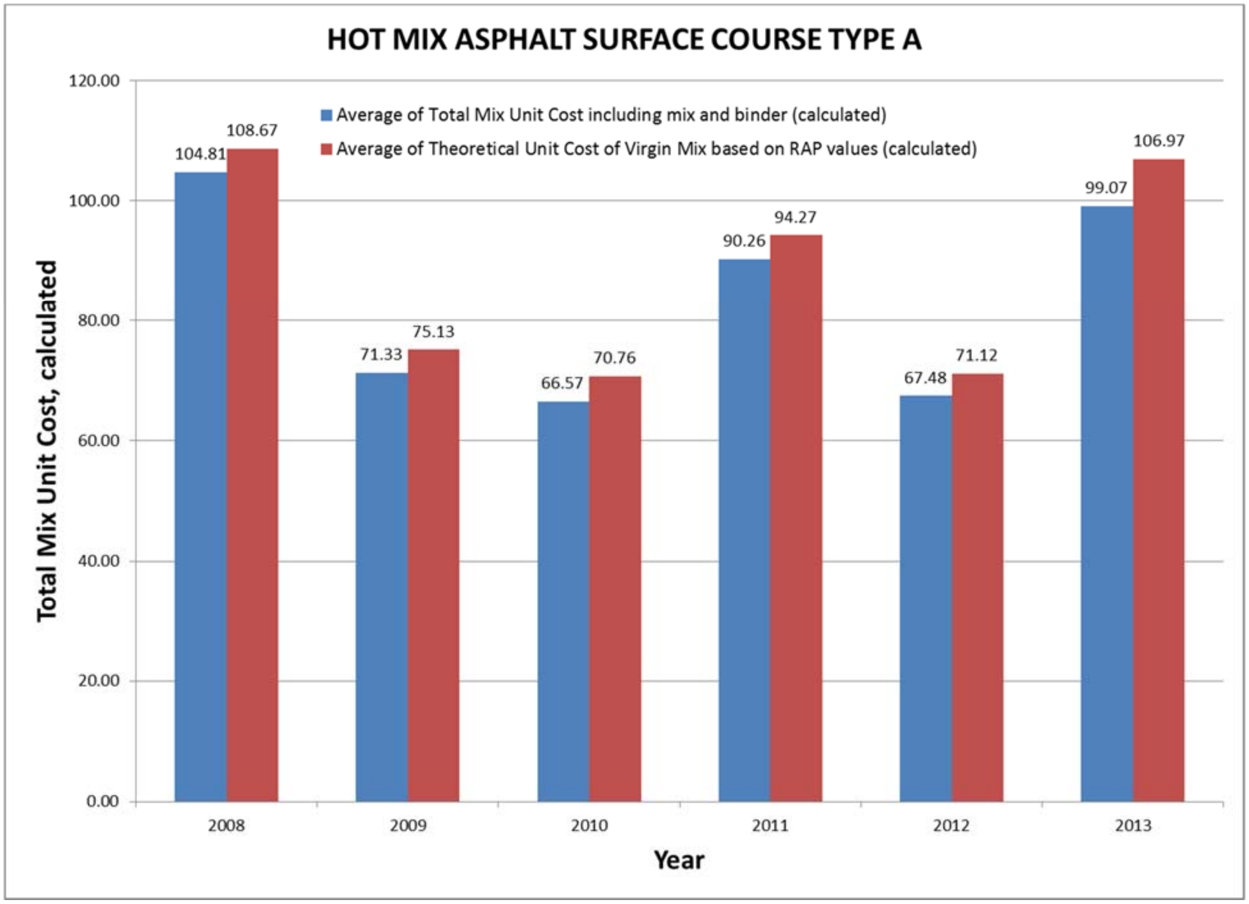


Figure 5-82: Comparison of Average Total Unit Mix Cost of RAP vs. Theoretical Virgin Mixes per Year for HMA Surface Course Type A

HMA Surface Course Type B

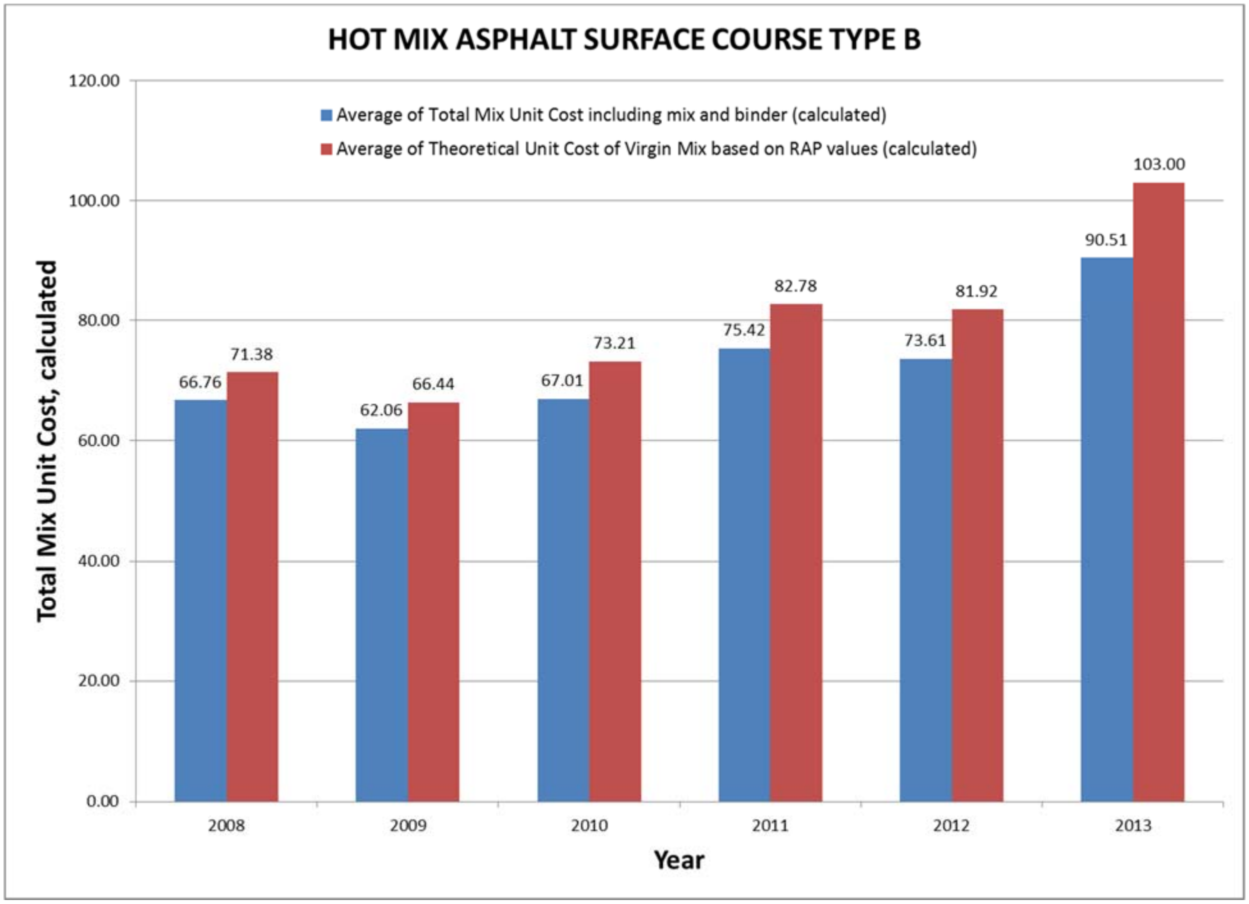


Figure 5-83: Comparison of Average Total Unit Mix Cost of RAP vs. Theoretical Virgin Mixes per Year for HMA Surface Course Type B

HMA Surface Course Type C

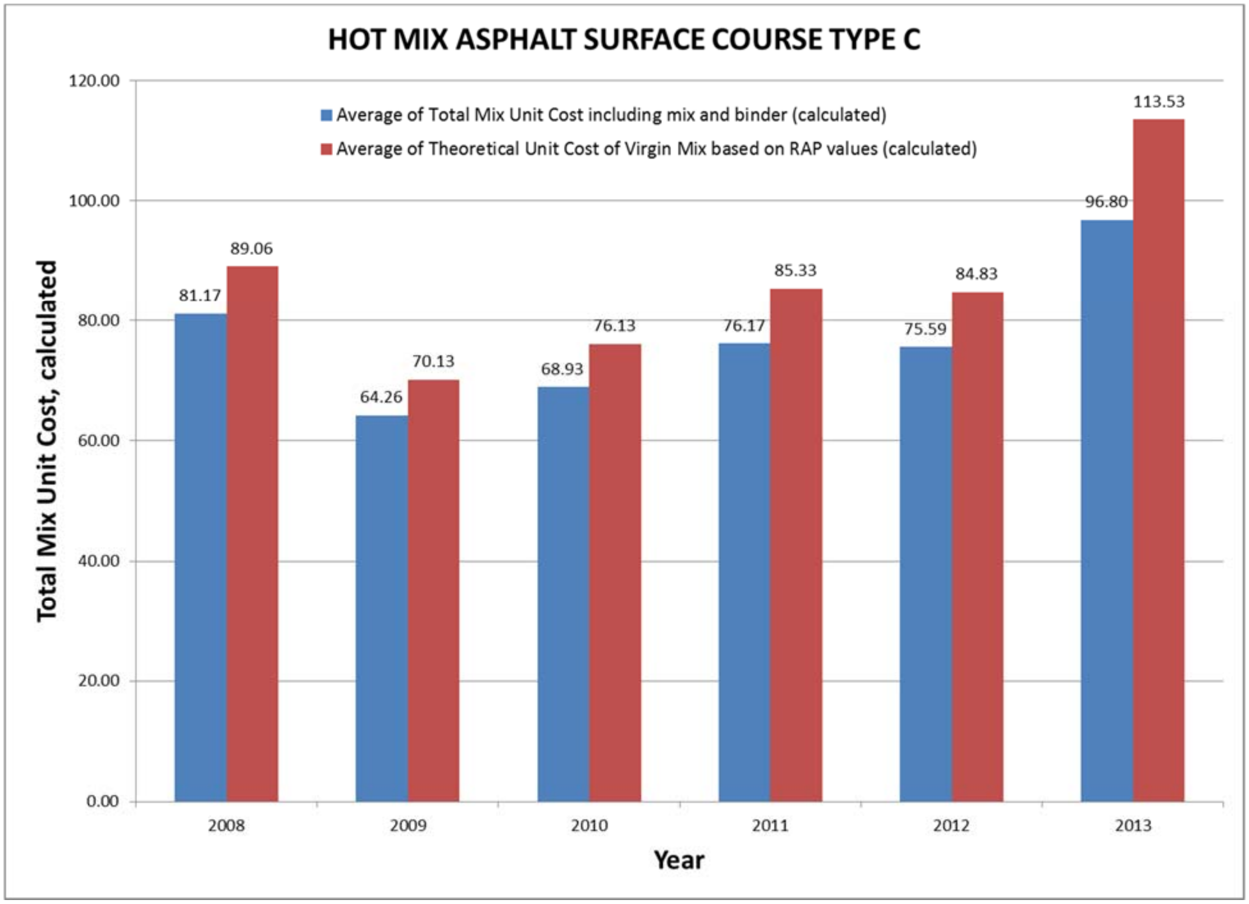


Figure 5-84: Comparison of Average Total Unit Mix Cost of RAP vs. Theoretical Virgin Mixes per Year for HMA Surface Course Type C

HMA Surface Course Type CM

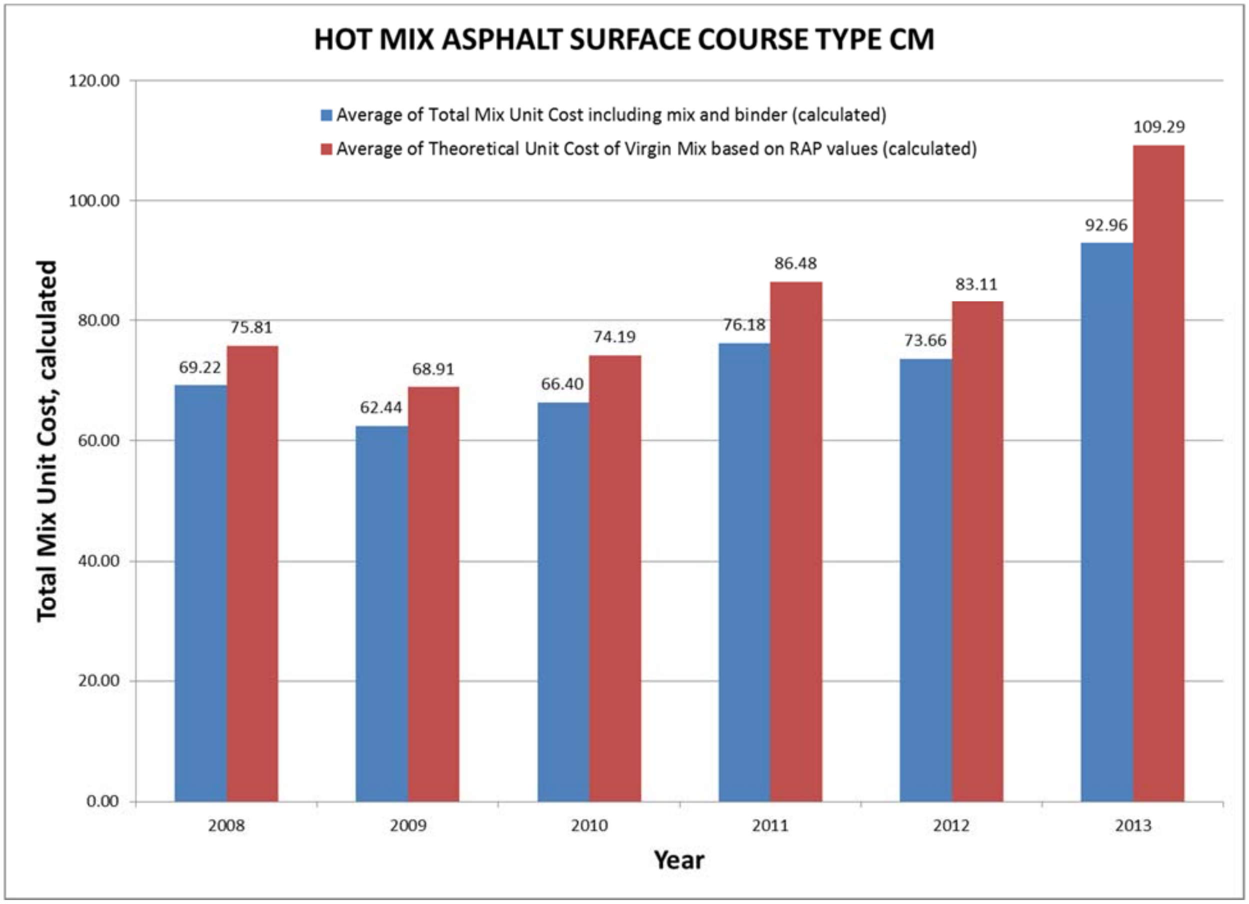


Figure 5-85: Comparison of Average Total Unit Mix Cost of RAP vs. Theoretical Virgin Mixes per Year for HMA Surface Course Type CM

HMA Surface Course Type D

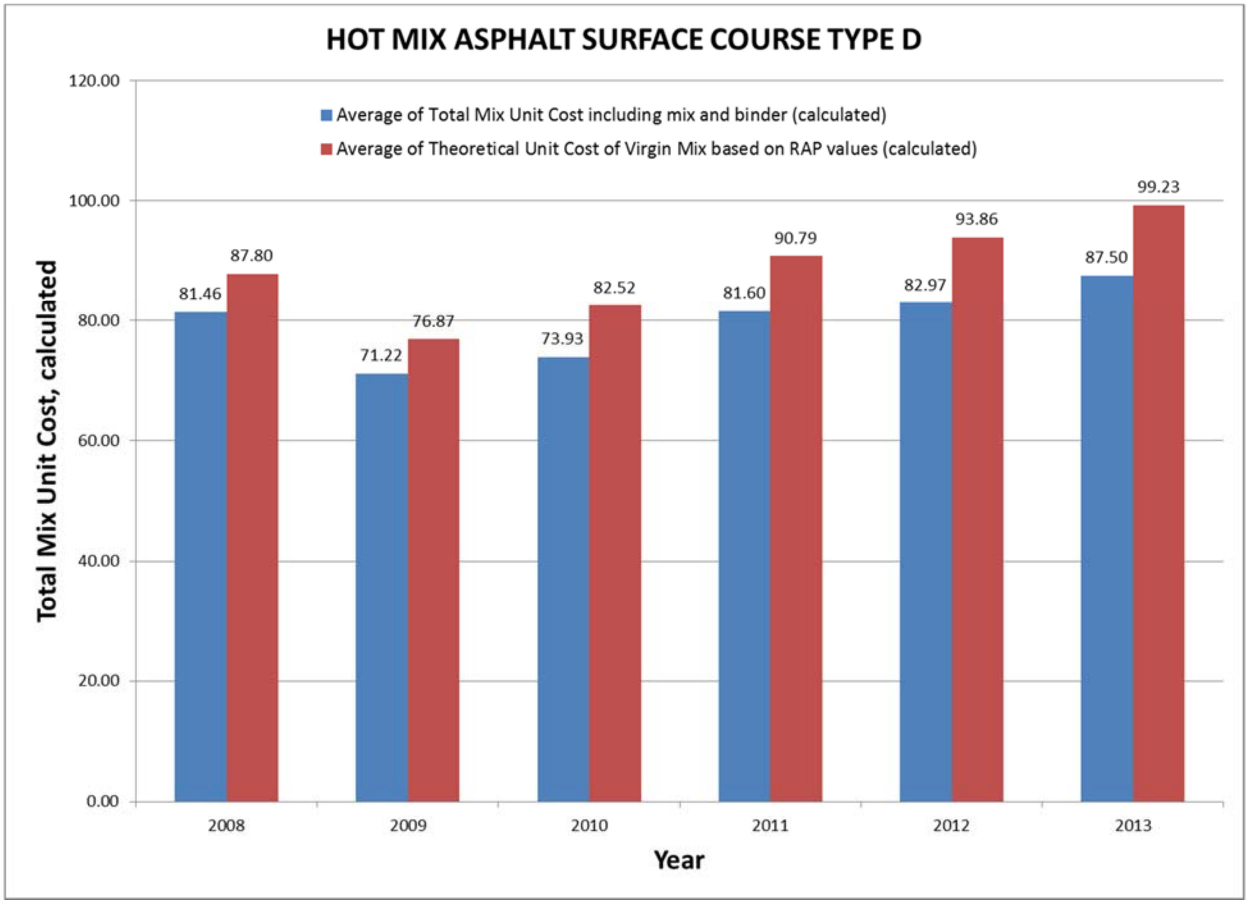


Figure 5-86: Comparison of Average Total Unit Mix Cost of RAP vs. Theoretical Virgin Mixes per Year for HMA Surface Course Type D

HMA Surface Course Type E

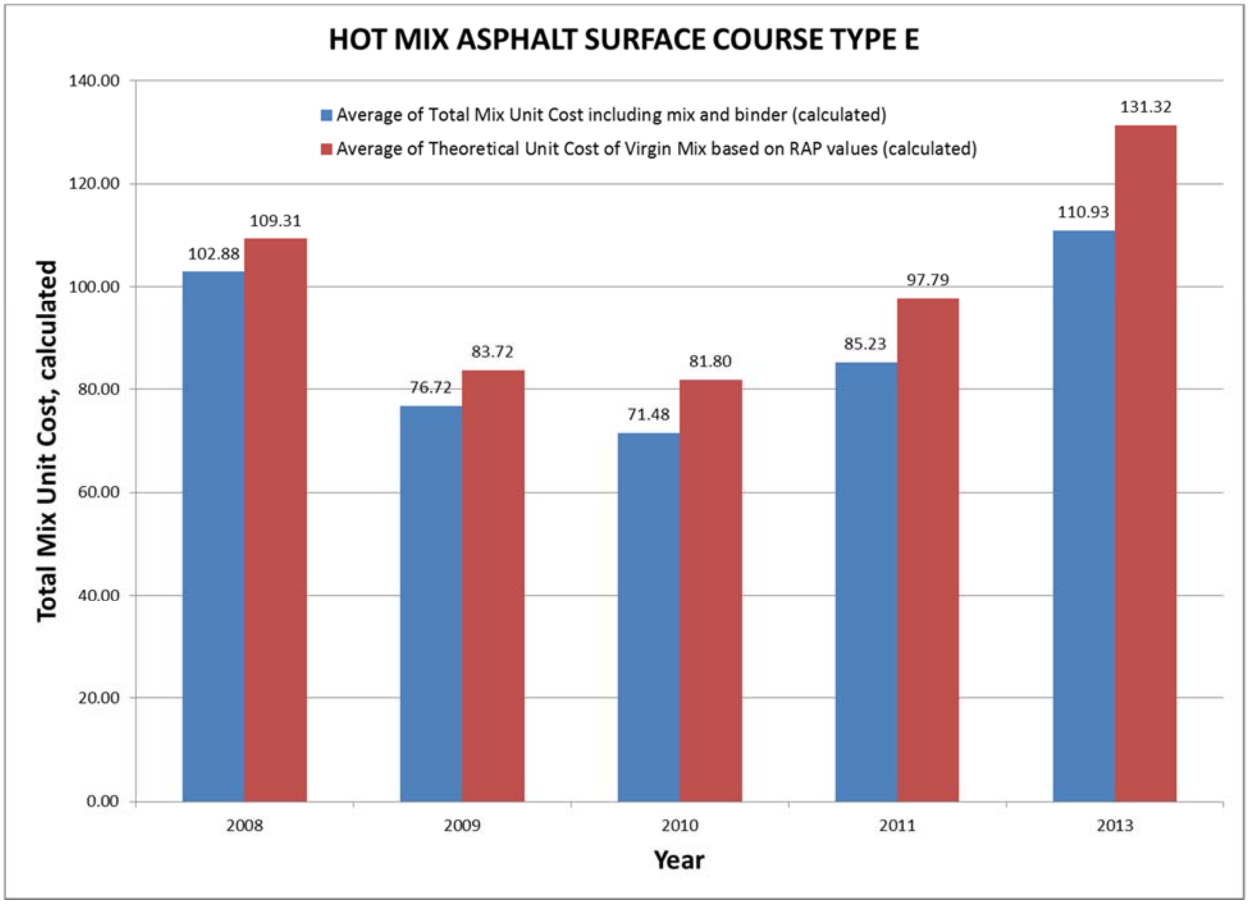


Figure 5-87: Comparison of Average Total Unit Mix Cost of RAP vs. Theoretical Virgin Mixes per Year for HMA Surface Course Type E

Cost Comparison of Total Costs of RAP and Virgin Mixes per Year

Asphalt pavement payment data for all mix types from SCDOT's database for the years 2008 through 2013 were used in this study. As in the previous portion of this study, in this section, all data points for mixes with less than 2,500 tons on a particular project were eliminated from the data. This deletion was approved by the Steering Committee for this project in an attempt to isolate the prices for mainline paving only in order to reduce the effect of small project size on unit prices.

For this section, the total mix cost paid including mix and asphalt binder was calculated using the actual mix price paid for each data point from Site Manager plus the respective calculated binder cost paid for each data point using the SCDOT monthly asphalt indices and the target asphalt binder content for each data point pulled from the associated SCDOT JMF form. In addition, the theoretical total mix cost of virgin mix including mix and asphalt binder was calculated using the actual mix price paid for each data point from Site Manager; the respective calculated binder cost paid for each data point using the SCDOT monthly asphalt indices; the estimated value of aggregate each year gathered from the aggregate industry; and the target asphalt binder content, percentage of RAP used, and binder content of the RAP used for each data point pulled from the associated SCDOT JMF form. The following are the formulas used for each of these calculated values.

- % Aged Binder =
$$\frac{\frac{\%\,Binder\ in\ RAP\ from\ JMF\ form}{100}\ \times\ \%RAP\ from\ JMF\ form}{Optimal\ Binder\ Content\ from\ JMF\ form}$$
- % Virgin Binder = $100 - \%\,Aged\ Binder$
- Quantity of Aged Binder =
$$\frac{\%\,Aged\ Binder}{100} \times \frac{Optimal\ Binder\ Content\ from\ JMF\ form}{100} \times Pd.\,Mix\ Qty.$$
- Value of RAP Binder = $Quantity\ of\ Aged\ Binder \times Binder\ Index\ on\ Pymt.\,Date$
- Quantity of RAP Aggregate =
$$\frac{\%\,RAP\ from\ JMF\ form}{100} \times Paid\ Mix\ Quanity$$
- Value of RAP Aggregate = $Quantity\ of\ RAP\ Agg. \times Agg.\,Index\ on\ Pymt.\,Date$
- Total Value of RAP = $Value\ of\ RAP\ Binder + Value\ of\ RAP\ Aggregate$
- Total Binder Quantity in Tons =
$$\frac{Optimal\ Binder\ Content\ from\ JMF\ form}{100} \times Pd.\,Mix\ Qty.$$
- Total Mix Cost Paid (including mix and binder) = $(Pd.\,Mix\ Qty. \times Unit\ Price) + (Total\ Binder\ Qty. \times Binder\ Index\ on\ Pymt.\,Date)$
- Total Mix Unit Cost =

$$\frac{Total\ Mix\ Cost\ Paid}{Paid\ Mix\ Quantity}$$

- Theoretical Total Cost of Virgin Mix (including mix and binder) =

$$Total\ Mix\ Cost\ Paid + Total\ Value\ of\ RAP$$

The comparison of total mix cost of RAP mix vs. theoretical virgin mix cost per year for many of the mixture types is shown in Figure 5-88 to Figure 5-99. Based on the data, in 2013 there was an average savings of $12.50/ton by using RAP (approximately $25,000,000 savings using RAP / approximately 2,000,000 tons placed).

