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FINAL REPORT ~ FHWA-OK-15-01

FATIGUE PERFORMANCE OF ASPHALT PAVEMENTS CONTAINING RAS AND RAP

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16. ABSTRACT

Rising oil and gas prices spurs development of methods and technologies for reducing fuel consumption and increased use of recycled materials. With increased environmental awareness, using reclaimed asphalt pavement (RAP) and reclaimed asphalt shingles (RAS) in pavements have been gaining momentum nationally and globally. However, despite their advantages, there are national concerns associated with fatigue and low-temperature cracking potential of pavements when containing increased amounts of RAS and RAP. Therefore, this study was undertaken to evaluate the fatigue performance of hot-mix asphalt (HMA) containing RAS and RAP. Specifically, changes in fatigue resistance and cycles to fatigue failure with changes in the amount of RAS and RAP were examined using both flexural fatigue (four-point beam) and axial fatigue (cyclic direct tension) tests on laboratory compacted specimens. Effect of virgin binder grade on the fatigue performance was also examined. In addition, the effect of RAS and RAP in HMA on its creep compliance and dynamic modulus was investigated. These properties are used in the evaluation of fatigue resistance based on the axial cyclic direct tension test. For this purpose, eight fine surface course mixes (S4) with different types of asphalt binders (i.e., PG 64-22 OK and PG 70-28 OK) containing different amounts of RAS and RAP were designed and tested in the laboratory. The amount of RAS and RAP in HMA mixes varied, but the total amount of replaced binder was kept within certain specifications (i.e., RAP and/or RAS limited to 30% binder replacement). It was concluded that the fatigue life of asphalt mixes with a PG 64-22 OK binder increased with use of RAP or a blend of RAP and RAS. Using a blend of 5% RAP and 5% RAS in a mix led to the maximum increase in fatigue life. However, it was observed that the fatigue life of the mix decreased when 6% RAS was used compared to that of virgin mix with the same type of asphalt binder (PG 64-22). Also, it was found that when a PG 70-28 OK asphalt binder was used, use of RAP and/or RAS in a mix resulted in a decrease in fatigue life. Using 6% RAS resulted in the maximum decrease in fatigue life, compared to that of virgin mix with the same type of asphalt binder (PG 70-28 OK). Use of a polymer-modified asphalt binder (PG 70-28 OK) was found to be an effective way to increase the fatigue life of virgin mixes. More specifically, if RAP and/or RAS was used fatigue life was a concern. Furthermore, it was concluded that high coefficient of variation values of the cycles to failure found for four-point beam fatigue test show that the repeatability of this method was not very good. The dynamic modulus and creep compliance test results revealed that addition of RAP and/or RAS to asphalt mixes increased their stiffness, for cases in which PG 64-22 OK or PG 70-28 OK asphalt binders were used. This may result in a better rutting performance, but may lead to a mix with a higher low-temperature cracking potential versus the virgin mixes. Finally, it was found that indirect tensile strength (IDT) of the asphalt mixes increased with use of RAP and/or RAS compared to those of virgin mixes. Use of 6% RAS resulted in the maximum increase in IDT values. Also, a comprehensive survey was conducted among the state departments of transportation for gathering data on the current practices including the methods and specifications associated with the use of RAS and RAP in pavements. The results from this study can be used to develop/update guidelines/special provisions for design of HMA containing RAP and RAS in Oklahoma.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS				
SYMBOL	**WHEN YOU KNOW**	**MULTIPLY BY**	**TO FIND**	**SYMBOL**
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
AREA				
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS				
SYMBOL	**WHEN YOU KNOW**	**MULTIPLY BY**	**TO FIND**	**SYMBOL**
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
AREA				
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
TEMPERATURE (exact degrees)				
^oC	Celsius	1.8C+32	Fahrenheit	^oF
ILLUMINATION				
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
FORCE and PRESSURE or STRESS				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

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Chapter 1 INTRODUCTION

1.1 General

Hot-mix asphalt (HMA) is the most widely used paving material in the U.S. More than 90 percent of U.S. pavements are paved with asphalt (NECEPT, 2010). Each year, over 550 million tons of HMA are produced and used for construction of flexible pavements. Rising oil and gas prices spurs development of methods and technologies for reducing fuel consumption and increased use of recycled materials. With increased environmental awareness, using reclaimed asphalt pavement (RAP) and reclaimed asphalt shingles (RAS) in pavements have been gaining momentum nationally and globally. Over the past two decades, many transportation agencies, asphalt producers and pavement construction companies have taken major initiatives to implement green paving technologies (NAPA, 2011; NAPA, 2007). Saving money by increased use of recycled materials is an important element of such initiatives. Many studies have been conducted and are being conducted in the United States and elsewhere to find innovative ways to design and construct environmental friendly and durable pavements by using recycled asphalt materials. Consequently, HMA producers and paving contractors are undergoing phenomenal changes in terms of material characterization, mix designs, construction and maintenance of pavements. The new characterization and test methods are more rigorous, mechanistic and performance-based.

Although previous studies have shown improved resistance to rutting and moisture damage, contradictory results have been reported on fatigue life and thermal cracking of pavements constructed with mixes containing RAS and RAP. Several states including Alabama, Georgia, Missouri, and Texas have specifications for design of mixes containing RAS and RAP, but such specifications are not yet developed by the Oklahoma Department of Transportation (ODOT). This is partly because laboratory and field data on fatigue resistance/life and thermal cracking of asphalt mixes containing RAS and RAP are seriously lacking. To this end, the present study seeks to evaluate the fatigue performance of HMA mixes containing RAS and RAP. Specifically, changes in fatigue resistance and cycles to fatigue failure with the changes in the amount of RAS and RAP were examined using both flexural fatigue (four-point beam) and axial fatigue (cyclic direct tension) tests on laboratory compacted specimens. Also, indirect tensile strength (ITS) tests were conducted and the results compared with the cycles to fatigue failure. Effect of virgin binder grade on the fatigue performance was also examined. In addition, effects of RAS and RAP on creep compliance and dynamic modulus (that is used in the evaluation of fatigue resistance based on the axial cyclic direct tension test) were evaluated. Results from this study are expected to be used to develop guidelines/special provisions for design of HMA containing RAS and RAP.

1.2 Objectives

The primary objectives of this study were: (i) to generate laboratory data on fatigue performance (or fatigue life) of HMA mixes containing RAS and RAP that will help address the aforementioned concerns and questions on the use of RAS and RAP in asphalt pavements in Oklahoma; and (ii) to make recommendations on guidelines/special provisions for the design of HMA containing RAS and RAP. Specifically, this study addresses the following:

1. Examine the influence of the use of RAS and RAP on the fatigue life with the changes in the amount of recycled materials. Specifically, changes in fatigue resistance or number of cycles to fatigue failure of HMA mixes due to changes in the RAS and RAP content were studied using flexural fatigue (four-point bending beam) and axial fatigue (cyclic direct tension) tests.
2. Investigate the effect of virgin binder grade (PG 64-22 vs. PG 70-28) on the thermal cracking potential with the changes in the amount of RAS and RAP. Specifically, evaluate changes in creep compliance and indirect tensile strength of HMA mixes containing RAS and RAP.
3. Investigate correlations between fatigue life (number of cycles to fatigue) and indirect tensile strength of HMA mixes containing RAS and RAP.
4. Investigate the effect of RAS and RAP on the dynamic modulus (needed for the evaluation of fatigue resistance based on the axial cyclic direct tension test) of HMA specimens with the changes in the amount of recycled materials.

5. Make recommendations on developing/adjusting guidelines/special provisions for incorporation of RAS and RAP in HMA mixes in Oklahoma.

1.3 Problem Statement

Although asphalt roofing shingles have commercial value, they are frequently disposed in landfills when replacing roofs (Zickell, 2003; Mallick and Teto, 2000; EPA, 1998). Nationwide, more than 11 million tons of asphalt shingle waste is generated annually (CIWMB, 2007; CMRA, 2007; Sengoz and Topal, 2005; Zickell, 2003). Roofing asphalt shingles are composed of hard crushed aggregate, high viscosity asphalt binder, and fibers that are desirable components of HMA. Consequently, recent years have seen a significant growth in the use of RAS in HMA. Use of RAS in HMA has both economic and environmental benefits. Economically, use of RAS in HMA will reduce the need for the virgin materials, both asphalt binders and aggregates (FVD, 2006; Sengoz and Topal, 2005; Foo et al., 1999). The RAS contains between 19% and 36% asphalt binder (by weight) and 20% to 38% ceramic, a source of fine aggregate (CIWMB, 2007; NAHB, 1998). Based on the literature, about $4.8 can be saved per ton of HMA, when using 5% RAS in the mix (CAPA, 2011). On the environmental side, use of RAS will reduce the consumption of landfill and reduce the use of virgin materials (Sengoz and Topal, 2005). A majority of waste shingles are from building activities, primarily renovation and demolition, called tear-offs or post-consumer waste; however, shingle waste is also produced by shingle manufacturers, which is called manufacturers' waste. Based on the results of a recent nationwide survey conducted by NAPA (2011), use of RAS (both manufacturers' waste and tear-offs from roofs) in HMA increased from 702,000 tons to 1.1 million tons from 2009 to 2010, a 57% increase. According to NAPA (2011), replacing only 20% of the virgin binder in a mix by the binder in RAS, 234,000 tons (1.5 million barrels) of asphalt binder can be conserved, annually. Furthermore, use of RAP in HMA is known to have several economic benefits. Recent studies have shown that, in addition to preserving the environment, significant savings in cost are realized with increased use of RAP due to reduced requirement of virgin binder. Based on the data from the Virginia Department of Transportation, about $3.7 can be saved per ton of mix, for each 10% increase in RAP amount (Maupin et al., 2008). With increased use of recycled materials (RAS and RAP), the asphalt industry as well as

Departments of Transportation (DOTs) have realized the necessity of updating their specifications and test protocols.

Based on a national survey conducted by Jones (2008), one of the major barriers for use of RAS and RAP in HMA mixes includes binder issues. Binder issues generally consist of binder grade, unknown properties of the blend, compaction issues and concerns related to early failure, specifically thermal cracking and fatigue failure. The aforementioned binder issues are mainly related to the hardness (viscosity, modulus) of the asphalt binder in the RAS and RAP. The asphalt binders in RAS are usually air-blown and aged, making them substantially harder than the normal asphalt binder used in HMA mixes. Despite higher stiffness and improved performance against rutting (Mogawer et al., 2011; Cascione et al., 2010; Johnson et al., 2010), stiffer binder generally have increased propensity to cracking and reduced tensile strength and fatigue life. Based on previous studies, addition of RAS to dense-graded mixes has been found to decrease the tensile strength of the mix (Button et al., 1995). Also, the mix’s susceptibility to fatigue failure and thermal cracking was found to increase as a result of adding RAS and RAP. Adverse effects of RAP on the fatigue life of pavements generally begin to show when the RAP content is greater than 20%, as reported by McDaniel et al. (2000).

The aforementioned concerns demonstrate a need for studying the performance of HMA mixes containing RAS and RAP, particularly from the fatigue and thermal cracking points of view. This study was intended to generate useful data for ODOT on the fatigue performance of HMA mixes containing RAS and RAP. The amount of RAS and RAP in HMA mixes varied, but the total amount of replaced binder was kept within certain specifications (i.e., RAP and/or RAS limited to 30% binder replacement).

Chapter 2

LITERATURE REVIEW

2.1 General

There is a wealth of available literature on the use of RAS and RAP in HMA. The literature review in the present study was focused on the concerns arising from the use of RAS and RAP in HMA pertaining to performance-measures of the mix, specifically fatigue life and low-temperature cracking. Use of RAS is generally considered as a partial replacement of virgin binder and aggregates in HMA. Several researchers have reported that using up to 5% RAS by weight of mix in the HMA is unlikely to have any significant negative effects on the mix performance. However, when increasing the RAS amount beyond a certain limit, the possibility of adverse impacts on the performance of the mix can increase significantly (Mallick and Mogawer, 2000; Janisch and Turgeon, 1996; Button et al., 1995; Newcomb et al., 1993). In order to gain an understanding of the effects of using RAS and RAP on the HMA, a comprehensive literature review was conducted, focusing on the characterization of HMA mixes containing RAS and RAP and their associated performance when combined with virgin materials. Sources of literature included, but was not limited to, TRIS, TRB, FHWA, NCHRP, and DOTs. Other sources such as society journals (e.g., ASCE and ASTM), Asphalt Institute (AI), Western Research Institute (WRI), and NCAT are also being consulted. A summary of the reviewed studies is given below.

2.2 Characteristics of HMA Mixes Containing RAS and RAP

Cooper et al. (2014) evaluated the asphalt mixes containing RAS, including a stone matrix mix (SMA), through a comprehensive laboratory testing program. Rutting performance, moisture resistance, and fracture resistance of laboratory-produced mixes were investigated by using the Hamburg wheel-tracking, semicircular bending, and thermal stress restrained specimen tensile strength tests. It was concluded that the draft revision of AASHTO PP 53 (AASHTO, 2011), Standard Practice for Design Considerations when using Reclaimed Asphalt Shingles (RAS) in New Hot-Mix Asphalt, overestimated the RAS asphalt binder availability factor. Also, it was found that the asphalt mixes containing 5% RAS at high, intermediate, and low temperatures perform as well as the control asphalt mixes containing no RAS. Furthermore, it was observed that the asphalt mixes containing RAS show a better rutting performance as compared with the control mix containing no RAS.

In a recent study conducted by Barry et al. (2014), the laboratory performance of a number of HMA mixes containing varying amounts of RAS from different sources was investigated. The laboratory testing consisted of dynamic modulus, phase angle and fatigue. It was found that mixes with higher amounts of binder replacement from RAS exhibited a higher stiffness at high temperatures and a lower stiffness at low temperatures, as compared with those containing lower amounts of binder replacement. However, an increase in amount of RAS resulted in a better fatigue performance. The mixes with various sources of RAS, whether pre- or post-consumer, showed similar low-temperature cracking performance, while those with a blend of both sources were found to be the stiffest at high temperatures. Also, it was found that the mixes containing only RAP exhibited a higher stiffness at intermediate and high temperatures but similar stiffness at low temperature, as compared to those which contained only RAS.

In a study conducted by Ozer et al. (2012) for the Illinois Center for Transportation, the effect of high asphalt binder replacement on a low N-design asphalt mix was studied including RAP and RAS on performance indicators such as permanent deformation, fracture, fatigue potentials, and stiffness. The asphalt binder replacement combinations of RAS and RAP asphalt binders in the mix were in the range of 43 to 64%. According to the test results, rutting resistance of the mixes was improved when RAS was used. Fracture tests at low-temperature did not show any significant difference between the asphalt mix specimens compacted at different amounts of binder replacement. Also, it was found that asphalt mixes become more prone to fatigue with increased RAS content and asphalt binder replacement. The specimens prepared with 2.5% RAS content using a PG 46-34 virgin asphalt binder showed the highest fatigue life. A bump in asphalt binder grade due to RAS was reported from the test results. Furthermore, an improvement in fatigue life and fracture energy was observed when the asphalt binder type was changed from PG 58-28 to PG 46-34 at the highest asphalt binder replacement level. Moreover, the complex modulus test results were found to characterize the viscoelastic properties of the mixes, such as relaxation potential and long-term stiffness. These material properties, along with fracture test results, are crucial to evaluate the asphalt mix brittleness when the asphalt binder replacement is high.

In another study conducted by Williams et al. (2011), laboratory performance of asphalt mixes containing RAS and higher percentages of fractionated RAP (FRAP) was evaluated. In that study three different mix types, namely base course (four mixes), binder course (two mixes), and surface course (two mixes), were evaluated. The laboratory tests conducted on the asphalt mixes consisted of dynamic modulus, flow number, tensile strength ratio, beam fatigue, and disk compact tension (DCT). It was found that the laboratory-produced samples which contained RAS exhibited higher modulus values than those collected from field. From dynamic shear Rheometer (DSR) test results, it was found that increasing the amount of FRAP with or without RAS in the asphalt mixes increased the rutting resistance. It was concluded that use of 50 percent recycled materials in a field-collected asphalt mix resulted in a bump in the performance grade of the asphalt binder to PG 88. Also, based on the flow number test results, very little rutting was observed, since all samples accumulated strains less than five percent after 10,000 load cycles. The beam fatigue test results indicate no clear trend in the data among different mixes.

In another study conducted by Tabaković et al. (2010), the effect of physical properties of RAP on the mechanical performance of asphalt mixes (binder course) containing varying percentages of RAP was evaluated. Also, an asphalt mix using only virgin binder was selected as the control mix. For this purpose, different laboratory tests, namely Marshall, indirect tensile stiffness modulus, indirect tensile fatigue and moisture sensitivity were conducted. Also, a special equipment, circular wheel track (CWT), capable of testing rectangular slab samples was developed and used to study the dynamic effects of a rolling wheel on asphalt pavement. The CWT test was conducted under a temperature-controlled condition. It was found that use of RAP in the tested mixes resulted in an improvement in all tested mechanical properties. Specifically, it was found that the mix containing up to 30% RAP exhibited improved fatigue resistance compared to that of the control mix prepared from the virgin materials.

Vavrik et al. (2010) investigated the performance of a HMA test section, containing high amounts (20% to 45%) of FRAP and some RAS materials. The FRAP/RAS-HMA shoulder mixes were sampled and laboratory tests were conducted. It was found that the stone matrix asphalt (SMA) mix containing RAS combined with 15% fine FRAP resulted in significant improvement fatigue resistance compared with equivalent SMA mixes containing no RAS or RAP materials. However, a lower FRAP amount resulted in lower dynamic modulus values. These results indicate that the material should have improved thermal cracking resistance when used on a limited basis in HMA mixes. Also, it was concluded that an improvement in fracture resistance translates into improved resistance to reflection and thermal cracking. Moreover, it was reported that in case of maintaining consistency and uniformity of RAS materials, no substantial changes to the existing mix design procedures are needed in order to accommodate a new source of RAS. Training and educating the asphalt materials suppliers, producers and personnel dealing with the RAS materials is of vital importance for their safety. This is due to the potential asbestos hazard associated with collecting, sorting, and processing RAS materials.

Button et al. (1996) and Abdulshafi et al. (1997) found that a finer grinded RAS produced a more consistent and better performing asphalt mix. Button et al. (1996) also found that the mixes containing a finer ground tear-off RAS increased the tensile strength more than a coarser grind.

Ali et al. (1995) studied the feasibility of using RAS in HMA. Three mixes containing different amounts (i.e., 0%, 15%, and 25%) of RAS were tested. Resilient modulus, creep compliance, fatigue, and moisture sensitivity tests were conducted. It was found that both the fatigue life and stiffness of the mix improved with an increase in the RAS content. It was also observed that the permanent deformation decreased with the addition of RAS, while the moisture sensitivity of the mixes was not affected. In a similar study, Button et al. (1995) conducted a laboratory investigation on HMA mixes containing RAS. Two types of fine-graded and coarse-graded surface mixes were modified with 5% and 10% RAS and tested. It was observed that the addition of RAS to dense-graded mixes decreased the tensile strength of the mix and resulted in an improved resistance to moisture damage. The addition of RAS generally decreased the creep stiffness, which was proportional to the amount of RAS added.

Schroer (2009) studied the effect of using RAS in HMA over an experimental pavement section constructed on Route 61/67 in St. Louis County. As a result of this study and additional testing, it was recommended that the maximum amount of RAS be limited to 30% binder replacement without changing the grade of the asphalt binder. Also, it was reported that presence of excessive demolition debris in RAS (in the case of tear-offs) can significantly reduce the fatigue and low-temperature cracking performance of pavements. Therefore, the deleterious material content was recommended to be limited to 0.5%.

Johnson et al. (2010) investigated the effect of RAS content on the dynamic modulus of the mix. It was observed that stiffness of the mix containing RAS was higher as compared to the control mix. Specifically, at low frequencies, stiffness of the mix containing tear-off RAS was higher at high temperatures as compared to the mix containing manufacturers' waste RAS. Similarly, Cascione et al. (2010) reported that rutting performance of the mix improved significantly with the addition of 5% RAS by weight of the mix, without compromising the low-temperature performance. It was observed that the addition of RAS increases the stiffness of the mix, leading to improved rut resistance. However, Newcomb et al. (1993) reported that the use of RAS may result in a lower fatigue life and premature low-temperature cracking of pavements. Several other researchers have also investigated the performance of mixes containing RAP. For example, Huang et al. (2004) conducted a laboratory study to investigate the effect of RAP content (varying between 0 to 30%) on the fatigue performance of the HMA. It was reported that inclusion of RAP in HMA improves the fatigue life of the pavement. It was also concluded that the use of higher RAP contents increases mix stiffness, leading to improved rut resistance and higher tensile strength. Similarly, McDaniel and Shah (2003) conducted a laboratory study with materials obtained from Indiana, Michigan, and Missouri. Field and laboratory-produced mixes with RAP contents of up to 50% were tested to evaluate the effect of RAP on the mix performance. Tests conducted with a Superpave® shear tester indicated that the use of RAP results in the stiffening of the mix, as compared to mixes produced with only virgin materials. Improved stiffness is beneficial to rut resistance, but may result in an increased potential for fatigue and thermal cracking. Adverse effects of increased RAP on the fatigue life of pavements generally begins to show when the RAP content is greater than 20%, as reported by McDaniel et al. (2000). Consequently, it was recommended that the virgin binder of a lower grade be used to address the fatigue performance issues, especially at high RAP contents (more than 20%). Scholz (2010) conducted laboratory tests on mixes prepared with blended RAS, RAP, and virgin materials. It was reported that addition of RAS and RAP increases the stiffness of the blended binder, making the resulting HMA more prone to fatigue cracking. From this study, it was also concluded that at sufficiently high RAP contents (i.e., 30% or more), combined with 5% RAS by weight of the mix, the low-temperature performance grades of the blended binders were lower than that of the blend containing only virgin binder and RAS. Similarly, at RAP contents of 30% and 40%, the high temperature performance grade of the blended binders equaled that of the blend containing only the virgin binder and RAS. It was also concluded that although inclusion of RAS and sufficient amounts of RAP in HMA mixes significantly affected the performance grades of the blended binders, high RAP contents alone (i.e., absence of RAS) did not have any significant impact on the low-temperature grade. Mogawer et al. (2011) evaluated the performance of thin-lift mixes incorporating RAS and a high RAP content. HMA mixes with 5% RAS and 40% RAP, and with 5% RAS and 35% RAP were produced in the laboratory and tested. Based on the dynamic modulus tests, it was concluded that mixes with high RAS content, high RAP content, or both, exhibited higher stiffness. Also, it was observed that the use of RAS or RAP or both reduced the reflective cracking resistance without any negative impact on the resistance to low-temperature cracking. It was concluded that the addition of RAS or RAP or both improved the mixes' resistance to moisture-induced damage.

The above summary of the open literature indicates that inconsistent results have been reported by the researchers on fatigue and low-temperature cracking performance of mixes containing RAS and RAP. This is partly because laboratory and field data on performance of asphalt mixes containing RAS and RAP are seriously lacking. Also, no standard guidelines/special provisions are available to design mixes using both RAS and RAP. Furthermore, the variability in the quality of RAS and RAP and unavailability of high-end equipment to conduct performance tests on mixes containing recycled materials appear to be major reasons for this gap. This study aimed to examine the fatigue and low-temperature cracking performance of mixes containing recycled materials, and to make recommendations for developing/adjusting guidelines/special provisions for incorporation of RAS and RAP in HMA mixes.

2.3 State of Practice in Different Transportation Agencies

The Oklahoma Department of Transportation (ODOT) prepared a special provision for use of RAS (and RAP) in HMA based on the maximum binder replacement (Hobson, 2014). According to Hobson (2014), 30% is the maximum allowable total replaced binder from RAP and RAS, for binder course. The amount of RAP and RAS are limited to 20% and 5% by the weight of the mix, respectively. Based on these limitations, there are possibilities of different combinations of different percentages of RAS and RAP satisfying the aforementioned criterion, which may affect the mix performance with respect to fatigue and thermal cracking. This research aimed to address the fatigue performance and low-temperature cracking issues and make recommendations for possible development of new special provisions. As a part of literature search for this study, a review of other states' construction specifications/practices was conducted. It was evident that some states allow the use of manufacturer's waste but not tear-off shingles. Currently, fifteen state agencies allow the use of RAS in HMA mixes (Table 2.1); other states are in the research phase of incorporating RAS in their specifications. Table 2.1 provides a summary of the states allowing the use of RAS in HMA, depending on the type of RAS (i.e., manufacturers' waste and tear-offs from roofs). Table 2 summarizes the state agencies with recommendations for use of RAS and RAP in HMA mixes, according to their specifications. Also, a comprehensive survey on the current practice of using RAS and RAP in HMA for different state DOTs was conducted in close cooperation with ODOT and is discussed in Chapter 3.

