Quality Improvement Series 124

NAPA
NATIONAL ASPHALT PAVEMENT ASSOCIATION

Designing HMA Mixtures with High RAP Content

A Practical Guide

American Association of State Highway and Transportation Officials
AASHTO
1914

U.S. Department of Transportation

Federal Highway Administration

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Designing HMA Mixtures with High RAP Content
A Practical Guide

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Background

The history of asphalt pavement recycling dates back to the early 1900s. However, it wasn't until the oil embargo of the 1970s that the modern practice of pavement recycling truly became widespread. At that time, there was little experience with the technology and mix design, pavement design, construction, and performance of recycled pavements were considered experimental or unknown. However, construction practices rapidly evolved, and in 1978 and 1980, the National Cooperative Highway Research Program (NCHRP) published Synthesis of Highway Practice No. 54, *Recycling Materials for Highways* and Report No. 224, *Guidelines for Recycling Pavement Materials* (Epps, 1978 and Epps et al, 1980) which drew upon the experience of numerous agencies and organizations and provided a practical approach to pavement recycling.

Since then, the technology for pavement recycling has become commonplace. State specifications typically allow the incorporation of reclaimed asphalt pavement in hot-mix asphalt (HMA) mixtures. The Superpave mix design procedure has been modified to evaluate HMA with RAP (McDaniel and Anderson, 2001). Milling machines make it possible to remove asphalt surfaces in a particle size range that can be used with minimal additional processing. Screens for sizing RAP materials at plants allow stockpiles of different size materials to be produced, increasing the flexibility of using RAP in mixes. Batch plants and drum plants are typically manufactured to handle RAP materials.

The HMA industry, in 2006, found itself in a situation comparable to that of the 1970s during the oil embargo. There was a rapid increase in energy costs as well as asphalt binder costs, resulting in increased manufacturing and transportation costs. There were asphalt binder shortages in some regions of the country. Furthermore, as in the 1970s, there was an increased environmental awareness that resulted in difficulty with permitting new aggregate reserves.

Recycling pavement materials has several advantages from environmental, economic, and engineering standpoints. Conservation of petroleum and aggregate resources as well as saving landfill space are the primary environmental advantages. There are fewer vehicles used in transportation resulting in less consumed energy and improved air quality as well as energy reduction in the manufacturing of aggregates and asphalt binder. The use of RAP in HMA creates an opportunity to reduce costs. It is also well accepted that, as long as the proper evaluation and mixture design are done, HMA mixtures produced with RAP can perform as well as, or in some cases better than, mixtures made with virgin materials. The appeal of HMA recycling has led to its designation as the most recycled material in America, with 80 percent of HMA that is removed being recycled back into roads as hot mix, unbound base, or cold mix. According to the FHWA (1993), this amounted to approximately 80 million tons of HMA recycled annually.

Initially, the introduction of Superpave and stone-matrix asphalt (SMA) mixtures resulted in a barrier to using high levels of RAP as researchers and engineers sought to make these new technologies work with virgin materials first. Most States now allow the introduction of RAP into Superpave mixes, although some States remain reluctant. Very few States allow RAP use in SMA. It should be noted, that if the proper engineering evaluation of mixtures is done, there is no reason RAP cannot be used to its fullest extent in any type of HMA mixture.

Often, the performance of RAP mixtures is cited as a concern on the use of recycled materials or the amount of RAP allowed in mixtures. Epps and his co-workers (1980) analyzed the performance of a number of pavements that were up to seven years old at the time, and found the recycled mixtures to be as good as, or better than, mixtures made with all new materials. Chen and Daleiden (2005) reviewed the performance of recycled HMA in specific pavement studies (SPS)-3 and SPS-5 sections of the Long-Term Pavement Performance program. They found that when 30 percent RAP mixtures were used with a softer binder, the performance for both 2-inch (50-mm) and 5-inch (125-mm) overlays was excellent over a 10-year period. Chen and Daleiden reported that the 5-inch (125-mm) overlays were slightly more resistant to reflective cracking. Brown (2000), reporting on results presented by Jon Epps at a conference sponsored by the National Asphalt Pavement Association, gave examples of five States where success with RAP in HMA produced excellent pavement performance. Epps went on to state that care must be taken at high levels of RAP.

It is time to re-examine the levels of RAP allowed in HMA. The question must be how to optimize RAP usage, not how to limit its use. New plant technology, a better understanding of mix design, environmental concerns, and current price and supply issues with liquid asphalt converge to make this the ideal time to make sure that construction funding is maximized while using sound engineering evaluation to ensure high quality mixtures resulting in good performance.

Purpose and Scope

This guideline is written to provide a practical means to allow up to 30 to 40 percent RAP to be used in HMA. It encompasses material selection, mix design, plant verification, and quality control. The value of the materials in RAP and the increased percentages suggested makes it necessary to perform a thorough evaluation of the component materials. The mixture must also undergo a thorough testing regimen and an aggressive quality control/quality assurance program.

This publication is a companion document to another NAPA report entitled *Recycling Hot-Mix Asphalt Pavements*, which describes methods used in the processing of RAP for use in HMA.

Overview

Recycling asphalt pavement back into HMA requires some modifications in engineering and process control since another material is being added to the mixture. For higher RAP contents, above 25 percent, this will likely take extra effort, but the savings in using the higher RAP contents significantly outweigh the cost for any extra testing that may be required. Blending to meet gradation and the appropriate binder grade in the final product are keys to successful mix design, production, and performance. The details of materials selection, mixture design, quality control/ quality assurance, and plant verification are found in subsequent sections of this publication. A general overview of these processes follows.

The selection of materials to go into an HMA mixture containing RAP receives the same treatment as a mixture of virgin materials. However, the RAP must be tested to ensure it meets the governing specifications for aggregate gradation and quality, as well as binder quality when more than 25 percent RAP is used. Figure 1 shows that stockpile aggregates and virgin binder go through a typical evaluation prior to consideration of their interaction with the RAP.

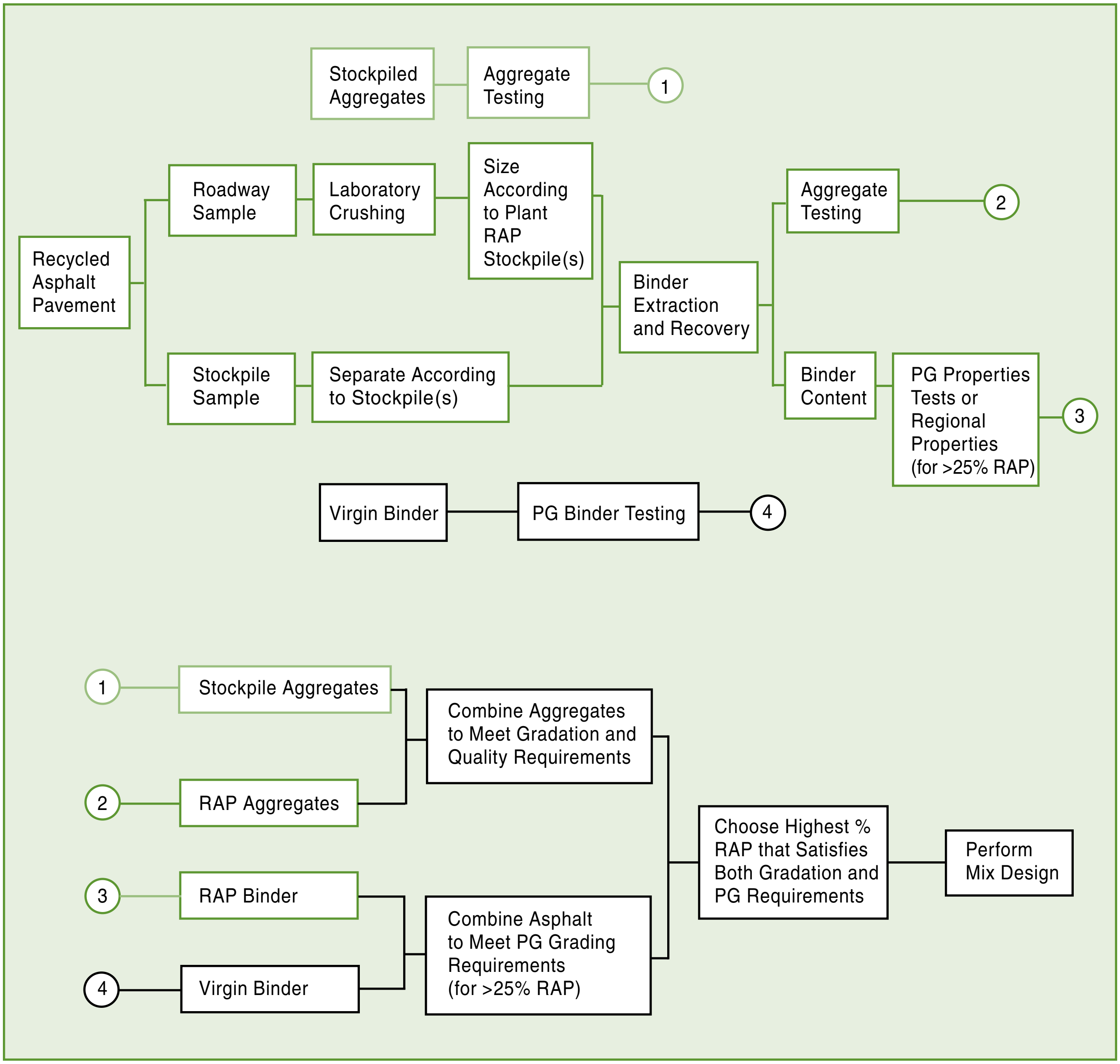
The RAP must be evaluated first with respect to its source. Some agencies allow RAP to be taken from a stockpile at the plant. In such cases, it is to the contractor's advantage to store the material according to the type of project it came from and to properly characterize its gradation and binder content. For instance, RAP from commercial projects such as parking lots is more likely to have a more rounded particle shape, a finer gradation, and perhaps a higher asphalt content than RAP taken from a high-volume road or commercial airport. Other considerations include different pavement ages and whether the RAP is from plant waste or returned HMA that has not been subject to aging or milling. In all cases, care must be taken to prevent RAP stockpiles from being contaminated with rubbish and other unwanted waste. Some agencies require that any RAP used in HMA must come from the project under construction. The recycled mixture which includes RAP must meet all of the requirements for aggregate quality, gradation, asphalt content, and blended asphalt properties. If care is not taken in managing the RAP stockpile, the contractor will not be able to consistently meet these requirements.

A study completed by Kandhal and Foo (1997) indicated that the evaluation of recycled mixture should be based on a three-tier process. Tier 1 included up to 15 percent RAP and would not require that anything be changed in the mix design process. Tier 2 included from 15 to 25 percent RAP and required that the new asphalt grade be dropped by one grade on the high and low ends of the PG grade. Tier 3 included more than 25 percent RAP and required that the asphalt be recovered from the RAP and blended with the virgin asphalt to produce a blended asphalt with the desired properties.