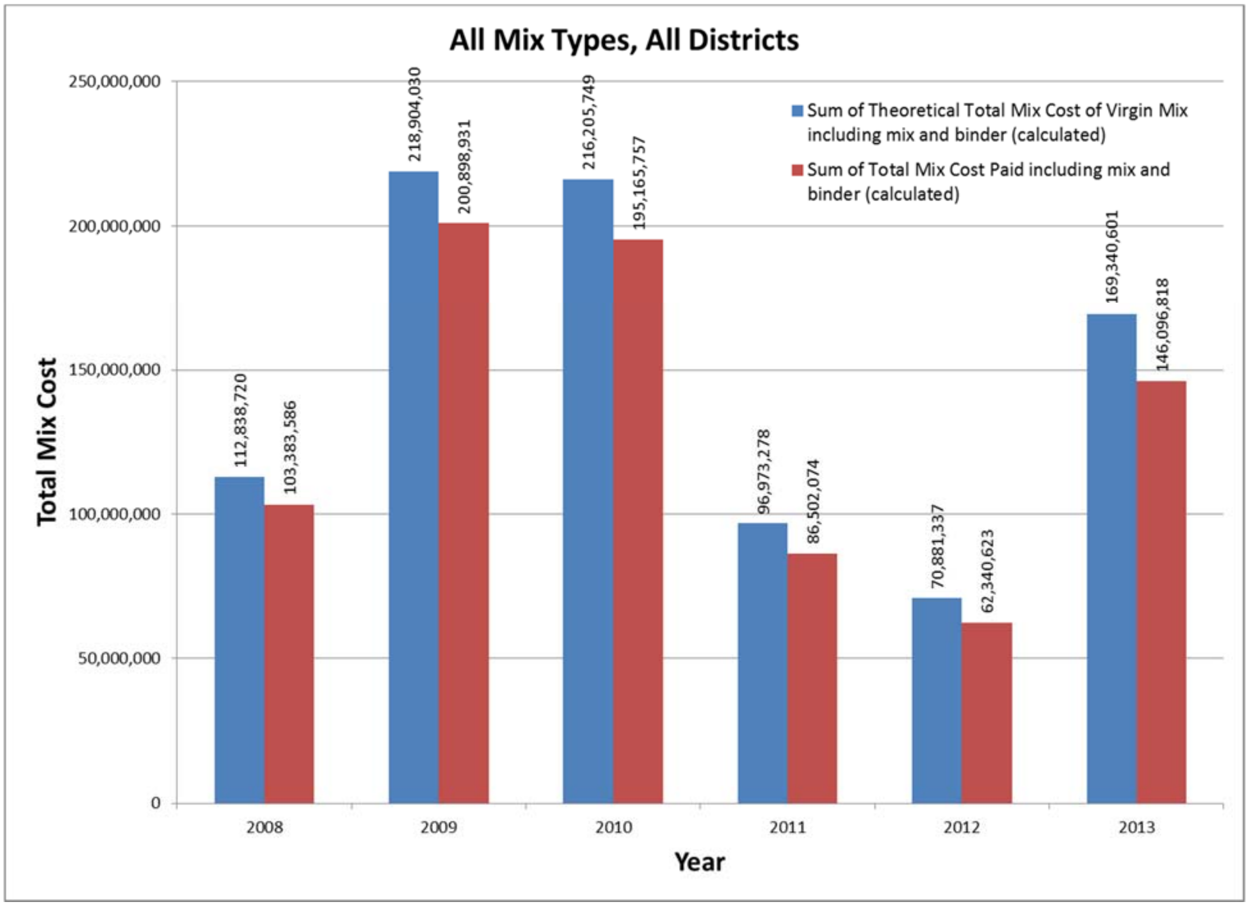


Figure 5-88: Comparison of Total Mix Cost of RAP vs. Theoretical Virgin Mix Cost per Year

HMA Shoulder Widening Course

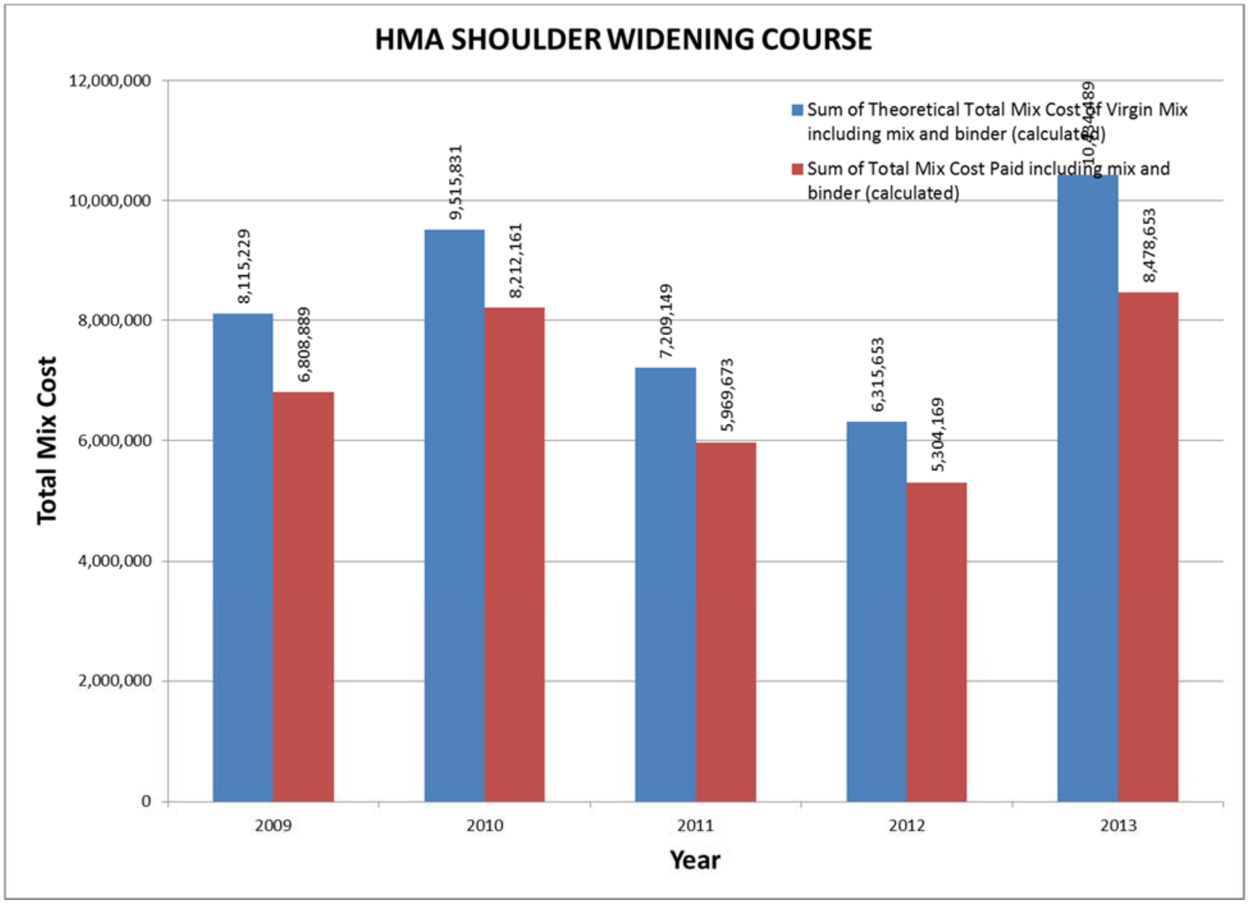


Figure 5-89: Comparison of Total Mix Cost of RAP vs. Theoretical Virgin Mix Cost per Year for HMA Shoulder Widening Course

HMA Base Course Type A

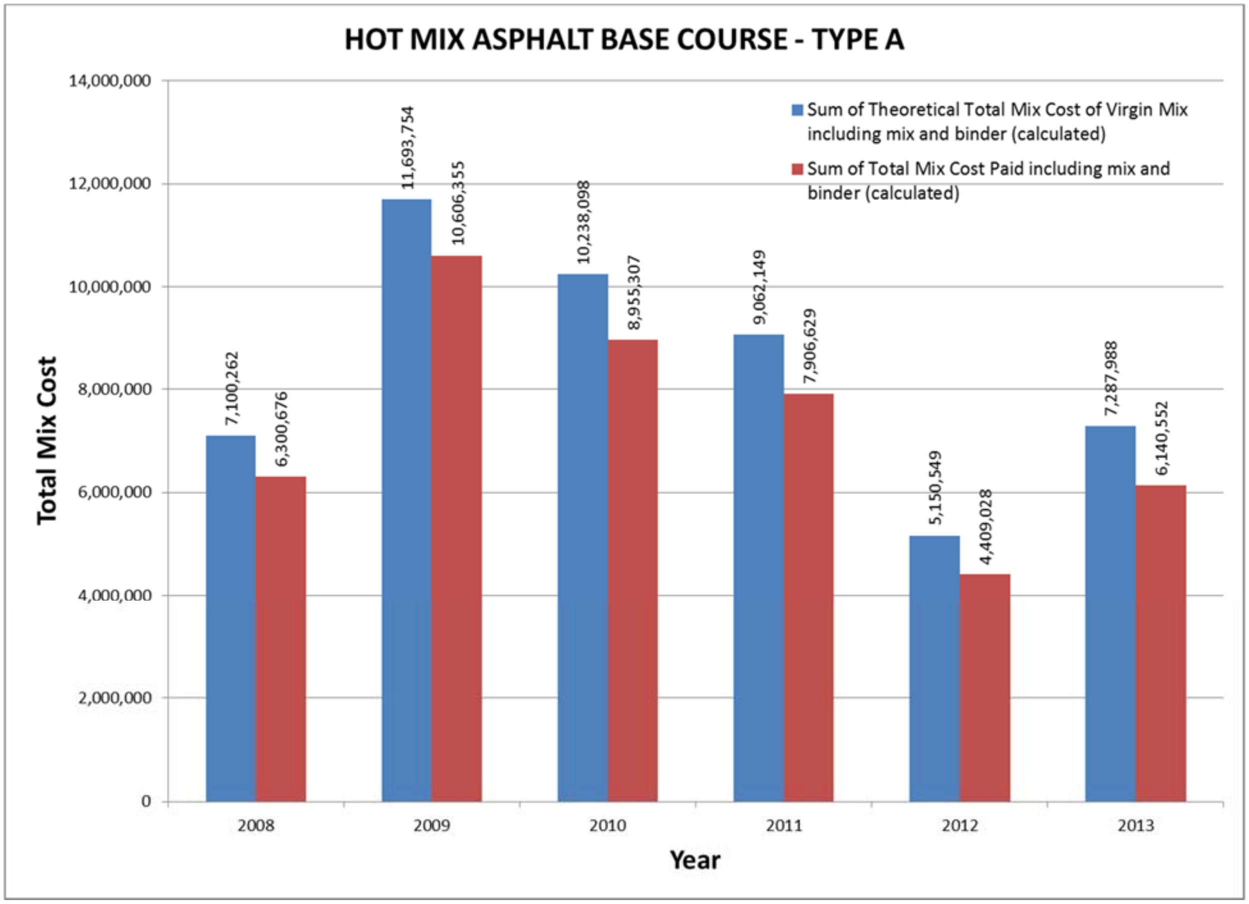


Figure 5-90: Comparison of Total Mix Cost of RAP vs. Theoretical Virgin Mix Cost per Year for HMA Base Course Type A

HMA Base Course Type B

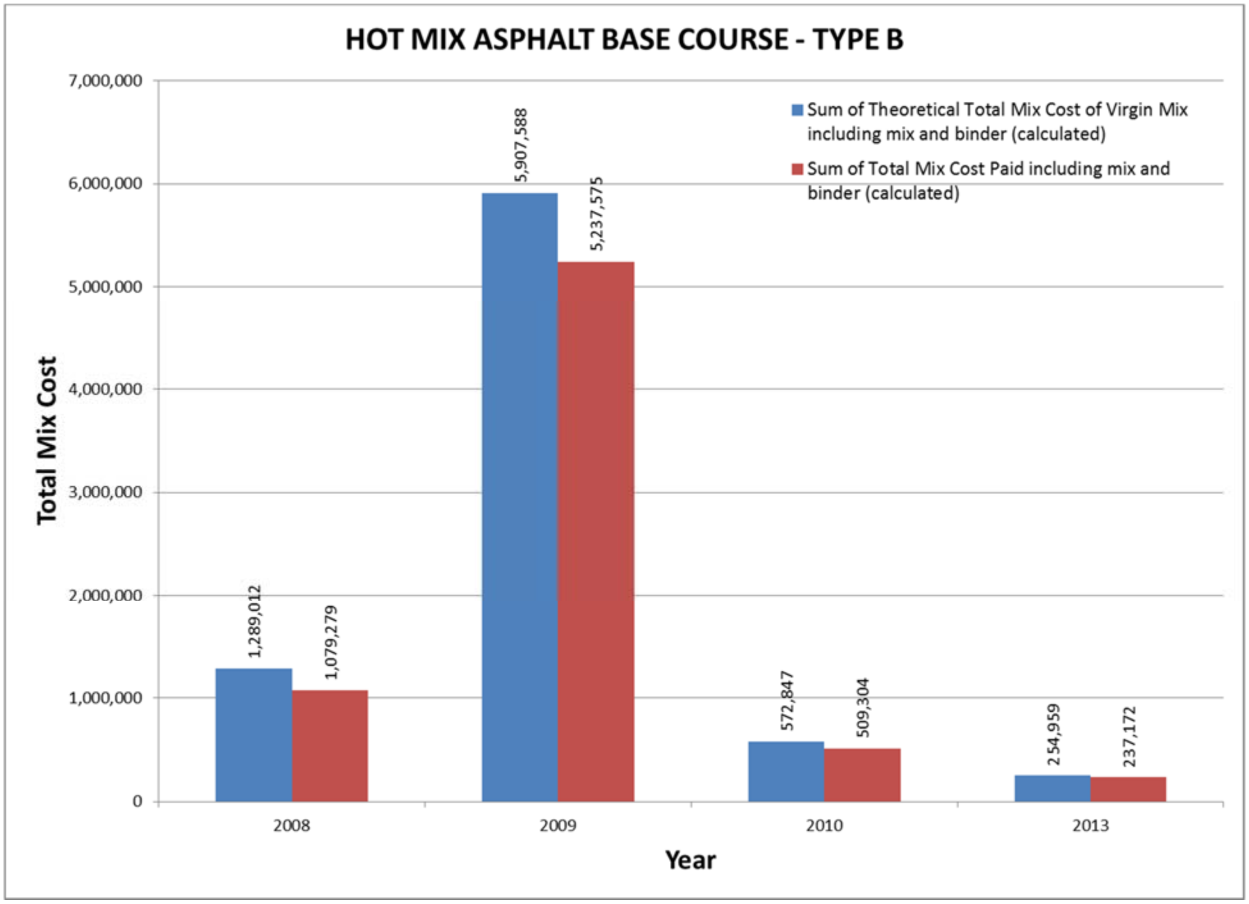


Figure 5-91: Comparison of Total Mix Cost of RAP vs. Theoretical Virgin Mix Cost per Year for HMA Base Course Type B

HMA Base Course Type C

HMA Base Course Type C had very limited use statewide and was used only in SCDOT District 2.

HMA Intermediate Course Type A

HMA Intermediate Course Type A had very limited use statewide and is used primarily on interstate projects. There were no projects where Intermediate A was placed in amounts greater than 2,500 tons during the years included in this project. As mentioned earlier, data points for mixes placed at less than 2,500 tons per project were not analyzed due to their potential to affect cost data.

HMA Intermediate Course Type B

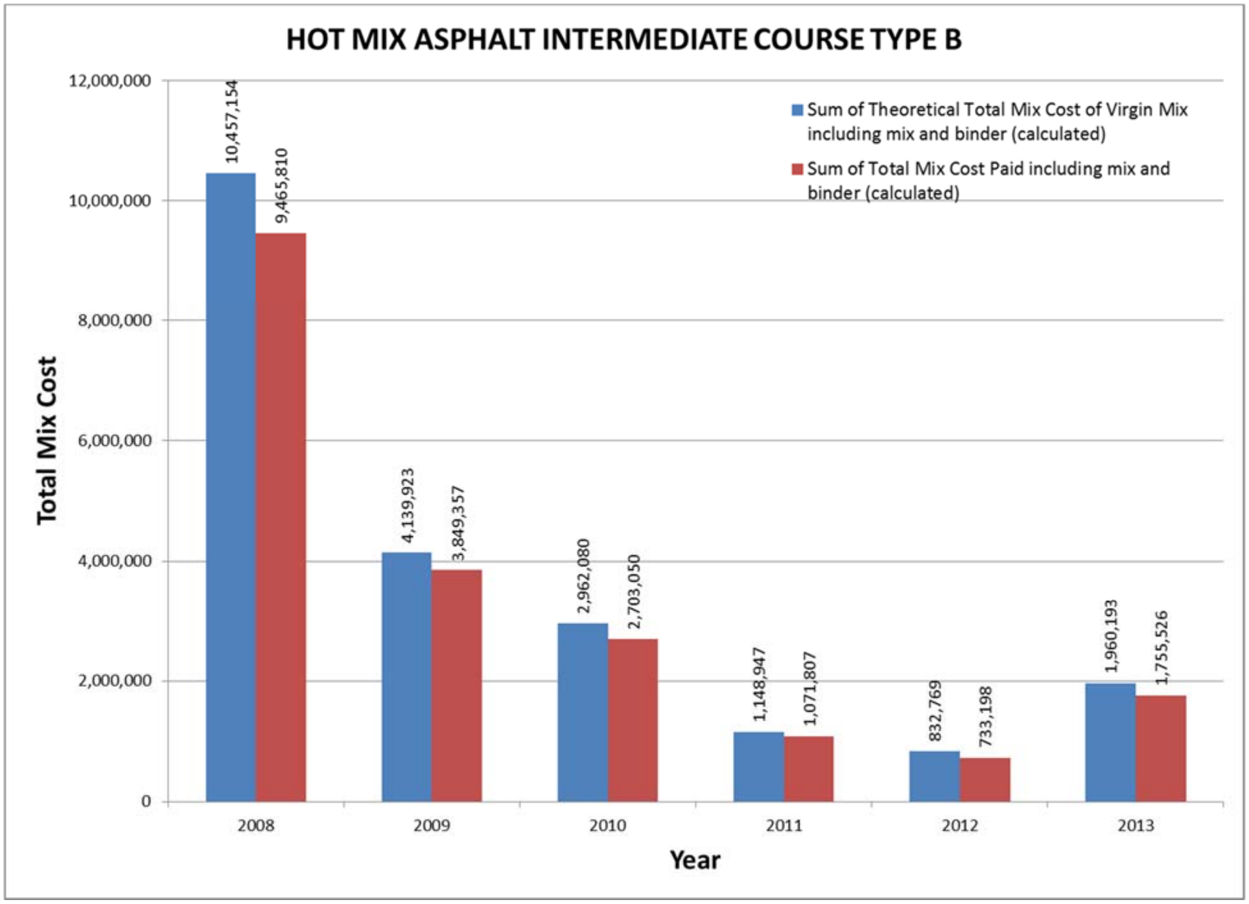


Figure 5-92: Comparison of Total Mix Cost of RAP vs. Theoretical Virgin Mix Cost per Year for HMA Intermediate Course Type B

HMA Intermediate Course Type C

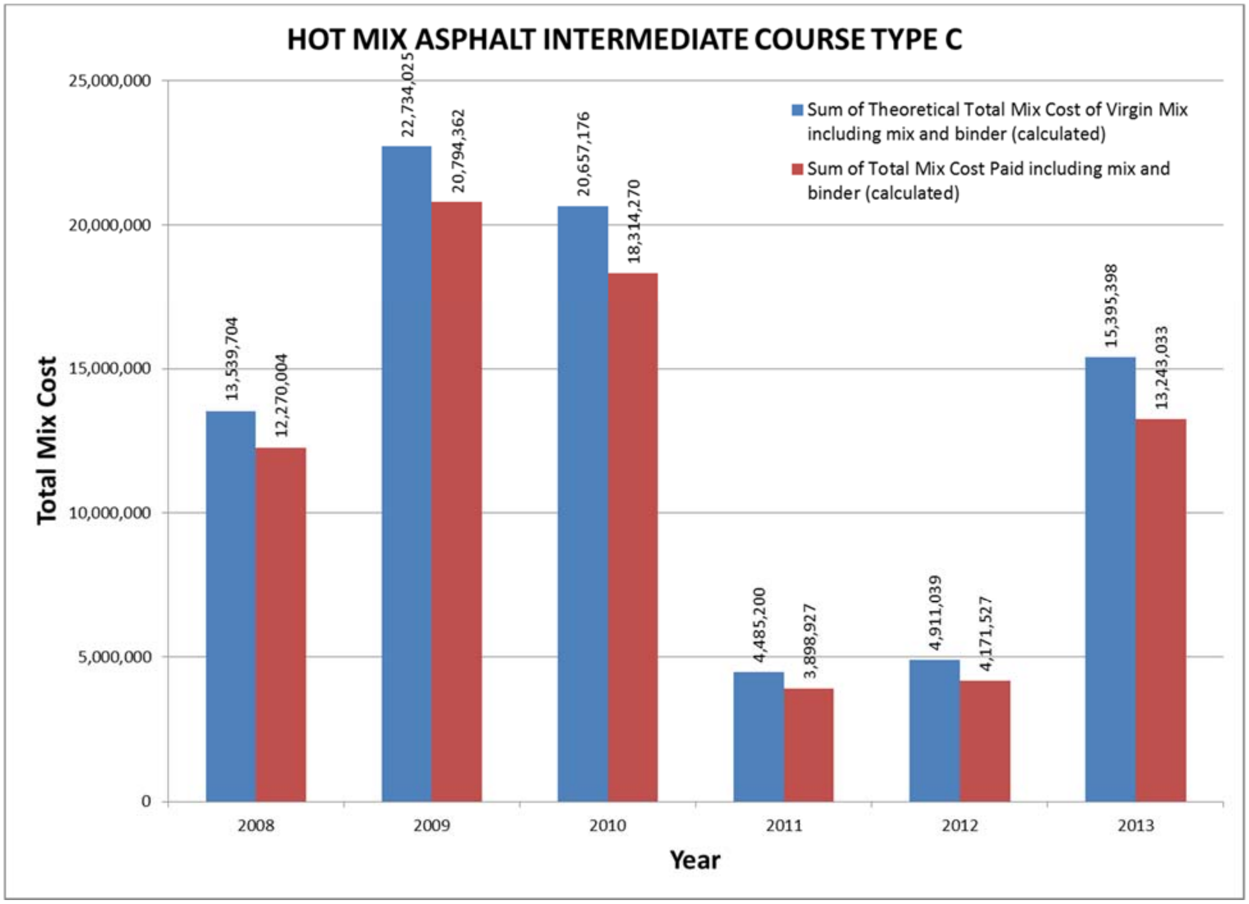


Figure 5-93: Comparison of Total Mix Cost of RAP vs. Theoretical Virgin Mix Cost per Year for HMA Intermediate Course Type C

HMA Surface Course Type A

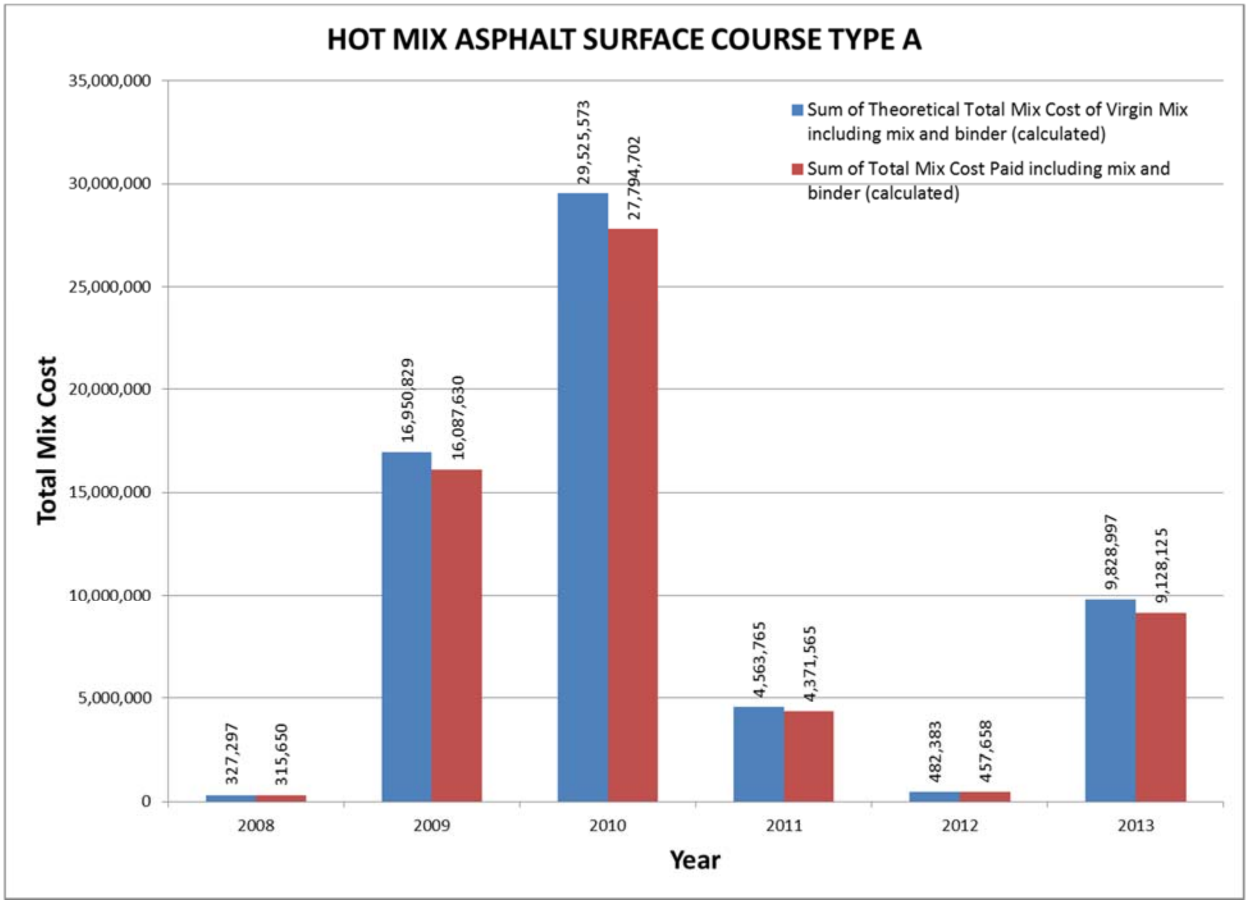


Figure 5-94: Comparison of Total Mix Cost of RAP vs. Theoretical Virgin Mix Cost per Year for HMA Surface Course Type A

HMA Surface Course Type B

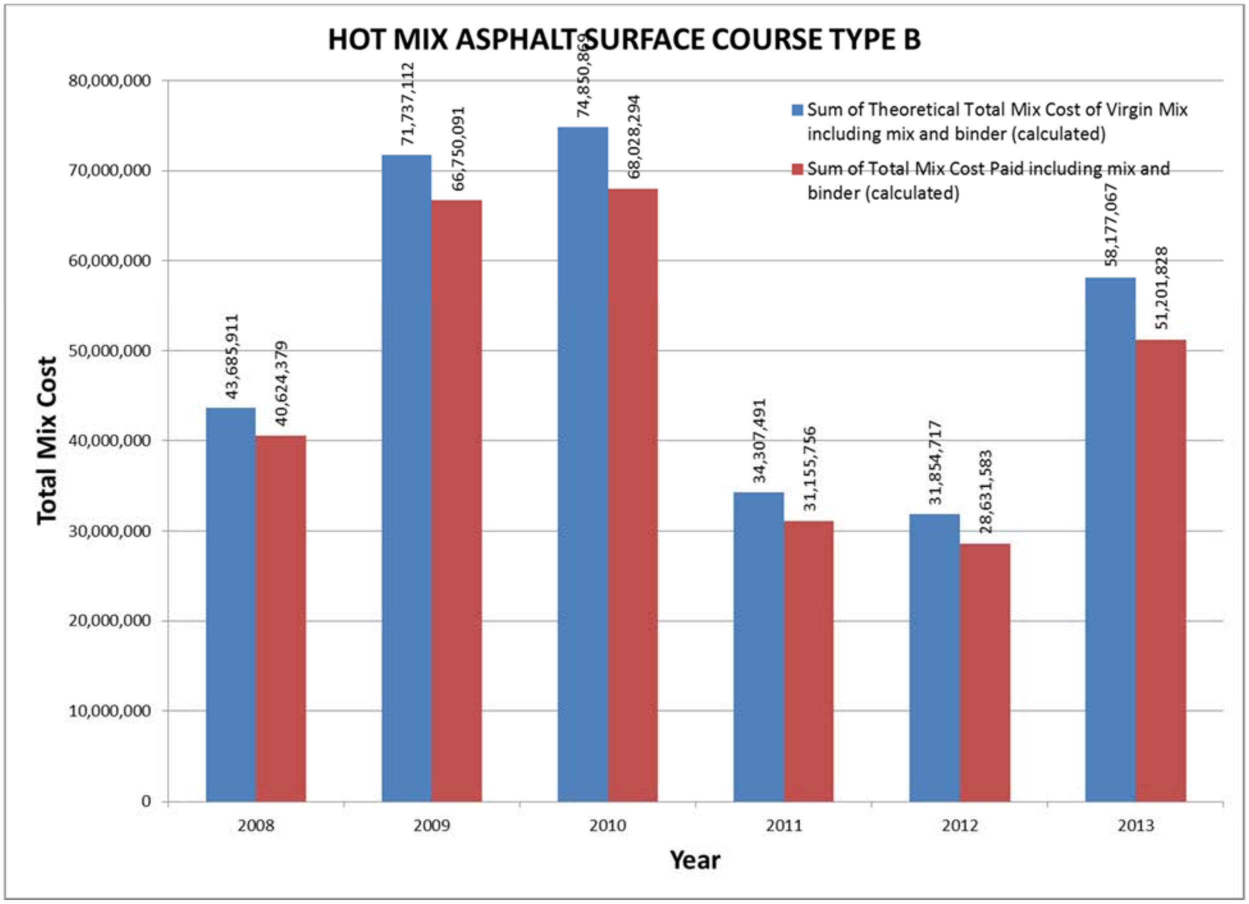


Figure 5-95: Comparison of Total Mix Cost of RAP vs. Theoretical Virgin Mix Cost per Year for HMA Surface Course Type B

HMA Surface Course Type C

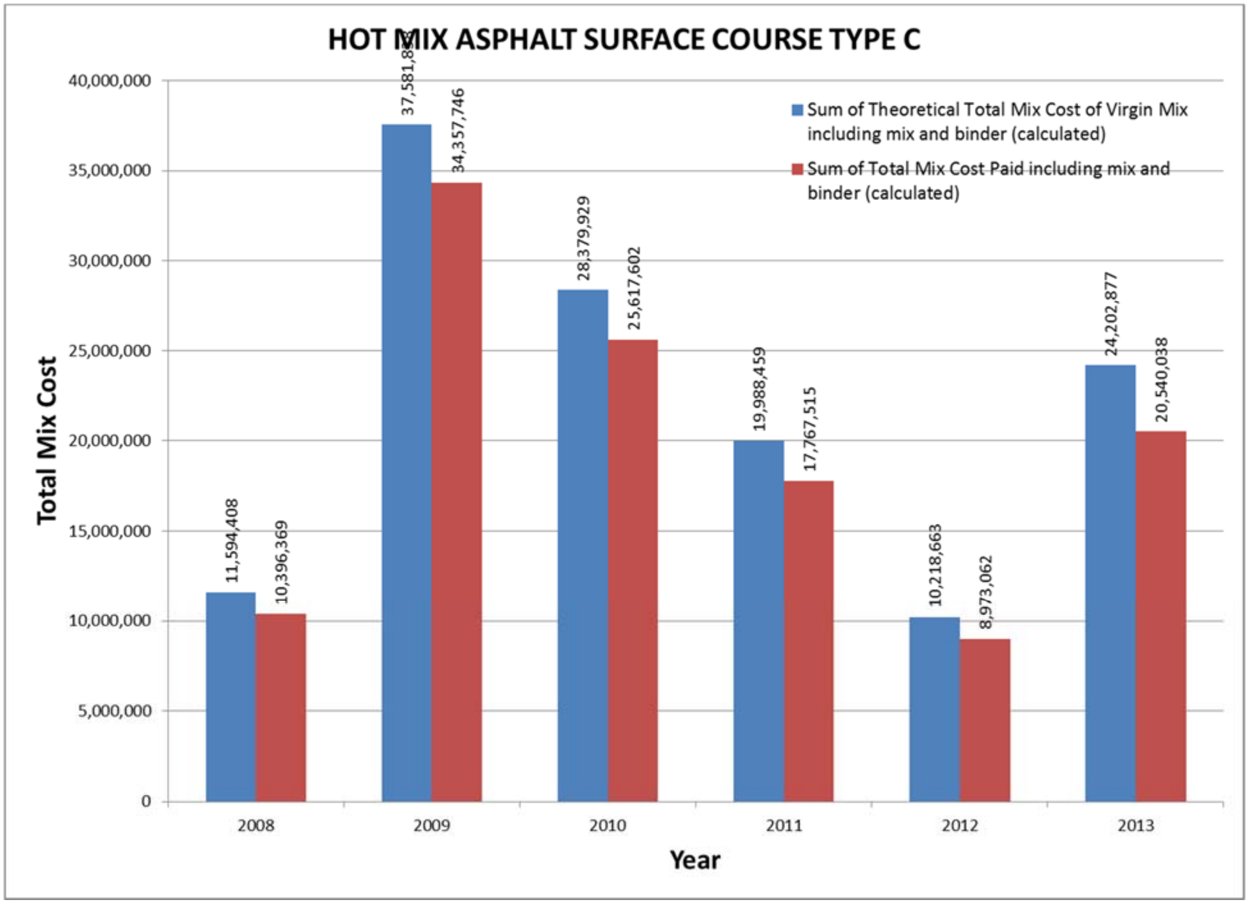


Figure 5-96: Comparison of Total Mix Cost of RAP vs. Theoretical Virgin Mix Cost per Year for HMA Surface Course Type C

