NCHRP
REPORT 452

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Recommended Use of Reclaimed Asphalt Pavement in the Superpave Mix Design Method: Technician's Manual

TRANSPORTATION RESEARCH BOARD

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Recommended Use of Reclaimed Asphalt Pavement in the Superpave Mix Design Method: Technician's Manual

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

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FOREWORD

By Staff
Transportation Research Board

This is a technician's manual for use of reclaimed asphalt pavement (RAP) in Superpave®-designed hot-mix asphalt (HMA). It will be of particular interest to materials engineers in state highway agencies and to contractor personnel responsible for designing HMA according to the current Superpave method.

When hot-mix asphalt (HMA) pavements reach the end of their usable service lives, the materials in them retain considerable value. In the early 1970s, states and paving contractors began making extensive use of reclaimed asphalt pavement (RAP) as a component in new HMA pavements. Besides possible cost savings, this use of RAP represents an environmentally positive method of recycling. Further, experience has shown that properly designed HMA containing RAP performs as well as HMA prepared exclusively with virgin materials.

From 1987 through 1993, the Strategic Highway Research Program carried out several major research projects to develop the Superpave method for performance-based HMA design. This method has now widely superseded the Marshall and Hveem design methods in the United States and Canada. A distinct shortcoming of the Superpave method is that it makes no specific provision for the use of RAP in the mix design process. This shortcoming has hindered RAP use by agencies that have adopted the Superpave mix design method.

To remedy this situation, the Federal Highway Administration's Superpave Mixtures Expert Task Group used past experience to develop interim guidelines for the use of RAP in the Superpave method. These guidelines reflect the fact that the effect of aged binder from RAP on the performance properties of the virgin binder depends upon the level of RAP in the HMA. When the level is low, the effect is minimal, and the RAP is likened to a "black rock" that influences the mix volumetrics and performance through its aggregate gradation and properties. As the level of RAP in the HMA increases, the black rock analogy breaks down; the aged binder blends with the virgin material in sufficient quantity to significantly affect its performance properties.

Under NCHRP Project 9-12, "Incorporation of Reclaimed Asphalt Pavement in the Superpave System," the North Central Superpave Center at Purdue University was assigned the tasks of developing recommended guidelines for incorporating RAP in the Superpave mix design method and preparing a technician's manual to implement these guidelines in routine laboratory operations.

The research team first conducted a comprehensive laboratory-testing program to test the null hypothesis that RAP does not act as a black rock. RAP materials from field projects in Florida, Connecticut, and Arizona that yielded recovered RAP binders of distinctly different stiffnesses were investigated in combination with two different virgin binders at RAP contents of 10 and 40 percent. Mix specimens fabricated to simulate three cases of blending—actual practice, black rock, and total blending—were

evaluated through the use of the Superpave shear tests (AASHTO TP7) at high temperatures and indirect tensile creep and strength tests (AASHTO TP9) at low temperatures. No statistically significant differences were found among the three blending cases at low RAP contents. However, at higher RAP contents, the actual practice and total blending cases were statistically different from the black rock case, but not from each other. Thus, the results provided compelling evidence that RAP does not act like a black rock, regardless of the stiffness of the RAP binder. The research team then investigated the effects of hardened RAP binder on the blended binder properties and of RAP on the blended mix properties.

The research findings largely confirm current practice as exemplified by the Superpave Mixtures Expert Task Group's interim guidelines. Low amounts of RAP, typically 10 to 20 percent, can be used without characterization of its recovered binder properties; there is not enough of the old, hardened RAP present to significantly change the properties of the asphalt binder, and the RAP may be solely accounted for as a component of the aggregate. When RAP is added in amounts greater than 20 percent, recovery and testing of its binder is recommended, along with the use of blending charts to determine what performance grade of virgin asphalt binder should be used in the mix design. The RAP aggregate properties should be considered as if the RAP is another aggregate stockpile. In the Superpave mix design, the RAP aggregates should be blended with the virgin aggregates so that the final blend meets the Superpave consensus properties. Most state highway agencies will find that the results of the research largely agree with their usual practice. This agreement should give highway agencies and contractors greater confidence in more widely extending the use of RAP in HMA, regardless of the mix design method used.

