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Recommended Use of Reclaimed Asphalt Pavement in the Superpave Mix Design Method: Guidelines

This NCHRP digest describes findings of NCHRP Project 9-12, "Incorporation of Reclaimed Asphalt Pavement in the Superpave System," conducted by Rebecca McDaniel of the North Central Superpave Center at Purdue University, West Lafayette, Indiana, with the assistance of R. Michael Anderson of the Asphalt Institute, Lexington, Kentucky. The digest is based upon Appendix D of the contractor's final report.

INTRODUCTION

Use of Guidelines

These guidelines are intended as reference material for agencies and hot-mix asphalt (HMA) producers using reclaimed asphalt pavement (RAP) in Superpave®. They include recommendations on aspects of sampling, testing, designing, producing, and placing Superpave mixtures with RAP. The guidelines are written for the engineers and supervisors selecting or approving RAP mixtures. Detailed, step-by-step procedures are provided in a companion document, *NCHRP Report 452,* "Recommended Use of Reclaimed Asphalt Pavement in the Superpave Mix Design Method: Technician's Manual."

These recommendations are based on the research conducted under NCHRP Project 9-12, "Incorporation of Reclaimed Asphalt Pavement in the Superpave System," including a detailed review of the literature. That work is summarized in the final report for the project.

Why Use RAP?

The materials present in old asphalt pavements may have value, even when the pavements have reached the end of their service lives. Recognizing the value of those existing aggregate and asphalt resources, states and contractors have made extensive use of RAP in the past when producing new asphalt pavements. Use of RAP has proven to be economical and environmentally sound. In addition, mixtures containing RAP generally have been found to perform as well as virgin mixtures.

Old asphalt pavements are milled-up and recycled into new mixtures for the same project or are stockpiled for later use. The value of the RAP needs to be adjusted to take into account the costs of transportation, stockpiling, processing (if any), handling, and testing. Testing is important to determine the characteristics of the RAP as a component of the HMA. Some state specifications allow the use of a higher percentage of RAP when it is reused on the same project because the RAP may be more consistent than stockpiled materials from mixed sources.

The original Superpave specifications contained no provisions to accommodate the use of RAP. Continued use of RAP in Superpave pavements is desired because

- RAP has performed well in the past and is expected to perform well in Superpave mixtures also if properly accounted for in the mix design,
- The use of RAP is economical and can help to offset the increased initial costs sometimes associated with Superpave binders and mixtures,
- The use of RAP conserves natural resources, and

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- The use of RAP can reduce disposal problems and associated costs.

When the aged binder from RAP is combined with new binder, the aged binder will have some effect on the resultant binder grade. At low RAP percentages, the change in binder grade is negligible. At higher percentages, however, the effect of the RAP becomes significant.

The aggregate in the RAP may also affect mixture volumetrics and performance. The design aggregate structure, crushed coarse aggregate content, dust proportion, and fine aggregate angularity should take into account the aggregate from the RAP. Again, at low RAP percentages, the effects may be minimal.

One recurring question regarding RAP is whether it acts like a "black rock." If RAP acts like a black rock, the aged binder will not combine to any appreciable extent with the virgin binder and will not change the binder properties. If this is the case, the premise behind blending charts—which combine the properties of the old and new binders—is void.

These questions were addressed in NCHRP Project 9-12, "Incorporation of Reclaimed Asphalt Pavement in the Superpave System." The objectives of the research effort were to address the black rock question, to investigate the effects of RAP on binder grade and mixture properties, and to develop guidelines for incorporating RAP in the Superpave system. The products of the research include proposed revisions to applicable American Association of State Highway and Transportation Officials (AASHTO) standards, a technician's manual (*NCHRP Report 452*), and guidelines for specifying agencies.

Summary of NCHRP Project 9-12 Research Findings

Black Rock Study

The research effort primarily was directed at resolving the issue of whether RAP acts like a black rock or whether some blending does occur between the old, hardened RAP binder and the added virgin binder. This question was addressed in NCHRP Project 9-12 by fabricating mixture specimens simulating actual practice, black rock, and total blending. The "black rock" and "total blending" cases represent the possible extremes of blending. The black rock case simulates no blending of the old and new binder by removing the old binder from the mixture. This removal was done by extracting the binder from a RAP mixture then blending the recovered RAP aggregate in the proper proportions with virgin aggregate and virgin binder. The actual practice samples were prepared by adding the RAP with its coating intact to virgin aggregate and virgin binder. The total blending samples were fabricated by extracting and recovering the RAP binder and physically blending it into the virgin binder, then combining the blended binder with the virgin and RAP aggregates. All the samples were prepared on the basis of an equal volume of total binder.

Three different RAPs, two different virgin binders, and two RAP contents (10 and 40 percent) were investigated in this primary phase of the project. The different cases of blending were evaluated through the use of various Superpave shear tests at high temperatures and of the indirect tensile creep and strength tests at low temperatures. The results indicated no significant difference among the three different blending cases at low RAP contents. At higher RAP contents, however, the differences became significant. In general, the black rock case demonstrated lower stiffnesses and higher deformations than did the other two cases. The actual practice and total blending cases were not significantly different.

These results provide compelling evidence that RAP does not act like a black rock. It seems unreasonable to suggest that total blending of the RAP binder and virgin binder ever occurs, but partial blending apparently occurs to a significant extent.

This partial blending means that at high RAP contents the hardened RAP binder must be accounted for in the virgin binder selection. The use of blending charts for determining the virgin binder grade or the maximum amount of RAP that can be used is a valid approach because blending does occur. Procedures for extracting and recovering the RAP binder with minimal changes in its properties and then for developing blending charts are detailed in the final report and in *NCHRP Report 452*. The recommended extraction-and-recovery procedure uses either toluene and ethanol, as specified in AASHTO TP2, or an n-propyl bromide solvent, which was proven suitable for use in this research.

The findings also support the concept of a tiered approach to RAP usage because the effects of the RAP binder are negligible at low RAP contents. This support is very significant because it means that lower amounts of RAP can be used without going to the effort of testing the RAP binder and developing a blending chart. The procedures for developing blending charts were perfected during the second portion of the project, the binder effects study.

Binder Effects Study

This secondary phase of the research investigated the effects of the hardened RAP binder on the blended binder properties and led to recommended procedures for testing the RAP binder for the development of blending charts.

The same three RAPs and two virgin binders were evaluated in this phase of the project at RAP binder contents of 0, 10, 20, 40, and 100 percent. The blended binders were tested according to the AASHTO MP1 binder tests.

The results show that the MP1 tests are applicable to RAP binders and that linear blending equations are appropriate. The recovered RAP binder should be tested in the dynamic shear rheometer (DSR) to determine the binder's critical high temperature as if it were unaged binder. The rest of the recovered binder should then be aged in a rolling thin film oven (RTFO); linear blending equations are not appropriate without this additional aging. The high temperature stiffness of the RTFO-aged binder should be determined. The remaining MP1 tests at intermediate and low temperatures should then be performed as if the RAP binder were RTFO-aged and aged in a pressure aging vessel (PAV). The RAP binder does not need to be PAV-aged before testing for fatigue or low-temperature cracking, as would be done for original binder. Because PAV-aging is not necessary, the testing process is shortened by approximately 1 day; conventional Superpave methods and equipment can be used with the recovered RAP binder. (Above 40 percent RAP or so, some nonlinearity begins to appear.)