After the RAP has been processed and sized, the asphalt needs to be extracted and recovered (if it is to be tested) and the aggregate needs to be tested according to gradation and quality. Current guidelines (McDaniel et al, 2003) suggest that when less than 15 percent RAP is used in HMA, the PG binder grade can remain the same as in a mixture made with virgin materials. When 15 to 25 percent RAP is incorporated, it is suggested that the PG binder grade be lowered by one grade on both the low temperature end and the high temperature end. At RAP levels above 25 percent, it is suggested that both the RAP and virgin binders be tested and that a blending chart be used to determine the allowable amount of RAP and the mechanical properties of the HMA be determined. However, some States have opted to use different percentages of RAP based on local experience rather than the guidelines. It is important to note that while guidelines are often based on total RAP content, the binder stiffness in the recycled mix is more affected by the RAP age and RAP binder content.

There are two options for RAP binder testing: 1) the binder from the RAP goes through a solvent extraction and recovery process for testing or 2) the binder may be burned off in an asphalt content oven and results from a regional characterization of binder may be used in lieu of project extraction and recovery. The first method assures that the binder being used in the project has been tested, but one is left to deal

FIGURE 1
Materials Evaluation



with disposal of the used solvent, which is increasingly problematic, and the testing requires a great deal of time. The second method is shorter, and if there is sufficient cause to believe that aging causes an asymptotical change in binder stiffness (less change in stiffness later in service), then an assumption can be made on the basis of a regional characterization of RAP binder. This would require a research effort to define aged binder characteristics on a regional basis to investigate the viability of such an approach. It is possible that other factors such as crude source could have a predominant effect, in which case other methods of characterization would need to be explored. However, it would be an important issue to resolve through research in order to minimize the amount of solvent extraction and recovery.

The regional characterization of RAP could be accomplished through either a national research program such as NCHRP or as a series of pooled fund studies through the Federal Highway Research Program. The objective would be to estimate the binder properties of RAP according to geographical locations such as the Southwest, Southeast, Northeast, etc. The generalized values for dynamic shear modulus, bending beam stiffness, and direct tension stiffness could then be used instead of having to extract and perform binder tests for each mix design containing high RAP percentages. Of course, this would not be necessary at RAP percentages less than 25 percent, where normal guidelines would apply.

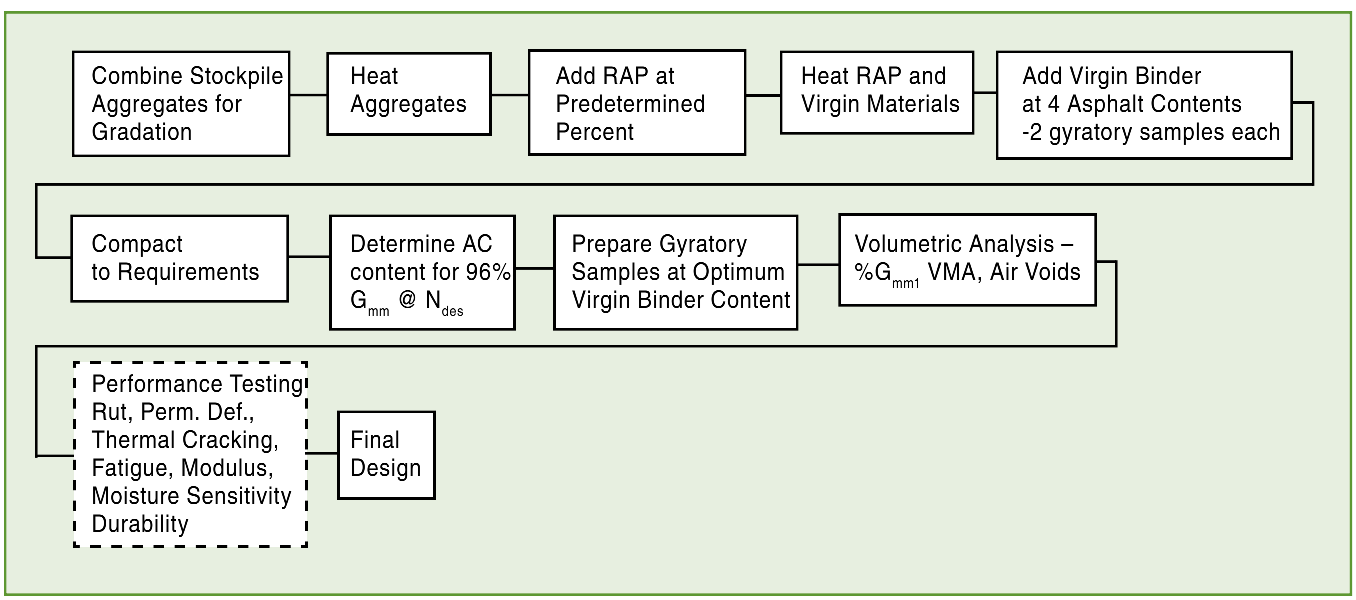
The aggregate gradation and quality must be checked to investigate its impact on the total HMA gradation and quality according to consensus properties. Certain types of testing may be superfluous, such as testing the cleanliness or plasticity of the finest fraction, but issues such as degradation or abrasion resistance may be important, especially in the larger sizes.

Once the RAP aggregate and asphalt have been sufficiently characterized, the combined aggregate and the combined binder need to be checked for compliance to the design mixture requirements. The gradation of the total aggregate and the quality need to be ascertained according to the combined properties of the stockpiles and RAP aggregate. The combined binder can be evaluated by means of a blending chart, if the RAP content is greater than 25 percent, where stiffness is defined according to the dynamic shear rheometer, the bending beam rheometer, and the direct tension test. When the material has been run through a plant, the mix can undergo a final check for mixture mechanical properties. Some engineers recommend that additional virgin binder be added to account for possible incomplete blending of virgin and aged binder. However, a recent study by Bonaquist et al. (2007) shows that it is possible that a high degree of the old binder is blended with the virgin in terms of asphalt mixture properties.

To proceed to the mix design phase, the highest available amount of RAP that will allow aggregate gradation and quality as well as binder requirements to be met should be selected. The amount of RAP used in design should be weighed against the availability of RAP for use throughout a given project so that the supply is not depleted before the construction ends. This will help ensure uniformity. In mix design, the focus is to achieve the volumetric and mechanical properties necessary to ensure performance.

Figure 2 presents an overview of the mix design process. The process is very similar to that for virgin mixtures: the process only deviates in terms of the handling of RAP material. Although the figure shows a Superpave mix design, the same basic process would apply to any mix design method. First, the virgin aggregate is heated, then the RAP is added and heated, and finally the virgin binder is added and mixed with the aggregate and RAP. Mixes containing four virgin asphalt contents are mixed and compacted. In the Superpave process, two samples at each asphalt content are prepared and compacted. A plot of density relative to the theoretical maximum specific gravity (%G_{mm}) versus the number of gyrations is

FIGURE 2
Mix Design Procedure



drawn. The asphalt content which produces 96% Gmm at the design number of gyrations is selected as the optimum asphalt content, although it should be noted that some States differ on the criterion for density for optimum asphalt content (e.g., Maryland uses 3.5 percent air voids or 96.5% of G_{mm}). At this point, three samples at the optimum asphalt content are mixed and compacted. Testing of the volumetric properties is conducted, and although it is optional, performance testing is highly recommended, particularly for high traffic volume facilities.

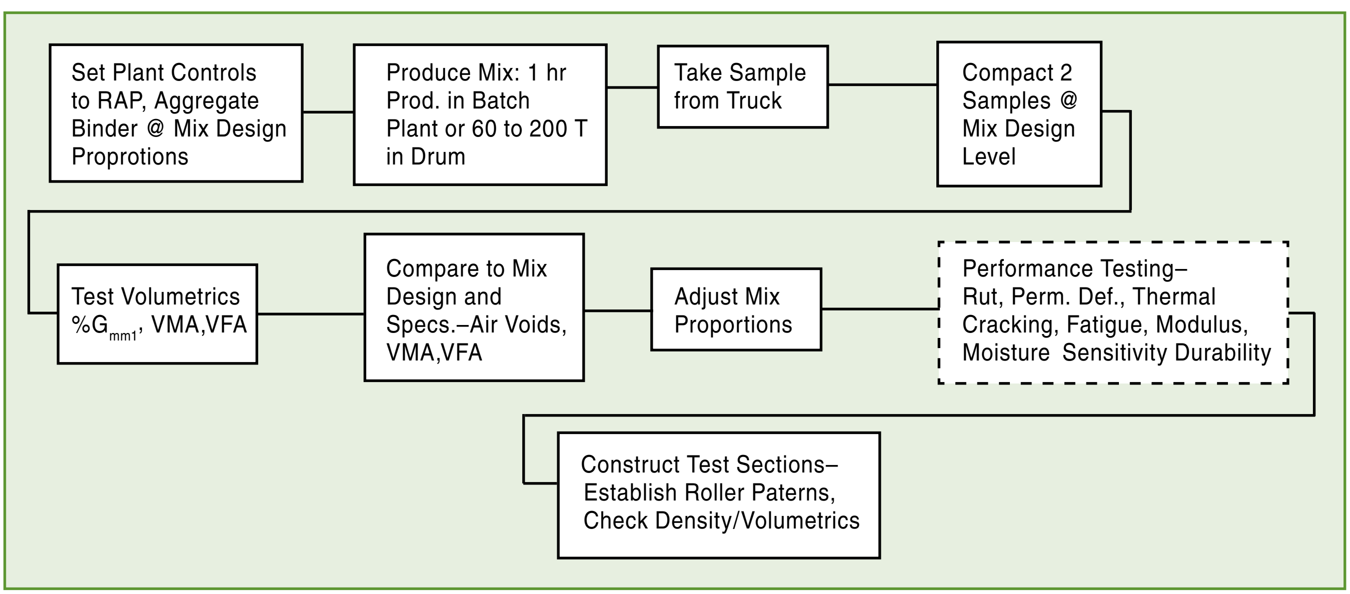
Plant verification of the mix design is the final step before production as shown in Figure 3. Here the plant controls are set according to the gradation and asphalt content established in mix design. After a batch plant has operated for approximately one hour or a drum plant has produced between 60 and 200 tons, a sample is taken from the truck. The plant sample is tested for volumetrics and the results are compared to mix design and specification requirements. In the meantime, a test strip is constructed at the job site and samples are taken to test roadway density and, possibly, volumetrics. If needed, adjustments to gradation or asphalt content are made prior to full production. The same density and volumetric testing should follow the production of an initial amount of mix prior to full production.

Quality control for HMA mixtures containing RAP still consists of monitoring parameters that the plant and paving crew have control over. Moisture content of the stockpile aggregates and RAP, gradation, asphalt content, and volumetric characteristics of field-mixed, laboratory-compacted samples are all essential parts of testing at the plant. Consistency in the materials going into the plant will be the key to maintaining production with minimum changes and delays. Following best practices and using the best available technology will contribute to maintaining consistent material flow. For instance, sizing, stockpiling, and having separate size bins will allow easier adjustment of both stockpile aggregates and RAP.