The technician's manual published herein was prepared by the North Central Superpave Center research team as Appendix E of the final report for NCHRP Project 9-12. The team's final report includes a detailed description of the experimental program, a discussion of the research results, and seven supporting appendices:

- Appendix A, Annotated Bibliography;
- Appendix B, Statistical Analysis of Black Rock Data;
- Appendix C, Flow Charts Showing Development of Blending Charts;
- Appendix D, Summary: Guidelines for Incorporating Reclaimed Asphalt Pavement in the Superpave System;
- Appendix E, Use of RAP in Superpave: Technicians' Manual;
- Appendix F, Use of RAP in Superpave: Implementation Plan; and
- Appendix G, Proposed Procedure for Determining the Asphalt Binder Grade Recovered from HMA.

Appendix D will be published as *NCHRP Research Results Digest 253*. The main report and Appendixes A, B, C, F, and G will be published as *NCHRP Web Document 30*. In addition, the entire final report, including all appendixes, will be distributed as a CD-ROM (*CRP-CD-8*) along with the complete final reports for NCHRP Projects 9-11 and 9-13.

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The support and guidance of Dr. Edward T. Harrigan and of the members of the project panel are also greatly appreciated.

CHAPTER **1**

INTRODUCTION

MANUAL PURPOSE

This manual is a reference guide for mix design and field testing technicians who deal with reclaimed asphalt pavement (RAP) in Superpave® mixtures. It will provide detailed descriptions and examples of each step involved in designing and testing a Superpave mix with RAP.

This manual is written assuming that you, the reader, are already familiar with basic asphalt mixture testing and mix design. If this is not the case, you may want to attend a training course or refer to other publications, such as *Superpave Level 1 Mix Design, SP-2* (*1*), *Hot Mix Asphalt Materials, Mixture Design and Construction* (*2*), *Background of Superpave Asphalt Mixture Design and Analysis* (*3*), or *Hot-Mix Asphalt Paving Handbook* (*4*). A step-by-step manual covering basic asphalt mixture test procedures is also available from FHWA (*5*). You should also have a copy of the AASHTO specifications for hot-mix asphalt, aggregates, and binders (*6*), or a copy of your state's specifications, or both.

Mix designers will be especially interested in Chapters 1 through 5. Quality-control technicians will be particularly interested in Chapters 1, 2, and 6. A glossary, which includes all equation variables used in the manual, follows the references.

This manual summarizes recommended guidelines for working with Superpave mixtures containing RAP. It is important to remember, however, that each state or agency you work with may have its own specifications and recommended practices that must be followed. You should be certain that you know the specifications for the agency with which you are working.

RAP

RAP is old asphalt pavement that is milled up or ripped off the roadway. This material can be reused in new asphalt mixtures because the components of the mix—the asphalt binder and aggregate—still have value. Using RAP in new mixtures can reduce the amount of new material that has to be added, saving money and natural resources. In addition, hot-mix asphalt mixtures with RAP can perform as well as mixtures made with all new material.

When RAP is reused in a new mixture, it is necessary to properly account for the old material in the new design. The aggregate from the RAP has to be included with the new aggregate, and that blend of aggregate has to meet certain physical properties. The old binder from the RAP may need to be tested and analyzed, too. The old binder may reduce the need for new binder to be added. During the construction and service life of the roadway from which the RAP was obtained, the asphalt binder in the roadway became aged or hardened by reacting with oxygen in the air. If the old asphalt is very hard or if there is a lot of it, blending the old asphalt with the new binder that is added may make the blend act like a much harder binder. This binder hardening can be counteracted by adding a softer binder to the mix and letting the RAP binder stiffen the softer binder. Sometimes, recycling agents also are used to soften the hardened RAP binder.

The materials in the RAP most likely met the specifications at the time of construction. However, overtime, and especially with the use of Superpave, the specifications have changed. Superpave specifications usually are tighter than the previous hot-mix specifications used in most states. In particular, controls on aggregate gradation and shape are frequently tighter than before. The new hot-mix asphalt produced with RAP must meet these new, tighter restrictions. For example, if the RAP gradation is very different from the Superpave specifications, the amount of RAP that can be used may be limited.

Past experience with RAP in Marshall and Hveem mixtures has shown that properly designed and constructed RAP mixes can perform as well as, or even better than, mixtures made with all new materials. The same should be true of Superpave mixtures made with RAP.

CHAPTER **2**

DETERMINING PROPERTIES OF RAP

This chapter describes how to sample and test RAP to get the basic information needed for the mix design. Testing the RAP binder properties is required when using higher percentages of RAP (this topic will be described in Chapter 3). Your state may have specific guidelines for sampling and testing.