Table 2.1 Agencies Incorporating RAS in HMA and Type of Allowable RAS

No.	State DOT	Max. RAS Allowed in HMA		No.	State DOT	Max. RAS Allowed in HMA	
		Man. Waste (%)	Tear-Offs (%)			Man. Waste (%)	Tear-Offs (%)
1	Alabama	5	3	9	New Jersey	5	0
2	Florida	5	0	10	N. Carolina	6	0
3	Georgia	5	5	11	Pennsylvania	5	5
4	Indiana	5	0	12	S. Carolina	3-5	3-5
5	Maryland	5	0	13	Texas	5	5
6	Massachusetts	5	0	14	Virginia	5	5
7	Minnesota	5	0	15	Wisconsin	Varies	Varies
8	Missouri	7	7				

Table 2.2 Summary of Specifications for RAS used by State Agencies

Agency	Maximum RAS content Allowed	Maximum RAP Content Allowed	Maximum Binder Replacement	Virgin Binder Adjustment
AL	Tear off RAS : 3% by wt. of agg. Man. waste RAS: 5% by wt. of agg.	25% for Plant-Mix Bit. Base; 20% for SMA/Superpave surface; 25% for other SMA/Superpave layers	RAS shall contain approx. 20-30% binder.	No adjustment found.
FL	5% by wt. of agg. (considered RAP in determining total RAP content in mix).	50% by wt. of agg. For Traffic Levels A, B, and C mixes (<10M ESALs); 30% by wt. of agg. For Traffic Levels D and E mixes (>=10M ESALs); 15% by wt. of agg. When using PG 76-22 (see exception for max. binder replacement)	15% RAP binder when >15% RAP by wt. of agg. used with PG 76-22.	< 20% RAP: PG 67-22* 20-29% RAP: PG 64-22 >= 30: Recycling Agent Maintain the absolute viscosity of the recycled mixture within the range of 5,000 to 15,000 poises.
GA	5% by wt. of total mix.	40% (mainline and ramps) for drum plants; 25% for batch plants	Not specified.	Recovered blended binder from mixture shall have an absolute viscosity between 6,000 and 16,000 poises.
IN	5% by wt. of total mix for RAS-only mixes; 3% for ESAL cats. 3, 4, and 5 (>3M)	25% RAP or 5% RAS by wt. of total mix for ESALs < 3M (1% RAS = 5% RAP for substitutions); 15% RAP or 3% RAS by wt. of total mixture for ESALs >= 3M	Not specified.	15-25% RAP (ESALs < 3M), reduce by one grade; <15% RAP, use specified grade.
IA	5% by wt. of agg.	Up to 15% for surface courses; no limit for base and intermediate courses utilizing "Classified RAP", 20% for "Certified RAP", 10% for "Unclassified RAP".	Not specified.	Not specified; mix design testing conducted by DOT, which indicates mix design adjustments may be needed.
MA	5% by wt. of total mixture for RAS-only mixtures	Based on maximum binder replacement.	40% for drum plants; 20% for mod. batch plants.	<=25% binder repl.: PG 64-28; >25% binder repl.: PG 52-34.
MN	5% by total wt. of mix.	30% (>1M ESALs); 30% for wearing surface and 40% for non-wearing surface when <1M ESALs	30% (virgin/total >=0.70).	Use specified grade for PG XX-28 and PG 52-34 independent of RAP content; Use specified grade for PG XX-34 with <=20% RAP; Use blending chart for PG XX-34 and >20%RAP. Percentage of RAS onsidered part of max. allowable RAP percentage.
MO	(see max. binder replacement criterion)	Based on maximum binder replacement.	30% w/o changing virgin grade.	PG64-22,PG 52-28 or PG 58-28 when virgin/total between 0.60 and 0.70
NH	Not specified (see max. binder replacement criterion)	Based on maximum binder replacement.	0.6% RAS binder content; up to 1.5% RAP/RAS binder content.	Shall meet specified grade in special provision for project (contractor responsible for determining virgin binder grade)

Table 2.2 Summary of Specifications for RAS used by State Agencies (continued)

<table>
<tr><th>Agency</th><th>Maximum RAS content Allowed</th><th>Maximum RAP Content Allowed</th><th>Maximum Binder Replacement</th><th>Virgin Binder Adjustment</th></tr>
<tr><td>NC</td><td>6% by wt. of total mix.</td><td>15% by wt. of total mixture (unless otherwise approved).</td><td>Not directly specified.</td><td>PG76-22; one grade (high & low) below specified grade for 15-25% RAP/RAS; Engineer to determine grade when >25% RAP/RAS used</td></tr>
<tr><td>PA</td><td>5% by wt. of total mixture mandated.</td><td>15% for wearing course.</td><td>Not specified.</td><td>Use specified grade for 5-15% RAP or 5% RAS; DOT to determine virigin binder grade
if >15% RAP or >5% RAP plus 5% RAS</td></tr>
<tr><td>SC</td><td>3-8% by wt. of agg.</td><td>20% for surface courses, 25% for intermediate course, and 30% for base courses. 15% when using batch plants and RAP/RAS introduced in hot elevator.</td><td>Not specified.</td><td>Recovered blended binder from mixture shall have an absolute viscosity less than 12,000 poises</td></tr>
<tr><td>TX</td><td>5% by wt. of total mix.</td><td>Mixes with fractionated RAP:
20% for surface courses, 30% for other layers.
Mixes with non-fractionated RAP:
10% for surface courses, 20% for other layers.</td><td>35% for surface courses;
40% for other layers.</td><td>Grade appears to based on M 320; no mention of adjustments found.</td></tr>
<tr><td>VA</td><td>5% by wt. of total mix.</td><td>Based on maximum binder replacement.</td><td>Combined RAP and RAS percentage shall not contribute more than 30% of the total asphalt content of the mix.</td><td>One PG grade lower (both temperatures) for mixtures with 20% or more RAP/RAS content (25% for 25-mm base mixtures).</td></tr>
<tr><td>WI</td><td>See max. binder replacement.</td><td>Based on maximum binder replacement.</td><td><table>
<tr><th rowspan="2">Recycled Asphalt Material</th><th colspan="2">Max. binder replacement</th></tr>
<tr><th>Lower Layers</th><th>Upper Layer</th></tr>
<tr><td>RAS only</td><td>25%</td><td>20%</td></tr>
<tr><td>RAP/FRAP</td><td>40%</td><td>25%</td></tr>
<tr><td>RAS, RAP, and FRAP*</td><td>35%</td><td>25%</td></tr>
<tr><td colspan="3">*5% max. RAS by total wt. of agg. Blend</td></tr>
</table></td><td>Designated in contract. Contractor may replace virgin binder with recovered binder up to the maximum percentages shown under max. binder replacement. Greater replacement percentages allowed if the resultant binder meets grade specified in contract.</td></tr>
</table>

Chapter

3 SURVEY OF DOTS' SPECIFICATIONS

3.1 General

Fatigue cracking is one of the dominant distresses in flexible pavements and therefore, fatigue performance evaluation of asphalt mixes containing RAS and RAP during the design stage is immensely important. Although many test methods, namely four-point beam fatigue (FTG), semi-circular bend (SCB), indirect tensile test (IDT), cyclic direct tension (CDT), and overlay tester (OT), are currently available to determine fatigue resistance of asphalt mixes, a clear consensus about the methods used for testing the mixes containing RAS and RAP has not yet been reached. A review of construction specifications used by different DOTs, which allow the use of RAS and RAP, was conducted in this study. Since the DOT practices are generally not available in the open literature, a survey was conducted which focused on gathering data on the current practices including the methods and specifications associated with the use of RAS and RAP in pavement by different DOTs. This task was pursued in Year 1, and the results are summarized in this chapter.

3.2 Objective of the Survey

The main objective of conducting the survey was to gather information on the mix design and construction specifications used by different DOTs, which allow the use of RAS and RAP. Currently, at least fifteen state agencies allow the use of RAS in HMA mixes, and other states are in the research phase of incorporating RAS in their specifications.

3.3 Execution of the Survey

The survey questionnaire used herein was prepared by the research team in close collaboration with the Materials Division of ODOT. A meeting was held on April 11, 2013 between the research team and the ODOT Materials Division (represented by Mr. Kenneth Hobson). The survey was conducted through an online data collection website, namely www.surveymonkey.com, to maximize the efficiency and productivity of data collection process. The access link to the survey website (https://www.surveymonkey.com/s/Asphalt-RAS-RAP) was sent to Mr. Kenneth Hobson of ODOT in July 2013 for distribution among different DOTs. Subsequently, it was distributed to different DOTs by Mr. Reynolds Toney, Materials & Research Division Engineer, ODOT.

3.4 Survey Questionnaire

The survey questionnaire, e-mailed to the different DOTs is provided below. This questionnaire consisted of 32 questions. Agency name and contact information were requested in the beginning. Other questions were related to the use of RAS and RAP in different types of asphalt mixes, strategies adopted for prevention of distresses, preference for fatigue performance evaluation, and any other measures DOTs may use to minimize distress.

Fatigue Performance of Asphalt Pavements Containing RAS and RAP

We greatly appreciate your participation in this survey, which is conducted as part of a research project funded by the Oklahoma Department of Transportation, in collaboration with Federal Highway Administration. Please provide and submit your input electronically, using this online survey questionnaire, if possible.

1. Participating Agency Name

2. Contact Name

3. Contact Phone No.

4. E-mail Address

5. Does your agency use Reclaimed Asphalt Shingles (RAS) in construction of pavement layers?

- ◯ Yes
- ◯ No; please specify reason, if possible:

6. Please specify allowable sources of RAS (i.e. tear offs, manufacturer waste, etc.) in the asphalt mixes (if none please indicate so).

Surface course:

Intermediate/Base course:

Fatigue Performance of Asphalt Pavements Containing RAS and RAP

7. Which method is used to estimate asphalt binder content in RAS?

- ◯ Chemical
- ◯ Ignition oven
- ◯ Other, please specify, if possible

8. Please specify allowable maximum RAS content (%) used in asphalt pavement layers.

Surface course (%):

Intermediate/Base course (%):

What is this RAS content measurement based on (i.e. weight of aggregate, total weight, binder replacement, etc.)?

9. Please specify the criteria for each test given below used to set the maximum RAS content (%) limit in surface course. If the test is not used by your agency, please indicate so.

4 point bending beam fatigue test (e.g. number of cycles to fatigue failure, 50% of initial stiffness, etc.)

Cyclic direct tension (e.g. number of cycles to fatigue failure, 50% of initial stiffness, etc.)

Creep compliance

Semi-circular bending beam (SCB)

Texas overlay tester

Indirect tensile strength

Indirect tensile strength ratio (TSR; AASHTO T283)

Other tests and criteria, if any

10. Please specify the criteria for each test given below used to set the maximum RAS content (%) limit in intermediate/base course. If the test is not used by your agency, please indicate so.

4 point bending beam fatigue test (e.g. number of cycles to fatigue failure, 50% of initial stiffness, etc.)

Cyclic direct tension (e.g. number of cycles to fatigue failure, 50% of initial stiffness, etc.)

Creep compliance

Semi-circular bending beam (SCB)

Texas overlay tester

Indirect tensile strength

Indirect tensile strength ratio (TSR; AASHTO T283)

Other tests and criteria, if any

11. Does your agency use Reclaimed Asphalt Pavement (RAP) in construction of pavement layers (please check)?

- Yes
- No; please specify reasons, if possible

12. Please specify allowable sources of RAP (i.e. Interstate highway, city road, etc.) in asphalt mixes.

Surface course:

Intermediate/Base course:

In each case please specify if the history of the RAP is tracked (Yes/No):

Fatigue Performance of Asphalt Pavements Containing RAS and RAP

13. If you track the RAP quality history, please specify the method used (multiple answers may be selected, if applicable).

- ☐ Identified with sign on the stockpile.
- ☐ By gradation.
- ☐ No RAP of unqualified sources is allowed to be added to the existing stockpile.
- ☐ The RAP quality is not tracked.
- ☐ Other, please specify, if possible

14. Which method is used to estimate asphalt binder content in RAP (please check)?

- ○ Chemical
- ○ Ignition oven
- ○ Other, please specify, if possible

Other, please specify, if possible

15. Please specify allowable maximum RAP content (%) used in asphalt pavement layers.

Surface course (%):

Intermediate/Base course (%):

What is this RAP content measurement based on (i.e. weight of aggregate, total weight, etc.)?

Fatigue Performance of Asphalt Pavements Containing RAS and RAP

16. Please specify the criteria for each test given below used to set the maximum RAP content (%) limit in surface course. If the test is not used by your agency, please indicate so.

4 point bending beam fatigue test (e.g. number of cycles to fatigue failure, 50% of initial stiffness, etc.)	
Cyclic direct tension (e.g. number of cycles to fatigue failure, 50% of initial stiffness, etc.)	
Creep compliance	
Semi-circular bending beam (SCB)	
Texas overlay tester	
Indirect tensile strength	
Indirect tensile strength ratio (TSR; AASHTO T283)	
Other tests and criteria, if any.	

17. Please specify the criteria for each test given below used to set the maximum RAP content (%) limit in intermediate/base course. If the test is not used by your agency, please indicate so.

4 point bending beam fatigue test (e.g. number of cycles to fatigue failure, 50% of initial stiffness, etc.)	
Cyclic direct tension (e.g. number of cycles to fatigue failure, 50% of initial stiffness, etc.)	
Creep compliance	
Semi-circular bending beam (SCB)	
Texas overlay tester	
Indirect tensile strength	
Indirect tensile strength ratio (TSR; AASHTO T283)	
Other tests and criteria, if any	

18. Please specify allowable maximum binder replacement by RAS and/or RAP binder in surface course.

Maximum from RAS (%):

Maximum from RAP (%):

Combined max. (%):

19. Please specify allowable maximum binder replacement by RAS and/or RAP binder in intermediate/base course.

Maximum from RAS (%):

Maximum from RAP (%):

Combined max. (%):

20. Please specify the criteria for each test given below used to set the maximum binder replacement limit from RAS and/or RAP in surface course. If the test is not used by your agency, please indicate so.

4 point bending beam fatigue test (e.g. number of cycles to fatigue failure, 50% of initial stiffness, etc.)

Cyclic direct tension (e.g. number of cycles to fatigue failure, 50% of initial stiffness, etc.)

Creep compliance

Semi-circular bending beam (SCB)

Texas overlay tester

Indirect tensile strength

Indirect tensile strength ratio (TSR; AASHTO T283)

Other tests and criteria, if any

Fatigue Performance of Asphalt Pavements Containing RAS and RAP

21. Please specify the criteria for each test given below used to set the maximum RAS content (%) limit in intermediate/base course. If the test is not used by your agency, please indicate so.

4 point bending beam fatigue test (e.g. number of cycles to fatigue failure, 50% of initial stiffness, etc.)	
Cyclic direct tension (e.g. number of cycles to fatigue failure, 50% of initial stiffness, etc.)	
Creep compliance	
Semi-circular bending beam (SCB)	
Texas overlay tester	
Indirect tensile strength	
Indirect tensile strength ratio (TSR; AASHTO T283)	
Other tests and criteria, if any	

22. Please specify if you bump the PG grade of the virgin binder down (or any other adjustments) in case of using RAS and/or RAP?

◯ Yes

◯ No

If the answer to this question is “Yes”, please specify the criteria used for this binder grade adjustment.

23. If agency has a guideline/procedure/specification for examining the RAS and/or RAP quality, before using it in the asphalt mix, please specify.

	Yes	No
Quality control on RAP:	☐	☐
Quality control on RAS:	☐	☐

Fatigue Performance of Asphalt Pavements Containing RAS and RAP

24. If there are no specific guidelines available for the quality control of RAS, please check the generally accepted criteria followed by your agency for this purpose (multiple answers may be selected, if applicable).

- ☐ Asbestos control
- ☐ Binder content
- ☐ Fractionizing
- ☐ Debris control
- ☐ Gradation
- ☐ Foreign particle control
- ☐ Other, please specify, if possible

25. If there are no specific guidelines available for the quality control of RAP, please check the generally accepted criteria followed by your agency for this purpose (multiple answers may be selected, if applicable).

- ☐ Binder content
- ☐ Fractionizing
- ☐ Debris control
- ☐ Gradation
- ☐ Foreign particle control

Other, please specify, if possible

26. Where do you use asphalt mixes containing RAS (multiple answers may be selected, if applicable)?

- [ ] Interstate
- [ ] City road
- [ ] State highway
- [ ] Other, please specify, if possible

27. Where do you use asphalt mixes containing RAP (multiple answers may be selected, if applicable)?

- [ ] Interstate
- [ ] City road
- [ ] State highway
- [ ] Other, please specify, if possible

28. Where do you use asphalt mixes containing RAS+RAP (multiple answers may be selected, if applicable)?

- [ ] Interstate
- [ ] City road
- [ ] State highway
- [ ] Other, please specify, if possible

29. What method(s) do you use to design asphalt mixes containing RAS (please check)?

- [ ] Superpave
- [ ] Marshall
- [ ] Hveem
- [ ] Other, please specify, if possible

Fatigue Performance of Asphalt Pavements Containing RAS and RAP

30. What method(s) do you use to design asphalt mixes containing RAP (please check)?

- [ ] Superpave
- [ ] Marshall
- [ ] Hveem
- [ ] Other, please specify, if possible

31. What method(s) do you use to design asphalt mixes containing RAS+RAP (please check)?

- [ ] Superpave
- [ ] Marshall
- [ ] Hveem
- [ ] Other, please specify, if possible

32. What laboratory performance tests are conducted on asphalt mixes containing RAS and/or RAP (multiple answers may be selected, if applicable)?

- [ ] Asphalt Pavement Analyzer (APA)
- [ ] Hamburg Wheel Tracking
- [ ] Four-Point Bending Beam Fatigue Test
- [ ] Cyclic Direct Tension Fatigue Test
- [ ] Creep Compliance
- [ ] Retained Tensile Strength Ratio (TSR)
- [ ] Dynamic Modulus
- [ ] Flow Number
- [ ] Flow Time
- [ ] Other, please specify, if possible

3.5 Analysis of the Survey Results

A total of 30 DOTs responded to this survey. A list of the DOTs which participated in the survey is provided in Table 3.1. Graphical analyses are presented in Figure 3.1 through Figure 3.17 and some tabular summaries of the collected responses are presented in Table 3.2 through Table 3.12. Each of these figures and tables include one question and statistical analyses of the answers to that question.

Based on the responses received, it was observed that about 50% of the DOTs use RAS in asphalt mixes (Figure 3.1). These agencies use both tear-off and manufacturer's waste; however, the majority of them prefer using manufacturer's waste (Figure 3.2). Additionally, the methods for asphalt content determination of RAS include NCAT ignition oven and chemical methods; about 40% DOTs use NCAT ignition oven, and about 35% use chemical methods (Figure 3.3). NCAT ignition oven is used by all DOTs for asphalt binder content determination of RAP (Figure 3.6). Also, it was found that indirect tensile strength ratio (TSR), Hamburg wheel tracking (HWT) and in some cases asphalt pavement analyzer (APA) rut test are the only tests conducted on the mixes containing RAS, RAP and both for mix design screening. No specific test is recommended for fatigue evaluation of these mixes at the mix design stage (Table 3.2 through Table 3.4). Only one DOT (New Mexico) uses CDT and FTG tests for the cases where the RAP content exceeds 25% in base and 15% in surface course mixes (Table 3.7 and Table 3.8). Also, it was observed that no specific regulations or specifications are used by DOTs to select RAP sources (Figure 3.4). Furthermore, more than 65% of DOTs bump the PG grade of virgin binder when RAS and/or RAP are used in the mix (Figure 3.7). It was also found that more than 70% of the DOTs control the RAP quality in stockpiles and less than 50% of them control the RAS quality (Figure 3.8). Asphalt binder content and gradation are the most common measures applied for quality control of the RAP and RAS stockpiles (Figure 3.9 and Figure 3.10). It was also found that a majority of mixes containing RAS is used in city roads and sometimes in state highways (Figure 3.11). However, a majority of the mixes containing RAP is used in interstate highways (Figure 12). Most of DOTs use Superpave® method for the design of mixes containing RAS and/or RAP (Figure 3.14 and Figure 3.15).

After reviewing the overall responses it is evident that a large number of responders expressed that there are no widely-accepted fatigue tests recommended for evaluation of mixes containing RAS and RAP. The findings of the current project are expected to provide useful test data on fatigue performance of mixes containing RAS and RAP and will help ODOT to address this concern.

Table 3.1 List of DOTs Participated in the Survey

No.	State	Department of Transportation
1	AL	Alabama Department of Transportation
2	AZ	Arizona Department of Transportation
3	AR	Arkansas State Highway and Transportation Department
4	CA	California Department of Transportation
5	CO	Colorado Department of Transportation
6	DE	Delaware Department of Transportation
7	FL	Florida Department of Transportation
8	ID	Idaho Department of Transportation
9	IL	Illinois Department of Transportation
10	KS	Kansas Department of Transportation
11	KY	Kentucky Transportation Cabinet
12	ME	Maine Department of Transportation
13	MD	Maryland State Highway Administration
14	MI	Michigan Department of Transportation
15	MN	Minnesota Department of Transportation
16	MS	Mississippi Department of Transportation
17	NV	Nevada Department of Transportation
18	NH	New Hampshire Department of Transportation
19	NM	New Mexico Department of Transportation
20	NY	New York State Department of Transportation
21	NC	North Carolina Department od Transportation
22	ND	North Dakota Department od Transportation
23	OH	Ohio Department of Transportation
24	OK	Oklahoma Department of Transportation
25	PA	Pennsylvania Department of Transportation
26	RI	Rhode Island Department of Transportation
27	SC	South Carolina Department of Transportation
28	TX	Texas Department of Transportation
29	UT	Utah Department of Transportation
30	VA	Virginia Department of Transportation

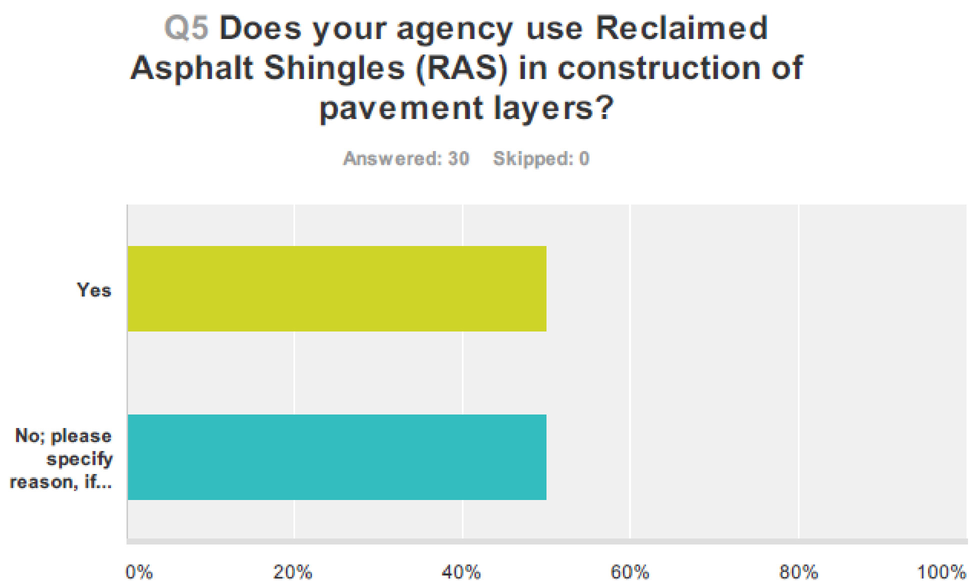

Figure 3.1The DOTs Allowing Use of RAS

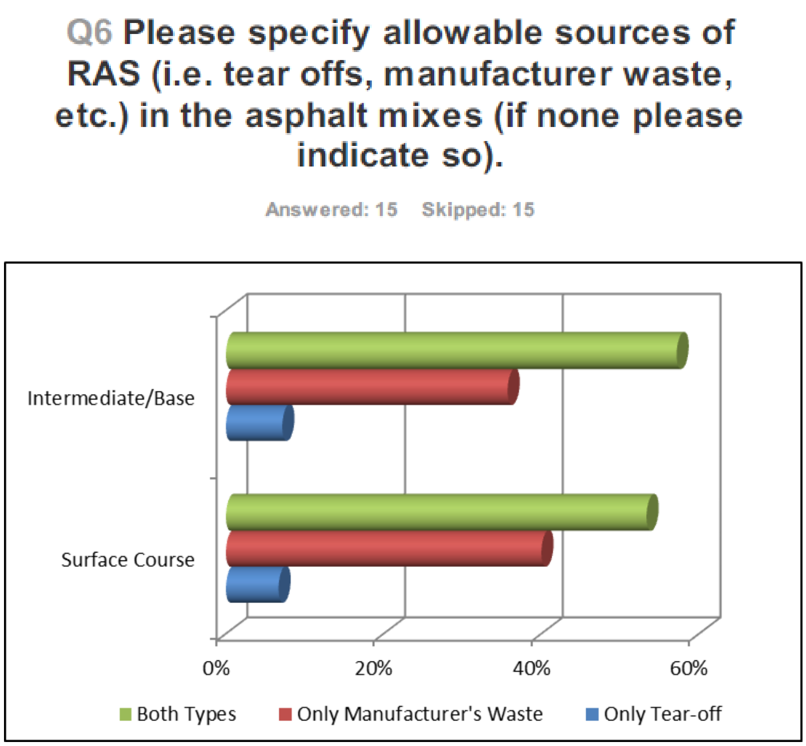

Figure 3.2 Allowable Sources of RAS

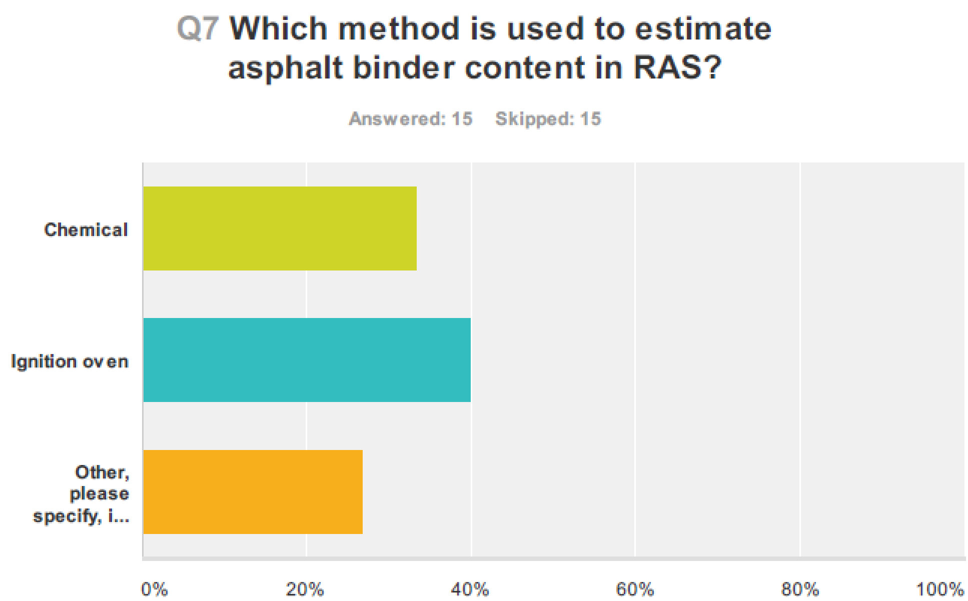

Figure 3.3 Methods Used by DOTs to Estimate Asphalt Binder Content in RAS

Q8 Please specify allowable maximum RAS content (%) used in asphalt pavement layers.

