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RECLAIMED ASPHALT SHINGLES CHARACTERIZATION: BEST PRACTICES

By
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INTRODUCTION

The competitive environment contractors are facing has encouraged the asphalt pavement industry to consider using recycled products such as reclaimed asphalt pavement (RAP), ground tire rubber (GTR), and reclaimed asphalt shingles (RAS) in their mixtures. While products like GTR serve as an asphalt modifier easing the industry's dependence on the supply of polymers such as styrene-butadiene-styrene (SBS), RAS and RAP allow contractors to replace both aggregate and asphalt in mixtures with materials previously produced and/or used for another purpose.

Additionally, as environmental standards have evolved forcing disposal sites to limit the dumping of this material, more than 11,000 disposal sites for RAS closed between 1980 and 1997 causing tipping fees to escalate to near $100 per ton (*1, 2, 3*). The nearly 11 million tons of waste shingles produced each year results in approximately 22 million cubic yards of waste material which will need to be landfilled (*4*). This, in turn, is approximately eight to ten percent of the annual building-related waste and construction debris, respectively, annually produced in the US (*5*). Thus, using RAS in asphalt mixtures, in effect, reduces both the fiscal and environmental costs of the asphalt mixtures being produced.

History

Replacing virgin asphalt with the asphalt from RAS was first considered in the early 1980s (*1*). As polymer modification became more commonplace with the introduction of the Superpave PG binder specifications in the 1990s, the concept of replacing a polymer modified binder with an aged or reclaimed binder was considered advantageous as it would further reduce the materials cost for asphalt mixture contractors. This brought about the advent of permissive specifications allowing contractors to use RAS in asphalt mixtures at contents of 5 percent or less which results in an approximate binder replacement of 15 to 20 percent (*6*).

It has been estimated that 11 million tons of roofing shingles are available for recycling each year in the United States (*1, 7*). 10 million tons are generated as tear-off or post-consumer (PC) shingles. PC shingles come from reroofing buildings, homes, and complexes. The properties of these shingles vary as engineers and contractors are uncertain of the length of time these asphalt shingle roofs have been oxidized due to exposure from the sun. As these shingles are exposed to the sun, the asphalt binder in the shingles is oxidized making the binder increase in stiffness over time.

The other 1 million tons stem from manufacturers' waste (MW) or factory rejects which may not meet all of the specifications required for the roofing industry. These MW asphalt shingles have not been exposed to the sun and hence have not experienced additional oxidation after manufacture. Therefore, while the binder has still been air blown in production, the binder in MW shingles is not as stiff as that in PC shingles (*6*).

Currently, 13 states permit MW RAS in asphalt mixtures while 10 states permit the use of PC RAS (*6*). Most specifications, however, require the contractor to choose MW or PC shingles for an individual mix and discourage mixing the two materials (*2*). At the time this report was written, RAS has been effectively used in projects throughout Alabama, Texas, Missouri, North Carolina, Georgia, Minnesota, and Florida (*1, 7, 8, 9*).

RAS COMPONENTS

While the composition of shingles varies depending on manufacturer and roofing application, most RAS is composed of four basic materials: asphalt cement, felt or fiber, mineral aggregate, and mineral filler. Organic or fiberglass felt backings form the basic platform for asphalt shingles. The organic felt is typically composed of either cellulose or wood fibers and is designed to support the asphalt and aggregate granules. Fiberglass backings are manufactured by mixing fine glass with water in the form of a glass pulp. The pulp is then formed into a sheet of fiberglass (*10, 11*).

Once the backing is created, it is then saturated with asphalt cement. This asphalt cement has been air-blown which increases the stiffness of the asphalt cement. The asphalt is further stabilized with a lime dust (70 percent passing the No. 200 sieve) (*11, 12*). A second application of air-blown asphalt is then used to cover both sides of the shingles before the top of the shingle is covered with granules. These granules are designed to protect the asphalt from both the sun's ultraviolet rays and physical damage due to abrasion on rooftops. Most shingle manufacturers use a combination of crushed rocks which have been coated with ceramic metal oxides as granules. Additional headlap granules can be used in this application. Both types of aggregate granules are ideal for roofing shingles due to their uniform size, toughness, and angular shape (*11*). In some cases, chemicals are added to the aggregate to prevent algae growth (*13*).

Shingles are finished with a dusting of fine sand to the back surface to prevent agglomeration of the shingles which might occur during transportation. A schematic of the final product is shown in Figure 1. Table 1 presents estimates of the percent of each material in organic and fiberglass shingles (*11*).

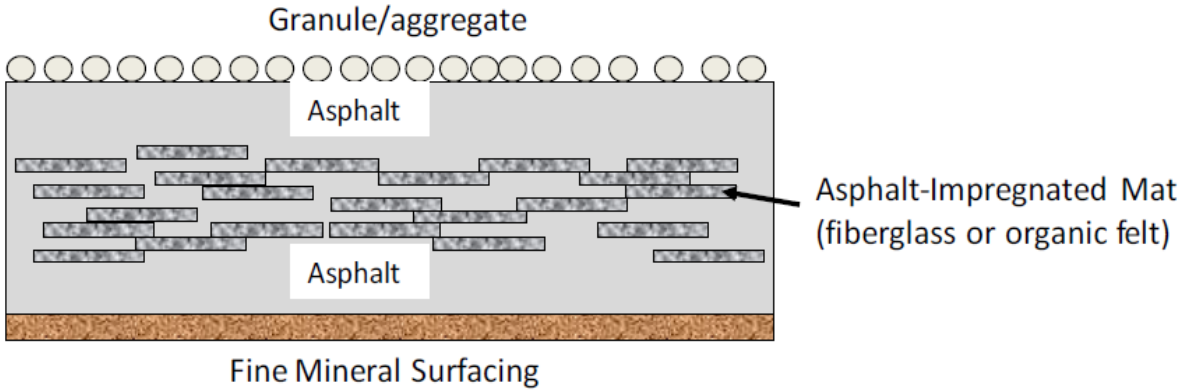

FIGURE 1 Schematic of asphalt shingle composition (*12*)

TABLE 1 Composition of Shingles (*13, 14, 15*)

Component	Organic Felt	Fiberglass Mat
Asphalt cement	30-36%	19-22%
Felt (fiber)	2-15%	2-15%
Mineral aggregate	20-38%	20-38%
Mineral filler	8-40%	8-40%

Though there are differences between organic and fiberglass shingles, there are also differences in the material composition of MW and PC shingles. PC shingles typically contain more asphalt than MW shingles due to weathering and loss of the aggregate granules over time. PC shingles also contain more deleterious materials such as paper, wood, and nails than MW shingles due to exposure to these contaminants when being removed from roofs; however, most of these are removed during the shingle grinding process (*11*).

PC shingle stockpiles tend to have shingles with more variability in material proportions and properties. There are a number of reasons (*16*) for this higher variability in PC shingle stockpiles as outlined below:

- Variability of shingle manufacturers
- Variations in type of shingle (organic or fiberglass)
- Age and weathering

PROCESSING RAS

Before MW or PC shingles can be used in asphalt mixtures they must first undergo processing or grinding. The American Association of State Highway and Transportation Officials (AASHTO) currently specifies that shingles should be ground so that 100 percent of the material can pass a ½-inch sieve (AASHTO MP 15-09). States such as Georgia, Oregon, South Carolina, Texas, and Virginia have specifications which reflect AASHTO's guidelines. Other states such as North Carolina and Minnesota have different specifications for shingle sizes. These requirements are given in Table 2 (*1, 9*).