Following techniques to minimize moisture in aggregates and RAP stockpiles, such as paving under stockpiles or even covering stockpiles, will result in fewer adjustments in cold feed rates and plant speed. RAP stockpiles also need to be as consistent as possible. Stockpiling RAP by particle size will allow the producer to maintain consistency more easily than by continuously adding RAP into one stockpile. If one stockpile is used, then the RAP should be sampled and tested more frequently to know when minor plant adjustments need to be made. Again, separating RAP into different size stockpiles will help in maintaining control of consistency.

The following are details for accomplishing the materials selection, mix design, and quality control. While the procedures given fall within the normal Superpave mix design practices, individual States and jurisdictions may have their own variations that should be accommodated.

FIGURE 3
Plant Verification Procedure



Materials Evaluation

In order to achieve the optimum use of recycled asphalt pavements, it is important to ensure that the quality of the constituent materials and their final combined properties meet the specifications for the application. The RAP, new aggregates, and virgin binder need to be processed and tested to judge their suitability for different types of HMA mixtures. The governing AASHTO, ASTM, State, or Federal requirements should be used to establish the quality of these constituent materials.

RAP

Before discussing methods to evaluate RAP materials, it is helpful to discuss their processing and treatment at the HMA plant. Similar to aggregates obtained from different sources, the better the sorting of materials from different types of projects, the better the consistency and the greater the flexibility in their utilization. This also increases the probability of meeting specifications in the final mix.

Stockpile Practices

Separating the RAP stockpile into at least two stockpiles has become a more common practice. If the amount of RAP is low, say 15 percent or less, there may be no need to separate the materials into additional stockpiles. For higher amounts of RAP, some fractionation of the RAP would be beneficial for controlling the quality of the recycled mixture. The separation of RAP into two or more stockpiles will help minimize the variability in recycled mixtures and provide a constructed HMA with better performance. It is important to note that the gradation of the RAP particles is not the gradation of the aggregate in the RAP because the binder film adds to the dimension of the aggregate and serves to agglomerate aggregate particles.

The millings from high-volume highway surfacing projects or commercial airfield surfaces are more likely to contain a high percentage of low-polishing, crushed aggregates and polymer modified asphalt. A premium was paid for these materials when they were first used in HMA, and their value in skid resistance and binding capability should not have diminished. On the other hand, materials taken from lower pavement layers or low-volume roads retain their value as well although they are not likely to have polymer modified binders and may contain aggregates with a higher polish value and which may be more rounded. It is also important to consider the amount of variability that may take place along the length of a project as large areas of patching or the combining of older and newer pavement surfaces can affect the properties of RAP.

There is a restriction in some specifications that only the RAP removed from the project site or other State projects may be recycled back into the mix being used on the project. Such a condition means that RAP from the State projects must be stockpiled separately, although the RAP could be fractionated into different stockpiles according to particle size. The consistency of the material should be considerably better than that in blended piles, so testing of the RAP would not have to be as frequent. This would mean that more RAP could be used in the final HMA because of flexibility in adjusting the aggregate gradation. In the end, some RAP milled from a project may not be used in the mixture for that project. However, it can be used in other types of paving.

In some plant sites, stockpile room is limited and it may be beneficial to combine RAP from different projects from a handling standpoint. When this is done, it is advisable to build the pile as uniformly as possible by blending the materials. It will be necessary to take a number of samples to test aggregate gradation and properties and binder content. The testing will indicate the average properties of the RAP and their variability. If the coefficient of variability is greater than about 15 to 20 percent on any control sieve, then it may be advisable to reblend the materials to achieve more consistency, or to use a lower percentage of RAP in the final HMA. The coefficient of variability is:

$$\text{C.V.} = \left[\frac{s}{\bar{x}}\right] 100$$

Where: $C.V.$ = *Coefficient of Variation*
$\bar{x}$ = *sample average*
s = *standard deviation*

Whether the recycled materials are all from the same project or different projects, constructing separate coarse and fine RAP stockpiles will minimize segregation of RAP particles, and allow greater flexibility in adjusting RAP content for the final aggregate gradation. The fine RAP material will have a greater asphalt content than coarse RAP stockpiles due to the higher surface area of fine material. The asphalt binder content in both the fine and coarse RAP stockpiles can be expected to be more uniform than the asphalt content of a single RAP stockpile. It may be possible to introduce more of the fine RAP in mixtures having a small nominal maximum aggregate size such as surface or leveling mixtures. Conversely, in large stone mixes, a larger portion of the coarse RAP can be used to help meet the gradation requirements. Plant waste and returned mix will have little or no breakdown of the aggregate and reduced aging of the binder. Thus, it may be desirable to reserve the sized RAP to be fed into a single small project rather than commingling it with other RAP sources.

Sampling of Materials

Prior to any testing, samples of the materials must be obtained. The most common method of sampling RAP is to take a number of random samples from throughout the RAP stockpile, test a portion of each of the individual samples (when over 25 percent RAP is to be used), and combine these random samples into one representative sample for conducting the mix design. Testing of the individual samples is required to determine the variability of the asphalt content and aggregate gradation. Approximately five to 10 individual samples are required for this testing and analysis to determine the consistency of the stockpile. Based on a literature review, values for standard deviation of the percent passing the No. 8 sieve in the RAP stockpile are 3 to 5 percent and 0.8 to 1.4 percent for the material passing the No. 200 sieve (FHWA, 1996). The aggregate gradation tests are to be done on the aggregate after the binder extraction. Typical values for the standard deviation of the asphalt content are 0.2 to 0.5. Obviously, RAP stockpiles having higher standard deviation values will be more difficult to control during the construction process. It is recommended that RAP sampled during processing be retained for mix design.

Blending of the individual random samples of each stockpile is required for providing a representative sample for conducting the mix design. This approach will provide a good representative sample of the stockpile. Many projects now use more than one stockpile for RAP so additional sampling is required if there is more than one RAP stockpile.

Testing RAP Materials

The two most important characteristics of the RAP are gradation of the aggregate and the asphalt content. Beyond this, especially in high RAP content mixes, surface mixtures, and high traffic volume facilities, one should quantify the quality of the aggregate and the binder properties.

As mentioned earlier, if a regional study on RAP binder properties is conducted, it may be possible to assume the aged binder properties. Figures 4 and 5 (Kandhal, 1977 and Petersen, 1989) show that as asphalt binders harden through aging, the penetration and viscosity change asymptotically, meaning that there is a point beyond which dramatic change will not occur. For different regions of the country, RAP will have different binder characteristics. In the desert southwest, the binder will be relatively hard compared to the north central part of the U.S. Such a study would make it possible to avoid having to do extraction and recovery procedures which necessitate the use and disposal of solvents. Until such research is done, the virgin binder grade should be determined according to current practice, i.e., no grade adjustments when less than 15 percent RAP is used, one temperature grade lower between 15 and 25 percent RAP, and determined by blending charts at higher RAP contents.

Most States do not require the testing of the combined binder as long as the amount of RAP to be used is relatively low. In fact, many States don't require testing of the asphalt binder until the amount of RAP exceeds 25 percent. They simply require that for AC, one grade softer be used when the amount of RAP exceeds 15 percent but less than 25 percent. If less than 15 percent RAP is used, then the mix is treated very similar to virgin asphalt mixture. Some States will not allow the binder to be changed more than one grade for fear that inadequate mixing may occur possibly resulting in an unstable mixture, although this has not been verified. While guidelines such as these are typically based on the percent of total RAP (including aggregate), it may be advisable to change to a RAP binder content basis instead, since not all RAP has the same binder content. This way decisions concerning the need for RAP binder characterization could be made according to the amount of binder replacement rather than the total RAP content.

If a softer AC grade or more than 25 percent RAP will be used, then extraction and recovery of the binder is normally necessary. The recommended procedures are AASHTO T164 or ASTM D2172 for the centrifuge or reflux extraction and AASHTO T170 or ASTM D1856 for the Abson method or ASTM D5404 using the rotary evaporator for the binder recovery. The method for extraction and recovery suggested by McDaniel and Anderson (2001) is AASHTO T319 which combines the two processes into one. At least 50g of material will need to be recovered to determine the binder properties in the Dynamic Shear Rheometer (DSR). If low temperature testing is desired then enough material for a bending beam rheometer sample must be extracted and recovered. For higher RAP percentages, it is recommended to blend the recovered RAP binder with the virgin asphalt. This is of particular interest where softer grades of virgin binder are being considered. Test Method ASTM D4887 may be used to guide the preparation of blends of recycled and virgin binder for testing. An exception to this method is that dynamic shear modulus at the desired high temperature designated by the Performance Grading should be used in lieu of the viscosity at 60oC (140oF). In all cases, a lab blend of the design ratio of old and new binders should be used in accordance with AASHTO M 320 to ensure it meets the desired PG. It should be noted that the current PG system does not address potential brittleness at intermediate temperatures. This issue is being discussed within the FHWA Expert Task Group on binders.

If the amount of RAP that is used is less than about 25 percent, very little material testing may be required but at the higher RAP contents additional testing is necessary. A crucial part of the mix design is to determine the percentage of each material (RAP, new asphalt binder, each virgin aggregate stockpile) to be used in the mixture. The grade of the new AC binder must also be determined as appropriate.

If extraction and recovery of the RAP binder is not necessary either due to the RAP content being low or because a regional study on RAP binder stiffness exists that shows sufficient consistency in the aged binder, then asphalt content determination by a calibrated ignition oven (AASHTO T308, ASTM D6307) is recommended. The use of a nuclear content gauge (AASHTO T287, ASTM D4125) is recommended only if the gauge is calibrated for the RAP binder content through solvent extraction or ignition oven.

Care must be used when using the ignition test since the calibration for the aggregate in the RAP is probably not known. If small amounts of RAP are used, the error in measured asphalt content in the RAP is not important since this will result in a small error in the asphalt content of the total mix. Also many aged asphalts are very difficult to extract so the solvent extraction test is not always accurate. This is especially true as more and more modified asphalts are used and recycled. There is very little information on RAP containing modified asphalts but this is a growing concern since the amount of modified asphalts used is increasing. As long as the amount of RAP is less than 25 percent, or as long as the percentage of modified asphalt in the RAP is small, this should not be a problem.

Aggregate

The evaluation of RAP and new aggregates should proceed along the lines of those typical for HMA mix design and production. RAP aggregates (post extraction) should be evaluated separately from new aggregates, and then their composite properties should be calculated using a blending formula. The composite properties for gradation, specific gravity, and consensus characteristics should be used in the determination of acceptability of the blended aggregates. Because RAP aggregate has previously been found suitable for use in HMA, there are some tests which may not need to be performed.

