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16. Abstract

The use of recycled asphalt shingles (RAS) in hot-mix asphalt (HMA) mixtures has the potential to significantly reduce the cost of asphalt paving mixes while conserving energy and preserving the environment. This report documents the best practices for the use of RAS in HMA in terms of RAS processing, characterizing the processed RAS (binder content, gradations, and performance grade [PG]), RAS mix design, production, and field construction. First, a six-step RAS processing guideline was proposed in this study, including collecting, asbestos testing for the tear-off asphalt shingles, sorting, grinding, screening, and storing the processed RAS. Researchers found that tear-off shingles have higher binder content than manufacture waste shingles. The manufacture waste shingles have a consistent 20 percent binder content; the tear-off shingles evaluated in this study have various binder contents, ranging from 23 percent to 28 percent. Furthermore, the overall RAS variability in terms of asphalt binder content and gradation is low for both manufacture waste and tear-off shingles. Obviously, the RAS binders are very stiff and their high temperature PG is beyond 140°C, and the low temperature PG is above 0°C. This study compared the ignition oven method with the extraction method, and found that, except for one shingle source, both methods produced similar aggregate gradations and asphalt contents.

Issues related to RAS mix design, production, and field construction were identified and discussed in this report. One important area needing further investigation is the long-term performance of RAS mixes. Generally, RAS mixes have good rutting resistance, but its resistance to reflective cracking, fatigue cracking, and potential raveling needs to be evaluated. Life-cycle cost analyses should be performed to determine the economic viability of using RAS.

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BEST PRACTICE OF USING RAS IN HMA

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CHAPTER 1: INTRODUCTION

The asphalt paving industry has always advocated recycling, including reclaimed asphalt pavement (RAP), recycled asphalt shingles (RAS), tires, etc. The earliest recycling asphalt pavement dates back to 1915. In addition to conserving energy and protecting the environment, the use of RAP/RAS can significantly reduce the cost of hot-mix asphalt (HMA) paving. RAP has been the most extensively recycled material in the history of asphalt paving industry. With recent increases in the price of asphalt cement and subsequent price fluctuations, the industry has further amplified its recycling efforts (Hansen, 2009). Most recently, the use of RAS in HMA has become another ‘black gold’ to the asphalt paving industry since RAS contains a significant amount of asphalt binder, (see Table 1). There are two basic types of roofing shingle scraps: (a) post-consumer asphalt shingles or tear-off asphalt shingles (TOAS), and (b) manufacture waste asphalt shingles (MWAS) including roofing shingle tab punch-outs and out-of-spec shingles. MWAS is called prompt roofing shingle scrap in some publications. In February 2009, the Texas Commission on Environmental Quality (TCEQ) issued an Authorization Memo to allow HMA plants to include either MWAS or TOAS under the TCEQ air quality standard permit for permanent HMA plants. Since then, RAS has been used in a variety of pavement constructions.

Table 1. Typical Compositions of New Residential Asphalt Shingles (modified after Townsend et al., 2007 and Krivit, 2007).

Component	Organic Shingles, % by wt.	Fiberglass Shingles, % by wt.
Asphalt Cement	30–36	19–22
Reinforcing Mat	2–15	2–15
Mineral Granules/aggregate	20–38	20–38
Mineral Filler/stabilizer	8–40	8–40
Adhesives (modified asphalt based)	0.2–2	0.2–2

More than 30 years ago, some of the original pioneers established the first shingle recycling plants, investigated HMA mix designs incorporating RAS, and then published the first technical literature in the late 1980s (Epps and Paulsen, 1986; Paulsen et al., 1986; and Shepherd et al., 1989). More recently, several additional HMA producers and departments of transportation have developed substantial in-house expertise in shingle recycling in HMA (Grzybowski, 1993; Newcomb et al., 1993; Button et al., 1996; Janisch and Turgeon, 1996; NAHB, 1999; Dykes, 2002; Lum, 2006; Brock 2007; Schroer, 2007). Within the last two or three years, a few contractors and state Departments of Transportation (DOTs) have begun using or studying the use of recycled shingles in warm mix asphalt (WMA) (Robinette and Epps, 2010; Maupin, 2010; Middleton and Forfylow, 2009).

With the recent increased use of asphalt shingles in asphalt mixtures, there is a need to further study this issue. The main objectives of this research report are to:

- Identify best practices for RAS collection, processing, screening, and stockpiling of processed shingles to develop associated guidelines.
- Characterize RAS physical and rheological properties.
- Identify best practice and potential problems for RAS mix design and production and pavement construction.

This report is organized in five chapters. Chapter 1 provides an introduction, and Chapter 2 presents the best practices for the RAS process in Texas and recommends guidelines for RAS collection and processing. Chapter 3 has the measured physical and rheological properties of processed RAS sampled from different contractors and shingles processors. Chapter 4 discusses the mix design issues when incorporating RAS, production, and field construction of RAS mixes. Finally, this report concludes with a summary described in Chapter 5. The Appendices give a detailed literature review on the use of RAS in asphalt mixes.

CHAPTER 2:
BEST PRACTICE FOR RAS PROCESSING AND PROPOSED GUIDELINES

RAS processing is one of the critical steps for using the RAS in HMA and producing high quality RAS mixes. As noted previously, two types of RAS are available for processing: MWAS and TOAS. For use in HMA, MWAS has traditionally been preferred over TOAS, primarily because MWAS contains fewer contaminants (Hansen, 2009; Maupin, 2008), plus the asphalt in MWAS is less oxidized (Button et al., 1996). MWAS only requires grinding with little or no sorting, inspection, testing, or separation of undesirable materials. Specifically, there is no need for asbestos testing for MWAS. However, MWAS is geographically significantly more restricted than TOAS, as shingle manufacturing facilities are typically located only in densely populated areas (see Figure 1). In contrast, TOAS are more readily available to contractors and recyclers. The main concerns with TOAS are potential asbestos, deleterious materials (including metal, wood, plastic, paper, etc.), and very hard highly oxidized asphalt. Consequently, it becomes more difficult to process the TOAS, and asbestos testing is required in Texas.

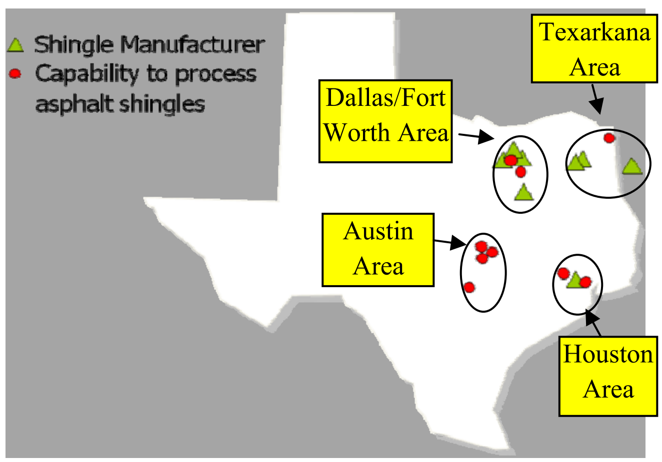

Figure 1. Shingle Manufacturers and Processors in Texas.

Processing RAS basically includes five steps: collecting, sorting, grinding, screening, and storing the processed RAS plus asbestos testing for the TOAS. The research team visited different recyclers and contractors in Texas and reviewed published literature to identify the best practices for each of the steps. Figure 2 shows the best practices identified; detailed explanations and associated guidelines follow.

Step 1: Collecting

Step 2: Asbestos testing for TOAS

Step 3: Sorting

Step 4: Grinding

Step 5: Screening

Step 6: Storing

Figure 2. Proposed RAS Processing Steps.

COLLECTING

Quality (cleanness) of RAS and a sustainable supply are two major issues related to collecting RAS. MWAS is relatively clean, but its supply is limited. In contrast, TOAS has relatively more supplies, but its cleanness (or contamination) is a bigger problem. According to Krivit (2007), the two basic types of strategies to develop a clean, secure supply are:

- *Source Separated*—Attracting high quality, separated loads of clean TOAS. The roofing contractor or hauler must first separate the non-shingle debris (e.g., plastic, metal, wood) before tipping at the shingle recycling plant. Source-separated TOAS should be kept separate from other roofing debris at the demolition site before loading and then are loaded separately onto haul units.
- *Mixed Roofing Material*—Attracting mixed loads of TOAS without requiring source separation, such that the shingle recycler conducts most, if not all, of the materials separation. Non-shingle debris is sorted from the tear-off shingles at a recycling facility. TOAS recyclers might instruct their suppliers to load the shingles first, at the bottom of the haul unit. Then, the non-shingle debris, which are placed on top of the shingles layer, can be easily separated when the load is tipped at the recycling plant.

Under either strategy, Krivit (2007) continues, TOAS recyclers must work proactively with suppliers to ensure that no asbestos containing material (ACM) is delivered to the recycling plant. After the TOAS are tipped at the recycling plant, a second stage of quality inspection and sorting occurs. Most facilities use both manual separation (e.g., 'dump and pick,' sorting conveyors) and mechanical equipment (e.g., screens, air classifiers). Shingle recyclers have demonstrated a wide variety of techniques to cost-effectively meet and exceed the minimum waste sampling and asbestos testing requirements. They have recently developed innovations, such as establishing in-house laboratories that use standard detection methods and certified personnel. Such internal laboratories minimize the turnaround time for test results. Together with other in-house personnel training and supplier technical assistance, TOAS recyclers are proactively managing their supplies through upstream quality control and quality assurance.

Hanson (2009) points out that as part of the quality control and acceptance program, shingle recycling operations need an inspection and testing plan for waste shingles delivered to the site, which should include:

- Type and quality of material that is acceptable.
- Criteria for rejecting loads.
- An asbestos management plan.

A list of prohibited materials for TOAS recyclers should include (Krivit, 2007):

- Cementitious shingles, shake shingles, and transite siding that may contain ACM.
- Any type of hazardous waste (e.g., mercury-containing devices such as thermostats, paint, solvents, or other volatile liquids).
- Significant amounts of other debris that are not asphalt shingles (e.g., plastic, paper glass, or metal).
- Significant amounts of trash.

ASBESTOS TESTING FOR TOAS

According to Hansen (2009), the main issue that impedes recycling of TOAS is concern over potential asbestos content. In the past, asbestos was sometimes used in manufacturing asphalt shingles and other shingle installation materials. Asphalt shingle manufacturers generally acknowledged that, between 1963 and the mid-1970s, some manufacturers did use asbestos in the fiber mat in some of their shingle products, but the total asbestos content of those shingles was always less than 1 percent. Other materials used in shingles, such as some tarpapers and some types of asphalt cement, also reportedly contained asbestos. In reality, while asbestos was heretofore used in some asphalt roofing materials, asbestos was rarely used in the shingles themselves.

Since TOAS may contain asbestos, the Texas Department of State Health Service (TDSHS) regulates asbestos-containing materials including TOAS. More detailed information on asbestos program can be found at TDSHS' website: http://www.dshs.state.tx.us/asbestos/pubs.shtm. Generally, asbestos testing (Figure 3) involves sampling each layer of roofing material. Details of asbestos testing are described in EPA/600/R-93/116, "Test Method for the Determination of Asbestos in Building Materials," (Perkins and Harvey, 1993). The complete test method is available at: http://www.rti.org/pubs/Test-Method-for-Determination.pdf. Representative samples must be properly selected, labeled, recorded in a sample log book, and then sent to an accredited asbestos testing laboratory for assay of asbestos content. TOAS recyclers should contact the appropriate state environmental and/or health agency to determine specific requirements for sample collection, analytical procedures, data reporting, and records preservation.

Figure 3. Setup for Asbestos Testing (after Krivit, 2007).