TABLE 2 Example Shingle Size Requirements

State	Percent Passing					
	¾"	½"	⅜"	#4	#100	#200
Georgia	-	100%	-	-	-	-
Iowa	-	100%	98% min	90% min	-	-
Minnesota	-	100%	-	90% min	-	-
North Carolina	-	-	100%	-	-	-
Oregon	-	100%	90% min	-	-	-
South Carolina	-	100%	-	70.0-95.0%	15% max	7% max
Texas	-	100%	-	-	-	-
Virginia	-	100%	-	-	-	-

NOTE: - = not applicable

While states do not have common specifications for shingle grinding size, most agencies and research organizations will concur that finer grinding for asphalt mixtures is preferable (*13*). One commonly stated reason for finer grinding is the utilization, or blending, of the RAS and virgin binders (*2*). AASHTO PP 53-09 states that using finer grinds of asphalt shingles can increase the amount of usable asphalt from the shingles which therefore increases the economic benefits of the material (*17*).

Another common reason for encouraging finer grinding of asphalt shingles is due to drum mixing (*20*). If the shingles are too large, they will not melt and mix with the virgin binder during production (*18*). If the shingle does not melt, the unactivated asphalt will then act more like an aggregate than asphalt. This will increase the surface area that virgin asphalt will need to coat and thus increase the overall virgin binder requirement (*17*). Finally, using a finer shingle grind has been shown to improve mat laydown and quality (*2, 14*).

Shingle grinding can be completed using crushers, hammermills, rotary shredders, or a combination of equipment (*19*). Many rotary shredders have two blades which grind at a rate of 50 revolutions per minute and are appropriate for initial grinding; however, the slow speed of this device prevents the material from being ground fine enough for most asphalt mixtures. High speed hammermillls which operate at speeds of 800 to 900 rotations per minute are more appropriate for reducing the size of RAS to appropriate levels for asphalt mixtures (*20*).

While the processes differ between equipment, most grinding operations consist of a loading hopper, feeding drum, and grinding chamber. The loading hopper places unprocessed shingles into the feeding drum which, in turn, moves the shingles to the grinding chamber. The grinding chamber contains the cutting teeth (Figure 3) which reduce the shingles to appropriate sizes before screening and exiting the chamber through a conveyor system (*20*). Upon leaving the grinding chamber, RAS is typically carried by a conveyor under a series of magnets designed to remove metal particles, such as nails, from the material before they are resized (Figure 4) (*21*).

FIGURE 3 Cutting teeth inside grinding chamber (*20*)

FIGURE 4 Grinding chamber sizing screens (*20*)

Numerous problems and challenges present themselves when trying to process RAS for asphalt mixtures. As shingles are ground, the shingle granules wear down the grinding equipment due to their abrasion properties. Due to the difficulty in breaking down these particles, heat accumulates in the grinding equipment and causes the shingle particles to reagglomerate (*20*). Shingle grinders will sometimes add water to the shingles as they enter the feeding chamber to limit the dust and keep the shingles cool so that they do not stick together (*19, 20*); however, engineers should be aware that this moisture should be removed from the material before it can adequately be used for asphalt mixtures.

Shingle grinders have also found it is easier to grind PC shingles than MW. Since PC shingles have been on rooftops, aged, and become stiffer, they are easier to shred. The asphalt from MW shingles has not oxidized and become as brittle as PC shingle asphalt. As the MW shingle asphalt is exposed to high temperature during the grinding process, the shingles develop plastic properties due to the heat which makes them difficult to grind uniformly. As previously mentioned, water can be used to alleviate many of the issues associated with high temperature during the grinding process (*19*).

A final concern related to shingle processing is homogeneity. After shingles are processed, the material should be homogeneous in size and composition. Contractors have reported seeing processed shingles which have large pieces of the recycled material and commonly refer to them as “corn flake” shingles (Figure 5). After processing, shingles should have the consistency and appearance of coffee grounds (Figure 6) which are uniform in size, shape, and asphalt content (*22*).

When shingles are not ground uniformly they do not blend well during mixing at plants, leaving mixtures brittle from a lack of available asphalt. Screens should be used during shingle processing to ensure all the material passes the ½-inch sieve. Any material which does not pass this criterion should be reground to ensure the material is of proper size (*19, 22*).

FIGURE 4 Cornflake shingles (*22*)

FIGURE 5 Coffee ground shingles (*22*)

STOCKPILING AND SAMPLING RAS

RAS, like virgin aggregate and RAP sources, is stockpiled until it can be used in asphalt mixtures. Ideally, MW and PC RAS should be placed in separate stockpiles to prevent possible contamination of MW RAS stockpiles and ensure more uniform RAS stockpiles.

RAS presents naturally inherent challenges to maintaining consistent and usable stockpiles. After RAS is processed, it typically has moisture from the grinding process. In order for RAS to be used in asphalt mixtures, it should contain less than ten percent and ideally between five to seven percent moisture (*20*). Two ways to prevent additional moisture from accruing in RAS stockpiles are to provide adequate drainage to the stockpile by building the stockpile on a slope or covering the stockpile to prevent precipitation from adding to the moisture content of the material (*23*).

While moisture can present one problem for RAS stockpiles, a second problem is agglomeration of RAS particles. As the RAS asphalt is exposed to higher temperatures, the asphalt softens and encourages the joining of previously processed RAS particles. This process can negatively influence the homogeneity of the stockpile and ultimately affect the blending of RAS particles with aggregate and virgin binder during production. The most common practice for preventing agglomeration of the material is to blend the RAS with a fine aggregate source suitable for SUPERPAVE asphalt mixtures (*24, 26*). This practice has been recommended by AASHTO MP 15-09. While natural sand is the most commonly used fine aggregate material used in this process, natural sand retains water more than other aggregate sources causing the moisture content of the RAS stockpile to increase (*26*). Aggregate such as #10 stone, ⅜" stone, and washed stone screenings have been used successfully to prevent RAS particles from joining in higher temperatures (*26, 27*). Many contractors blend RAP and RAS together to prevent the high asphalt content RAS particles from reforming. It was suggested in *Recycling Tear-Off Asphalt Shingles; Best Practices Guide* that shingle suppliers mix RAP and RAS at a 3:1 ratio to aid in the practice of stockpiling (*20, 26*). Contractors could perform this task but diligence must be used to ensure the RAP and RAS are first properly proportioned and second thoroughly mixed together.

When RAS is sampled, a minimum of five tests (with as many as ten preferred) should be used to characterize a RAS stockpile in at least three locations throughout the stockpile using AASHTO T 2. Iowa defines a sample as at least 20 pounds of RAS. These samples are used to characterize the asphalt and aggregate components of the RAS material. Once a stockpile has been characterized, the addition of new material requires recharacterizing the RAS material. This aids in ensuring the material characterized is the material used in production (*2*). During production, RAS should continually be characterized in a manner similar to RAP or virgin aggregates. Iowa requires at least three samples be taken for every 1000 tons to determine material characterization (*23*). This testing is conducted to confirm homogeneity of the RAS throughout the stockpile which ensures adequate mixing of the material will take place during construction (*2*).

Once processed RAS has been sampled from stockpiles, AASHTO T 248, *Reducing Samples of Aggregate to Testing Size*, should be followed for splitting and preparing the samples for further testing.