Answered: 14   Skipped: 16

Table 3.2 Allowable Maximum RAS Content in Asphalt Pavement

Participating Agency Name	Allowable RAS in Surface course (%):	Allowable RAS in Intermediate/Base course (%):	RAS content based on
North Carolina Department of Transportation	6%	6%	Weight of Mix. When RAS is used, we also have limits on the % Contributed recycled binder percentage. Therefore, both limits are checked.
Arkansas State Highway and Transportation Department	3%	3%	Total mix weight
Kentucky Transportation Cabinet	13% without binder grade change, 20% with change change in binder	16% without binder grade change, 24% with change in binder	Effective Binder Replacement
Texas Department of Transportation	5%	5%	Total mix weight
Maryland State Highway Administration	5%	5%	Total mix weight
Ohio Department of Transportation	5% low traffic only, 0 high traffic	5%	Total mix weight
Delaware Department of Transportation	5% pure shingles	5% pure shingles	total weight and blended binder assuming 100% blend
Maine Department of Transportation	Up to 5% - only in maintenance overlays - not in spec mixes	N/A	Total mix weight
Illinois Department of Transportation	Depend on Ndesign	Depend on Ndesign	Binder Replacement
Kansas Department of Transportation	max of 5% RAS with up to 10% RAP	x of 5% RAS with up to 10% R	Total mix weight
Pennsylvania Department of Transportation	5%	5%	Total mix weight
Michigan Department of Transportation	17%	17%	RAS materials must not contribute more than 17 percent by weight of the total binder content for any HMA mixture.
Minnesota Department of Transportation	5%	5%	Weight of aggregate and binder replacement
Alabama Department of Transportation	5%	5%	Total aggregate weight.

Q9 Please specify the criteria for each test given below used to set the maximum RAS content (%) limit in surface course. If the test is not used by your agency, please indicate so.

Table 3.3 Criteria Used to Set the Maximum RAS Content (%) Limit in Surface Course

Participating Agency Name	4 point bending beam fatigue test	Cyclic direct tension	Creep compliance	Semi-circular bending beam (SCB)	Texas overlay tester	Indirect tensile strength	Indirect tensile strength ratio (TSR; AASHTO T283)	Other tests and criteria, if any
North Carolina Department of Transportation							85% Surface	APA Rut Testing of all Surface mixes.
Arkansas State Highway and Transportation Department								3% based on research
Kentucky Transportation Cabinet								BBR, DSR
Illinois Department of Transportation								Hamburg Wheel Tracking
Florida Department of Transportation								
Oklahoma Department of Transportation								
Pennsylvania Department of Transportation							0.80 minimum.	
Alabama Department of Transportation							0.8	RAS % is set by Specification

Q10 Please specify the criteria for each test given below used to set the maximum RAS content (%) limit in intermediate/base course. If the test is not used by your agency, please indicate so.

Answered: 14 Skipped: 16

Table 3.4 Criteria Used to Set the Maximum RAS Content (%) Limit in Intermediate/ Base Course

Participating Agency Name	4 point bending beam fatigue test	Cyclic direct tension	Creep compliance	Semi-circular bending beam (SCB)	Texas overlay tester	Indirect tensile strength	Indirect tensile strength ratio (TSR; AASHTO T283)	Other tests and criteria, if any
North Carolina Department of Transportation							85% Surface	APA Rut Testing of all Surface mixes.
Arkansas State Highway and Transportation Department								3% based on research
Kentucky Transportation Cabinet								BBR, DSR
Illinois Department of Transportation								Hamburg Wheel Tracking
Florida Department of Transportation								
Oklahoma Department of Transportation								
Pennsylvania Department of Transportation							0.80 minimum.	
Alabama Department of Transportation							0.8	RAS % is set by Specification

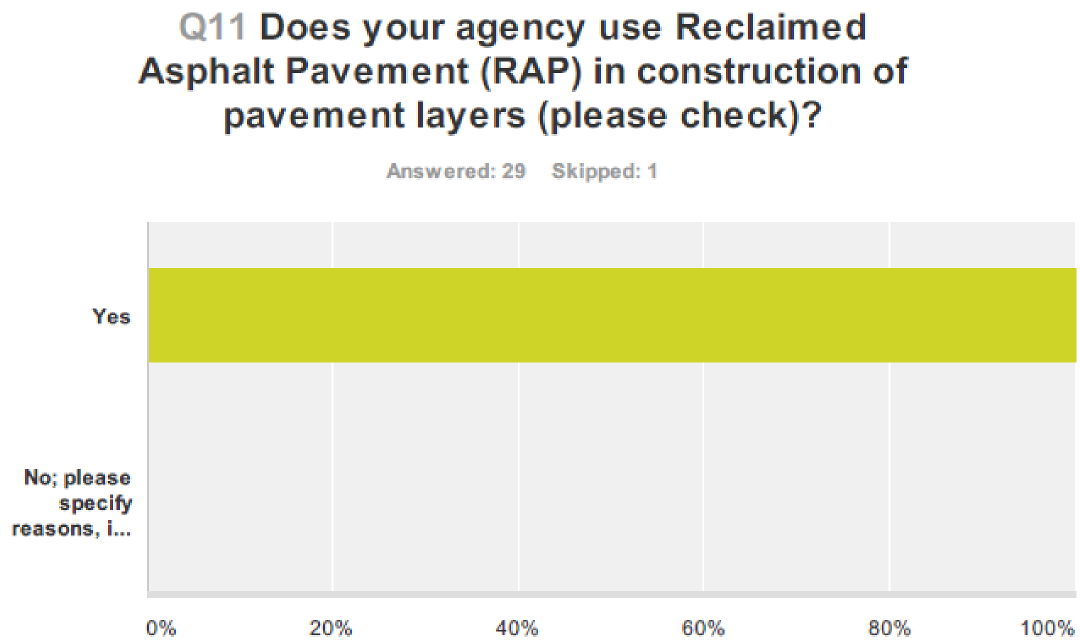

Figure 3.4 Agencies using Reclaimed Asphalt Pavement (RAP) in Construction of Pavement Layers

Q12 Please specify allowable sources of RAP (i.e. Interstate highway, city road, etc.) in asphalt mixes.

Answered: 29 Skipped: 1

Table 3.5 Allowable Sources of RAP

Participating Agency Name	Surface course:	Intermediate/Base course:	History of the RAP is tracked (Yes/No):
Utah Department of Transportation	Yes	Yes	No, We do know if RAP is in a mix and how much
Idaho Transportation Department	Any source allowed if testing or history confirms quality	Any source allowed if testing or history confirms quality	Yes. Contractor is supposed to verify history of RAP used.
Virginia Department of Transportation	All roadways, within allowable specification limits for % use	All roadways, within allowable specification limits for % use	No - the "history" of the RAP is not tracked in any case in Virginia
South Carolina Department of Transportation			
North Carolina Department of Transportation	All roads	All roads	Yes.
Arkansas State Highway and Transportation Department	any source	any source	no
Nevada Department of Transportation	All	All	Yes in the intermediate/base cource
New York State Department of Transportation	There is no restriction other than the final mix product has to meet the friction aggregate requirements.	No restriction.	NO.
Kentucky Transportation Cabinet	All, Not unless they are seeking polish resistant credit for the aggregate.	All, no.	No
Texas Department of Transportation	any state road	any state road	yes, somewhat
North Dakota Department of Transportation	has to be from the project	has to be from the project	N/a
Arizona Department of Transportation	RAP not permitted - Arizona uses open graded friction course as surface.	Any source	No
Colorado Department of Transportation	23% Binder Replacement	23% Binder Replacement	yes
New Mexico Department of Transportation	We use upto 35% of RAP in our surface courses. The sources of RAP include mainly the project millings.	We use upto 50% of RAP in Base Course.	Yes, we are satisfied with the outcome and savings.
New Hampshire Department of Transportation	Processed RAP / Millings	Processed RAP / Millings	On some projects Yes. Normally No.
Maryland State Highway Administration	any	any	no
Rhode Island Department of Transportation	All	All	No
Ohio Department of Transportation	ODOT/ Turnpike only	ODOT/Turnpike only	Yes, by past project history.
Caltrans	25% with limitation on binder and Rice variance	Same	no
Delaware Department of Transportation	any	any	RAP properties are measured on historical data and averages.
Mississippi Department of Transportation	previous state job	previous state job	No
Maine Department of Transportation	Any roadway	Any roadway	Yes - RAP is classified by material proerties
Illinois Department of Transportation	Yes	Yes	Yes
Florida Department of Transportation	<=20% dense friction course, 0% for porous friction courses	Unlimited	yes
Oklahoma Department of Transportation	None	All	Total tonnage is estimated.
Kansas Department of Transportation	millings from project must be used if available, no specific restrictions on permissive RAP	millings from project must be used if available, no specific restrictions on permissive RAP	Yes for each case
Pennsylvania Department of Transportation	All, but RAP added at greater than 15% by total weight must be evaluated for RAP extracted aggregate skid resistance level (SRL) or be a documented SRL source RAP pile	All	No, only if SRL is an issue.
Michigan Department of Transportation	must meet design specifications (most likely trunkline routes)	must meet design specifications (most likely trunkline routes)	no- must meet mix design properties
Minnesota Department of Transportation	ALL RECYLED MIXES	ALL RECYLED MIXES	NO
Alabama Department of Transportation	20	25	RAP history is not really tracked. No chert. Contractor can propose 35% for intermediate layers.

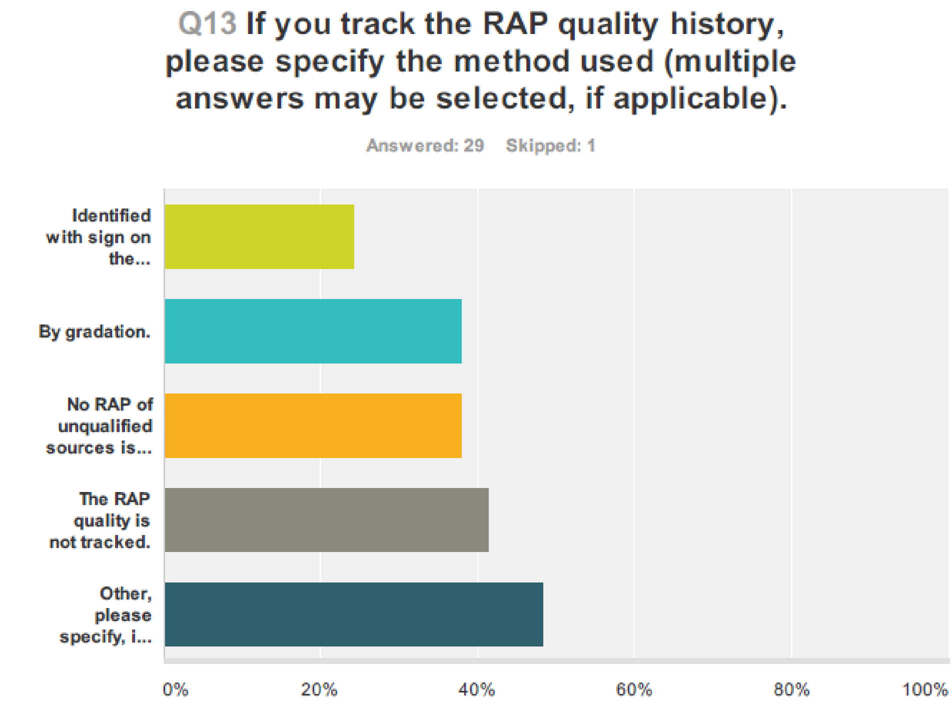

Figure 3.5 Methods Used by DOTs to Track RAP Quality

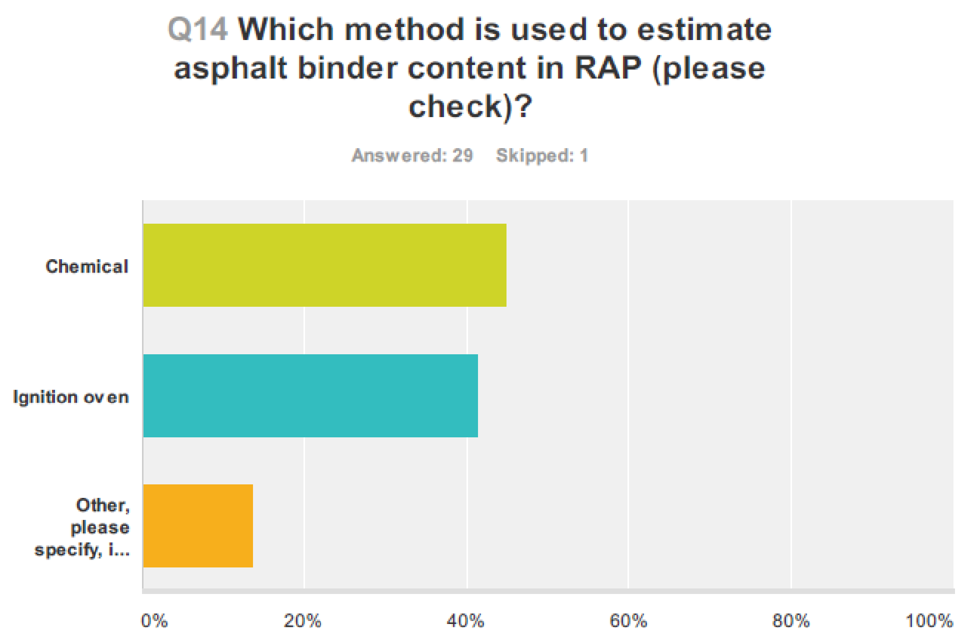

Figure 3.6 Methods Used by DOTs for Asphalt Binder Content Determination in RAP

15. Please specify allowable maximum RAP content (%) used in asphalt pavement layers.

Table 3.6 Allowable RAP Content in Surface and Intermediate/Base Courses

Participating Agency Name	Allowable RAP in Surface course (%):	Allowable RAP in Intermediate/Base course (%):	RAP content based on
Utah Department of Transportation	25 percent max for HMA, None for OGSC and SMA	25 percent max	Total weight
Idaho Transportation Department	Unlimited depending on quality of RAP and the ability to produce an acceptable mixture.	Unlimited depending on quality of RAP and the ability to produce an acceptable mixture.	Measured by perecent of RAP binder replacement.
Virginia Department of Transportation	variable	variable	Total weight
North Carolina Department of Transportation	50% (additional testing performance testing of mix and/or PG grading of extracted binder required above 30%).	50% (additional testing performance testing of mix and/or PG grading of extracted binder required above 30%).	Total weight
Arkansas State Highway and Transportation Department	30	30	Total weight
Nevada Department of Transportation	15% type2/2C. 0% on friction course	15% type 2/2C. 0% type 3	Dry weight of aggregate
New York State Department of Transportation	20	30	Total weight
Kentucky Transportation Cabinet	20% without binder grade change, 30% with binder grade change	25% without binder grade change, 35% with binder grade change	Effective Replacement of Binder
Texas Department of Transportation	20	30 Inter / 40 Base	Total weight
North Dakota Department of Transportation	20	20	
Arizona Department of Transportation	0	20% intermediate course / 25% base course	Based on either total weight of aggregate or total weight of binder, whichever reaches allowable limit first.
Colorado Department of Transportation	23% BInder Replacement	23% Binder Replacement	Amount of effective binder in the RAP
New Mexico Department of Transportation	15% w/o blending charts and >15 upto 35% with Blending Charts	Bottom Mats - 15% w/o changing grade / blending charts,>15 to 25% by dropping a grade or blending charts, >25% upto 35% with blending charts.Upto 50% is allowed in Base Course	Total Weight
New Hampshire Department of Transportation	1% Replacement Binder from the RAP	1% Replacement Binder from the RAP	Asphalt content in the RAP
Maryland State Highway Administration	based on binder properties of RAP/RAS	based on binder properties of RAP/RAS	Total weight
Rhode Island Department of Transportation	0	up to 25%	weight of aggregate
Ohio Department of Transportation	15- heavy traffic mix, 25 lower traffic mix	40 int, 45 base, 55 base for repairs	Total weight
Caltrans	25% by weight, 25% binder replacement	25% by weight, 40% binder replacement	Total weight
Delaware Department of Transportation	have used up to 40%. No maximum is specified. must follow PP53	have used up to 40%. No maximum is specified. must follow PP53	Total weight
Mississippi Department of Transportation	20%	30%	Weight of aggregate
Maine Department of Transportation	Depends on RAP Class: 10, 20 or 30%	Depends on RAP Class: 10, 20 or 30%	Total weight
Illinois Department of Transportation	Depend on Ndesign	Depend on Ndesign	Binder Replacement
Florida Department of Transportation	<=20% Dense friction, 0% porous friction	unlimited for neat binders, if PG 76-22 then <=20%	weight of total aggregate
Oklahoma Department of Transportation	0	25	Total weight
Kansas Department of Transportation	15% permissive, 25% millings from project, or more if blending charts used - millings from project	15% permissive, 25% millings from project, or more if blending charts used - millings from project	Total weight
Pennsylvania Department of Transportation	No maximum specified. Must meet all volumetric criteria.	No maximum specified. Must meet all volumetric criteria.	Total weight
Michigan Department of Transportation	no limit- must meet spec requirements	no limit- must meet spec requirements	binder by weight of the total binder in the mixture.
Minnesota Department of Transportation	NO LIMIT	NO LIMIT	Weight of Aggregate
Alabama Department of Transportation	20	25 or 35 by special request (more if WMA)	Total Aggregate Content

Q16 Please specify the criteria for each test given below used to set the maximum RAP content (%) limit in surface course. If the test is not used by your agency, please indicate so.

Answered: 27 Skipped: 3

Table 3.7 Criteria Used for Setting Maximum Allowable RAP Content in Surface Course

Participating Agency Name	4 point bending beam fatigue test	Cyclic direct tension	Creep compliance	Semi-circular bending beam (SCB)	Texas overlay tester	Indirect tensile strength	Indirect tensile strength ratio (TSR; AASHTO	Other tests and criteria, if any
Idaho Transportation Department							Immersion-Compression (ASTM D 1075)	Asphalt Pavement Analyzer (AASHTO T 340)
Virginia Department of Transportation	unclear at this time	unclear at this time	unclear at this time	unclear at this time	unclear at this	unclear at this time	unclear at this time	unclear at this time
North Carolina Department of Transportation							85% Surface	Above 30% (by weight): Add'l testing is required to characterize the recycled binder.
Nevada Department of Transportation						Yes, but not for max. %	Yes, bit not for max. %	Hveem Stability
Kentucky Transportation Cabinet								BBR, DSR
Colorado Department of Transportation						Used	80% for Design / 75% for field produced	Gradation
New Mexico Department of Transportation	More than 15% RAP, it is used.	More than 15% RAP, it is used.	Not required.	Not required.	Not required.	Yes	TSR	DSR, BBR, PAV, RTFO
New Hampshire Department of Transportation								1% Replacement Binder
Caltrans						110 psi dry, 84 psi wet	No TSR	
Delaware Department of Transportation								PP53
Mississippi Department of Transportation							85% min	not used
Maine Department of Transportation								RAP Class, based on P200, binder content, variability
Illinois Department of Transportation								Hamburg Wheel
Florida Department of Transportation							TSR>=80%	Typical Superpave Design Criteria
Pennsylvania Department of Transportation						See email Q16.	80% minimum.	N/A
Minnesota Department of Transportation								BINDER REPLACEMENT
Alabama Department of Transportation							0.8	Maximum percentage is set by specification

Q17 Please specify the criteria for each test given below used to set the maximum RAP content (%) limit in intermediate/base course. If the test is not used by your agency, please indicate so.

Answered: 28 Skipped: 2

Table 3.8 Criteria Used for Setting Maximum Allowable RAP Content in Intermediate/ Base Course

Participating Agency Name	4 point bending beam fatigue test	Cyclic direct tension	Creep compliance	Semi-circular bending beam (SCB)	Texas overlay tester	Indirect tensile strength	Indirect tensile strength ratio (TSR; AASHTO T283)	Other tests and criteria, if any
Utah Department of Transportation							was used in the past for mix design approval, not fatigue	no mix tests for fatigue, control with binder testing and adequate pavement thickness
Idaho Transportation Department							Immersion-Compression (ASTM D 1075)	Asphalt Pavement Analyzer (AASHTO T 340)
Virginia Department of Transportation	unclear at this time	unclear at this time	unclear at this time	unclear at this time	unclear at this time	unclear at this time	unclear at this time	unclear at this time
North Carolina Department of Transportation							85% Intermediate; 80% Base	Above 30% (by weight): Add'l testing is required to characterize the recycled binder.
Nevada Department of Transportation						Yes, but not for max. %	Yes, but not for max. %	Hveem stability
Kentucky Transportation Cabinet								BBR, DSR
Colorado Department of Transportation							80% for Design / 75% for Field	Gradation
New Mexico Department of Transportation	More than 25% RAP, it is used.	More than 25% RAP, it is used.				Yes	TSR	DSR, BBR,RTFO, PAV
New Hampshire Department of Transportation								1% Replacement Binder
Caltrans						See above # 11	See above # 11	
Delaware Department of Transportation								PP53
Mississippi Department of Transportation							85% min	
Maine Department of Transportation								RAP Class, based on P200, binder content, variability
Illinois Department of Transportation						Yes	Yes	Hamburg Wheel
Florida Department of Transportation							>=80%	Typical Superpave Design Criteria
Oklahoma Department of Transportation							Indirectly	Volumetrics
Pennsylvania Department of Transportation						See email Q17.	80% minimum.	N/A
Minnesota Department of Transportation								BINDER REPLACEMENT
Alabama Department of Transportation						For mixes with Greater than 25% RAP	0.8	Maximum percentage is set by specification

Q18 Please specify allowable maximum binder replacement by RAS and/or RAP binder in surface course.

Answered: 27 Skipped: 3

Table 3.9 Allowable Maximum Binder Replacement By RAS and/or RAP Binder in Surface Course

Participating Agency Name	Maximum from RAS (%)	Maximum from RAP (%)	Combined max. (%):
Utah Department of Transportation	RAS not used	for HMA 25 percent, no RAP used for OGSC or SMA	
Idaho Transportation Department	Unlimited	0	
North Carolina Department of Transportation	50% (although most mixes are <25%)	50% (although most mixes are <25%)	50% (although most mixes are <25%)
Arkansas State Highway and Transportation Department	no maximum specified	no maximum specified	no maximum specified
New York State Department of Transportation		100	100
Kentucky Transportation Cabinet	13% without binder grade change, 20% with binder grade change	20% without binder grade change, 30% with binder grade change	15% without binder grade change, 25% with binder grade change
Texas Department of Transportation			30
Colorado Department of Transportation	30	23	23
New Mexico Department of Transportation		35%	
New Hampshire Department of Transportation	Currently 0.6%	1%	1%
Rhode Island Department of Transportation	No RAP in surface	No RAP in surface	No RAP in surface
Ohio Department of Transportation	We set min virgin binder, not replacement	same	same, 5.0 min virgin for polymer binder, 4.8 other
Caltrans		25%	
Mississippi Department of Transportation		100	
Illinois Department of Transportation	40%	40%	40%
Florida Department of Transportation		20%	
Oklahoma Department of Transportation	0	0	0
Michigan Department of Transportation	17%	no limit	no limit
Minnesota Department of Transportation	SEE COMBINED	SEE COMBINED	30% BUT W/ PG64-34 OR 58-34 BINDERS 20%

Q19 Please specify allowable maximum binder replacement by RAS and/or RAP binder in intermediate/base course.