The binder effects study also supports the tiered-usage concept. At low RAP contents, the effects of the RAP binder are negligible. At intermediate RAP contents, the effects of the RAP binder can be compensated for by using a virgin binder that is one grade softer on both the high- and low-temperature grades. The RAP binder stiffens the blended binder. At higher RAP contents, a blending chart should be used to either determine the appropriate virgin binder grade or to determine the maximum amount of RAP that can be used with a given virgin binder. The limits of the three tiers vary depending on the recovered binder stiffness. Higher RAP contents can be used if the recovered RAP binder stiffness is not too high.

These findings mean that in general, conventional equipment and testing protocols can be used with RAP binders. The tiered approach allows for the use of up to 15 to 30 percent RAP without extensive testing. Higher RAP contents can also be used when additional testing is conducted.

Mixture Effects Study

The same three RAPs and two virgin binders were used in this tertiary phase of the research to investigate the effects of RAP on the resulting mixture properties. Shear tests and indirect tensile tests were conducted to assess the effects of RAP on mixture stiffness at high, intermediate, and low temperatures. Beam fatigue testing was also conducted at intermediate temperatures. RAP contents of 0, 10, 20, and 40 percent were evaluated.

All of the tests indicated a stiffening effect from the RAP binder at higher RAP contents. At low RAP contents, the mixture properties were not significantly different from those of mixtures with no RAP. The shear tests indicated an increase in stiffness and a decrease in shear deformation as the RAP content increased. These changes indicate that higher RAP content mixtures (with no change in binder grade) would exhibit more resistance to rutting. The indirect tensile testing also showed increased stiffness for the higher RAP content mixtures, which could lead to increased low-temperature cracking if no adjustment is made in the virgin binder grade. Beam fatigue testing also suggests an increase in stiffness because the beam fatigue life decreased at higher RAP contents. The decrease in beam fatigue life is related to the increase in stiffness.

The significance of these results is that the concept of using a softer virgin binder with higher RAP contents is supported. The softer binder is needed to compensate for the increased mixture stiffness and to help improve the fatigue and low-temperature cracking resistance of the mixture. The results also support the tiered concept because low RAP contents (i.e., below 20 percent) yield mixture properties that are statistically the same as the virgin mixture properties.

Conclusions

The findings of the NCHRP Project 9-12 research effort largely confirm current practice. The concept behind the use of blending charts is supported. A tiered approach to the use of RAP is found to be appropriate. The advantage of this tiered approach is that relatively low levels of RAP can be used without extensive testing of the RAP binder. If the use of higher RAP contents is desirable, conventional Superpave binder tests can be used to determine how much RAP can be added or which virgin binder to use.

The properties of the aggregate in the RAP may limit the amount of RAP that can be used. The RAP aggregate properties, with the exception of sand equivalent value, should be considered as if the RAP is another aggregate stockpile, which, in fact, it is. Because the mixtures being recycled presumably met specifications when constructed, certain minimum aggregate properties and mixture properties were met. Past specifications, however, likely differed from Superpave specifications. In the mix design, the RAP aggregates should be blended with virgin aggregates, so the blend meets the consensus properties. Also in the mix design, the RAP binder should be taken into account, and the amount of virgin binder added should be reduced accordingly.

Many specifying agencies will find that these recommendations largely agree with past practice. DSR and bending beam rheometer (BBR) tests may replace the viscosity tests that were previously used, but the concepts are still the same. Perhaps these results should not be surprising; the asphalt binders and mixtures are largely the same as those that were previously used. This research effort, however, should give agencies confidence in extending the use of RAP to Superpave mixtures.

DETERMINING THE PROPERTIES OF RAP

RAP sampling for Superpave mixtures is essentially no different than sampling for conventional Marshall or Hveem mixtures. When collecting RAP materials to be used in the mix design process, however, larger samples may be needed because Superpave specimens are much larger than Marshall or Hveem specimens.

Some of the tests done for Superpave are different from those done for Marshall or Hveem designs. Under the

Superpave method, the blend of aggregates must meet certain gradation limits and consensus properties; these same limit and property requirements also apply to blends with RAP. Superpave binders also need to meet certain property requirements. If a high percentage of RAP is used (i.e., greater than 15 to 30 percent, depending on the recovered RAP binder grade), the RAP binder will have to be considered when choosing the virgin asphalt grade.

RAP Variability

One concern many agencies have about the use of RAP is the variability of the material. Because RAP is removed from an old roadway, it may include the original pavement materials, plus patches, chip seals, and other maintenance treatments. Base, intermediate, and surface courses from the old roadway may all be mixed together in the RAP. RAP from several projects may be mixed in a single stockpile. Mixed stockpiles may also include materials from private work that may not have been built to the same original standards.

Because of variability concerns, some states limit the amount of RAP that can be included in new mixtures. Statistically based limits on the variability of the final mixture properties can encourage proper RAP processing and stockpiling by contractors to help them meet these mixture properties.

Variability is a concern for both the agency and the contractor. If the RAP varies widely in properties such as gradation or asphalt content, the resulting HMA may also be variable. This variability will make it harder for the contractor to meet specifications. In states that incorporate penalties and bonuses (e.g., disincentives and incentives) for meeting the specifications, variability can lead to reduced pay for the material produced; therefore, it is to the contractor's advantage to control variability as much as possible.

Good stockpile management practices should be followed to keep material variability in check. Research has shown that the variability of RAP can be controlled and may not be as great as expected (*1*). Processing the RAP by crushing or screening, or both, can help also to reduce variability. The National Asphalt Pavement Association has an excellent publication entitled *Recycling Hot Mix Asphalt Pavements* (*2*) that discusses processing and handling RAP at the plant and during construction.

Sampling RAP

RAP can be sampled from the roadway (by coring before the pavement is milled), from a stockpile, or from haul trucks. The process for stockpile or haul-truck sampling is similar to the sampling process used for aggregates. It is important to get samples that accurately reflect the material that is available for use. For example, in a stockpile of RAP, some segregation may have occurred, and there may be parts of the pile that are coarser than the rest of the pile. (RAP materials are not as likely to segregate as aggregates because the asphalt binder in the RAP helps keep coarse and fine aggregate bound together.) When sampling a pile, it is important to sample from several locations to avoid taking the entire sample from a segregated area.

FHWA's *Pavement Recycling Guidelines for State and Local Governments* (*3*; pp. 5-1 through 7-26) includes a detailed discussion of sampling RAP. Many of the recommendations in this digest are found in that FHWA report.

Roadway Sampling

Many states use cores from existing roadways to measure the properties of the in-place pavement before recycling. Sometimes this information is available before a contract is bid. Cores may be pulled and analyzed for gradation, asphalt content, and, possibly, binder properties.

If roadway sampling is used, it is important to remember that the milling and processing of the RAP may change the sampling's gradation when compared with roadway cores. Some states have developed degradation factors for the change in gradation based on state experience with local materials. Stockpiles should be checked at the plant during construction to verify the actual RAP gradation.

Random sampling is recommended to get the best representation of the materials present. If historical construction records are available, they may be used to divide the project length into segments that were constructed at the same time to the same standards. Each section can then be randomly sampled to determine its specific properties. If the sections are very different, they may need to be handled separately during recycling.

At least one sample should be taken in each 1.6 lane-km (1 lane-mi). Each sample should consist of a minimum of three cores. Cores may then be sawed into layers, or the total depth to be milled or recycled can be combined for testing.