Krivit (2007) advised that shingle recycling operators should attend state-sponsored training courses to become licensed asbestos inspectors. Trained personnel should inspect each load to visually detect possible ACM. This will help increase the awareness of potential asbestos containing materials and allow company personnel to help provide accurate, timely, and state-approved information and related technical assistance to material suppliers and other customers. Shingle recycling operators should contact their state representative for the National Emission Standards for Hazardous Air Pollutants (NESHAP) to explore technical assistance resources, including a listing of organizations providing asbestos inspector training. The website www.shinglerecycling.org is an excellent source of EPA and other regulatory information regarding asbestos, management, and recommended best practices. Specifically, in Texas TCEQ has several regulations that may impact asphalt shingle processors, which can be found using the following links:

- Recycling: http://www.tceq.state.tx.us/permitting/waste_permits/msw_permits/MSW_amIregulatedrecycling.html.
- Industrial Storm Water: http://www.tceq.texas.gov/permitting/stormwater/TXR05_AIR.html.
- Storm Water from Construction Activities: http://www.tceq.texas.gov/permitting/stormwater/TXR15_AIR.html.

SORTING

Generally, little sorting work is needed for MWAS. However, substantial sorting work is required for TOAS because various debris (e.g., nails, wood, and insulation) contaminate this type of shingle. Any debris must be removed to prevent equipment damage during size reduction and produce high-quality processed RAS. There is no standard processing equipment to accomplish this task; in most cases, the debris has to be sorted out manually (see Figure 4).

Figure 4. Sorting RAS Manually (Picture (1) one after Krivit, 2007).

Note that most facilities will recover metal and cardboard (perhaps in baled form) as secondary recyclable products. Trash from such sorting consists of plastic, non-recyclable metal, and paper. Recovery rates of TOAS from mixed waste sorting systems range from 15 to over 90 percent, depending on the feedstock and the efficiency of the separation (Krivit, 2007).

GRINDING

The vast majority of RAS used in asphalt paving mixes is ground into pieces smaller than ½ inch (13 mm) in size using a shingle grinding or shredding machine consisting of a rotary shredder and/or a high-speed hammer mill. It seems logical that, as shingles are ground finer, more RAS asphalt can be mobilized into the paving mixture.

According to Krivit (2007), each grinder manufacturer uses a unique combination of material handling and size reduction designs. RAS sizing is a key specification and will determine the product's suitability for various applications. For example, the larger particle size (+ 3/4 inch) may be more suitable for aggregate supplement. In general, the grinder will include a loading hopper; a grinding chamber that includes cutting teeth, sizing screens, and exit conveyor; and a feeding drum to present the shingles into the grinding chamber. A pulley head magnet at the end of the exit conveyor is standard equipment for removing nails and other ferrous metal. The final RAS product is stacked using a stacking conveyor and/or front-end loader. During visits to recyclers and contractors, the research team noted that it is important and necessary to pick up some debris left in the 'sorted, clean' pile before feeding to the grinder (see Figure 5).

Figure 5. Preparation for Grinding.

To prevent agglomerating during grinding, the material may be passed through the grinding equipment only once to reduce heating or it is kept cool with water spray at the hammer mill. However, the application of water is not very desirable, since the processed material becomes quite wet and must be dried (thus incurring additional fuel cost) prior to introduction into the HMA (Chesner et al., 1997).

SCREENING

Ground shingles may contain oversize pieces that do not meet the specification requirement. To remove the oversize pieces, the operators ideally should screen the processed RAS using a trommel screener (Figure 6). This equipment can help customize the size of processed RAS, thus guaranteeing that the specifications are met. Furthermore, the oversize pieces can be reground to the ideal size. Chesner et al. (1997) contends that scrap shingle greater than ½ inch may not readily disperse in HMA and may function much like aggregate particles; too small particles can release short fibers, which act as a filler substitute. Hansen (2009) adds that several HMA producers have found that grinding to less than ⅜ inch improves blending. Texas DOT specifies 100 percent passing the ½-inch sieve with 95 percent passing the ⅜-inch sieve.

Figure 6. Screening RAS Using Trommel Screen Machine.

STORING

Storing the processed RAS is typically conducted similar to that of aggregate or RAP. Because the average gradation of RAS is very small, a stockpile can absorb a large amount of water, which can cause problems during HMA mixing (inadequate coating), compaction (mat tenderness), and performance (higher stripping potential) as well as require more fuel for drying. Ideally, a RAS stockpile should be covered (Figure 7). Additionally, it is important to keep loaders off RAS stockpiles and separate high AC RAS (tear-offs) from low AC RAS (manufacture waste).

Button et al. (1996) deduced that, during static storage in a stockpile, shredded roofing shingle material can agglomerate. High temperatures and the stickier manufacturing waste shingles can magnify this issue. Significant agglomeration or consolidation of processed roofing material necessitates reprocessing and rescreening prior to introduction into the hot mix plant. To mitigate this problem, processed roofing shingle scrap may be blended with a small amount of less sticky carrier material, such as sand or RAP, to prevent the RAS particles from clumping together.

Figure 7. Covered RAS Storing Facility.

SUMMARY

This chapter discussed best practices for RAS processing and proposed guidelines for collecting, sorting, grinding, screening, and storing the processed RAS. The asbestos test is required for the TOAS.

CHAPTER 3:
PHYSICAL AND RHEOLOGICAL PROPERTIES
OF PROCESSED RAS

To use the processed RAS in HMA, at least four physical and rheological properties need to be determined. These four properties are (1) gradation of processed RAS, (2) gradation of RAS aggregates, (3) RAS binder content, and (4) RAS binder performance grade (PG), which are all important to HMA mix design. It is well known that the finer the processed RAS, the potentially better mixing with the virgin binder. Therefore, many states including Texas specify the gradation of the processed RAS. This chapter presents the laboratory test results of a variety of processed RAS including MWAS and TOAS in terms of the four physical and rheological properties.

PROCESSED RAS SAMPLES

The research team visited different contractors and recyclers around Texas, and sampled a total of seven different types of processed RAS stockpiles. These seven processed RAS stockpiles include three MWAS, three TOAS, and one MWAS/TOAS blend. For simplicity, these are named RAS-A, RAS-B, RAS-C, RAS-D, RAS-E, RAS-F, and RAS-G. For each processed RAS stockpile, the team collected seven replicates and brought these back to TTI for laboratory testing.

LABORATORY TESTS

Researchers characterized each processed RAS collected in this study according to TxDOT's test procedures (see Table 2). Note that for RAS aggregate gradation, they performed two different tests—ignition method and extraction method—to compare the results. Specifically, the centrifuge plus the Rotavapor recovery method (Figure 8) were used to recover the binder from the processed RAS. For the extracted and recovered RAS binder, the dynamic shear rheometer (DSR) and the bending beam rheometer (BBR) were used to determine the PG grade.

Table 2. Physical and Rheological Properties of Processed RAS and Associated Tests.

Physical Properties of Processed RAS	Laboratory Test
Gradation of processed RAS	Tex-200-F, Part I Dry Sieve Analysis
Asphalt binder content	Tex-236-F, Ignition Method and Tex-210-F, Extraction Method
Gradation of RAS aggregates (or solids)	
Asphalt binder PG grade	Tex-211-F, Binder Recovery and then Dynamic Shear Rheometer (DSR) Test and Bending Beam Rheometer (BBR) Test

Figure 8. Centrifuge-Rotavapor Recovery Method.

TEST RESULTS AND DISCUSSION

Dry Sieve Analysis Results

Table 3 presents the dry sieve analysis test results for seven replicates of all seven processed RAS stockpiles. Currently, TxDOT's specification requires 100 percent passing the ½-inch sieve and 95 percent passing a ⅜-inch sieve. All seven processed RAS stockpiles tested met the specification. In fact, three processed RAS stockpiles (B, F, and G) had 100 percent passing the ⅜-inch sieve.

Ignition Oven Test and Associated Results

For RAP and conventional asphalt mixes, the ignition oven test method, Tex-236-F, requires 1300 grams of representative material to determine the asphalt content and a washed sieve analysis. However, since this material has very high asphalt content (more than 20 percent), 1300 grams of RAS could not be completely burned even if the specimen is burned more than three times. After many trials, researchers found that approximately 500 grams of RAS material provides complete burning and consistent results in terms of RAS binder content and RAS aggregate (solids) gradation. After presenting these results to TxDOT, the recommended RAS sample size was changed to 500–700 grams in the ignition oven test procedure. Tables 4 through 10 tabulate the test results for seven replicates of all seven processed RAS stockpiles (RAS-A to G, respectively).

The results shown in Tables 4 through 10 clearly indicate that:

- TOAS have higher binder content than MWAS. MWAS have a consistent 20 percent binder content; TOAS have various binder contents, ranging from 23 percent to 28 percent.
- MWAS have slightly finer gradations than TOAS.
- Overall, the RAS variability in terms of asphalt binder content and gradation are low for both MWAS and TOAS. MWAS have a slightly lower variability.

Table 3. Dry Sieve Analysis Results of Seven Processed RAS Materials.

RAS	Sieve No.	#1	#2	#3	#4	#5	#6	#7	Average	Standard Deviation
A Blended (manu.+tear.)	1/2"	100	100	98	99	100	100	100	100	0.6
	3/8"	99	98	96	99	99	99	99	98	1.1
	#4	91	82	87	91	88	88	90	88	3.1
B Manufacture waste	1/2"	100	100	100	100	100	100	100	100	0.0
	3/8"	100	100	100	100	100	100	100	100	0.1
	#4	85	80	89	93	87	89	90	87	4.1
C Manufacture waste	1/2"	99	99	99	100	100	100	99	100	0.2
	3/8"	97	96	97	97	98	96	96	97	0.8
	#4	78	77	78	74	82	68	67	75	5.4
D Manufacture waste	1/2"	100	100	100	100	99	100	99	100	0.5
	3/8"	94	96	97	97	97	96	94	96	1.5
	#4	80	83	85	84	84	83	81	83	1.7
E Tear-off	1/2"	100	100	100	100	100	100	100	100	0.1
	3/8"	97	98	95	92	97	96	96	96	2.0
	#4	85	90	82	76	88	85	85	84	4.5
F Tear-off	1/2"	100	100	100	100	100	100	100	100	0.1
	3/8"	99	100	99	100	100	100	99	100	0.2
	#4	81	86	82	84	88	86	84	84	2.3
G Tear-off	1/2"	100	100	100	100	100	100	99	100	0.4
	3/8"	100	100	100	100	100	100	98	100	0.9
	#4	94	93	95	94	93	94	89	93	2.2

Table 4. Ignition Test Results: RAS-A (Blended MWAS+TOAS).

Sieve size	#1	#2	#3	#4	#5	#6	#7	Average	Standard Deviation
1/2"	100	100	100	100	100	100	100	100	0.0
3/8"	100	100	100	100	100	100	100	100	0.0
#4	99	99	98	99	99	99	99	99	0.4
#8	98	96	97	97	98	97	97	97	0.5
#16	82	79	81	82	83	79	80	81	1.4
#30	61	60	61	61	66	58	59	61	2.2
#50	52	52	52	51	56	49	51	52	2.0
#100	42	42	41	40	45	38	41	41	1.7
#200	30	31	29	29	33	28	31	30	1.4
Binder content	20	22	20	20	19	20	20	20	0.7

Table 5. Ignition Test Results: RAS-B (Manufacture Waste).