Answered: 27 Skipped: 3

Table 3.10 Allowable Maximum Binder Replacement by RAS and/or RAP Binder in Intermediate/Base Course

Participating Agency Name	Maximum from RAS (%)	Maximum from RAP (%)	Combined max. (%)
Utah Department of Transportation	RAS not used	25 percent	NA
North Carolina Department of Transportation	50% (although most mixes are <25%)	50% (although most mixes are <25%)	50% (although most mixes are <25%)
New York State Department of Transportation		100	100
Kentucky Transportation Cabinet	16% without binder grade change, 24% with binder grade change	25% without binder grade change, 35% with binder grade change	18% without binder grade change, 30% with binder grade change
Texas Department of Transportation			35 Inter / 40 Base
Arizona Department of Transportation	None	20 or 25% of total binder weight	20 or 25% of total binder weight
Colorado Department of Transportation	30	23	23
New Mexico Department of Transportation	N/A	35%	N?A
New Hampshire Department of Transportation	Currently 0.6%	1%	1%
Rhode Island Department of Transportation	100	100	Meet the design optimum asphalt content
Ohio Department of Transportation	same	same	3.0 min virgin
Caltrans		40%	
Mississippi Department of Transportation		100	
Illinois Department of Transportation	40%	40%	40%
Florida Department of Transportation		20% if using PG 76-22 or higher, otherwise NA	
Oklahoma Department of Transportation	0	25	25
Michigan Department of Transportation	17%	no limit	no limit
Minnesota Department of Transportation	SEE COMBINED	SEE COMBINED	30% BUT W/ PG64-34 OR 58-34 BINDERS 20%

Q20 Please specify the criteria for each test given below used to set the maximum binder replacement limit from RAS and/or RAP in surface course. If the test is not used by your agency, please indicate so.

Answered: 25 Skipped: 5

Table 3.11 Criteria Used for Setting Maximum Allowable RAS Content in Surface Course

Participating Agency Name	4 point bending beam fatigue test	Cyclic direct tension	Creep compliance	Semi-circular bending beam (SCB)	Texas overlay tester	Indirect tensile strength	Indirect tensile strength ratio (TSR; AASHTO T283)	Other tests and criteria, if any
Utah Department of Transportation							same as previously given	same as previously given
Idaho Transportation Department							Immersion-Compression (ASTM D 1075)	Asphalt Pavement Analyzer (AASHTO T 340)
North Carolina Department of Transportation							85% Surface	Above 30% (by weight): Add'l testing is required to characterize the recycled binder.
Kentucky Transportation Cabinet								BBR, DSR
Colorado Department of Transportation						Used	80% for Design / 75% for field	Gradation
Delaware Department of Transportation								pp53
Maine Department of Transportation	Do not use BRDo not use BRV	Do not use BRV	Do not use BRV	Do not use BRV	Do not use BRV	Do not use BRV	Do not use BRV	Do not use BRV
Florida Department of Transportation								Calculation based on binder content of RAP
Pennsylvania Department of Transportation						See email Q20.	80% minimum.	N/A
Alabama Department of Transportation							0.8	

Q21 Please specify the criteria for each test given below used to set the maximum RAS content (%) limit in intermediate/base course. If the test is not used by your agency, please indicate so.

Answered: 25 Skipped: 5

Table 3.12 Criteria Used for Setting Maximum Allowable RAS Content in Intermediate/Base Course

Participating Agency Name	4 point bending beam fatigue test	Cyclic direct tension	Creep compliance	Semi-circular bending beam (SCB)	Texas overlay tester	Indirect tensile strength	Indirect tensile strength ratio (TSR; AASHTO T283)	Other tests and criteria, if any
Utah Department of Transportation							same as previously given	
North Carolina Department of Transportation							85% Intermediate; 80% Base	Above 30% (by weight): Add'l testing is required to characterize the recycled binder.
Kentucky Transportation Cabinet								BBR, DSR
Colorado Department of Transportation						Used	80% for Design / 75% for Field	Gradation
Delaware Department of Transportation								pp53
Maine Department of Transportation	Do not use BRV	Do not use BRV	Do not use BRV	Do not use BRV	Do not use BRV	Do not use BRV	Do not use BRV	Do not use BRV
Florida Department of Transportation								Calculation based on binder content of RAP
Pennsylvania Department of Transportation						See email Q21.	80% minimum	
Alabama Department of Transportation							0.8	

Q22 Please specify if you bump the PG grade of the virgin binder down (or any other adjustments) in case of using RAS and/or RAP?

Answered: 27 Skipped: 3

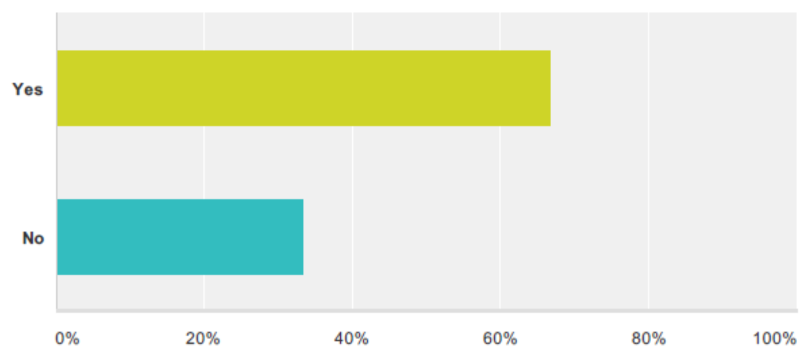

Figure 3.7 Agencies Bumping the PG Grade of the Virgin Binder Down (or any other adjustments) in Case of Using RAS/RAP

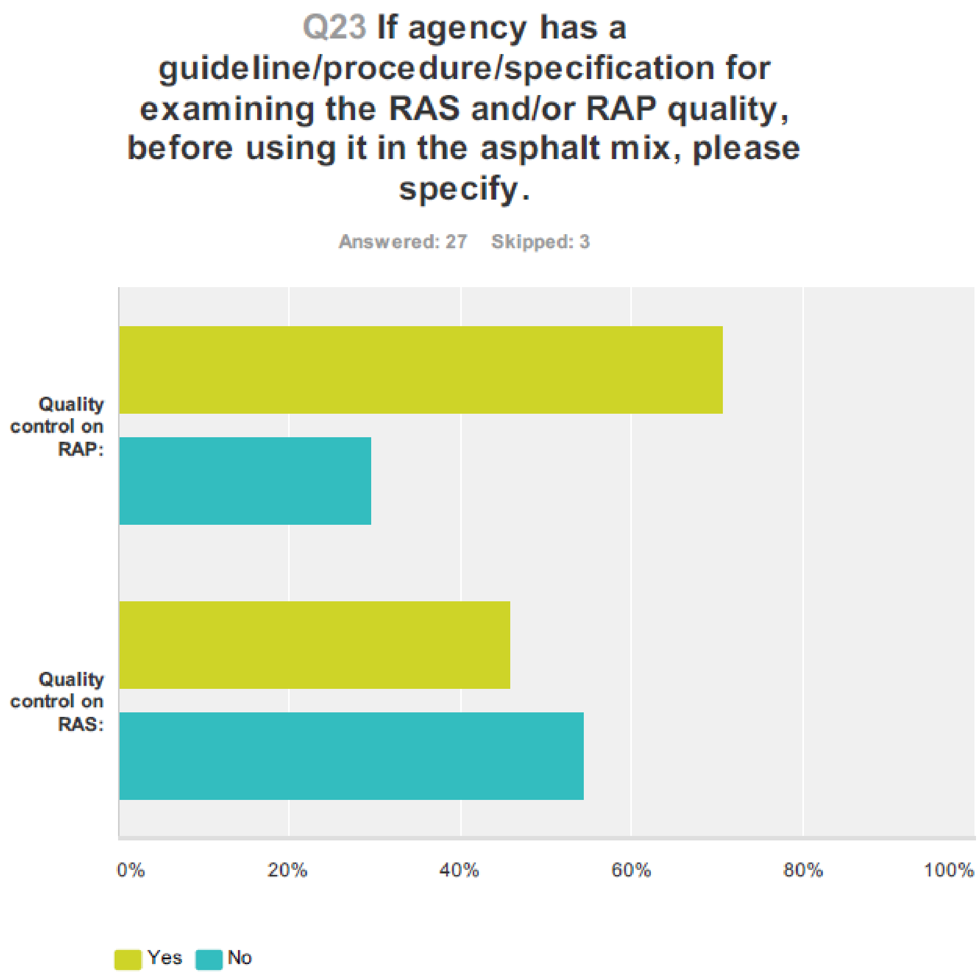

Figure 3.8 Agencies with Guideline/Procedure/Specification for Examining the RAS and/or RAP Quality

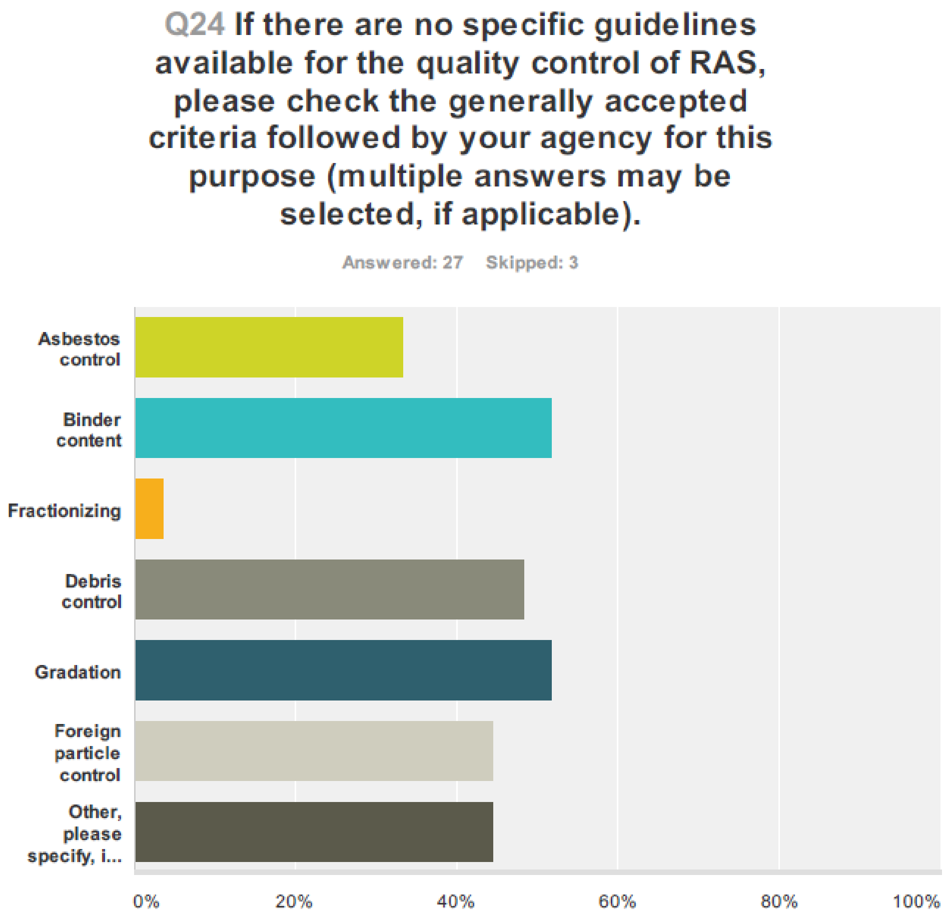

Figure 3.9 Generally Accepted Criteria Followed by Agencies for Quality Control of RAS

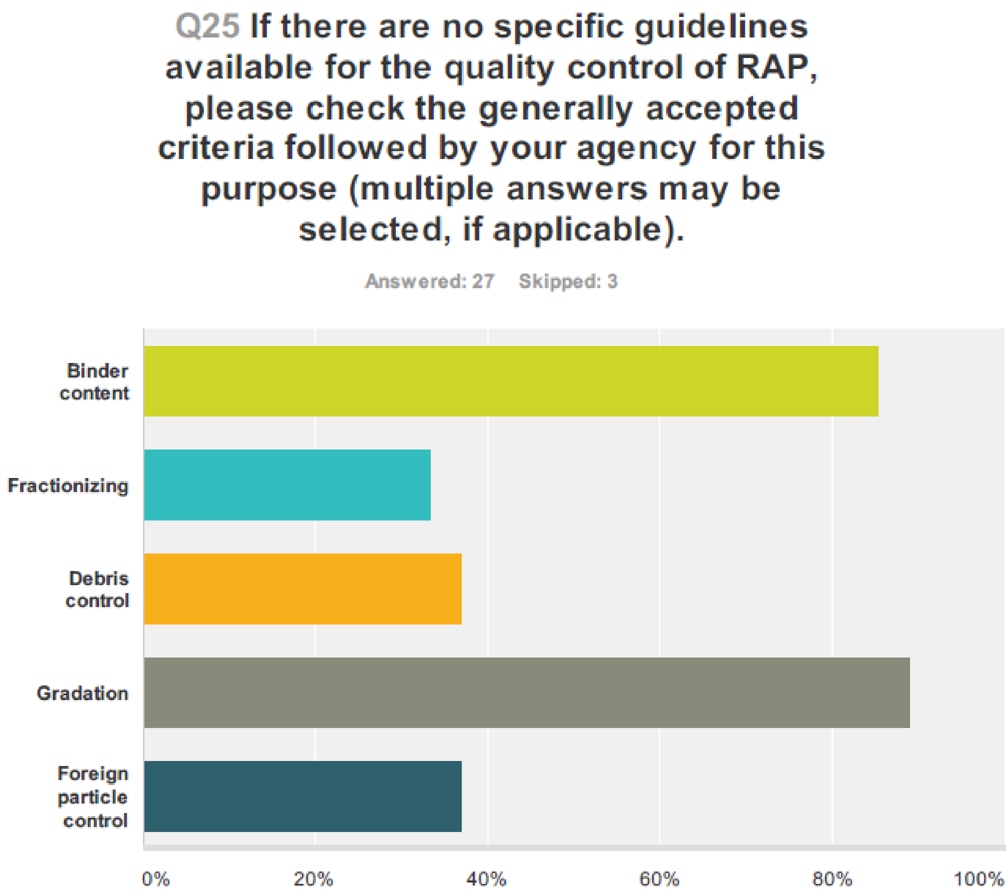

Figure 3.10 Generally Accepted Criteria Followed by Agencies for Quality Control of RAP