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

Some of the tests done for Superpave are different than those done for Marshall or Hveem designs. In using Superpave, the blends of aggregates must meet certain gradation limits and consensus properties; these same requirements also apply to blends with RAP. Superpave binders also need to meet certain properties. If a high percentage of RAP is used (greater than 15 to 30 percent, depending on virgin binder grade), the RAP binder will have to be considered when choosing the virgin asphalt grade.

RAP VARIABILITY

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

Because of variability concerns, some states limit the amount of RAP that can be included in new mixtures. Some states allow the use of higher percentages of RAP if the material is milled off the same project where the new mix will be placed; if RAP is used from a stockpile that includes material from several projects, less RAP may be used.

RAP stockpiles may also include what is called "deleterious material." Deleterious material includes anything that does not belong in the stockpile—aluminum cans, wood scraps, portland cement concrete, trash, and the like. These materials are undesirable in the finished product, and their presence in the stockpile should be limited.

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

Good stockpile management practices should be followed to keep material variability in check. Research has shown that the variability of RAP can be controlled and may not be as great as expected (*7*).

Stockpiles should be built with materials from one source (i.e., one project) to keep them as consistent as possible. Achieving this consistency is frequently difficult, however, because there is not enough room at the plant to build separate stockpiles. Mixing materials from multiple projects is undesirable because it can greatly increase the variability of the stockpile. If materials from several projects are combined in a stockpile, they should be blended together using a front-end loader or other equipment. Processing the RAP by crushing or screening can also greatly help to mix the pile and remove oversized material. The National Asphalt Pavement Association has an excellent publication entitled *Recycling Hot Mix Asphalt Pavements* (*8*) that discusses processing and handling RAP at the plant and during construction.

Some states require that stockpiles be tested and identified. After the stockpile is sampled for testing, it may be assigned a number. New materials cannot be added to that stockpile. Be sure to find out what your state requires for stockpile management and what limits the agency places on variability of RAP properties or on the maximum allowable percentage of RAP in specific mixtures.

SAMPLING RAP

RAP can be sampled from the roadway (by coring before the pavement is milled), from a stockpile, or from haul trucks. The process for stockpile or haul-truck sampling is similar to

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

FHWA's *Pavement Recycling Guidelines for State and Local Governments* (*9*; pp. 5-1 through 7-26) includes a detailed discussion of sampling RAP. Many of the recommendations included this manual are found in that FHWA report. Your state will likely have its own recommended sampling locations, procedures, and frequencies.

Roadway Sampling

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

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

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

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

Stockpile Sampling

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

Sampling from Haul Trucks

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

Sample Size

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

EXTRACTION AND RECOVERY OF RAP BINDER AND AGGREGATES

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

Sometimes, it is also necessary to know something about the physical properties of the asphalt binder, not just how much binder there is. In these cases, it is necessary to extract the asphalt binder from the RAP using a solvent so that the binder can be tested. If more than 15 to 30 percent RAP is to be used, depending on the grade of the RAP binder, blending charts are needed to determine the appropriate virgin binder grade to use or to determine how much RAP can be used with a given virgin binder grade (this topic will be discussed in Chapter 3).

If the binder content and aggregate information are all that are needed, several different methods can be used. The asphalt can be extracted from the RAP using a solvent in a centrifuge, vacuum, or reflux extractor, or the asphalt can be burned off the aggregate in an ignition oven. The asphalt content should be calculated, and the aggregate should be saved for later evaluation. Because ignition ovens may cause degradation of some aggregates, care should be used when analyzing the gradation of aggregates after the ignition oven. Care should also be used when determining the asphalt content of some aggregates with the ignition oven, especially for RAP

for which a correction factor for the aggregate may have to be estimated, not measured. Experience with your local aggregates can indicate whether the ignition oven is an appropriate method to use in your area.

DETERMINING AGGREGATE PROPERTIES

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

Care should be used when testing aggregates for gradation after burn-off in the ignition oven. Some aggregates break down or are lost in the ignition oven, changing the gradation; others do not. Even though the use of ignition ovens is increasing rapidly, some states do not allow ignition ovens to be used if aggregate gradation is needed. Individual state guidelines on the use of ignition ovens vary depending on the common types of aggregates available and on how much breakdown aggregates typically undergo.

RAP Aggregate Gradation

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

RAP Aggregate Specific Gravity

To calculate the voids in the mineral aggregate (VMA) or to use the Superpave method for estimating the binder content of a mixture, it is necessary to know the combined aggregate bulk specific gravity. When that aggregate includes RAP, the process can be more complicated.