Sieve size	#1	#2	#3	#4	#5	#6	#7	Average	Standard Deviation
1/2"	100	100	100	100	100	100	100	100	0.0
3/8"	100	100	100	100	100	100	100	100	0.0
#4	100	100	100	100	99	98	99	99	0.5
#8	99	98	99	99	98	95	97	98	1.5
#16	85	83	85	86	83	80	83	83	2.0
#30	66	63	64	65	63	59	61	63	2.1
#50	57	53	54	55	52	50	51	53	2.3
#100	45	42	42	43	37	37	37	40	3.1
#200	33	30	30	32	27	27	28	30	2.2
Binder content	21	19	21	19	20	20	19	20	0.7

Table 6. Ignition Test Results: RAS-C (Manufacture Waste).

Sieve size	#1	#2	#3	#4	#5	#6	#7	Average	Standard Deviation
1/2"	100	100	100	100	100	100	100	100	0.0
3/8"	100	100	100	100	100	100	100	100	0.0
#4	100	100	100	99	99	99	99	99	0.3
#8	99	97	98	99	99	98	99	98	0.7
#16	80	77	78	84	80	85	87	81	3.5
#30	60	58	59	65	57	67	70	62	4.9
#50	54	52	53	58	51	62	65	56	5.1
#100	46	42	42	48	42	52	54	47	4.5
#200	36	32	32	38	33	40	40	36	3.5
Binder content	20	20	20	23	19	24	24	22	2.0

Table 7. Ignition Test Results: RAS-D (Manufacture Waste).

Sieve size	#1	#2	#3	#4	#5	#6	#7	Average	Standard Deviation
1/2"	100	100	100	100	100	100	100	100	0.0
3/8"	100	100	100	100	100	100	100	100	0.0
#4	99	99	99	99	99	99	99	99	0.1
#8	96	97	97	97	97	97	98	97	0.5
#16	81	82	81	80	81	81	83	81	0.9
#30	63	62	61	60	61	61	64	62	1.3
#50	53	52	52	50	51	51	54	52	1.3
#100	41	40	40	38	39	39	41	40	1.1
#200	30	30	29	28	29	29	31	30	0.9
Binder content	21	21	21	20	19	20	20	20	0.6

Table 8. Ignition Test Results: RAS-E (Tear-off).

Sieve size	#1	#2	#3	#4	#5	#6	#7	Average	Standard Deviation
1/2"	100	100	100	100	100	100	100	100	0.0
3/8"	100	100	100	100	100	100	100	100	0.1
#4	98	91	98	99	94	98	99	97	2.7
#8	95	86	96	96	86	93	95	92	4.1
#16	75	65	76	80	66	72	74	73	5.0
#30	53	44	53	64	48	49	52	52	5.8
#50	48	38	47	60	43	43	46	46	6.2
#100	41	31	39	54	36	35	38	39	6.6
#200	30	22	28	46	28	25	27	30	7.2
Binder content	25	24	28	28	28	28	28	27	1.5

Table 9. Ignition Test Results: RAS-F (Tear-off).

Sieve size	#1	#2	#3	#4	#5	#6	#7	Average	Standard Deviation
1/2"	100	100	100	100	100	100	100	100	0.0
3/8"	100	100	100	100	100	100	100	100	0.0
#4	100	99	98	96	99	100	100	99	1.1
#8	99	96	89	87	94	98	98	95	4.6
#16	82	77	67	65	72	72	77	73	5.5
#30	58	53	44	44	48	47	51	50	4.8
#50	51	46	36	37	40	41	44	42	4.9
#100	44	38	27	29	31	31	37	34	5.6
#200	33	28	17	19	20	21	27	24	5.3
Binder content	33	29	28	28	27	27	27	28	1.9

Table 10. Ignition Test Results: RAS-G (Tear-off).

Sieve size	#1	#2	#3	#4	#5	#6	#7	Average	Standard Deviation
1/2"	100	100	100	100	100	100	100	100	0.0
3/8"	100	100	100	100	100	100	100	100	0.0
#4	98	99	99	94	97	97	97	97	1.5
#8	93	98	98	90	94	95	93	94	2.5
#16	72	79	80	71	75	76	74	75	3.1
#30	52	58	58	50	54	54	55	54	2.6
#50	45	52	52	44	47	49	49	48	2.7
#100	36	44	44	37	40	41	41	40	2.7
#200	25	33	32	27	29	30	31	30	2.4
Binder content	22	24	22	23	23	23	24	23	0.7

RAS Binder Extraction and Recovery Test and Associated Results

In addition to the ignition oven test, researchers performed the extraction and recovery test with seven replicates to characterize RAS binder content and RAS aggregate gradation. They also used the recovered RAS binder to determine the PG grade (discussed in the next section). Two MWAS and TOAS were tested; Tables 11 through 14 present the test results in terms of binder content and aggregate gradation (wet sieve analysis) for RAS-B, C, E, and F.

The results in Tables 11 through 14 show similar trends:

- TOAS have higher binder content than MWAS. MWAS have a consistent 20 percent binder content; TOAS have various binder contents, ranging from 24 percent to 26 percent.
- MWAS have slightly finer gradations than TOAS.
- Overall, the RAS variability in terms of asphalt binder content and gradation are low for both MWAS and TOAS.

Table 11. Extraction and Recovery Test Results: RAS-B (Manufacture Waste).

Sieve size	#1	#2	#3	#4	#5	#6	#7	Average	Standard Deviation
1/2"	100	100	100	100	100	100	100	100	0.0
3/8"	100	100	100	100	100	100	100	100	0.0
#4	97	99	99	99	98	98	99	98	0.5
#8	96	98	98	98	97	97	97	97	0.8
#16	80	83	84	84	83	83	83	83	1.3
#30	62	62	64	64	61	64	63	63	1.1
#50	54	52	55	55	52	55	54	54	1.2
#100	40	36	44	44	40	43	43	41	2.8
#200	25	20	33	32	30	32	32	29	4.5
Binder content	21	20	20	20	19	20	20	20	0.7

Table 12. Extraction and Recovery Test Results: RAS-C (Manufacture Waste).

Sieve size	#1	#2	#3	#4	#5	#6	#7	Average	Standard Deviation
1/2"	100	100	100	100	100	100	100	100	0.0
3/8"	100	100	100	100	100	100	100	100	0.2
#4	98	99	98	97	97	96	97	97	0.9
#8	97	98	97	96	95	95	97	96	1.0
#16	78	80	80	84	79	83	83	81	2.3
#30	58	59	61	66	62	67	64	63	3.2
#50	53	54	56	60	58	62	59	57	3.2
#100	43	44	46	50	49	52	47	47	2.9
#200	33	34	36	38	37	40	34	36	2.4
Binder content	19	19	20	22	22	24	20	21	1.9

Table 13. Extraction and Recovery Test Results: RAS-E (Tear-off).

Sieve size	#1	#2	#3	#4	#5	#6	#7	Average	Standard Deviation
1/2"	100	100	100	100	100	100	100	100	0.0
3/8"	97	98	97	97	97	98	97	97	0.5
#4	95	94	94	95	93	94	95	94	0.8
#8	93	92	92	91	89	92	93	92	1.4
#16	76	74	74	70	73	75	75	74	2.0
#30	54	51	51	54	51	50	53	52	1.6
#50	47	45	45	47	42	46	46	45	1.7
#100	40	38	38	40	39	41	40	39	1.1
#200	29	27	28	23	27	30	25	27	2.4
Binder content	24	23	25	24	24	25	25	24	0.8

Table 14. Extraction and Recovery Test Results: RAS-F (Tear-off).

Sieve size	#1	#2	#3	#4	#5	#6	#7	Average	Standard Deviation
1/2"	100	100	100	99	98	100	100	100	0.7
3/8"	100	99	99	97	96	99	100	99	1.2
#4	96	96	94	94	92	96	98	95	1.8
#8	95	95	91	93	90	94	95	93	2.0
#16	79	78	74	77	74	76	78	77	2.0
#30	57	55	51	56	53	54	59	55	2.4
#50	48	49	44	49	46	47	52	48	2.5
#100	40	42	38	42	39	41	44	41	2.0
#200	32	33	31	33	30	32	35	32	1.4
Binder content	26	27	27	26	27	27	20	26	2.3

RAS BINDER PG GRADE

It is important to know the true PG grade of the RAS binder since it has significant influence on virgin binder selection and the allowable, maximum amount of RAS used in the asphalt mixes. The binders extracted and recovered from either MWAS or TOAS are very stiff, compared with virgin paving asphalts. During a visit to one of the shingles manufacturers in Texas, the research team was informed that the RAS binder is an air-blown AC 5 binder. It is far stiffer than any PG76-22 binder, which is the most stiff binder used in Texas. Consequently, the research team had three difficulties during the process of determining RAS binder PG grade.

- The first difficulty was to recover the TOAS binder. It was too stiff to flow out of the beaker even at 165°C after finishing the recovery process. In one case, the temperature was raised to 200°C to drain out the TOAS binder.
- The second difficulty was to grade the recovered RAS binder at high temperature. Due to the upper limitation of test temperature, a regular DSR cannot accurately grade extracted RAS binder. To solve this problem, TTI purchased a new DSR (Figure 9) that can test binders at temperatures up to 200°C.

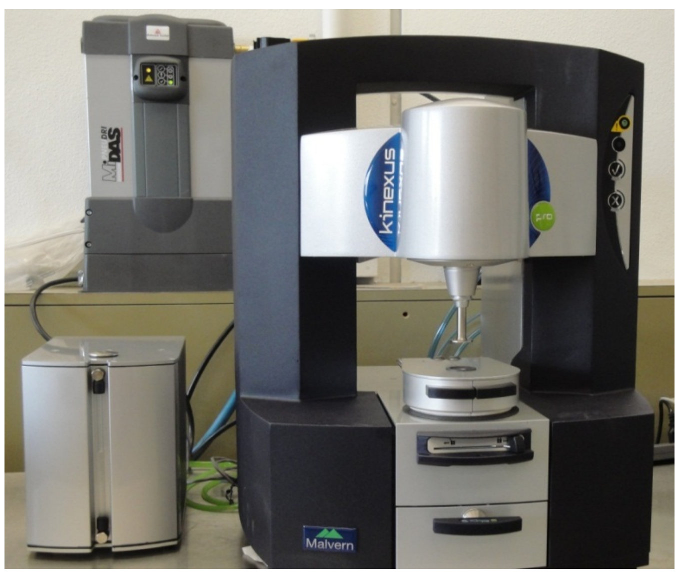

Figure 9. TTI Advanced DSR Test Machine.

- The third difficulty was to grade the recovered RAS binder at a low temperature using the BBR test. There are two criteria (S and m) for the low temperature PG grade. The RAS binders met the S (300 MPa) criteria, but the m values just could not reach 0.3 due to substantial aging. (Note that the m value indicates the binder's capability to relax under stress.) The research team even tried the time-superposition principle to estimate the m values, but no acceptable results could be obtained.

So far the extracted and recovered binders from two MWAS and two TOAS have been graded using DSR for high temperature and no low temperature PG could be determined from BBR test. The results are listed below:

- RAS-B (manufacture waste): PG136.
- RAS-C (manufacture waste): PG118.
- RAS-E (tear-off): PG157.
- RAS-F (tear-off): PG203+higher than 25°C.

Obviously, the RAS binders are very stiff. It is critical to investigate the blending between virgin binders and these RAS binders. Note that the low temperature PG of RAS binder is ABOVE 0°C.

DISCUSSION: IGNITION METHOD VS. EXTRACTION METHOD

As presented earlier, two methods—ignition and extraction—determine the RAS binder content and RAS aggregate gradation. The ignition method is preferred due to its simplicity and effectiveness. However, the concern is that some fibers and fines are also burned off and, accordingly, the RAS binder content is overestimated. This study compared the two methods, and Table 15 lists the results. Two observations are made:

- Generally, the ignition oven method gives a little higher binder content, but not much when comparing the high binder content of the RAS itself.
- Except for RAS-F (tear-off shingle), both methods produce almost the same RAS aggregate gradation.