DRYING RAS FOR CHARACTERIZATION

Before RAS is tested, care should be taken to ensure it is in a dry condition. Two common methods are used for drying aggregates, RAP, and RAS: fan drying and oven drying. AASHTO T 255 is the current specification that defines the methodology for oven drying aggregate. The common procedure is to dry the material at 110 ± 5°C. The sample is considered dry when further heating causes additional mass loss of less than 0.1 percent. While drying can typically be achieved overnight in an oven, drying materials which contain asphalt (such as RAP and RAS) in an oven could change the properties of the asphalt binder by further driving light oils out of the binder. . Therefore, fan drying RAS is more appropriate if the material is to be used for asphalt mixtures or assessing RAS binder properties.

While oven-drying RAS is expedient, fan drying RAS (Figure 6) ensures the properties of the RAS binder are not altered by subjecting the material to additional heat. There are no current specifications which provide guidance for fan drying the material. However, if RAS is placed in a thin layer approximately ⅜" thick in a large flat pan and placed in front of a fan, the material can be dried overnight. The material should be considered dry when further drying causes additional mass loss of less than 0.1 percent.

FIGURE 6 Fan drying

RAS ASPHALT

The desire to use RAS in asphalt mixtures stems from the ability to replace virgin asphalt with reclaimed asphalt in a mixture design which can substantially reduce the overall material cost of the asphalt mixtures. In order for RAS to be cost-effective, one must be able to quantify the asphalt content of the RAS for mixture proportioning and its performance grade (PG) to ensure mixture performance.

Asphalt Content

While states and organizations vary in how much they believe RAS binder blends with virgin asphalt binder (Table 3), quantifying the asphalt content of RAS is a critical component of material proportioning in an asphalt mixture design and is the driving economic incentive for using RAS in asphalt mixtures. Recent research studies have shown that PC shingles can contain an average of 30 to 36 percent asphalt binder while MW shingles have closer to 19 or 20 percent asphalt binder (*28*).

TABLE 3 Available Asphalt for Blending

Organization	Amount of RAS Binder Available for Mix
AASHTO	Calculate shingle binder availability factor based on differences between required binder of virgin and shingle designs
Alabama Department of Transportation	100% of RAS binder
Iowa Department of Transportation	66.7% of RAS binder
Missouri Department of Transportation	100% of RAS Binder

Two methods are available for determining the asphalt content of RAS today: ignition oven and chemical extraction. While both methods are available, current AASHTO specifications require chemical extractions be used for determining asphalt content of RAS.

Chemical Extraction

RAS binders can be extracted and recovered using AASHTO T 164 or ASTM D2172. To determine the asphalt content of a RAS source using the centrifuge (ASTM D2172 Method B), the RAS sample is placed in a centrifuge bowl and covered with a chemical solvent (Figure 7). Currently four solvents are used for chemical extractions: trichloroethylene (TCE), methylene chloride, ammonium carbonate solutions, and n-Propyl Bromide.

FIGURE 7 Centrifuge bowl

The sample soaks in the solvent at room temperature for no more than one hour before the centrifuge is activated. As the centrifuge spins at a maximum speed of 3600 revolutions per minute, the solvent-asphalt solution is removed from the bowl where it then passes through a paper filter to remove any fine aggregate material light enough to be removed with the solvent (Figure 8).

FIGURE 8 Paper filter ring

The process of soaking and spinning is repeated until the solvent removed from the bowl appears to be the color of straw. At this point all of the binder is considered to have been removed from the aggregate. The centrifuge bowl is then removed and the remaining aggregate and paper filter ring are allowed to dry and weighed in order to perform asphalt content calculations. The solvent solution is passed through a second high-speed centrifuge procedure like the one shown in Figure 9 to remove any remaining fine material small enough to have passed through the paper filter.

FIGURE 9 Pouring solvent solution into high speed centrifuge

After the extraction procedure is completed, a distillation procedure is used to remove the solvent from the binder if performance grade testing is required. The roto-vap procedure (ASTM D5404), shown in Figure 10, can be used to complete this process.

FIGURE 10 Roto-vap recovery equipment

In this procedure, the solvent solution is placed into a rotating flask which is submerged in a heated oil bath (140 $\pm$ 3 °C) under partial vacuum with a flow of nitrogen gas. As the solvent evaporates it is collected in a glass condenser and allowed to drip into a separate recovery flask. The recovered asphalt binder remains in the submerged rotating flask and is collected into a sample tin following the procedure. All extraction/recovery procedures are required to be completed in less than eight hours to minimize solvent hardening effects.

South Carolina requires 200 to 300 gram samples be used in the extraction process while North Carolina specifies 500 grams for this procedure. Common specifications require the asphalt content of RAS be checked by three samples for every 2000 tons of mix.

One disadvantage of the chemical extraction process is that all four solvents are somewhat hazardous. Each is classified as at least an eye and skin irritant and care should be taken when using each of them. As safety is a primary concern, fume hoods and respirators should be used by laboratory staff conducting the tests. The use of these chemicals is encouraging states and laboratories to look for other methods of quantifying binder contents and properties without the use of hazardous materials.

Ignition Oven

AASHTO Specification T 308 currently provides the methodology for determining the asphalt content of materials using the ignition oven (Figure 11). While this is the most common method for determining the asphalt content of RAP, some organizations are hesitant to use the ignition oven for RAS.

The ignition oven determines the asphalt content of asphalt mixtures, RAP, and RAS by heating an oven dried sample of RAS to 1072°F until the mass loss is less than 0.01 percent. Breakdown of some aggregates can occur due to the excessive heat in the oven; therefore, it is critical to determine an asphalt correction factor for the material being used in the ignition oven. Additionally, one should use a smaller sample size for determining the AC of RAS. At high temperatures, RAS asphalt has the tendency to have a significant flame. Additionally, due to the amount of asphalt on the sample, the time of the test will be much longer than a typical RAP sample.

An asphalt correction factor can be determined by running two sample mixtures at a design asphalt content in the ignition oven and calculating the asphalt content. The difference between the average measured asphalt content and actual asphalt contents is the correction factor. Once the correction factor for the aggregate is determined, the asphalt content can be calculated using Equation 1.

$$AC, \% = \left[\frac{(W_s - W_a)}{W_s} * 100\right] - C_F \quad (1)$$

where

AC = asphalt content, %
W_s = total weight of the HMA sample prior to ignition, g
W_a = total weight of aggregate remaining after ignition, g
C_F = correction factor

While developing asphalt correction factors for standard aggregates is straightforward, the uncertainty of the composition of RAS makes it much more difficult to develop accurate correction factors. Though it is difficult, to trust the results of the ignition oven one must ignore the need for this correction factor, develop correction factors, or assume shingle binder contents (*27, 29*).

FIGURE 11 Ignition oven

Extraction and Ignition Oven.

Virginia is one state which allows contractors to determine asphalt content by either ignition oven or chemical extraction (AASHTO T 164 Method B). However, some research has shown that there can be differences of up to five percent asphalt content (i.e., 21.4 vs. 16.4 percent) when comparing the results of the two methods, while other studies have shown there can be good agreement. This will typically depend on the makeup of the shingle (*27*). This reiterates the need to develop accurate correction factors for shingles in the ignition oven if state agencies and contractors want to move away from chemical extraction tests for measuring asphalt content.

Performance Grade (PG) of RAS Binder

Since RAS binders have been air blown, they are inherently stiffer and have different rheological properties than virgin and modified binders (Figure 12) (*2, 30, 31*). The most common tool for assessing asphalt binders today is AASHTO M 320, *Standard Specification for Performance Grade Binder Grading*. While many states do not require the asphalt binder on shingles be PG graded in order to use higher shingle or binder replacements, AASHTO PP 53 requires users to know the PG grade of the RAS binder to complete blending charts.