Stockpile Sampling

Sampling RAP from a stockpile is similar to sampling aggregate from a stockpile. However, the RAP stockpile may "crust over," so the top 150 mm (6 in.) of RAP should be shoveled off before taking the sample. Samples should be taken from at least 10 places around the stockpile. At each random location, then, the top 150 mm (6 in.) should be removed before shoveling the sample out of the pile.

Sampling from Haul Trucks

RAP can be sampled from the trucks hauling milled material from the roadway to the plant location. When sampling RAP from a truck, a trench with a level bottom is dug across the RAP. Samples should be collected at three locations spaced equally across the trench by digging in with a shovel.

Sample Size

The size of sample needed depends on the purpose of the sampling. To test the RAP for gradation and asphalt content or to monitor variability for quality-control testing, sample sizes of about 10 kg (22 lb) are usually adequate. If the sample of material will be used for mix design, a larger sample size will be needed. Superpave specimens are much larger than Marshall or Hveem specimens, so more material will be needed when doing a Superpave mix design. Typically, a sample of at least 25 kg (55 lb) is needed.

Extraction and Recovery of RAP Binder and Aggregates

It is important to know how much asphalt binder is present in the RAP material, so it can be accounted for in the mix design process. It is also important to know some physical properties of the RAP aggregate, such as the gradation and angularity. These properties can be determined by doing an extraction on the RAP to measure the asphalt content and obtain the "bare" aggregate for testing.

Sometimes, it is also necessary to know something about the physical properties of the asphalt binder, not just how much there is. In these cases, it is necessary to extract the asphalt binder from the RAP using a solvent, so the binder can be tested. If more than 15 to 30 percent RAP is to be used, depending on the grade of the recovered RAP binder, blending charts are needed to determine the appropriate virgin binder grade to use or to determine how much RAP can be used with a given virgin binder grade. (This will be discussed further under Determining RAP Binder Properties.)

Each agency may want to evaluate various RAP materials typical to their state to attempt to determine the approximate recovered RAP binder grades. This information is needed to determine which column of the binder grade selection chart (which will be discussed under Determining RAP Binder Properties) should be used. Choosing the column that is appropriate for a given state may simplify the binder selection process.

Binder content and aggregate properties can be determined by one of several different methods. The asphalt can be extracted from the RAP using a solvent in a centrifuge, vacuum, or reflux extractor; or the asphalt can be burned off the aggregate in an ignition oven. The asphalt content should be calculated and the aggregate should be saved for later evaluation.

An ignition oven can change the gradation and properties of some aggregates because some aggregates break down or are lost in the oven; therefore, local experience with typical aggregate types in ignition ovens should be considered. These breakdowns can also lead to erroneous estimates of the binder content with some aggregates, especially for RAP for which a correction factor for the aggregate may have to be estimated. Experience with local aggregates can indicate if an ignition oven is an appropriate method to use in a given area. Many states are now evaluating the effects of ignition ovens on typical aggregate properties. These evaluations also can be valuable when assessing RAP aggregate properties.

If the recovered RAP binder grade needs to be determined, the modified AASHTO TP2 procedure should be used to extract and recover and binder for later testing. This modified procedure will be described briefly under Determining RAP Binder Properties; more detail is provided in *NCHRP Report 452*.

Determining Aggregate Properties

The aggregate saved after determining the binder content must be analyzed to determine its gradation and certain physical properties. If a solvent extraction was used to recover the aggregate, the aggregate should be thoroughly dried in an ignition oven or in front of a fan before testing. If an ignition oven was used, the aggregate should be completely cooled before handling.

RAP Aggregate Gradation

The RAP aggregate should be sieved over the standard nest of sieves according to AASHTO T30, "Mechanical Analysis of Extracted Aggregate," or AASHTO T27, "Sieve Analysis of Fine and Coarse Aggregates."

RAP Aggregate Specific Gravity

To calculate the voids in the mineral aggregate (VMA) or to utilize the Superpave method for estimating the binder content of a mixture, it is necessary to know the combined aggregate bulk specific gravity. The combined aggregate bulk specific gravity is calculated using the bulk specific gravity of each aggregate stockpile, including the RAP aggregate. (See Appendix, Equation A-1, for the commonly used formulae.)

It can be difficult, however, to accurately measure the bulk specific gravity of the RAP aggregate. Measuring the RAP aggregate specific gravity would require extracting the RAP, sieving it into coarse and fine fractions, and determining the specific gravity of each fraction. The extraction process, however, can change the aggregate properties and may result in a change in the amount of fine material, too, which could also affect the specific gravity.

In the past, some states have used the effective specific gravity of the RAP aggregate instead of its bulk specific gravity. The effective specific gravity can be calculated from the RAP mixture maximum specific gravity, which can easily be determined by conducting AASHTO T209. The asphalt content of the RAP is determined by extraction or ignition oven; the binder specific gravity is assumed. The effective specific gravity is then calculated (see Appendix, Equation A-2). This estimate of the RAP aggregate effective specific gravity can be used to calculate the combined aggregate specific gravity, which is then used to calculate the VMA.

The bulk specific gravity (G_{sb}) is always smaller than the effective specific gravity (G_{se}) for a given aggregate. Substituting the G_{se} for the G_{sb} of RAP will result in overestimating both the combined aggregate bulk specific gravity and the VMA. The error introduced by the substitution of G_{se} for G_{sb} will be greater when higher percentages of RAP are used. For this reason, some states that allow the use of G_{se} for the RAP aggregate also change their minimum VMA requirements to account for this error.

An alternative approach used by some states is to assume a value for the absorption of the RAP aggregate. On the basis of past experience with the same aggregates, some states can estimate this value quite accurately. The G_{sb} of the RAP aggregate can be calculated based on this assumed absorption (see Appendix, Equations A-3 and A-4). This G_{sb} value can then be used to estimate the combined aggregate bulk specific gravity and to calculate VMA.

Each agency should evaluate materials typically used in their area and determine which approach above gives the agency the most confidence. If historical records are available that can indicate the source of the predominant aggregates in the RAP, it may be possible to accurately estimate aggregate properties, such as asphalt absorption. If a state determines that it will substitute the effective RAP aggregate specific gravity for the bulk specific gravity, that state should also examine, and attempt to minimize, the error introduced in VMA calculations by the substitution. Adjusting the minimum VMA requirements to compensate for the error introduced by the substitution may help to minimize the error.

Consensus Properties

The RAP aggregate may also be tested to determine its consensus properties, as is done with virgin aggregates for Superpave mixtures. It is important to remember, however, that the Superpave consensus properties apply to the total blend of aggregates (RAP plus virgin, in this case), not to the individual aggregate components. Again, knowledge of how locally available aggregates are changed by ignition ovens may help to determine if an ignition oven is a viable technique for obtaining bare RAP aggregate for testing.

The RAP aggregate should be sieved to separate it into coarse and fine fractions. The coarse aggregate (retained on the 4.75-mm [No. 4] sieve) should be analyzed for coarse aggregate angularity. Coarse aggregate angularity is determined by manually counting aggregate particles with one or more than one fractured face (ASTM D5821). The fine aggregate angularity (AASHTO T304, Method A) can be determined on the aggregate from the RAP that passes a 2.36-mm (No. 8) sieve. The fine aggregate angularity of the RAP aggregate may be changed (usually decreased) by the extraction process. Different aggregates will change by differing amounts; some will change not at all.