Gradation

The washed gradation of stockpile aggregates should follow typical gradation procedures as outlined in AASHTO T27 and ASTM C136, using sample sizes called for according to the nominal maximum aggregate size. The aggregate extracted from the RAP is sized according to AASHTO T30 and ASTM

FIGURE 4
Change in Penetration with Time (after Kandhal, 1977)

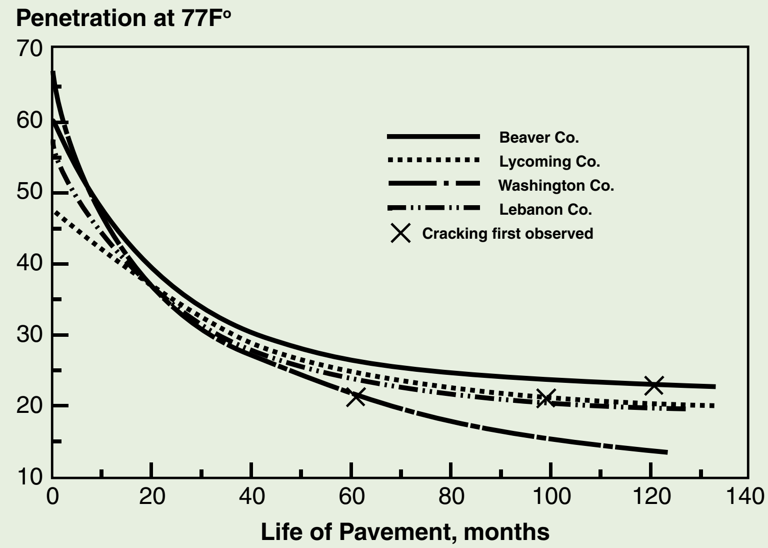
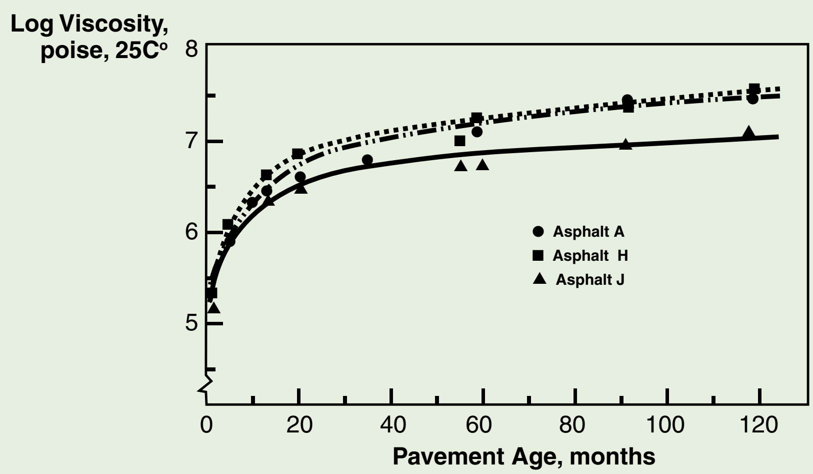


FIGURE 5
Change in Viscosity with Time (after Petersen, 1989)



D5444. The main difference between the RAP and stockpile aggregates gradation procedures is that the ash content from solvent extraction must be accounted for in the RAP aggregate, if solvents were used. For stockpile and RAP aggregates not subjected to solvent extraction, AASHTO T11 or ASTM C117 can be used in quantifying the amount of material passing the 0.075-mm (No. 200) sieve.

The combined gradation of RAP and stockpile aggregates must meet the gradation requirement of the final HMA mixture. In the Superpave system, control points are set according to the nominal maximum aggregate size. The restricted zone has been removed from most specifications. Requirements that sometimes cause problems include the amount of material passing the No. 200 (0.075 mm) sieve size, the dust to asphalt ratio, voids in mineral aggregate (VMA), the amount of natural sand in the combined mixture, and complete mixing of the old and new binders.

It is important to note that RAP generally has a finer gradation than may be desirable in the final mix owing to the generation of fine material in the milling and/or crushing operations. This must be compensated for by the gradation of the new aggregates.

Specific Gravity/Absorption

The measurement of specific gravity plays a key role in the volumetric calculations of the mix design. As such, it is important to account for specific gravity of the RAP aggregate in the mix. Since most of the absorption in the RAP aggregate has already occurred, the absorption is not generally of interest. In the calculation of the VMA in the mix design process, the bulk specific gravity of the aggregate in a dry condition is the parameter used. The maximum theoretical specific gravity of the RAP is used to backcalculate the bulk specific gravity of the RAP aggregate which can be used to estimate the bulk specific gravity. This procedure is outlined in the mix design method proposed by McDaniel et al (2000) and McDaniel and Anderson (2001) as shown below:

$$G_{se} = \frac{100 - P_b}{\frac{100}{G_{mm}} - \frac{P_b}{G_b}}$$

$$G_{sb} = \frac{G_{se}}{\left[\frac{P_{ba}\,G_{se}}{100G_b} + 1\right]}$$

Where: G_{mm} = *theoretical maximum specific gravity of RAP*

G_b = *specific gravity of RAP binder*

P_b = *RAP binder content*

G_{se} = *effective specific gravity of aggregate*

G_{sb} = *bulk specific gravity of aggregate*

P_{ba} = *absorbed binder, % weight of aggregate*

McDaniel and Anderson (2001) recommend an estimated Pba of 1.5 percent, if data from similar aggregate sources are not available. If absorption data are available from past records on similar aggregates, then it should be used as the estimate. They also recommend a value of 1.020 for G_b, and since the specific gravity of asphalt tends to have a relatively narrow range, this is reasonable and it is not expected to have a significant impact on the calculation.

Hardness/Wear

Traditionally, the Los Angeles Abrasion Test (AASHTO T96, ASTM C131) has been used as a measure of the likelihood that a given coarse aggregate will degrade during production and placement or during its performance life. This test requires a great deal of aggregate to perform. It is intended as a test for virgin aggregates, and its usefulness in characterizing RAP aggregate is questionable. RAP aggregates were most likely tested for hardness and wear before their initial use. Also, most of the breakdown caused during production and construction has already occurred with RAP. In most drum plants, the RAP is added downstream of the stockpile aggregates, so they are subjected to less mechanical agitation.

If abrasion resistance in the RAP aggregate is considered important to its ability to provide skid resistance in a wearing course, then the use of the Micro-Deval test (AASHTO T58) should be considered. Although it is a more recently developed test than the L.A. Abrasion, it requires a smaller sample. The procedure rolls a cylindrical container with the aggregate, water, and a number of steel balls for a certain number of cycles. The cylindrical container does not have a ledge that lifts the balls and aggregate, and causing an impact as in the L.A. Abrasion procedure. Thus, it is more of a wear test.

Cleanliness

Aggregate cleanliness can be tested through several means, but again, the RAP aggregate was already used in HMA, so testing it for cleanliness may be superfluous. Virgin aggregate should be subjected to the normal evaluation used within a jurisdiction. The sand equivalent value can be found using AASHTO T176 or ASTM D2419. Organic impurities can be quantified by AASHTO T21 or ASTM C40. Clay lumps and friable particles are tested for according to AASHTO T112 or ASTM C142.

Particle Shape and Angularity

Particle shape and angularity are especially important for aggregates that are closer to the pavement surface. Superpave usually defines requirements according to traffic level and position within the pavement structure (within or below 100 mm (4 inches) of the surface).

Particle shape is usually characterized as the number of flat and elongated particles (ASTM D4791) in the aggregate blend. This is done by measuring the aspect ratio of the coarse aggregate particles (greatest dimension to smallest) and calculating the percent mass of flat and elongated coarse aggregate. The weight percentage of particles having a certain aspect ratio (2:1, 3:1, or 5:1) is reported and compared to the requirements of the agency. Because of the way RAP is processed, it is unlikely that the coarse aggregate fraction will contain a great deal of flat and elongated particles unless the original material had an excessive amount.

Coarse aggregate angularity is usually quantified in terms of the amount of material having either one or two or more fractured faces (AASHTO TP61 or ASTM D5821). Although this type of test tends to be dependent upon the experience of the technician, it does provide some assurance that aggregate interlock can be achieved between the coarse particles. Determining fractured faces from coarse aggregate in RAP can be problematic. If the RAP contains a significant portion of uncrushed gravel, say more than 20 percent of the RAP coarse aggregate, this test may be worthwhile. Otherwise, the RAP processing does provide some crushing, and separating RAP into stockpiles containing similar qualities of materials may help avoid problems. If testing is done, the combined RAP and virgin coarse aggregate should meet the consensus properties specified for Superpave.

Fine aggregate angularity is determined using AASHTO TP56, in which the fine aggregate portion is poured into a mold, and the amount of voids in the uncompacted sample is supposedly indicative of the angularity. This requirement has been dropped by some States. Unless there is reason to suspect an overabundance of rounded particles in the fine aggregate of the RAP, for instance more than about 30 percent of the RAP fine aggregate, this test is probably not necessary for the RAP aggregate. Residual asphalt coating and the effects of the asphalt recovery process may influence the results. If testing is done, the combined RAP and virgin fine aggregate should meet the requirements for Superpave.

Soundness

Although its relationship to freeze-thaw fracturing is sometimes questionable, either a sodium or magnesium sulfate soundness test (AASHTO T104, ASTM C88) is sometimes required for stockpile aggregates. Its usefulness in evaluating RAP aggregates is debatable because RAP has already been exposed to field environmental conditions.

Mineralogy

It is important to know if the HMA material being used for RAP had problems associated with moisture sensitivity during its previous performance period. RAP with siliceous aggregates in particular should be examined to see if there is an excess of uncoated faces or particles. The RAP still may be used, but precautions such as the use of anti-stripping agents and the evaluation of moisture sensitivity in the final mix should be taken. The Wyoming DOT has found that RAP aggregates that stripped in previous mixtures did not cause problems in their recycled mixtures, so anti-stripping additives were not necessary. However, all HMA mixtures should be evaluated for moisture susceptibility by either the Hamburg rut tester or AASHTO T 283, regardless of whether they contain RAP or not.

Binder

Recycled HMA

Testing of recycled HMA binder has always been somewhat controversial because there are two extremes of how it may act in the final mix. One is that the aged binder is completely non-reactive in the new mix, and that the RAP acts as a "black rock." The other side of the argument is that upon reheating the binder becomes fluid and mixes with the virgin binder. The conclusion of NCHRP project 9-12 (McDaniel and Anderson, 2001) was that the RAP binder neither completely mixed with the virgin binder nor was it non-reactive. Further results from Soleymani, Anderson, McDaniel, and Abdelrahman (1999) showed that the binder more closely resembled the complete mixing scenario. This was somewhat validated by results reported by Bonaquist (2007). Therefore, at high levels of RAP content, there is probably a justification for using a lower temperature PG grade. The need to perform extraction and recovery of the RAP binder should be carefully considered. The time necessary to run the extraction and recovery, the amount of waste solvent generated, and the value of the information gained by testing all need to be balanced. It is highly recommended that a regional study on RAP binder be conducted and that the information be used to select virgin binders appropriate for the level of RAP to be used for different applications.

To find the percentage of RAP that will result in the proper high-temperature grading, the extracted and recovered RAP binder should be tested in an unaged state according to AASHTO T315 for dynamic shear modulus G* and phase angle to find the critical high temperature (Tc). The critical low temperature (Tl) can be found by determining the PG grade based on AASHTO M 320 of a lab blend of the recovered and new binders.