FIGURE 12 Differences in appearance between modified asphalt and RAS asphalt (*21*)

To determine the PG of RAS binders, they must first be extracted and recovered using methods previously mentioned. In the current PG grading system, the viscosity of the asphalt binder is then assessed three different times. First, the original binder is assessed. Second, the asphalt binder undergoes a simulated short-term aging in the rolling thin film oven (RTFO) before being assessed again. The final assessment occurs after a simulated long-term aging in the pressure aging vessel (PAV). Current mix design and binder grading specifications do not require RAP binders to undergo long-term aging since they have already been aged in the field.

While this provision is given for RAP binders, no such guidance is provided for RAS binders. It is known that air blowing during shingle production increases the binder viscosity (*31*). The binder of PC shingles is further aged while the shingle is acting as a roofing material. Still, researchers have presented results using both the RTFO and PAV aging procedures (*30*).

Agencies have reported using cheese graters to shred RAS binder so it could be PG graded (*21*). Additionally, common equipment cannot be used to assess the high temperature grade of the RAS binder since many RAS binders have critical high temperatures above the boiling point of water (*30*). In many cases, RAS binders also are difficult to test for critical low temperatures as the binders must proceed below -36°C to reach the critical low temperature stiffness but have m-values which will only pass at temperatures greater than 0°C (*30*). Example performance grades of shingle binders are presented in Table 3 to show the difficulties and extreme critical temperatures determined when assessing RAS binders.

TABLE 4 RAS PG Grades

Source	RAS Type	High PG	Low PG
Scholz 2010	MW	134	NA
Bonaquist	MW	124-154	0+
Schroer 2009	MW	143+	0+
McGraw	MW	134-153.9	(-12.7)-(-6.1)
McGraw	PC	121.2-133.1	(-6.9)- (10.6)
NCAT	PC	175.4	41.7
NCAT	MW	132.6- 137.2	(-18.6)- (-13.0)

Despite the difficulty in handling and testing RAS binders, it is important that the blended RAS and virgin binder meets the same PG grade for the pavement design in terms of binder grade, strength, and durability (*2*).

RAS AGGREGATE

RAS contains aggregate granules which can serve as a substitute for virgin fine aggregate sources in asphalt mixtures (*33*). Research has suggested the hard granules used in shingle production will give the asphalt mixture additional resistance to permanent deformation (*36*); however, the gradation, bulk specific gravity, consensus aggregate properties, and deleterious materials of the RAS aggregate must be properly quantified before the RAS should be used in an asphalt mixture.

Most aggregate properties are determined by testing the aggregate granules which have been separated from the other RAS material components. Both chemical extraction and the ignition oven methods for extracting asphalt from processed RAS discussed earlier in this document can be considered appropriate for recovering the RAS aggregate as well. AASHTO TP 2 provides guidance for conducting chemical extraction and recovery of the asphalt binder and aggregate if one requires recovering the asphalt binder for further testing. However, if asphalt binder recovery is not necessary, the ignition oven methodology defined in ASTM D228 sections 13 and 14 can be used to recover the RAS aggregate. While a study at NCAT and the University of Nevada at Reno has shown with limited data that both aggregate recovery processes did not significantly affect the aggregate properties of RAP aggregate, little research has been published which assesses the effect of extraction methodology on RAS consensus aggregate properties (*48*).

Gradation

AASHTO PP 53-09 and some states, like Iowa, have a design gradation which can be assumed for RAS aggregate instead of conducting a mechanical sieve analysis (Table 5).

TABLE 5 AASHTO Assumed RAS Aggregate Gradation

Sieve Size	Percent Passing by Weight
⅜” (9.5 mm)	100
#4 (4.75 mm)	95
#8 (2.36 mm)	85
#16 (1.18 mm)	70
#30 (600 µm)	50
#50 (300 µm)	45
#100 (150 µm)	35
#200 (75 µm)	25

Mechanical sieve analyses can also be conducted on recovered RAS aggregate to quantify the material’s gradation. AASHTO PP 53-09 recommends that fibers from shingles be manually

removed from the RAS aggregate before determining the gradation as most of the fibers will be retained on the No. 4 sieve and could prevent aggregate particles from being characterized correctly. Once the fibers have been removed from the RAS aggregate, AASHTO T 30 *Standard Specification for Mechanical Analysis of Extracted Aggregate* provides guidance for determining the particle sizes of aggregate extracted from asphaltic materials using the ignition oven. The methodology contains a standard washed gradation similar to that of AASHTO T 27; however, when using an ignition oven, engineers must develop correction factors which account for any material breakdown which can occur due to the extreme temperatures encountered in the ignition oven.

Correction factors for aggregate breakdown require running at least three mechanical sieve analyses. First, the gradation of a "blank" aggregate blend is determined. The "blank" gradation is aggregate which has not been coated with asphalt and has known properties. The other two aggregate blends have been coated with a specified asphalt content. After placing the two coated aggregate samples in the ignition oven and determining asphalt content, mechanical sieve analyses are conducted on the recovered aggregate. The average deviation of the recovered aggregate from the "blank" gradation on each sieve is considered the correction factor for each sieve size.

While the process of determining correction factors is fairly straightforward, acquiring the raw materials from shingle manufacturers necessary to determine correction factors is problematic. Additionally, the change in shingle manufacturing and design over the past 30 years prevents contractors from fully knowing what a "blank" gradation of PC RAS aggregate would be.

Chemical extraction allows engineers to quantify the RAS aggregate gradation without breaking down the aggregate particles; however, numerous labs and states avoid conducting chemical extractions due to safety and health concerns. Therefore, while chemical extraction may give one an accurate quantification of the RAS aggregate gradation, it may not be practical to conduct this type of analysis.

Typical RAS aggregate gradations for MW and PC RAS are shown in Tables 6 and 7, respectively. These results are a combination of ignition oven and chemical extraction results. These results are compared to the assumed gradation provided by AASHTO and Iowa DOT. Tables 8 and 9 show additional analyses using the chemical extraction test (*7*). Based on these limited data, strong conclusions cannot be made whether chemical extraction or ignition oven results are most appropriate for determining RAS gradations. It can be concluded the assumed gradation is not always appropriate for RAS mixture design. The assumed gradations were reasonably close to the PC RAS shown in Table 6; however, the results did not match well with the PC results from Table 8.