The percentage of particles that are flat and elongated must also be determined (ASTM D4791). Some aggregates tend to crush into flat, elongated particles. Some types of crushers also tend to produce more particles with this undesirable shape. Agencies generally know if they tend to have excessive amounts of flat and elongated materials with certain aggregate sources.

The sand equivalent test (AASHTO T176) determines the percentage of fine clay particles contained in the fine aggregate compared with the amount of sand in the aggregate. The percentage is an indication of how clean the fine aggregate is and how well the binder can coat the fine aggregate. This test is not required for the RAP aggregate because the fine aggregate is already coated with asphalt. Also, the test is probably not meaningful for extracted aggregate because fines may be washed away during solvent extraction or additional fines may be created by aggregate degradation during extraction. The sand equivalent test should be conducted on the virgin aggregates used in the mix design.

Moisture in RAP

When conducting a mix design in the lab, the RAP has been thoroughly heated to bring it to the proper temperature for mixing and compaction. This heating also serves to dry any moisture that may be present in the RAP. When using RAP in the field, however, moisture may still be present in the RAP. It is important to determine how much moisture is in the RAP. When determining batch weights for the RAP at the plant, the weight of the moisture in the RAP must be accounted for, just as it is for virgin aggregates. If the weight of the moisture is not accounted for, the actual weight of RAP added will be lower than required because part of the weight will be moisture instead of RAP.

The RAP moisture content can also be a limiting factor for plant production. High moisture contents take a long time and a lot of energy to dry; this can severely affect production. The virgin aggregates need to be heated to higher temperatures to transfer enough heat to the RAP to dry it (*4*). Also, in batch plants, high moisture contents can produce steam clouds in the pugmill that need to be vented.

The moisture content in the RAP is determined in much the same way as the moisture content of a sample of stockpiled aggregates is checked: the RAP is sampled; weighed; dried to constant mass in an ignition oven (or, if in the field, in an electric skillet); and weighed again. Agencies generally have their own particular methods (temperatures, heating times, etc.) for RAP in this test. The moisture content is then expressed as the weight of water, indicated by the change in mass from before and after drying, divided by the dry weight of the RAP (see Appendix, Equation A-5).

DETERMINING RAP BINDER PROPERTIES

This section describes the process of extracting, recovering, and testing the RAP binder properties, when needed. (More detailed information is provided in *NCHRP Report 452,* Chapter 3.) For low RAP contents, 10 to 20 percent, it is not necessary to do this testing because there is not enough of the old, hardened RAP binder present to change the total binder properties. At higher RAP contents, however, the RAP binder will have a noticeable effect, and it must be accounted for by using a softer grade of binder. For intermediate ranges of RAP, the virgin binder grade can simply be dropped one grade. For higher percentages of RAP, the RAP binder must be tested to develop blending charts.

Under the recommended guidelines for using RAP in Superpave mixtures, there are three levels, or tiers, of RAP usage. Table 1 shows these tiers for Superpave RAP mixtures and the appropriate changes to the binder grade. The limits of these tiers depend on the recovered RAP binder grade. With softer RAP binders, it is possible to use higher percentages of RAP. The first tier establishes the maximum amount of RAP that can be used without changing the virgin binder grade. The second tier shows the percentages of RAP that can be used when the virgin grade is decreased by one grade (a 6-degree increment) on both the high- and low-temperature grades. The third tier is for higher RAP contents; for these higher contents, it is necessary to extract, recover, and test the RAP binder and construct a blending chart.

Obviously, it is necessary to know the low-temperature grade of the extracted and recovered RAP binder in order to determine the appropriate column of Table 1 to use. It may be possible to assess typical values on a statewide basis to simplify this process.

Extraction-and-Recovery Process When Testing RAP Properties

A solvent extraction must be used when recovering the RAP binder for testing. Various extraction techniques exist, such as centrifuge, reflux, vacuum, and AASHTO TP2 modified extractions. Various methods are also available for recovery of the binder from the solvent solution. One method—AASHTO T170, "Recovery of Asphalt from Solution by Abson Method"—has been widely used for many years. This method involves boiling the solvent off and leaving the asphalt behind. The solvent is then condensed back into a liquid. This method has been found to significantly alter the binder properties. The Rotavapor® method is similar but the solvent-asphalt mixture is heated more gently in a rotating flask in water.

The AASHTO TP2 modified procedure is the preferred method to extract and recover the asphalt binder because the method results in less severe changes to the binder properties. This extraction/recovery technique uses an extraction cylinder that is rotated on its side to thoroughly mix the solvent with the asphalt mixture. The solvent and the binder it carries are removed from the sample by attaching a vacuum at the bottom of the flask. This extract is then filtered to remove fine aggregate particles before it is collected in a recovery flask. The Rotavapor method is then used to recover the binder from the solvent. (The method is fully described in *NCHRP Report 452*.)

Determining Binder Properties

To construct a blending chart, the desired final binder grade and the physical properties (and critical temperatures) of the recovered RAP binder are needed, plus one of the following pieces of information:

TABLE 1 Binder Selection Guidelines for RAP Mixtures

	RAP Percentage		
	Recovered RAP Grade		
Recommended Virgin Asphalt Binder Grade	**PG xx-22 or lower**	**PG xx-16**	**PG xx-10 or higher**
No change in binder selection	<20%	<15%	<10%
Select virgin binder one grade softer than normal (e.g., select a PG 58-28 if a PG 64-22 would normally be used)	20–30%	15–25%	10–15%
Follow recommendations from blending charts	>30%	>25%	>15%

- The physical properties (and critical temperatures) of the virgin binder, or
- The percentage of RAP in the mixture.

Once the RAP binder has been extracted and recovered, its properties need to be determined. The RAP binder must be tested in the DSR at high temperature as if it were original, unaged binder. Then the remaining RAP binder is aged in the RTFO and is tested in the DSR and BBR.

Following the extraction and recovery of at least 50 g of recovered RAP binder, the critical properties of the RAP binder are determined. The recovered RAP binder is tested as original material in the DSR. The rest of the recovered binder is then RTFO-aged, and the remaining binder properties are determined; PAV-aging is not required. The critical high temperature of the recovered RAP binder is the lower of the original DSR and RTFO DSR critical temperatures. The high-temperature performance grade of the recovered RAP binder is based on this single critical high temperature. The RTFO-aged RAP binder is then tested in the DSR to determine the critical intermediate temperature as if it were PAV-aged (PAV DSR). BBR testing is performed on the RTFO-aged recovered RAP binder to determine the critical low temperature based on BBR stiffness (*m*-value). The higher of these two critical temperatures represents the low critical temperature for the recovered asphalt binder. The low-temperature performance grade of the recovered RAP binder is based on this single critical low temperature.

Once the physical properties and critical temperatures of the recovered RAP binder are known, two blending approaches may be used (see Appendix). In one approach (designated Method A), the percentage of RAP that will be used in an asphalt mixture is known, and the appropriate virgin asphalt binder grade for blending needs to be determined. In the second approach (designated Method B), the maximum percentage of RAP that can be used in an asphalt mixture while still using the same virgin asphalt binder grade needs to be determined. Both approaches assume that the specifying agency will specify the performance grade of the final blended binder.