Therefore, the ignition oven method is acceptable for determining RAS binder content and aggregate gradation based on limited data from this study. The current TxDOT HMA specifications that allow the usage of RAS require the asphalt content and gradation of the RAS material to be determined for mixture design purposed in accordance with the ignition oven test method.

Table 15. Comparison between Ignition Method and Extraction Method.

Sieve size	RAS-B (manufacture waste)		RAS-C (manufacture waste)		RAS-E (Tear-off)		RAS-F (Tear-off)	
	Ignition	Extraction	Ignition	Extraction	Ignition	Extraction	Ignition	Extraction
1/2"	100	100	100	100	100	100	100	100
3/8"	100	100	100	100	100	97	100	99
#4	99	98	99	97	96	94	99	95
#8	98	97	98	96	92	92	95	93
#16	83	83	81	81	72	74	73	77
#30	63	63	62	63	50	52	50	55
#50	53	54	56	57	44	45	42	48
#100	40	41	47	47	37	39	34	41
#200	30	29	36	36	27	27	24	32
Binder content	20	20	22	21	26	24	28	26

SUMMARY

This chapter investigated the physical and rheological properties of processed RAS, including processed RAS gradation, RAS binder content, RAS aggregate (or solid) gradation, and RAS binder PG grade. Both MWAS and TOAS were evaluated in this study. Based on the results presented in this chapter, the following conclusions are made:

- Currently, TxDOT's specification requires 100 percent passing the ½-inch sieve and 95 percent passing the ⅜-inch sieve. All the processed RAS investigated in this study met the specification. Actually, three processed RAS materials (B, F, and G) even passed the ⅜-inch sieve 100 percent.
- TOAS have higher binder content than MWAS. MWAS have a consistent 20 percent binder content; TOAS have various binder contents, ranging from 23 percent to 28 percent.
- MWAS have slightly finer gradations than TOAS.
- Overall, the RAS variability in terms of asphalt binder content and gradation are low for both MWAS and TOAS. MWAS yielded a slightly lower variability.

- The RAS binders are very stiff. It is critical to investigate the blending between virgin binders and these RAS binders. Note that the low temperature PG of RAS binder is ABOVE 0°C.
- Generally, the ignition oven method gives a slightly higher binder content, but not much when comparing the high binder content of RAS itself. Except for RAS-F (TOAS), both methods produce almost the same RAS aggregate gradation. Researchers can conclude that the ignition oven method is acceptable for determining RAS binder content and aggregate gradation based on limited data from this study.

CHAPTER 4:
ISSUES ON RAS MIX DESIGN, PRODUCTION, AND CONSTRUCTION

HMA MIX DESIGN WITH RAS

Although there is no significant difference between RAS mixes and virgin mixes in terms of production in the plant, designing RAS mixes is more complicated than that for virgin asphalt mixes. Not only must the virgin aggregate and virgin binder information be obtained, but RAS binder content and RAS aggregate gradation must be determined through the ignition oven. Asphalt binder recovery tests may be needed to grade the RAS binder in order to use the asphalt blending chart. Additionally, there are at least five more challenges when designing RAS mixes in Texas.

Cracking Resistance of HMA Mixes with RAS

Virgin HMA mixes designed using the Texas gyratory compactor (TGC) are generally dry and have good rutting resistance but relatively poor fatigue and reflection cracking resistance. Poor cracking resistance may become even worse when mixes containing stiff, hard RAS binders are placed. It is critical for HMA mix designs with RAS to have acceptable cracking resistance through increasing the density requirement for TGC designed mixes or reducing N_{design} for SGC designed mixes so that enough virgin binder is included in the mix. Alternatively, a balanced mix design approach Zhou et al. (2007) proposed can be used to design mixes with RAS, whereby the optimum asphalt content (OAC) is selected based on target air voids (or density), rutting/moisture, and cracking resistances determined using the Hamburg wheel tracking test (HWTT) and the Overlay test (OT), respectively.

Virgin and RAS Binder Blending

The virgin and RAS binder blending issue has not been well investigated. The actual blending between virgin and RAS binder during production is unknown. Although some approaches (e.g., dynamic modulus-based approaches) have been proposed for RAP/virgin binder blending, how much of the RAS binder actually blends with the virgin binder is very difficult, if not impossible, to determine accurately. Apparently, more work is needed in this area.

RAS Heating

RAS needs heating to make it workable and activate RAS binder. Many methods are available for handling RAS in the lab during the mix design process, but none of them can truly simulate the plant production process.

It is important to heat RAS materials to ensure the RAS binder becomes an active part of the HMA binder. Basically, there are two issues with RAS heating in the laboratory: time and temperature. Different methods are available. Some designers preheat RAS materials at the target mixing temperature for a certain period of time before mixing with virgin aggregates. Others superheat the virgin aggregate to ensure heat transfer to the RAS, which is added at room temperature. There is no specific information on RAS heating in the literature. Based on the research team's experience with RAP mix design and limited data on RAS mix design, a two-step preheating process is recommended: (1) warm the RAS overnight (12–15 hours) at 140°F

(60°C), which is a common temperature to dry materials, and 2) preheating the RAS at the mixing target temperature for two hours, which is a common time for preheating virgin binder. This two-step preheating process needs further verification.

Mixing and Compaction Temperatures

It is well-known that mixing and compaction temperatures are important and influence compaction, volumetrics (e.g., air voids, VMA), and consequently OAC. For any virgin asphalt mix, the mixing and compaction temperatures are selected based on virgin binder properties (i.e., viscosity). When RAS is added, one has to consider both virgin binder and RAS binder properties. Guidelines are needed for selecting suitable mixing and compaction temperatures, especially when designing HMA mixes with high RAS content.

Mixing and compaction temperatures for high RAS mixes have not been well addressed in the literature. For RAS mixes, there are at least three options for selecting laboratory mixing and compaction temperatures:

- Those corresponding to the virgin binder.
- Those corresponding to the blended virgin/RAS binder.
- Those corresponding to the RAS binder.

Generally RAS binder is stiffer than virgin binder. The virgin binder will be overheated and, consequently, significantly aged if Option 3 (those corresponding to the RAS binder) is chosen. It is well-known that increasing the mixing and compaction temperatures lowers the OAC and consequently, cracking resistance of RAS mixes, since the higher mixing and compaction temperatures lead to lower OAC. Therefore, from the conservative point of view, researchers propose to use Option 1: the mixing and compaction temperatures corresponding to virgin binder. This potentially provides RAS mixes adequate OAC and thus better cracking resistance.

RAS in Warm Mix Asphalt

A few researchers (Robinette and Epps, 2010; Middleton and Forfylow, 2009) recently reported that RAS had been used in WMA, but not much lab testing has been done to make conclusive findings on RAS/WMA. The only one report (Maupin, 2010) was found in which testing of WMA containing RAS was performed. However, after carefully reviewing the work done by Maupin (2010), apparently it was found that neither additives nor forming system was used to produce the WMA. Instead, he simply lowered the mixing temperature to 250°F from the regular HMA temperature of 300°F. Therefore, more work is definitely needed in this area.

RAS MIX PRODUCTION

Producing RAS mixes is similar to that for RAP mixes. Normally RAS is treated like RAP with a cold bin and is fed into the plant. As Morton (2011) noted, there are at least four specific issues that are worth watching when producing RAS mixes:

- Keep RAS bin empty when not in use.
- Use a vibratory scalping screen to help break down or remove clumps that may be in the RAS material before entering the drum.

Figure 10. Vibratory Scalping Screen (after Morton, 2011).

- Don’t superheat the mix; it makes the RAS mix stiffer and more difficult to work with in the field.
- Avoid holding RAS mix in silo overnight.

RAS MIX CONSTRUCTION

Construction of RAS mixtures is similar to that for RAP mixes. Again there are several specific issues to consider during RAS mix construction, as Morton (2011) pointed out:

- Consider the weather.
- Consider the haul distance.
- Consider the trucks that haul the mix.
- Do not let mix set in trucks too long on job site.
- Check RAS mix temperature when unloading trucks.
- Mix tends to stiffen quicker in trucks than standard hot mix.
- More difficult to hand work.
- Mat can be more sensitive to temperature segregation.

CHAPTER 5: SUMMARY AND RECOMMENDATION

This report presented the best practices for using RAS in asphalt mixes in terms of RAS processing, characterization (binder content, gradations, and PG grade), mix design, production, and field construction. Based on the information presented, the following findings and conclusions are offered.

- A six-step RAS processing guideline is proposed in this study, which includes five steps: collecting, sorting, grinding, screening, and storing the processed RAS plus asbestos testing for TOAS.
- Currently, TxDOT's specification requires 100 percent passing ½-inch sieve and 95 percent passing ⅜-inch sieve. All processed RAS investigated in this study meet the specification. In fact, three processed RAS: B, F, and G passed the ⅜-inch sieve 100 percent.
- Tear-off shingles have higher binder content than manufacture waste shingles. Manufacture waste shingles have a consistent 20 percent binder content; tear-off shingles have binder contents that range from 23 percent to 28 percent.
- Manufacture waste shingles have slightly finer gradations than the tear-off shingles.
- Overall, RAS variability in terms of asphalt binder content and gradation are low for both manufacture waste and tear-off shingles. Manufacture waste shingles have a slightly lower variability.
- RAS binders are very stiff. It is critical to investigate blending between virgin binders and RAS binders. Note that the low temperature PG of RAS binder is ABOVE 0°C.
- Generally, the ignition oven method yields a slightly higher binder content than the solvent extraction method. Except for RAS-F (tear-off shingle), both methods produced almost the same RAS aggregate gradation. Therefore, the ignition oven method is acceptable for determining RAS binder content and aggregate gradation based on limited data from this study.
- Issues related to RAS mix design, production, and construction were identified and discussed. Some of them are addressed in this report, and some need further investigation:
    - Very little information was found in published literature regarding the use of RAS in warm asphalt mixtures. For WMA, the question remains: does the harder roofing asphalt in RAS soften sufficiently during plant mixing process to become a functional part of the WMA binder system? This is a particular dilemma when using RAS in WMA.
    - Most studies have shown good rutting resistance when RAS is combined with HMA. Long-term performance of asphalt mixtures incorporating RAS material needs to be evaluated with respect to fatigue cracking, low-temperature cracking, stripping, and raveling. Life-cycle cost analyses should be performed to determine the economic viability of using RAS.

- Since RAS will likely be used along with RAP more often than not, long-term performance of HMA and particularly WMA incorporating both RAS and RAP needs to be evaluated with respect to common performance measures (e.g., rutting, fatigue, low-temperature cracking, stripping, and raveling).

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APPENDIX A:
LITERATURE REVIEW ON THE USE OF SHINGLES IN ASPHALT PAVING MIXTURES

INTRODUCTION

To sustain economic advantages and preserve the environment, the asphalt paving industry has been a national leader in recycling for decades. Many different products have been studied for potential use in asphalt pavements and some are used routinely (e.g., scrap tires, crushed glass; steel, aluminum, and boiler slag, coal fly ash, kiln dust, foundry sand, and roofing shingles). However, their most extensively recycled product is, by far, reclaimed asphalt pavement (RAP) (Newcomb et al., 2007).

With recent increases in the price of asphalt cement and subsequent price fluctuations, the industry has further amplified its recycling efforts (Hansen, 2009). Since recycled asphalt shingles (RAS) may contain <20 to >35 percent asphalt (Townsend et al., 2007; McGraw et al., 2007), contractors have seen significant economic benefits in using shingles in paving mixtures. There are two basic types of roofing shingle scraps: (1) post-consumer or tear-off asphalt shingles (TOAS) or tear-off roofing shingles and (2) manufacturing by-product or waste asphalt shingles (MWAS) including roofing shingle tab punch-outs and out-of-spec shingles. MWAS is called prompt roofing shingle scrap in some publications. TOAS may contain significantly higher weight percentages of asphalt than MWAS, because a significant portion of the aggregate particles have worn off during service and demolition operations.