Calculating the combined bulk specific gravity requires knowing the bulk specific gravity of each aggregate component (i.e., stockpile). It can be difficult, however, to accurately measure the bulk specific gravity of the RAP aggregate. Measuring the RAP aggregate specific gravity would require extracting the RAP, sieving it into coarse and fine fractions, and determining the specific gravity of each fraction. The extraction process, however, can change the aggregate properties and also may result in a change in the amount of fine material—which could also affect the specific gravity.

There are two approaches to avoid this problem. The first approach is to use the effective specific gravity of the RAP aggregate instead of its bulk specific gravity. Many states used this approach in the past. The second approach is to calculate the RAP aggregate bulk specific gravity based on the maximum theoretical specific gravity of the RAP mixture and an assumed value for the absorption of the RAP aggregate. This approach works well if you can predict the absorption of the RAP aggregate with some confidence. (A discussion of these alternate methods and the equations used is contained in Appendix A of *NCHRP Web Document 30*.) Check with your state on how it determines the combined bulk specific gravity and VMA when using RAP.

Consensus Properties

The RAP aggregate may also be tested to determine its consensus properties as is done with virgin aggregates for Superpave mixtures. It is important to remember, however, that the Superpave consensus properties apply to the total blend of aggregates (RAP plus virgin in this case), not to the individual aggregate components. It is helpful to know the properties of the RAP aggregate because that knowledge can help the mix designer determine how much RAP can be added to the new mix and still meet the consensus properties for the blend. Because each state has its own unique materials and issues, you should check with your state on how it handles RAP aggregate consensus properties.

The RAP aggregate should be sieved to separate it into coarse and fine fractions. The coarse aggregate (retained on the 4.75-mm [No. 4] sieve) should be analyzed for coarse aggregate angularity. Coarse aggregate angularity is determined by manually counting aggregate particles with one or more than one fractured face (ASTM D5821). A fractured face is defined as a fractured surface that is at least 25 percent of the maximum area of the aggregate particle.

The fine aggregate angularity (AASHTO T304, Method A) can be determined on the aggregate from the RAP that passes a 2.36-mm (No. 8) sieve. The fine aggregate angularity of the RAP aggregate may be changed (usually decreased) by the extraction process. Different aggregates will change by differing amounts; some will change not at all.

The percentage of particles that are flat and elongated must also be determined (ASTM D4791). Some aggregates tend to crush into flat, elongated particles. Some types of crushers also tend to produce more particles with this undesirable shape. If the RAP aggregate has a high percentage of flat and elongated particles, it can be blended with more cubical aggregate so that the resulting blend meets the requirements.

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

The sand equivalent test should be conducted on the virgin aggregates used in the mix design.

MOISTURE IN RAP

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

The RAP moisture content can also be a limiting factor for plant production. High moisture contents take a long time and a lot of energy to dry; this can severely affect production. The virgin aggregates need to be heated to higher temperatures to transfer enough heat to the RAP to dry it (*10*). Also, in batch plants, high moisture contents can produce steam clouds in the pugmill that need to be vented.

The moisture content in the RAP is determined in much the same way as the moisture content of a sample of stockpiled aggregate is checked: you sample the RAP; weigh it; dry it to constant mass in an oven (or, if in the field, in an electric skillet); and weigh it again. Agencies generally have their own particular methods (temperatures, heating times, etc.) for drying RAP in this test. The moisture content is then expressed as the weight of water, indicated by the change in mass from before and after drying, divided by the dry weight of the RAP as shown below:

$$\%\text{Moisture} = \frac{W_w - W_d}{W_d} \times 100\%$$

where

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

Often you need to know how much RAP with moisture to weigh out to provide a certain dry mass of RAP. This can be calculated as follows:

$$W_w = W_d(1 + \%\text{Moisture})$$

CHAPTER 3

DETERMINING RAP BINDER PROPERTIES

This chapter describes the process of extracting, recovering, and testing the RAP binder properties, *when needed*. For low RAP contents, 10 to 20 percent, it is not necessary to do this testing because there is not enough of the old, hardened RAP binder present to change the total binder properties. At higher RAP contents, however, the RAP binder will have a noticeable effect, and it must be accounted for by using a softer grade of binder. For intermediate ranges of RAP, the virgin binder grade can simply be dropped one grade. For higher percentages of RAP, you will need to extract and recover the RAP binder and determine its properties.