Virgin Binder

The virgin binder should be subjected to the typical series of tests used for characterizing binders. In the vast majority of States, this would mean performing tests needed for the PG system at a minimum. The critical high temperature, can be defined by testing both the RAP binder and the virgin binder. Blending charts may be devised by plotting the percentage of RAP versus the critical temperature. This is shown using the critical high temperature in Figure 6. In Figure 6a, the percentage of RAP is shown for two different high temperature grades of combined binder. Logically, more RAP may be used where a stiffer high temperature binder is desired. In Figure 6b, the amount of RAP is used to determine the critical high temperature (Tc).

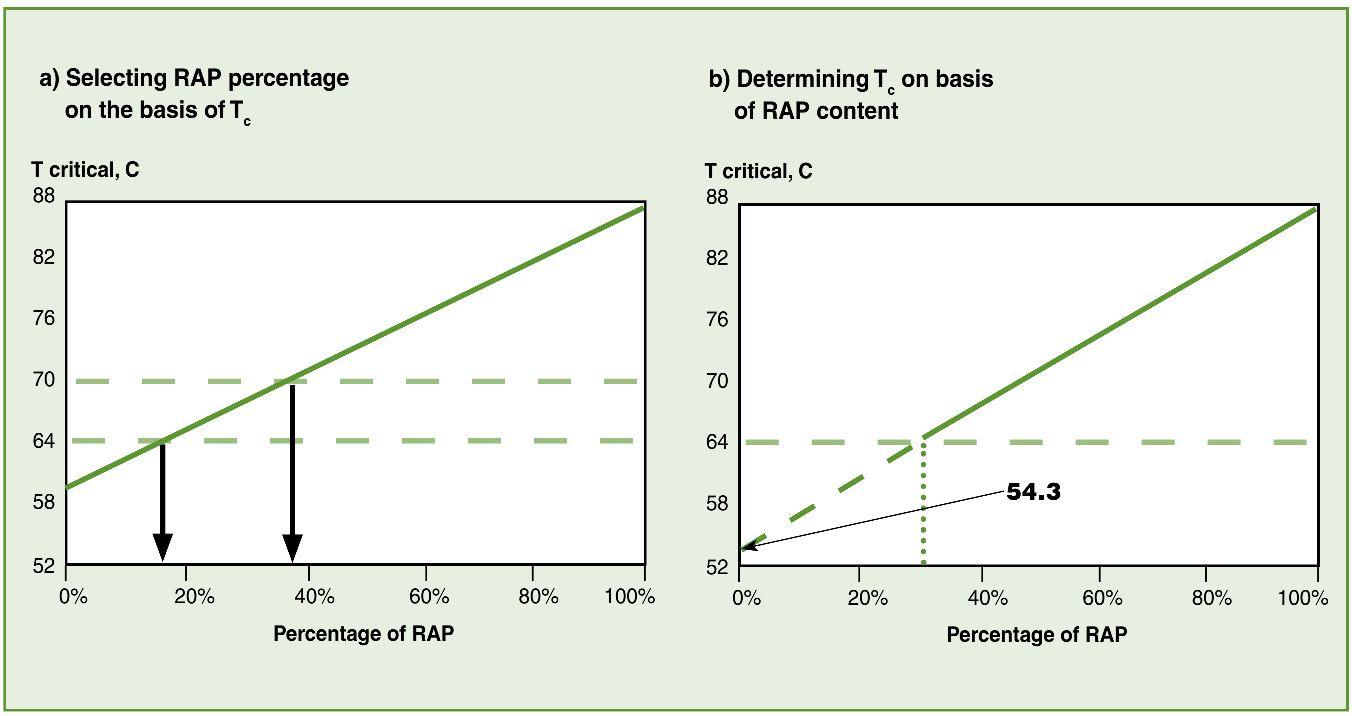
Recycling or rejuvenating agents are sometimes used in high RAP content mixtures. In such cases, the applicable standards are AASHTO R14 or ASTM D4552. Superpave binder specifications for recycling agents have not been developed.

Blended Binder

Once an estimated RAP percentage has been determined, the RAP binder and virgin binder should be combined at that percentage, and put through the suite of PG testing (if the RAP content exceeds 25 percent) to see that it conforms to the PG grading requirement for the application (AASHTO R29, ASTM D6323). This is especially true for variable RAP products or sources. It is possible to try different grades of virgin binder or recycling agents (AASHTO R14, ASTM D4552). In the end, the percentage of RAP should be determined based upon a combination of performance and economy.

Traditionally, the extracted and recovered RAP binder is blended with the virgin binder to perform this characterization. Other techniques that have been

FIGURE 6
Methods for Selecting RAP Content for the Desired Properties



suggested include subjecting the virgin binder to the same recovery process, or mixing the RAP with the virgin mix and extracting and recovering the blended binder.

Dynamic shear modulus and phase angle (AASHTO T315), bending beam rheometer stiffness (AASHTO T313, ASTM D6648), and direct tension test (AASHTO T314, ASTM D6723) are the performance indicators used in the PG binder grading system. Safety is checked as a function of the flash point temperature under AASHTO T48, and is particularly important in instances where recycling agents may be used. Workability is defined as the viscosity measured in a rotational viscometer at 135oC (275oF) according to AASHTO T316. Short-term aging is accomplished using a rolling thin-film oven (AASHTO T240, ASTM D2872) and long-term aging is done with a pressure aging vessel (AASHTO R28, ASTM D6521).

Additives and Modifiers

Anti-stripping Additives

As with virgin mixtures, moisture sensitivity is sometimes a problem in recycled mixtures where stripping was the major distress in the RAP being used. This also may be of concern when there is a lack of bond between a softer virgin asphalt and stockpile aggregate. In any case, moisture sensitivity should be evaluated under the mixture design process, and either liquid anti-stripping agents or lime should be used if necessary. The choice whether to use a liquid or lime is usually based upon economy and performance, although some specifications may dictate a particular choice. It should be noted that if local experience does not indicate a stripping problem exists with RAP from previously stripped mixtures, then the use of an anti-stripping agent should be specified only if moisture sensitivity tests indicate a problem.

Polymers

Polymer modifiers are often used to improve the high-temperature properties of asphalt. In other words, they may be added to help guard against permanent deformation. Recycled mixtures are known for their resistance to rutting, and if rutting resistance is the intended use of polymers in a mixture, then it is recommended that a performance test, such as one of those described under Mix Design, directed at permanent deformation be conducted to make the determination if a polymer modifier is needed.

Mineral Fillers

Mineral fillers are employed to serve a number of functions in recycled mixtures. They can be used to help fill the voids in mineral aggregate, increase stability, meet aggregate gradation requirements, and improve the bond at the binder-aggregate interface. The amount of filler is usually restricted by the dust to binder ratio specified in mix design. In recycled mixtures, additional mineral fillers must be used carefully since the recycling process often generates a considerable amount of fine material. If there is too much dust generated by milling or crushing operations, then there may be little to no room for additional fines in the virgin aggregate, depending upon the amount of RAP to be used.

Mix Design

Introduction

There have been few changes in the mix design procedures of recycled mixtures since hot-mix recycling began to become popular in the mid-1970s. Even with these changes, the mix design methods developed during the 1970s have provided reasonable guidance.

The mix design procedures basically involve blending the reclaimed asphalt pavement (RAP) with the virgin aggregates and asphalt cement to produce the recycled mixture. It is important that the blended binder and combined aggregate have properties similar to those required for conventional HMA and that the volumetrics of the mixture be within specification requirements.

During the 1970s, it was suggested that the amount of RAP allowable in drum mixers could be as high as 70 percent and the amount of RAP in batch plants could be as high as 50 percent (Newcomb and Epps, 1981). These high RAP contents required that low viscosity recycling agents (ASTM D 4552 or AASHTO R14) be used to properly modify the old binder to meet desired requirements. There were a number of problems observed at that time resulting from high RAP contents. These problems included the flammability of some recycling agents, some emissions problems due to high temperatures and plants not designed for recycled asphalt, poor control of recycling agent quantities, questions about the variability of the RAP materials, as well as questions concerning the amount of mixing between the recycling agent and old asphalt cement.

Because of these early issues, the actual amount of RAP currently used on projects does not normally exceed approximately 25 percent. In many cases, specifications do not allow high RAP contents and in other cases, contractors elect not to use high RAP contents for various reasons. Sometimes it is difficult to add a significantly high RAP content and control the quality of the mixture when the gradation or aggregate properties of the RAP or the RAP binder properties must be significantly modified. Again, it is more important to acknowledge the contribution of the RAP binder content rather than the total amount of RAP.

Many States specify that the grade of virgin binder cannot be more than one or two grades different than that required for virgin HMA. In fact, most States have adopted the Superpave recommendations that state for up to 15 percent RAP, the standard binder grade is used; between 15 and 25 percent, the grade of virgin binder is one grade softer; and when the amount of RAP exceeds 25 percent, the grade is selected so that the combined binder properties will meet the specified properties. This practice was verified in a study by Kennedy, Tam, and Solaimanian (1998a) as well as other researchers.

An FHWA report indicated that variability of RAP may change according to source and removal and processing methods, just as virgin materials may change based on source and producer (FHWA, 1996). The report went on to indicate that limitations placed in specifications are major obstacles for increasing the use of RAP.

A step-by-step mix design process for recycled mixtures is presented in NCHRP Report No. 452. This method follows the Superpave method of mix design, but could easily be adapted to any mix design procedure. As stated by McDaniel and Anderson (2001), the only changes in mix design from an all-virgin mix are:

1. Heating the RAP more gradually and to a lower temperature than aggregates are normally heated.
2. Estimating the RAP aggregate specific gravity.
3. Accounting for the RAP binder in the aggregate batching.
4. Reducing the new binder content to account for the RAP binder.
5. Possibly using a lower virgin binder grade to account for the RAP binder aging.

Sample Preparation

If the RAP is not yet processed, then it is important that it be crushed to the same approximate gradation expected in production. If it is still on the roadway, then a milled sample using the anticipated milling process should be obtained. If it is to be processed through a crusher, then the sample should be obtained from the crushing unit. It is best, however, to work from a stockpile that has already been produced.

Prior to mixing, all of the components must be dried and heated at the desired mixing temperature. Care must be exercised when heating the RAP so that the asphalt binder is not overheated, thus significantly changing the binder properties. Typically, the binder is heated to the desired mixing temperature and the aggregate is heated to 18°F (10°C) above the desired mixing temperature so that once all the ingredients are mixed, the appropriate temperature is reached. Heating the RAP for an extended period of time is not recommended. Normally it is heated for no more than two hours at a temperature of 230°F (110°C) and added soon after heating. Placing the mix in an oven for a short time after mixing is recommended to provide for better equalization of temperature throughout the sample. This can be part of the short term aging time.

The virgin asphalt binder should be heated to a temperature that provides the appropriate viscosity for mixing.

Laboratory Mixing and Compaction

All of the components of the mixture thoroughly mixed prior to compaction. The RAP and virgin aggregate are mixed and then the virgin asphalt is added to the mixture. The use of a timer can help ensure thorough mixing of the RAP and virgin materials. Some experimenting may be needed to determine the proper mixing time.

Compaction of mixtures in the laboratory is very similar to that required for virgin HMA (AASHTO T312 and ASTM D4013). The number of gyrations is selected based on expected traffic or according to local specifications. As far as compaction of the recycled mixture in the laboratory, there are no special precautions needed.