TABLE 6 MW RAS Aggregate Gradations

Sieve Size	AASHTO	NCAT RAS		Foo	Fiberglass Shingle (MN)	Felt Shingle (MN)	Oregon
		C	I	C	**	**	I
1”	100	100	100	100	100	100	100
¾”	100	100	100	100	100	100	100
½”	100	100	99.8	100	100	100	100
⅜”	100	99.7	99.5	99.9	100	100	99
#4	95	99.2	98.3	98.8	100	100	97
#8	85	97.7	97.3	97.3	89	69	95
#16	70	79.5	82.6	89.2	-	-	92
#20	-	-	-	-	65	45	70
#30	50	53.6	62.0	70.1	-	-	46
#50	45	42.6	52.6	56.7	11	5	39
#100	35	32.1	43.2	45.5	1	0	33
#200	25	22.2	33.3	35.5	-	-	27.1

NOTE: C = chemical extraction; I = ignition oven; ** = unknown testing methods, - = not applicable

TABLE 7 PC RAS Aggregate Gradations

Sieve Size	AASHTO Assumed	NCAT RAS	
		Chemical Extraction	Ignition Oven
1”	100	100	100
¾”	100	100	100
½”	100	100	100
⅜”	100	99.8	98.7
#4	95	97.1	96.1
#8	85	92.7	92.8
#16	70	75.3	75.9
#30	50	54.4	55.6
#50	45	44.8	47.1
#100	35	35.9	39.9
#200	25	25.5	30.5

TABLE 8 PC Shingle Extracted Gradation (*7*)

3/8	#4	#8	#10	#16	#40	#50	#100	#200	Fibers	Paper	Total
100	100	99	99	82	54	50	42	34.3	0.53	14.2	14.73
100	100	99	99	86	61	57	48	40.1	0.58	20.2	20.78
100	100	99	99	82	54	50	43	35.4	0.61	17.1	17.71
100	100	99	99	83	56	52	45	37.5	0.69	18.5	19.19
100	100	99	99	85	61	57	51	42.7	0.92	19.2	20.12
100	100	99	99	85	58	54	46	37.6	0.93	16.6	17.53
100	100	99	99	84	55	50	43	34.4	0.47	13.7	14.17
	100	99	99	84	57	52	44	36.5	0.52	16.5	17.02
100	100	99	99	85	59	54	46	37.4	0.85	18.2	19.05
100	100	99	99	85	58	53	45	36.4	0.54	15.4	15.94
								Average	0.66	16.96	17.62
								Std. Deviation	0.17	2.12	2.22

TABLE 9 MW Shingle Extracted Gradation (*7*)

1/2	3/8	#4	#8	#10	#16	#40	#50	#100	#200	Fibers	Paper	Total
100	99	97	96	95	78	51	45	34	27.4	3.76	2.25	6.01
100	100	100	99	99	88	51	40	28	22.0	0.88	1.15	2.03
100	100	99	99	98	89	54	43	30	22.3	1.06	1.16	2.22
100	100	99	99	98	89	54	43	30	22.3	1.9	1.6	3.5
100	100	100	99	99	86	55	46	34	26.5	0.9	0.91	1.81
	100	100	100	100	88	50	41	29	22.2	0.3	0.98	1.28
	100	100	100	99	89	54	43	31	24.2	1.43	0.99	2.42
	100	100	100	100	88	51	41	29	22.8	1.17	0.82	1.99
	100	99	98	98	81	55	49	39	31.9	2.60	1.92	4.52
	100	99	99	98	81	54	48	39	31.5	3.35	1.59	4.94
									Average	1.74	1.34	3.07
									Std. Deviation	1.15	0.48	1.59

Bulk Specific Gravity of RAS Aggregate

In volumetric mixture designs, the bulk specific gravity of the aggregate structure (G_{sb}) must be quantified to calculate properties such as voids in mineral aggregate (VMA) as shown in Equation 2.

$$VMA = 100 - \frac{G_{mb} * P_s}{G_{sb}} \quad (2)$$

where

VMA = voids in mineral aggregate, %
G_{sb} = bulk specific gravity of aggregate
P_s = percent stone
G_{mb} = bulk specific gravity of mixture

Currently, AASHTO T 84 is used to assess the bulk specific gravity of fine aggregate; however, this testing procedure is time consuming and would require removing all of the asphalt from the aggregate via chemical extraction or ignition oven testing without affecting the specific gravity and absorption properties of the aggregate. Thus, while studies have shown G_{sb} of RAS aggregate can be determined using AASHTO T 84 (34), it is not practical for routine material characterization.

AASHTO PP 53 allows engineers to assume the G_{sb} of the RAS aggregate is equivalent to the effective specific gravity (G_{se}) of the RAS aggregate. The primary difference between bulk specific and effective specific gravities are their respective volumes. Bulk specific gravity includes all the volume of aggregate solids and the volume of the aggregate pores which are penetrable by water. The effective specific gravity of the aggregate excludes the pores which are penetrable by asphalt. Therefore, to assume G_{sb} is equivalent to G_{se}, one assumes that no binder is absorbed by the RAS aggregate (*35*). For low absorptive aggregates this is a reasonable assumption but, this could provide a significant error for high absorptive aggregates.

Heritage Research Group has investigated three different methods of determining G_{se} for RAS aggregate: maximum theoretical specific gravity of mixture (G_{mm}), vacuum sealing, and alternative G_{mm} (*35*). These three methods are discussed below.

Maximum Theoretical Specific Gravity

The G_{mm} of an asphalt mixture is determined using AASHTO T 209, and the amount of material required to run the test is based on the nominal maximum aggregate size (NMAS) of the aggregate or RAS. The test is conducted by placing a specified mass of the RAS material in a vacuum pycnometer for at least 15 minutes. The vacuum is designed to work in conjunction with the agitation of the sample to remove any air from the mixture before being weighed underwater (Figure 13) (*35*).

The G_{se} of the RAS is then calculated using Equation 3 based on the known asphalt content of the RAS, the assumed asphalt binder specific gravity, and the measured G_{mm}.

$$G_{se} = \frac{(100-P_b)}{\left(\frac{100}{G_{mm}}\right)-\left(\frac{P_b}{G_b}\right)} \quad (3)$$

where

G_{se} = effective specific gravity of RAS
P_b = percent binder in RAS from either ignition oven or chemical extraction
G_{mm} = maximum theoretical specific gravity of mixture
G_b = assumed specific gravity of RAS binder

FIGURE 13 Standard maximum theoretical specific gravity test

Since RAS is made up of very fine particles, RAS will sometimes float to the top of the water bath when this test is conducted at room temperature (Figure 14). To alleviate this problem, AASHTO PP 53 suggests using "a fine spray of alcohol" to reduce the surface tension. Alternatively, hot water (approximately 170°F) can be poured into the G_{mm} sample (Figure 15). As the sample is stirred, the particles will settle to the bottom of the pycnometer. If the water is heated, one must remember to cool the sample back to room temperature before applying the vacuum to prevent the occurrence of floating particles.

FIGURE 14 Floating RAS (*35*)

Figure 15 Heated RAS (*35*)

Alternative G_{mm} Method

The standard G_{mm} procedure can be modified slightly to also produce a RAS mixture which is less susceptible to floating particles. To determine G_{se} using this method, the RAS sample should be pre-heated to 230°F for approximately one hour. At this point, virgin asphalt binder at a temperature of 300°F should be added to the RAS at 15 percent by total weight of the RAS sample. Using a known quantity of asphalt binder will allow one to calculate the G_{se} of the RAS aggregate from the G_{mm} test procedure.

Vacuum Sealing Method

The G_{se} of the RAS aggregate can also be determined effectively using AASHTO T 331, *Standard Specification for Determining the Bulk Specific Gravity and Density of Compacted Hot Mix*

Asphalt (HMA) Using Automatic Vacuum Sealing Method. The test method is completed by placing the RAS inside a plastic bag and placing the plastic bag containing the sample inside a vacuum chamber (Figure16). The chamber is sealed and a vacuum is applied which removes the air and seals the bag. Once the chamber has achieved atmospheric pressure it will open and the sample can be removed carefully to ensure the bag is not punctured (Figure17). The G_{mb} of the RAS can then be calculated using the following equation.

$$G_{mb} = \frac{A}{[C+(B-A)]-E-[\frac{B-A}{F}]} \quad (4)$$

where

G_{mb} = bulk specific gravity of the RAS
A = initial weight of the dry specimen in air, g
B = calculated dry weight of dry, sealed specimen, g
C = final weight of specimen after removal from the sealed bag, g
E = weight of sealed specimen in water, g
F = apparent specific gravity of plastic sealing bag, provided by manufacturer

It is assumed that the G_{mb} is equivalent to the G_{mm} of the RAS in this state since there are no air voids in the RAS. Therefore, once the G_{mb} is determined, the G_{se} of the RAS can be backcalculated using Equation 3.