HMA Surface Course Type CM

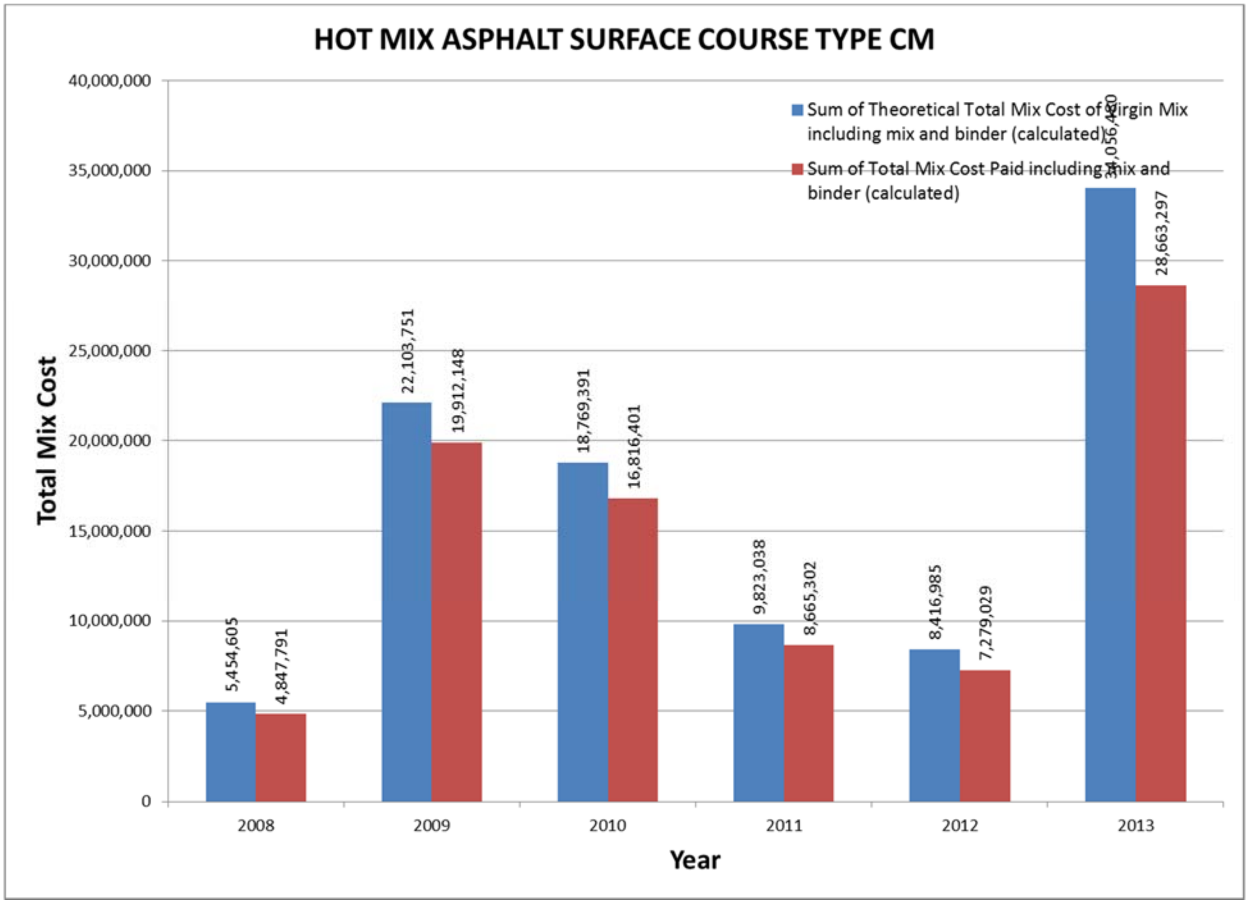


Figure 5-97: Comparison of Total Mix Cost of RAP vs. Theoretical Virgin Mix Cost per Year for HMA Surface Course Type CM

HMA Surface Course Type D

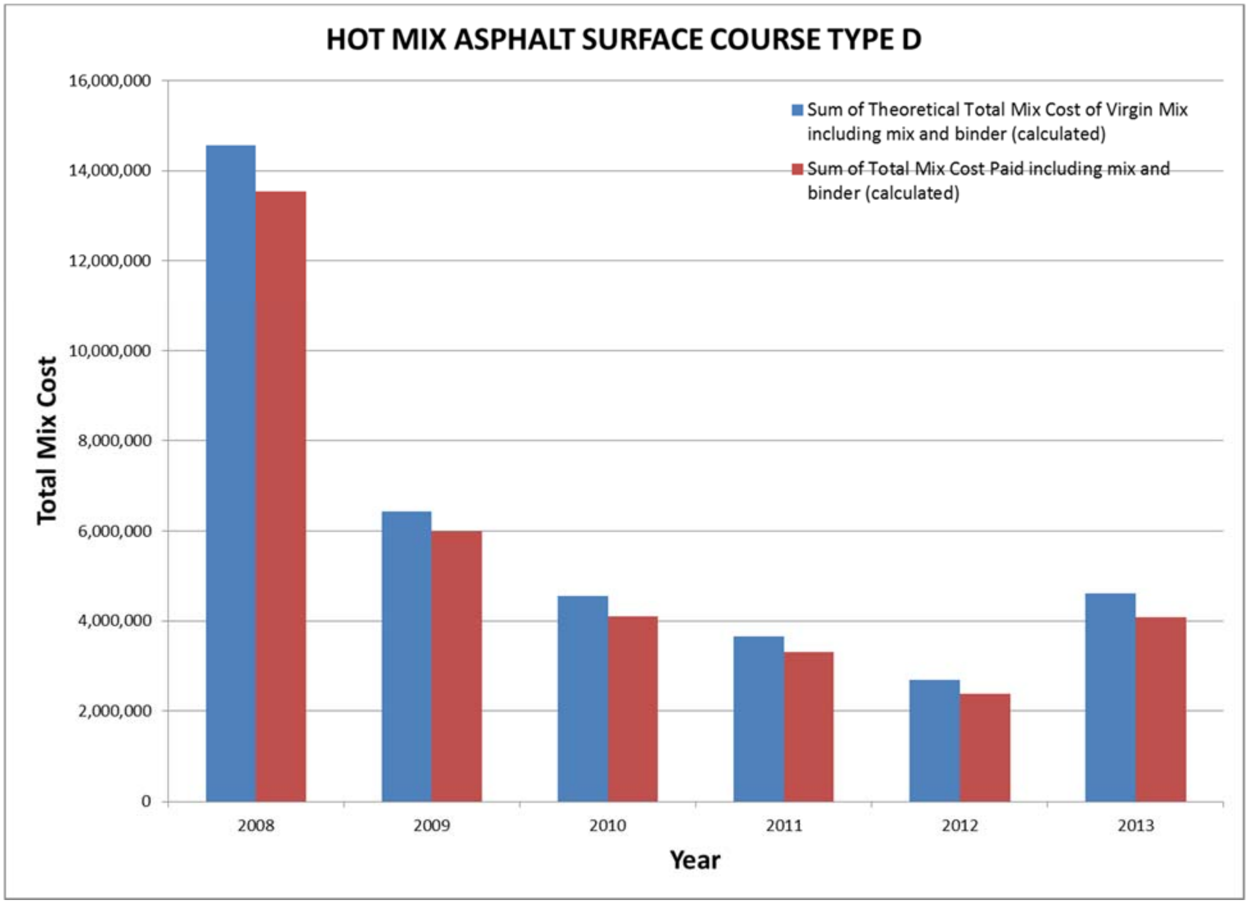


Figure 5-98: Comparison of Total Mix Cost of RAP vs. Theoretical Virgin Mix Cost per Year for HMA Surface Course Type D

HMA Surface Course Type E

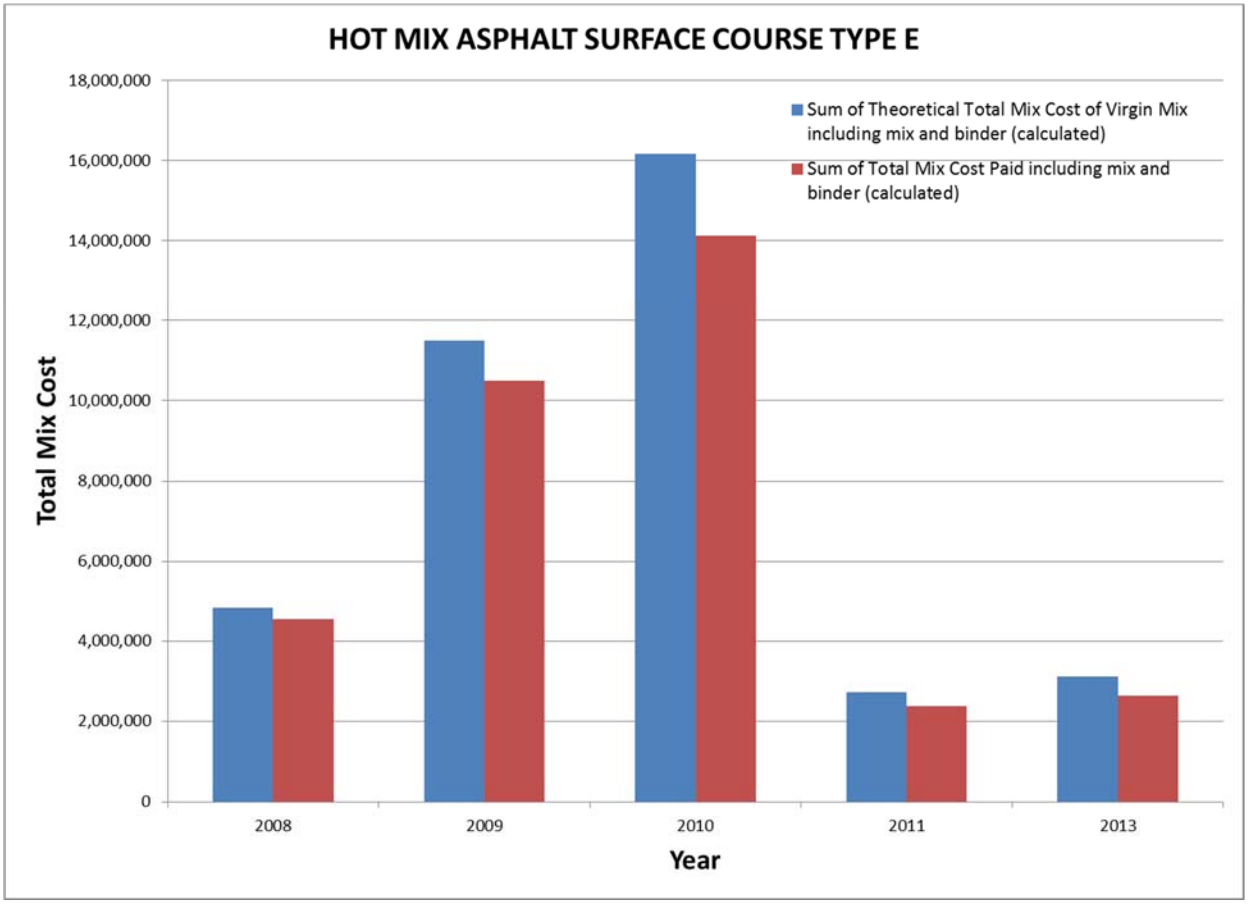


Figure 5-99: Comparison of Total Mix Cost of RAP vs. Theoretical Virgin Mix Cost per Year for HMA Surface Course Type E

Estimated Cost Savings

If the estimated percent savings to SCDOT is expressed as a percent of the total mix cost paid, the percent savings appeared to increase steadily from 9% in 2008 to 16% in 2013 (Figure 5-100). The total estimated savings values for these same years showed a low of $8.5 million in 2012 and a high of $23.2 million in 2013(Figure 5-101). The varying dollar amounts of savings per year were affected by the total volume of paving paid each year, so they did not show a clear trend of any sort. The total estimated savings to SCDOT by utilizing RAP mixtures between 2008 and 2013 was approximately $90.7 million, which is equivalent to a savings of 11% during this time period.

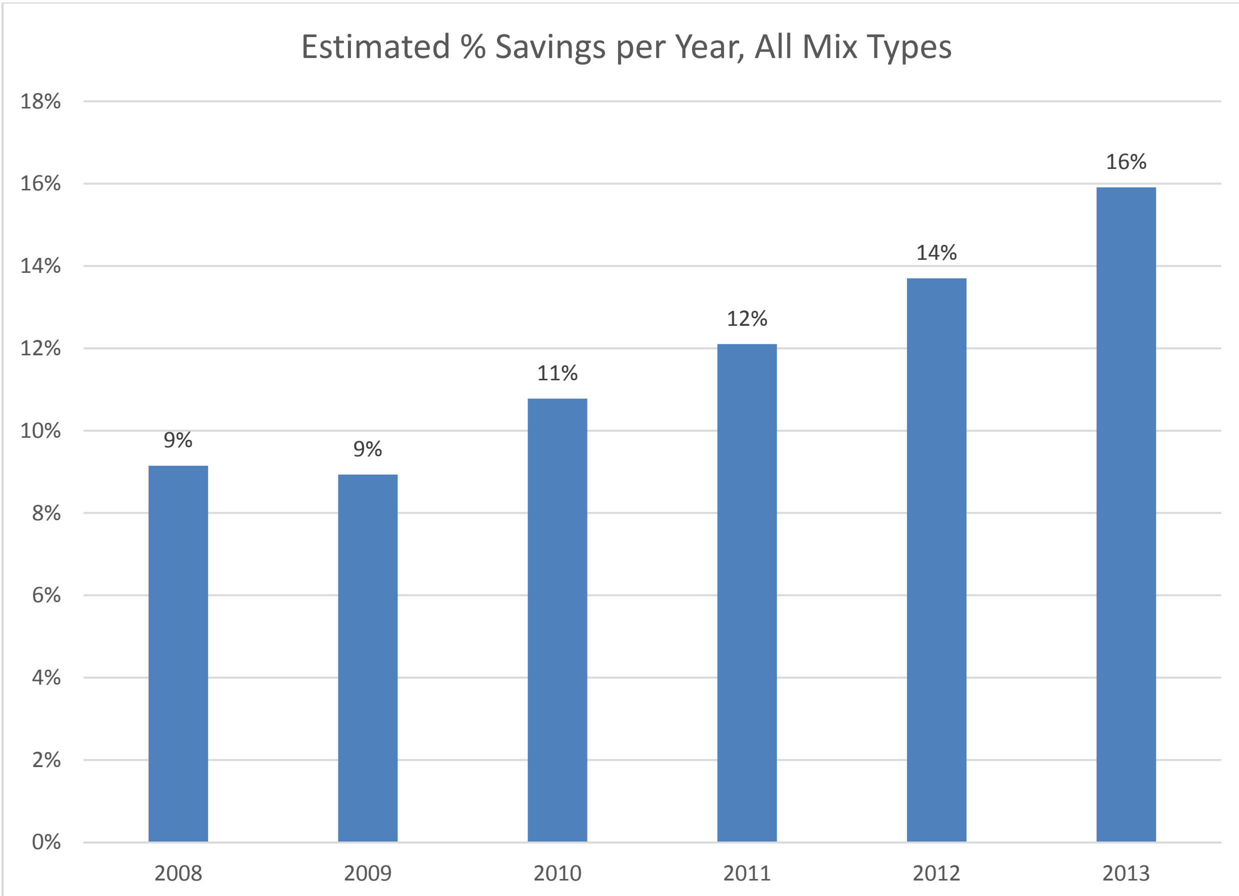


Figure 5-100: Estimated % Savings per Year, All Mixture Types Combined

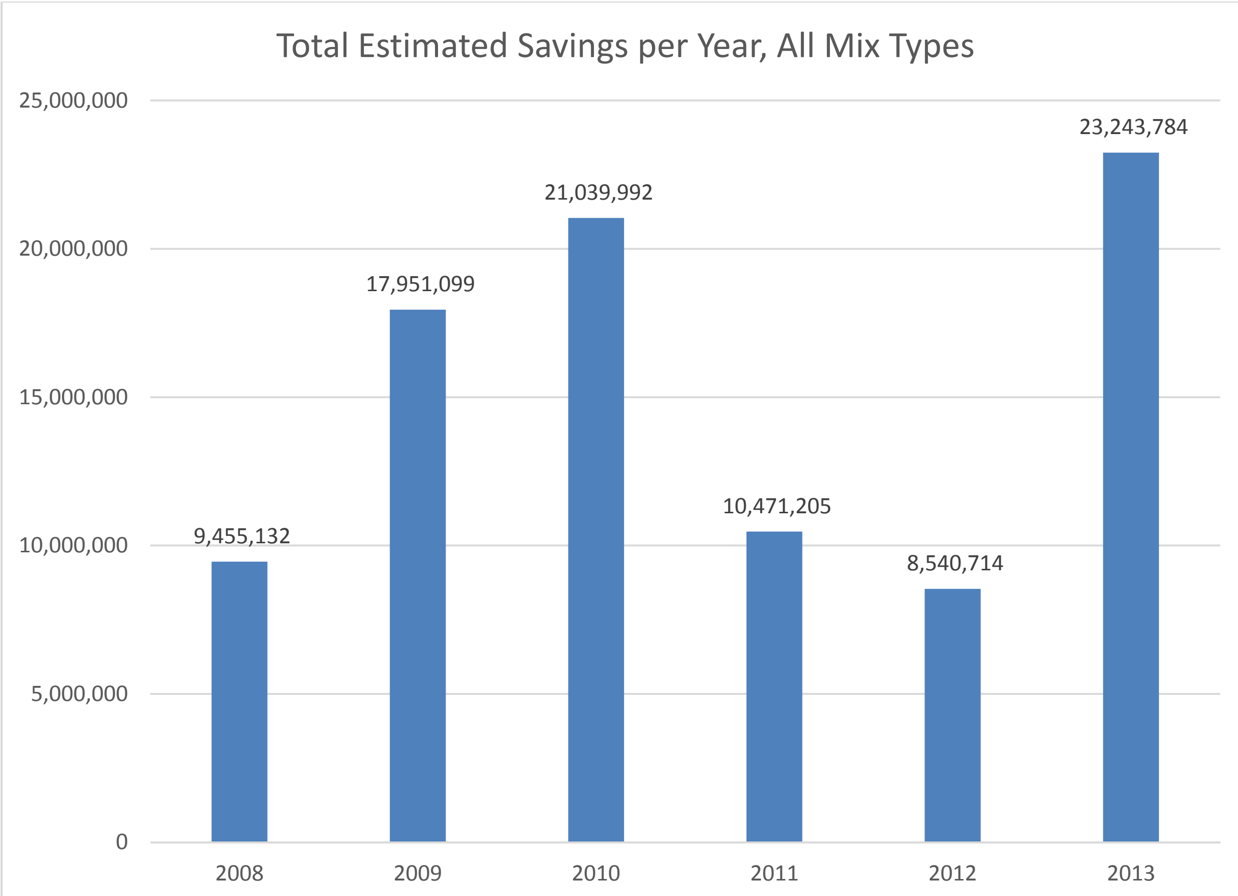


Figure 5-101: Total Estimated Savings per Year, All Mixture Types Combined

Chapter 6 – Development of Cost Models for RAP/RAS Mixtures in South Carolina

Within the data set, important information such as quantity of material, District that the paving took place in, percentage of aged binder used in the asphalt mix, and the total unit cost of the mix was also utilized to sort and arrange the data for performing the tests. After examining the data set visually, only unit cost data associated with total quantities exceeding 500 tons were used in the analysis in order to include as much data as possible. This differs from the analysis in previous sections of this study in which all projects less than 2,500 tons were disregarded. These data were chosen because the variability in the unit cost became more stable and would allow for a more direct comparison of the difference of quantiles between binder groups without being greatly influenced by high variability due to lower asphalt quantities. A graph of the box plots of the unit cost for the less than ten percent aged binder group and the greater than 30 percent aged binder group for each District is shown in Figure 6-1.

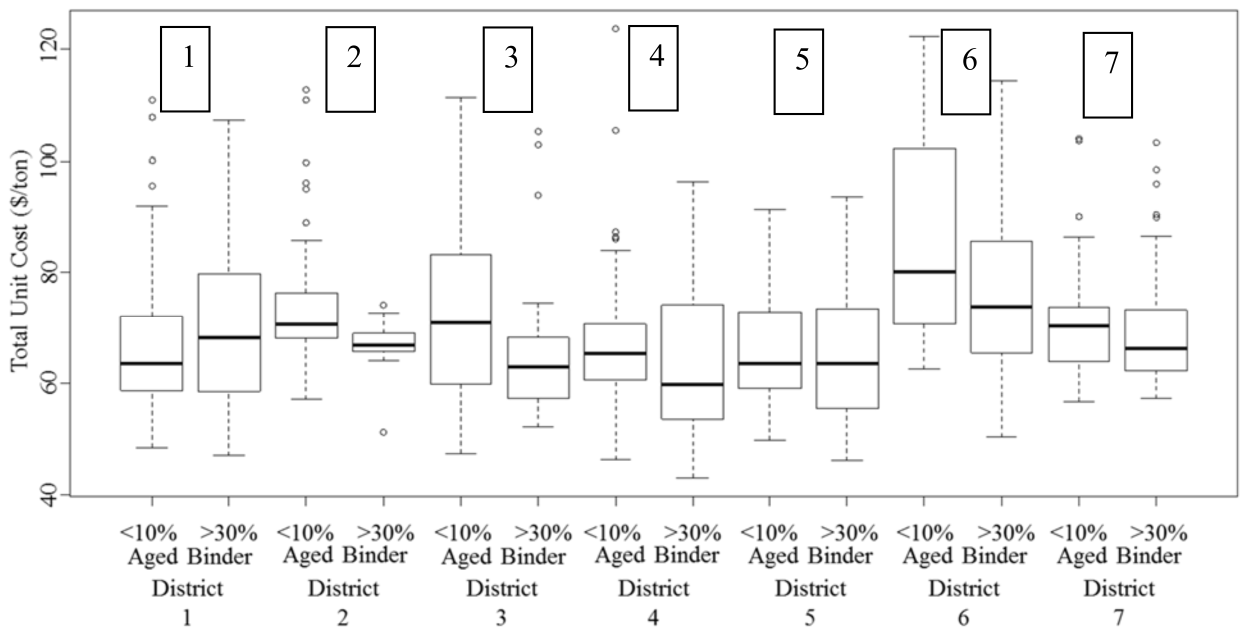


Figure 6-1: Box plot of Unit Cost Data for Mixes Containing < 10% Aged Binder and > 30% Aged Binder per SCDOT District between 2008 and 2013

Error! Reference source not found. contains summary statistics of the unit cost data for the two aged binder groups within each SCDOT District. Excluding the data values of the asphalt pavements containing greater than 30 percent within District 2, all groups within all districts have a mean unit cost greater than the sample median unit cost and a skewness value less than zero, indicating that the distribution of unit costs are positively skewed. It is important to note that some districts have good quality and adequate quantity of aggregate sources; therefore, affecting the prices. The results show some of these variations in prices.

Table 6-1: Summary Statistics for Aged Binder Groups within each SCDOT District

District	Percentage of Aged Binder	*n*	Mean ($/ton)	Median ($/ton)	Standard Deviation ($/ton)	Skewness	Kurtosis
1	<10%	88	66.28	63.44	12.78	1.232	4.716
1	>30%	61	69.91	68.18	14.70	0.503	2.581
2	<10%	61	73.62	70.55	11.33	1.562	5.554
2	>30%	29	66.81	66.85	3.94	-1.815	9.135
3	<10%	83	72.90	71.09	15.53	0.293	2.113
3	>30%	34	65.33	63.01	12.94	1.745	5.638
4	<10%	75	67.26	65.38	12.17	1.693	8.427
4	>30%	36	63.24	59.91	13.50	0.708	2.454
5	<10%	217	66.11	63.49	9.90	0.630	2.586
5	>30%	51	64.36	63.52	12.30	0.522	2.526
6	<10%	49	86.18	80.09	17.71	0.360	1.884
6	>30%	48	76.44	73.66	15.02	0.570	2.551
7	<10%	52	71.73	70.19	9.57	1.469	5.667
7	>30%	38	70.54	66.29	12.38	1.328	3.443

The results of the comparisons of the five quantiles, $q_{0.50}$, $q_{0.60}$, $q_{0.70}$, $q_{0.80}$, and $q_{0.90}$, between the unit costs for mixes using less than ten percent aged binder and the unit costs for mixes containing more than 30 percent aged binder for all seven highway Districts within the state of South Carolina is provided in **Error! Reference source not found.**.

From **Error! Reference source not found.**, only District 2 has all quantiles of the unit cost of the asphalt containing greater than 30 percent aged binder in the mix as statistically significantly less than the unit cost quantiles of asphalt mixes containing less than ten percent aged binder. There is significantly less risk of exceeding a given cost within this District when using a mix containing greater than 30 percent aged asphalt binder. It is interesting to note that the differences in the unit cost estimates at each of the five quantiles are all negative within District 1. This could be due to multiple factors, including RAP availability as well as raw material prices in this area. While the differences in quantile estimates between the two binder groups were not shown to be statistically significant, the negative values indicate that there is greater cost risk associated with asphalt mixes containing more than 30 percent aged binder. This negative difference between the estimated quantiles was also noticed at the 80th and 90th quantiles for Districts 4, 5, and 7, indicating that the unit costs for mixes containing greater than 30 percent aged binder has a higher cost risk at the upper tails of the unit cost distribution.

Table 6-2: Results of Quantile Comparison between Aged Binder Groups within SCDOT Districts

District	q	$\hat{\theta}^*_{<10\%}$	$\hat{\theta}^*_{>30\%}$	$\hat{\theta}^*_{<10\%} - \hat{\theta}^*_{>30\%}$	95% CI (Lower, Upper)	p-value (critical)	p-value	Significant?
1	0.50	63.287	68.583	-5.295	-11.052, 1.094	0.025	0.098	NO
1	0.60	66.513	73.233	-6.721	-12.406, -0.426	0.013	0.044	NO
1	0.70	70.140	77.686	-7.545	-12.807, -1.233	0.010	0.016	NO
1	0.80	75.279	81.765	-6.486	-13.995, -0.171	0.017	0.048	NO
1	0.90	83.294	90.877	-7.583	-17.992, 4.321	0.050	0.237	NO
2	0.50	70.542	67.175	3.367	0.975, 6.212	0.025	0.002	YES
2	0.60	72.723	68.123	4.600	1.774, 7.718	0.050	0.005	YES
2	0.70	75.267	68.797	6.470	3.788, 11.387	0.017	0.000	YES
2	0.80	80.387	69.132	11.255	5.762, 17.758	0.013	0.000	YES
2	0.90	89.684	70.578	19.106	10.335, 30.307	0.010	0.000	YES
3	0.50	71.767	62.252	9.515	4.303, 15.297	0.013	0.001	YES
3	0.60	75.873	64.888	10.985	5.079, 17.483	0.010	0.000	YES

3	0.70	81.138	67.668	13.470	5.688, 20.961	0.017	0.006	YES
3	0.80	88.572	71.745	16.827	2.531, 24.753	0.025	0.029	NO
3	0.90	95.777	85.023	10.754	-6.484, 24.747	0.050	0.331	NO
4	0.50	65.458	59.281	6.177	-0.373, 10.422	0.010	0.060	NO
4	0.60	67.036	63.308	3.728	-5.363, 9.910	0.013	0.344	NO
4	0.70	69.426	69.495	-0.069	-8.912, 8.936	0.050	0.965	NO
4	0.80	74.223	76.722	-2.499	-11.293, 8.424	0.017	0.676	NO
4	0.90	82.423	84.228	-1.804	-11.208, 8.750	0.025	0.736	NO
5	0.50	63.813	62.646	1.167	-3.541, 5.833	0.010	0.673	NO
5	0.60	66.812	66.431	0.381	-5.088, 5.754	0.013	0.855	NO
5	0.70	70.668	70.378	0.289	-4.896, 5.623	0.025	0.907	NO
5	0.80	74.388	74.999	-0.611	-6.689, 4.976	0.017	0.872	NO
5	0.90	82.223	82.558	-0.335	-7.843, 7.141	0.050	0.976	NO
6	0.50	82.770	73.699	9.071	0.682, 19.105	0.025	0.034	NO
6	0.60	89.932	78.932	11.000	0.309, 21.715	0.050	0.040	YES
6	0.70	96.787	83.830	12.957	1.997, 23.216	0.017	0.021	NO
6	0.80	104.19	89.497	14.691	3.077, 24.079	0.010	0.01	NO

							1	
6	0.90	112.57	98.950	13.618	2.956, 24.219	0.013	0.01 5	NO
7	0.50	70.372	66.007	4.365	0.223, 7.921	0.010	0.04 5	NO
7	0.60	72.451	67.949	4.502	-1.734, 7.922	0.013	0.11 0	NO
7	0.70	74.048	71.369	2.678	-8.476, 7.943	0.025	0.54 7	NO
7	0.80	77.182	80.271	-3.088	-15.626, 8.692	0.050	0.72 9	NO
7	0.90	84.166	93.020	-8.854	-17.932, 8.339	0.017	0.31 6	NO

The average cost of materials from 2008 to 2013 per each month is shown in **Error! Reference source not found.**. This figure shows some variation from month-to-month for the unit cost of materials. **Error! Reference source not found.** shows the average unit cost of each binder group for the 5 year period. Many probabilistic distributions were conducted and an example of the results is shown in **Error! Reference source not found.**. To conduct this analysis, the data were grouped by districts, aged binder group (by percent), and by total unit cost of the mix. Then, an attempt was made to fit Johnson SI or Sb distributions to each group within each district. Five thousand iterations were conducted for each item to conduct simulation for each category.