Volumetric Testing

Volumetric properties are a key part to the successful completion of a mix design for recycled mixtures. It is very important that the designed mixture meet the requirements for voids as well as VMA and voids filled with asphalt. Calculating the VMA requires that the bulk specific gravity of the aggregate be known. This is simple to determine for the virgin aggregate, but determining the bulk specific gravity of the aggregate in the RAP is difficult. If the aggregate source for the RAP is known, then the known aggregate bulk specific gravity properties can be used. However, if the source is unknown then the bulk specific gravity has to be estimated.

Conducting bulk specific gravity of recovered aggregate is not very accurate. This is true regardless of whether the ignition test or solvent extraction is used to obtain the aggregate from the RAP. The ignition test can affect the aggregate in the RAP by changing its physical characteristics, so it is not recommended that the bulk specific gravity be conducted after the ignition test. Solvent extraction of the binder does not always remove all of the asphalt from the pores of the aggregate, leading to some error in the measured bulk specific gravity of aggregate afterwards. In mixtures with a low RAP content, this inaccuracy is not a problem, but in high RAP content mixes, it may be a significant problem. If the source of the aggregate is not known, then one approach is to use the effective specific gravity, which can be backcalculated from the maximum theoretical specific gravity test (AASHTO T209 and ASTM D 2041), to estimate the bulk specific gravity of the aggregate in the RAP (Kandhal and Foo, 1996). This approach was discussed in more detail earlier.

Three mix properties are necessary to calculate the mixture volumetric properties. These are the bulk specific gravity of the compacted mixture (AASHTO T166 and ASTM D2726), bulk specific gravity of the aggregate, and theoretical maximum specific gravity of the loose mixture (AASHTO T209 and ASTM D 2041). Accurate measurement of these properties should not be significantly affected by the use of RAP in the mixture.

Determination of Optimum Binder Content

RAP contains a significant amount of asphalt cement, and a higher RAP content will require a lower optimum asphalt content in the resulting HMA. When the RAP content exceeds 25 percent, the grade of the virgin asphalt binder to be added should be lowered appropriately to provide the proper grade of the blended binder as shown by a blending chart.

The optimum binder content is selected to provide 4 percent or other applicable specified air voids similar to that for virgin mixtures. So if 25 percent RAP (containing 5 percent asphalt) is included in the mixture, this provides a total of 1.25 percent of the required binder content. After determining the optimum virgin asphalt to be added, for example say 4.0 percent, it would be wise to ensure that the combined binder meets the specification requirements. If a regional study on recovered binder is available, it may be possible to create a blending chart that would provide an estimate of the combined binder properties. The optimum asphalt content is determined from mix volumetrics and the grade of virgin asphalt to be used can be determined from a blending chart or from the binder recovered from the recycled mixture.

Generally, States that use less than 15 percent RAP do not change the grade of asphalt binder to use in the mix since the small amount of RAP will not add enough old binder to require a change in binder grade in the new mixture. Generally with 15 to 25 percent RAP, States will require the contractor to reduce the grade of new asphalt by one grade on the high and low temperature end (for example a PG 64-22 would be reduced to a PG 58-28) to allow for some softening of the old asphalt. Higher percentages of RAP will require special consideration and testing for the combined asphalt grade, and it is more important to consider how much binder the RAP is contributing to the HMA rather than the total amount of RAP in the mixture.

States that allow higher percentages of RAP to be used generally require that the contractor select a grade of binder that produces the correct grade of blended asphalt. Based on a study by McDaniel and Shah (2003), it has been recommended that up to 40 to 50 percent RAP can be effectively used in recycled mixtures. Their work also indicated that when approximately 20 to 25 percent RAP is used in the recycled mixture, the virgin asphalt cement should be lowered by one temperature grade as recommended by most State DOTs.

Binder Testing

As stated earlier, binder testing of the RAP mixture is suggested when the RAP content exceeds 25 percent. Testing the binder in the recycled mixture requires that the binder in the mixture be recovered, tested, and compared with specification requirements. The hardening of the asphalt in the laboratory during mixing and compaction will not be the same as the hardening at the asphalt plant and so the mix design will very likely need to be adjusted based on tests of plant produced materials.

There are two ways that the total blended binder can be tested in the laboratory. First of all, the asphalt can be recovered from the RAP and blended with the new asphalt to be added to the binder. The second approach is to blend the RAP with the new aggregate and asphalt and then extract and recover the blended binder for testing. Plant verification of the combined binder properties is recommended.

It would be possible to avoid extensive testing of the binder if there were a series of mixture performance tests available which would ensure that the finished product had the desired mechanical characteristics and properties. These tests would need to include rut resistance, thermal and fatigue crack resistance, durability, and moisture sensitivity analysis. Work is underway to develop, verify, and adopt these performance tests, and this will eventually result in some reduction in the amount of testing required for the RAP materials.

Mechanical Property Testing

Testing of the designed mixture to evaluate performance is important whether designing virgin HMA or recycled HMA. There are no nationally accepted performance tests being used to evaluate performance, but there are some widespread practices.

For instance, many States use the Tensile Strength Ratio (TSR) test (AASHTO T283) as a way of gauging resistance to moisture damage. Rutting is most often controlled by using angular aggregates, the proper grade of binder, and selecting the proper asphalt content. There are a few States that perform rut testing using either the Asphalt Pavement Analyzer or the Hamburg Rut Tester. Both of these tests have shown some capability to identify mixtures with a tendency to rut. Generally, the binder grade is selected and controlled to provide resistance to thermal cracking. While there are some mix tests available to test the resistance to thermal cracking, this is not normally a part of the mix design or quality control process. There are also fatigue tests that can be conducted in the laboratory to help evaluate expected fatigue performance. These tests require a significant amount of time and specialized equipment and typically are considered research tools.

Other tests including permanent deformation, creep, and dynamic modulus have been evaluated to predict rutting in NCHRP Project 9-19, but to date these have not been extensively used on paving projects. It is important that more effort be directed toward this type of characterization in order to allow more innovation in using RAP in new HMA mixtures.

Plant Verification

Plant verification is the process that allows the HMA producer to compare the characteristics of plant manufactured mix to the job mix formula and specifications and to adjust the material quantities going into the plant before the start of full-scale production. Once the plant settings have been fixed according to the gradation, aggregate moisture content, asphalt content, and RAP percentage, quality control is used to monitor the consistency of HMA production.

Initial Settings

To make the initial settings on the plant for verification of the mixture design, the following information should be known:

1. Aggregate gradation of each virgin stockpile/ aggregate bin.
2. Moisture content of each virgin aggregate.
3. Bulk specific gravity of each virgin aggregate.
4. Aggregate gradation of each RAP stockpile.
5. Asphalt content of each RAP stockpile.
6. Aggregate bulk specific gravity of each RAP stockpile.
7. Moisture content of each RAP stockpile.

In some instances, drum plant operators find it useful to run a portion of the new aggregate, with the weights corrected for moisture, through the plant without the asphalt binder. In other cases, particulate emissions and the opportunity for uncoated material trapped in the plant to later contaminate the HMA would be cause to add a small amount of binder to this material during the plant calibration. This could amount to about 20 tons of material. The aggregate is then weighed to check for any residual moisture and a sieve analysis is performed to check for any degradation that may have occurred in the plant. Excessive breakdown of the aggregate particles can result in the generation of excess fine particles and loss of VMA. Degradation should be addressed by correcting the stockpile aggregate feed into the plant. RAP is generally not subject to a significant amount of degradation.

The inclusion of a high content of RAP in a mix, however, can lead to problems in plant verification. If the aggregate gradation, asphalt content, type of aggregate or moisture content in the RAP differ significantly from the mix design or the last measurements made, then it will cause a variation in the field mix from the job mix formula. During mix design, RAP will be heated to the mixing temperature with the virgin aggregate, ensuring that moisture has been removed. In the plant, RAP that has high moisture content may not be completely dried prior to being mixed with the virgin binder. Incomplete drying of the RAP may lead to greater residual moisture in the virgin aggregate due to incomplete veiling of the material. This will affect the volumetric properties of the mix, and may cause problems with moisture susceptibility in the mix. Separating RAP stockpiles according to size and type of mix, as well as following good stockpiling practices, will help minimize differences between mix design and production.

Once corrections to the aggregate feed have been made, a trial run of the mix should be produced. It is suggested that mix be put through the plant, and that a sample of the material be taken from the bed of a dump truck about half way through the trial run or at about 30 minutes into the production. This sample should be properly split, sized, and tested for all quality control characteristics. The extra material should be reserved and saved for retesting if needed. This will allow the plant to warm up and production to stabilize before sampling. More samples can be taken and tested in the mix verification process, as a function of time. For instance, if production continues, a sample may be taken at 45 minutes or one hour into production. A test strip of the material should be placed, compacted, and tested for density using this material, preferably on the project to be paved. The paver operations, roller types and roller patterns necessary to get the best mat density and smoothness can be established.

Testing

At this point, it is necessary to check the mix composition and properties to ensure that it meets the job mix formula requirements. It is emphasized that the mix design provided a starting point. Differences between the job mix formula and field produced properties should be carefully scrutinized before making adjustments. Although attempts should be made to adjust the field produced mix to the job mix formula, it may become necessary to readjust the mix to meet the field conditions. It is important that any adjustments to the JMF meet the requirements of the broad band specification.

Enough material should be taken to perform maximum theoretical density, asphalt content, and gradation testing on loose mix as well as volumetric testing on compacted specimens. Approximately 100 lbs (45 kg) of material should be sufficient for testing. Sampling and sample splitting can be accomplished using AASHTO T168 or ASTM D979.

Loose Mix

The gradation and asphalt content should be tested first to ensure they are correct. The easiest way to check this is through the use of a properly calibrated ignition oven (AASHTO T308, ASTM D6307). If the aggregate is soft, high in absorption, or subject to change during the oven heating, then it is critical to first calibrate the mix in the laboratory during the mix design phase and apply these corrections. If the mix meets the job mix formula requirements, then testing for the maximum theoretical specific gravity can proceed (AASHTO T209, ASTM D2041).

Three samples of mix should be compacted in the gyratory compactor (AASHTO T312, ASTM D4013) to the design number of gyrations. The increase in density with gyrations should be checked for any unusual behavior (e.g. unexpectedly steep slopes or flat slopes in the curve).

Compacted Mix

Depending upon the requirements for field volumetric testing, the following parameters should be examined:

Air Voids (lab compacted): The air void content should be within one percent of the target voids at Ndesign.

Voids in Mineral Aggregate (lab compacted): Typically field VMA is on the order of 0.5 to 1.0 percent lower than that achieved in mix design. This happens due to a number of reasons. For instance, sharp angles on the aggregate may become more rounded during the mixing process, generating more fines and allowing a tighter packing of the particles. Also, if production temperatures are high, there may be appreciably more asphalt absorption in the field materials than during mix design, especially with highly absorptive aggregates.