Figure 16 Vacuum Sealing Device

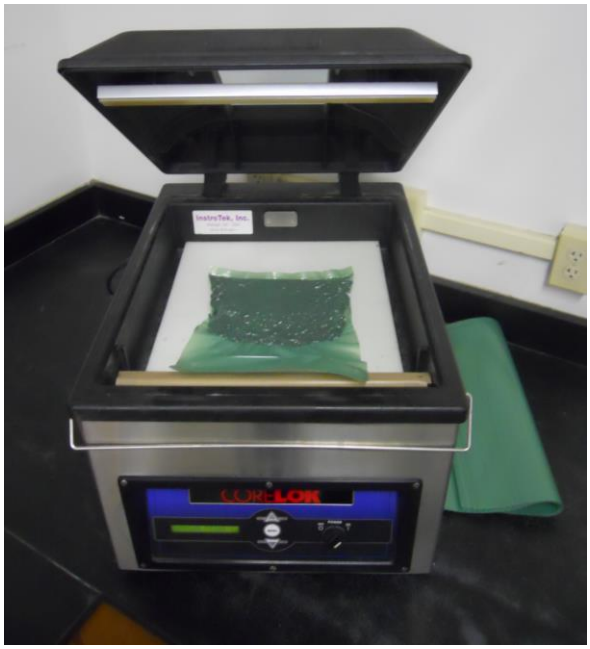

Figure 17 Sample in Vacuum Device

Most fiberglass RAS sources will have G_{se} values between 2.500 and 2.600. Cellulose RAS samples may have lower specific gravities.

Consensus Aggregate Properties

It is critical for mixture performance that using recycled materials not diminish the aggregate quality in the mixture as it provides the skeletal framework for the asphalt mixture. However, little has been documented relating the consensus aggregate properties of the fine RAS aggregate. The state of Pennsylvania requires no consensus aggregate property testing on RAS mixtures and many other states are mute on the point in their design methodologies.

Deleterious Materials

While MW RAS is typically free of deleterious materials, the retrieval process for PC RAS commonly allows the material to become contaminated with unwanted waste such as plastics, paper, wood, and metal. RAS needs to be free of debris such as trash, nails, and other foreign matter which might negatively influence the performance of the asphalt mixture design (*2*).

Three basic approaches to specifications are being used by states to quantify deleterious materials in their processed RAS. The first approach, AASHTO PP 53-04, states that RAS should have at most 0.5 percent deleterious materials after processing. Deleterious material is defined as a cumulative amount of metal, glass, paper, rubber, wood, nails, plastic, brick, and/or tar (*21*). A similar specification was in place in Missouri (*21*); however, their specification has recently been modified to reflect the amount of material retained on the No. 4 sieve out of a 500 to 700 gram sample. Other states such as Minnesota and Colorado are also implementing specifications which limit the particle size of materials tested for deleterious materials. Common limits for this type of specification are three percent deleterious materials on the No.

4 sieve if those particles include metals, rubber, glass, soil, and brick, but lighter materials such as paper, plastic, and wood are limited to 1.5 percent (*21, 22, 28*). This new concept is reflected in the current AASHTO specification MP 15-09.

The second approach is Iowa's current specifications only require one to take a 200 gram sample of processed RAS and determine if the deleterious material content is less than 1.5 percent.

In the third approach, Texas developed a unique specification for determining the deleterious material content in its processed RAS. For this specification, a 1000 gram sample of RAS is poured over a specially designed pan (Figure 18). A magnet has been placed across the middle of the pan to catch any metal which remains in the processed RAS as the material passes over it. The metal pieces are then weighed to determine how much metal was in the RAS. The remaining RAS is then sieved over the ⅜-inch, No. 4, No. 8, and No. 30 sieves. The material passing the No. 30 material is discarded. The deleterious materials retained on each sieve are then determined by manual separation and weighed by sieve size. The total percent deleterious materials in the RAS sample is then quantified using Equation 5. Texas requires less than 1.5 percent deleterious materials in their processed RAS.

$$P = \frac{M+N_{3/8}+N_4+N_8+N_{30}}{W_t} * 100 \quad (5)$$

where

P = percent of deleterious matter by weight
M = weight of material retained by magnet, g
$N_{\#}$ = weight of deleterious material on sieve #, g
W_t = total weight of sample, g

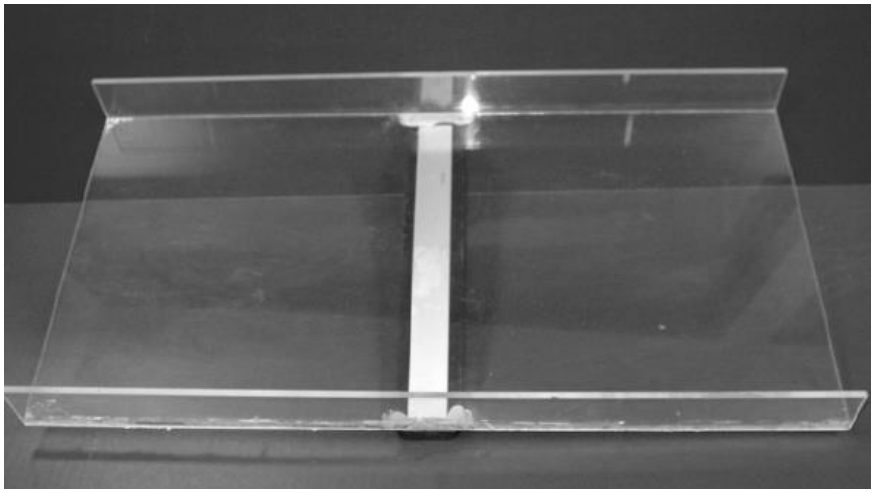

FIGURE 18 TxDOT deleterious material pan (*40*).

RAS FIBERS

As shown earlier, fibers (either in the form of cellulose or fiberglass) are commonly present in RAS. Past research has shown that MW shingles can average 1.7 percent fibers by weight of the shingle; however, this value can be much higher (*7*). While the fibers are an integral part of RAS, very little work has been done in quantifying the effect of RAS fibers in asphalt mixtures. People have suggested the fibers might increase the mixture durability; however, no definitive work has been completed to confirm this conclusion.

Fibers are commonly used in open-graded asphalt mixtures and stone matrix asphalt (SMA) mixtures to prevent asphalt draindown. There is potential for using the RAS fibers as a substitute for virgin cellulose fibers in these mixtures, simplifying mixture product at the plant.

The roofing industry commonly uses ASTM D4-86 to assess the bitumen content of its asphalt shingles; however, using this standard, one can additionally assess the filler and fiber content of the shingles. The current specification (ASTM D4-86 (2010)) uses carbon disulfide to dissolve the sample of processed RAS. Once the asphalt is removed from the shingle, the filler and fiber can be manually separated to quantify the amount of fiber and filler in the RAS.