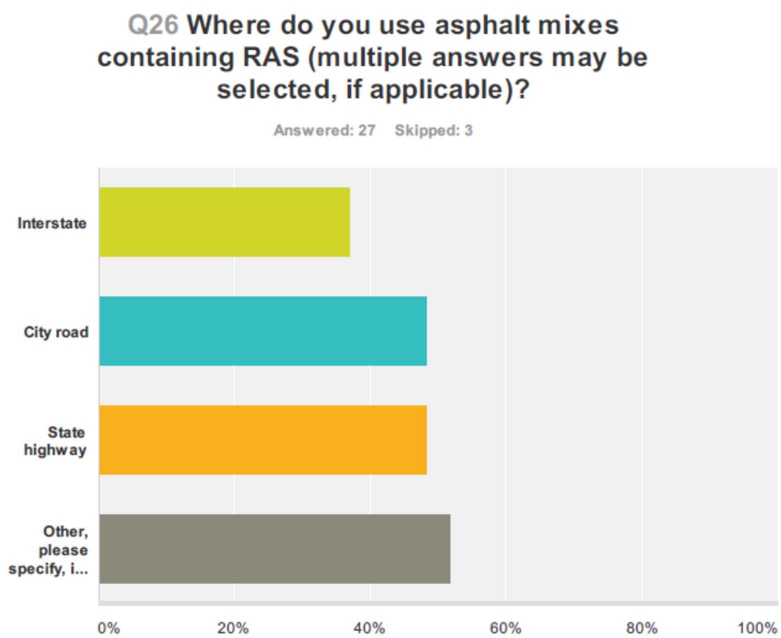

Figure 3.11 Project Types in Which Asphalt Mixes Containing RAS are Used

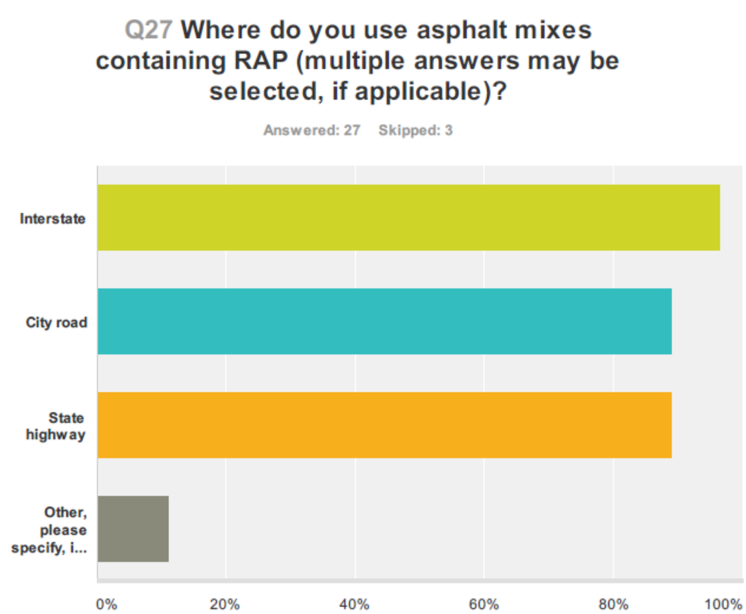

Figure 3.12 Project Types in which Asphalt Mixes Containing RAP are Used

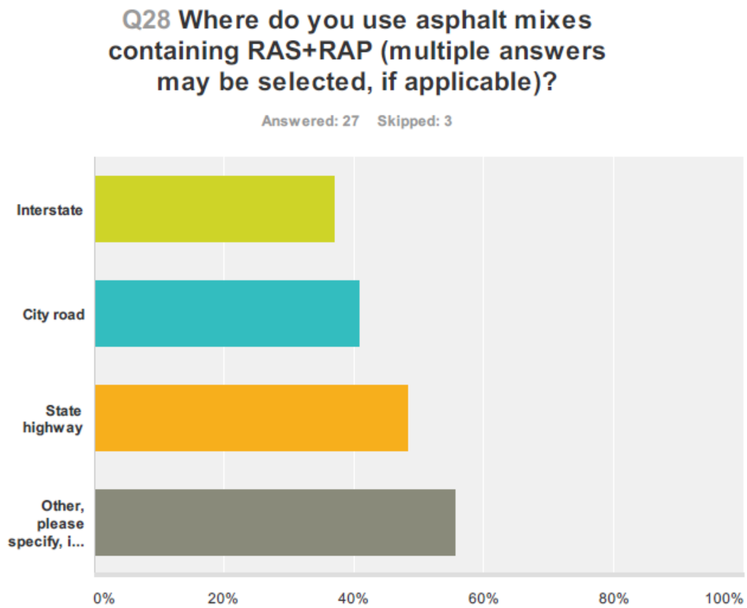

Figure 3.13 Project Types in which Asphalt Mixes Containing RAS+RAP are Used

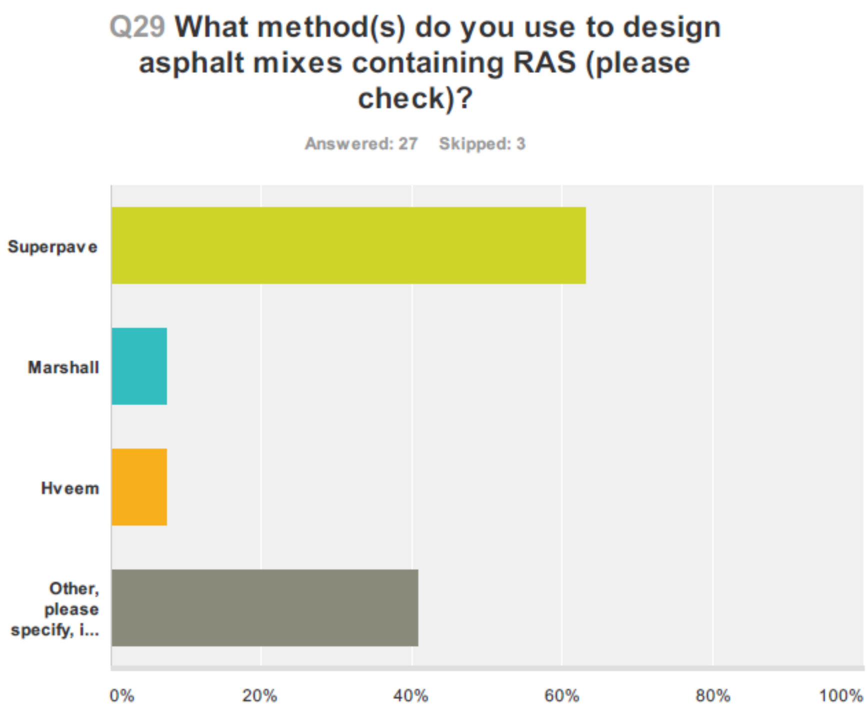

Figure 3.14 Mix Design Methods Used for Designing Mixes Containing RAS

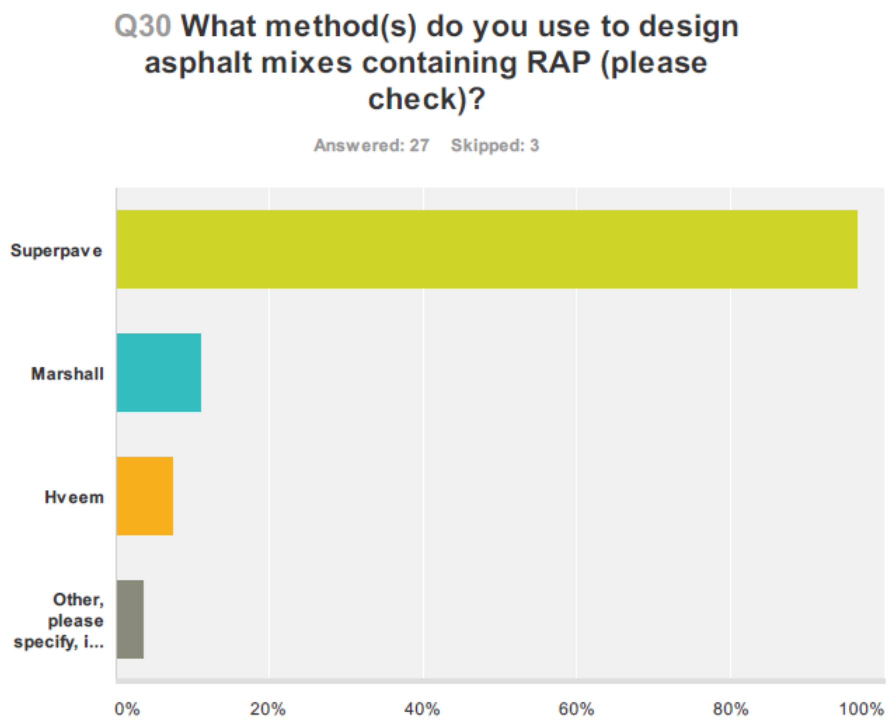

Figure 3.15 Mix Design Methods Used for Designing Mixes Containing RAP

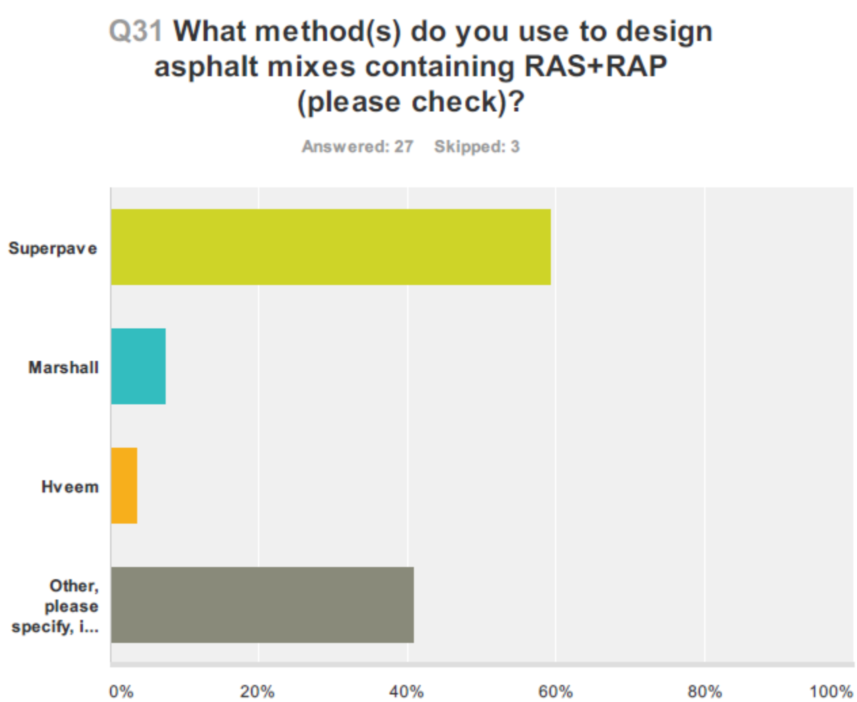

Figure 3.16 Mix Design Methods Used for Designing Mixes Containing RAS+RAP

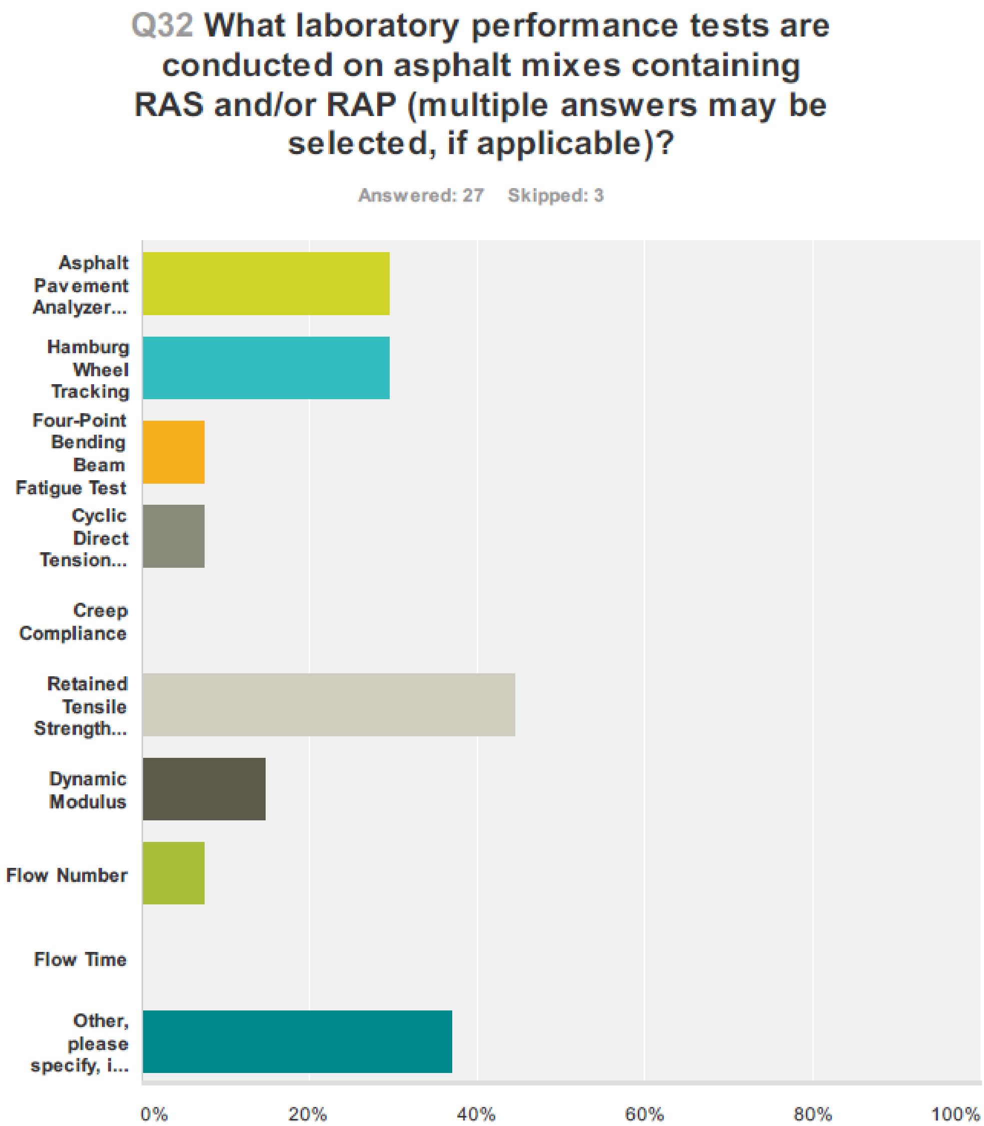

Figure 3.17 Laboratory Performance Tests Used for Evaluation of the Mixes Containing RAP and/or RAS

Chapter

4 COLLECTION OF MATERIALS AND SAMPLES

4.1 General

To achieve the objectives of this study, different types of materials, namely bulk RAS, RAP, aggregates, and asphalt binders were collected from the asphalt mix producers. The identification and selection of materials and field sites was done in close cooperation with the ODOT Capital Programs Division and Materials & Research Division. One type of representative tear-off RAS and one source of RAP were selected in consultation with the Project Panel. Also, bulk aggregate samples were collected from asphalt plant for HMA production in the laboratory. The ODOT Materials & Research Division was actively involved in selection of the stockpiles. An emphasis was given to maintaining the same aggregate type and source (i.e., limestone) throughout the project to minimize the effect of geological properties of aggregates on the fatigue performance of mixes. Also, bulk asphalt binder samples were collected from the asphalt plant. Two different types of asphalt binders were collected: a PG 64-22 OK and a PG 70-28 OK. This chapter discusses the types, amounts and the sources of the collected materials during the project.

4.2 Collection of RAS

Dr. Musharraf Zaman from OU visited the Schwarz Paving Co. on December 12, 2012 to observe the grinding of tear-off shingles. Mr. Ken Hobson, Mr. Reynolds Toney from Oklahoma Department of Transportation, Mr. Larry Patrick from Oklahoma Asphalt Pavement Association, and several other people attended the event. The OU team sampled one bucket of processed RAS and transported to OU Broce Asphalt Laboratory, for further evaluation. After this visit, it was decided to collect and use the same RAS throughout the course of project. Figure 4.1 shows the grinding of RAS, demonstrated by Schwarz Paving Company.

Figure 4.1 Grinding Tear-off RAS by Schwarz Paving Co.

After deciding the source of RAS for this project, 500 kg (1102 lb.) of the ground tear-off RAS was collected from Schwarz Paving Co. asphalt plant facility located in Oklahoma City, OK. The OU team used plastic bags for the collection of RAS and labeled each bag properly with pertinent information. The collected bulk RAS samples were transported to and stored at a storage facility. Due to the large amount of materials required for this research, and because of space limitations in Broce Asphalt Laboratory for storage of materials, the Switzer's Locker Room, located at 3290 S. Classen, Norman, OK, was rented for this purpose. Figure 4.2 shows the collected RAS from Schwarz Paving Co.

Figure 4.2 Collected Tear-off RAS from Schwarz Paving Co. Facility

4.3 Collection of RAP

The OU research team worked closely with Silver Star Construction Co. in Moore, OK to collect the RAP materials. Based on discussions with Mr. Craig Parker, RAP used by Silver Star Construction Co. was milled from interstate and highway projects in Oklahoma. After necessary coordination with the asphalt plant, more than 900 kg of RAP materials was collected from the Silver Star asphalt plant in Moore, OK on January 8, 2013. Plastic bags were used for the collection of RAP and each bag was labeled properly with the material's information. The collected bulk RAP samples were transported to and stored at the storage facility located at the Switzer's Locker Room. Figure 4.3 and Figure 4.4 show the collection of RAP from Silver Star Construction Co.

Figure 4.3 Collection of RAP from Silver Star Asphalt Plant Facility

Figure 4.4 Loading of Collected RAP to Truck

4.4 Collection of Aggregates

Similarly, collection of aggregates from Silver Star Construction Co. in Moore, OK was carried out on February 27, 2013. The collected aggregates were used for mix design and production of asphalt mixes in the laboratory. Plastic bags were used for collection of aggregates and each bag was labeled properly with pertinent information. The collected aggregates consisted of stockpiles, namely 5/8-in. Chips and Screening from Hanson, Martin Marietta Stone Sand from Davis, and Natural Sand from General Materials. The collected bulk aggregate samples were stored at the rented storage facility. Figure 4.5 and Figure 4.6 show the aggregate collection from Silver Star Construction Co.

Figure 4.5 Collection of Aggregates from Silver Star Asphalt Plant Facility


Figure 4.6 Loading of Collected Aggregates to Truck

4.5 Collection of Asphalt Binders

According to the research proposal, effect of RAS and RAP was investigated on asphalt mixes produced with two different types of virgin asphalt binders, namely PG 64-22 OK from Wynnewood, OK and PG 70-28 OK from the Lion Oil Company, Muskogee, OK. Therefore, more than approximately 20 gallons of the aforementioned asphalt binders were collected and transported to OU Broce Asphalt Laboratory for testing. The collected asphalt binders were used for the volumetric mix design and asphalt mix production in the laboratory.

Chapter

5 CHARACTERIZATION OF COLLECTED MATERIALS

5.1 General

The collected materials were characterized to obtain the necessary information for volumetric mix designs. The following tests were conducted for this purpose: determination of asphalt binder contents in collected RAS and RAP, specific gravity of coarse and fine aggregates (AASHTO T 84, T 85) (AASHTO, 2011), and gradation (AASHTO T 27, T 30) (AASHTO, 2011) of the virgin aggregates collected from the stockpiles. In addition, some physical and mechanical properties, namely L.A. Abrasion and soundness were obtained from the ODOT database (ODOT, 2009).

5.2 Asphalt Content Determination of RAS

In close cooperation with Mr. Kenneth Hobson, it was decided that the asphalt content (AC) of RAS be determined using a chemical extraction process, with the help of ODOT Liquid Asphalt Laboratory. For this purpose, 5 kg of collected RAS was sent to ODOT for asphalt content determination. Binder contents of RAS and RAP were also determined using the NCAT ignition oven in Broce Asphalt Laboratory. The AC content obtained from the NCAT ignition oven was compared with the results from the chemical extraction. Also, aggregates were extracted from the bulk RAS and RAP samples by using the NCAT ignition method, and gradation tests were conducted on the extracted aggregates.

The NCAT ignition oven was used in accordance with the OHD L-26 Method – A for extraction of aggregates and AC content determination of RAS. The amount of material for each batch of the extraction process was determined based on the nominal maximum aggregate size (NMAS). The NCAT oven was preheated to 538°C (1000°F), and an automated ignition process was initiated. The samples were burned until the measured weight loss did not exceed 0.1 gram for three consecutive minutes. The time required to achieve a constant weight was approximately 110 minutes. The extracted aggregates from the NCAT ignition oven were then set outside the oven to cool down to room temperature, before handling for further testing. The gradations of the extracted aggregates were analyzed in accordance with AASHTO T 30 (AASHTO, 2011). Two samples were tested for each material and the results were averaged.

Table 5.1 Summary of AC Content Test Results Conducted on RAS using NCAT Ignition Oven

Material	Replicate No.		Average	Standard Deviation
RAS	1	2		
AC (%)	26.9	27.8	27.3	0.655

It should be noted that Ignition Oven Correction factor (IOC) was assumed as zero for the determination of AC content of RAS.

5.3 Preliminary Tests on Aggregates

5.3.1 Gradation

As noted earlier, bulk aggregates were collected from the Silver Star Construction Co. in Moore, OK. Aggregates were collected from four different stockpiles, namely 5/8-in. Chips, Screening, Stone Sand, and Natural Sand. The gradation of the collected aggregates was determined in accordance with AASTO T 27. A summary of the gradation is given in Table 5.2.

Table 5.2 Gradation of Aggregates Collected from Silver Star Stockpiles

Sieve Size		Percent Passing (%)			
		5/8" Chips	Screening	Stone Sand	Sand
AASHTO	(mm)	Hanson 5008	Hanson 5008	Dolese Davis 5005	Gen. Mat.1402
3/4"	19	100	100	100	100
1/2"	12.5	89	100	100	100
3/8"	9.5	70	100	100	100
No. 4	4.75	25	78	93	99
No. 8	2.36	6	50	54	98
No. 16	1.18	4	34	30	97
No. 30	0.6	3	25	19	92
No. 50	0.3	3	19	11	62
No. 100	0.150	3	15	7	14
No. 200	0.075	2.1	11.1	4.3	1.2

5.3.2 Specific Gravity

The specific gravity of aggregates was expressed as a bulk specific gravity. In this study, the bulk specific gravity tests of coarse aggregates and fine aggregates were conducted in accordance with the AASHTO T 85 and T 84 test methods (AASHTO, 2011), respectively. The coarse aggregate portion was defined as the portion retaining on a No. 4 (4.75 mm) sieve.

5.3.2.1 Coarse Aggregate Specific Gravity

The coarse aggregates sampled from each stockpile were reduced to the required size in accordance with the AASHTO T 248 (AASHTO, 2011) test method. The apparatus used to conduct the coarse aggregates' specific gravity is shown in Figure 5.1. For this purpose, an oven-dried aggregate sample was soaked for fifteen to nineteen hours, as per specifications. Then, it was removed from the soaking water and placed in the specified wire mesh basket. The basket and sample were placed in water and agitated to remove any trapped air from the sample. The mass in water was recorded on a test data sheet. The sample was then removed from the water and placed on a damp cloth towel. Then, the aggregates were moved around on the towel until the film of water on the surface of the aggregate particles was no longer visible. Care was taken to make sure the aggregate particles were not too dry. The sample was then weighed and recorded as the saturated-surface-dry (SSD) weight. Finally, the sample was placed in an oven until a constant mass was reached. The constant mass was recorded as the oven-dried weight. The three recorded masses, namely oven-dried test sample in air, SSD sample in air, and saturated sample in water, were used to calculate the bulk specific gravity using Equation 6.1. The results from these tests are presented in Table 5.3.

$$G_{sb} = \frac{A}{B-C} \tag{6.1}$$

where,

Gsb = Bulk specific gravity,

A = Oven dry weight,

B = SSD weight, and

C = Weight in water.

Figure 5.1 Apparatus Used for Determination of Specific Gravity of Coarse Aggregates

Table 5.3 Specific Gravity Values of Collected Aggregates

Source/Producer	**Hanson Aggregate 5008**	**Hanson Aggregate 5008**	**Dolese Davis 5005**	**Gen. Mat. Sand OKC, OK 1402**
Type of Aggregates	5/8" Chips	Screening	Stone Sand	Sand
Coarse Aggregates G_{sb}	2.716	-	-	-
Fine Aggregates G_{sb}	-	2.629	2.618	2.636

5.3.2.2 Specific Gravity of Fine Aggregates

The bulk specific gravity, apparent specific gravity and percent absorption of each fine aggregate sample were determined in accordance with the AASHTO T 84 test method (AASHTO, 2011). Figure 5.2 shows the apparatus used for conducting the fine specific gravity test. For this purpose, the fine aggregates were first sampled and then reduced to the required size in accordance with the AASHTO T 248 test method (AASHTO, 2011). The sample size for this procedure is approximately 2.2 lbs. (1,000 g) of material passing a No. 4 (4.75 mm) sieve. The test sample was dried to a constant weight in an oven set at 230 ± 9°F (110 ± 5°C), and then cooled to room temperature in one to three hours. Following the cooling period, the sample was soaked by maintaining it at a moisture content of at least 6% for a fifteen to nineteen-hour period. After the soaking period, the sample was spread on a flat non-absorbent surface, and dried to the SSD condition. The SSD condition was determined using a specified conical mold and a tamper (Figure 5.2). The material was placed in the cone, tamped twenty five times and then the cone was removed. If the material slumped, the SSD condition was reached, but if it did not slump, it was necessary to dry the sample further.

Figure 5.2 Apparatus Used for Determination of Specific Gravity of Fine Aggregates

After reaching the SSD condition, 1.1 ± 0.0022 lb (500 ± 1 g) of the sample was placed in a pycnometer filled with water. All air voids were removed by hand agitation, and the pycnometer was filled with water to the calibration line, and the mass was recorded. The material was then taken out and placed in an oven at a temperature of 230˚F (110˚C) for drying. Then, the mass of the dry material was determined. The bulk specific gravity was then calculated using Equation 6.2. The results are presented in Table 5.2.

$$G_{sb} = \frac{A}{B - S - C} \tag{6.2}$$

where,

G_{sb} = Bulk specific gravity,

A = Weight of oven dry sample,

B = Weight of flask filled with water to the calibration line,

C = Weight of flask, sample and water to the calibration line, and

S = Weight of SSD sample.

Chapter 6

VOLUMETRIC MIX DESIGN

6.1 General

At the initial stage of the project, a total of ten different mixes (two control mixes and eight recycled mixes), containing varying amounts of RAS and RAP, were planned to be designed and tested (Table 6.1). As a result of a meeting with the ODOT Materials & Research Division (represented by Mr. Kenneth Hobson) on June 1, 2014, different aspects of the project were discussed and the project's test matrix was revised. Based on this revision, mixes M-3 and M-8 were omitted from the test matrix.

Therefore, the volumetric mix designs of eight asphalt mixes were conducted in accordance with the Superpave® requirements (AASHTO M 323) and the procedure (AASHTO R 35) (AASHTO, 2011). The optimum asphalt binder content was determined for each asphalt mix based on the 4% target air voids at 100 gyrations in a Superpave® gyratory compactor (SGC). Also, different types of aggregate structures (gradations) were tried to ensure the mix compliance with the mix design requirements. During the mix design, recommended volumetric properties, namely bulk specific gravity (Gmb) (AASHTO T 166) (AASHTO, 2011), maximum specific gravity (Gmm) (AASHTO T 209) (AASHTO, 2011), voids in mineral aggregate (VMA), voids filled with asphalt (VFA), and dust-to-binder ratio were determined.

Table 6.1 HMA Mixes and Test Matrix

Mix No.	Mix Type/ Binder Type	Reclaimed Material (%)		Four-Point Bending Beam	Cyclic Direct Tension	Dynamic Modulus	Creep Compliance	Indirect Tensile Strength
		RAP	RAS	(AASHTO T 321)	(AASHTO PP xx)	(AASHTO TP 62)	(AASHTO T 322)	(AASHTO T 322)
M-1	S4 - PG 64-22 OK	0	0	x	x	x	x	x
M-2		30	0	x	x	x	x	x
M-3*		15	3	x	x	x	x	x
M-4		5	5	x	x	x	x	x
M-5		0	0	x	x	x	x	x
M-6	S4 - PG 70-28 OK	0	0	x	x	x	x	x
M-7		30	0	x	x	x	x	x
M-8*		15	3	x	x	x	x	x
M-9		5	5	x	x	x	x	x
M-10		0	0	x	x	x	x	x

* Mixes M-3 and M-8 were omitted from the test matrix, after discussing with ODOT Material Division.

6.2 Volumetric Mix Design

The collected aggregates and binders (PG 64-22 OK and PG 70-28 OK) were used in the volumetric mix design. The control mixes did not contain any RAS and/or RAP. A naming convention for asphalt mixes was used in this study in order to facilitate recognizing each asphalt mix easily, according to its gradation, amounts and types of recycled materials and asphalt binder type. The details of this system are shown in Figure 6.1. For example M1-S4-0-0-PG 64-22 OK is a short name used for Mix-1 (as noted in Table 6.1) having a S4 gradation with a nominal maximum aggregate size (NMAS) of 12.5 mm (0.5 in.), and containing 0% RAS and 0% RAP (control mix), and a PG 64-22 OK binder. However, for simplicity throughout this report only mix number will be used to identify a mix (e.g., M-1, M-2 etc.)

M1 -	**S4 -**	**0 -**	**0 -**	**PG 64-22**
Mix Number	Gradation	Percent RAS	Percent RAP	Asphalt Binder Performance Grade

Figure 6.1 Naming System Used for Different Mixes

As discussed before, a total of eight mix designs, namely M1, M2, M4, M5, M6, M7, M9 and M10, were developed in this study. The mix design procedure consisted of mixing different percentages of virgin aggregates, virgin binder, RAS and/or RAP to satisfy the combined mix gradation requirements. The gradations of the designed aggregate blends were well-within the minimum and maximum limits of the ODOT requirements for S4 mixes. The prepared asphalt mixes were then conditioned and used to prepare cylindrical samples in a SGC in accordance with the AASHTO T 312 (AASHTO, 2011) test method. The final mix designs were those which satisfied the Superpave® volumetric mix design requirements. The mixes were designed for an equivalent single axle load (ESAL) level of 3M – 10M. Details of the aggregate source, gradation, and asphalt binder contents of M1, M2, M4, M5, M6, M7, M9 and M10 mixes are presented in Table 6.2 - Table 6.9, respectively.

Table 6.2 Mix Design Details of M1-S4-0-0-PG 64-22 OK

No.	Aggregate	Producer/Supplier	% Used
1	5/8" Chips	Hanson 5008	35
2	Screening	Hanson 5008	27
3	Stone Sand	Dolese Davis 5005	23
4	Sand	Gen. Mat.1402	15

Sieve Size		Percent Passing (%)				Comb.
AASHTO	(mm)	No. 1	No. 2	No. 3	No. 4	Agg.
3/4"	19	100	100	100	100	100
1/2"	12.5	89	100	100	100	96
3/8"	9.5	70	100	100	100	90
No. 4	4.75	25	78	93	99	66
No. 8	2.36	6	50	54	98	43
No. 16	1.18	4	34	30	97	32
No. 30	0.6	3	25	19	92	26
No. 50	0.3	3	19	11	62	18
No. 100	0.150	3	15	7	14	9
No. 200	0.075	2.1	11.1	4.3	1.2	4.9
AC	Gary Williams PG64-22 OK					4.7

Table 6.3 Mix Design Details of M2-S4-0-30-PG 64-22 OK

No.	Aggregate	Producer/Supplier	% Used
1	5/8" Chips	Hanson 5008	28
2	Screening	Hanson 5008	10
3	Stone Sand	Dolese Davis 5005	25
4	Sand	Gen. Mat.1402	7
5	RAP	Fine RAP	30

Sieve Size		Percent Passing (%)					Comb.
AASHTO	(mm)	No. 1	No. 2	No. 3	No. 4	No. 5	Agg.
3/4"	19	100	100	100	100	100	100
1/2"	12.5	89	100	100	100	98	96
3/8"	9.5	70	100	100	100	95	90
No. 4	4.75	25	78	93	99	79	69
No. 8	2.36	6	50	54	98	60	45
No. 16	1.18	4	34	30	97	49	34
No. 30	0.6	3	25	19	92	37	26
No. 50	0.3	3	19	11	62	29	18
No. 100	0.150	3	15	7	14	16	10
No. 200	0.075	2.1	11.1	4.3	1.2	9.6	5.7
AC (%)						5.0	4.3
AC	Gary Williams PG 64-22 OK						2.8

Table 6.4 Mix Design Details of M4-S4-5-5-PG 64-22 OK

No.	Aggregate	Producer/Supplier	% Used
1	5/8" Chips	Hanson 5008	35
2	Screening	Hanson 5008	16
3	Stone Sand	Dolese Davis 5005	28
4	Sand	Gen. Mat.1402	11
5	RAP	Fine RAP	5
6	RAS	Fine RAS	5

Sieve Size		Percent Passing (%)						Comb. Agg.
AASHTO	(mm)	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	
3/4"	19	100	100	100	100	100	100	100
1/2"	12.5	89	100	100	100	98	100	96
3/8"	9.5	70	100	100	100	95	100	89
No. 4	4.75	25	78	93	99	79	100	67
No. 8	2.36	6	50	54	98	60	99	44
No. 16	1.18	4	34	30	97	49	81	32
No. 30	0.6	3	25	19	92	37	58	25
No. 50	0.3	3	19	11	62	29	52	18
No. 100	0.150	3	15	7	14	16	46	10
No. 200	0.075	2.1	11.1	4.3	1.2	9.6	37.8	6.2
AC (%)						5.0	17.9	4.9
AC	Gary Williams PG 64-22 OK							3.6

Table 6.5 Mix Design Details of M5-S4-6-0-PG 64-22 OK

No.	Aggregate	Producer/Supplier	% Used
1	5/8" Chips	Hanson 5008	35
2	Screening	Hanson 5008	20
3	Stone Sand	Dolese Davis 5005	28
4	Sand	Gen. Mat.1402	11
6	RAS	Fine RAS	6

Sieve Size		Percent Passing (%)					Comb. Agg.
AASHTO	(mm)	No. 1	No. 2	No. 3	No. 4	No. 6	
3/4"	19	100	100	100	100	100	100
1/2"	12.5	89	100	100	100	100	96
3/8"	9.5	70	100	100	100	100	90
No. 4	4.75	25	78	93	99	100	67
No. 8	2.36	6	50	54	98	99	44
No. 16	1.18	4	34	30	97	81	32
No. 30	0.6	3	25	19	92	58	25
No. 50	0.3	3	19	11	62	52	18
No. 100	0.150	3	15	7	14	46	10
No. 200	0.075	2.1	11.1	4.3	1.2	37.8	6.6
AC (%)						17.9	5.1
AC	Gary Williams PG 64-22 OK						3.9