Adjustments

Before making adjustments, plant personnel should review all the available data. Obviously, if the asphalt content or gradation does not comply with the job mix formula, then appropriate changes in the asphalt feed or aggregate feed should be made. If the proportion of dust in the mix is too great, the return from the baghouse may need to be checked and adjusted.

If the volumetric controls are outside the job mix formula, then the cause should be found and corrected. For instance, if the air void content is low and the VMA is low, two approaches can be tried to correct the problem. First, an adjustment of the aggregate gradation to move it further from the line of maximum density should be tried. This may involve increasing the coarse or fine aggregate, while attempting to keep the gradation within the JMF. Secondly, the amount of filler used in the mixture may be reduced to increase the VMA and air voids. If air voids are high and VMA is low, consideration should be given to increasing the asphalt content slightly and adjusting the aggregate gradation. If it is not possible to stay within the JMF, then the broad band specifications should be followed and adjustments in the mix should be considered.

While the mix validation is being performed, a test strip should be placed to ensure the compactibility of the mix and to determine an effective rolling pattern.

Test Strip

In many cases, a section of the project will be set aside for the construction of a test strip. If this is not the case, then a test strip may be built off the project, but the pavement support conditions and the environmental conditions should mimic the construction site as closely as possible.

The test strip serves to provide experience for the paving crew to the mix characteristics. It should be used as an opportunity to work out potential problems with:

1. lift thickness
2. segregation
3. smoothness
4. in-place density

Several observations and measurements should be made during this stage of construction. Lift thickness should be set using controls on the paver and screed. The loose mix behind the screed should be checked at approximately 20-ft (6-m) intervals behind the screed allowing for about 0.25 inch (6 mm) compaction per inch (25 mm) of compacted mat thickness. As the material is being placed, evidence of segregation should be noted, and best practices to eliminate it should be implemented (AASHTO, 1997).

One of the most important functions of the test strip is to establish a rolling pattern for optimum density. There are publications available to provide guidance on field compaction (NAPA, 2002 and 2002b). Most problems with in-place density surround the inability to meet specifications. Checking density nondestructively before compaction could help identify the source of potential inconsistencies. If after several rolling patterns are tried, the density is still too low, then a number of factors need to be checked.

One of the first should be the lift thickness specified for the mixture supplied. If the mix is a coarse gradation, then the lift thickness should be 4 times the nominal maximum aggregate size (NMAS). If it is a fine gradation, then it should be at least 3 times the NMAS. If the specified lift is too thin, the mix will not compact adequately, and the contractor and agency should consult to see if the lift thickness can be changed. As a last resort, the mix may need to be redesigned with a smaller NMAS.

If the designed lift thickness is appropriate, the next step is to review the delivery temperature of the mix, and whether there is a general problem with low temperature, or if there are low temperatures present in different areas of the mat. A general problem could be addressed through either:

1. Increasing the plant temperature slightly, allowing more workability in the RAP and the virgin binder.
2. Keeping trucks moving so they are not waiting to discharge their loads.
3. Paving during improved environmental conditions (e.g., increasing air temperature, dry weather, etc.)
4. Keeping the rollers close behind the paver.

If the low temperatures are associated with the end-of-loads, then keeping the paver running smoothly and continuously should stop these from forming. If the paver hopper is loaded through end-dumping, then the starting and stopping of the paver should be done both rapidly and smoothly to avoid a rough surface.

Balancing production is the key to a successful paving job. An insufficient number of rollers or a paving speed that is too fast can lead to low densities. The paver should operate at a speed that allows the compaction train to keep up with it. If vibratory compactors try to keep up with a high paver speed, the impact spacing will be too great and density will not be achieved. Likewise, if static or pneumatic rollers are traveling too fast, there will not be an adequate dwell time for compaction.

Using too high of an amplitude in vibratory compaction may lead to fractured aggregate particles and a low density. If fractured aggregate are visible on the surface, the rolling equipment and techniques should be reviewed. If a vibratory compactor is used in the intermediate position, consider reducing the amplitude or replacing it with a pneumatic compactor. Make sure that the mix temperature is in the range that will allow compaction.

Production

Once the plant adjustments and the proper balancing of production, paving, and compaction have been completed, production can start and the process of quality control is used to make sure that consistency is maintained. Quality control (QC) uses measurements of material components and HMA properties to provide feedback to the plant and paving crew. Adjustments at this stage should be in response to a number of tests showing either a drift or shift in the production. The next section discusses QC procedures.

Notes

Introduction

Quality control procedures ensure the consistency of the recycled HMA mixture produced in a plant and placed on the roadway. A sound quality control plan will help maintain both the production and desired level of quality, especially for recycled mixtures with high RAP contents. While the discussion here is limited to testing attributes over which the producer has control, quality control also involves providing feedback to the individuals who are involved in the manufacturing process. In other words, all plant, transportation, paving, and management personnel have quality control responsibilities. Good procedures include conducting appropriate tests and analyzing the results in a timely manner as well as observing all aspects of the mix production, placement, and compaction process. This section provides a discussion of the steps necessary to ensure a quality construction project.

Testing

Quality control testing should focus on providing information that can be acted upon by plant or paving personnel to provide the desired characteristics in the mix or mat. While not every test result deviation from a target value needs or should get a corrective action, patterns of drift or abnormally high variability should be identified and the proper adjustments should be made. Drift can be detected by monitoring the running average of test results with time. The presence of RAP will require testing beyond that for QC of an all virgin material HMA, since the ingredients of the RAP adds extra components to the mixture input.

Tables 1 through 4 provide some suggested schedules of testing for aggregate, RAP, asphalt binder, and mixture, respectively. The test method, the AASHTO and ASTM test designations, the sampling location, sampling rate range, and the priority of the test are given. It is recognized that other schedules of testing have been established by experience in various States. The guidance given here is largely taken from the experience with the WesTrack project where the impact of construction variability on pavement performance was documented (Epps et al, 2002) and it is not intended to supplant specifications that are currently working well. Priorities are listed as either high, medium, or low, depending upon how critical the information is to making adjustments. Variability will also dictate the frequency of testing. For instance, testing gravel sources for flat and elongated particles may not be useful. Also, if RAP stockpiles are separated according to size or type of material, the consistency may be such that the frequency of testing can be lower than for cases where only one stockpile is used.

Aggregate

Testing of aggregate stockpiles should be accomplished during the materials evaluation phase of the mix design. If stockpiles are replenished during production, they should be tested as materials are added, at an approximate rate of about once every 5000 tons, to make sure that the characteristics have not changed significantly since the mix design. As long as new materials are not added to the stockpile during the production operation then little additional testing of the stockpile is needed. Proper stockpiling practices should always be followed.

Table 1 shows the recommended schedule of testing for aggregates during mix production. Sampling of the combined aggregates should take place on the conveyor going into the plant. If the contractor has a good process control program for production of aggregates, the sampling frequency can be greatly reduced. However, if the gradation is not being closely controlled at the quarry then more testing should be done by the contractor. Once it has been verified that the stockpile is homogenous and within specifications, additional testing of materials being hauled to the stockpile can be limited to one or two tests per day for each stockpile.

TABLE 1
Suggested Quality Control Schedule for Aggregate (after Epps et al, 2002)

Test Description	Test Number		Sampling Location	Frequency[1] (samples/lot)	Priority
	AASHTO	ASTM			
Coarse aggregate angularity		D5821	Combined cold feed	1 - 5	Medium – Low
Fine aggregate angularity	TP56		Combined cold feed	1 - 5	Medium – Low
Flat and Elongated Particles		D4791	Combined cold feed	1 - 5	Medium – Low
Sand Equivalent	T176	D2419	Combined cold feed	1 - 5	Medium – Low
Los Angeles abrasion	T96	C131	Combined cold feed	1 - 5	Medium – Low
Soundness	T104	C88	Combined cold feed	1 - 5	Medium – Low
Deleterious materials	T112	C142	Combined cold feed	1 - 5	Medium – Low
Gradation	T27	C136	Combined cold feed	5	High

1 Frequency and types of testing will depend upon variability of source materials and the intended end-use of the HMA. Historical records and materials evaluation should be consulted before determining testing frequency.

TABLE 2
Suggested Quality Control Schedule for RAP

Test Description	Test Number		Sampling Location	Frequency[1,2] (samples/lot)	Priority
	AASHTO	ASTM			
Asphalt content	T308, T287, or T164	D6307, D4125 or D2172	Stockpile or combined RAP feed	1 - 5	High
Gradation	T27 RAP feed	C136	Stockpile or combined	1 - 5	High
Binder extraction and recovery	T164 and T170	D2172 and D1856 or D5404	Stockpile or combined RAP feed	1	Low
Binder properties – See Table 3			Post extraction and recovery	1	Low
Aggregate properties – See Table 1			Post extraction	1	Medium – Low

1 Frequency and types of testing will depend upon variability of source materials and the intended end-use of the HMA. Historical records and materials evaluation should be consulted before determining testing frequency.
2 If the RAP stockpile is built ahead of production and additions are not being made to the pile, it may be possible to dramatically reduce the sampling frequency.

TABLE 3
Suggested Quality Control Schedule for Asphalt Binder (after Epps et al, 2002)

Test Description	Test Number		Sampling Location	Frequency (samples/lot)	Priority
	AASHTO	ASTM			
Rotational viscometer (unaged)		D4402	Virgin[1] – storage Blended[3]	1	Virgin – high Blended[2] – medium
Dynamic shear rheometer (DSR) (unaged)	T315		Virgin[1]– storage Blended[3]	1	Virgin – high Blended[2] – medium
DSR (RTFO)	T315		Virgin[1]– storage Blended[3]	1	Virgin – high Blended[2] – low
DSR (PAV)	T315		Virgin[1] – storage Blended[3,4]	1	Virgin – high Blended[2] – low
Bending beam rheometer (PAV)	T313	D6648	Virgin[1] – storage Blended[3,4]	1	Virgin – high Blended[2] – low
Direct tension (PAV)	T314	D6723	Virgin[1] – storage Blended[3,4]	1	Virgin – high Blended[2]– low
Flash Point	T48		Virgin[1] – storage Blended[3,4]	1	Virgin – high Blended[2] – low

1 For virgin materials, a certificate of compliance from the binder supplier and quality assurance testing may suffice for testing requirements.
2 For blended binders, testing is only recommended for mixtures with RAP contents exceeding 25 percent, and the frequency will depend upon variability of materials in stockpiles.
3 Recommended for blended virgin and extracted and recovered RAP binder.
4 Recommended for extracted and recovered binder from produced mix.

TABLE 4
Suggested Quality Control Schedule for HMA Mixtures (after Epps et al, 2002)

Test Description	Test Number		Sampling Location	Frequency[1] (samples/lot)	Priority
	AASHTO	ASTM			
Gradation	T27	C136	Truck or Behind Paver	2 - 5	High
Asphalt content	T308, T287, or T164	D6307, D4125 or D2172	Truck or Behind Paver	2 - 5	High
Gyratory Compaction Properties @ N_{design}	T312	D4013	Truck or Behind Paver	2 - 5	High
Air voids	T269	D3203	Truck or Behind Paver	2 - 5	High
Voids in mineral aggregate			Truck or Behind Paver	2 - 5	High – Medium
Voids filled with asphalt			Truck or Behind Paver	2 - 5	High – Medium
Bulk specific gravity	T166	D2726	Truck or Behind Paver	2 - 5	High
Dust to binder ratio			Truck or Behind Paver	2 - 5	Medium
Theoretical Max. Specific Gravity	T209	D2041	Truck or Behind Paver	2 - 5	High
In-place air voids	T269	D3203, D2950	Compacted Mat	5 -10	High

1. Frequency and types of testing will depend upon variability of source materials and the intended end-use of the HMA. Historical records and materials evaluation should be consulted before determining testing frequency.