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

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

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

EXTRACTION-AND-RECOVERY PROCESS WHEN TESTING RAP PROPERTIES

The modified version of the AASHTO TP2 procedure that is used when recovering the RAP binder for later testing can be described as follows:

1. Obtain a 1000- to 1100-g sample of RAP by sampling and quartering. This is an appropriate sample size to obtain approximately 50 to 60 g of recovered asphalt binder.
2. Dry the RAP sample to a constant mass using an oven operating at 110°C. Determine the weights of the sample and filters used in the extraction and recovery procedures.
3. Place the RAP sample in the extraction vessel and secure the lid. Add 600 ml of solvent to the extraction vessel. (Either n-propyl bromide or toluene may be used unless otherwise noted.) Inject nitrogen gas into the vessel at a rate of 1000 ml/min for 1 min.
4. Place the extraction vessel containing the RAP and solvent on its side and rotate for 5 min.
5. Place the extraction vessel vertically on a stand and connect it to a recovery flask by a vacuum line. Introduce nitrogen into the vessel at a rate of 400 ml/min. Apply a vacuum (700 mm Hg) to the vessel to draw the effluent into the first recovery flask. Next, switch the vacuum to draw the effluent from the first recovery flask, through a 0.020-mm cartridge filter, into the second recovery flask. Finally, switch the vacuum again to draw the effluent from the second recovery flask into the Rotavapor recovery flask.
6. Once the effluent is in the Rotavapor recovery flask, begin the primary distillation. Distill the effluent at 700 mm Hg vacuum in the oil bath at 100 ± 2.5°C. Maintain the distillation flask two-thirds full at all times.

TABLE 1 Binder Selection Guidelines for RAP Mixtures

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

7. Repeat Steps 3 through 6, but use 400 ml of solvent and rotate the extraction vessel 10 min.
8. Continue to repeat Steps 3 through 6 again, using 400 ml of solvent and a 30-min rotational time, until the extract becomes a "light straw" color. At this point, continue primary distillation until the distillation flask is approximately one-thirds full. (If using toluene as the solvent, it is recommended that washes after the third wash be done with 400 ml ± 10 ml of toluene with 15 percent ethanol by volume. Condensate from the primary distillation can be used for the extraction after the third wash.)
9. Pour the effluent into centrifuge bottles. Centrifuge the bottles for 25 min at 3,600 rpm.
10. Pour the centrifuged effluent back into the distillation flask. Increase the Rotavapor oil bath temperature to 174 ± 2.5°C.
11. Continue distillation until the condensation rate is less than one drip every 30 s. Then introduce nitrogen into the flask at a rate of 1000 ml/min for 30 ± 1 min.
12. Pour the recovered asphalt binder from the distillation flask into a container for testing.

At least 50 g of recovered binder are needed for testing.

DETERMINING BINDER PROPERTIES

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

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

Once the RAP binder has been extracted and recovered, its properties need to be determined. The RAP binder must be tested in the dynamic shear rheometer (DSR) at a high temperature as if it were original, unaged binder. Then the remaining RAP binder is aged in the rolling thin film oven (RTFO) and is tested in the DSR and bending beam rheometer (BBR).

The following steps should be followed to determine the physical properties and critical temperatures of the RAP binder. These steps are illustrated in Figures 1 and 2.

1. The RAP binder should be recovered using the modified AASHTO TP2 method (described previously) with an appropriate solvent. At least 50 g of recovered RAP binder are needed for testing.
2. Perform binder classification testing using the tests in AASHTO MP1. Rotational viscosity, flash point, and mass-loss tests are not needed.
   2.1 Perform original DSR testing on the recovered RAP binder to determine the critical high temperature, $T_c(High)$, based on original DSR values where $G^*/\sin\delta = 1.00$ kPa. Calculate the critical high temperature as follows:
      2.1.1 Determine the slope of the stiffness-temperature curve as $\Delta \text{Log}(G^*/\sin\delta)/\Delta T$.
      2.1.2 Determine $T_c(High)$ to the nearest 0.1°C using the following equation:

$$T_c(High) = \left(\frac{\text{Log}(1.00) - \text{Log}(G_1)}{a}\right) + T_1$$

where

G_1 = the $G^*/\sin\delta$ value at a specific temperature, T_1; and
a = the slope of the stiffness–temperature curve described in 2.1.1.

Note: Although any temperature (T_1) and the corresponding stiffness (G_1) can be selected, it is advisable to use the $G^*/\sin\delta$ value closest to the criterion (1.00 kPa) to minimize extrapolation errors.