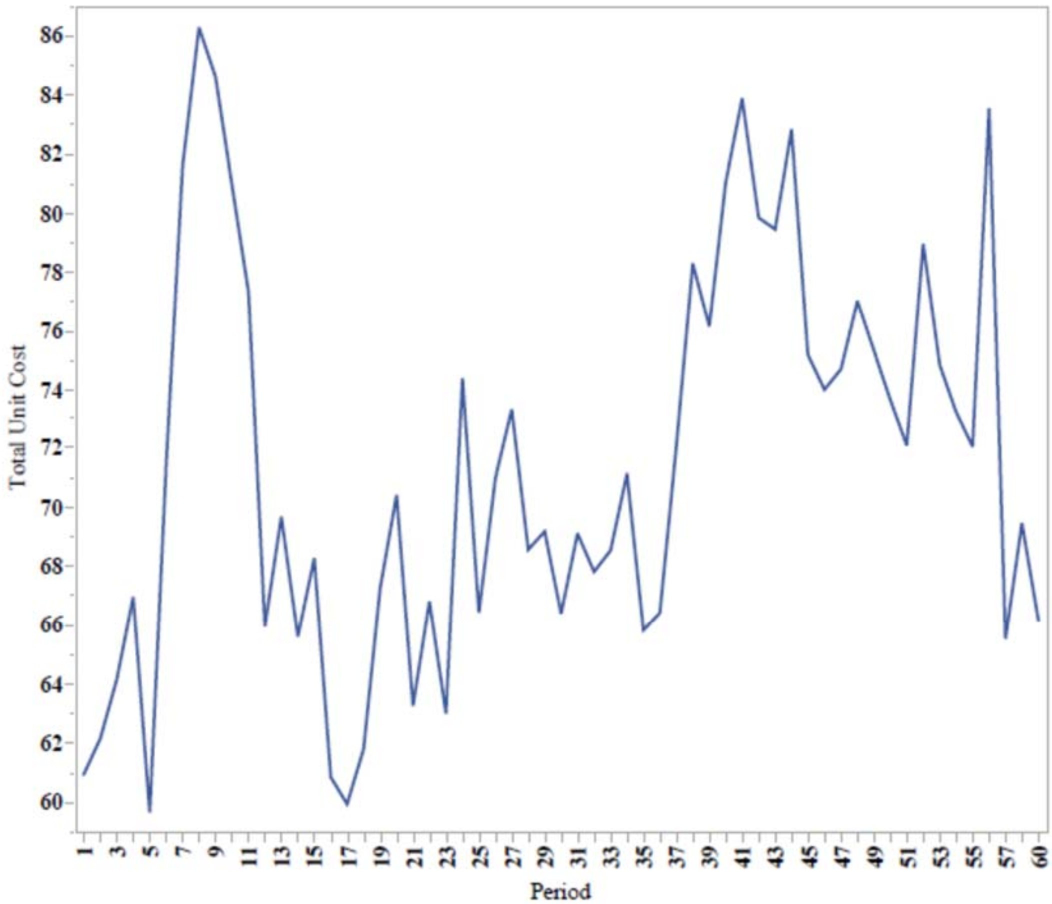


Figure 6-2: Average Unit Cost of Materials for Each Month (2008-2013)

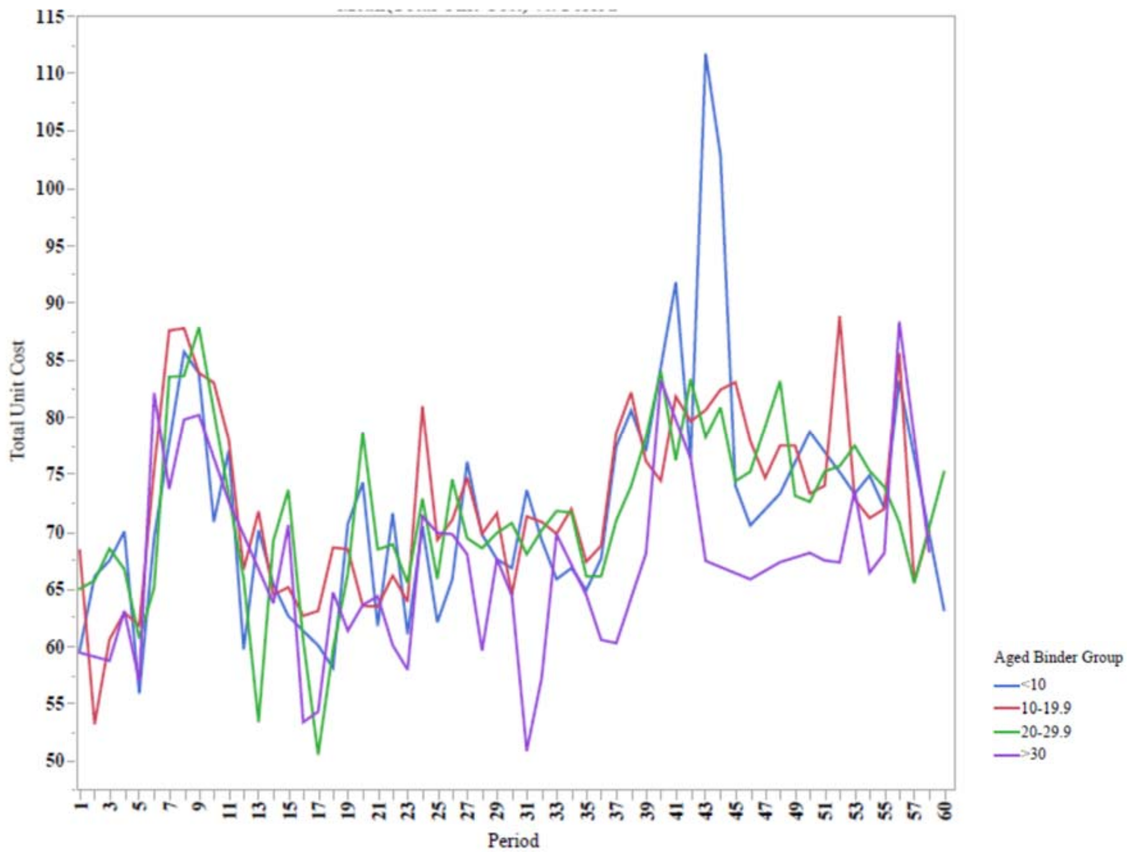


Figure 6-3: Average Unit Cost per Each Binder Group for Each Month (2008-2013)

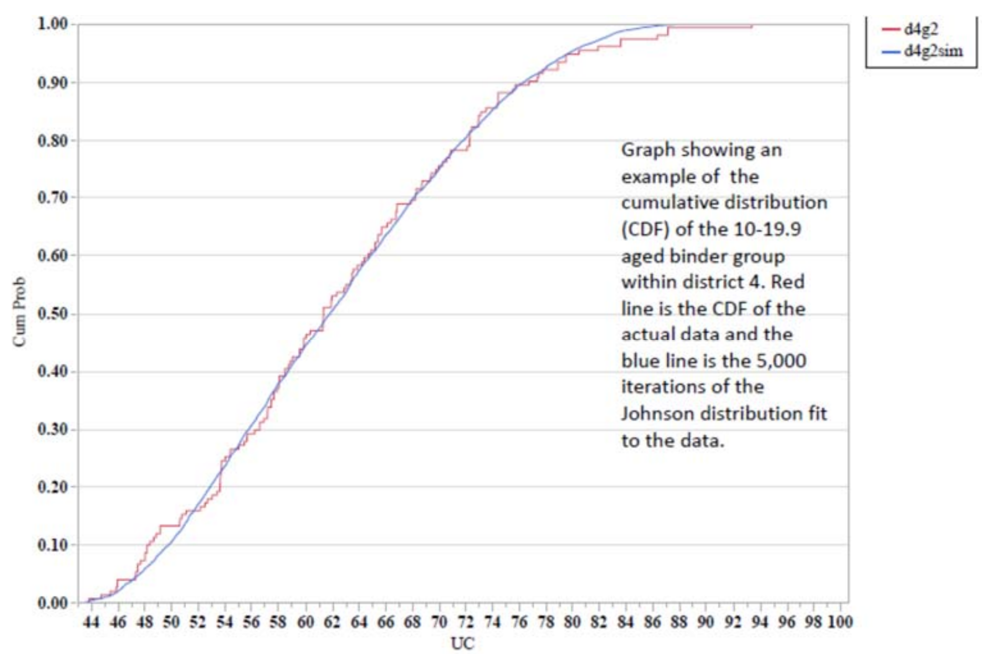


Figure 6-4: Example Cumulative Distribution of Aged Binder Group (within District 4)

Quantile Regression and RAP Unit Cost Data

Most prediction models used in cost estimating applications focus on how the conditional mean of the cost changes in response to changes in the covariates. For example, ordinary least square (OLS) regression models for pavement data will model the change in the mean unit cost for a given value of an independent variable of interest, such as quantity of material used in the paving project. These models assume that the shift in the mean is purely a shift in the location of the conditional distribution of the response variable; only the location of the conditional distribution of the response variable is assumed to change while the scale of the conditional distribution is assumed to be constant for all values of the independent variable. Assumptions of these regression models include the following: the distribution of the errors are normally distributed and that the variance is constant (or homoscedastic). However, these assumptions can fail in practice, especially when mean models are used to model pavement cost data. The distributions of pavement unit costs are typically skewed to the right and possess heavy upper tails, and the location and scale of the unit cost distribution will typically change as the independent variables change in value. For example, the distribution of the unit cost of asphalt pavement will typically be skewed with greater variability for lower quantities of pavement while distribution of the unit cost for higher quantities of asphalt will have smaller variability.

While the focus on the conditional mean models can be beneficial in several applications, the change in the conditional distribution may also be beneficial to an analyst investigating the factors influencing the unit costs of pavement data. The conditional distribution of a response variable can be modeled by using quantile regression techniques. Quantile regression models are able to model shifts in the location of the conditional distribution as well as detect changes to the scale and shape of the conditional distribution of the response variable. This flexibility has attracted greater attention recently, and quantile regression techniques are seeing increasing usage in areas such as finance, marketing, ecology, forestry, and building energy consumption.

Essentially, quantile regression can develop a model for every quantile of interest. Therefore, if a model is constructed for the 0.90 quantile, a model for the 0.90 alone will be created. The same is true if one wanted to explore the median (0.50 quantile) or any other quantile. When enough of the models are constructed for a range of quantiles, say 0.10 through 0.90, a location, shape, and scale of the distribution can be modeled for a given value of the predictor variable(s). There are more advantages to using quantile regression instead of OLS regression. One advantage is that quantile regression does not assume that the distribution of the error terms are normally distributed. Quantile regression also accommodates heteroscedasticy, or non-constant variance.

The following is a simple example comparing OLS and quantile regression. The graph on the left-hand side of Figure 6-5 shows the distribution of a small simulated data set at $x = 0$ while the graph on the right-hand side of Figure 6-5 shows the distribution of the data set at $x = 1$. As shown in the figures, the data at $x = 0$ is skewed with a heavy tail while the data at $x = 1$ is approximately normally distributed. Figure 6-6 shows the regression models for the example data. The black dashed line is the mean (or OLS) model for the data while the colored solid lines represent the quantile regression models for the 0.10, 0.25, 0.50, 0.75, and 0.90 quantiles. By examining the graphs in Figure 6-5 and the models in Figure 6-6, it is easily seen that the assumptions of the mean model are violated (error terms will not be normally distributed and the variance across the model is not constant). The quantile models are an improved way of viewing the distribution of this data set.

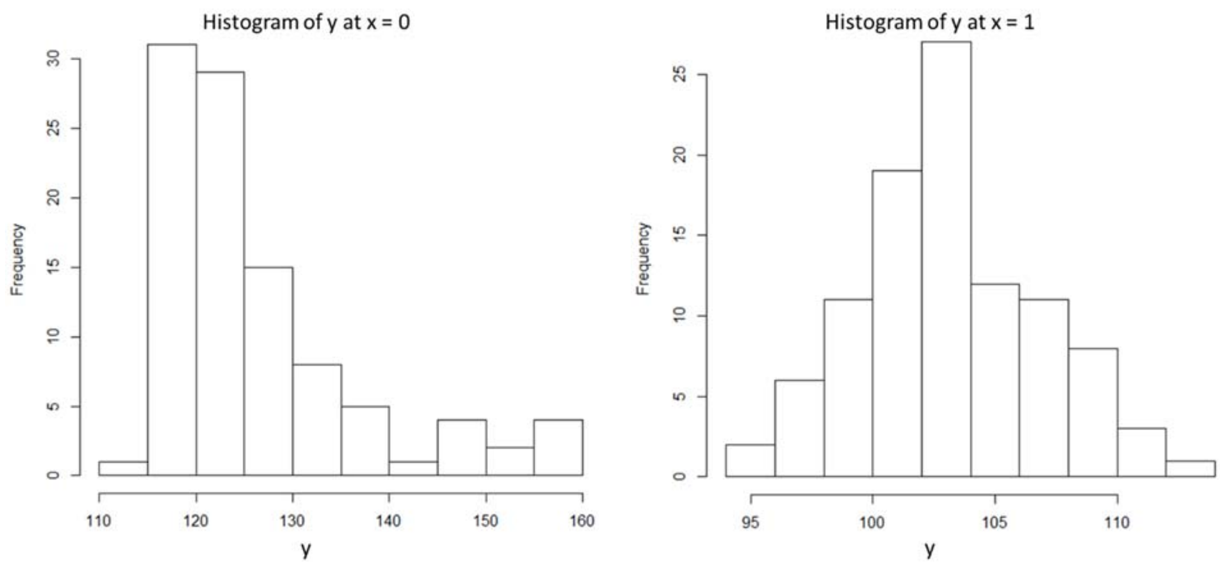


Figure 6-5: Data Distributions at x = 0 and x= 1

If we use the 0.90 quantile model as an example, we will see that for any *x* value (in our case *x* will be either 0 or 1), there is a 10 percent chance that a predicted *y* value will be above this line, and similarly, 90 percent of the *y*'s will be below this line for a given *x* value. Using this example data, at $x = 0$ there is a 10 percent chance that the value of *y* will exceed 141.17 while at $x = 1$ there is a 10 percent chance that the value of *y* will exceed 108.71.

The change in the distribution of the *y* data at both values of *x* can also be seen using the quantile models. At $x = 0$, we see that the 0.10, 0.25, and the 0.50 quantile models are spaced closer together while the 0.75 and 0.90 quantile models are spaced further from the 0.50 quantile model. This indicates that the distribution of *y* at $x = 0$ is skewed and has more *y* values at the upper end of the distribution (heavier tail). At $x = 1$, the quantiles are spaced more uniformly, indicating the distribution of the *y* data at this value is more symmetric.

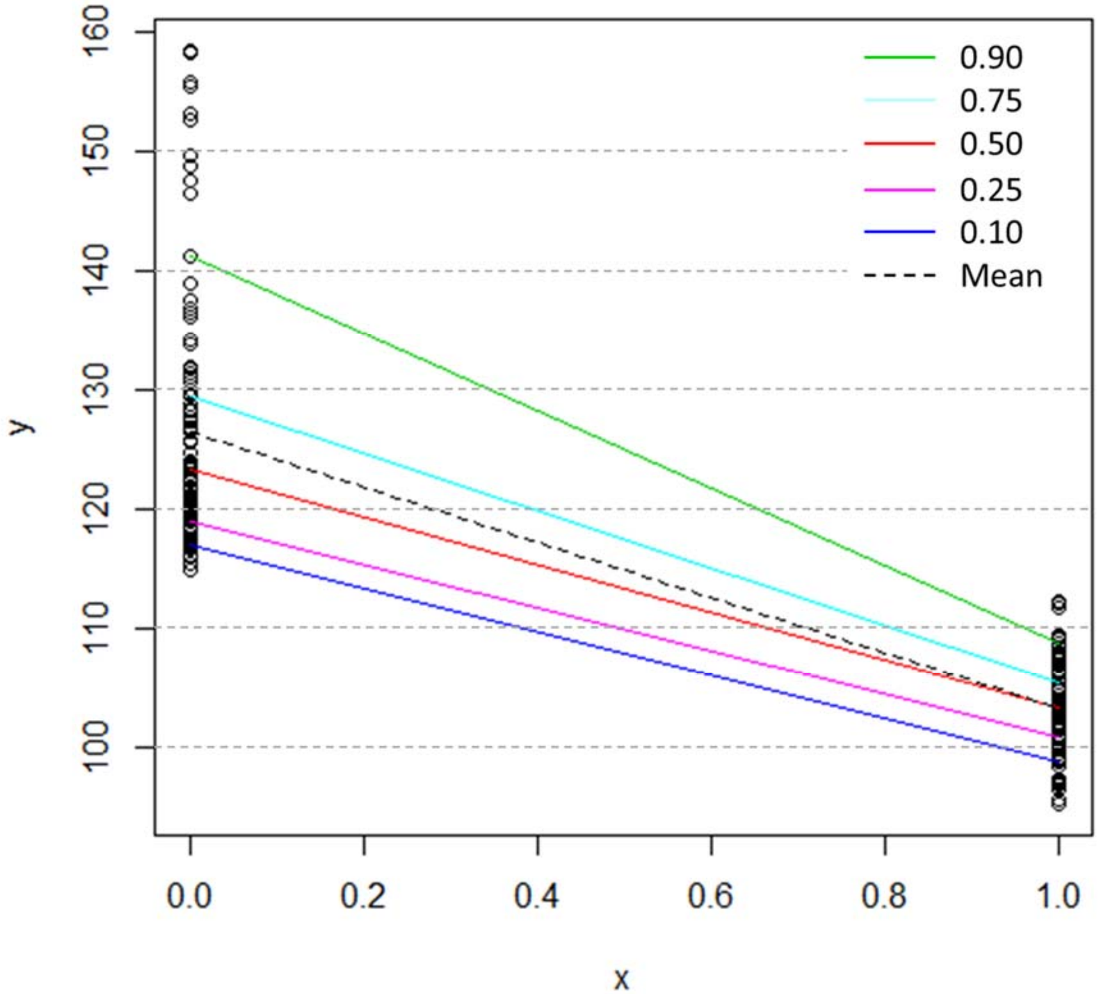


Figure 6-6: Comparing Quantile Regression and OLS Regression Models for Example Data

Using this simple example, it is demonstrated that using quantile regression methods could aid in creating better cost estimation models. Using the asphalt pavement data as the main data set, this particular research thrust has two phases:

1. Create models that will predict the conditional distribution of unit costs based on variables such as quantity of asphalt needed for the project and percent aged binder in the mix (Figure 6-7 and Figure 6-8, for preliminary models)
2. Using the conditional distributions obtained in Phase 1 to fit probability distributions that can be used in probabilistic analyses

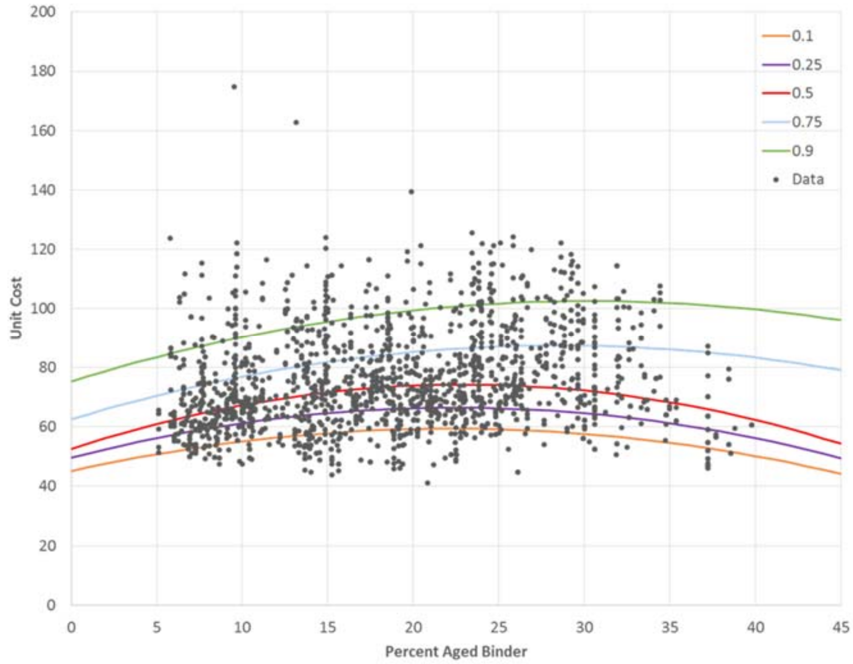


Figure 6-7: Nonlinear Quantile Models for Asphalt Unit Cost and Percent Aged Binder

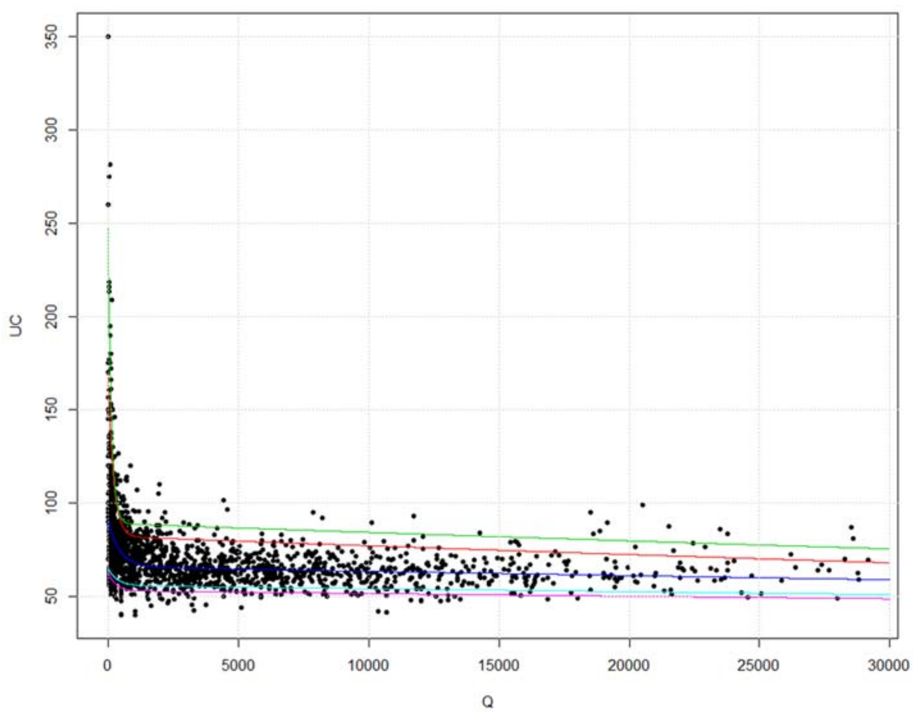


Figure 6-8: Nonlinear Quantile Models for Asphalt Unit Cost and Quantity

The quantile regression could also benefit the cost estimation of RAPs concerns the spatial component of the costs. For example, the analysis of the data has indicated that there is a difference in costs associated with different highway districts of South Carolina (Figure 6-9 for the mean unit costs for the seven districts based on the aged binder groups).

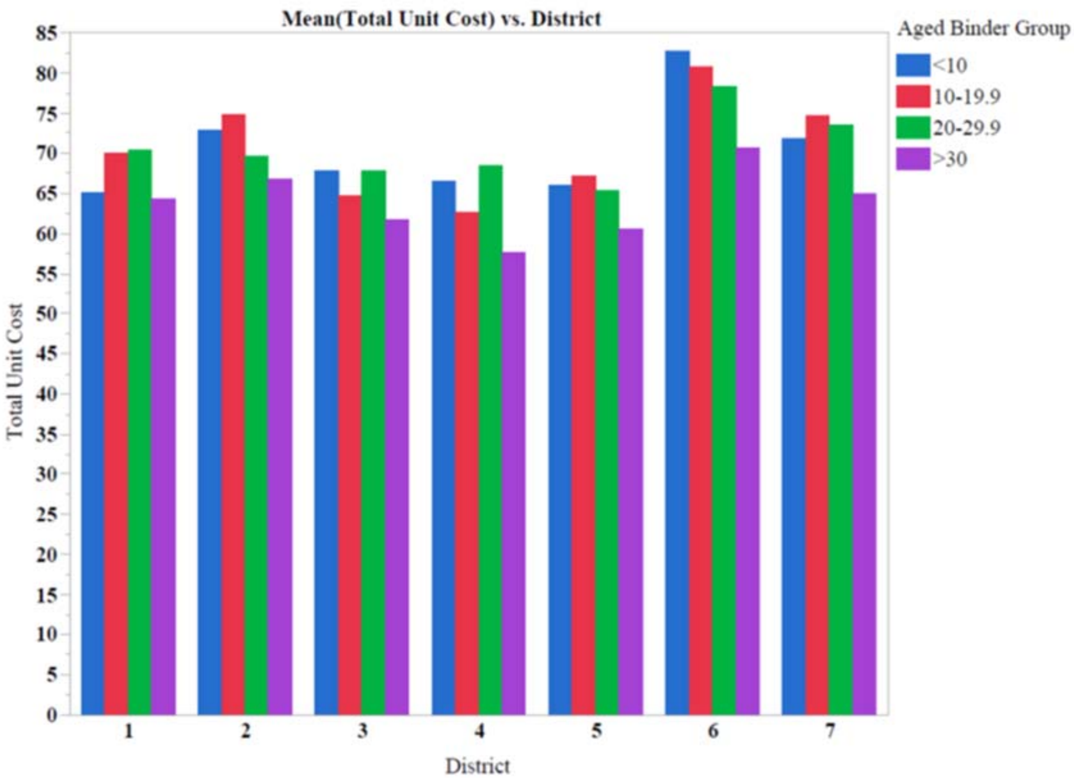


Figure 6-9: RAP Unit Cost by District and Aged Binder Group

Using the cost data, variables (percent aged binder, quantity, etc.), and the location of the project, one can develop models that will show the distribution of the conditional distribution across the state of South Carolina. Figure 6-10 shows an illustration of the type of map that has been created for this research project. In this figure, the 0.90 quantile unit cost for 30 percent aged binder may be $110/ton for the Charleston area. As you get farther from Charleston, the 0.90 quantile unit cost will decrease but may increase around another metropolitan area such as Columbia. Similar maps should be created for other quantiles of interest.