RAP

RAP may be material removed from the project being constructed or from other similar projects. Some State DOTs require that any RAP used in recycled mixtures be recovered from State projects. This tends to reduce the variability of the RAP, since material removed from State projects will be more uniform than RAP collected from a wide range of sources. This is also true for plant waste stockpiles. More attention must be provided when RAP is being collected from various sources. Any material delivered must be blended with other materials to produce a uniform stockpile. A uniform stockpile is essential in the production of a uniform recycled mixture. This is especially true when using high RAP contents.

As mentioned before, the RAP material may be separated into at least two stockpiles prior to use according to the particle sizes. Other stockpiles may reflect differences in materials used in different kinds of paving projects. Some contractors have chosen to do this simply because it provides more control over the properties of the recycled HMA. It also offers greater flexibility in proportioning different types of mixtures.

It is important to measure the asphalt content and gradation at several sampling locations on each of the RAP stockpiles before beginning production. Table 2 gives ranges for sampling and testing RAP materials during production. Depending upon the variability of materials in RAP and the type of mix being produced, the type of testing and frequency should be adjusted. If the RAP is known to be consistent in asphalt content and gradation, then the frequency can be minimized. However, for a high coefficient of variability (say 20 percent or higher), it would be wise to set up a regular sampling and testing program. Likewise, if the HMA being produced is for a less critical structure or layer in the pavement, frequent testing of aggregate characteristics such as polishing or crushed face count may be superfluous.

It is easier to tailor the mixture and maintain gradation and asphalt content control by separating the material into two or more sizes. If RAP is obtained from the project being constructed, care should be exercised when the depth of RAP removal is adjusted. If the depth changes, the gradation and asphalt content of the RAP may change since different mixes are typically used in different pavement layers.

The two methods that are normally used to determine the asphalt content and gradation are the solvent extraction method and the ignition oven test. Both methods will provide reasonably accurate data if properly conducted. However, the solvent extraction method results in the need for used solvent disposal. As the amount of RAP is increased, the importance of the accuracy of these tests increases. There is very little information involving testing of recycled mixture where the RAP contains modified binders but this is beginning to be a bigger issue. If the amount of RAP is low, the modified asphalt is likely not to impact the properties. However, as the amount of RAP is increased, this may become a more important issue.

Binder

Generally, once a grade of binder is selected for a project, the grade is not changed during the construction of the project unless there is a problem. Most of the binder evaluation should be done prior to mix design. However, with high RAP contents any significant change in the gradation and/or amount of RAP may result in the need for a change in the grade of asphalt that is being used to produce the mixture. Adjustments in the mix should be made to provide the needed binder properties without having to change the binder grade.

Table 3 presents suggested rates for QC testing of both virgin and recycled AC binders. At most, this should be done at a rate of once per lot. However, certificates of compliance from binder producers could suffice for testing of virgin binder, or Quality Assurance testing could be used to indicate any changes in the virgin binder. Also, unless there is sufficient reason to believe that the RAP binder has changed during the course of production, it is not necessary to test it beyond the materials evaluation stage of the mix design process.

Florida recommends taking a sample of the recycled mixture for testing for every 4,000 tons of production, which could translate to about once or twice per lot.

Mix

It is important that a mix have consistent properties that meet the desired requirements. Mixture properties that are important include gradation, asphalt content, air voids, VMA, voids filled with asphalt, and properties of blended binder. The rate of testing should be between 2 and 5 sets for a lot of material. Table 4 shows the recommended tests and frequency of testing for the HMA mixture. The point of sampling for the QC testing should coincide with the point of sampling for Quality Assurance. This is usually either the transport vehicle or behind the paver.

There are a number of performance tests mentioned in the Mixture Design section that could be useful, but many States have not adopted them as of yet. The most common performance test used is some type of wheel tracking test which provides some indication of the rutting potential of an asphalt mixture. The recovered asphalt binder properties are generally used to get some indication of the potential for thermal cracking. Generally, it is believed that adding as much asphalt binder as possible without failing the rutting test is the best way to design a mixture that is resistant to cracking, raveling, and moisture susceptibility.

Adjustments

Gradation

The gradation should be adjusted as necessary to satisfy the requirements of the specification. When the VMA is low, the gradation will probably have to be adjusted to increase the VMA. The gradation should also be adjusted when necessary to meet specification requirements for the job mix formula of the mixture. The easiest way to increase the VMA is to reduce the amount of material passing the No. 200 sieve.

One issue that should be considered in recycled HMA is the amount of material passing the No. 200 sieve for RAP. The milling operation will breakdown some aggregates, especially soft aggregates, and provide a high percentage of material passing the No. 200 sieve.

If the gradation of the RAP changes, this will have to be offset by adjusting the gradation of the virgin aggregate. Significantly changing the percentage of RAP to improve gradation may cause problems since this will affect the amount of binder in the mixture.

Binder Grade

The virgin asphalt binder grade is selected to provide the desired properties in the blended asphalt binder. When the amount of RAP is increased, the amount of the new binder to be added to the mixture is reduced, and the viscosity or stiffness of the virgin binder will likely need to be reduced.

The asphalt binder grade should not normally have to be adjusted during the construction project unless it is necessary in order to provide the needed properties of the combined binder. If the amount of RAP is increased, the PG grade of the new binder may have to be reduced to provide the desired combined binder properties.

Binder Content

The most important property in an asphalt mixture is the amount of air voids in the mix, and this is generally controlled by the amount of binder in the mixture. If the amount of binder is higher, then the air voids will be lower and vice versa.

If the measured air voids criterion is not satisfactory, then the binder content may have to be adjusted to provide the needed air voids. However, any change in binder content will change the properties of the combined binder and thus may require that a change in grade of new binder be used and/or the amount of RAP modified to provide the desired properties.

RAP Content

Generally, the RAP content is controlled by the State specifications or, in some cases, it is set by the contractor based on experience. When the RAP binder content increases, the amount of new asphalt needed is reduced, making it necessary to use a lower viscosity virgin asphalt in order to have the proper workability and crack resistance. It may be more difficult to control the gradation and volumetrics with higher RAP contents, unless more effort is taken to control the uniformity of RAP stockpiles. Depending upon the type and age of the plant being used to manufacture the HMA, it may be necessary to limit RAP usage to satisfy emissions requirements.

Higher RAP content will reduce the overall cost of the mix being produced. So as long as the quality of the recycled HMA is not compromised, the amount of RAP used in the mixture should be optimized. With the price of asphalt cement increasing, the savings for using higher percentages of RAP is significant. Increased quality control is key to monitoring the consistency and value of the HMA being produced.

Notes

Summary

It is certainly possible to design HMA mixtures with RAP contents of 30 to 40 percent. The two biggest impediments to designing high RAP content mixes are:

1. The stiffness of the RAP binder which controls the virgin binder or recycling agent grade needed to produce a mix with the desired blended binder characteristics. If the RAP content is high, then the PG grade of new binder may be so low as to cause problems with blending and softness early in the performance of the pavement.
2. The gradation of the RAP may contain too much material passing the No. 200 sieve to allow the use of more than a certain percentage of RAP in the mixture. This can be overcome by separating RAP materials according to size. In doing this, the mixture can be tailored for specific uses.

Other issues exist as well, such as the consensus properties of the aggregate, plant limitations, ambient temperature restrictions, and RAP moisture content. The first of these could be handled by separating stockpiles according to the type of mix in the RAP. The other issues require knowledge of the plant, balancing the economics of production, and good construction judgment.

Mix design methods exist for recycled hot mix asphalt, and a step-by-step process is presented in NCHRP Report No. 452. This method follows the Superpave method of mix design, but could easily be adapted to any mix design procedure. As stated by McDaniel and Anderson (2001), the only changes in mix design from an all-virgin mix are:

1. Heating the RAP more gradually than aggregates are normally heated.
2. Estimating the RAP aggregate specific gravity.
3. Accounting for the RAP binder in the aggregate batching.
4. Reducing the new binder content to account for the RAP binder.
5. Possibly using a lower virgin binder grade to account for the RAP binder aging.

With the higher prices for asphalt and energy, there are certainly economic incentives to use higher percentages of RAP. RAP with higher binder contents will have more asphalt added from the RAP and thus require less costly new asphalt. With a higher total RAP content, there will also be lower cost in the production and transportation of virgin aggregate. However, mixtures with RAP contents exceeding 25 percent normally will require significant changes in testing and plant operations, whereas those with lower RAP contents will require fewer changes.

Higher RAP content will reduce the overall cost of the mix being produced. So as long as the quality of the recycled HMA is not compromised, the amount of RAP used in the mixture should be optimized. With the price of asphalt cement increasing, the savings for using higher percentages of RAP is significant. Because of high asphalt prices, it is time to review specifications which may limit RAP usage and not fully exploit this resource. The industry needs to work with agencies to ensure the quality of mixtures being produced with RAP and to work toward a performance test that will allow rapid evaluation of important performance characteristics without relying solely on recipe type of guidelines for mix design.

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SI* (MODERN METRIC) CONVERSION FACTORS

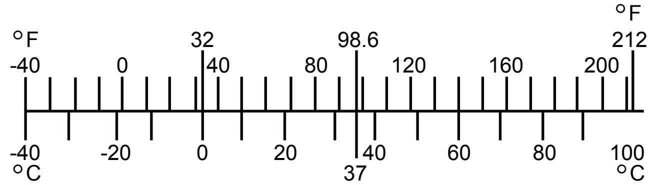
APPROXIMATE CONVERSION TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
inches	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
AREA				
in^2	square inches	645.2	millimeters squared	mm^2
ft^2	square feet	0.093	meters squared	m^2
yd^2	square yards	0.836	meters squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometers squared	km^2
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	meters cubed	m^3
yd^3	cubic yards	0.765	meters cubed	m^3
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
TEMPERATURE (exact)				
°F	Fahrenheit temperature	5(F-32)/9	Celsius temperature	°C

NOTE: Volumes greater than 1000 L shall be shown in m^3.

APPROXIMATE CONVERSION FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
AREA				
mm^2	millimeters squared	0.0016	square inches	in^2
m^2	meters squared	10.764	square feet	ft^2
ha	hectares	2.47	acres	ac
km^2	kilometers squared	0.386	square miles	mi^2
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	meters cubed	35.315	cubic feet	ft^3
m^3	meters cubed	1.308	cubic yards	yd^3
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons(2000 lb)	T
TEMPERATURE (exact)				
°C	Celsius temperature	1.8C + 32	Fahrenheit temperature	°F



*SI is the symbol for the International System of Measurement.

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