Table 6.6 Mix Design Details of M6-S4-0-0-PG 70-28 OK

No.	Aggregate	Producer/Supplier	% Used
1	5/8" Chips	Hanson 5008	35
2	Screening	Hanson 5008	27
3	Stone Sand	Dolese Davis 5005	23
4	Sand	Gen. Mat.1402	15

Sieve Size		Percent Passing (%)				Comb. Agg.
AASHTO	(mm)	No. 1	No. 2	No. 3	No. 4	
3/4"	19	100	100	100	100	100
1/2"	12.5	89	100	100	100	96
3/8"	9.5	70	100	100	100	90
No. 4	4.75	25	78	93	99	66
No. 8	2.36	6	50	54	98	43
No. 16	1.18	4	34	30	97	32
No. 30	0.6	3	25	19	92	26
No. 50	0.3	3	19	11	62	18
No. 100	0.150	3	15	7	14	9
No. 200	0.075	2.1	11.1	4.3	1.2	4.9
AC PG 70-28						5.1

Table 6.7 Mix Design Details of M7-S4-0-30-PG 70-28 OK

No.	Aggregate	Producer/Supplier	% Used
1	5/8" Chips	Hanson 5008	28
2	Screening	Hanson 5008	10
3	Stone Sand	Dolese Davis 5005	25
4	Sand	Gen. Mat.1402	7
5	RAP	Fine RAP	30

Sieve Size		Percent Passing (%)					Comb. Agg.
AASHTO	(mm)	No. 1	No. 2	No. 3	No. 4	No. 5	
3/4"	19	100	100	100	100	100	100
1/2"	12.5	89	100	100	100	98	96
3/8"	9.5	70	100	100	100	95	90
No. 4	4.75	25	78	93	99	79	69
No. 8	2.36	6	50	54	98	60	45
No. 16	1.18	4	34	30	97	49	34
No. 30	0.6	3	25	19	92	37	26
No. 50	0.3	3	19	11	62	29	18
No. 100	0.150	3	15	7	14	16	10
No. 200	0.075	2.1	11.1	4.3	1.2	9.6	5.7
AC (%)						5.0	4.4
AC PG 70-28 OK							2.9

Table 6.8 Mix Design Details of M7-S4-5-5-PG 70-28 OK

No.	Aggregate	Producer/Supplier	% Used
1	5/8" Chips	Hanson 5008	35
2	Screening	Hanson 5008	16
3	Stone Sand	Dolese Davis 5005	28
4	Sand	Gen. Mat.1402	11
5	RAP	Fine RAP	5
6	RAS	Fine RAS	5

Sieve Size		Percent Passing (%)						Comb. Agg.
AASHTO	(mm)	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	
3/4"	19	100	100	100	100	100	100	100
1/2"	12.5	89	100	100	100	98	100	96
3/8"	9.5	70	100	100	100	95	100	89
No. 4	4.75	25	78	93	99	79	100	67
No. 8	2.36	6	50	54	98	60	99	44
No. 16	1.18	4	34	30	97	49	81	32
No. 30	0.6	3	25	19	92	37	58	25
No. 50	0.3	3	19	11	62	29	52	18
No. 100	0.150	3	15	7	14	16	46	10
No. 200	0.075	2.1	11.1	4.3	1.2	9.6	37.8	6.2
AC (%)						5.0	17.9	5.1
AC PG 70-28 OK								3.8

Table 6.9 Mix Design Details of M7-S4-6-0-PG 70-28 OK

No.	Aggregate	Producer/Supplier	% Used
1	5/8" Chips	Hanson 5008	35
2	Screening	Hanson 5008	20
3	Stone Sand	Dolese Davis 5005	28
4	Sand	Gen. Mat.1402	11
6	RAS	Fine RAS	6

Sieve Size		Percent Passing (%)					Comb. Agg.
AASHTO	(mm)	No. 1	No. 2	No. 3	No. 4	No. 6	
3/4"	19	100	100	100	100	100	100
1/2"	12.5	89	100	100	100	100	96
3/8"	9.5	70	100	100	100	100	90
No. 4	4.75	25	78	93	99	100	67
No. 8	2.36	6	50	54	98	99	44
No. 16	1.18	4	34	30	97	81	32
No. 30	0.6	3	25	19	92	58	25
No. 50	0.3	3	19	11	62	52	18
No. 100	0.150	3	15	7	14	46	10
No. 200	0.075	2.1	11.1	4.3	1.2	37.8	6.6
AC (%)						17.9	5.3
AC PG 70-28 OK							4.1

Chapter 7

PREPARATION OF SAMPLES

7.1 General

Two different types of samples (i.e., cylindrical and beam) were prepared to conduct the laboratory testing for this project. Cylindrical samples of different geometries and dimensions were required to conduct cyclic direct tension (CDT), dynamic modulus (DM), indirect tensile strength (IDT), and creep compliance (CC) tests, and beam samples were needed to conduct four-point beam fatigue (FTG) tests. This chapter provides an overview of the sample preparation methods.

7.2 Preparation of Cylindrical Samples

Cylindrical samples were required for conducting CDT, DM, IDT and CC tests. The required sample dimensions for these tests are given in Table 7.1. The cylindrical samples were compacted using a SGC. A 150-mm-diameter (6-in) mold was used for this purpose. In order to prepare 100-mm-diameter (4-in) specimens, the SGC-compacted samples were cored and sawed to required dimensions using a coring and a heavy duty saw, respectively. The samples were compacted to target air voids of 7.0 ± 0.5%. The air voids of the compacted cylindrical samples were determined in accordance with AASHTO T 166 (AASHTO, 2011). Figure 7.1 and Figure 7.2 show the coring and the sawing machine, respectively. Figure 7.3, shows a DM test specimen cored and cut from a SGC-compacted sample.

Table 7.1 Dimensions of the Cylindrical Samples

Test	Standard	Diameter (mm)	Height (mm)
Cyclic Direct Tension	AASHTO TP xx	100	130
Dynamic Modulus	AASHTO TP 62	100	150
Indirect Tensile Strength	ASTM D6931	150	75
Creep Compliance	AASHTO T 322	150	50

Figure 7.1 Coring Machine used for Coring 100-mm-Diameter Samples

Figure 7.2 Saw Machine in Broce Asphalt Laboratory

Figure 7.3 The DM Sample Cored and Cut from a 150-mm-Diameter SGC Sample

7.3 Preparation of Beam Samples

Loose asphalt mixes were used to compact slab samples using a linear kneading compactor (Figure 7.4). Slabs with dimensions of 406 mm (L) by 152 mm (W) by 76 mm (H) (16 in. x 6 in. x 3 in.) were compacted for this purpose. The weights of the asphalt mixes used for compaction of slab samples were adjusted to attain air voids of 7.0 ± 0.5%. Two beam specimens with dimensions of 380 mm (L) by 63 mm (W) by 50 mm (H) (15 in. x 2.5 in. x 2 in.) were saw-cut from each compacted slab, using a heavy duty saw machine available in the OU Sarkeys Energy Center. The cut beam samples were measured for dimensional accuracy. The air voids of beam samples were determined in accordance with the AASHTO T166 test method (AASHTO, 2011). Finally, a metallic LVDT stud was attached to the specimen. An asphalt beam sample ready for the four-point beam fatigue testing is shown in Figure 7.5.

Figure 7.4 Linear Kneading Compactor in Broce Asphalt Laboratory

Figure 7.5 Asphalt Beam Specimen with Installed Metallic LVDT Stud

Chapter 8 LABORATORY PERFORMANCE TESTS

8.1 General

As mentioned earlier, the primary performance concerns over the mixes containing RAS and RAP are fatigue and low-temperature cracking. To evaluate the effects of using RAS and RAP in asphalt mixes, different performance tests, namely FTG, CDT, DM, CC and IDT were conducted on all eight mixes (M1, M2, M4, M5, M6, M7, M9 and M10). The DM tests were conducted in order to provide necessary mechanistic inputs required for analyzing the CDT test results using the simplified viscoelastic continuum damage (S-VECD) approach.

The tests proposed in this study were conducted as per the AASHTO and pertinent ODOT standards. Therefore, a specific evaluation of climate data was not required. The test temperature for fatigue tests (four-point beam and cyclic direct tension) was set at 20°C (68°F) (Hobson, 2012). Furthermore, standard test temperatures ranging from 4 to 54°C (39.2 to 129.2°F) were used for dynamic modulus testing (AASHTO, 2011). Similarly, the test temperatures for indirect tensile test and creep compliance tests were maintained according to AASHTO T 322 (AASHTO, 2011). This chapter discusses the methodology used for conducting the above mentioned tests.

8.2 Project Kick-off Meeting Discussion

Many important items of the project tasks, including the testing temperatures for cyclic direct tension (CDT), indirect tensile strength (IDT) and four-point beam fatigue test (FTG) were discussed in the project kick-off meeting. Dr. Musharraf Zaman, Prof. David Boeck, Dr. Dharamveer Singh, and Dr. Rouzbeh Ghabchi from OU and Mr. Bryan Hurst, Mr. Kenneth Hobson, Mr. Gary Hook and Ms. Terri Holly from ODOT, participated in a meeting on October 29, 2012 at 11:00 A.M., in ODOT’s main office, Oklahoma City, OK. Based on the outcome of this meeting, it was decided that CDT, ITS and FTG tests on asphalt mixes be conducted at 20°C (68°F).

8.3 Four-Point Beam Fatigue Test (Flexural Fatigue)

The fatigue life of an asphalt mix is its ability to withstand repeated traffic loading without experiencing premature failure. Fatigue cracking as a result of repetitive stress and strain caused by traffic and environmental conditions is considered a primary distress mechanism in asphalt pavements. Therefore, fatigue performance of asphalt pavements should be considered as an important design parameter. Although existing design standards aim to ensure the quality of the HMA, the fatigue performance of asphalt mixes is frequently not taken into account during the mix design stage. The current mix design procedure used in Oklahoma is primarily intended to eliminate mixes that might be susceptible to rutting and moisture-induced damage problems. But, the fatigue performance is not directly evaluated in the mix design process. Evaluation of the fatigue life of a mix becomes more critical when asphalt mixes contain RAS and/or RAP. This is due to the incorporation of highly-aged asphalt binders from RAS and RAP sources in the mix.

The flexural fatigue resistance or number of cycles to flexural fatigue failure was determined by testing beam specimens, prepared at target air voids of 7.0 ± 0.5%, using a four-point beam fatigue apparatus. The fatigue tests were conducted using a newly-purchased universal asphalt material testing device from GCTS (ATM-100). The AASHTO T 321 (AASHTO, 2011) standard test method was applied for this purpose. This test was conducted in a strain-controlled mode at a tensile strain level of 400 micro-strain. In these tests, the test temperature was kept at 20°C (68°F) and the loading frequency was kept at 10 Hz. A 5-kN (1100-lbf.) load cell was used to measure the cyclic loads applied to the beam specimen. A linear variable differential transformer (LVDT) with a maximum stroke length of ±1 mm (0.04 in.) and mounted on a target glued at the center of the beam was used to measure the vertical deformation of the beam. The initial stiffness of the beam was determined at the 50^{th} load cycle. The total number of load repetitions leading to a 50% reduction in the initial stiffness was considered as the criterion for termination of a test, and was reported as the fatigue life (AASHTO, 2011). Figure 8.1 shows the beam specimen and the fatigue fixture before starting the test.

Figure 8.1 Beam Specimen in Fatigue Fixture Inside Temperature Chamber

8.4 Cyclic Direct Tension Fatigue Test (Axial Fatigue)

Preparation of the required procedures and test setup for conducting cyclic direct tension (CDT) tests was pursued as an important part of this study. Since CDT is a relatively new test, the research team had to spend a significant amount of time on training, developing the test procedure, fabricating, purchasing the equipment and fixture, and conducting the CDT tests on dummy specimens. The methodology used for this purpose is summarized in this section.

8.4.1 CDT Test Samples

In order to perform CDT tests on asphalt mixes, cylindrical specimens of 100-mm (4-in.) diameter and 130-mm (5.1-in.) height, in accordance with AASHTO TP xx-xx (AASHTO, 2013), were prepared. Test samples were compacted in the laboratory at the target air voids of 7.0±0.5%.

8.4.2 LVDT Stud Gluing Jig

Attaching the LVDT studs to the CDT sample is an important step of the sample preparation procedure for CDT tests. The LVDT studs should have the right distance (70 mm ± 1 mm) and glued securely to the specimen, to ensure stability and adhesion to specimen during testing. For this purpose, two types of LVDT stud gluing jigs were used: one obtained from North Carolina State University (NCSU) (Figure 8.2), and another one purchased from IPC (Figure 8.3).

Figure 8.2 LVDT Stud Gluing Jig Received from NCSU

Figure 8.3 LVDT Stud Gluing Jig Received from IPC

8.4.3 Sample Gluing Jig

Preparing a quality sample for CDT test is immensely important for obtaining meaningful test results. Since in a CDT test, the axial tension is directly applied to the specimen on its two ends, any type of eccentricity in load application may result in a premature failure. This type of failure may occur at the gluing surface or beyond the gauge length, which is not desirable. Therefore, sample gluing jigs were used for this purpose: one fabricated in OU laboratory (Figure 8.4), one received from NCSU (Figure 8.5), and another one accompanied by the newly-purchased IPC asphalt mix performance tester (Figure 8.6). The gluing jig setup ensures the vertical alignment of the CDT test specimen and concentricity of the end plates glued to the sample.

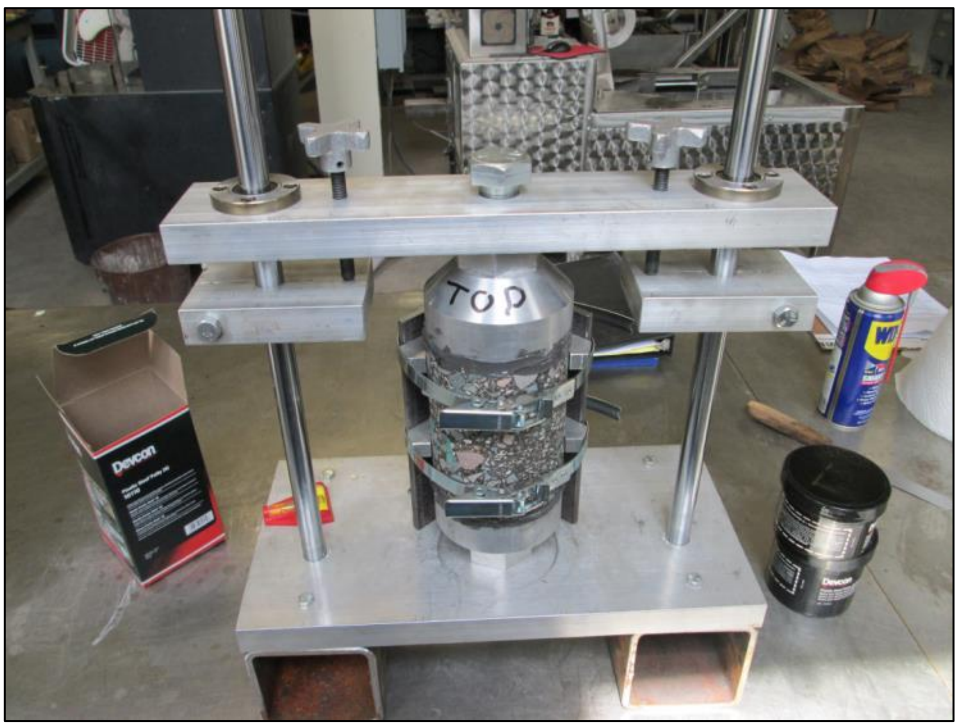

Figure 8.4 CDT Sample, Fabricated End Plates and Fabricated Sample Gluing Jig

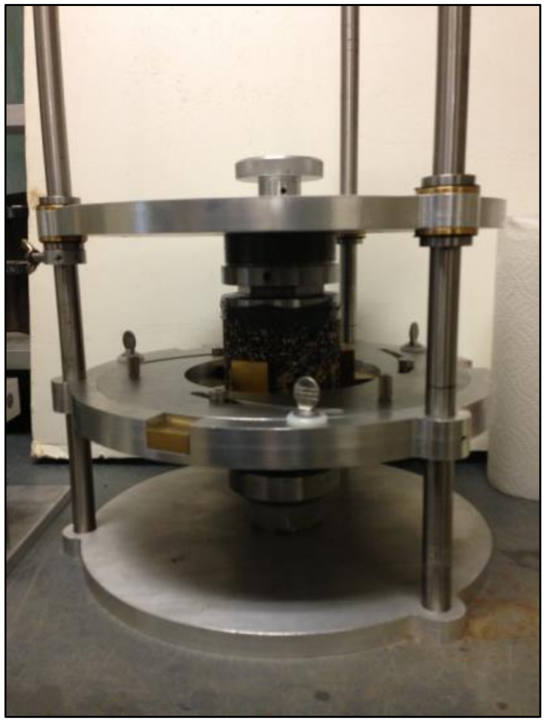

Figure 8.5 CDT Sample, End Plates and Sample Gluing Jig Received from NCSU

Figure 8.6 CDT Sample, End Plates and Sample Gluing Jig Received from IPC

In order to glue the end plates to the test specimen, epoxy glue was mixed using the recommended glue and hardener proportions (Figure 8.7). For this purpose, about 100 grams of adhesive (Devcon 10110 steel putty) was weighted and applied to the end plates (Figure 8.8). The gluing process required approximately 10 to 20 minutes. To apply the epoxy glue to sample and end plates, it was divided into four quarters and was spread evenly between the end plates and the specimen end faces (i.e., ¼ to the top plate, ¼ to the bottom plate, ¼ to the bottom face and ¼ to the top face). Before application of the glue, the end plates were thoroughly cleaned by first heavily brushing the face of each platen using a hand wire brush. Then, the platens' surfaces were cleaned of any dust and rust by applying WD40 and cleaning and drying using a paper towel. Then the plates were attached to the top and bottom parts of the sample gluing jig and glued to the specimen using the mechanisms in the jig, designed for this purpose. The final glue thickness, as recommended, was kept to approximately 1 mm (0.04 in.). The excess glue was wiped or scraped away before the glue stiffened. Then, the adhesive was allowed to reach its initial set before moving the specimen from the jig. The sample was kept in the jig for approximately 24 hours for curing, before conducting the CDT test. Figure 8.9 shows the materials and setups used for gluing the end plates to CDT sample.

Figure 8.7 Preparing the Epoxy Glue used for Attaching the Sample End Plates

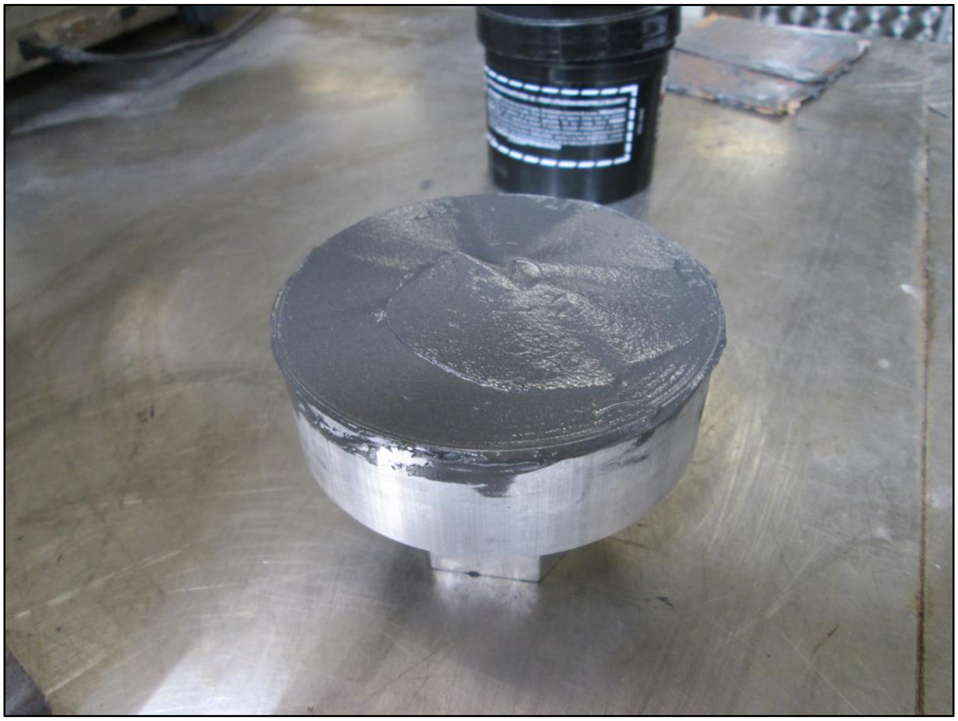

Figure 8.8 Epoxy Glue Applied to an End Plate Surface

Figure 8.9 Materials and Setup used for Gluing the End Plates to CDT Sample

8.4.4 Developing Test Procedure using the Existing MTS Load Frame

Development of the CDT test procedure according to the AASHTO TP-xx-xx test method was done using a MTS load frame. Development of the test procedure included fingerprint testing and full S-VECD testing. The CDT tests were conducted at 20°C (68°C). In this test, a cyclic load was applied to the cylindrical specimen (under direct tension) until failure. The applied stress and on-specimen axial strain response were measured and used to develop the damage characteristic curve. The damage characteristic curves represent a fundamental relationship between damage and material integrity (of asphalt mixes) and can be used to analyze the fatigue performance of tested mix (AASHTO, 2013). It should be noted that the development of the damage characteristic curve needs the dynamic modulus values of the mixes. Therefore, dynamic modulus tests were also conducted on asphalt mixes.

The developed test procedure was used to conduct tests on several dummy CDT samples. Each CDT sample was attached securely to the loading frame (MTS machine). In order to make sure that the specimen was attached properly to the actuator and concentricity was maintained without the application of any unwanted moments at the end plates, a ball joint mechanism proposed by the test procedure (AASHTO TP xx-xx) was used. At the beginning, due to complexities involved in the proposed ball joint, the research team fabricated an alternate design for this part. A photographic view of the complete CDT test setup fabricated at OU on the MTS load frame is shown in Figure 8.10. The fabricated ball joint replacement was replaced later, with an actual ball joint ordered from NCSU, shown in Figure 8.11.

Figure 8.10 Complete CDT Test Setup Installed on MTS Load Frame

Figure 8.11 Ball Joint for Conducting CDT Test Received from NCSU

8.4.5 Conducting the CDT Test using the IPC-AMPT

The IPC-AMPT was purchased in this project and used for testing the actual CDT samples in the laboratory (Figure 8.12). The test setup and software for conducting the fingerprint test, procedure of S-VECD and data analysis were easily accessed and controlled by the operator on this equipment.

Prior to testing, the samples were conditioned for at least six hours at 20°C. Then each test specimen was placed inside the testing frame and was secured to the bottom support. When the specimen was located firmly in its place, the actuator was brought into position and a sitting load of approximately 0.09 kN (20 lb.) was applied to the sample. Then the sample was secured to the upper loading platen using screws, while making sure not to shear the specimen unnecessarily. The spring-loaded LVDTs were then attached to the LVDT studs on the sample using special stud clamps (Figure 8.13). The free ends of the LVDTs were adjusted prior to testing to provide sufficient expansive stroke length during the test.

Figure 8.12 The IPC Asphalt Mix Performance Tester

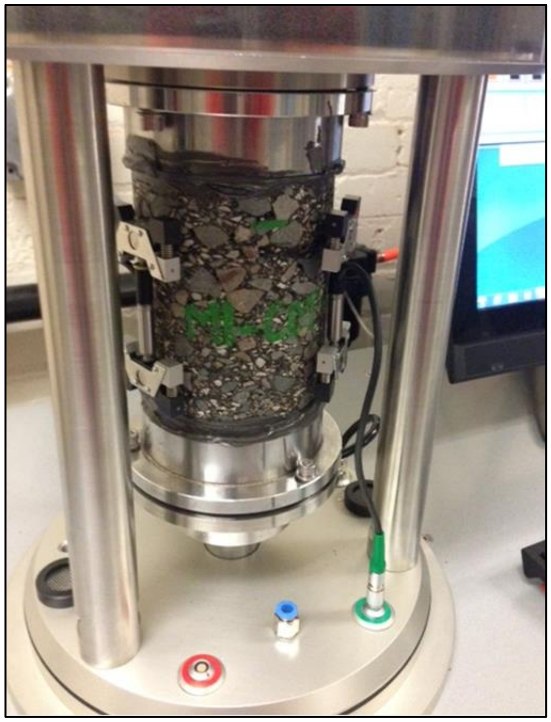

Figure 8.13 CDT Sample in IPC-AMPT Loading Frame

After reaching the testing temperature, the fingerprint dynamic modulus test was performed at a frequency of 10 Hz and at the target test temperature of 20°C (68°F). The fingerprint test was performed in the tension-compression mode of loading. The on-specimen strain was controlled automatically and the time history of the applied load and axial deformations during the test were measured and recorded in a data file. The machine automatically adjusted the applied load level to achieve 50 to 75 micro-strains for 50 cycles. Then, the fingerprint dynamic modulus was calculated for the last five cycles, according to the method recommended in the AASHTO T 342 and AASHTO TP 79 test methods (AASHTO, 2011). The fingerprint test results were used to calculate the machine compliance factor (K) using the following equation:

$$K = \frac{\varepsilon_{act}}{\varepsilon_{os}} \qquad (8.1)$$

where,

ε_{act} = the peak-to-peak on-specimen strain amplitude, and

ε_{act} = the peak-to-peak actuator displacement.