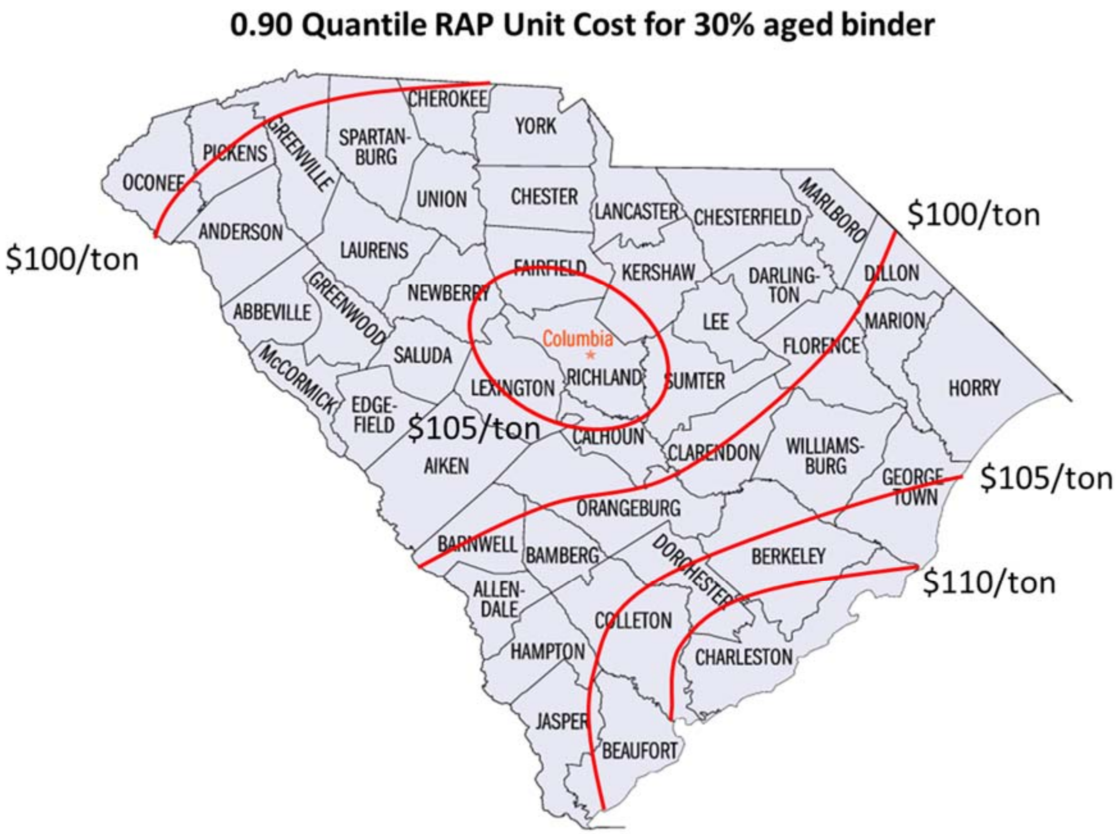


Figure 6-10: 0.90 Quantile RAP Unit Cost for 30% Aged Binder (Illustrative Purposes Only)

Mean total unit cost, median total unit cost and range of total unit cost for all districts and aged binder groups are shown in Table 6-3 and Table 6-4, respectively. The relationship between aged binder groups verses total unit cost and mean unit cost for all districts are shown in Figure 6-11 and Figure 6-12, respectively. The relationship between all districts and the total unit cost and mean unit cost for all aged binder groups are shown in Figure 6-13 and Figure 6-14, respectively. Figure 6-16 shows the predicted total unit cost verses residual total unit cost. The regression model (percent aged binder as continuous variable) for all districts is shown in Figure 6-17. In addition, Figure 6-18 shows the regression model for the predicted total unit weight verses residual total unit cost, where percent aged binder groups was considered as continuous variable. The prediction expression for the percent aged groups and the districts are shown below:

Prediction Expression

$$
\begin{aligned}
&757.926397808485\\
&+\mathrm{Match}\left(\text{Aged Binder Group}\right)\begin{pmatrix} \text{"<10"} & \Rightarrow 1.14303636754671 \\ \text{"10-19.9"} & \Rightarrow 1.75848451574525 \\ \text{"20-29.9"} & \Rightarrow 1.71546604075831 \\ \text{">30"} & \Rightarrow -4.6169869240503 \\ \text{else} & \Rightarrow . \end{pmatrix}\\
&+\mathrm{Match}\left(\text{District}\right)\begin{pmatrix} 1 & \Rightarrow -1.6042275108858 \\ 2 & \Rightarrow 3.04739241693477 \\ 3 & \Rightarrow -3.4591023665744 \\ 4 & \Rightarrow -5.9113387100591 \\ 5 & \Rightarrow -3.7676647045707 \\ 6 & \Rightarrow 8.25873468583458 \\ 7 & \Rightarrow 3.4362061893207 \\ \text{else} & \Rightarrow . \end{pmatrix}
\end{aligned}
$$

Table 6-3: Mean Total Unit Cost, Median Total Unit Cost and Range of Total Unit Cost for All Districts

District	Aged Binder Group	Mean(Total Unit Cost)	Std Dev (Total Unit Cost)	Median (Total Unit Cost)	Range (Total Unit Cost)
1	<10	65.01	11.26	61.95	59.33
1	10-19.9	70.00	13.16	68.39	68.37
1	20-29.9	70.30	10.85	67.68	53.10
1	>30	64.30	11.40	60.80	42.46
2	<10	72.82	10.60	70.55	55.50
2	10-19.9	74.71	10.47	71.16	59.22
2	20-29.9	69.57	5.42	70.26	28.33
2	>30	66.73	3.98	66.72	22.89
3	<10	67.80	13.41	67.41	49.64
3	10-19.9	64.63	8.53	63.16	40.03
3	20-29.9	67.76	8.63	68.69	39.33
3	>30	61.70	6.69	60.08	22.31
4	<10	66.41	11.80	65.06	77.42
4	10-19.9	62.54	10.48	61.39	49.58
4	20-29.9	68.42	12.34	67.24	89.96
4	>30	57.46	8.20	55.52	36.45
5	<10	65.86	9.73	63.44	41.50
5	10-19.9	67.10	10.86	65.27	66.99
5	20-29.9	65.23	10.54	64.54	48.50
5	>30	60.42	12.78	57.48	64.35
6	<10	82.63	14.92	79.87	49.14
6	10-19.9	80.75	13.47	79.70	69.19
6	20-29.9	78.19	12.21	75.33	82.71
6	>30	70.63	12.13	67.83	58.46
7	<10	71.73	9.57	70.19	47.28
7	10-19.9	74.60	8.73	72.69	65.60
7	20-29.9	73.45	9.31	70.86	58.74
7	>30	64.89	4.41	63.46	19.08

Table 6-4: Mean Total Unit Cost, Median Total Unit Cost and Range of Total Unit Cost for Aged Binder Group

Aged Binder Group	District	Mean(Total Unit Cost)	Std Dev (Total Unit Cost)	Median (Total Unit Cost)	Range (Total Unit Cost)
<10	1	65.01	11.26	61.95	59.33
<10	2	72.82	10.60	70.55	55.50
<10	3	67.80	13.41	67.41	49.64
<10	4	66.41	11.80	65.06	77.42
<10	5	65.86	9.73	63.44	41.50
<10	6	82.63	14.92	79.87	49.14
<10	7	71.73	9.57	70.19	47.28
10-19.9	1	70.00	13.16	68.39	68.37
10-19.9	2	74.71	10.47	71.16	59.22
10-19.9	3	64.63	8.53	63.16	40.03
10-19.9	4	62.54	10.48	61.39	49.58
10-19.9	5	67.10	10.86	65.27	66.99
10-19.9	6	80.75	13.47	79.70	69.19
10-19.9	7	74.60	8.73	72.69	65.60
20-29.9	1	70.30	10.85	67.68	53.10
20-29.9	2	69.57	5.42	70.26	28.33
20-29.9	3	67.76	8.63	68.69	39.33
20-29.9	4	68.42	12.34	67.24	89.96
20-29.9	5	65.23	10.54	64.54	48.50
20-29.9	6	78.19	12.21	75.33	82.71
20-29.9	7	73.45	9.31	70.86	58.74
>30	1	64.30	11.40	60.80	42.46
>30	2	66.73	3.98	66.72	22.89
>30	3	61.70	6.69	60.08	22.31
>30	4	57.46	8.20	55.52	36.45
>30	5	60.42	12.78	57.48	64.35
>30	6	70.63	12.13	67.83	58.46
>30	7	64.89	4.41	63.46	19.08

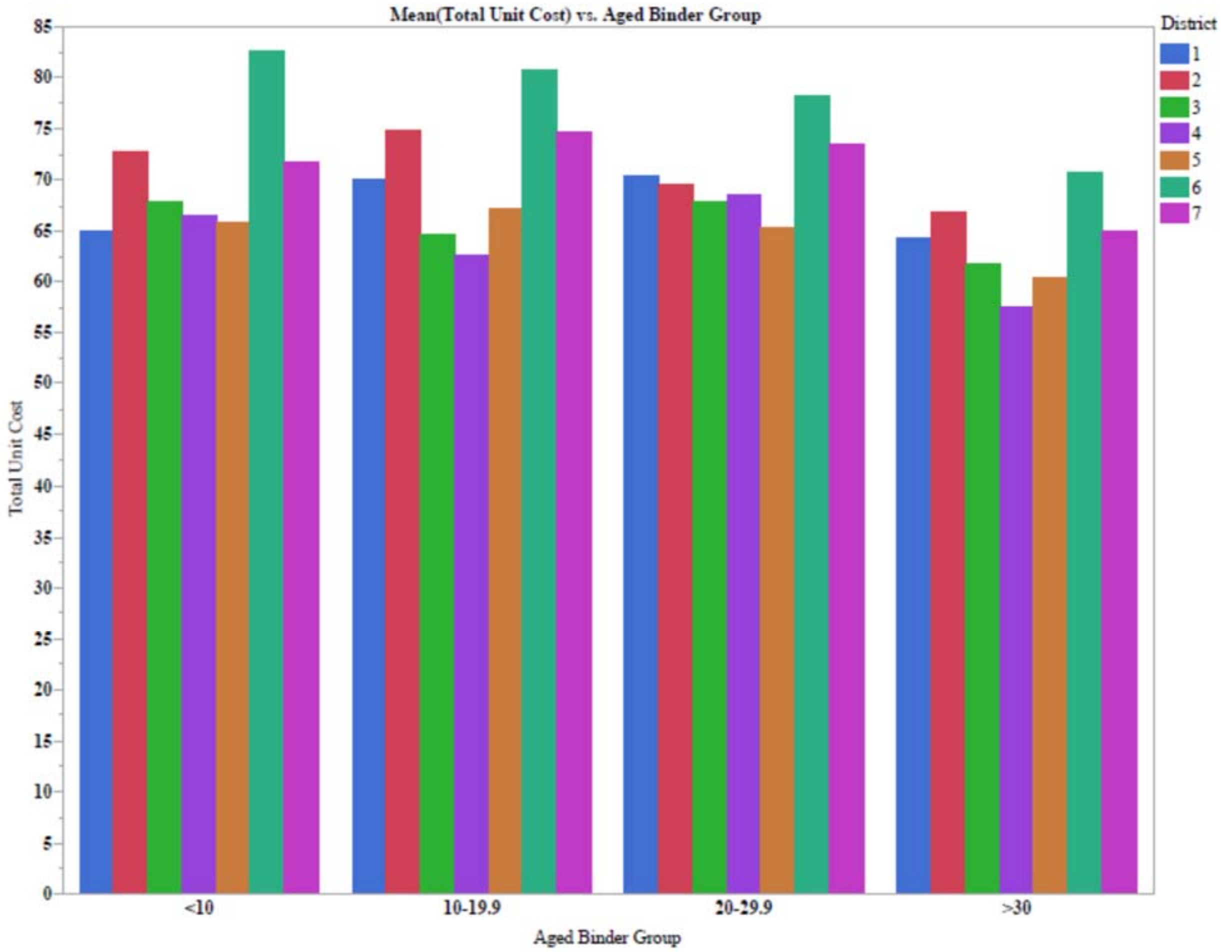


Figure 6-11: Relationship between Aged Binder Group and Total Unit Cost for All Districts

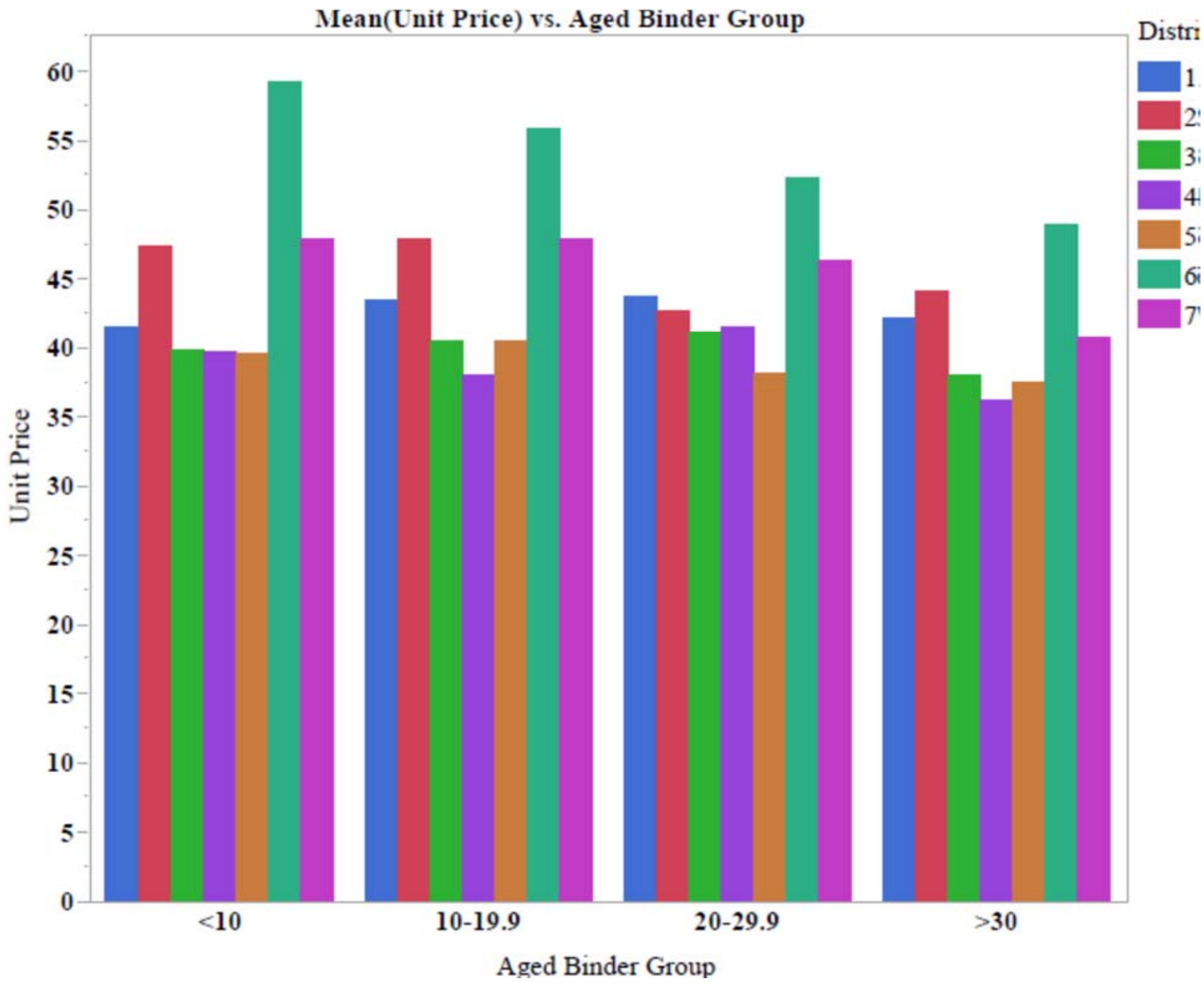


Figure 6-12: Relationship between Aged Binder Group and Mean Unit Price

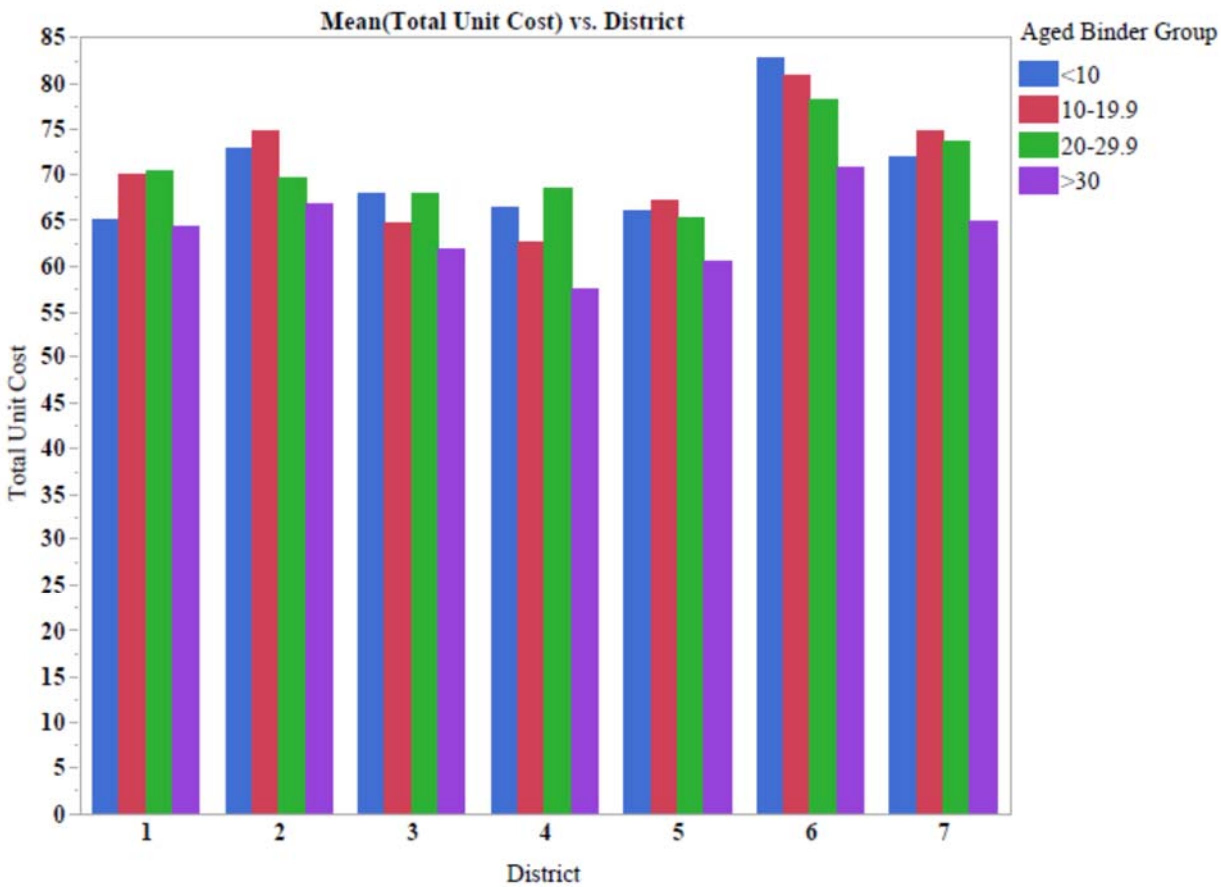


Figure 6-13: The relationship between All Districts and Total Unit Cost per Aged Binder Group

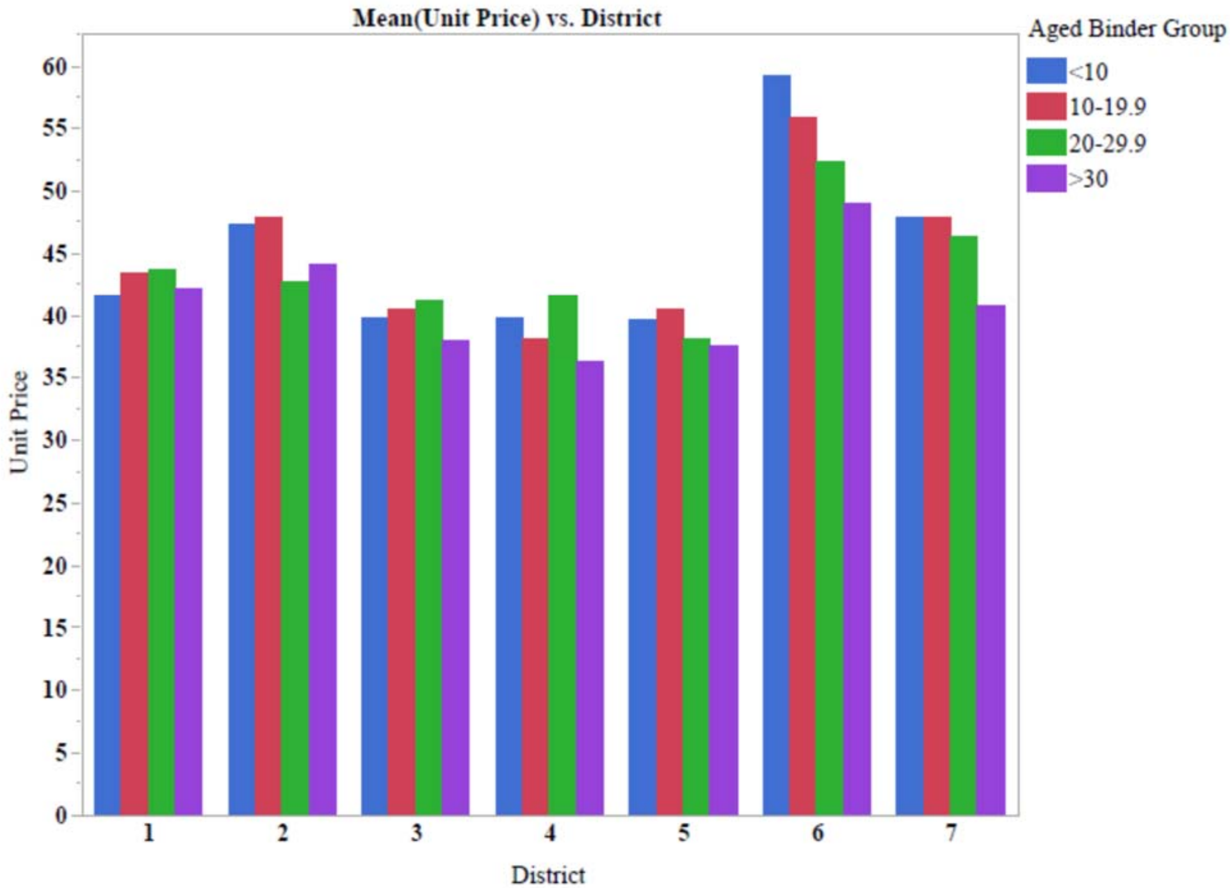
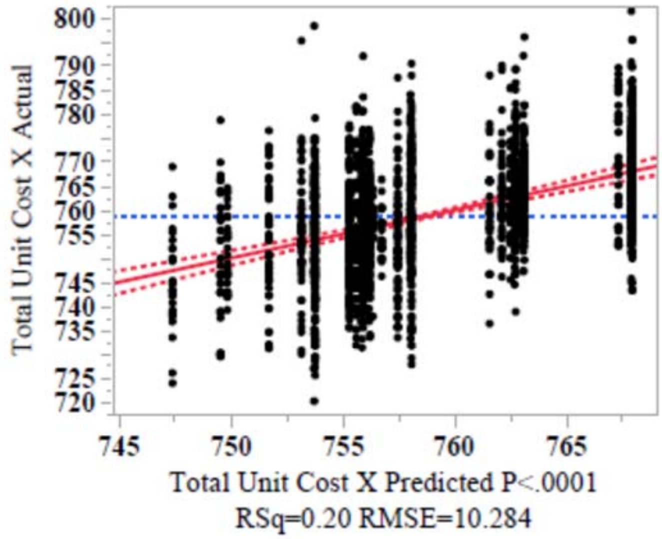


Figure 6-14: The Relationship between All Districts and Unit Price per Aged Binder Group



Summary of Fit	
RSquare	0.201126
RSquare Adj	0.198
Root Mean Square Error	10.28428
Mean of Response	758.7245
Observations (or Sum Wgts)	2310

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	9	61244.21	6804.91	64.3390
Error	2300	243262.83	105.77	Prob > F
C. Total	2309	304507.04		<.0001*

Figure 6-15: The Regression Model, Percent Aged Binder Groups as Categorical Variable

Parameter Estimates							
Term	Estimate	Std Error	t Ratio	Prob>|t|	Lower 95%	Upper 95%	VIF
Intercept	757.9264	0.244647	3098.0	<.0001*	757.44665	758.40615	.
Aged Binder Group[<10]	1.1430364	0.395965	2.89	0.0039*	0.3665503	1.9195225	1.1348887
Aged Binder Group[10-19.9]	1.7584845	0.344623	5.10	<.0001*	1.0826797	2.4342894	1.0532496
Aged Binder Group[20-29.9]	1.715466	0.388439	4.42	<.0001*	0.9537391	2.4771929	1.1137852
District[1]	-1.604228	0.521189	-3.08	0.0021*	-2.626278	-0.582177	1.5642315
District[2]	3.0473924	0.557613	5.47	<.0001*	1.9539154	4.1408694	1.645963
District[3]	-3.459102	0.593868	-5.82	<.0001*	-4.623676	-2.294529	1.7331153
District[4]	-5.911339	0.535529	-11.04	<.0001*	-6.961508	-4.861169	1.5973303
District[5]	-3.767665	0.462775	-8.14	<.0001*	-4.675164	-2.860165	1.4946885
District[6]	8.2587347	0.515325	16.03	<.0001*	7.2481849	9.2692844	1.576095

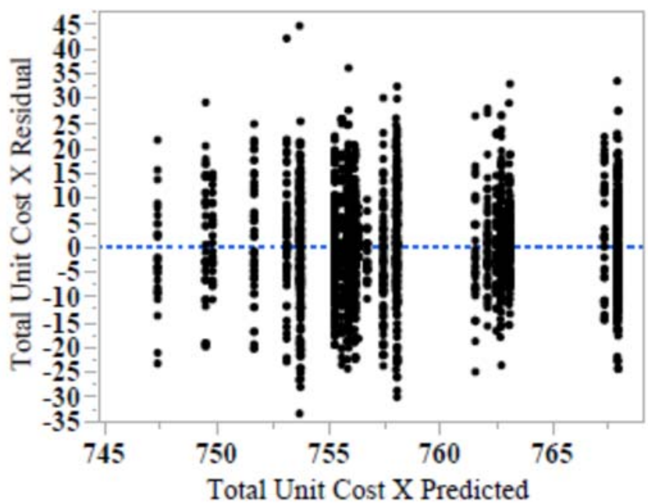
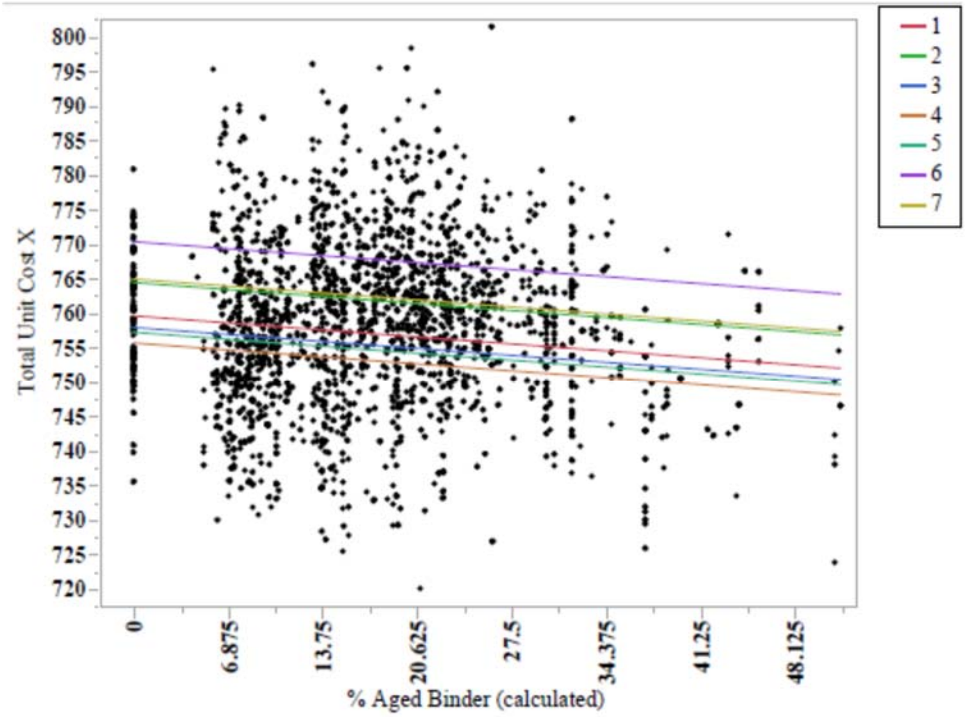


Figure 6-16: The Predicted Total Unit Cost versus Residual Total Unit Cost



Summary of Fit	
RSquare	0.187814
RSquare Adj	0.185344
Root Mean Square Error	10.36511
Mean of Response	758.7245
Observations (or Sum Wgts)	2310

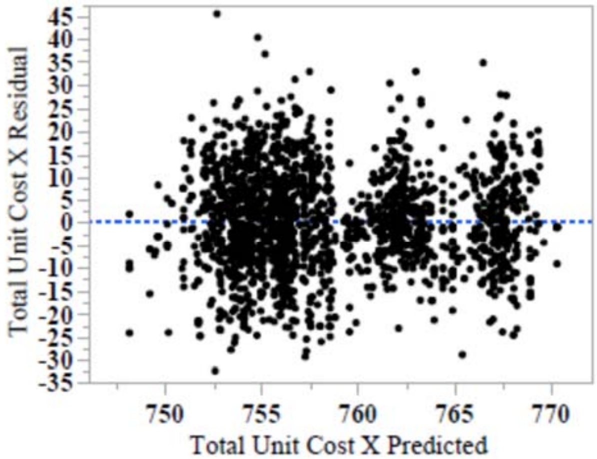
Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	7	57190.60	8170.09	76.0464
Error	2302	247316.45	107.44	Prob > F
C. Total	2309	304507.04		<.0001*

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|	VIF
Intercept	761.42784	0.466667	1631.6	<.0001*	.
% Aged Binder (calculated)	-0.147114	0.023638	-6.22	<.0001*	1.0474022
District[1]	-1.855093	0.524433	-3.54	0.0004*	1.5591586
District[2]	2.9787012	0.561595	5.30	<.0001*	1.6436205
District[3]	-3.520283	0.598345	-5.88	<.0001*	1.7320139
District[4]	-5.763364	0.538371	-10.71	<.0001*	1.5892551
District[5]	-4.219965	0.459804	-9.18	<.0001*	1.4526368
District[6]	8.8942616	0.518763	17.15	<.0001*	1.5723852

Figure 6-17: The Regression Model (Percent Aged Binder as Continuous Variable) for All Districts



$$761.427839574067 + -0.1471137395841 * \%\ \text{Aged Binder (calculated)} + \text{Match}\left(\text{District}\right)\begin{pmatrix} 1 & \Rightarrow -1.8550926879705 \\ 2 & \Rightarrow 2.97870118443289 \\ 3 & \Rightarrow -3.5202832689794 \\ 4 & \Rightarrow -5.763364043649 \\ 5 & \Rightarrow -4.2199650421998 \\ 6 & \Rightarrow 8.89426163513861 \\ 7 & \Rightarrow 3.48574222322733 \\ \text{else} & \Rightarrow . \end{pmatrix}$$

Figure 6-18: Regression Model, Predicted Total Unit Cost versus Residual Total Unit Cost, Percent Aged Binder Groups as Continuous Variable

Chapter 7 – Development of Alternate Pay Schedule

Nebraska's Payment Method

One of the objectives of this research project was to investigate the alternate pay schedule methodology used by other states. Out of the surveys returned by the State DOTs, Nebraska DOT was found to be the only state utilizing a methodology that accounts for the use of aged binder. The intent of Nebraska's DOT's payment method is to incentivize incorporating the maximum allowable RAP into asphalt mixtures. The following methodology and equation are used for paying for asphalt mix and binder in Nebraska.

1. The RAP Incentive Payment shall be based on the actual total of asphalt production for the entire project. A RAP Incentive Payment shall be calculated for each eligible asphaltic concrete type.

2. The following formula is used to calculate the "RAP Incentive Factor".

RAP Incentive Factor = [(A-B) ÷ 100] x C x D

Where:

A = State's Established Percent Binder – based on gradation band.

B = Actual Percentage of Binder – added to asphaltic mixture.