Binder Grade Selection

The desired binder grade for a mixture is determined based on the climate and traffic level for the particular project where the mixture will be used. Usually the specifying agency determines what the binder grade should be and specifies that in the contract documents. When RAP is used, however, the virgin binder grade may need to be changed (i.e., softened) to account for the addition of the old, hardened RAP binder. Because it is usually the mix designer who determines how much RAP to use in the mix, the designer may need to determine what that virgin binder grade should be.

It should be noted that the effects of RAP on polymer modified binders are still unknown, so care should be exercised when using RAP with modified binders. Additional laboratory testing may be needed to ensure compatibility and to verify final blended binder grade or mixture properties, or both.

Method A: Blending at a Known RAP Percentage (Virgin Binder Grade Unknown)

In some cases, a certain RAP content may be desired. For example, use of a certain percentage of RAP may allow use of all of the millings generated on a given project, or recycling may be most economical if a certain range of RAP contents is used. In other cases, gradation or mix properties may limit the amount of RAP that can be used. If the desired RAP content is known and falls in the third tier, the appropriate binder grade needed to blend with the RAP to get a particular grade for the blend of old and new binder is determined from the blending charts.

Method B: Blending with a Known Virgin Binder Grade (RAP Percentage Unknown)

There may be cases in which use of a particular virgin binder in a RAP mixture is desired. The binder grade may be fixed, based on economics and availability or on the specifications for a given project. In these cases, the amount of RAP that can be used with that specific virgin binder grade and still meet the final blended binder properties can be determined from the blending charts. If the final blended binder grade, virgin asphalt binder grade, and recovered RAP properties are known, then the appropriate amount of RAP to use can be determined. The specific details of how to construct a blending chart are included in *NCHRP Report 452*, Chapter 3.

DEVELOPING THE MIX DESIGN

The amount of RAP to include in the new mixture may be limited by many different factors, including the following:

- Specification limits for mix type, plant type, or other reason;
- Gradation;
- Aggregate consensus properties;
- Binder properties:
- Heating, drying, and exhaust capacity of the plant;
- Moisture content of the RAP and virgin aggregates;
- Temperature to which the virgin aggregate must be superheated;
- Ambient temperature of the RAP and virgin aggregate; and
- Other factors.

These limiting factors could be considered material-related factors and production-related factors. The production-related factors include such factors as the plant capacity for heating and drying the RAP and virgin aggregates. If the ambient temperature is low or the moisture content of the materials is high, it will take more energy to heat and dry the materials. These factors, in turn, will affect the rate of HMA production. Superpave mixtures with RAP will have the same types of production-related limits as Marshall or Hveem mixtures have.

The material-related limits on the amount of RAP that can be used may be different for Superpave mixtures than for Marshall or Hveem mixtures because of the differing specification limits. The allowable gradation, for example, may be different for Superpave mixtures; frequently, lower fines contents are required. Also, the blend of virgin and RAP aggregates has to meet the consensus properties, which may be tighter than previous aggregate requirements.

Overall, however, the situation when using RAP in Superpave mixtures is similar to the situation when using RAP in Marshall or Hveem mixtures. The blend of materials has to meet certain properties and the plant must be capable of drying and heating the materials. Many of the techniques used to evaluate the RAP are similar to previous techniques. Other techniques, particularly the binder evaluations described under Determining RAP Binder Properties, are quite different.

Determining Combined Aggregate Gradation

Once the RAP aggregate gradation has been determined, that aggregate must be blended with the virgin aggregates to meet the overall mixture gradation requirements. The total blend must pass between the control points; it is also recommended that it avoid the restricted zone. There are a number of computer software programs or simple spreadsheets that allow blending of different aggregate stockpiles and observation of how the combination fits the gradation requirements. These programs can be used with RAP by simply treating the RAP aggregate as another stockpile. Blending can also be done by hand using conventional mathematical or graphical techniques.

The Superpave mix design procedure recommends that at least three trial blends be evaluated. When RAP is used, these blends may include different percentages of RAP or may be different combinations of virgin stockpiles with a set percentage of RAP. The proposed aggregate blends must meet the gradation requirements as well as the consensus aggregate properties. In addition, the final blend selected must meet the required volumetric properties (i.e., VMA, voids filled with asphalt [VFA], dust proportion, and densification properties) at 4 percent air voids.

Verifying Aggregate Properties

As mentioned above, the trial blends must meet the consensus aggregate properties. These properties vary for different traffic levels, but they always apply to the total combined aggregate blend. Coarse aggregate angularity, flat and elongated particle content, and sand equivalent content can be calculated as weighted averages based on individual stockpile data, if available. (Sand equivalent value is not required for the RAP stockpile.) It is recommended, however, that fine aggregate angularity actually be measured for the final blend. Because this property depends on how individual aggregate particles slide past each other, a simple weighted average may give erroneous results, especially if the bulk specific gravities of the different stockpiles vary.

Handling RAP in the Lab

The RAP must be heated in the lab to make it workable and to mix it with the virgin materials. In general, the shorter the heating time, the better. A heating temperature of 110°C (230°F) for a time of no more than 2 h is recommended for sample sizes of 1 to 2 kg. Higher temperatures and longer heating times have been shown to change the properties of some RAPs.

The virgin aggregate should be heated to 10°C above the mixing temperature prior to mixing with the RAP and virgin binder. The mix components should then be mixed, aged, and compacted as usual.

Modifications to Standard Mix Design Procedures

The overall Superpave mix design process is very much the same regardless of whether RAP is included. The differences include the following:

- The RAP aggregate is treated like another stockpile for blending and weighing, but must be heated gently to avoid changing the RAP binder properties;
- The RAP aggregate specific gravity must be estimated;
- The weight of the binder in the RAP must be accounted for when batching aggregates;
- The total asphalt content is reduced to compensate for the binder provided by the RAP; and
- A change in virgin binder grade may be needed depending on the amount of RAP, desired final binder grade and RAP binder stiffness.

With these exceptions, the procedure is basically the same with or without RAP. A detailed step-by-step mixture design procedure and an example mix design are included in *NCHRP Report 452*, Chapters 4 and 5.

FIELD QUALITY CONTROL–QUALITY ASSURANCE TESTING

In most states, bituminous mixtures containing RAP are sampled and tested in the same way as virgin mixtures are sampled and tested. If there are any problems with the RAP, such as excessive moisture or variability, it is assumed that these problems will show up in the recycled mixture and be detected by the usual quality-assurance testing. Some additional testing of the RAP may be required by the state at the mix design stage or during construction.

The basic premise governing the use and testing of RAP mixtures should be that RAP mixtures are expected to perform at least as well as virgin mixtures perform. Past experience shows that this goal can be achieved when RAP mixtures are properly designed, produced, and constructed. RAP does provide another possible source of variability, but that variability can be controlled as was discussed under Determining the Properties of RAP. Requiring RAP mixtures to meet the same limits as virgin mixtures will encourage good practices for processing and stockpiling RAP to reduce variability.

Typical mixture acceptance tests include tests of mixture composition (e.g., binder content, gradation, and maximum theoretical specific gravity) and of volumetric properties (e.g., V_a [air voids], VMA, VFA, etc.). These properties usually do not vary if RAP is included in the mixture. One exception to this rule is gradation. Some states allow the testing of belt samples or cold or hot bin samples for the aggregate gradation; with RAP mixtures, those states may require the use of extracted gradations of the RAP mixture.