ASBESTOS IN RAS

Federal regulations in the National Emission Standards for Hazardous Air Pollutants state that recycled materials must have less than one percent asbestos if they are to be used in roadway projects (*36*). Asbestos is one of six fibrous silicate minerals found in nature: chrysolite, termoble, actinolie, anthophyllite, crocidolite, and amosite (*37, 38*). Exposure to these fibers has been shown to increase the risk of diseases such as lung cancer, asbestotsis, and mesothelioma. Asbestos is hazardous when it is in a free state such as during the grinding process (*37, 42*).

Asbestos minerals were commonly used in materials such as cement wallboard, heating and electrical ducts, and roofing shingles because of their mechanical and thermal properties. In asphalt shingles, asbestos fibers (typically in the form of chrysolite) were used to reinforce and fireproof/insulate the mat (*12*).

While these fibers were present in asphalt shingles, they were typically placed in low dosages. The average asbestos content in 1964 was 0.02 percent while the amount decreased in 1973 to 0.00016 percent (*44*). However, asbestos fibers are not used in asphalt shingles today, nor have they been used since the 1980s (*12, 49*). Therefore, MW shingles should not contain asbestos, and contractors should ask shingle manufacturers for documentation stating their shingles were free of asbestos before they are used in asphalt mixtures (*19*).

Though asphalt shingles are typically replaced every 15 to 25 years, many roofers place a layer of new asphalt shingles on top of old shingles, thus burying asphalt shingles which may contain

asbestos (*12, 46*). Therefore, asbestos can be present in PC waste RAS even after more than 30 years.

Numerous studies have been conducted to determine the prevalence of asbestos in shingles throughout the country. Table 10 provides these test results by state. As can be seen, asbestos is rarely found in today's roofing waste; however, one must still exercise caution in using PC waste, and mandatory testing of these materials for asbestos is required by some agencies (*9*).

Some agencies require asbestos testing once for every 100 tons of material (*28*); however, other state agencies have not developed protocols for RAS asbestos testing. Asbestos sampling protocol can be found elsewhere in Dan Krivit Associates *Recycling Tear-off Asphalt Shingles: Best Practices Guide* (*20*).

One concept critical to preventing asbestos contamination is related to RAS stockpiling. Once a RAS stockpile has been tested for asbestos, it is critical that no more shingles be added to ensure the "new shingles" do not contaminate a stockpile which has been certified as clean.

TABLE 10 Asbestos Testing Results (*12*)

State	Date	Number of Samples	Number of Samples Detected Below 1%	Number of Samples Detected Above 1%	Total Percent of Samples Detected
Maine	1994-1995	146	2	2	2.7%
Iowa	1999-2001	1,791	0	0	0.0%
Florida	2000-2001	591	3	2	0.8%
Missouri	2001	6	0	0	0.0%
Missouri	2000	45	0	0	0.0%
Minnesota	2001-2002	206	1	0	0.5%
Massachusetts	2000-2001	2,288	11	1	0.5%
Massachusetts	2002	6	1	0	16.7%
Massachusetts	2006-2007	6,461	0	2	<0.01%
Massachusetts	2004-2007	16,541	0	401	2.5%

Asbestos Testing

If PC is to be used in asphalt mixtures, contractors should make plans to test stockpiles for asbestos by trained personnel. A list of accredited laboratories can be found on the National Institute of Standards and Technology website (*48*). In order to test RAS for this contaminant, the asphalt must first be removed from the shingle by means of non-acidic chemicals, as research has shown that acidic chemicals and heat affect both the optical and mineralogical properties of the asbestos fibers. At temperatures below 350°C, there is little effect on the individual asbestos fibers; however, as temperatures approach 600°C, there are appreciable changes in the optical characteristics and possible mineralogy of the asbestos. Additionally, acidic chemicals will have similar effects.

Once the asphalt has been removed, the fibers and granules can be examined using a stereomicroscope under 200 times magnification. If there are no fibrous or cylindrical specimens in the sample, asbestos is not present; however, if they are present, the samples should be sent to a laboratory capable of conducing polarized light microscopy (PLM) or transmission electron microscopy (TEM).

Polarized Light Microscopy

PLM is one option contractors can use to determine if asbestos is present in RAS using specialized equipment (Figure 19). Once fibers have been grain mounted, two drops of an oil with a refractive index of 1.550 is added to the fibers. Asbestos fibers which are classified as amphiboles (chrysotile, amosite, tremolite, actinolite, anthophyllite, and crocidolite) can be visually quantified at this refractive index. They will tend to show a yellow color to indicate that materials higher than the refractive index are in the liquid. If they are present, further testing must be completed to assess which fibers are present. Table 11 presents a list of the six asbestos-forming fibers and their respective refractive indices. The concentration of asbestos is reported as the percent of occluded area in the sample. This does not take into account the differences in density of the fibers and species in the sample.

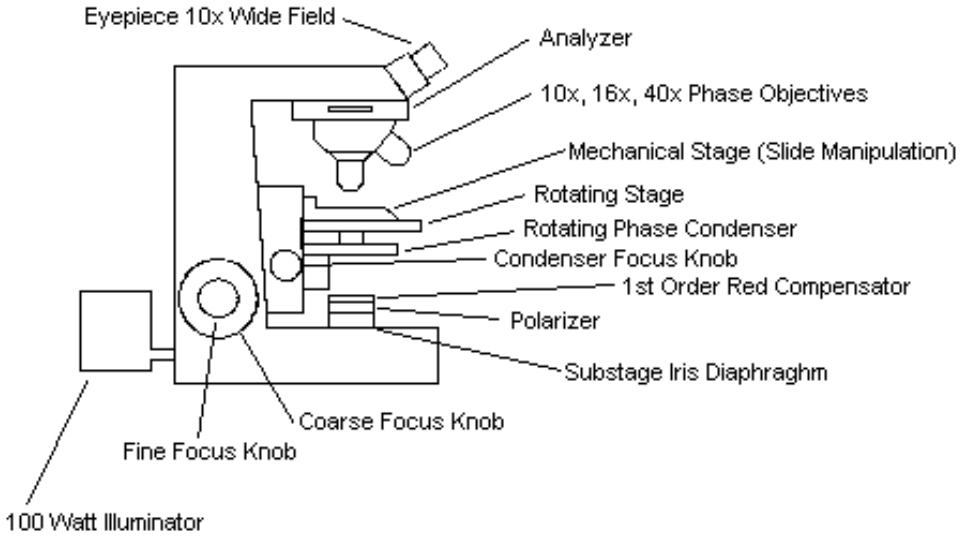

FIGURE 19 Polar microscope (*48*)

TABLE 11 Refractive Indices of Asbestos Fibers

Fiber	Refractive Index
Chrysotile	1.550
Amosite	1.670 or 1.680
Crocidolite	1.690
Anthophyllite	1.605 and 1.620
Tremolite	1.605 and 1.620
Actinolite	1.620

One should be aware that the presence of fibers which are visible at the refractive indices is not indicative of asbestos. The six mineral forms of asbestos can occur in two states: asbestos and cleavage. While the fibers are being visually assessed under the microscope the examiner will assess their shape. If the fibers have ends which are splayed and curved, the fiber is in asbestos form; however, if the fibers have a definitive step-like shape to them and large diameters (> 1 μm), they are in cleavage form and, thus, they are non-hazardous.

A diagram of PLM testing methodology is presented below.