C = Unit Bid price of Binder

D = RAP Pay Factor

The Nebraska DOT procedures use the following established percent binder values ('A' values) for the above mentioned equation:

Asphaltic Concrete Types	***'A' Value***
SPH having 0.500-inch grading band	*5.2% Binder*
SPS, SPL, SPR and SPR (Fine)	*5.2% Binder*
SLX	*5.5% Binder*
SPH having 0.375-inch grading band	*5.8% Binder*
LC	*6.2% Binder*
SRM	*4.8% Binder*

Incentive payments will be made for only the mix types list in this table.

Note: Nebraska DOT mix type designations are as follows:

- *SPH – Superpave Heavy*
- *SPS – Superpave Shoulder*
- *SPL – Superpave Light*
- *SPR – Superpave Regular*
- *SLX – Thin Lift Overlay*
- *LC – Leveling Course*
- *SRM – Special Reclamation Mix (Warm)*

The actual percentage of binder added to the particular asphaltic mixture ('B' value) shall be, according to Nebraska DOT, calculated as follows:

$$B = (\text{Actual Pay Tons of Binder} \div \text{Actual Pay Tons of Asphaltic Concrete}) \times 100$$

The Unit Bid Price of Binder ('C' value) is the established contract price for the performance graded binder type used to produce the mix for which the incentive is being calculated. The RAP Pay Factor ('D' value) shall be used as follows:

RAP Source	***'D' Value***
Contractor supplied RAP	*0.15*
*State supplied RAP coming from an **OFF**-project source*	*0.35*
* *RAP coming from an **ON**-project source*	*0.15*

After extensive literature review, it was not clear exactly how the "D" Values were derived in the Nebraska DOT payment method.

Basis of Payment (Nebraska DOT)

1. *Pay Item* — *Pay Unit*

   RAP Incentive Payment ____ — *Each (ea)*

2. *The overall RAP Incentive Payments shall be full compensation for all RAP materials and all hauling, handling and processing necessary to complete the work.*

3. *The overall RAP Incentive Payments – for each eligible mix type and/or RAP source – shall be the RAP Incentive Factor multiplied by the total accepted tons of asphaltic concrete in which the RAP was incorporated.*

4. *RAP Incentive Payment is paid for as an "established" contract unit price which is shown in the bid proposal "Schedule of Items".*

5. *The actual quantity for RAP Incentive Payment will be calculated based on the Method of Measurement stated above in this provision.*

In Nebraska, after milling on state-funded projects the state, not the contractors, owns the RAP. This issue appears to make the Nebraska specification non-compatible with current practices regarding RAP in South Carolina since contractors own the RAP after milling in South Carolina. Another concern is how binder contents of field mixtures compare to those presented as “A” values for common Nebraska mixes. It is important to note that these variations would affect the pay. In addition, more information would be needed on how the coefficients for the RAP Pay Factor (“D” value) are determined for Nebraska since these inputs may or may not be valid under SCDOT specifications. If SCDOT were to follow Nebraska’s precedent, optimum asphalt binder contents would also need to be determined for eligible SCDOT asphalt mixes.

Taking these issues into consideration, the following equation was developed that could potentially be used by SCDOT for calculating the RAP pay factor:

RAP Pay Factor = [(A – B)/100]*C*D

A = Average AC Binder Content per lot[1]

B = Actual Virgin % Binder used in mix per lot[2]

C = Unit Bid Price of Binder[3]

D = Aged Binder Value Factor per Mix Type[4]

1. Based on average of sublot ignition oven tests
2. Based on either/or tank stabs/asphalt binder supplier receipts per sublot

   B = [Actual Tons of Virgin Binder Paid/Actual Tons of Asphalt Mix Produced}*100
3. Adjusted unit price based on SCDOT’s Binder Index
4. Data yet to be obtained.

   D = Historical RAP Mix Unit Price/Historical Virgin Mix Unit Price

It is important to note that the virgin and RAP mix unit prices would have to be bid as individual line items for a period of time to collect mix price data for various project sizes and mix types. As far as payment, the RAP Pay Factor would be multiplied by tons of asphalt concrete produced for the lot. However, if this alternate payment method were implemented, it is hypothesized that contractor bid prices would adjust for this new payment method, resulting in a zero net change in overall payment by the SCDOT as shown in the numerical examples that follow. Thus, it is not recommended to change the Department’s current procedures for pay factors at this time.

<u>Numerical Examples of the Developed Equation</u>

The following is a numerical example comparing the current payment method to the alternate payment method. The following data used in this example are taken from this project and are average numbers from the 2013 data (for all mixture types and all Districts):

- Average mix bid unit price for 2013 projects = \$40.86 per ton
- Average binder index value for 2013 projects = 967.53 per ton (use as unit price of virgin binder)
- Average % aged binder for 2013 projects = 21.80%
- Average % virgin binder for 2013 projects = 78.20%
- Average % binder content for 2013 projects = 5.21%
- Average % virgin binder used = $\frac{Avg\ \%\ virgin\ binder\ in\ 2013}{100\%} \times Avg\ \%\ binder\ in\ 2013$
- Average theoretical virgin mix unit price, including mix and binder = \$105.86 per ton*
- Average RAP mix unit price, including mix and binder = \$91.27 per ton*

*Taken from data in this project for this example, but should be collected by SCDOT as separate line item bid prices for a period of time and then used to develop average "D" values for each mixture type.

Current Payment Method Example

The following is an example using the current payment method, assuming a 2,500-ton project:

$$Mix\ payment = Avg\ mix\ bid\ unit\ price\ for\ 2013 \times tons\ of\ mix = \$40.86 \times 2{,}500\ tons$$

$$Mix\ payment = \$102{,}150.00$$

$$Tons\ of\ binder = \frac{Avg\ \%\ binder\ in\ 2013}{100\%} \times tons\ of\ mix = \frac{5.21\%}{100\%} \times 2{,}500\ tons = 130.25$$

$$Binder\ payment = virgin\ binder\ unit\ price \times tons\ of\ binder = \$967.53 \times 130.25\ tons$$

$$Binder\ payment = \$126{,}020.78$$

$$Total\ payment = Mix\ payment + Binder\ payment = \$228{,}170.78$$

1st Alternate Payment Method Example

The following is an example using the alternate payment method, assuming the same 2,500-ton project:

$$D = \frac{historical\ RAP\ mix\ unit\ price^{*}}{historical\ Virgin\ mix\ unit\ price^{*}} = \frac{\$91.27}{\$105.86} = 0.86$$

*Taken from data from this project for this example, but should be collected by SCDOT as separate line item bid prices for a period of time and then used to develop average "D" values for each mixture type.

$$Avg\ \%\ virgin\ binder\ used = \frac{Avg\ \%\ virgin\ binder\ in\ 2013}{100\%} \times Avg\ \%\ binder\ content\ in\ 2013$$

$$Avg\ \%\ virgin\ binder\ used = \frac{78.20\%}{100\%} \times 5.21\% = 4.07\%$$

$$RAP\ Pay\ Factor = \frac{(Avg.\%\ Binder - \%\ Virgin\ Binder\ used)}{100\%} \times unit\ price\ of\ virgin\ binder \times D$$

$$RAP\ Pay\ Factor = \frac{(5.21\% - 4.07\%)}{100\%} \times 967.53 \times 0.86 = 9.49$$

$$RAP\ payment = RAP\ Pay\ Factor \times tons\ of\ mix = 9.49 \times 2{,}500\ tons = \$23{,}725.00$$

$$Mix\ payment = Avg\ mix\ bid\ unit\ price\ for\ 2013 \times tons\ of\ mix = \$40.86 \times 2{,}500\ tons$$

$$Mix\ payment = \$102{,}150.00$$

$$Tons\ of\ binder = \frac{Avg\ \%\ virgin\ binder\ used}{100\%} \times tons\ of\ mix = \frac{4.07\%}{100\%} \times 2{,}500\ tons = 101.75$$

$$Binder\ payment = virgin\ binder\ unit\ price \times tons\ of\ binder = \$967.53 \times 101.75\ tons$$

$$Binder\ payment = \$98{,}446.18$$

$$Total\ payment = Mix\ payment + Binder\ payment + RAP\ payment = \$224{,}321.18$$

However, if one assumes that the current contractor bid prices using the current payment method are actually the income required for contractors to stay in business, then it can be predicted that the contractors would simply begin adjusting their mix bid prices to account for any reduction in payment for aged binder through the alternate payment methods detailed in this report. If that happens, the following is an example of how the first alternate payment method would shift to paying the exact same total amount as the current payment method.

1st Alternate Payment Method Example after Bid Prices Stabilize

Prior to bid price adjustment:

$$Cost\ difference\ per\ ton = \frac{Total\ payment_{current} - Total\ payment_{alternate}}{tons\ of\ mix}$$

$$Cost\ difference\ per\ ton = \frac{\$228{,}170.78 - \$224{,}321.18}{2{,}500\ tons\ of\ mix} = \$1.54\ per\ ton$$

After bid price adjustment by contractors:

$$Adjusted\ bid\ price = original\ bid\ price + cost\ difference\ per\ ton = \$40.86 + \$1.54$$

$$Adjusted\ bid\ price = \$42.40\ per\ ton$$

$$Mix\ payment = Adjusted\ mix\ bid\ price \times tons\ of\ mix = \$42.40 \times 2{,}500\ tons$$

$$Mix\ payment = \$106{,}000.00$$

$$D = \frac{historical\ RAP\ mix\ unit\ price^*}{historical\ Virgin\ mix\ unit\ price^*} = \frac{\$91.27}{\$105.86} = 0.86$$

*Taken from data from this project for this example, but should be collected by SCDOT as separate line item bid prices for at least a year and then used to develop average "D" values for each mixture type.

$$Avg\ \%\ virgin\ binder\ used = \frac{Avg\ \%\ virgin\ binder\ in\ 2013}{100\%} \times Avg\ \%\ binder\ content\ in\ 2013$$

$$Avg\ \%\ virgin\ binder\ used = \frac{78.20\%}{100\%} \times 5.21\% = 4.07\%$$

$$RAP\ Pay\ Factor = \frac{(Avg.\%\ Binder - \%\ Virgin\ Binder\ used)}{100\%} \times unit\ price\ of\ virgin\ binder \times D$$

$$RAP\ Pay\ Factor = \frac{(5.21\% - 4.07\%)}{100\%} \times 967.53 \times 0.86 = 9.49$$

$$RAP\ payment = RAP\ Pay\ Factor \times tons\ of\ mix = 9.49 \times 2{,}500\ tons = \$23{,}725.00$$

$$Tons\ of\ binder = \frac{Avg\ \%\ virgin\ binder\ used}{100\%} \times tons\ of\ mix = \frac{4.07\%}{100\%} \times 2{,}500\ tons$$
$$= 101.75$$

$$Binder\ payment = virgin\ binder\ unit\ price \times tons\ of\ binder = \$967.53 \times 101.75\ tons$$

$$Binder\ payment = \$98{,}446.18$$

$$Total\ payment = Mix\ payment + Binder\ payment + RAP\ payment = \$228{,}171.18$$

After bid price adjustment by contractors:

$$Cost\ difference\ per\ ton = \frac{Total\ payment_{current} - Total\ payment_{alternate}}{tons\ of\ mix}$$

$$Cost\ difference\ per\ ton = \frac{\$228{,}171 - \$228{,}171}{2{,}500\ tons\ of\ mix} = \$0\ per\ ton$$

2nd Alternate Payment Method Example

The following is an example using a second alternate payment method that does not pay for aged binder at all, assuming the same 2,500-ton project:

$$Avg\ \%\ virgin\ binder\ used = \frac{Avg\ \%\ virgin\ binder\ in\ 2013}{100\%} \times Avg\ \%\ binder\ content\ in\ 2013$$

$$Avg\ \%\ virgin\ binder\ used = \frac{78.20\%}{100\%} \times 5.21\% = 4.07\%$$

$$Mix\ payment = Avg\ mix\ bid\ unit\ price\ for\ 2013 \times tons\ of\ mix = \$40.86 \times 2{,}500\ tons$$

$$Mix\ payment = \$102{,}150.00$$

$$Tons\ of\ binder = \frac{Avg\ \%\ virgin\ binder\ used}{100\%} \times tons\ of\ mix = \frac{4.07\%}{100\%} \times 2{,}500\ tons$$
$$= 101.75$$

$$Binder\ payment = virgin\ binder\ unit\ price \times tons\ of\ binder = \$967.53 \times 101.75\ tons$$

$$Binder\ payment = \$98{,}446.18$$

$$Total\ payment = Mix\ payment + Binder\ payment = \$200{,}596.18$$

However, if one assumes that the current contractor bid prices using the current payment method are actually the income required for contractors to stay in business, then it can be predicted that the contractors would simply begin adjusting their mix bid prices to account for any reduction in payment for aged binder through the alternate payment methods detailed in this report. If that happens, the following is an example of how the second alternate payment method would shift to paying the exact same total amount as the current payment method.

2nd Alternate Payment Method Example after Bid Prices Stabilize

Prior to bid price adjustment:

$$Cost\ difference\ per\ ton = \frac{Total\ payment_{current} - Total\ payment_{alternate}}{tons\ of\ mix}$$

$$Cost\ difference\ per\ ton = \frac{\$228{,}170.78 - \$200{,}596.18}{2{,}500\ tons\ of\ mix} = \$11.03\ per\ ton$$

After bid price adjustment by contractors:

$$Adjusted\ bid\ price = original\ bid\ price + cost\ difference\ per\ ton = \$40.86 + \$11.03$$

$$Adjusted\ bid\ price = \$51.89\ per\ ton$$

$$Mix\ payment = Adjusted\ mix\ bid\ price \times tons\ of\ mix = \$51.89 \times 2{,}500\ tons$$

$$Mix\ payment = \$129{,}725.00$$

$$Avg\ \%\ virgin\ binder\ used = \frac{Avg\ \%\ virgin\ binder\ in\ 2013}{100\%} \times Avg\ \%\ binder\ content\ in\ 2013$$

$$Avg\ \%\ virgin\ binder\ used = \frac{78.20\%}{100\%} \times 5.21\% = 4.07\%$$

$$Tons\ of\ binder = \frac{Avg\ \%\ virgin\ binder\ used}{100\%} \times tons\ of\ mix = \frac{4.07\%}{100\%} \times 2{,}500\ tons = 101.75$$

$$Binder\ payment = virgin\ binder\ unit\ price \times tons\ of\ binder = \$967.53 \times 101.75\ tons$$

$$Binder\ payment = \$98{,}446.18$$

$$Total\ payment = Mix\ payment + Binder\ payment = \$228{,}171.18$$

After bid price adjustment by contractors:

$$Cost\ difference\ per\ ton = \frac{Total\ payment_{current} - Total\ payment_{alternate}}{tons\ of\ mix}$$

$$Cost\ difference\ per\ ton = \frac{\$228{,}171 - \$228{,}171}{2{,}500\ tons\ of\ mix} = \$0\ per\ ton$$

Chapter 8 - Conclusions and Recommendations

Conclusions on RAP/RAS Usage, Specifications and Cost Calculations in Other States

Nineteen states responded to the survey that was conducted as part of this research project. The amount of hot mix asphalt (HMA) and warm mix asphalt (WMA) mixtures placed in 2012 varied from over 350,000 tons (Connecticut) to almost 4.7 million tons (Florida) of HMA and/or WMA mixtures. The results indicated that most states allow RAP and many allow RAS in their mixtures. The following were the additional results from the states responding to the survey:

- 70% specify percent RAP by weight of the mix
- 30% specify percent aged binder by total weight of the binder
- 90% allow higher percentages of RAP in their mixes when using WMA
- 70% allow the use of RAS in their mixtures
- 60% allow the use of RAP and RAS in the same mix
- Only 5% have a method to estimate the cost savings for mixtures containing RAP or RAS
- 75% calculate the aged binder contents in their mixes
- Only one state has a separate pay schedule (Nebraska Department of Roads) for the virgin and aged binders.
- Over 63% require softer binder with the mixes using higher percentages of RAP or RAS (>30%).

Based on the responses from the initial survey, a follow-up survey of Illinois, Kansas, Maryland, and Michigan was conducted to gather more information regarding the utilization of high percentages of RAP in the HMA mixtures. The results are as follows:

- Illinois DOT indicated that although their threshold for using a softer asphalt binder grade is 20%, the economic threshold for contractors' usage is around 31%.
- Kansas DOT uses separate maximum limits depending on whether or not millings are available from the project being conducted.
    - If millings from the project are used, the maximum allowed RAP is 25%.
    - If millings from the project are not available, the maximum allowed RAP is 15%.
    - On projects where plenty of millings are available, blending charts are used to establish the maximum allowable percentage of RAP.
        - Contractors generally like the blending chart projects as it often allows them to add more than the conventional 25% RAP to the mix.
        - In some cases, mixes with up to 50% RAP and even higher levels of binder replacement are used.
        - In most instances, the contractors have been able to meet volumetric requirements on these high RAP mixtures without fractionating.
- Kansas DOT allows RAS in any mix that is allowed to have RAP; however, the RAP is capped at 10% and the RAS at 5%.
- Maryland officials allows the following maximum amounts of RAP:
    - Up to 15% in polymer-modified surface mixes and mixes requiring high-polish-resistant aggregate
    - Up to 20% RAP in other surface mixes

  - Up to 25% in base courses
  - Contractors can get approved for higher amounts if they do the additional testing and develop blending charts and follow TP-62 for plant mixing capability analysis.
- Michigan DOT allows up to 17% RAP with no change in binder grade and larger amounts with adjustments to the binder grade.

Conclusions on Percentage of South Carolina Mixtures Containing RAP/RAS

Contractors in the urban Districts of South Carolina are known to be aggressive in pursuit of maximizing RAP usage. They have made investments in equipment, procedures and person power to more readily control RAP variability when using higher percentages of RAP per mix type.

There are a few South Carolina contractors that are utilizing maximum RAP percentages that are allowed under SCDOT specifications. However, average percent RAP per mix was not being utilized to its full extent by the majority of contractors during the time period of this study for the mixes studied. Before major changes to the upper limits of the specification are made to increase RAP's upper limits, it would seem there is a great economic advantage that can be gained through the maximization of current RAP percentages used by all contractors around the entire state. However, RAP availability in rural areas may prohibit this to some degree. In addition, even contractors in urban areas with high RAP availability would need to consider if asphalt plant capabilities would be exceeded or if any modifications would be needed to run mixes with higher RAP contents.

Generally speaking, the trends indicate that SCDOT specifications and contractors' willingness to use RAP in SCDOT mixes has produced very high percentages of SCDOT mixes that use RAP, and most Districts are near 100% usage. The few data points where RAP was not used can be attributed to a small number of contractors that have chosen not to use RAP in their SCDOT mixes. These contractors either may not bid large SCDOT projects that generate RAP or just simply have chosen not to use it. Low RAP supply in rural areas can contribute to a rate of less than 100% of mixes using RAP as well.

Conclusions on Cost Differences among SCDOT Districts and SC Counties

Districts 2 and 6 generally had the highest unit costs per mix type per from 2008-2013. In general, standard deviations of average unit cost per District and County seemed to be within reasonable limits. In addition, it was observed that the highest unit cost per County seemed to be variable at best. This could be due to low total amount of data per County over the course of this study. Project size, mix quantities, and other variables have a greater potential to skew data with a limited number of overall data points per county. General trends indicate that most mixes increased in unit cost per mix over the course of the study (2008-2013). These increases seemed incremental in nature and seem attributable to inflationary reasons over the same time period.

For this project, researchers mined data from three different databases (Site Manager, Job-Mix-Formula Log, and each individual SCDOT JMF Mix Design Form per project) in order to generate the necessary information to complete project objectives. These objectives included calculations such as percentage of mixes containing RAP, average percent RAP per mix type, and economic ramifications of RAP usage per year in South Carolina. These calculated values were generated from individual line item payment records from Site Manager in conjunction with several additional values acquired from each SCDOT JMF Form per project, including percentage of RAP in mix, percent binder content of RAP/RAS, and target binder content.

Conclusions on Past Cost Savings to SCDOT

Asphalt pavement payment data for all mix types from SCDOT's database for the years 2008 through 2013 were used in this study. In order to isolate mainline paving, all data points for mixes with less than 2,500 tons on a particular project were eliminated from the data. As discussed in Chapters 3 and 5, the total mix cost paid (RAP mixes) as well as the theoretical total mix cost of virgin mixes were calculated. The estimated percent savings to SCDOT (expressed as a percent of the total mix cost paid) increased steadily from 9% in 2008 to 16% in 2013. The total estimated savings to SCDOT by utilizing RAP mixtures between 2008 and 2013 was approximately $90.7 million.

Recommendations for Payment of RAP, RAS and RAP/RAS Mixtures

The results of the survey completed during this project indicated that only one state is utilizing a payment model that considers aged binder. Although an alternate payment method was developed and outlined in this report, it is predicted that contractor bid prices would adjust over time for this new payment method, resulting in a zero net change in overall payment by the SCDOT. Thus, at this point, this method is not recommended by the researchers to be used by SCDOT. The current method used by the Department is what most states are currently using to pay for asphalt mixtures containing RAP, RAS and RAP/RAS. If SCDOT makes a few recommended changes to the current data collection system, it should be relatively simple to obtain and track the cost savings for utilizing RAP, RAS or RAP/RAS in asphalt mixtures.

Recommendations for Future Estimation of Cost Savings

It is recommended that SCDOT use the following equations discussed in Chapter 3 of this report (Experimental Design: Analysis of SCDOT Project Data as Related to RAP Usage and Economic Benefits) to calculate cost savings from utilization of RAP.

- % Aged Binder =
$$\frac{\frac{\%\,Binder\ in\ RAP}{100} \times \%RAP}{Optimal\ Binder\ Content} \times 100$$
- % Virgin Binder = $100 - \%\ Aged\ Binder$
- Quantity of Aged Binder =
$$\frac{\%\ Aged\ Binder}{100} \times \frac{Optimal\ Binder\ Content}{100} \times Pd.Mix\ Qty.$$
- Value of RAP Binder = $Quantity\ of\ Aged\ Binder \times Binder\ Index\ on\ Pymt.Date$
- Quantity of RAP Aggregate =

$$\frac{\%\ RAP}{100} \times Paid\ Mix\ Quanity$$

- Value of RAP Aggregate = $Quantity\ of\ RAP\ Agg. \times Agg. Index\ on\ Pymt. Date$
- Total Value of RAP = $Value\ of\ RAP\ Binder + Value\ of\ RAP\ Aggregate$
- Total Binder Quantity in Tons =
$$\frac{Optimal\ Binder\ Content}{100} \times Pd. Mix\ Qty.$$
- Total Mix Cost Paid (including mix and binder) =
$(Pd. Mix\ Qty. \times Unit\ Price) + (Total\ Binder\ Qty. \times Binder\ Index\ on\ Pymt. Date)$
- Total Mix Unit Cost =
$$\frac{Total\ Mix\ Cost\ Paid}{Paid\ Mix\ Quantity}$$
- Theoretical Total Cost of Virgin Mix (including mix and binder) =
$$Total\ Mix\ Cost\ Paid + Total\ Value\ of\ RAP$$
- Theoretical Unit Cost of Virgin Mix (including mix and binder) =
$$\frac{Theoretical\ Total\ Cost\ of\ Virgin\ Mix}{Paid\ Mix\ Quantity}$$
- Estimated Savings =
$$Theoretical\ Total\ Cost\ of\ Virgin\ Mix - Total\ Mix\ Cost\ Paid$$
- Estimated % Savings =
$$\frac{Estimated\ Savings}{Total\ Mix\ Cost\ Paid} \times 100$$

These same equations can also be utilized to calculate potential cost savings for using higher percentages of RAP by inputting the proposed % RAP value instead of the % RAP from the Job Mix Formula into the equations. However, it is highly recommended to collect a few additional data points in Site Manager for ease of performing this calculation. Because the alternate payment methods developed in this report is predicted to result in a zero net change in overall payment by the SCDOT over time compared to SCDOT's current payment method, a change in payment model is not recommended at this point.

<u>Recommendations for Improvements to Current Data Collection System</u>

Because of the current SCDOT procedures for collection of this data, determining those items of interest (% of mixes containing RAP, average % RAP utilized per mix type, and economic ramifications of RAP usage in South Carolina) currently requires a very time-consuming process of manually cross-referencing three sets of data (Site Manager, Job Mix Formula Log, and SCDOT JMF Forms). In order to allow SCDOT to more quickly and easily determine those values for future years, it is recommended that SCDOT begin collecting the following information in Site Manager for each payment line item:

1. <u>The Approved SCDOT JMF Form Mix Number per Project per Mix Type</u>: The SCDOT JMF mix identification number would separate mixes as virgin, RAP mixes, RAP and RAS mixes, or just RAS mixes. For example, Q350 is a virgin mix, Q350R is a RAP mix, Q350R/S is a RAP and RAS combination mix, and Q350S would be a RAS mix. By recording this information in Site Manager, future specific recycled mix data can be sorted more efficiently and with greater precision than matching data from three separate databases, which is currently the case.
2. <u>% RAP, % Binder Content in RAP, Optimal Binder Content and Asphalt Binder Index</u>: In addition to the SCDOT JMF Mix Design Form identification number, additional information contained on this form including optimal binder content of the mix and either aged binder percentage in the mix or RAP percentage in mix and the percent binder content of the recycled materials (RAP/RAS) in the mix should be added as individual line items for each entry per mix type in Site Manager. In addition, the asphalt binder index on the date of each mix payment entry should be entered into Site Manager. With these few additional data entries, the formulas generated in this study, and the variables already being entered into Site Manager, RAP usage and the associated cost savings could be quickly and easily sorted and analyzed as needed by SCDOT personnel.

It is apparent from this investigation that most state agencies are either unaware of exact recycled materials usage rates and/or economic impact their usage. At best, estimates are based on tonnages placed, an average percentage of RAP used, and average binder and aggregate material costs that were replaced. By entering the data in Site Manager as described above, information about recycled materials usage could be attained quite easily by SCDOT personnel. This proposed system would give SCDOT one of the most accurate accounts in the United States of current and future recycled materials usage and the associated cost savings. It would be based on real data already generated and tracked by SCDOT in Site Manager rather than assumptions made by individuals.