Additional Quality-Control Procedures with RAP Mixtures

Although the state may not require any changes from its standard quality assurance–quality control procedures, it may be in the contractor's best interest to sample the RAP material more frequently than he or she samples the virgin aggregate. This frequency of sampling will depend on many factors, including

- The consistency of the RAP source,
- How the stockpiles have been managed,
- How much processing of the RAP has occurred,
- The availability of testing personnel,
- Testing costs, and
- Other factors.

Good construction practice may require extra testing to verify the consistency of the RAP and final mixture. Certainly, if problems begin to occur with the mixture properties, the RAP is one of the potential sources of the variability and should be checked.

Testing of the RAP to ensure consistency and quality should include verifying the binder content and gradation. Variations in the RAP material would appear as changes in these properties. Moisture content of the RAP should also be verified if moisture in the mixture becomes a concern.

The frequency of testing the RAP stockpile for quality-control purposes may vary depending on many factors. A minimum frequency of testing based either on the amount of RAP used (e.g., 1 test per 1000 Mg used) or on production (e.g., 1 test per lot) is recommended. Additional testing can then be performed if the contractor suspects the RAP stockpile may be changing, if problems begin to develop in the mixture properties, or for other reasons.

Quality-control plans should address (1) the techniques taken for processing and stockpiling the RAP to ensure consistency and (2) what steps will be taken if excess variability is observed. In other words, RAP should be treated as another source of variation that needs to be monitored and controlled like the other stockpiles.

Meeting tight tolerances based on the laboratory trial mix formula with RAP material may be a challenge. Variability of the RAP will translate into mixture variability, especially at high RAP contents. If mixtures with RAP are expected to perform as well as virgin mixtures perform, however, it is important to meet the same standards at the time of construction. Past experience clearly shows that RAP mixtures can indeed perform as well as do virgin mixtures. There is no reason the situation will be different under Superpave.

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3. Kandhal, P.S., and R.B. Mallick. *Pavement Recycling Guidelines for State and Local Governments*. Report No. FHWA-SA-98-042. Federal Highway Administration: Washington, DC (1997).

4. *Asphalt Hot-Mix Recycling (MS-20)*. Asphalt Institute: College Park, MD (1986).

APPENDIX

Equations

Combined Aggregate Bulk Specific Gravity

$$G_{sb} = \frac{P_1 + P_2 + \cdots + P_N}{\frac{P_1}{G_1} + \frac{P_1}{G_2} + \cdots + \frac{P_N}{G_N}} \qquad \text{(Equation A-1)}$$

where

G_{sb} = bulk specific gravity of the total aggregate;
P_1, P_2, P_N = individual percentages by mass of virgin aggregate and RAP; and
G_1, G_2, G_N = individual bulk specific gravities of aggregate and RAP.

Aggregate Effective Specific Gravity

$$G_{se} = \frac{100 - P_b}{\frac{100}{G_{mm}} - \frac{P_b}{G_b}} \qquad \text{(Equation A-2)}$$

where

G_{se} = effective specific gravity of aggregate;
G_{mm} = theoretical maximum specific gravity of the paving mixture from the AASHTO T209 test;
P_b = RAP binder content at which the AASHTO T209 test was performed, percent by total mass of mixture; and
G_b = specific gravity of RAP binder.

Asphalt Binder Absorption

$$P_{ba} = 100 \times \frac{G_{se} - G_{sb}}{G_{sb} G_{se}} \times G_b \qquad \text{(Equation A-3)}$$

where

P_{ba} = absorbed asphalt binder, percent by weight G_{sb} of aggregate;
G_{se} = effective specific gravity of aggregate;
G_{sb} = bulk specific gravity of aggregate; and
G_b = specific gravity of RAP binder.

Bulk Specific Gravity as a Function of Absorption

$$G_{sb} = \frac{G_{se}}{\left(\frac{P_{ba} G_{se}}{100 \times G_b}\right) + 1} \qquad \text{(Equation A-4)}$$

where variables are as above (in Equation A-3).

Moisture Content

$$\%Moisture = \frac{W_w - W_d}{W_d} \times 100\% \qquad \text{(Equation A-5)}$$

where

W_w = mass of wet RAP, g; and
W_d = mass of RAP after drying to constant mass, g.

Flow Charts for RAP Blending

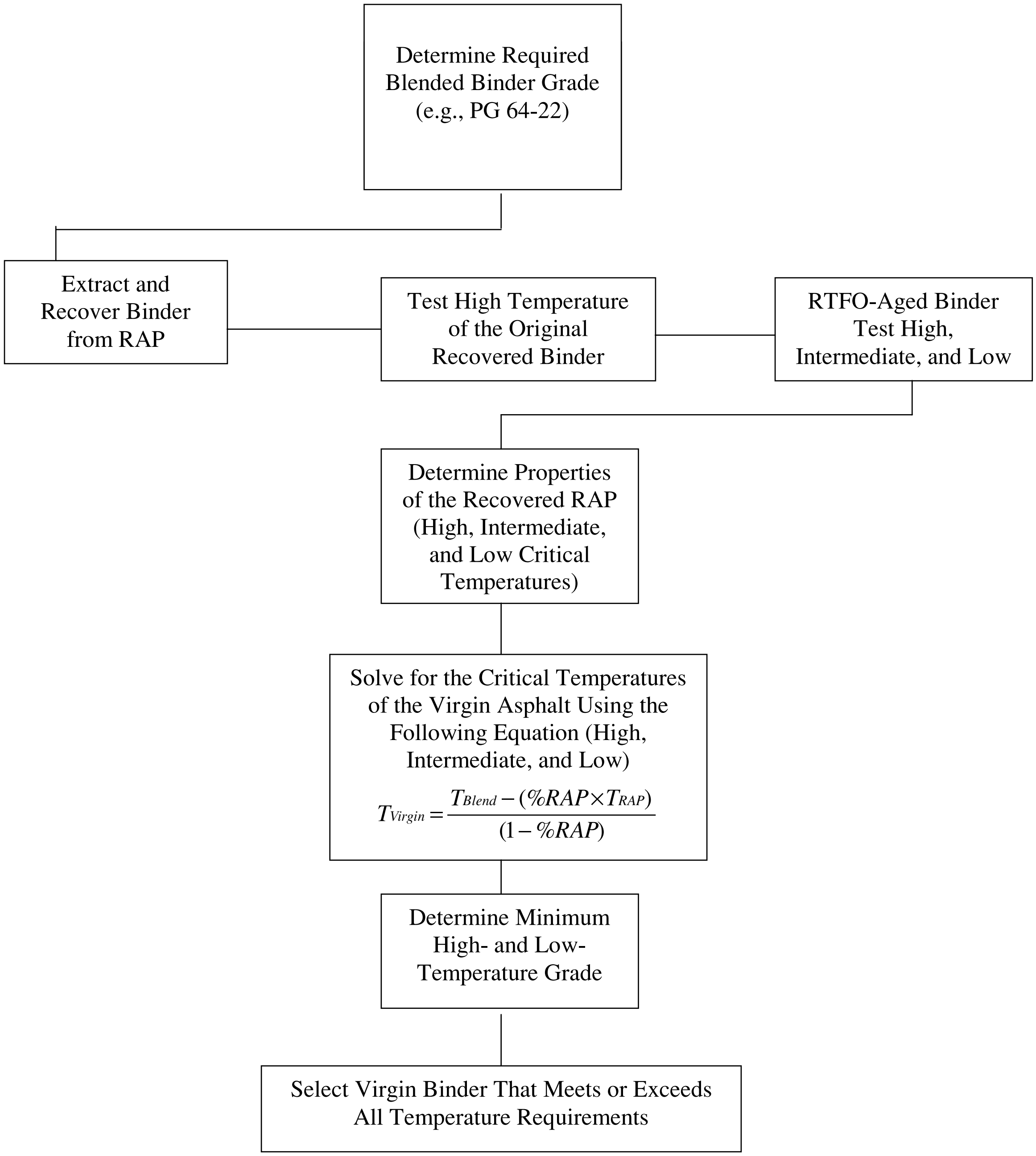

Figure A-1. Method A: Blending at a known RAP percentage (virgin binder grade unknown).