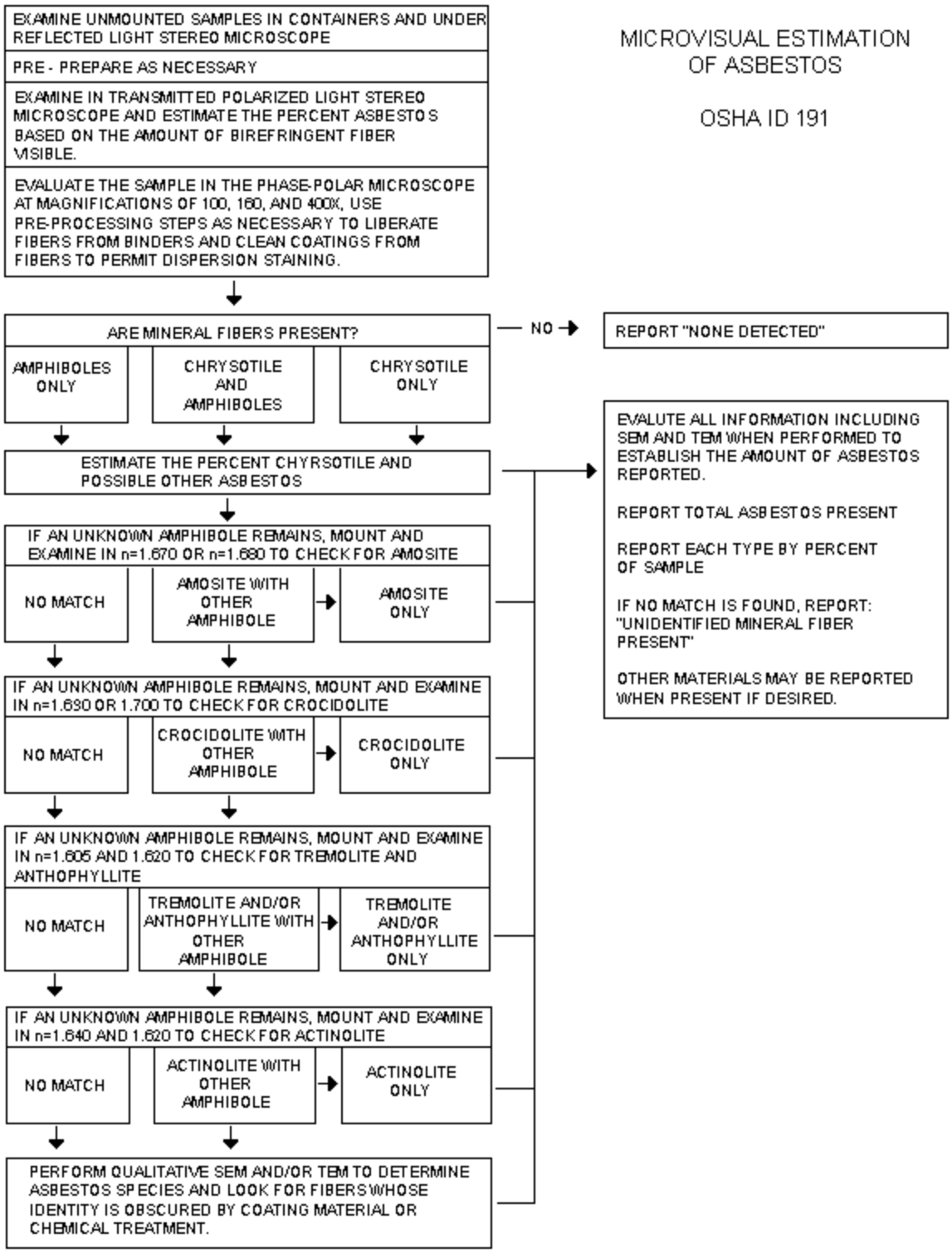

FIGURE 20 PLM testing methodology (*48*)

Transmission Electron Microscopy (TEM)

As suggested by the PLM diagram, there are times when another testing method is needed to determine if asbestos is present in shingles. Transmission electron microscopy can be used to assess asbestos which might be obscured by a certain coating or chemical treatment during PLM testing. Again, this testing should be conducted by an accredited laboratory. NIST provides such a list of these laboratories on its website (*47*).

TEM is the most sophisticated method for determining asbestos type and quantity in shingles, and most TEM asbestos testing is conducted using ASTM D6281-09 *Standard Test Method for Airborne Asbestos Concentration in Ambient and Indoor Atmospheres as Determined by Transmission Electron Microscopy Direct Transfer*. This test is completed on a 100 to 500 mg sample of RAS which is dried and then digested in an acid-water mixture for 15 minutes. After vacuuming the sample, a grid of the fiber residue is prepared and allowed to dry under heat lamps.

CURRENT SPECIFICATIONS

Specifications allowing RAS in asphalt pavements vary from state to state. While some states limit the total amount of RAS in the mixtures by the weight of the mix, other states are moving toward specifications which limit the amount of recycled binder which can be contributed to a new asphalt mixture. A list of some of the current allowances for RAS is given in Table 12.

TABLE 12 Current Specifications (*17, 22*)

State	Allowable RAS, %	Allowable % Recycled Binder
Alabama	5	-
Indiana	5	-
Iowa	7	-
Maryland	5	-
Michigan (tier 2 mixtures)	-	27
Minnesota	5	25
Missouri	7	-
New Jersey	5	-
North Carolina	6	-
Ontario	5	-
South Carolina	5	-
Texas	5	35
Virginia	5	-
Wisconsin (base course)	-	20
Wisconsin (binder/surface course)	-	15

NOTE: - = not applicable

SUMMARY AND RECOMMENDATIONS

From 2009 to 2010, the use of RAS in asphalt mixtures increased by over 50 percent. As more contractors use this material, it is critical that engineers spend the time to correctly characterize its material properties for mixture design and mixture quality. To ensure both of these ideals, the following recommendations are made for characterizing RAS.

- Always process RAS to ensure it has a gradation with at least 100 percent passing the ½-inch sieve. This will aid in activating the asphalt on the shingle and aid in mat placement.
- Minimize deleterious materials in the RAS.
- All PC RAS should be tested for asbestos. Require manufacturers to ensure MW RAS does not have asbestos.
- Once a stockpile has been tested for asbestos, do not place any additional RAS on the stockpile.
- Cover RAS stockpiles or ensure adequate drainage is available to prevent excess moisture in the shingle stockpiles. Additional moisture will require plants to operate at higher temperatures or provide increased drying times to drive off the moisture.
- Unless determining the performance grade of the RAS asphalt, RAS can be dried in an oven; however, oven drying may drive off additional light oils which will stiffen the RAS binder. If the binder is to undergo performance grade testing, dry RAS using a fan.
- RAS asphalt is stiffer than RAP or virgin asphalt since it has been air blown and/or been aged on rooftops. RTFO and PAV aging makes the material more challenging to mold and characterize. Standard water bath DSRs cannot be used to conduct performance grade testing since much RAS asphalt has a PG grade greater than the boiling point of water.
- RAS asphalt content should be determined by chemical extraction unless an appropriate ignition oven correction factor can be determined. Comparisons should be conducted to determine the relative closeness of ignition oven and chemical extraction asphalt contents of same-source RAS.
- Do not use an assumed RAS aggregate gradation. Conduct RAS aggregate gradation of materials recovered from chemical extraction or ignition oven testing to ensure the correct gradation is used in the mixture design process.
- Use the effective specific gravity of the RAS aggregate as the bulk specific gravity of the RAS aggregate. This can be determined using standard theoretical maximum specific gravity testing or using vacuum saturation to backcalculate the effective specific gravity of the material.

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