Then, the specimen was kept in rest for a period of 20 minutes, following the fingerprint test.

After the rest period, the fatigue test conducted by application of a constant pull-pull actuator oscillation at a frequency of 10 Hz. The calculated machine compliance factor (K) was used by the controller software to automatically adjust actuator displacement in order to attain the target on-specimen strain amplitude. The load and LVDT readings were recorded as functions of time for the first half of the first cycle of loading (from zero to first peak) at a rate of 1,000 samples per second. For the rest of the applied cycles only the cycle number, peak and valley values of force, and the peak and valley values of sensor displacements were acquired. The test was stopped when propagated micro-cracks form one clear macro-crack on the specimen, or when a sudden drop in phase angle was observed. The macro-crack was visually observed on the surface of the specimen which caused it to break into two completely separate parts (Figure 8.14).

Figure 8.14 A Failed CDT Sample

The first cyclic fatigue test was conducted with the peak-to-peak on-specimen strain amplitude of 300 micro-strains, set in the machine. Based on the number of the cycles to failure of the first sample, the strain amplitude of the second and third samples were determined using the values recommended by AASHTO TP xx-xx shown in Table 8.1 (AASHTO, 2013).

Table 8.1 On-Specimen Strain Levels for the Second and Third Specimens (AASHTO, 2013)

Case	ε_{os2}	ε_{os3}
$500<N_{f1}<1,000$	ε_{os1}-100	ε_{os1}-150
$1,000<N_{f1}<5,000$	ε_{os1}-50	ε_{os1}-100
$5,000<N_{f1}<20,000$	ε_{os1}+50	ε_{os1}-50
$20,000<N_{f1}<100,000$	ε_{os1}+100	ε_{os1}+50
$100,000<N_{f1}$	ε_{os1}+150	ε_{os1}+100

8.4.6 CDT Test Data Analysis Software

Simplified viscoelastic continuum damage (S-VECD) model was used for analyzing the CDT test results and to develop the damage characteristics of the tested asphalt samples. More theoretical and technical details on S-VECD method can be found in FHWAHRT-08-073 report (Kim et al., 2008). The damage function developed in S-VECD model can be used for determining the fatigue characteristics of asphalt materials. For analyzing the CDT data using the S-VECD approach, a commercially-available software, Asphalt Pavement Hierarchical Analysis Toolbox – Fatigue Program (ALPHA-F™) was used to develop damage characteristic curves (C vs. S curves).

8.5 Dynamic Modulus Test

The dynamic modulus tests were conducted in accordance with AASHTO TP 62 (AASHTO, 2011) at the following temperatures: -10.0°C, 4.4°C, 21.1°C, 37.8°C, and 54°C (14°F, 40°F, 70°F, 100°F and 130°F), starting at the lowest temperature and proceeding to the highest temperature. For each temperature, the test was conducted at six different frequencies from the highest to lowest using the following frequencies: 25 Hz, 10 Hz, 5 Hz, 0.5 Hz, 0.1 Hz. Dynamic modulus tests were conducted, using a GCTS ATM-100 loading frame. The specimen was first placed in an environmental chamber and allowed to attain equilibrium at the specified test temperature (± 0.5). Prior to testing, the sample was first conditioned by applying 200 cycles of load at a frequency of 25 Hz. The magnitude of load was adjusted based on the material stiffness, air voids content, temperature, and frequency to keep the strain response within 50 – 150 micro-strains. The data was recorded for the last 5 cycles of each sequence.

The master curves for each mix were generated at a reference temperature of 21.1°C (70°F) using the procedure outlined in Bonaquist and Christensen (2005). Equations 9.2 and 9.3 show the sigmoidal function and shift factor functions used for developing the master curves, respectively. The default values of ASTM ‘A’ (i.e., 10.980) and ‘VTS’ (i.e., -3.680) for a typical PG 64 - 22 binder were taken from the new MEPDG (AASHTO, 2004). A nonlinear optimization program was used to solve for these unknown parameters simultaneously.

$$\log\left(E^*\right) = \delta + \frac{\alpha}{1 + e^{\beta + \gamma\left\{\log(\omega) + c\left[10^{A + VTS \log T_R - \log \eta_{70RTFOT}}\right]\right\}}} \quad (8.2)$$

The shift factor a(T) is given by:

$$a(T) = \frac{f_r}{f} \quad (8.3)$$

where,

E^* = dynamic modulus,

a(T) = shift factor as a function of temperature and age,

δ,β,α,and c = fitting parameters,

$\eta_{70RTFOT}$ = viscosity at reference temperature of interest of 70°F (21°C) and under rolling thin-film oven aged condition,

ω = loading frequency,

f_r = reduced frequency at the reference temperature,

f = frequency at particular temperature,

T_R = temperature in Rankine,

A = regression intercept, and

VTS = regression slope of viscosity-temperature susceptibility.

8.6 Creep Compliance Test

In AASHTO T 322 (AASHTO, 2011), the creep compliance is defined as "the time-dependent strain divided by the applied stress." In this study, creep compliance tests were conducted at -10˚C, 0˚C and 10˚C (14˚F, 32˚F, and 50˚ F) on cylindrical cores having a diameter of 6.0 in. (150 mm) and a height of 1.8 in. (46 mm), in accordance with the AASHTO T 322 (AASHTO, 2011) test method. The test method consists of applying a static load of fixed magnitude along the diametric axis of the specimen for 100 seconds. A 100 kN (22,000 lbs.) load cell was used for loading the specimen. The vertical and horizontal deformations were measured by two LVDTs having a stroke length of 5 mm (0.2 in.), and attached in the diametrically perpendicular direction. A gauge length of approximately 38 mm (1.5 in.) was used for mounting the LVDTs on one face of the specimen. The horizontal and vertical deformations measured near the center of the specimen were used for calculating the tensile creep compliance, as a function of time. The load level was selected to keep horizontal deformation in the linear viscoelastic range 0.0125 – 0.0190 mm (0.000492 – 0.0007480 in.) during the creep test. Figure 8.15 and Figure 8.16 show photographic views of the setup used for conducting creep compliance test using the MTS machine.

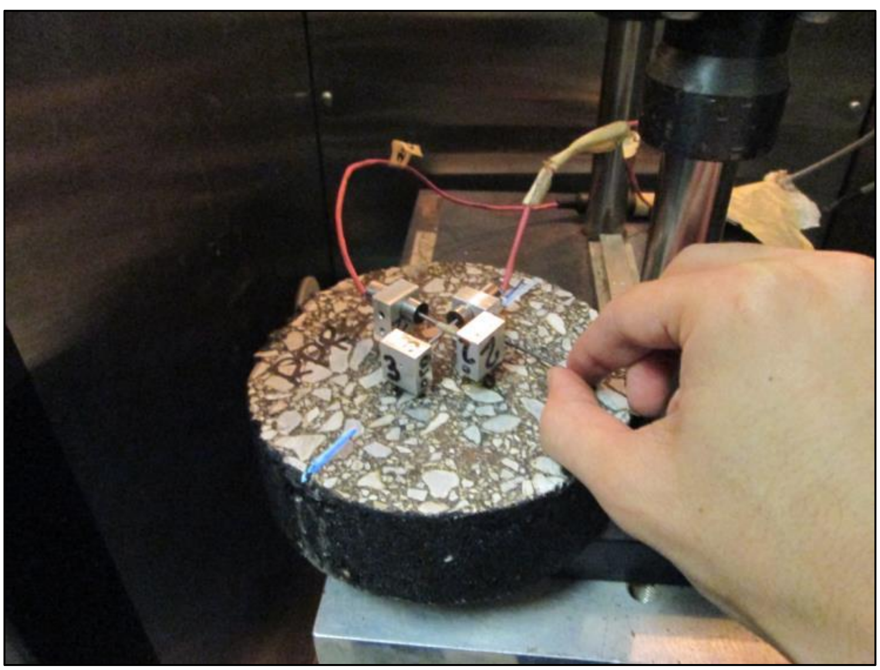

Figure 8.15 Attachment of LVDTs on the Creep Compliance Sample

Figure 8.16 The Creep Test Setup Inside Environmental Chamber in MTS Machine

The creep compliance was calculated as a function of the horizontal and vertical deformations, the gauge length over which these deformations are measured, the dimensions of the test specimen, and the magnitude of the static load. The following steps are used in determining creep compliance, as defined in the AASHTO T 322 (AASHTO, 2011) test method:

$$D(t) = \frac{\Delta X_{tm,t} D_{avg} b_{avg}}{P_{avg} GL} C_{cmpl} \qquad (8.4)$$

where,

D(t) = creep compliance at time t $(kPa)^{-1}$,

GL = gauge length in inch (1.5 in., 38 mm),

D_{avg} = average diameter of the specimens,

b_{avg} = average thickness of all specimens,

$\Delta X_{tm,t}$ = trimmed mean of the normalized, horizontal deformations (nearest to 0.001 in.) of all specimens faces of the specimen at time t,

P_{avg} = average creep load (lb., kN), and

C_{cmpl} = correction factor that can be defined as follows:

$$C_{cmpl} = 0.6354\left(\frac{X}{Y}\right)^{-1} - 0.332 \qquad (8.5)$$

where,

X/Y = absolute value of ratio of the normalized, trimmed mean of the horizontal deformations ($\Delta X_{tm,t}$) to the normalized, trimmed mean of the vertical deformations ($\Delta Y_{tm,t}$) at a time corresponding to ½ of the total creep compliance test time.

The range of the correction factor is given by the following equation:

$$\left[0.704 - 0.213\left(\frac{b_{avg}}{D_{avg}}\right)\right] \le C_{cmpl} \le \left[1.566 - 0.195\left(\frac{b_{avg}}{D_{avg}}\right)\right] \qquad (8.6)$$

The creep compliance master curve was created by using the time-temperature superposition principle. Properties of time and temperature-dependent material can be represented by using reduced time (t_r) (Richardson and Lusher, 2008). Finally, using the time-temperature superposition principle, the creep compliance master curves were constructed for each mix. At 10°C (50°F) reference temperature, the shapes of adjacent creep compliance curves obtained from different temperatures were shifted with respect to time to obtain an exact matching and form a smooth function (Ferry, 1980). This function is expressed in the form of Equation 8.7.

$$D(t) = D_0 + D_1 t^m \qquad (8.7)$$

where,

$D(t)$ = creep compliance in 1/MPa,

t = time in seconds, and

D_0, D_1, m = model constants.

A nonlinear optimization program (Solver of MS-Excel) was used to solve for the shift factors at different temperatures and master curve coefficients, namely D_0, D_1, m.

The creep compliance versus time curves obtained from several individual temperatures were shifted along the time or frequency axis to create one continuous creep compliance versus reduced time master curve. For a constant temperature, the reduced time (t_r) is defined as follows:

$$t_r = t \times a_t \tag{8.8}$$

where,

a_t = time-temperature shift factor, and

t = time (seconds).

The Poisson's ratio, ν, was calculated as follows:

$$\upsilon = -0.10 + 1.480\left(\frac{X}{Y}\right)^2 - 0.778\left(\frac{b_{avg}}{D_{avg}}\right)^2\left(\frac{X}{Y}\right)^2 \tag{8.9}$$

where,

D_{avg} = average diameter of the specimens,

b_{avg} = average thickness of all specimens, and $0.05 \leq \nu \leq 0.50$.

8.7 Indirect Tensile Strenght Test

Indirect tensile strength (IDT) tests were conducted at -10°C and 20°C (14°F and 68°F) on cylindrical specimens. The IDT tests on CC test specimens at -10°C (14°F) (after CC tests) were conducted in accordance with the AASHTO T 322 test method (AASHTO, 2011). The portion of T 322 related to the tensile strength testing is destructive. The IDT tests at 20°C (68°F) were conducted on cylindrical specimens of 150-mm (6-in.) diameter and 75-mm (3-in.) height. The specimen was loaded until failure occured. This test involves applying a load to the specimen at a rate of 13 mm (0.5 in.) of vertical movement of the actuator per minute. The vertical deformations of the specimen and the load were recorded until the load started to decrease. The vertical crosshead displacement was measured by the actuator LVDT. A 100-kN (22-kip) load cell was used for load measurement. The test results obtained at 20°C (68°F) were compared with those obtained from the fatigue test (number of cycles to failure). Three replicates were used for the IDT test at each temperature. The tensile strength was calculated by using the equation below.

$$S_{t,m} = \frac{2xP_{f,n}}{\pi x b_n x D_n} \qquad (8.10)$$

where,

$S_{t,n}$ = tensile strength of the specimen, n, and

$P_{f,n}$ = maximum load observed for specimen, n.

Chapter

9 RESULTS AND DISCUSSION

9.1 General

The data collected from different tests, namely four-point beam fatigue (FTG), indirect tensile strength (IDT), dynamic modulus (DM), and creep compliance (CC) was analyzed and presented in this chapter. The number of cycles to failure, initial stiffness, and failure stiffness of the mixes were summarized from the FTG tests. The IDT data was also analyzed and the effect of using RAS and RAP on asphalt mixes' tensile strength was investigated. Also, the DM and CC master curves were developed and presented in this chapter.

9.2 Fatigue Life (Flexural Fatigue)

The fatigue life of an asphalt mix is its ability to withstand repeated traffic loads without experiencing failure. The FTG tests were conducted at a temperature of 20°C (68°F) and at a constant frequency of 10 Hz. The tests were conducted in strain-controlled mode at 400 micro-strains. The initial stiffness and the number of cycles to failure obtained from conducting FTG tests on asphalt mixes are presented in Table 9.1 and graphically shown in Figure 9.1.

From Figure 9.1 and Table 9.1, it is evident that when a PG 64-22 OK asphalt binder was used, increasing the RAP content from 0% (M1) to 30% (M2) resulted in an increase in fatigue life by 17%. Also, it was found that using a blend of 5% RAP and 5% RAS (M4) in a mix led to an increase in fatigue life by 39% with respect to control mix (M1). However, it was evident that using 6% RAS (M5) resulted in 24% decrease in fatigue life compared to that of control mix (M1), which does not contain any RAP and RAS.

From Figure 9.1 and Table 9.1, it was observed that when a PG 70-28 OK asphalt binder was used, increasing the RAP content from 0% (M6) to 30% (M7) resulted in a decrease in fatigue life by 102%. Also, it was found that using a blend of 5% RAP and 5% RAS (M9) in a mix led to a decrease in fatigue life by 69% with respect to control mix (M6). Furthermore, it was seen that using 6% RAS (M10) resulted in

191% decrease in fatigue life compared to that of control mix (M6), which does not contain any RAP and RAS.

Table 9.1 Summary of the FTG Tests Conducted on Asphalt Mixes

Mix Type	Average Failure Cycles @50% Initial Stiffness	Standard Deviation (Cycles)	COV (%)	Average Initial Stiffness (MPa)	Standard Deviation (MPa)
M1	122,312	12,351	10	4,822	596
M2	142,777	14,012	10	5,028	239
M4	170,419	46,354	27	5,094	138
M5	93,433	15,062	16	5,344	948
M6	343,397	39,491	12	3,771	148
M7	219,224	39,241	18	4,907	211
M9	258,891	34,691	13	5,881	265
M10	110,364	42,187	38	6,547	220

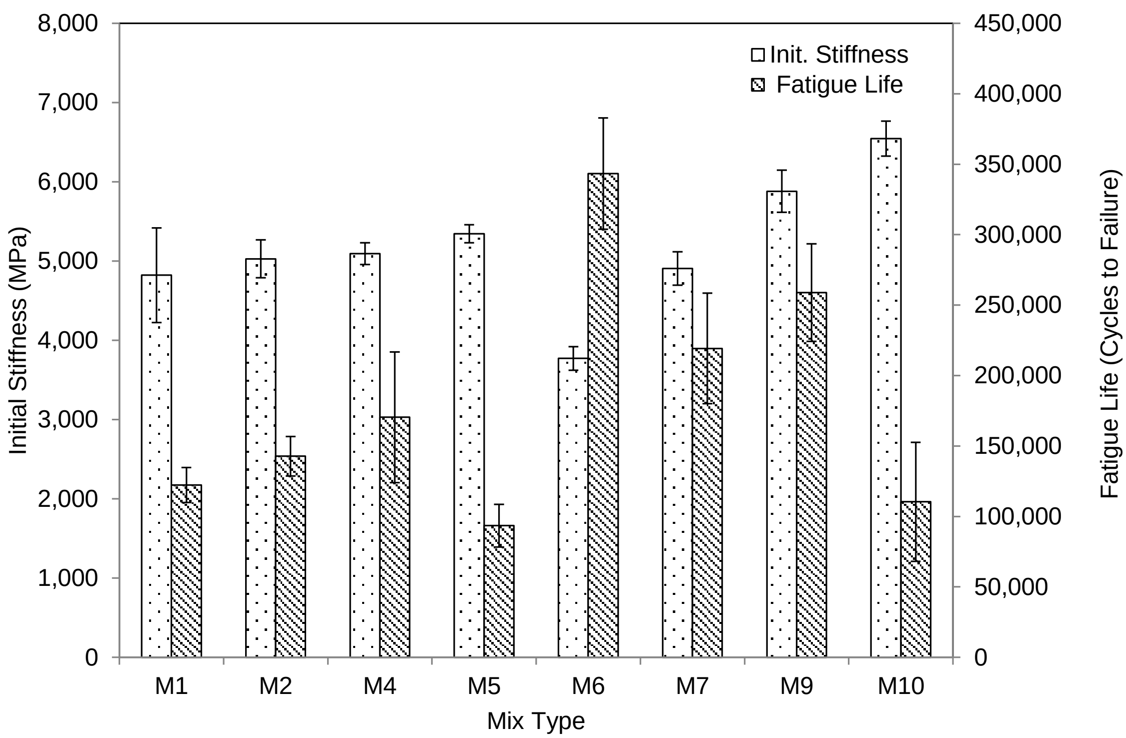

Figure 9.1 Fatigue Life and Initial Stiffness Values of Asphalt Mixes in FTG Tests

From Figure 9.1, it was also observed that using a polymer-modified asphalt binder significantly increased the fatigue life of the mixes with and without RAP and RAS. For example, the fatigue life of the M1, which is a virgin mix with a PG 64-22 OK asphalt binder, increased by 181% when a polymer-modified PG 70-28 OK asphalt binder was used (M6). Similarly, the fatigue life of M2, which is a mix containing 30% RAP with a PG 64-22 OK asphalt binder, increased by 54% when a PG 70-28 OK binder was used (M7). Also, the fatigue life of M4, which is a mix containing 5% RAP and 5% RAS with PG 64-22 binder, increased by 52% when the asphalt binder was replaced with PG 70-28 OK (M9). Furthermore, the fatigue life of M5, which is a mix containing 6% RAS with a PG 64-22 OK asphalt binder, increased by 18% when a PG 70-28 OK binder was used (M9). From the presented test results, it can be concluded that use of a polymer-modified asphalt binder may improve the fatigue life of an asphalt mix which may or may not contain RAP and/or RAS. Also, one can say that the mixes which contained a blend of RAP and RAS (M4 and M9) exhibited a better fatigue performance compared to those which contained only RAP (M2 and M7) or only RAS (M5 and M10).

Figure 9.1 also revealed that using RAP and RAS increased the flexural stiffness of the asphalt mixes. However, RAS content was found to have a greater contribution to increasing the flexural stiffness of the mix. The coefficients of variation (COV) of the cycles to failure in FTG tests were found to range from 10% to 38% (Table 9.1). This shows that the repeatability of the test results in the four-point beam fatigue tests was not very good.

9.3 Dynamic Modulus

The dynamic modulus master curves of the tested asphalt mixes with PG 64-22 OK and PG 70-28 OK binders are shown in Figure 9.2 and Figure 9.3, respectively. Also, the master curves' model parameters developed for different asphalt mixes, are presented in Table 3. A reference temperature of 21.1°C (70°F) was used for constructing the master curves. From Table 9.2 and based on the goodness-of-fit statistics, it is evident that the dynamic modulus models used for developing the master curves are all rated as "excellent". In other words, the sigmoidal fit functions are able to satisfactorily predict the dynamic modulus values at a reference temperature of 21.1°C (70°F).

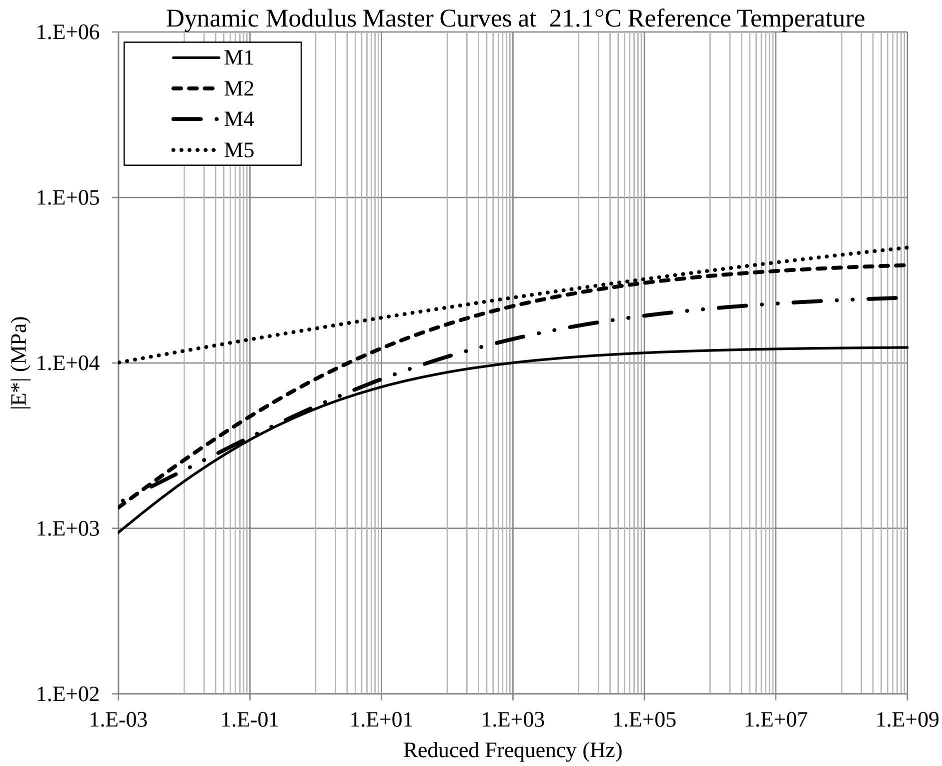

Figure 9.2 Dynamic Modulus Master Curves of Mixes with PG 64-22 OK Binder

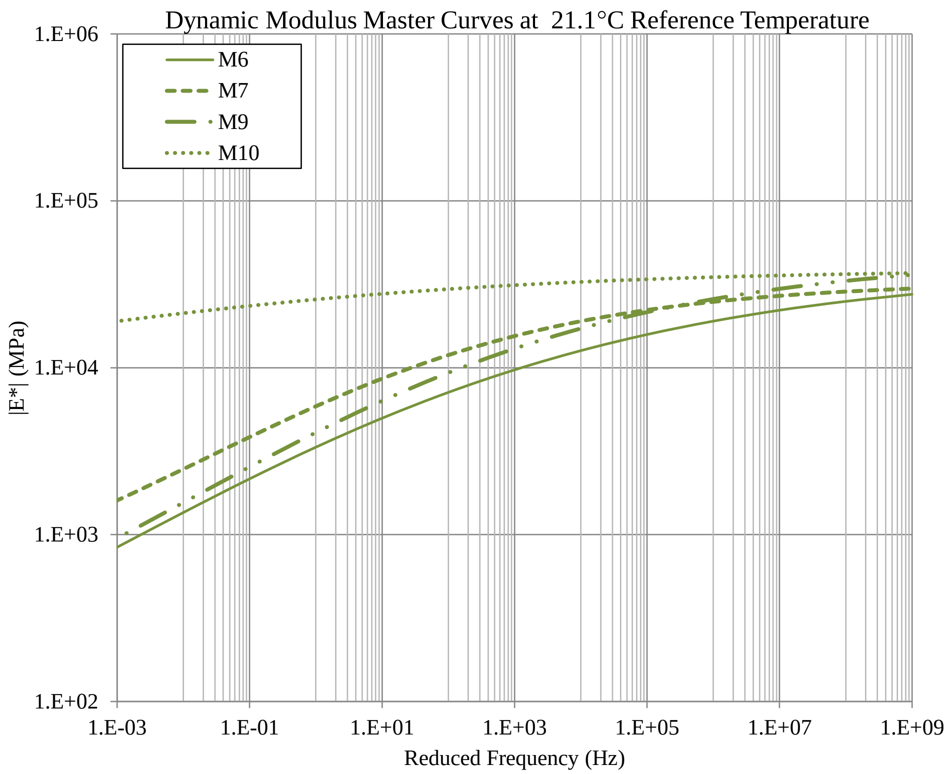

Figure 9.3 Dynamic Modulus Master Curves of Mixes with PG 70-28 OK Binder

Table 9.2 Dynamic Modulus Master Curves' Model Parameters

Mix Type	|E*| Master Cuve Parameters (MPa)				Goodness-of-fit Statistics		
	α	β	γ	δ	R^2	S_e/S_y	Rating
M1	2.898	-1.903	-0.482	1.201	0.961	0.113	Excellent
M2	3.200	-1.235	-0.369	1.424	0.993	0.053	Excellent
M4	2.109	-0.722	-0.381	2.318	0.996	0.055	Excellent
M5	3.354	-0.789	-0.091	1.902	0.960	0.293	Excellent
M6	3.354	-0.750	-0.249	1.246	0.999	0.038	Excellent
M7	2.105	-0.596	-0.366	2.411	0.995	0.075	Excellent
M9	2.921	-0.566	-0.295	1.749	0.996	0.057	Excellent
M10	0.856	-1.318	-0.253	3.734	0.995	0.102	Excellent

From Figure 9.2 and Figure 9.3, it was observed that dynamic modulus of all mixes tested herein increase with an increase in the loading frequency and a reduction in temperature. A similar trend of dynamic modulus with temperature and loading frequency is reported in the literature (e.g., Tashman and Elangovan, 2008; Flintsch et al., 2007; Singh et al., 2011a).