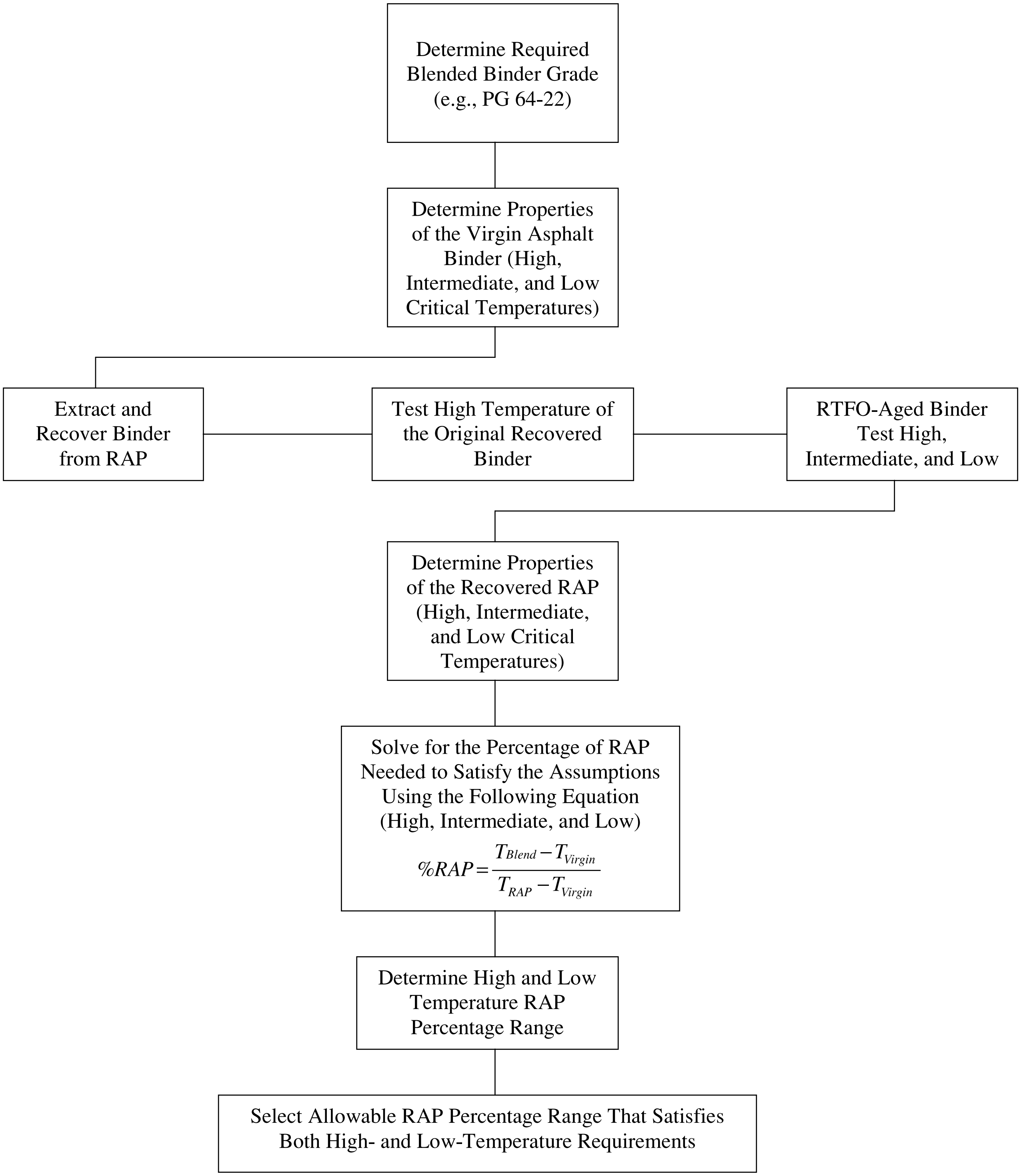

Figure A-2. Method B: Blending with a known virgin binder (rap percentage unknown).