Roofing shingle manufacturers in the United States generate approximately one million tons of MWAS (Newcomb et al., 1993a). According to www.shinglerecycling.org, an additional 10 million tons/year of TOAS are generated, and this amount will increase with time (Ali et al., 1995). Most of these waste shingles are deposited in landfills, creating a sizable disposal problem and gradual loss of precious landfill space (Zickell, 2003). According to Mallick et al., 2000), roofing shingles constitute a major waste product in the United States in that the shortage of landfill space in Massachusetts is reflected in a recent significant increase in landfill deposit fee, from \$10−\$20 per ton to \$90−\$100 per ton.

More than 30 years ago, some of the original pioneers established the first shingle recycling plants, investigated HMA mix designs incorporating RAS, and then published the first technical literature in the late 1980s (Epps and Paulsen, 1986; Paulsen et al., 1986; and Shepherd et al., 1989). More recently, several additional HMA producers and departments of transportation have developed substantial in-house expertise in shingle recycling in HMA (Grzybowski, 1993; Newcomb et al., 1993a; Button et al., 1996; Janisch and Turgeon, 1996; NAHB, 1999; Dykes, 2002; Peterson, 2003; Lum, 2006; Brock 2007; Schroer, 2007). Within the last two or three years, a few contractors and DOTs have begun using or studying the use of recycled shingles in warm mix asphalt (WMA) (Robinette and Epps, 2010; Maupin, 2010; Middleton and Forfylow, 2009).

With the recent increased use of asphalt shingles in asphalt mixtures, there is a need to further study this issue. The main objectives of this literature review are to identify best practices for:

- Collection of shingles.
- Storage (stockpiling).
- Asbestos testing.
- Processing (size reduction).
- Stockpiling of processed shingles.

Additional objectives of this exercise are to explain any available information regarding the use of both RAP and RAS in asphalt paving mixtures and the use of RAS in WMA. Shingles use much harder grades of asphalt than those used in paving operations. Many engineers are concerned that the temperatures used to produce WMA may not be sufficient to activate the harder asphalt in shingles, particularly those highly oxidized asphalts in tear-off shingles.

COMPOSITION OF RESIDENTIAL ASPHALT SHINGLES

Basic knowledge of the composition of asphalt shingles is valuable for better management of shingle recycling. There are many brands of asphalt shingles, and their individual material composition can be a primary indicator of the best and highest value use as a recyclable commodity. Of course, for residential tear-off shingles, the different types of shingles available in a given area are blended during demolition, collection, and processing. Table A-1 shows typical compositions of new residential shingles with fibrous mats of either organic felt (cellulose) or fiberglass.

Table A-1. Typical Compositions of New Residential Asphalt Shingles (modified after Townsend et al., 2007 and Krivit, 2007).

Component	Organic Shingles, % by wt.	Fiberglass Shingles, % by wt.
Asphalt Cement	30−36	19−22
Reinforcing Mat	2−15	2−15
Mineral Granules/aggregate	20−38	20−38
Mineral Filler/stabilizer	8−40	8−40
Adhesives (modified asphalt based)	0.2−2	0.2−2

The obvious reason for the high value of recycled shingles is that they contain ingredients that HMA contractors purchase to fabricate their paving mixtures (e.g., asphalt cement, mineral aggregate [sand and filler] and, occasionally, fibers [from the fibrous mat made of organic felt or fiberglass that is valuable as fiber in certain asphalt paving mixes]). Clearly, HMA remains the preferred market for most asphalt shingle recyclers today. According to Krivit (2007), supplementary pavement construction applications for RAS include:

- Aggregate supplement for road base and subbase.
- Aggregate supplement for preparation of roadbed subgrade (or underlayment).
- Surface layers for low-volume roads, driveways, and parking lot surfaces (sometimes preblended with RAP and emulsified asphalt, then spread and compacted.
- Dust control on unpaved roads.
- Cold patching materials (fibers in RAS enhance structural integrity of a patch).

Krivit (2007) provides some details regarding these functions of RAS. Aggregate supplements, when used underneath pavement structures, such as base or subgrade, will surely have less stringent final product quality specifications than those for HMA.

Furthermore, Krivit (2007) points to two alternative applications in the developmental stage, which may be more tolerant of the greater variability of tear-off RAS:

- Feedstock supplement in cement kilns.
- Fuel supplement in coal-fired boilers.

As a general rule, the five additional pavement construction applications listed above will probably not enjoy the same value as the other three end uses (i.e., HMA, cement kilns, and coal-fired boilers). However, collectively, all these applications may be able to consume large quantities of RAS and conserve landfill space.

Many specifications for asphalt shingles, roll roofing, and roofing asphalt are provided in the *Annual Book of ASTM Standards*, Volume 04.04 (ASTM, 2010). These can be helpful in understanding the composition and properties of asphalt shingles.

COLLECTION OF SCRAP SHINGLES

For use in HMA, MWAS has traditionally been preferred over TOAS primarily because MWAS contains fewer contaminants (Hansen, 2009; Maupin, 2008), plus the asphalt in MWAS is less oxidized (Button et al., 1996). MWAS only requires grinding/shredding with little or no sorting, inspection, testing, or separation of undesirable materials. However, MWAS is geographically significantly more restricted than TOAS, as shingle manufacturing facilities are typically located only in densely populated areas. Moreover, as previously stated, the volume of TOAS is about tenfold that of MWAS.

Nationwide, only a handful of enterprises collect, test, and grind TOAS. Zickell (2003) points out that this market is small due primarily to the following factors:

- Unknown business risks involved in processing shingles that possibly contain asbestos.
- Lack of investment due to the potential liability of changing solid waste disposal regulations.
- Costs involved in pre-sorting shingles, testing for asbestos, and developing end uses for the processed material.

Since TOAS typically comes from roofing companies that have other options for disposing of their waste shingles, it is necessary to make recycling attractive via reduced tipping fees, convenient locations, less stringent requirements on non-hazardous contaminants, or other incentives.

Establishing a continuous supply of TOAS is the first step in a successful recycling system. Operators have shown feasible, cost-effective best practices, and employed a wide variety of supply development strategies, depending on local market conditions. Krivit (2007) states that the two basic types of strategies to develop a clean, secure supply are:

- *Source Separated*—Attracting high quality, separated loads of clean TOAS. The roofing contractor or hauler must first separate the non-shingle debris (e.g., plastic, metal, wood) before tipping at the shingle recycling plant. Source-separated TOAS should be kept separate from other roofing debris at the demolitions site before loading and then loaded separately onto haul units.

- *Mixed Roofing Material*—Attracting mixed loads of TOAS without requiring source separation, such that the shingle recycler conducts most, if not all, of the materials separation. Non-shingle debris is sorted from the tear-off shingles at a recycling facility. TOAS recyclers might instruct their suppliers to load the shingles first, at the bottom of haul unit. Then, the non-shingle debris, placed on top of the shingles layer, can be easily separated when the load is tipped at the recycling plant.

Under either strategy, Krivit (2007) continues, TOAS recyclers must work proactively with suppliers to ensure that no asbestos containing material (ACM) is delivered to the recycling plant. After the TOAS are tipped at the recycling plant, a second stage of quality inspection and sorting occurs. Most facilities use both manual separation (e.g., dump and pick, sorting conveyors) and mechanical equipment (e.g., screens, air classifiers). Shingle recyclers have demonstrated a wide variety of techniques to cost-effectively meet and exceed the minimum waste sampling and asbestos testing requirements. They have recently developed innovations, such as establishing in-house laboratories that use standard detection methods and certified personnel. Such internal laboratories minimize the turnaround time for test results. Together with other in-house personnel training and supplier technical assistance, TOAS recyclers are proactively managing their supplies through upstream quality control and quality assurance.

According to Hansen (2009), as part of the quality control and acceptance program, shingle recycling operations need an inspection and testing plan for waste shingles delivered to the site, which should include:

- Type and quality of material that is acceptable.
- Criteria for rejecting loads.
- An asbestos management plan.

Krivit (2007) gives a list of prohibited materials for TOAS recyclers:

- Cementitious shingles, shake shingles, and transite siding that may contain ACM.
- Any type of hazardous waste (e.g., mercury containing devices such as thermostats, paint, solvents, or other volatile liquids).
- Significant amounts of other debris that is not asphalt shingles (e.g., plastic, paper glass, or metal).
- Significant amounts of trash.

Krivit (2007) advised that shingle recycling operators should attend state-sponsored training courses to become licensed as asbestos inspectors. Trained personnel should inspect each load to visually detect possible ACM. This will help increase the awareness of potential asbestos containing materials and allow company personnel to help provide accurate, timely, and state-approved information and related technical assistance to material suppliers and other customers. Shingle recycling operators should contact their state representative for National Emission Standards for Hazardous Air Pollutants (NESHAP) to explore technical assistance resources including a listing of organizations providing asbestos inspector training.

The website www.shinglerecycling.org has an excellent source of EPA and other regulatory information regarding asbestos, management, and recommended best practices.

Krivit (2007) recommended that shingle recyclers publish written specifications describing the type and quality of material that is acceptable and the criteria for rejecting loads. When shingle recyclers explain to haulers the type of end-use applications for waste shingles, haulers will better understand the reasons for (and will be better able to comply with) the strict supply quality requirements and inspections. For convenience, he provides an example supply specification along with related certification forms in Appendix C of his best practices at http://your.kingcounty.gov/solidwaste/linkup/documents/shingles-CMRA-best-practices.pdf.

REGULATORY COMPLIANCE

General Requirements

Collection of waste shingles requires certain permits and licenses from local, state, and federal authorities. According to Hansen (2009), these vary from state to state and may include:

- Zoning, construction, and operation permits.
- Solid waste facility licenses/permits.
- Recycling facility licenses/permits.

Additional state and federal regulations that may apply are:

- Worker health and safety regulations.
- Water quality protection.
- Air emissions regulations.
- Asbestos management regulations (e.g., U.S. EPA rules for NESHAP, Subpart M: National Emission Standard for Asbestos (40 CFR 61, Subpart M) (http://www.slocleanair.org/business/pdf/40cfr61m.pdf). Specific state and county asbestos regulations may also apply.

Krivit (2007) affirmed that TOAS recyclers have demonstrated the ability to consistently meet or exceed compliance with typical applicable regulations.

Asbestos Testing

According to Hansen (2009), the main issue that impedes recycling of TOAS is concern over potential asbestos content. In the past, asbestos was sometimes used in manufacturing asphalt shingles and other shingle installation materials. Asphalt shingle manufacturers generally acknowledge that, between about 1963 and the mid-1970s, some of their colleagues did use asbestos in the fiber mat in some of their shingle products; however the total asbestos content of those shingles was always less than 1 percent. Other materials used in shingles, such as some tarpapers and some types of asphalt cement, also reportedly contained asbestos. In reality, while heretofore used in some asphalt roofing materials, asbestos was rarely used in the shingles themselves.

Generally, asbestos testing (Figure A-1) involves sampling each layer of roofing material using standard methods that NESHAP prescribed. Samples must be properly labeled, recorded in a sample log book, and then sent to an accredited asbestos testing laboratory for assay of asbestos content. TOAS recyclers should contact the appropriate state environmental and/or health agency to determine specific requirements for sample collection, analytical procedures, data reporting, and records preservation.

Figure A-1. Setup for Asbestos Testing (after Krivit, 2007).