From Figure 9.2 it is evident that in general, the dynamic modulus values of the M1, which is a virgin mix with a PG 64-22 OK asphalt binder, are lower than those of the other mixes with the same type of asphalt binder. Also, it can be seen that M5, which is a mix with 6% RAS and a PG 64-22 OK asphalt binder, has the highest dynamic modulus values compared to the other mixes. Furthermore, M2 and M4 mixes, which contain 30 %RAP and 5% RAP + 5% RAS with PG 64-22 OK binder, respectively, have dynamic modulus values which lie between those of M5 and M1.

From Figure 9.3 it is clear that the dynamic modulus values of the M6, which is a virgin mix with a PG 70-28 OK asphalt binder, are lower than those of the other mixes with the same type of asphalt binder. Also, it can be seen that M10, which is a mix with 6% RAS and a PG 70-28 OK asphalt binder, has the highest dynamic modulus values compared to the other mixes. Furthermore, M7 and M9 mixes, which contain 30 %RAP and 5% RAP + 5% RAS with PG 70-28 OK binder, respectively, have dynamic modulus values which lie between those of M10 and M6.

According to dynamic modulus test results, it can be concluded that addition of RAP and/or RAS to the asphalt mix increased the dynamic modulus values, for both cases when PG 64-22 OK or PG 70-28 OK asphalt binders were used. More aged binder from RAP and RAS leads to a stiffer mix and therefore a higher dynamic modulus. However, for the same amount of binder replacement, use of only RAS was found to increase the stiffness more than using other combinations of RAS and RAP contents. The binder from RAS is highly aged in the refinery (air-blown) and during its service life as roofing shingles, and therefore has a higher stiffness compared to the virgin asphalt binder and that from RAP. Therefore, it is expected to observe higher moduli for M5 and M10 mixes, specifically at lower frequencies, compared to those of other mixes. According to time-temperature superposition principle, a lower reduced frequency is equivalent to a higher temperature. Therefore, effect of highly aged binder M5 and M10 mixes was more pronounced at lower frequencies, leading to higher moduli, when compared to those of other mixes. Also, it was observed that using a blend of RAP and RAS (5% RAP and 5% RAS) resulted in the lowest increase in dynamic modulus values, when compared to control mix which contains no RAP and/or RAS. It should be noted that the dynamic moduli of the surface course mixes used in this study, due to a finer gradation, are more sensitive to binder type, and therefore addition of small quantities of RAP and/or RAS results in a significant change in moduli.

Increasing dynamic modulus with an increase in the amounts of RAP and RAS are in agreement with the results reported in the literature (e.g., Yang et al., 2014; Li et al., 2008; McGraw et al., 2007; Uzarowski, 2006). A low dynamic modulus value in asphalt mixes is known to result in a higher rutting potential compared to stiffer mixes. However, very stiff mix may result in a lower fatigue life compared to those with lower stiffness. Therefore, it is important to evaluate the fatigue and rutting potential of the asphalt mixes through performance tests.

9.4 Creep Compliance

The M-EPDG uses the creep compliance as an input parameter to predict the thermal cracking of pavements over their service life. The methodology discussed earlier in Chapter 8 was used to determine the creep compliance master curve model parameters (Equation 8.7). The creep compliance master curve model parameters, goodness-of-fit statistics, and rating of each model are presented in Table 9.3. From Table 9.3 it was observed that, based on the goodness-of-fit statistics, the models used for development of master curves were all rated as "excellent". In other words, the master curve functions are able to satisfactorily predict the creep compliance values at a reference temperature of 10°C (50°F).

Table 9.3 Creep Compliance Master Curve Model Parameters of the Tested Mixes

Mix Type	Creep Complinace Master Cuve Parameters (1/MPa)			Goodness-of-fit Statistics		
	D_o	D_1	m	R^2	S_e/S_y	Rating
M1	7.74E-05	8.18E-06	0.378	0.99	0.110	Excellent
M2	7.33E-05	5.02E-06	0.390	0.99	0.177	Excellent
M4	6.12E-05	5.94E-06	0.335	0.99	0.147	Excellent
M5	6.69E-05	8.56E-06	0.330	0.99	0.174	Excellent
M6	6.77E-05	1.44E-05	0.439	0.99	0.137	Excellent
M7	7.27E-05	4.31E-06	0.396	0.99	0.167	Excellent
M9	8.28E-05	5.31E-06	0.351	0.99	0.151	Excellent
M10	7.44E-05	6.87E-06	0.343	0.99	0.121	Excellent

The creep compliance master curves of the tested asphalt mixes with PG 64-22 OK and PG 70-28 OK binders are shown in Figure 9.4 and Figure 9.5, respectively. From Figure 9.4 and Figure 9.5, it was observed that the creep compliance increased with an increase in loading time and temperature. This is consistent with the findings reported in the literature (Vargas, 2007).

From Figure 9.4 it is evident that the creep compliance values of the M1, which is a virgin mix with a PG 64-22 OK asphalt binder, are higher than those of the other mixes with the same type of asphalt binder. Also, it was observed that M4, which is a mix with 5% RAP and 5% RAS and a PG 64-22 OK asphalt binder, had the lowest creep compliance values compared to those of the other mixes. Furthermore, M2 and

M5 mixes, which contain 30% RAP and 6% RAS, respectively, with a PG 64-22 OK binder, have creep compliance values which lie between those of M4 and M1.

From Figure 9.5 it is clear that the creep compliance values of the M6, which is a virgin mix with a PG 70-28 OK asphalt binder, are higher than those of the other mixes with the same type of asphalt binder. Also, it was found that M9, which is a mix with 5% RAP and 5% RAS and a PG 70-28 OK asphalt binder, had the lowest creep compliance values compared to those of the other mixes. Furthermore, M7 and M10 mixes, which contain 30% RAP and 6% RAS, respectively, with a PG 64-22 OK binder, have creep compliance values which lie between those of M9 and M6.

It can be concluded that the use of aged binders from RAP and/or RAS sources results in a stiffer mix (Swiertz et al., 2011), which in turn leads to lower creep compliance, as expected. This reduction was more pronounced when a blend of RAP and RAS was used in the mix (M4 and M9). However, use of RAP as the only reclaimed material in a mix (M2 and M7) resulted in the lowest reduction in creep compliance as compared to those of the virgin mixes (M1 and M6). Although use of a polymer-modified asphalt binder (PG 70-28 OK) in a virgin mix (M6) resulted in higher creep compliance values compared to those of virgin mix with PG 64-22 OK binder (M1), no significant benefit in terms of increasing the creep compliance values was observed as a result of changing the binder.

Decreasing creep compliance values with an increase in the amounts of reclaimed asphalt materials (RAP and/or RAS), is consistent with the observations reported in the literature (e.g. You et al., 2011a, Vargas, 2007). A low creep compliance value of an asphalt mix is known to result in a change in relaxation modulus, which may lead to more thermal stress buildup in asphalt pavement as a result of temperature change. This may make the mix prone to low-temperature cracking (Lytton et al., 1993).

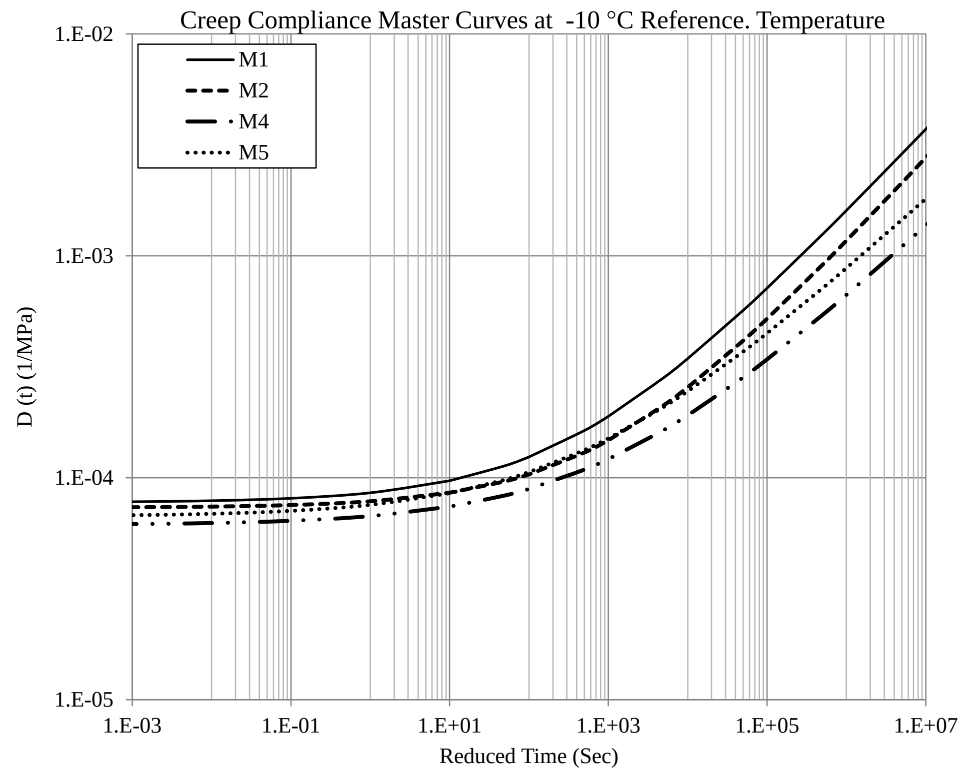

Figure 9.4 Creep Compliance Master Curves of Mixes with PG 64-22 OK Binder

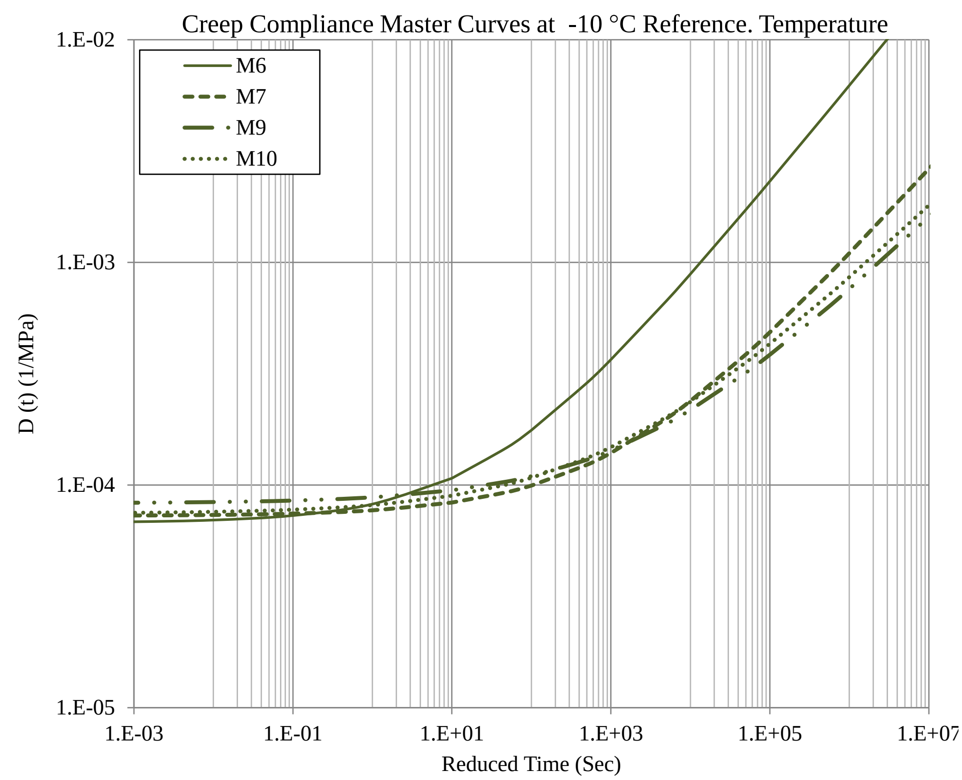

Figure 9.5 Creep Compliance Master Curves of Mixes with PG 70-28 OK Binder

9.5 Indirect Tensile Strength

A summary of the IDT test results conducted on asphalt mixes is shown in Table 9.4, and graphically presented in Figure 9.6. From Table 9.4 and Figure 9.6 it is evident that addition of RAP and/or RAS to asphalt mixes increased the tensile strength of the mixes. For example, for the same amount of binder replacement from RAS/RAP sources, the average IDT value of the M1, which is a virgin mix with a PG 64-22 OK asphalt binder, increased by 61% by addition of 30% RAP to the mix (M2). Similarly, using 5% RAP and 5% RAS (M4) resulted in an increase in IDT value by 91%, when it was compared with that of virgin mix (M1). Also, it was found that an asphalt mix containing 6% RAS with a PG 64-22 OK binder (M5) had an IDT value which was 131% higher than that of the virgin mix with the same type of binder (M1).

Table 9.4 Summary of the IDT Test Results Conducted on Asphalt Mixes

Mix Type	Indirect Tensile Strenght (kPa)		COV (%)
	Average	Standard Deviation	
M1	770	46.7	6.1
M2	1242	31.9	2.6
M4	1469	84.9	5.8
M5	1783	75.9	4.3
M6	681	26.8	3.9
M7	1104	94.5	8.6
M9	1200	49.4	4.1
M10	1514	24.5	1.6

The same trend of improvement observed in IDT values of the mixes with use of RAP and/or RAS and PG 64-22 OK was also seen when a polymer-modified (PG 70-28 OK) asphalt binder was used. From Table 9.4 and Figure 9.6 it is evident that the average IDT value of the M6 mix, which is a virgin mix with a PG 70-28 OK asphalt binder, increased by 62% when 30% RAP was used (M7). Also, using 5% RAP and 5% RAS (M9) resulted in an increase in IDT value by 76%, when it was compared with that of virgin mix (M6). Furthermore, it was found that an asphalt mix containing 6% RAS with a PG 70-28 OK binder (M10) had an IDT value which was 122% higher than that of the virgin mix with the same type of binder (M6). In addition, from Figure 9.6, it was found that asphalt mixes with PG 64-22 OK binder had IDT values higher than those of the mixes produced with a PG 70-28 OK asphalt binder. The low coefficients of variation, which range from 1.6 to 8.6% (Table 9.4), show the high repeatability of this test. However, no correlations between the fatigue life of asphalt mixes (FTG test) and their IDT values were found. It is recommended to investigate the fatigue life of the asphalt mixes in conjunction with simple tests involving the fracture energy results, such as semi-circular beam (SCB).

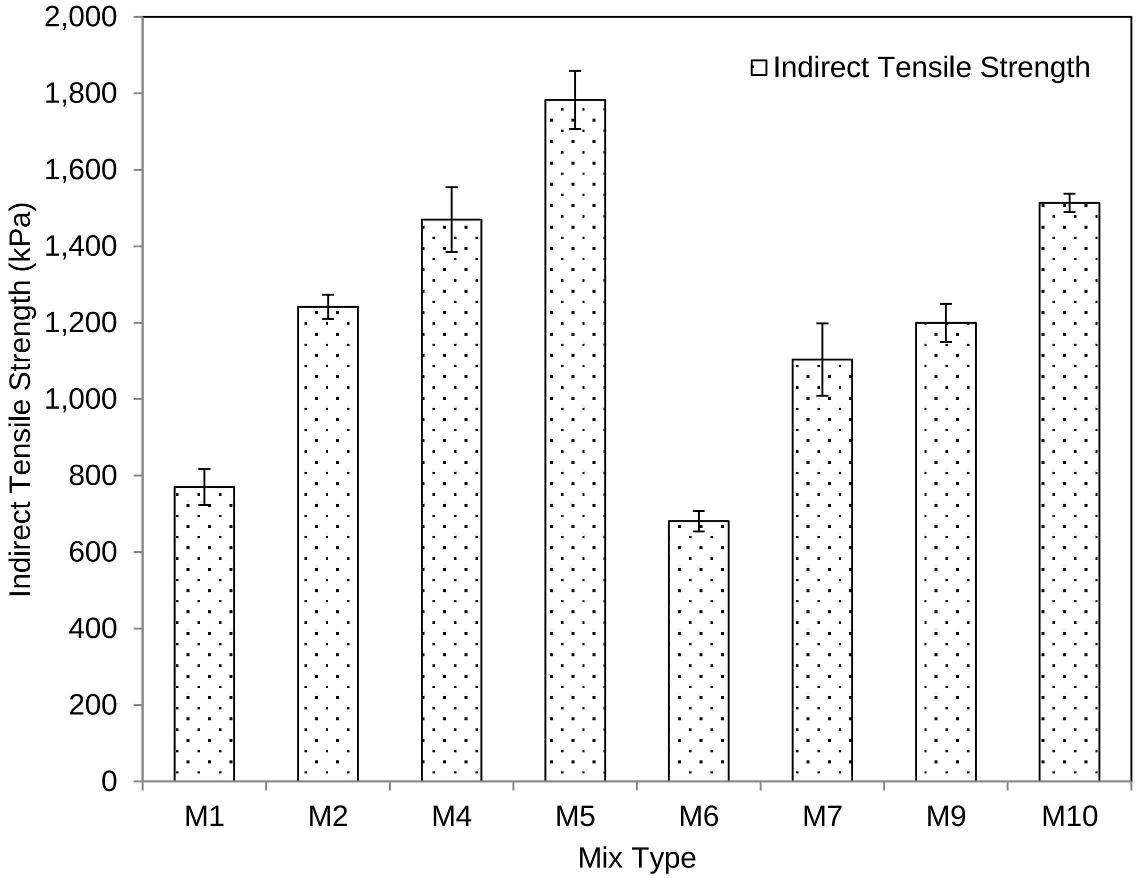

Figure 9.6 Summary of the IDT Test Results Conducted on Asphalt Mixes

Chapter
10 CONCLUSIONS AND RECOMMENDATIONS

10.1 General

Despite their advantages, there are national concerns associated with fatigue and low-temperature cracking potential of pavements when containing increased amounts of RAS and RAP. Therefore, this study was undertaken to evaluate the fatigue performance of hot-mix asphalt (HMA) containing RAP and RAS. Specifically, changes in fatigue resistance and cycles to fatigue failure with changes in the amount of RAP and RAS were examined using both flexural fatigue (four-point beam) and axial fatigue (cyclic direct tension) tests on laboratory-compacted specimens. Effect of virgin binder grade on the fatigue performance was also examined. In addition, the effect of RAP and RAS in HMA on its creep compliance and dynamic modulus was investigated. These properties are used in the evaluation of fatigue resistance based on the axial cyclic direct tension test. For this purpose, eight fine surface course mixes (S4) with different types of asphalt binders (i.e., PG 64-22 OK and PG 70-28 OK) containing different amounts of RAP and RAS were designed and tested in the laboratory. The amounts of RAP and RAS used in HMA mixes varied, but the total amount of replaced binder was kept within certain specifications (i.e., RAP and/or RAS limited to 30% binder replacement). Also, a comprehensive survey was conducted among the state departments of transportation for gathering data on the current practices including the methods and specifications associated with the use of RAP and RAS in pavements. The results from this study can be used to develop and update guidelines/special provisions for design of HMA containing RAS and RAP in Oklahoma. This chapter presents the conclusions drawn, and the recommendations made based on the findings of this study. Also, the status of the technology transfer workshop is presented in this chapter.

10.2 Conclusions

Based on the results and discussion presented in this study, the following conclusions can be drawn:

1. The fatigue life of asphalt mixes with a PG 64-22 OK binder increased with use of RAP or a blend of RAP and RAS. Using a blend of 5% RAP and 5% RAS in a

mix led to the maximum increase in fatigue life, among the mixes tested in this study. However, it was observed that the fatigue life of the mix decreased when 6% RAS was used compared to that of virgin mix with the same type of asphalt binder (PG 64-22).

2. When a PG 70-28 OK asphalt binder was used, use of RAP and/or RAS in a mix resulted in a decrease in fatigue life. Using 6% RAS resulted in the maximum decrease in fatigue life, compared to that of virgin mix with the same type of asphalt binder (PG 70-28 OK).

3. Use of a polymer-modified asphalt binder (PG 70-28 OK) was found to be an effective way to increase the fatigue life of the mix. Specifically, it was observed that replacing the PG 64-22 OK binder with a PG 70-28 OK resulted in an increase in fatigue life of the virgin mixes by 271%. In a similar way, use of a polymer-modified binder (PG 70-28 OK) in the mixes containing 30% RAP led to an increase in fatigue life by 54% compared to those with a PG 64-22 binder. Also, it was found that use of the PG 70-28 OK asphalt binder in the mixes containing a blend of 5% RAP and 5% RAS resulted in an increase in fatigue life by 52% as compared with those with PG 64-22 OK binder. Finally, when 6% RAS was used, replacing the PG 64-22 OK to PG 70-28 OK, led to an increase in fatigue life by 18%.

4. Using RAP and RAS increased the flexural stiffness of the asphalt mixes. Specifically, RAS content was found to have a greater contribution to increasing the flexural stiffness of the mix.

5. High coefficients of variation of the cycles to failure found for four-point beam fatigue test show that the repeatability of this method was not very good.

6. According to dynamic modulus test results, addition of RAP and/or RAS to asphalt mixes increased their dynamic modulus values, for cases in which PG 64-22 OK or PG 70-28 OK asphalt binders were used.

7. Use of aged binders from RAP and/or RAS sources resulted in stiffer mixes, which in turn lowered the creep compliance values as compared to those without

RAP and/or RAS. This may result in an increase in low-temperature cracking potential.

8. Indirect tensile strength (IDT) of the asphalt mixes increased with use of RAP and RAS compared to those of virgin mixes. Use of 6% RAS resulted in the maximum increase in IDT values.

9. The low coefficients of variation show the high repeatability of the IDT tests. However, no correlations between the fatigue life of asphalt mixes and their IDT values were found.

10. A comprehensive survey conducted among the state departments of transportation for gathering data on the current practices including the methods and specifications associated with the use of RAS and RAP in pavements.

10.3 Recommendations

Based on the results, discussion and literature review presented in this study, the following recommendations were made:

1. Different fatigue test methods are recommended to be investigated, based on their repeatability, mechanistic significance and ease of conducting the test for different mixes.

2. It is recommended to investigate the fatigue life of the asphalt mixes using simple tests involving the fracture energy, such as semi-circular bend (SCB).

3. It is recommended to study the effect of the deleterious material in RAS on the fatigue performance of the asphalt mixes. Based on the literature review presented in this study, the deleterious material content was recommended to be limited to 0.5%.

4. The laboratory test results presented herein are recommended to be verified in a separate study by construction of field test sections using different mixes containing RAP and RAS and conducting a long-term field investigation.

10.4 Outreach and Technology Transfer Workshop

To promote ODOT's outreach and technology transfer goals, a technology transfer workshop was organized in close collaboration with ODOT and Southern Plains Transportation Center (SPTC) to allow broader participation by ODOT employees, Oklahoma Asphalt Pavement Association (OAPA) members and others. The workshop was held in the Commission room at ODOT headquarter on March 12, 2015, where the results of this research were presented. Due to a relatively significant number of participants (more than 30) from the asphalt industry and timeliness of the topic, an interactive discussion was held after the presentation. The discussions covered a broad range of related issues and lasted more than an hour. Figure 10.1 shows the workshop session including presenters and participants.

Figure 10.1 The Workshop Presenters and Participants (March 12, 2015)

Also, a poster was presented at the ODOT-SPTC Transportation Research Day on October 21, 2014 in OSU-OKC Conference Center, Oklahoma City, OK, to disseminate the findings of this study. About 170 people attended this event. Figure 10.2 shows the poster presentation session of the ODOT-SPTC Transportation Research Day.

Figure 10.2 ODOT-SPTC Transportation Research Day (October 21, 2014)

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