Flow Charts Showing Development of Blending Charts

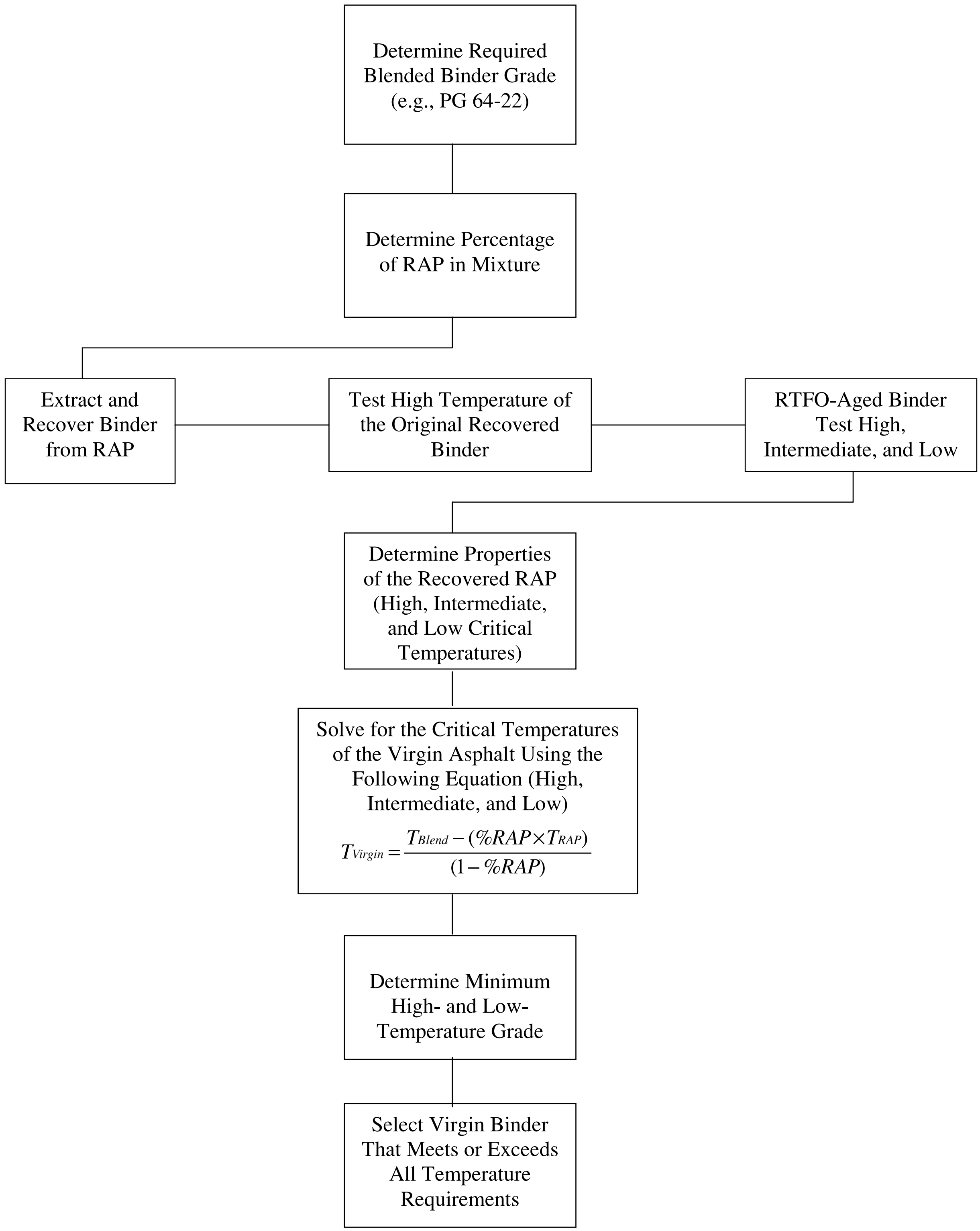

Figure A-3. Method A: Blending at a known RAP percentage (virgin binder grade unknown).

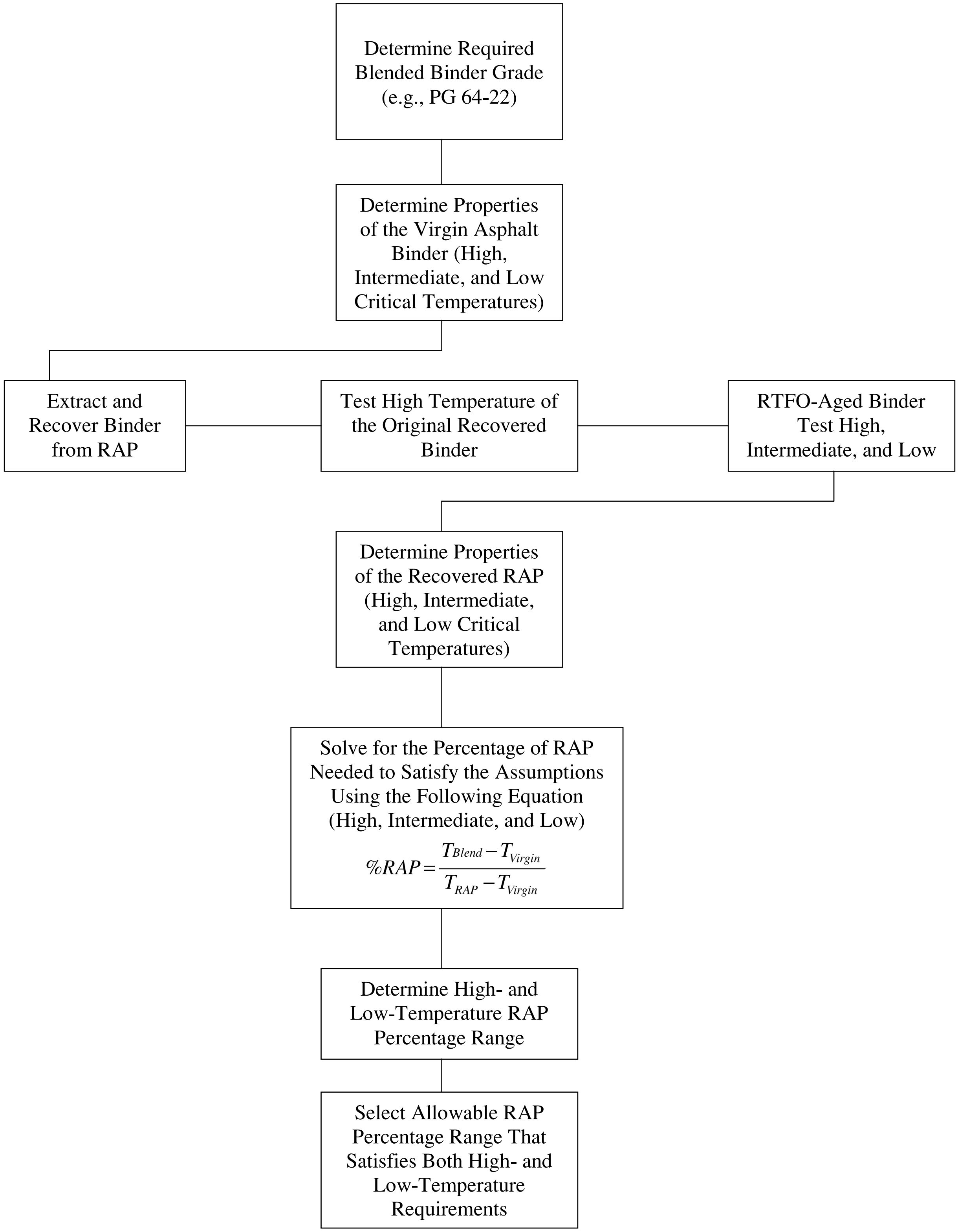

Figure A-4. Method B: Blending with a known virgin binder (RAP percentage unknown).

GLOSSARY

BBR: bending beam rheometer.

Binder: asphalt cement with or without the addition of modifiers.

DSR: dynamic shear rheometer.

Extraction: the process of removing asphalt binder from a sample of hot-mix asphalt, leaving the aggregate behind.

G_b: specific gravity of binder.

G_{mm}: maximum specific gravity of voidless paving mix.

G_{sb}: bulk specific gravity of total aggregate.

G_{se}: effective specific gravity of total aggregate.

Hot-mix asphalt (HMA): a mixture of aggregate and asphalt cement, sometimes including modifiers, that is produced by mixing hot, dried aggregate with heated asphalt in a plant designed for the process.

Hot-mix asphalt recycling: the process in which reclaimed asphalt pavement materials are combined with new or virgin materials to produce hot-mix asphalt mixtures.

***m*-value:** the rate of change with time of the creep stiffness, S, as measured by AASHTO TP1 and used as a specification parameter in AASHTO MP1.

PAV: pressure aging vessel as described in AASHTO PP1.

P_b: the percent by mass of asphalt binder in the total mixture.

P_{ba}: absorbed binder, percent by weight G_{sb} of aggregate.

Reclaimed asphalt pavement (RAP): asphalt paving material milled or scraped off an existing bituminous pavement, consisting of aggregate and asphalt binder.

Recovery: the process of separating asphalt binder from the solvent used to extract the binder from a sample of hot-mix asphalt.

Recycled mixture: the finished mixture of reclaimed asphalt pavement, new binder, and new aggregate; may also include a recycling agent.

Recycling agent: organic materials with chemical and physical characteristics selected to restore aged asphalt to desired specifications.

RTFO: rolling thin film oven.

Specific gravity: the ratio of the density of an object to the density of water at a stated temperature (usually 25°C).

T_c: critical temperature; the temperature at which a binder just meets the performance grading specification limit.

V_a: the total volume of air voids in a compacted paving mix, expressed as percent of the bulk volume of the compacted mix.

VFA: voids filled with asphalt.

VMA: voids in the mineral aggregate.

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