Chapter 9 - References

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Chapter 10 – Appendices

Appendix A: Survey Results

Table 10-1: Compiled Survey Results

1. Name	2. Agency	3. Title	4. Mailing Address	5. City/State/Zip	6. Email Address	7. Phone Number	8.1 Tons of HMA/WMA Used in 2012	8.2 Tons of HMA/WMA containing RAP in 2012	8.3 Tons of HMA/WMA containing RAS in 2012	8.4 Tons of HMA/WMA containing a combination of RAP/RAS in 2012
Lyndi Blackburn	Alabama Department of Transportation	Asst. Materials and Test Engineer	1409 Coliseum Blvd	Montgomery, Al 36110	blackburnl@dot.state.al.us	334-206-2203	not tracked			
Chad Auker	Arizona Department of Transportation	Quality Assurance Section Manager - Materials Group	1221 N. 21st Ave.	Phoenix, AZ 85009	cauker@azdot.gov	928-606-1666	1,150,000 approximately	800,000 approximately		
Joseph F.Peterson	Caltrans	Office Chief, Office of Roadway Materials Testing	5900 Folsom Blvd	Sacramento, CA 95819	joe.peterson@dot.ca.gov	916-227-7303				
Eliana Carlson, P.E.	Connecticut DOT	Tranportation Supervising Engineer	280 West St.	Rocky Hill, CT 06067	Eliana.Carlson@ct.gov	860-258-0325	350,000	880,000	1000	
Tanya M. Nash	Florida DOT	Bituminous Engineering Specialist	5007 NE 39th Avenue	Gainesville, Florida 32609	tanya.nash@dot.state.fl.us	352-955-2903	4,662,942	3,912,111		
Peter Wu, P.E.	Georgia DOT	Assistant State Materials Engineer	15 Kennedy Drive	Forest Park, GA 30297	pwu@dot.ga.gov	404-608-4840	4,403,740	4,298,708		4,298,708
Jim Trepaniaer	Ilinois D.O.T.	HMA Operation Engineer	126 E Ash St	Springfield, IL 62704	james.trepanier@illinois.gov	217-782-9607	4,532,131			

1. Name	2. Agency	3. Title	4. Mailing Address	5. City/State/Zip	6. Email Address	7. Phone Number	8.1 Tons of HMA/WMA Used in 2012	8.2 Tons of HMA/WMA containing RAP in 2012	8.3 Tons of HMA/WMA containing RAS in 2012	8.4 Tons of HMA/WMA containing a combination of RAP/RAS in 2012
Blair Heptig	KDOT	Materials Engineer	700 SW Harrison	Topeka, KS 66603	blair.heptig@ksdot.org	785-296-1198	N/A	N/A	N/A	N/A
Chris Abadie	LADOTD	Materials Engineer	5080 Florida Blvd	Baton Rouge, LA 70808	chris.abadie@la.gov	225-248-4131	2,000,000	1,200,000	0	400,000
Barry Catterton	Maryland State Highway Adminstration	Director/Office of Materials and Technology	7450 Traffic Drive	Hanover, MD 21076	Bcattererton@sha.state.md.us	443-572-5051	1,524,826	1,336,336	0	55,840
Kevin Kennedy	Michigan Department of Transportation	HMA Operation Engineer	885 Ricks Road P.O. Box 30049	Lansing, MI 48909	kennedyk@michigan.gov	517-322-6043	not tracked	not tracked		
Kevin McCaskill	Mississippi DOT	Materials E.I.T.	412 E. Woodrow Wilson Ave.	Jackson, MS 39216	kmccaskill@mdot.ms.gov	601-359-1749	2.0 million	1.6 million		
Robert Rea	Nebraska Department of Roads	Assistant Materials and Research Engineer	1400 Hwy 2	Lincoln, NE 68509	robert.rea@nebraska.gov	402-279-3839	2,300,000	500,000	30,000	10,000
Matthew Courser	NHDOT Materials and Research	Bituminous Supervisor	5 Hazen Drive	Concord, NH 03301	mcourser@dot.state.nh.us	603-271-1663	654,991	640,204	11,490	
Eileen Sheehy	NJDOT	Manager Bureau of Materials	P.O. Box 607	Trenton, NJ 08625	eileen.sheehy@dot.state.nj.us	609-530-2307	1,725,732	247,579 of just RAP - HMA containing RAP not tracked		

1. Name	2. Agency	3. Title	4. Mailing Address	5. City/State/Zip	6. Email Address	7. Phone Number	8.1 Tons of HMA/WMA Used in 2012	8.2 Tons of HMA/WMA containing RAP in 2012	8.3 Tons of HMA/WMA containing RAS in 2012	8.4 Tons of HMA/WMA containing a combination of RAP/RAS in 2012
Nilesh Surti, PE	NCDOT	State Pavement Construction Engineer	1 South Wilmington Street	Raleigh, NC 27601	nsurti@ncdot.gov	919-707-2403	7,367,028.50	3,212,410.10	467,535.60	416,688.65
Cliff Selkinghaus	SCDOT	Asphalt Materials Manager	1406 Shop Road	Columbia, SC 29201	selkinghcb@scdot.org	803-737-6700	2,418,000			
Robert Lee	TxDOT	Senior Materials Engineer	125 East 11th Street	Austin, TX 78701	robert.lee@txdot.gov	512-506-5938	7.5 million	1.2 million	152,000	unknown
Howard Anderson	UDOT	Engineer For Asphalt Materials	4501 South 2700 West Box 145950	Salt Lake City, Utah 84114-5950	handerson@utah.gov	801-965-4426	1,886,608	Unknown; total RAP used is 342,311		

2. Agency	9.1 Maximum % RAP specified based on weight of total mix	9.2 Maximum % RAP specified based on % aged binder based on weight of total binder	9.3 Maximum % RAP specified based on Other, please explain	10. Does your state allow a higher % of RAP when using WMA?	10.a. If yes, how much more do you allow?	11. Does your state allow for the use of RAS?
Alabama Department of Transportation	Yes			No		Yes
Arizona Department of Transportation		Yes	ADOT limits RAP usage by both % RAP Aggregate based on weight of total aggregate AND % RAP Binder based on weight of total Binder	No		No
Caltrans	Yes			No		Yes
Connecticut DOT	Yes			No		No
Florida DOT			%RAP by weight of aggregate	No		No
Georgia DOT	Yes			Yes	Maximum RAP 40% for drum plant, and 25% for batch plant. Please see Section 402 of the following spec book: http://www.dot.ga.gov/doingbusiness/TheSource/specs/DOT2013.pdf	Yes
Ilinois D.O.T.		Yes		No		Yes

2. Agency	9.1 Maximum % RAP specified based on weight of total mix	9.2 Maximum % RAP specified based on % aged binder based on weight of total binder	9.3 Maximum % RAP specified based on Other, please explain	10. Does your state allow a higher % of RAP when using WMA?	10.a. If yes, how much more do you allow?	11. Does your state allow for the use of RAS?
KDOT	Yes			No		Yes
LADOTD	Yes			No		No
Maryland State Highway Adminstration	Yes			No		Yes
Michigan Department of Transportation	Yes			No		Yes
Mississippi DOT	Yes			No		No
Nebraska Department of Roads	Yes	Yes		No		Yes
NHDOT Materials and Research		Yes		No		Yes
NJDOT	Yes			No		Yes

2. Agency	15.d.3 Average % RAP/% Aged Binder in other mixes.	15.d.4 Average % RAS/% Aged Binder in other mixes.	16.1 Additives allowed in RAP/RAS mixes	16.2 Additives required in RAP/RAS mixes	16.3 Additives prohibited in RAP/RAS mixes	17. Does your state require the use of a softer binder grade for High-RAP and/or High-RAS projects (>30%)?	17.a If yes, please provide your specification for this.
NCDOT			Antistrip			Yes	
SCDOT	30	permitted	LASA (Surface C-E, Int C, and Base B-D)			No	
TxDOT						Yes	
UDOT			None			Yes	Contractors can use up to 25% RAP if they want to. From 0 to less than15% RAP they don't have to change the virgin binder. From 15% to 25% RAP they must drop the PG binder one grade in temperature, however, the low end does not go below 34 (PG XX-34). They can not use more than 25% RAP. Here is a link to our HMA specification 02741. WMA can be used with this spec as a drop down if the contractor wants to. http://www.udot.utah.gov/main/f?p=100:pg:0:::1:T,V:3694, RAP is discussed on page 11 of 17 of this spec.

2. Agency	15.d.3 Average % RAP/% Aged Binder in other mixes.	15.d.4 Average % RAS/% Aged Binder in other mixes.	16.1 Additives allowed in RAP/RAS mixes	16.2 Additives required in RAP/RAS mixes	16.3 Additives prohibited in RAP/RAS mixes	17. Does your state require the use of a softer binder grade for High-RAP and/or High-RAS projects (>30%)?	17.a If yes, please provide your specification for this.
KDOT			Antistrip			Yes	Blending charts.
LADOTD	Rejuventator by special provision for 100% in-place recycling					Yes	
Maryland State Highway Adminstration			None			Yes	If you utilize RAP and RAS in amounts greater than allowed in the specifications, M323 is used to determine the amont of reclaimed materail allowed.
Michigan Department of Transportation						Yes	
Mississippi DOT			Allowed on a contract by contract basis. No additional additives used in 2012 or 2013.			No	
Nebraska Department of Roads			Evotherm, Advera, Rediset 1102C			Yes	We use exclusively PG minus 34 grade bindrs in all our mixes. 52-34 in shoulder, 64-34 in all other mixes
NHDOT Materials and Research	% Aged Binder		None			No	
NJDOT					Prohibitied	No	

2. Agency	15.d.3 Average % RAP/% Aged Binder in other mixes.	15.d.4 Average % RAS/% Aged Binder in other mixes.	16.1 Additives allowed in RAP/RAS mixes	16.2 Additives required in RAP/RAS mixes	16.3 Additives prohibited in RAP/RAS mixes	17. Does your state require the use of a softer binder grade for High-RAP and/or High-RAS projects (>30%)?	17.a If yes, please provide your specification for this.
Alabama Department of Transportation			Antistrip			No	
Arizona Department of Transportation						Yes	If the RAP binder exceeds 15% of the total binder, the contractor is required to perform PG Verification on the blended RAP / Virgin binder (AASHTO R29) at the blend percentage established by the mix design. A softer grade binder is allowed to be used in the mix design to meet the specified binder grade in the contract. (See ARIZ 833 Section 7 - attached)
Caltrans					Prohibited	No	
Connecticut DOT							
Florida DOT				Binder grade adjustment is made for specific RAP Contents; PG 52-28 (>30%RAP), PG 58-22 (16-30%RAP) Hydrated Lime - Surface mixes with granite LASA listed on FDOT Qualified Products List		Yes	Supplemental Specification Section 334-2.3.5 http://www.dot.state.fl.us/specificationsoffice/Implemented/WorkBooks/JulWorkbook2013/Default.shtm#ss
Georgia DOT						Yes	Regular grade: PG 67-22, Softer grade: PG 64-22; Please see Section 820 of the following spec book: http://www.dot.ga.gov/doingbusiness/TheSource/specs/DOT2013.pdf
Ilinois D.O.T.			Antistrip			Yes	Illinois required high and low temperature grades be reduced when percent ABR exceeds 20%. See spec. Http://www.dot.il.gov/desenv/specrev/80306.pdf

2. Agency	15.a.3 Average % RAP/% Aged Binder in Surface mixes.	15.a.4 Average % RAS/% Aged Binder in Surface mixes.	15.b.1 Intermediate mix types that contain RAP.	15.b.2 Traffic level of Intermediate mixes that contain RAP.	15.b.3 Average % RAP/% Aged Binder in Intermediate mixes.	15.b.4 Average % RAS/% Aged Binder in Intermediate mixes.	15.c.1 Base mix types that contain RAP.	15.c.2 Traffic level of Base mixes that contain RAP.	15.c.3 Average % RAP/% Aged Binder in Base mixes.	15.c.4 Average % RAS/% Aged Binder in Base mixes.	15.d.1 Other mix types that contain RAP.	15.d.2 Traffic level of other mixes that contain RAP.
NCDOT	21.0% +/-	0	RI 19.0B	Less than 3	21.1% +/-	4.1% +/-	RB 25.0B	Less than 3	20.9% +/-	3.6% +/-		
	17.0% +/-	0	RI 19.0C	3 to 30	22.7% +/-	4.0 +/-	RB 25.0C	More than 3	20.5% +/-	4.6% +/-		
	22.7% +/-	4.5% +/-	Ri 19.0D	More than 30	23.7% +/-	0						
	24.3% +/-	5.2% +/-										
	19.0% +/-	0										
	21.1% +/-	4.9% +/-										
	10.0% +/-	5.0% +/-										
SCDOT	15	not permitted	A	High	35	not permitted	A	High	35	permitted	PMTLSC	Medium to Low
	25	not permitted	B	High to Medium	30	not permitted	B	Medium to Low	35	permitted		
	30	permitted	C	Medium to Low	30	permitted	C	Medium to Low	35	permitted		
	30	permitted					D	Low	35	permitted		
	30	permitted					Shoulder	Medium to Low	45	permitted		
TxDOT	15.60%		same				Same					
UDOT												

2. Agency	15.a.3 Average % RAP/% Aged Binder in Surface mixes.	15.a.4 Average % RAS/% Aged Binder in Surface mixes.	15.b.1 Intermediate mix types that contain RAP.	15.b.2 Traffic level of Intermediate mixes that contain RAP.	15.b.3 Average % RAP/% Aged Binder in Intermediate mixes.	15.b.4 Average % RAS/% Aged Binder in Intermediate mixes.	15.c.1 Base mix types that contain RAP.	15.c.2 Traffic level of Base mixes that contain RAP.	15.c.3 Average % RAP/% Aged Binder in Base mixes.	15.c.4 Average % RAS/% Aged Binder in Base mixes.	15.d.1 Other mix types that contain RAP.	15.d.2 Traffic level of other mixes that contain RAP.
KDOT	15%	0	SR-12.5A	All	25%	0%	SR-19A	All	25%	0		
	25%	0	SR-12.5A	All	10%	5%	SR-19A	All	10%	5%		
	10%	5%	SR-19.A	All	25%	0%						
	25%	0	SR-19A	All	10%	5%						
	10%	5%										
LADOTD	Allow 15%	0	Binder	All	Allow 20%	None	Base	All	Allow 30% (PG 58-28 r'd if using 30%		None	
Maryland State Highway Adminstration	15, 17.5, 14, 13.5	5%	same				Same					
	16, 13											
	18,26	5%										
	24, 25											
	25											
Michigan Department of Transportation												
Mississippi DOT	20	0	HT	High	30	0	HT	High	30	0		
	20	0	MT	Medium	30	0	MT	Medium	30	0		
	20	0	ST	Low	30	0	ST	Low	30	0		
	25	0										
Nebraska Department of Roads	44.4% RAP		Same as above				Same as above					
	23.1% RAP											
	39.3% RAP											
NHDOT Materials and Research	1.0% Aged Binder		¾ 50 Gyr	Low	0.4% Aged Binder	0.6% Aged Binder	1" Base 50 Gry	Low	1.0 % Aged Binder		PMST	All
	0.4% Aged Binder	0.6% Aged Binder	¾ 50 Gyr	Low	1% Aged Binder		1" Base 75 Gry	Medium	1.0% Aged Binder			
	1.0% Aged Binder		¾ 50 Gyr	Low	2.0 % Aged Binder							
	1.0% Aged Binder		¾ 75 Gyr	Medium	1.0% Aged Binder							
	2.0% Aged Binder											
NJDOT	10-15%		Superpave	All	15-20%		Superpave	All	20-25%			

2. Agency	15.a.3 Average % RAP/% Aged Binder in Surface mixes.	15.a.4 Average % RAS/% Aged Binder in Surface mixes.	15.b.1 Intermediate mix types that contain RAP.	15.b.2 Traffic level of Intermediate mixes that contain RAP.	15.b.3 Average % RAP/% Aged Binder in Intermediate mixes.	15.b.4 Average % RAS/% Aged Binder in Intermediate mixes.	15.c.1 Base mix types that contain RAP.	15.c.2 Traffic level of Base mixes that contain RAP.	15.c.3 Average % RAP/% Aged Binder in Base mixes.	15.c.4 Average % RAS/% Aged Binder in Base mixes.	15.d.1 Other mix types that contain RAP.	15.d.2 Traffic level of other mixes that contain RAP.
Alabama Department of Transportation	% RAP 20%	%RAS 5%	Superpave	All	%RAP 25	% RAS 5%	Superpave	All	%RAP 25	% RAS 5%		
	% RAP 20%	%RAS 5%	SMA	High	%RAP 25	% RAS 5%	SMA	High	%RAP 25	% RAS 5%		
	Limited to 10%	N/A										
Arizona Department of Transportation	15-20%	N/A	¾" SHRP/Marshall	All	15-20%	N/A	¾" SHRP/Marshall	All	15-25%	N/A		
Caltrans	15%											
Connecticut DOT	10, 15, 20		same				Same					
Florida DOT	0		12.5 mm	Medium	26 % RAP							
	19 % RAP		12.5 mm	High	21 % RAP							
	19 % RAP		9.5 mm	Medium	25 % RAP							
	19 % RAP		9.5 mm	High	20 % RAP							
			19.0 mm	High	28 % RAP							
Georgia DOT	20		19.0 mm	All	25		25.0 mm	All	25		N/A	
	20											
	20											
	15											
	0											
Ilinois D.O.T.												

2. Agency	12.c. If yes for RAS, what was your total estimated amount of savings for using RAS in 2012?	13. Is percent aged binder content determined in your state?	13.a. If yes, what tests are used and what is the frequency of testing done to determine aged binder?	14. Does your state have a separate pay schedule for virgin and aged binder?	14.a. If yes, please provide information describing it.	15.a.1 Surface mix types that contain RAP.	15.a.2 Traffic level of surface mixes that contain RAP.
NCDOT		No		No		RS 12.5 C	3 to 30
						RS 4.75A	Less than 1.0
						RS 9.5 B	.3 to 3
						RS 9.5C	3 to 30
						RS 9.5 D	More than 30
						RSF 9.5 A	Less than .3
						RSA -1	Less than .3
SCDOT		Yes	Determined during design based on optimum binder content and the QC data submitted by the contractor tracking RAP and RAS binder contents determined by AASHTO T308 or SC-T-75. Information is randomly turned into the SCDOT when requested by the SCDOT OMR, often when revisions to JMF have been requested by the HMA Contractor. The binder content is rechecked to ensure maximum aged binder binder is not exceeded or JMF	No		A	High
						B	High
						C	Medium
						D	Low
						E	High to Low
TxDOT		Yes	nothing other than % recycled binder	No		Densed Graded	All
UDOT		Yes	AASHTO T 308 Ignition Burn Off Test is used on the RAP. The RAP is fractionated in coarse and fine stock piles, but combined for the AC content test. This check is done only with the mix design.	No	We pay for HMA/WMA by the mix ton.	We don't have this information	

2. Agency	12.c. If yes for RAS, what was your total estimated amount of savings for using RAS in 2012?	13. Is percent aged binder content determined in your state?	13.a. If yes, what tests are used and what is the frequency of testing done to determine aged binder?	14. Does your state have a separate pay schedule for virgin and aged binder?	14.a. If yes, please provide information describing it.	15.a.1 Surface mix types that contain RAP.	15.a.2 Traffic level of surface mixes that contain RAP.
KDOT		Yes	ignition oven	No		SR-4.75A	
						SR-9.5.A	All
						SR-9.5A	All
						SR-12.5A	All
						SR-12.5A	All
LADOTD		Yes	oven extracted % ac of PAP less 0.6%. (TR 322?)	No		Surface	Wearing
Maryland State Highway Adminstration		Yes.	MD is transitioning to ABR. Contractors are requested to turn in gradations and aged binder content of their RAP and/or RAS weekly and true PG grading of the recovered binder 3 times per year.	No		9.5mm	1,2,3,4
						12.5 mm	2,4
						19 mm	2,4
						25 mm	2,4
						37 mm	4
Michigan Department of Transportation		No		No			
Mississippi DOT		Yes	Methods: ignition burnoff T-308 and solvent extraction T-164; Frequency: Once per design by contractor; Once during design approval process by Department; After approval, once per every 8 production QC samples with a minimum of once per week by contractor.	No		HT	High
						MT	Medium
						ST	Low
						Thin Lift	Low
Nebraska Department of Roads	Around $175,000, fairly limited use	Yes	Yes based on ignition oven total binder content less the add oil at the plant, and we also have a minimum ac content	Yes	We only pay for virgin add oil and this is its own separate pay item	SPS	Shoulder/Low
						SPH	Interstate/High
						SPR	Med. 80% of tonnage
NHDOT Materials and Research		Yes	same link	No		¾ 75 Gyr	All
						½ 50 Gyr	Low
						½ 50 Gyr	Low
						½ 75 Gyr	Medium
						½ 75 Gyr	Medium
NJDOT		No	The % RAP binder and % RAP aggregate is tracked daily with calculations based on the RAP binder ignition furnace results, virgin binder used per day, and weights reported from the Hot Plant Report.	No		Superpave	All

2. Agency	12.c. If yes for RAS, what was your total estimated amount of savings for using RAS in 2012?	13. Is percent aged binder content determined in your state?	13.a. If yes, what tests are used and what is the frequency of testing done to determine aged binder?	14. Does your state have a separate pay schedule for virgin and aged binder?	14.a. If yes, please provide information describing it.	15.a.1 Surface mix types that contain RAP.	15.a.2 Traffic level of surface mixes that contain RAP.
Alabama Department of Transportation		No		No		Superpave	All
						SMA	High
						OGFC	High
Arizona Department of Transportation		Yes	ADOT performs one ignition furnace binder content test on each RAP stockpile used per lot/day of HMA production. At the start of production the first two RAP samples taken are split and the binder content is tested both by ignition furnace and solvent extraction. A RAP Binder Content Correction Factor is established based on the difference between the ignition furnace and solvent extraction results. This correction factor is applied to all daily ignition furnace test results for each RAP stockpile taken on the project. (See attached PPD No 20a Section 8 AND 416-7.04 (C) and (D))	No		½" & ¾" SHRP/Marshall	All
Caltrans		Yes	Per ASTM D2172 Method B	No		HMA Type A	High
Connecticut DOT		Yes		No		RAP by weight	All
Florida DOT		Yes	FM 5-563 (Quantitative Determination of Asphalt Content from Asphalt Paving Mixtures by the Ignition Oven) http://www.dot.state.fl.us/statematerialsoffice/administration/resources/library/publications/fstm/fstmpage5.shtm	No		Open-Graded	High
						12.5 mm	High
						12.5 mm	Medium
						9.5 mm	Medium
Georgia DOT		No		No		9.5 mm	Low
						12.5 mm	Medium
						12.5 mm polymer	High
						SMA	High
						OGFC/PEM	High
Ilinois D.O.T.		Yes	We require the residual asphalt binder content for RAP and RAS to know what the percent asphalt binder replacement is for spec compliance. This is done by either reflux or centrifuge extraction, or ignition oven	No			

2. Agency	11.a. If yes, how much do you allow?	11.b. If yes, does your state allow for the use of RAP and RAS in the same mix?	11.b.1. If yes, how much do you allow?	12. Does your state have a method to estimate the cost savings of using RAP and/or RAS?	12.a. If yes, please provide information describing it.	12.b. If yes for RAP, what was your total estimated amound of savings for using RAP in 2012?
NCDOT	6% by total wt.	Yes	When both RAP and RAS are used, do not use a combined percentage of RAS and RAP greater than 20% by weight of total mixture, unless	No		
SCDOT	5% maximum; http://www.scdot.org/doing/technicalPDFs/supTechSpecs/SC-M-407_05-11.pdf	Yes	Still 5% maximum RAS, and the combination can not exceed the maximum allowable aged binder	No		
TxDOT	Same link	Yes	Same link	Yes	Based on replacement costs	
UDOT		No		No		

2. Agency	11.a. If yes, how much do you allow?	11.b. If yes, does your state allow for the use of RAP and RAS in the same mix?	11.b.1. If yes, how much do you allow?	12. Does your state have a method to estimate the cost savings of using RAP and/or RAS?	12.a. If yes, please provide information describing it.	12.b. If yes for RAP, what was your total estimated amound of savings for using RAP in 2012?
KDOT	5% max	Yes	A maximum of 5% RAS and 10% RAP is allwed in any mix specified to use RAP.	No		
LADOTD		No		No	Replacement cost of HMA (or price of asphalt mix FOB Plant) = value of RAP.	avg 15% of 2 million = 300,000 tons x $40 = $12,000,000 per year
Maryland State Highway Adminstration	5% max by weight. Manufacturer's waste only	Yes	20% total in surface mixes with up to 5% coming from RAS. 25% in base mixes with up to 5% coming	No		
Michigan Department of Transportation	17% by weight of binder	Yes	see spec	No		
Mississippi DOT				No		
Nebraska Department of Roads	5% mailine and 10% shoulders	Yes	The minimum virgin add binder content will usually control	Yes	We use the aggregate savings based on $12 per ton and the binder savings based on $675 per ton for 2013, these will change each year as average unit prices change. We then use the simple	$35.3 Million Dollars
NHDOT Materials and Research	http://www.nh.gov/dot/org/projectsdevelopment/highwaydesign/specifications/documents/2010_Division_400.pdf	same link		No		
NJDOT	5% in base course mixes only and the RAS must be pre-consumer	No		No		

2. Agency	11.a. If yes, how much do you allow?	11.b. If yes, does your state allow for the use of RAP and RAS in the same mix?	11.b.1. If yes, how much do you allow?	12. Does your state have a method to estimate the cost savings of using RAP and/or RAS?	12.a. If yes, please provide information describing it.	12.b. If yes for RAP, what was your total estimated amound of savings for using RAP in 2012?
Alabama Department of Transportation	5% max	Yes	Surface 20% with max 5% RAS, All other layers - 35% with max	No		
Arizona Department of Transportation				No	ADOT does not have a formal method to estimate cost savings using RAP. ADOT pays for binder as a separate bid item and we see a cost savings in the competitive bid process.	
Caltrans	0-5%	Yes	nent in the upper .2' a	No		
Connecticut DOT		No		No		
Florida DOT				Yes	We look at two comparable mix designs - one with RAP and one without RAP - but otherwise using the same basic aggregate combinations. We have a spreadsheet and we plug in the costs for each component (ie., Agg "A" 20% @ $22.00/ton, Agg "B" 30% @ $25.33/ton, RAP 25% @ $5.00/ton, binder 5.5% @ $550/ton, etc.). The binder added from the RAP is subtracted from the total binder content. We call different contractors to get prices on the RAP and aggregate. Asphalt binder prices come from out binder index. This is only done periodically - we do not track statewide savings due to RAP.	We do not do this.
Georgia DOT	Allow maximum RAS 5% of total mix weight. We had a couple of RAS mix designs approved in 2013 but no usage in the production so far. Please see Section 402 of the following spec book: http://www.dot.ga.gov/doingbusiness/TheSource/specs/DOT2013.pdf	Yes	Maximum RAS is 5%; Totally RAP shall not exceed 40% for drum plant, and 25% for batch plant.	No		
Ilinois D.O.T.	http://www.dot.il.gov.desenv/specrev/80306.pdf	Yes		No		

2. Agency	9.1 Maximum % RAP specified based on weight of total mix	9.2 Maximum % RAP specified based on % aged binder based on weight of total binder	9.3 Maximum % RAP specified based on Other, please explain	10. Does your state allow a higher % of RAP when using WMA?	10.a. If yes, how much more do you allow?	11. Does your state allow for the use of RAS?
NCDOT	N/A	N/A	RAP may constitute up to 50% of the total material used in recycled mixes except types S12.5D, 9.5D and mixtures containing RAS	No		Yes
SCDOT		Yes		No		Yes
TxDOT	Yes			Yes	http://www.dot.state.tx.us/apps-cg/specs/ShowAll.asp?year=3&type=SS&number=3	Yes
UDOT	Yes	Yes		No		No

Table 10-2: Compiled Survey Follow-up Results

State: Illinois

Follow-up Questions: In a survey SCDOT conducted last year, you responded that Illinois requires high and low temperature grades to be reduced when ABR exceeds 20%. How frequently do contractors take advantage of this spec and how many projects have been conducted to date? Performance or placement issues? How high did they go with the RAP when dropping binder grades?

Response: The following link will take you to our RAP/RAS specification which lists the maximum allowable RAP/RAS usage. The upper limits are commonly employed. While the threshold for grade bumping down to a softer asphalt binder grade is set at 20%, the economic threshold for contractors' usage is around 31%. There is not enough cost savings below 31% to offset the additional cost associated with the softer asphalt binder grade.

http://www.dot.il.gov/desenv/specrev/80306.pdf

State: Kansas

Follow-up Questions: In a survey SCDOT conducted last year, you responded that Kansas allows the use of blending charts to determine allowable %RAP that can be used in the mix for a given binder. Are contractors taking advantage of this option (frequency) and what percentages of RAP are they attaining with this spec?

Response: On a lot of preservation jobs where millings from the project are used as the RAP source, we are capping the RAP at 25%. If millings are not available from the project and permissive RAP is allowed, we typically cap the RAP at 15%. On some of the projects where plenty of millings are available, e.g. 2" mill and inlay, we are specifying the use of our blending chart to establish the allowable percentage of RAP that can be used in the mix. The grade of the RAP binder and the virgin binder are input into the blending chart, and it establishes the allowable percentage of RAP by assuming complete blending of the binders. Currently it is set up for target binder grades of PG64-22 or PG70-22. The PG64-22 target only has a requirement for the low end blended grade. The PG70-22 has it for both the high end and low end which in some instances can create a narrow window of allowable percentage of RAP (low end grade establishes maximum percentage of RAP and low end grade establishes minimum percentage of RAP).

The contractors generally like our blending chart projects as it often allows them to add more than the conventional 25% RAP to the mix. We have seen some mixes with up to 50% RAP and even higher levels of binder replacement. In most instances the contractors have been able to meet volumetric requirements on these high RAP mix without fractionating. But we have seen some bag house problems as they struggle to meet our dust to binder requirement of 1.2. We do have a few contractors that really like to use RAS. We allow RAS in any mix that is allowed to have RAP, but we cap the RAP at 10% and the RAS at 5%. Some use RAS even on blending chart projects where a high percentage of RAP is allowed. I would estimate we

specify the blending chart on 15% of preservation projects, and I would estimate the contractors use it 90% of the time to establish the amount of RAP that can be used. If millings from the project are required as the RAP source, we stockpile a small amount of millings from the project prior to letting and let the contractors evaluate the quality of the RAP. On our blending chart projects we also grade the RAP binder prior to the project letting and provide that information in the letting documents. So basically they use the blending chart and establish the allowable percentage of RAP that can be used prior to bidding.
State: Maryland **Follow-up Questions:** In a survey SCDOT conducted last year, you responded that Maryland allows 15- 20% RAP in surface mixes. How long have you been allowing 15-20% rap in surface mixes and have you noticed or observed any differences in long-term performance in particular as it relates to fatigue cracking? **Response:** We allow up to 20% in surface, with up to 15% in polymer modified surface mixes and mixes requiring high polish aggregate, and up to 25% in base. Producers can get approved for higher amounts if they do the additional testing and develop blending charts and follow TP-62 for plant mixing capability analysis. That spec has been in place for several years and we have not seen any negative effects (including fatigue cracking).
State: Michigan **Follow-up Questions:** MI allows 17% aged binder in their mixes. Can you explain how that limit was determined or in other words what the engineering basis was for allowing 17% aged binder? How often are contractors taking advantage of changing binder grades to attain higher percentages of RAP? In SC dropping binder grades is expensive due to the base grades refineries produce in our area. **Response:** To clarify, we allow up to 17% with no change in binder. We do allow larger amounts with adjustments to the binder. The 17% was prior to me being in my current position but my understanding is that it was based on national research and national best practices. We don't have exact numbers would estimate they are above 17% approximately 70% of the time.