The California Integrated Waste Management Board reported that the asbestos content in asphalt shingles was as high as 0.02 percent in 1963, but that this dropped to 0.00016 percent by 1977 (CIWMB, 2001). The U.S. Environmental Protection Agency's National Emission Standards for Hazardous Air Pollutants regulates how asbestos containing material (ACM) is handled during building demolition or renovation and ACM is determined using polarized light microscopy. According to these data, recycled shingles will almost never be considered ACM.

Townsend et al. (2007) reviewed more than 27,000 asbestos test results from shingle recyclers and found that just over 1 percent contained asbestos; in many cases, the asbestos is found because other materials were present in the sample. Zickell (2003) reported that a study in Massachusetts revealed that less than 0.3 percent of 1771 TOAS samples collected over a 2.5 year period were ACM. The following studies showed no ACM at all: Iowa, 3000 TOAS samples; New Hampshire, 444 samples; and Maine, 118 samples. Because shingles have not been manufactured with asbestos since around 1980, and the life of shingles is 12−25 years, one would expect that the amount of ACM shingles will further decrease with time (Hansen, 2009).

Zickell (2003) concluded that these data and others that the Construction Materials Recycling Association (http://www.cdrecycling.org) is collecting should allow the potential risk of exposure to asbestos during asphalt shingle processing and reuse to be more fully evaluated. Appropriate and realistic regulatory policies, processing protocols, and testing frequencies can then be agreed upon, hopefully leading to increased recycling of both MWAS and TOAS and conservation of landfill space.

Some specifying agencies may be overreacting and need to make corrections (Hansen, 2009b). Zickell (2003) indicated that the Massachusetts Department of Environmental Protection calls for asbestos testing of each incoming load of TOAS, any suspect materials, along with a composite sample from each outgoing load of processed shingles. If asbestos greater than 1 percent is found, a licensed asbestos abatement contractor must segregate and remove it. This testing frequency is greater than that performed by other TOAS recyclers in the U.S. and is causing significant financial burdens for shingle recyclers. By comparison, asbestos testing is no longer required in Maine, testing is required once every 500 tons in New Jersey, and testing is specified for every 30 tons in North Carolina.

Details of asbestos testing are described in EPA/600/R-93/116, "Test Method for the Determination of Asbestos in Building Materials," (Perkins and Harvey, 1993). The complete test method is available at: http://www.rti.org/pubs/Test-Method-for-Determination.pdf. Generally, testing described in this method involves stereomicroscopic examination followed by polarized light microscopy. These analyses are usually sufficient for identification and quantification of major concentrations of asbestos. However, during these analyses, it may be found that other techniques are needed to improve accuracy. These may include X-ray diffraction, analytical electron microscopy, and gravimetry, which are all included in the EPA method.

MATERIAL PROCESSING REQUIREMENTS

Feedstock Quality Control/Assurance

Chesner et al. (1997) indicated that normally, no special quality control practices are required for MCAS; however, TOAS is more difficult to process because of contaminants and debris (e.g., nails, wood, and insulation). Any debris must be removed to prevent equipment damage during size reduction. There is no standard processing equipment to accomplish this task.

Krivit (2007) adds that many facilities relying on source separation of TOAS perform only a minimum amount of feedstock quality assurance through further inspection of the stockpile. Most often, the front-end loader or skid steer operator is in charge of inspection at the time material is loaded into the first feed hopper (see Figure A-2). Other facilities, relying on mixed waste sorting systems, must employ more intensive manual inspection and separation at the TOAS recycling plant. Grapple cranes are often used instead of front-end loaders to assist with pile management while rejecting large bulky items and loading the cleaner TOAS into the feed hopper. Manual sorting to remove non-shingle debris is most often employed at the tipping floor in close coordination with the grapple crane or loader.

Figure A-2. Front-End Loader Moving Material from a Pile of Source Separated TOAS (after Krivit, 2007).

Most facilities recover metal and cardboard (perhaps in baled form) as secondary recyclable products. Trash from such sorting consists of plastic, non-recyclable metal, and paper. Recovery rates of TOAS from mixed waste sorting systems range from 15 to over 90 percent, depending on the feedstock and the efficiency of the separation (Krivit, 2007).

Shredding

The vast majority of roofing shingle scrap used in asphalt paving mixes is shredded into pieces smaller than ½ inch (13 mm) in size using a shingle shredding machine that consists of a rotary shredder and/or a high-speed hammer mill. It seems logical that, as shingles are ground more finely, more RAS asphalt can be mobilized into the paving mixture.

According to Krivit (2007), each grinder manufacturer uses a unique combination of material handling and size reduction designs. RAS sizing is a key specification and will determine the product's suitability for various applications. For example, the larger particle size (¾ inch or bigger) may be more suitable for aggregate supplement. In general, the grinder will include a loading hopper, feeding drum to present the shingles into the grinding chamber, grinding chamber including cutting teeth, sizing screens, and exit conveyor. A pulley head magnet at the end of the exit conveyor is standard equipment for removing nails and other ferrous metal. The final RAS product is stacked using a stacking conveyor or front-end loader.

Shredded shingles may contain oversize pieces, but these are typically removed at the asphalt mix plant using a scalping screen.

Screening

Chesner et al. (1997) reported that shredded shingles are typically discharged from the shredder or hammer mill and screened (see Figure A-3) to the desired gradation and stockpiled. Experience indicates that the size of the processed shingles should be no larger than approximately ½ inch (13 mm) to enhance digestion of the particles and uniform incorporation into the HMA. Hansen (2009) adds that several HMA producers have found that grinding to less than ⅜ inch improves blending. Texas DOT specifies 100 percent passing the ½-inch sieve with 90 percent passing the ⅜-inch sieve. Chesner et al. (1997) contends that scrap shingle greater than ½ inch in size may not readily disperse in HMA and may function much like aggregate, and that too small particles sized can release short fibers, which act as a filler substitute.

Figure A-3. Shingle Grinder Followed by Trommel Screen (after Krivit, 2007).

Watering

To prevent agglomeration during processing, roofing shingle material may either be passed through the shredding equipment only once or kept cool by water spray at the hammer mill. However, the application of water is not very desirable, since the processed material becomes quite wet and must then be dried (which incurs fuel cost) prior to introduction into the HMA asphalt (Chesner et al., 1997).

Stockpiling of Processed RAS

Stockpiling of RAS is typically conducted similar to that of aggregate or RAP. Because the average gradation of RAS is very small, a stockpile can absorb a large amount of water, which can cause problems during HMA mixing (inadequate coating), compaction (mat tenderness), and performance (higher stripping potential) as well as require more fuel for HMA drying. Ideally, a RAS stockpile should be covered.

Button et al. (1996) deduced that, during static storage in a stockpile, shredded roofing shingle material can agglomerate. High temperatures and the stickier manufacturing waste shingles can magnify this issue. Significant agglomeration or consolidation of processed roofing material necessitates reprocessing and rescreening prior to introduction into the hot mix plant. To address this problem, processed roofing shingle scrap may be blended with a small amount of less sticky carrier material, such as sand or RAP, to prevent the RAS particles from sticking together.

When blending such materials, the gradation of the blended product should be designed to maximize utility during mixture design and subsequent mixture design HMA production. This blending can be accomplished at the RAS recycling facility or at the HMA plant. Blending at the recycling facility should be carefully coordinated with the HMA contractors who are customers.

SHINGLE PROCESSING DESIGN CONSIDERATIONS

Krivit (2007) affirmed that TOAS recyclers should optimize their operations to produce a RAS product that meets or exceeds specifications of their end markets. The TOAS processing design plan should link all components of the recycling system together (i.e., supply development, sorting, processing, RAS storage, and marketing) to assure that a high-quality, final RAS product is consistently produced. A primary design criterion to consider when planning a shingle processing system is to maximize the processing capacity while assuring that the final RAS product will meet or exceed market specifications.

MARKETING WASTE SHINGLES

According to Krivit (2007), to promote end-market development during the early stages of a new business, the shingles recycling processor should provide for agency inspections of the sourcing, processing, and final RAS product stockpiles. Government agencies that should be invited to conduct these inspections include the local and/or state DOTs that are using the RAS in their paving projects and the environmental regulator(s). To verify quality, sampling of RAS may be required before it is incorporated into HMA or blended into other road construction materials (e.g., aggregate for road base). The opportunity for such recycling plant inspections and RAS product sampling may become part of the regular QA/QC plan for each new customer.

Shingle recycling operators should provide the local and state agency staff with a description of the TOAS processing and worker health and safety plans as part of the facility planning and permitting process. Updated versions of these plans, based on initial operating experience and employee feedback, may also be submitted after facility construction and initial shakedown operations.

EXTRACTED BINDER PROPERTIES

Maupin (2008) conducted tests on binders recovered from two mixtures: one containing 5 percent MWAS and another with 10 percent RAP (see Table A-2). Gradations, binder contents, volumetric properties, and field compaction characteristics of the mixtures were very similar. The virgin binder for each mixture was from the same PG 64-22 source. Binders recovered from each mixture were graded as a PG 70-22. When the results were interpolated to determine the exact grading, the MWAS mixture contained a PG 74-24 binder and the RAP mixture contained a PG 70-25 binder. There was little difference in the low-temperature grading of the two recovered binders, but there was almost a full PG difference at the high-temperature end.

Table A-2. Dynamic Shear Rheometer (DSR) and Bending Beam Test Results of Virgin Binder and Abson Recovered Binders (after Maupin, 2008).

Binder Properties	Virgin Binders		Recovered Binders	
	10% RAP Mix	5% MWAS Mix	10% RAP Mix	5% MWAS Mix
No Lab Aging				
G*/sin δ, kPa > 1.0	1.282 @ 64°C 0.630 @ 70°C[a]	1.333 @ 64°C 0.663 @ 70°C[a]	--	--
Rolling Thin-Film Oven				
G*/sin δ, kPa > 2.20	4.014 @ 64°C 1.884 @ 70°C[a]	3.648 @ 64°C 1.710 @ 70°C[a]	4.546 @ 64°C 2.252 @ 70°C 1.145 @ 76°C[a]	6.943 @ 64°C 3.447 @ 70°C 1.758 @ 76°C[a]
Pressure aging vessel				
G*sin δ, kPa < 5000	3026 @ 22°C 2113 @ 25°C	3255 @ 22°C 2259 @ 25°C	2413 @ 25°C 1682 @ 28°C	2298 @ 25°C 1647 @ 28°C
Creep Stiffness, MPa < 300	128 @ −12 °C	129 @ −12°C	126 @ −12°C 257 @ −18°C	113 @ −12°C 243 @ −18°C
m-value > 0.300	0.319 @ −12 °C	0.314 @ −12°C	0.322 @ −12°C 0.287 @ −18°C[a]	0.312 @ −12°C 0.283 @ −18°C[a]

RAP = recycled asphalt pavement.
[a] Failed the criteria.

Binder was also recovered from a sample of the MWAS, which produced a high-temperature grading of approximately 90. The resultant high-temperature grading of the MWAS-virgin binder combination was calculated based on the properties of the shingle binder and virgin binder. The high-temperature grading was calculated to be PG 71, and the actual recovered grading was PG 74.

Maupin (2008) indicated that the slightly stiffer MWAS mix binder could account for less rutting in the MWAS mixture, as measured using the Asphalt Pavement Analyzer.

ASPHALT MIXTURE DESIGN

Designing asphalt mixtures containing RAS is similar to designing them with RAP. Standard asphalt mixture design procedures are applicable, particularly when adding only 2 to 5 percent RAS. A few key differences between RAS and RAP are delineated below.

Binder Issues

Hansen (2009) affirmed that, as with paving grade asphalts, the grade of roofing asphalts varies with the climate in which they are designed for use (i.e., harder asphalt in warmer climates and vice versa). Plus, one should realize that RAS contains four to seven times more asphalt than typical RAP. The incorporation of RAS in HMA will increase the viscosity of the virgin asphalt and thus the stiffness of the mixture. Therefore, it is important to match the grade of the virgin binder in the HMA with the binder from the RAS to ensure that the desired combined grade for the particular situation (i.e., climate, traffic, mixture type) is achieved.