Appendix B: Cost and Usage Data

Table 10-3: Sample of Cost and Usage Data (from SCDOT database plus calculations)

Data Point	File Number	Project Number	District	County	YYYYMMDD	YYYY	YYYYMM	ITM_CD	Matl Catg
1	28.038278	SP09(002)	1	28	20091110	2009	200911	3104000	HMA Base Course
2	28.038278	SP09(002)	1	28	20091110	2009	200911	3104000	HMA Base Course
3	28.038278	SP09(002)	1	28	20091110	2009	200911	3104000	HMA Base Course
4	31.038325	SP09(049)	1	31	20090414	2009	200904	3104000	HMA Base Course
5	31.038325	SP09(049)	1	31	20090414	2009	200904	3104000	HMA Base Course
6	31.101001	MR10	1	31	20090714	2009	200907	3104000	HMA Base Course
7	31.101001	MR10	1	31	20090714	2009	200907	3104000	HMA Base Course
8	31.038414C	SP09(098)	1	31	20091110	2009	200911	3104000	HMA Base Course
9	31.038414C	SP09(098)	1	31	20091110	2009	200911	3104000	HMA Base Course
10	31.038414C	SP09(098)	1	31	20091110	2009	200911	3104000	HMA Base Course
11	32.101001	MR10	1	32A	20091013	2009	200910	3104000	HMA Base Course
12	40.038411	SP09(095)	1	40A	20090728	2009	200907	3104000	HMA Base Course
13	42.038426C	SP09(110)	3	42A	20091110	2009	200911	3104000	HMA Base Course
14	42.038426C	SP09(110)	3	42A	20091110	2009	200911	3104000	HMA Base Course
15	11.038341	SP09(065)	4	11	20090414	2009	200904	3104000	HMA Base Course
16	11.038341	SP09(065)	4	11	20090414	2009	200904	3104000	HMA Base Course
17	12.038342	SP09(066)	4	12	20090414	2009	200904	3104000	HMA Base Course
18	12.038428C	SP09(112)	4	12	20090929	2009	200909	3104000	HMA Base Course
19	12.038428C	SP09(112)	4	12	20090929	2009	200909	3104000	HMA Base Course
20	13.038343	SP09(067)	4	13	20090428	2009	200904	3104000	HMA Base Course
21	16.038348	SP09(072)	5	16	20090414	2009	200904	3104000	HMA Base Course
22	16.038348	SP09(072)	5	16	20090414	2009	200904	3104000	HMA Base Course
23	16.101001	MR10	5	16	20090609	2009	200906	3104000	HMA Base Course

Data Point	Matl Description	Bid Qty	CO Qty	Cont Qty	Paid Qty	Unit	Unit Price
1	HMA SHOULDER WIDENING COURSE	253.44	31.30	284.74	284.74	TON	32.50
2	HMA SHOULDER WIDENING COURSE	1,314.13	(307.53)	1,006.60	1,006.60	TON	32.50
3	HMA SHOULDER WIDENING COURSE	2,341.97	84.13	2,426.10	2,426.10	TON	32.50
4	HMA SHOULDER WIDENING COURSE	2,200.29	-	2,200.29	2,647.39	TON	30.00
5	HMA SHOULDER WIDENING COURSE	3,254.83	-	3,254.83	3,326.82	TON	30.00
6	HMA SHOULDER WIDENING COURSE	1,777.89	-	1,777.89	1,606.41	TON	31.00
7	HMA SHOULDER WIDENING COURSE	530.35	1,117.91	1,648.26	1,648.26	TON	31.00
8	HMA SHOULDER WIDENING COURSE	1,285.97	-	1,285.97	821.64	TON	30.09
9	HMA SHOULDER WIDENING COURSE	1,008.48	(4.24)	1,004.24	1,104.24	TON	30.09
10	HMA SHOULDER WIDENING COURSE	1,774.08	(319.83)	1,454.25	1,454.25	TON	30.09
11	HMA SHOULDER WIDENING COURSE	5,297.89	-	5,297.89	4,709.33	TON	39.00
12	HMA SHOULDER WIDENING COURSE	2,557.87	-	2,557.87	2,442.95	TON	29.50
13	HMA SHOULDER WIDENING COURSE	1,551.15	(202.12)	1,349.03	1,248.30	TON	33.00
14	HMA SHOULDER WIDENING COURSE	1,815.15	-	1,815.15	1,514.04	TON	33.00
15	HMA SHOULDER WIDENING COURSE	3,083.52	(299.87)	2,783.65	2,642.83	TON	34.35
16	HMA SHOULDER WIDENING COURSE	3,850.88	-	3,850.88	3,726.43	TON	34.35
17	HMA SHOULDER WIDENING COURSE	4,206.55	(578.21)	3,628.34	3,628.34	TON	27.75
18	HMA SHOULDER WIDENING COURSE	2,590.72	(573.30)	2,017.42	1,900.06	TON	31.50
19	HMA SHOULDER WIDENING COURSE	3,703.04	-	3,703.04	2,560.10	TON	31.50
20	HMA SHOULDER WIDENING COURSE	6,673.92	-	6,673.92	6,602.03	TON	25.70
21	HMA SHOULDER WIDENING COURSE	1,267.20	(68.42)	1,198.78	1,198.78	TON	29.00
22	HMA SHOULDER WIDENING COURSE	2,418.24	(206.55)	2,211.69	2,211.69	TON	29.00
23	HMA SHOULDER WIDENING COURSE	58.08	-	58.08	59.73	TON	35.08

Data Point	**% RAP (from 310 form)**	**Percent Avg**	**% Binder in RAP (from 310 form)**	**% Optimum Binder (from 310 form)**	**% Aged Binder (calculated)**	**% Virgin Binder (calculated)**	**Quantity of Aged Binder from RAP on Payment Date (calculated)**	**Asphalt Binder Index Value on Payment Date (from SCDOT website)**	**Value of RAP Binder on Payment Date, based on monthly indices (calculated)**	**Quantity of RAP Aggregate on Payment Date (calculated)**	**Aggregate Index Value on Payment Date (from industry data)**
1	30.00	100	5.00	4.90	30.61	69.39	4.27	405.00	1729.80	81.15	15.38
2	30.00	100	5.00	4.90	30.61	69.39	15.10	405.00	6115.10	286.88	15.38
3	30.00	100	5.00	4.90	30.61	69.39	36.39	405.00	14738.56	691.44	15.38
4	35.00	100	5.00	4.70	37.23	62.77	46.33	362.78	16807.35	880.26	15.38
5	35.00	100	5.00	4.70	37.23	62.77	58.22	362.78	21120.82	1106.17	15.38
6	35.00	100	5.00	4.70	37.23	62.77	28.11	385.63	10840.90	534.13	15.38
7	35.00	100	5.00	4.70	37.23	62.77	28.84	385.63	11123.32	548.05	15.38
8	10.00	100	5.00	4.80	10.42	89.58	4.11	405.00	1663.82	78.06	15.38
9	10.00	100	5.00	4.80	10.42	89.58	5.52	405.00	2236.09	104.90	15.38
10	10.00	100	5.00	4.80	10.42	89.58	7.27	405.00	2944.86	138.15	15.38
11	30.00	100	5.00	5.00	30.00	70.00	70.64	403.75	28520.88	1342.16	15.38
12	35.00	100	5.00	4.70	37.23	62.77	42.75	383.75	16405.94	812.28	15.38
13	40.00	100	5.00	5.20	38.46	61.54	24.97	405.00	10111.23	474.35	15.38
14	40.00	100	5.00	5.20	38.46	61.54	30.28	405.00	12263.72	575.34	15.38
15	50.00	100	5.00	5.70	43.86	56.14	66.07	362.78	23969.15	1255.34	15.38
16	50.00	100	5.00	5.70	43.86	56.14	93.16	362.78	33796.86	1770.05	15.38
17	50.00	100	5.00	5.70	43.86	56.14	90.71	362.78	32907.23	1723.46	15.38
18	50.00	100	5.00	4.90	51.02	48.98	47.50	405.00	19238.11	902.53	15.38
19	50.00	100	5.00	4.90	51.02	48.98	64.00	405.00	25921.01	1216.05	15.38
20	50.00	100	5.00	4.90	51.02	48.98	165.05	353.11	58281.07	3135.96	15.38
21	35.00	100	5.00	4.70	37.23	62.77	20.98	362.78	7610.63	398.59	15.38
22	35.00	100	5.00	4.70	37.23	62.77	38.70	362.78	14041.25	735.39	15.38
23	10.00	100	5.00	4.80	10.42	89.58	0.30	361.88	108.08	5.67	15.38

Data Point	Value of RAP Aggregate on Payment Date, based on indices (calculated)	Total Value of Rap (Agg + Binder)	Total Qty Binder in Tons (calculated)	Total Mix Cost Paid including mix and binder (calculated)	Total Mix Unit Cost including mix and binder (calculated)	Total Unit Cost - Virgin Mix	Total Unit Cost - RAP Mix
1	1248.10	2977.896	13.95	14904.72	52.35		52.35
2	4412.23	10527.32	49.32	52690.48	52.35		52.35
3	10634.32	25372.88	118.88	126994.20	52.35		52.35
4	13538.36	30345.71	124.43	124561.45	47.05		47.05
5	17012.86	38133.67	156.36	156529.08	47.05		47.05
6	8214.94	19055.84	75.50	78914.26	49.12		49.12
7	8428.95	19552.28	77.47	80970.13	49.12		49.12
8	1200.50	2864.319	39.44	40695.83	49.53		49.53
9	1613.41	3849.491	53.00	54693.01	49.53		49.53
10	2124.80	5069.661	69.80	72029.00	49.53		49.53
11	20642.41	49163.29	235.47	278733.47	59.19		59.19
12	12492.88	28898.82	114.82	116128.68	47.54		47.54
13	7295.56	17406.79	64.91	67483.10	54.06		54.06
14	8848.66	21112.38	78.73	81849.00	54.06		54.06
15	19307.19	43276.34	150.64	145430.86	55.03		55.03
16	27223.43	61020.29	212.41	205059.70	55.03		55.03
17	26506.84	59414.07	206.82	175714.92	48.43		48.43
18	13880.89	33119	93.10	97558.58	51.35		51.35
19	18702.81	44623.82	125.44	131448.33	51.35		51.35
20	48231.13	106512.2	323.50	283903.07	43.00		43.00
21	6130.38	13741.02	56.34	55204.61	46.05		46.05
22	11310.25	25351.5	103.95	101849.78	46.05		46.05
23	87.27	195.347	2.87	3132.85	52.45		52.45

Appendix C: Anova Tables

Table 10-4: Anova Data Assuming Equal Variances for Figure 5.1: Average % RAP used in SC per Year (all SCDOT Engineering Districts Combined)

	2008	2009	2010	2011	2012	2013
2008	N/A	2.8E-05	1.39E-11	1.25E-19	5.1E-12	6.85E-23
2009			0.00107	2.01E-10	8.64E-05	1.17E-13
2010				0.000224	0.115202	6.78E-05
2011					0.113969	0.698159
2012						0.17265

Table 10-5: Anova Data Assuming Equal Variances for Figure 5.2: Average % RAP in all Mixes per SCDOT Engineering District per Year (2008)

	District 1	District 2	District 3	District 4	District 5	District 6	District 7
District 1	N/A	0.148518	0.009056	0.275822	0.388745	0.173845	7.41E-06
District 2			0.420859	0.030976	0.419245	0.012714	0.006476
District 3				0.00031	0.065682	0.000147	0.00526
District 4					0.073915	0.988699	5.76E-06
District 5						0.022896	5.11E-05

District 6							1.01E-07

Table 10-6: Anova Data Assuming Equal Variances for Figure 5.2: Average % RAP in all Mixes per SCDOT Engineering District per Year (2009)

	District 1	District 2	District 3	District 4	District 5	District 6	District 7
District 1		0.760085	0.626544	0.002896	0.853623	1.67E-06	0.676621
District 2			0.379834	0.000871	0.797384	9.45E-08	0.238557
District 3				0.056851	0.532579	0.000694	0.857063
District 4					0.002017	0.13	0.048926
District 5						1.07E-06	0.617788
District 6							0.000358

Table 10-7: Anova Data Assuming Equal Variances for Figure 5.2: Average % RAP in all Mixes per SCDOT Engineering District per Year (2010)

	District 1	District 2	District 3	District 4	District 5	District 6	District 7
District 1		0.046869	0.082614	0.459065	1.74E-07	7.01E-06	0.378185
District 2			0.983808	0.336959	8.67E-05	3.39E-12	0.810633

District 3				0.406214	0.000523	6.46E-10	0.516673
District 4					4.66E-05	2.81E-06	0.871948
District 5						9.98E-17	0.000556
District 6							7.37E-07

Table 10-8: Anova Data Assuming Equal Variances for Figure 5.2: Average % RAP in all Mixes per SCDOT Engineering District per Year (2011)

	District 1	District 2	District 3	District 4	District 5	District 6	District 7
District 1		0.110655	0.81892	0.263705	0.593074	0.124463	0.570634
District 2			0.154894	0.830188	0.604784	4.86E-05	0.010609
District 3				0.307293	0.649519	0.0463	0.378422
District 4					0.709834	0.000369	0.029217
District 5						0.266726	0.161202
District 6							0.250871

Table 10-9: Anova Data Assuming Equal Variances for Figure 5.2: Average % RAP in all Mixes per SCDOT Engineering District per Year (2012)

	District 1	District 2	District 3	District 4	District 5	District 6	District 7

District 1		0.34178	0.246954	0.492632	0.513406	0.003069	0.000811
District 2			0.345012	0.074119	0.230785	0.408146	0.530752
District 3				0.489805	0.657669	0.0566	0.047367
District 4					0.916445	0.003881	0.003881
District 5						0.028475	0.017705
District 6							0.632268

Table 10-10: Anova Data Assuming Equal Variances for Figure 5.2: Average % RAP in all Mixes per SCDOT Engineering District per Year (2013)

	District 1	District 2	District 3	District 4	District 5	District 6	District 7
District 1		0.000518	0.00373	0.335361	1.11E-06	0.162649	0.067088
District 2			0.536131	0.007072	0.489194	1.62E-06	2.51E-07
District 3				0.056221	0.146716	3.32E-05	4.5E-05
District 4					0.000504	0.019356	0.00411
District 5						9.17E-10	7.96E-08
District 6							0.470742

Table 10-11: Anova Data Assuming Equal Variances for Figure 5.2: Average % RAP in all Mixes per SCDOT Engineering District per Year (District 1)

	2008 District 1	2009 District 1	2010 District 1	2011 District 1	2012 District 1	2013 District 1
2008 District 1	N/A	0.947478	0.00036	0.008284	0.576861	1.82E-07
2009 District 1		N/A	4.46E-05	0.011795	0.549016	7.21E-10
2010 District 1			N/A	0.685792	0.047403	0.054007
2011 District 1				N/A	0.060889	0.528631
2012 District 1					N/A	0.001939

Table 10-12: Anova Data Assuming Equal Variances for Figure 5.2: Average % RAP in all Mixes per SCDOT Engineering District per Year (District 2)

	2008 District 2	2009 District 2	2010 District 2	2011 District 2	2012 District 2	2013 District 2
2008 District 2	N/A	0.193202	0.000464	0.014101	0.011965	0.020656
2009 District 2		N/A	0.001245	0.041991	0.016965	0.056779
2010 District 2			N/A	0.882908	0.046997	0.575267

2011 District 2				N/A	0.651457	0.78569
2012 District 2					N/A	0.068595

Table 10-13:Anova Data Assuming Equal Variances for Figure 5.2: Average % RAP in all Mixes per SCDOT Engineering District per Year (District 3)

	2008 District 3	2009 District 3	2010 District 3	2011 District 3	2012 District 3	2013 District 3
2008 District 3	N/A	0.012625	3.6E-06	1.11E-07	1.61E-05	0.00029
2009 District 3		N/A	0.161526	0.044126	0.156947	0.159657
2010 District 3			N/A	0.145144	0.510538	0.805202
2011 District 3				N/A	0.532465	0.354762
2012 District 3					N/A	0.068595

Table 10-14: Anova Data Assuming Equal Variances for Figure 5.2: Average % RAP in all Mixes per SCDOT Engineering District per Year (District 4)

	2008 District 4	2009 District 4	2010 District 4	2011 District 4	2012 District 4	2013 District 4

2008 District 4	N/A	0.389612	0.302415	0.624471	0.739945	0.013808
2009 District 4		N/A	0.797775	0.750127	0.611177	0.06349
2010 District 4			N/A	0.621134	0.490603	0.133848
2011 District 4				N/A	0.839321	0.070633
2012 District 4					N/A	0.037573

Table 10-15: Anova Data Assuming Equal Variances for Figure 5.2: Average % RAP in all Mixes per SCDOT Engineering District per Year (District 5)

	2008 District 5	2009 District 5	2010 District 5	2011 District 5	2012 District 5	2013 District 5
2008 District 5	N/A	0.488367	0.475938	0.008064	0.025513	0.196062
2009 District 5			0.001245	0.041991	0.016965	0.056779
2010 District 5				0.000599	0.007495	0.034398
2011 District 5					0.64541	0.099449
2012 District 5						0.300341

Table 10-16: Anova Data Assuming Equal Variances for Figure 5.2: Average % RAP in all Mixes per SCDOT Engineering District per Year (District 6)

	2008 District 6	2009 District 6	2010 District 6	2011 District 6	2012 District 6	2013 District 6
2008 District 6	N/A	0.006346	2.61E-10	2.24E-07	0.000983	5.31E-08
2009 District 6		N/A	5.29E-06	0.004589	0.07968	0.000886
2010 District 6			N/A	0.030806	0.17629	0.088715
2011 District 6				N/A	0.971944	0.709409
2012 District 6						0.845399

Table 10-17: Anova Data Assuming Equal Variances for Figure 5.2: Average % RAP in all Mixes per SCDOT Engineering District per Year (District 7)

	2008 District 7	2009 District 7	2010 District 7	2011 District 7	2012 District 7	2013 District 7
2008 District 7	N/A	0.000886	1.11E-08	4.9E-12	1.68E-12	5.05E-18
2009 District 7		N/A	0.096224	0.000182	0.000151	7.78E-09
2010 District 7			N/A	0.030407	0.010302	1.3E-05

2011 District 7				N/A	0.686255	0.042926
2012 District 7					N/A	0.105138

Table 10-18: Anova Data Assuming Equal Variances for Figure 5.3: Average % RAP in all Mixes per SCDOT Engineering District 2008-2013

	District 1	District 2	District 3	District 4	District 5	District 6	District 7
District 1	N/A	0.001439	0.047347	0.321805	1.31E-06	1.74E-11	0.403176
District 2		N/A	0.337936	4.51E-05	0.106698	2.14E-23	0.000166
District 3			N/A	0.004903	0.017376	3.52E-16	0.010138
District 4				N/A	4.4E-08	5.67E-08	0.924163
District 5					N/A	2.38E-29	4.15E-07
District 6						N/A	1.67E-07

Table 10-19: Anova Data Assuming Equal Variances for Figure 5.4: Shoulder Widening Course Average % RAP Per District 2008-2013

	District 1	District 2	District 3	District 4	District 5	District 6	District 7
District 1	N/A	0.045521	0.398028	0.990624	0.042271	0.00653	0.706701
District 2		N/A	0.409975	0.188907	0.852216	3.65E-06	0.0008

District 3			N/A	0.579396	0.418562	0.001737	0.108039
District 4				N/A	0.111066	0.082968	0.826315
District 5					N/A	0.000115	0.006976
District 6						N/A	0.000138

Table 10-20: Anova Data Assuming Equal Variances for Figure 5.5: HMA Base Course A Average % RAP Per District 2008-2013

	District 1	District 2	District 3	District 4	District 5	District 6	District 7
District 1	N/A	3.23E-06	0.448783	0.200141	0.00032	0.106888	0.005239
District 2		N/A	0.000366	3.26E-10	0.153013	1.13E-08	0.143969
District 3			N/A	0.042898	0.027533	0.033653	0.034438
District 4				N/A	3.92E-05	0.636517	1.28E-07
District 5					N/A	8.49E-06	0.913667
District 6						N/A	4.06E-05

Table 10-21: Anova Data Assuming Equal Variances for Figure 5.6: HMA Base Course B Average % RAP Per District 2008-2013

	District 1	District 2	District 3	District 4	District 5	District 6	District 7

District 1	N/A	0.081882	0.121487	0.82985	0.024895	0.129244	0.715364
District 2		N/A	0.397743	0.007323	0.499549	0.001128	0.348259
District 3			N/A	0.043386	0.118061	0.001709	0.595568
District 4				N/A	0.000227	0.076231	0.496984
District 5					N/A	8.42E-05	0.147609
District 6						N/A	0.140557

Table 10-22: Anova Data Assuming Equal Variances for Figure 5.9: HMA Intermediate Course B Average % RAP Per District 2008-2013

	District 1	District 2	District 3	District 4	District 5	District 6	District 7
District 1	N/A	0.027339	0.905115	0.789798	0.22994	0.018466	0.652855
District 2		N/A	0.019568	0.020972	0.287026	7.52E-05	0.393708
District 3			N/A	0.852545	0.256976	0.03085	0.57334
District 4				N/A	0.276473	0.0077445	0.502777
District 5					N/A	0.00198	0.00198
District 6						N/A	0.085814

Table 10-23: Anova Data Assuming Equal Variances for Figure 5.10: HMA Base Course C Average % RAP Per District 2008-2013

	District 1	District 2	District 3	District 4	District 5	District 6	District 7
District 1	N/A	0.62478	0.608284	0.616212	0.590039	0.000634	0.859491
District 2		N/A	0.890698	0.865905	0.157308	4.06E-08	0.55758
District 3			N/A	0.970192	0.16556	1.62E-06	0.599191
District 4				N/A	0.226406	0.226406	0.549094
District 5					N/A	0.000569	0.892806
District 6						N/A	0.017418

Table 10-24: Anova Data Assuming Equal Variances for Figure 5.11: HMA Surface Course A Average % RAP Per District 2008-2013

	District 1	District 2	District 3	District 4	District 5	District 6	District 7
District 1	N/A	0.894899	0.042281	0.440743	0.000548	0.87625	0.006666
District 2		N/A	0.113035	0.496226	0.007465	0.811868	0.022451
District 3			N/A	0.102453	0.28537	0.11074	0.386216
District 4				N/A	0.012658	0.415922	0.018452
District 5					N/A	0.004888	0.910343
District 6						N/A	0.022499

Table 10-25: Anova Data Assuming Equal Variances for Figure 5.12: HMA Surface Course B Average % RAP Per District 2008-2013

	District 1	District 2	District 3	District 4	District 5	District 6	District 7
District 1	N/A	0.823984	0.833942	0.193834	2.99E-05	8.61E-05	0.150603
District 2		N/A	0.674228	0.425551	0.001382	0.008069	0.324206
District 3			N/A	0.10838	0.000743	0.000221	0.074088
District 4				N/A	2.49E-08	0.004085	0.666438
District 5					N/A	2.7E-15	5.03E-07
District 6						N/A	0.040117

Table 10-26: Anova Data Assuming Equal Variances for Figure 5.13: HMA Surface Course C Average % RAP Per District 2008-2013

	District 1	District 2	District 3	District 4	District 5	District 6	District 7
District 1	N/A	0.03587	0.007475	0.284085	4.27E-05	0.0048	0.008241
District 2		N/A	1.06E-07	0.000223	0.002063	4.08E-09	0.082971
District 3			N/A	0.062137	5.03E-08	0.479819	5.55E-05
District 4				N/A	1.15E-05	0.126792	0.001635

District 5					N/A	6.75E-12	0.507276
District 6						N/A	7.82E-07

Table 10-27: Anova Data Assuming Equal Variances for Figure 5.14: HMA Surface Course CM Average % RAP Per District 2008-2013

	District 1	District 2	District 3	District 4	District 5	District 6	District 7
District 1	N/A	0.457116	0.154769	0.837392	0.282694	0.028917	0.365156
District 2		N/A	0.581112	0.237393	0.737722	0.002361	0.761614
District 3			N/A	0.041184	0.867428	1.27E-05	0.922496
District 4				N/A	0.113221	0.010859	0.186478
District 5					N/A	0.000457	0.973063
District 6						N/A	0.003356

Table 10-28: Anova Data Assuming Equal Variances for Figure 5.15: HMA Surface Course D Average % RAP Per District 2008-2013

	District 1	District 2	District 3	District 4	District 5	District 6	District 7
District 1	N/A	0.210338	0.110714	0.013011	0.000202	0.002851	0.972392
District 2		N/A	0.108672	0.329626	0.087477	0.000488	0.177178

District 3			N/A	0.011174	0.027658	0.376626	0.133116
District 4				N/A	0.56192	1.35E-06	0.012793
District 5					N/A	3.14E-09	1.95E-05
District 6						N/A	0.00223

Table 10-29: Anova Data Assuming Equal Variances for Figure 5.16: HMA Surface Course E Average % RAP Per District 2008-2013

	District 1	District 2	District 3	District 4	District 5	District 6	District 7
District 1	N/A	0.058623	0.010727	0.021215	0.01437	0.00079	0.117732
District 2		N/A	0.844259	0.447737	0.62734	0.000209	0.518092
District 3			N/A	0.158046	0.677997	1.4E-05	0.257461
District 4				N/A	0.107141	1.27E-07	0.849168
District 5					N/A	8.71E-05	0.207821
District 6						N/A	0.000109

Table 10-30: Anova Data Assuming Equal Variances for Figure 5.43: HMA Shoulder Widening Course Average Unit Cost Per District from 2008-2013

	District 1	District 2	District 3	District 4	District 5	District 6	District 7
District 1	N/A	0.109724	0.486672	0.526153	0.327977	0.020059	0.011973

District 2		N/A	0.792453	0.002292	0.003695	0.16172	0.561085
District 3			N/A	0.792453	0.161819	0.41095	0.604893
District 4				N/A	0.951372	0.001287	0.001456
District 5					N/A	0.000151	7.06E-06
District 6						N/A	0.463698

Table 10-31: Anova Data Assuming Equal Variances for Figure 5.46: HMA Base Course A Average Unit Cost Per District from 2008-2013

	District 1	District 2	District 3	District 4	District 5	District 6	District 7
District 1	N/A	0.066473	0.081788	0.344983	0.001833	0.586225	0.630271
District 2		N/A	0.752103	0.28049	0.655312	0.063376	0.202598
District 3			N/A	0.418961	0.371326	0.139434	0.444034
District 4				N/A	0.047155	0.583416	0.859845
District 5					N/A	0.002386	0.058868
District 6						N/A	0.829397

Table 10-32: Anova Data Assuming Equal Variances for Figure 5.52: HMA Intermediate Course B Average Unit Cost Per District from 2008-2013

	District 1	District 2	District 3	District 4	District 5	District 6	District 7
District 1	N/A	0.436885	0.037147	0.296981	0.601185	0.580978	No Data
District 2		N/A	0.000439	0.051135	0.145255	0.682968	No Data
District 3			N/A	0.665644	0.090698	0.001563	No Data
District 4				N/A	0.41653	0.090007	No Data
District 5					N/A	0.173436	No Data
District 6						N/A	No Data

Table 10-33: Anova Data Assuming Equal Variances for Figure 5.55: HMA Intermediate Course C Average Unit Cost Per District from 2008-2013

	District 1	District 2	District 3	District 4	District 5	District 6	District 7
District 1	N/A	0.000946	0.06015	0.633457	0.314432	0.000227	n = 1
District 2		N/A	0.623205	6.65E-05	0.018065	0.008172	n = 1
District 3			N/A	0.00904	0.111632	0.016194	n = 1
District 4				N/A	0.085302	1.32E-05	n = 1
District 5					N/A	6.23E-05	n = 1

District 6						N/A	n = 1

Table 10-34: Anova Data Assuming Equal Variances for Figure 5.58: HMA Surface Course A Unit Cost Per District from 2008-2013

	District 1	District 2	District 3	District 4	District 5	District 6	District 7
District 1	N/A	0.118022	0.129939	0.077216	0.032707	0.007162	0.263384
District 2		N/A	0.952045	0.054597	0.072827	5.73E-05	0.568055
District 3			N/A	0.004253	0.012331	4.97E-05	0.441098
District 4				N/A	0.226752	0.002181	0.406395
District 5					N/A	7.78E-05	0.571421
District 6						N/A	0.012113

Table 10-35: Anova Data Assuming Equal Variances for Figure 5.61: HMA Surface Course B Unit Cost Per District from 2008-2013

	District 1	District 2	District 3	District 4	District 5	District 6	District 7
District 1	N/A	0.061227	0.717447	0.266915	0.207419	2.23E-11	0.020196
District 2		N/A	0.144928	0.428386	0.402798	0.000441	0.815181
District 3			N/A	0.533714	0.477834	3.7E-08	0.065312

District 4				N/A	0.975553	6.35E-07	0.383615
District 5					N/A	5.03E-08	0.363582
District 6						N/A	5.82E-07

Table 10-36: Anova Data Assuming Equal Variances for Figure 5.64: HMA Surface Course C Unit Cost Per District from 2008-2013

	District 1	District 2	District 3	District 4	District 5	District 6	District 7
District 1	N/A	0.109812	0.009303	0.147013	0.394125	6.88E-06	0.783632
District 2		N/A	0.051489	0.527871	0.003298	4.69E-05	0.101105
District 3			N/A	0.460366	0.00028	0.198997	0.00185
District 4				N/A	0.020136	0.050829	0.106836
District 5					N/A	1.56E-09	0.182131
District 6						N/A	7.9E-08

Table 10-37: Anova Data Assuming Equal Variances for Figure 5.67: HMA Surface Course CM Unit Cost Per District from 2008-2013

	District 1	District 2	District 3	District 4	District 5	District 6	District 7

District 1	N/A	0.28878	0.307298	0.000263	0.42513	0.051818	0.041528
District 2		N/A	0.892847	0.003132	0.090591	0.001481	0.00211
District 3			N/A	0.000975	0.0751	0.00049	0.001195
District 4				N/A	0.000165	2.39E-09	4.35E-07
District 5					N/A	0.505669	0.322556
District 6						N/A	0.468804

Table 10-38: Anova Data Assuming Equal Variances for Figure 5.70: HMA Surface Course D Unit Cost Per District from 2008-2013

	District 1	District 2	District 3	District 4	District 5	District 6	District 7
District 1	N/A	0.953232	0.249155	0.043808	0.567542	0.939166	0.160673
District 2		N/A	0.281685	0.102314	0.723161	0.990226	0.323929
District 3			N/A	0.053406	0.343683	0.421584	0.426245
District 4				N/A	0.009566	0.110578	0.000566
District 5					N/A	0.71996	0.396627
District 6						N/A	0.322668

Table 10-39: Anova Data Assuming Equal Variances for Figure 5.73: HMA Surface Course E Unit Cost Per District from 2008-2013

	District 1	District 2	District 3	District 4	District 5	District 6	District 7
District 1	N/A	0.191974	0.083669	0.063121	0.661024	0.458361	0.044878
District 2		N/A	0.940793	0.924515	0.426379	0.318391	0.374528
District 3			N/A	0.946726	0.269608	0.369336	0.403601
District 4				N/A	0.219808	0.572001	0.625266
District 5					N/A	0.594227	0.247663
District 6						N/A	0.123302