In an Oregon DOT laboratory study, Scholz (2010) documented that the addition of asphalt from RAP and/or TOAS increased both the high-temperature and low-temperature PGs of the virgin binder of HMA. As one might expect, the high-temperature PG of the blended binder asymptotically approached that of the high-temperature PG of the RAP/RAS binder.

One should use solvent extraction and binder recovery procedures to obtain asphalt from RAS and estimate the grade of asphalt in the RAS. The ignition oven can be used to determine asphalt content of RAS; however, fibers other than fiberglass will be destroyed in the furnace, so in these instances, extraction must be done. Due to the high asphalt content in RAS, safe operation of the ignition oven will require smaller sample sizes than for typical asphalt mixtures. Some state DOT specifications only require extraction and testing of RAS asphalt when the percent of RAS or binder replacement exceeds a certain threshold (e.g., 15 to 30 percent binder replacement) (Hansen, 2009). Because there is more and harder asphalt in RAS (particularly TOAS) than in HMA, extraction of asphalt from RAS will require more time.

One should be aware that, if asphalt is solvent-extracted and recovered from a RAS and/or RAP-modified mixture, the asphalts from the different products will be intimately mixed. However, complete blending of the asphalts may not (and probably does not) occur in the mixing plant. Based on experience and some limited testing, Hansen (2009) estimated that the range of virgin and RAS binder blending may vary between 40 and 90 percent, with finer ground RAS making more of its asphalt available. Further, it currently appears that, as the mixing temperature is decreased (e.g., in the case of WMA), mixing of the virgin and recycled asphalts may be further diminished.

The AASHTO provisional standards, PP 53-09, Design Considerations When Using RAS in New HMA (AASHTO, 2009), suggests a method for estimating the contribution of the shingle asphalt binder to the viscosity of the final blended binder in new HMA. AASHTO PP 53-09 also describes a procedure for determining the required PG (or high, intermediate, and low critical temperatures) for the virgin asphalt binder in accordance with AASHTO M 323.
PP 53-09 advises that it is unlikely that all of the RAS binder will dissolve and blend with the virgin asphalt binder and that particles of undissolved RAS may act like aggregate particles that require more virgin binder to accomplish coating (i.e., increase the overall optimum asphalt content).

AASHTO PP 53-09 cautions that the location in an HMA plant where RAS is introduced into new HMA can also affect the binder blending process. This point of introduction must minimize damage to the RAS from excess heat and minimize the softening of shingle asphalt binder to facilitate the blending of the RAS binder with the virgin asphalt binder.

Aggregate Issues

Button et al. (1996) maintained that the aggregate gradation in RAS is normally very fine, generally with 100 percent of the material passing the No. 8 (2.36 mm) sieve and up to 40 percent passing the No. 200 sieve. The exact gradation depends on the type of shingle, but it should be measured, using an extraction procedure, and considered during HMA mixture design. In some cases, it may be necessary to reduce the amount of fine aggregate used in the HMA mixture to accommodate the fines contained in the RAS. Further, the majority of the fine aggregate in shingles is very angular, freshly crushed material. Consequently, for compacted

HMA mixtures that typically exhibit low voids in the mineral aggregate (VMA), the addition of RAS can help increase the VMA.

AASHTO PP 53-09, Design Considerations When Using RAS in New HMA (AASHTO, 2009), offers guidance for determining RAS aggregate gradation and specific gravity. It states that the amount of aggregate contributed by RAS produces an almost negligible effect in the overall mixture gradation.

Fiber Issues

RAS, unlike RAP, contains a significant quantity of fibers. Typical modern shingles contain a fiberglass mat that makes up about 2 percent of the weight of the shingle (Button et al., 1996). When adding 5 percent RAS containing 2 percent glass fibers, the amount of fibers in the asphalt mix becomes 0.1 percent. The specific gravity of glass fiber (2.58) is about the same as that of the aggregate; however, the specific gravity of most organic or synthetic fibers (1.0 or less) is much less. Therefore, it may be advisable to consider low-density fibers by volume of HMA rather than by weight.

FIELD GUIDELINES

A significant amount of valuable information is available for those interested in or involved in using waste shingles as an additive in asphalt paving materials.

In 2007, to help develop the market for recycling of tear-off asphalt shingles, the Construction Materials Recycling Association (CMRA) produced a very detailed 80-page guideline titled, *Recycling Tear-Off Asphalt Shingles: Best Practices Guide* (Krivit, 2007). Although this guide addresses essentially all current and potential uses of waste shingles, the main focus is on using shingles in HMA. This best practices guide is available at the CMRA shingle recycling website (http://www.shinglerecycling.org/). This comprehensive document provides valuable information for:

- Shingle recyclers (e.g., roofing companies and/or haulers) who collect, haul, sort, sample, and test waste shingles.
- Shingle processors concerned with plan development, grinding, attaining materials specifications, proper sampling, quality control testing, environmental compliance, and health/safety issues.
- Paving contractors and their relationships with shingle processors and owner agencies, concerns with sustained material quality, and consideration of economics.
- Owner agencies that may be developing/updating specifications, responsible for HMA mixture design, practicing quality assurance testing, and engaged in tax-dollar and environmental stewardship.

In 2009, the National Asphalt Pavement Association published *Guidelines for the Use of Reclaimed Asphalt Shingles in Asphalt Pavements* (Hansen, 2009). Their concise guide covers sources of RAS, RAS composition, inspection, and testing of RAS, shingle processing, HMA mixture design, production and construction, and economics.

Guide specifications and practices for using RAS in HMA are available in AASHTO's Standard Specification for Use of Reclaimed Asphalt Shingles as an Additive in Hot Mix Asphalt

(AASHTO MP 15-09) and Standard Practice for Design Considerations When Using RAS in New HMA (AASHTO PP 53-09) (AASHTO, 2009). Hansen (2009) summarized most of the state DOT specifications for using RAS in asphalt mixtures as of 2009; it is reproduced in Appendix B of this literature review.

About 15 years ago, Button et al. (1996) prepared field construction guidelines for using RAS in HMA paving operations for TxDOT. These guidelines address shingle processing, RAS composition, mixture design, plant production, along with placement and compaction. Because of the recent increase in the use of RAS, these guidelines should be reviewed and updated, as necessary, using the most up-to-date information, and published on TxDOT's website so these will be readily available to contractors, materials suppliers, consultants, and paving engineers. Certainly, the items listed above in this subsection should be used to revise the TxDOT guidelines.

SUMMARY OF FINDINGS FROM LABORATORY AND FIELD EXPERIMENTS

During the past 25 years, several state agencies have evaluated waste shingles in HMA. Findings from selected agencies and researchers (Paulson et al., 1986; Grzybowski, 1993; Janisch and Turgeon, 1996; Button et al., 1996; Abdulshafi, 1997; Watson et al., 1998; Foo et al., 1999; Mallick et al., 2000; Amirkhanian and Vaughan, 2001; Sengoz and Topal, 2005; Lum, 2006; Maupin, 2008; Schroer, 2009; Maupin, 2010; and Ul-Islam et al., 2010) that have conducted and reported on laboratory and field experiments where waste shingles are incorporated into HMA are reasonably uniform and generally consist of the following:

- Using RAS in essentially all types of HMA is a viable solution to its expensive and environmentally unacceptable disposal in landfills.
- Most DOTs require that approximately100 percent of processed RAS passes the ½-inch sieve. Texas DOT specifies 100 percent passing the ½-inch sieve with 95 percent passing 3/8-inch sieve.
- Standard HMA mixture design procedures and quality control procedures appear satisfactory for mixtures containing RAS.
- Mixture design and construction of HMA containing RAS can be conducted using techniques already established for RAP.
- RAS will stiffen HMA (TOAS more, MWAS less). This is expected due to the higher viscosity asphalt in the shingles along with the reinforcing effect of the fiber and fillers.
- Attention should be given to selection of the grade of virgin asphalt to be used with RAS to ensure the final blended binder grade is appropriate for the conditions.
- There is little difference in laboratory and field results for HMA mixtures containing RAS and corresponding control mixtures. Laboratory and field tests indicate RAS mixtures may offer better rutting resistance (Baaj and Paradis, 2008) and that they meet specifications related to cracking resistance in milder climates. However, Minnesota DOT (McGraw et al., 2007) indicated that the stiffening effects of TOAS on HMA might yield large thermal stresses in their cold climate and lead to thermal cracking.
- Extracted asphalt cement in HMA containing RAS is harder than that in the control sections. This is expected, since the grade of asphalt used in both MWAS and TOAS is

harder than that typically used in pavements. However, this slight increase in asphalt hardness did not exhibit negative effects on cracking. More caution regarding cracking when RAS is used in cold climates may be justified.

- In some instances, RAS mixtures exhibit approximately equivalent resistance to moisture damage as conventional mixtures. However, Newcomb et al. (1993b) reported that while MWAS had no effect on moisture resistance, the more oxidized TOAS had negative effects.
- A reasonable maximum quantity of RAS in HMA appears to be about 5 percent.
- State DOTs have prepared specifications that allow from 3 (MnDOT) up to 5 percent MWAS and/or TOAS in HMA mixtures. Most allow up to 5 percent.
- Conventional, RAP, and RAS-modified HMA mixtures behave similarly during placement, compaction, and short-term performance. RAS can improve workability and compaction of HMA.
- Long-term performance of HMA containing RAS has not been well established.
- There is an economic benefit to using RAS in HMA if the cost of incorporating the shingle scrap into the mix is less than the savings that result from the need for less asphalt cement.
- No particular or recurring problems related to the incorporation of RAS in HMA were reported in the literature reviewed to prepare this report.

Additional specific findings from selected references include the following.

- When RAS is used in HMA where the amount of virgin binder in the mix is 60–70 percent, no change in virgin binder grade is normally required (Hansen, 2009).
- Each percentage point of RAS added to HMA wearing courses contributed between 0.27 and 0.30 percent asphalt by weight of mix. Each percentage point of shingle scrap used added to HMA binder/base courses contributed between 0.12 and 0.22 percent asphalt by weight of mix (Janisch and Turgeon, 1996).
- Owner agencies should retain AASHTO PP 53, which requires a ratio of at least 70 percent new asphalt binder to total asphalt binder (Johnson et al., 2010).
- Because of their higher VMA relative to dense-graded HMA mixtures, SMA (Newcomb et al., 1993a) and CMHB (Button et al., 1996) mixtures should accommodate and benefit from the use of RAS.
- Even with RAS added, the SMA may still need polymer-modified asphalt and/or fiber to control asphalt draindown (Foo et al., 1999).
- Replacing 5 percentage points of RAP with RAS does not have an appreciable effect on the recovered binder stiffness (McGraw et al., 2007).
- A Minnesota DOT study (MnDOT, 1991) research showed that adding 10 percent of MWAS to the mix resulted in a 25–40 percent reduction in the required neat binder content.

- Schroeder (1994) reported that New Jersey DOT experimented with an asphalt cold-patch material made using TOAS. The resulting patch material showed only minor signs of distress after 22 months of service, whereas conventional cold-patch material generally lasted only three to six months.
- Uzarowski et al. (2010) demonstrated, in a laboratory study, that RAS and/or RAP can be used in HMA with an asphalt rejuvenating agent to soften the resulting blended binder. This appeared particularly beneficial in their Canadian environment.

RAS IN WARM MIX ASPHALT

Four researchers (Robinette and Epps, 2010; Middleton and Forfylow, 2009) reported that RAS had been used in WMA, but only one report (Maupin, 2010) was found in which testing of WMA containing RAS was performed.

Maupin (2010) conducted indirect tension tests on a Virginia DOT asphalt surface mix containing PG 70-22. He performed on laboratory-prepared asphalt mixtures containing 0–5 percent TOAS that had been mixed at 300°F (HMA) or 250°F (WMA) to determine how mixing temperature affected mixture stiffness. He postulated that if the TOAS binder and virgin binder combined to the same degree at both mixing temperatures, then the mix stiffness should have exhibited the same differential increase at both mixing temperatures as shingle content was increased.

Table 3 lists the strengths and strength differences attributable to inadequate blending of the virgin and RAS binders. In Figure A-4, the 300°F curve was shifted downward to the 250°F curve to eliminate the additional aging effects. Maupin (2010) indicated that the strength differences between the shifted curve and 250°F curve can be attributed to inadequate blending of RAS and virgin binders. With 5 percent shingles, the strength of the WMA mixture increased only about half as much as that of the HMA without RAS [(190−155) / (245−183)] = 0.56.

This limited indirect tensile testing indicated that blending of the virgin and RAS binder will be less for WMA than for HMA. He admitted that it is difficult to duplicate field conditions in the laboratory, and perhaps better binder blending would normally occur in a hot-mix plant than in a laboratory experiment because of more vigorous mixing.

Table A-3. Tensile Strengths from Virginia DOT WMA Study (modified after Maupin, 2010).

RAS, %	Tensile Strength, psi		Difference in Tensile Strength, psi
	Mixed at 250°F (WMA)	Mixed at 300°F (HMA)	
0	155	183	28
2	165	210	45
3	168	220	52
4	173	240	67
5	190	245	55

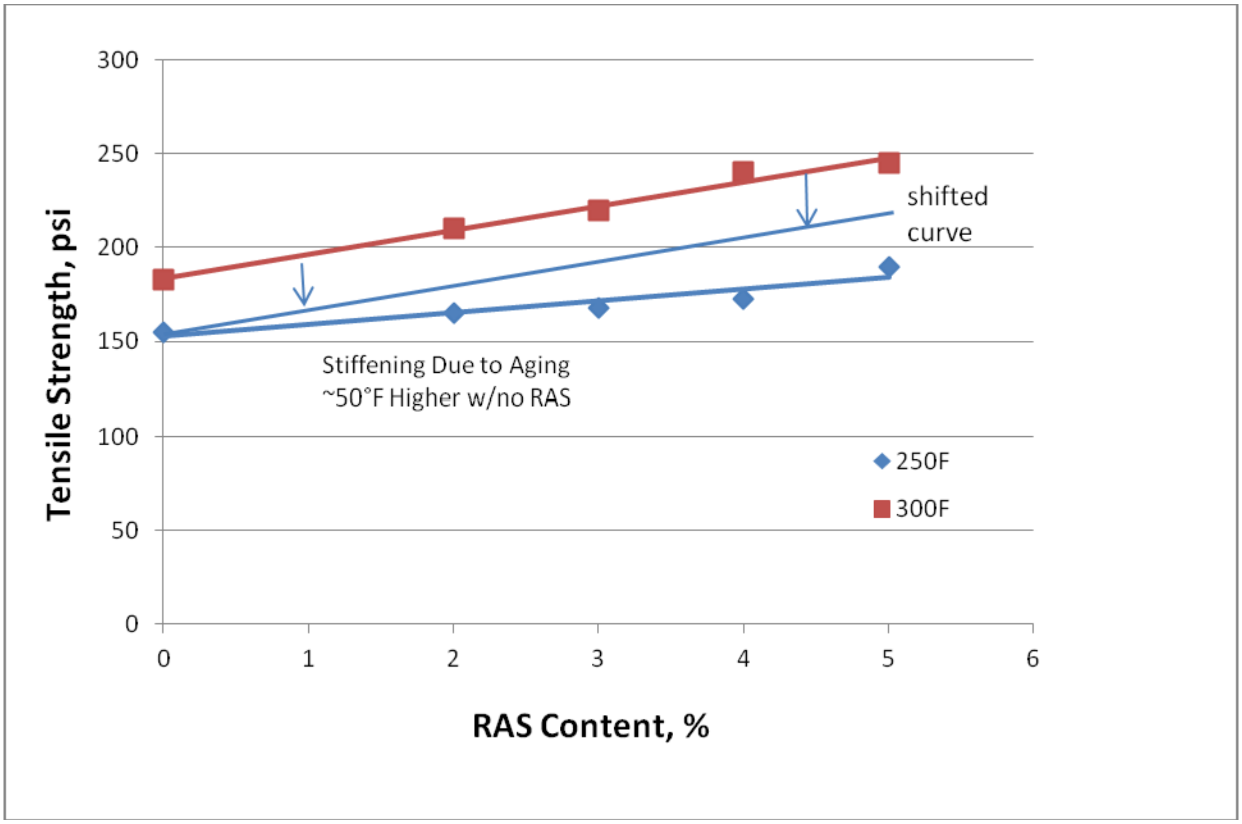

Figure A-4. Effect of Mixing Temperature on Shingle and Virgin Binder Blending (after Maupin, 2010).

RESEARCH NEEDS

Of interest to this TxDOT study (Project 0-6614) is a proposed national Transportation Pooled-Fund Study to conduct research on RAS in HMA. Objectives are to encourage state DOTs to accept and use this innovative, cost-saving, and environmentally friendly technology. Missouri DOT will serve as the lead state (Schroer, 2009). The Project 0-6614 researchers plan to stay abreast of this study and report relevant findings to TxDOT.

Most studies have shown good rutting resistance when RAS is combined with HMA. Long-term performance of asphalt mixtures incorporating RAS material needs to be evaluated with respect to fatigue cracking, low-temperature cracking, stripping, and raveling. Life-cycle cost analyses should be performed to determine the economic viability of using RAS.

Since RAS will likely be used along with RAP more often than not, long-term performance of HMA and, particularly, WMA incorporating both RAS and RAP needs to be evaluated with respect to common performance measures (e.g., rutting, fatigue, low-temperature cracking, stripping, and raveling).

Very little was found in published literature regarding the use of RAS in warm asphalt mixtures. For WMA, the question remains, "Does the harder roofing asphalt in RAS soften sufficiently in the plant mixing process to become a functional part of the WMA binder system?" This is a particular dilemma when using TOAS in WMA.

The amount of mixing of the binders from RAS, RAP, and virgin asphalt needs to be determined. Bonaquist (2007) proposed a method using the Simple Performance Tests to evaluate the effective stiffness of RAS/RAP-modified mixtures and the amount of effective binder mixing in those mixtures. Mixture master curve data are used to calculate binder properties that, in turn, are compared to recovered binder properties. The difference in the master curves gives an indication of the amount of binder mixing. Bonaquist commented that the degree of grinding of the processed shingles and the mixing dwell time can affect the amount of RAS/RAP binder that mixes with the virgin binder. This method will be considered in TxDOT Project 0-6614 to compare effects of adding RAS to asphalt mixtures. (Details of this method are described at http://www.ucs.iastate.edu/mnet/_repository/2007/asphalt/pdf/a%20new%20tool%20to%20design%20and%20characterize%20higher%20rap%20hma%20-%20bonaquist.pdf.)

Recyclability of asphalt pavements incorporating RAS at the end of their service lives needs to be evaluated.

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APPENDIX B:
SUMMARY OF STATE DOT SPECIFICATIONS FOR RAS IN ASPHALT MIXTURES

Table B-1. Summary of State DOT Specifications for RAS in Asphalt Mixtures (after Hansen, 2009).

State DOT	Allowable RAS	Special Requirements
Alabama	Manufacturing Waste & Tear-off	• Allowed in dense-grade and SMFC • Not allowed in OGF or ATPB • Manufacturing waste 5% max • Tear-off 3% max • Maximum particle size ½"
Alaska	None	
Arizona	None	
Arkansas	None	
California	None	
Colorado	None	
Connecticut	None	
Delaware	None	
Florida	Manufacturing Waste	• Up to 5% RAS
Georgia	Manufacturing Waste Tear-off	• 5% maximum RAS • Tear-off test for asbestos per 100 tons • Maximum particle size ½" • Used according to the same requirements as described for RAP material
Hawaii	None	
Idaho	None	
Illinois	None	
Indiana	Manufacturing Waste	• 5% maximum RAS except 3% maximum for category 3, 4, or 5 surface mixtures and open graded mixtures • 1% RAS equivalent to 5% RAP
Iowa	None	• Have constructed test sections using tear-off
Kansas	None	
Kentucky	None	
Louisiana	None	
Maine	None	
Maryland	Manufacturing Waste	• 5% maximum RAS • Not used in gap-graded mixes or mixes of polymer binders
Massachusetts	Manufacturing Waste	• 5% maximum RAS • Not allowed in surface mixes
Michigan	None	
Minnesota	Manufacturing Waste	• 5% maximum RAS • Have done research with tear-off and pilot projects
Mississippi	None	

State DOT	Allowable RAS	Special Requirements
Missouri	Manufacturing Waste Tear-off	• Maximum of 7% RAS using PG 64-22 • When the ratio of virgin binder to total binder in the mixture is less than 70%, the grade of the virgin binder shall be PG 52-28 or PG 58-28 • Shingles shall be ground to ½" minus • Post-consumer RAS shall be certified to contain less than the maximum allowable amount of asbestos as defined by national or local standards. The gradation of the aggregate may be determined by solvent extraction of the binder or using a standard gradation
Montana	None	
Nebraska	None	
Nevada	None	
New Hampshire	None	
New Jersey	Manufacturing Waste	• 5% maximum RAS • Not allowed in surfaces
New Mexico	None	
New York	None	
North Carolina	Manufacturing Waste	• Maximum 5% RAS by weight of total mixture for any mix • RAP and RAS combined less than 15% by weight of total mixture • When the percent of binder contributed from RAS or a combination of RAS and RAP exceeds 20% of the total binder in the completed mix, the virgin binder PG shall be one grade below (both high and low temperature grade) the binder grade specified
North Dakota	None	
Ohio	Manufacturing Waste	• Base and intermediate course only • Amount limited by quantity of binder replaced • Asphalt mix producer needs to request to be allowed
Oklahoma	None	
Oregon	None	
Pennsylvania	Manufacturing Waste Tear-off	
Rhode Island	None	
South Carolina	Manufacturing Waste Tear-off	• 3–8% RAS • 99.7% free of debris

State DOT	Allowable RAS	Special Requirements
		• Test absolute viscosity of binder recovered from mix during mix design
South Dakota	None	
Tennessee	None	
Texas	Manufacturing Waste Tear-off	• 5% maximum RAS • Maximum size ½" • Minimum ratio virgin binder/total binder 65% surface mixes, 60% non-surface mixes • For RAS/fractionated RAP combination, use no more than 20% combined RAS and RAP for surface mixtures, and no more than 30% combined RAS and RAP in non-surface mixtures • For RAS/un-fractioned RAP, use no more than 10% combined RAS and RAP for surface mixtures, and no more than 20% combined RAS and RAP in non-surface mixtures
Utah	None	
Vermont	None	
Virginia	Manufacturing Waste Tear-off	• 5% maximum RAS • Test for asbestos 1 per 100 tons before processing • Combined RAP and RAS asphalt limited to 25% of total binder • 1% RAS = 4% binder for binder grade selection
Washington	None	
West Virginia	None	
Wisconsin	Manufacturing Waste Tear-off	• Allowable quantity based on binder replacement: RAS only 20% lower layers, 15% upper layers; RAS and RAP 30% lower layers, 20% upper layer; RAS and RAP 30% lower layers, 25% upper layers • Higher percentages binder replacement may be allowed but required recovered binder testing
Wyoming	None	