3. Perform RTFO aging on the remaining RAP binder.
4. Perform RTFO DSR testing on the RTFO-aged recovered RAP binder to determine the critical high temperature (based on RTFO DSR). Calculate the critical high temperature (based on RTFO DSR) as follows:
   4.1 Determine the slope of the stiffness-temperature curve as $\Delta \text{Log}(G^*/\sin\delta)/\Delta T$.
   4.2 Determine $T_c(High)$, based on RTFO DSR, to the nearest 0.1°C using the following equation:

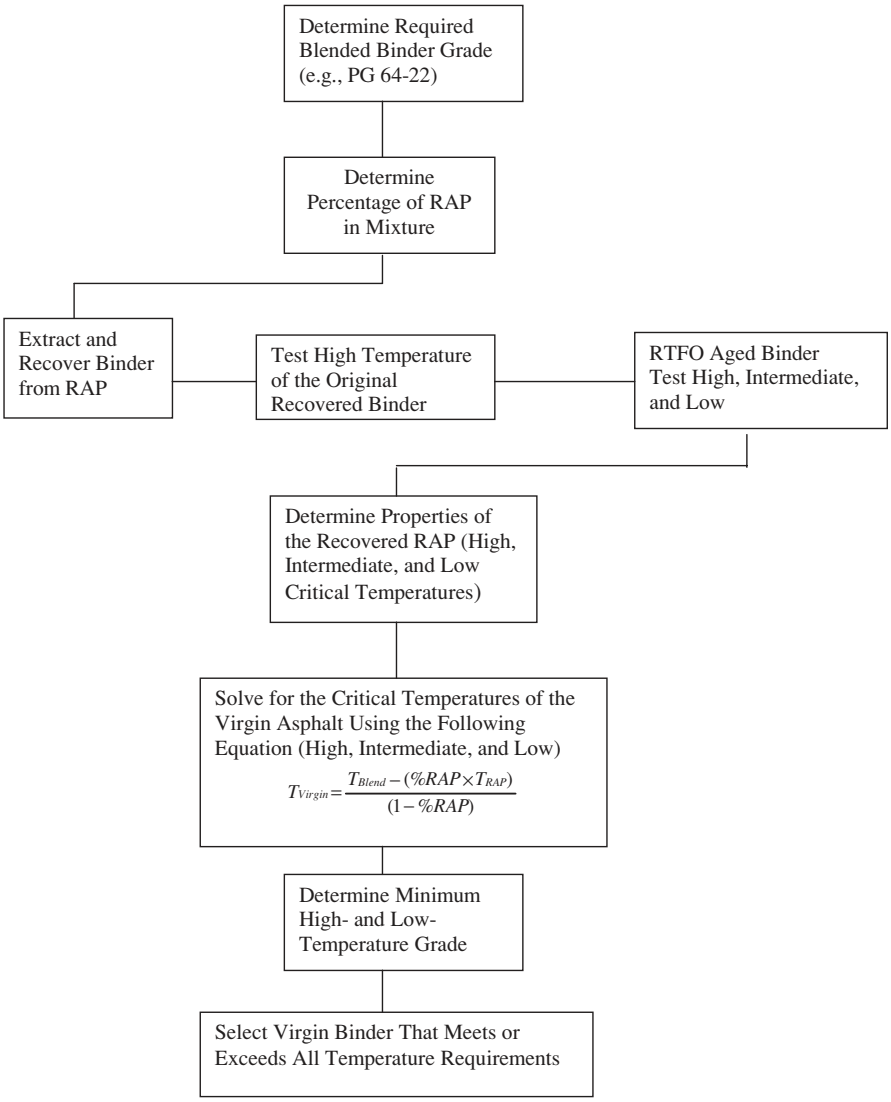

Figure 1. Method A: Blending at a known RAP content (virgin binder grade unknown).

$$T_c(High) = \left(\frac{\text{Log}(2.20) - \text{Log}(G_1)}{a}\right) + T_1$$

where

G_1 = the $G^*/\sin\delta$ value at a specific temperature, T_1; and
a = the slope of the stiffness–temperature curve described in 4.1.

Note: Although any temperature (T_1) and the corresponding stiffness (G_1) can be selected, it is advisable to use the $G^*/\sin\delta$ value closest to the criterion (2.20 kPa) to minimize extrapolation errors.

5. Determine the critical high temperature of the recovered RAP binder as the lower of the original DSR and RTFO DSR critical temperatures. Determine the high-temperature performance grade of the recovered RAP binder based on this single critical high temperature.
6. Perform intermediate temperature DSR testing on the RTFO-aged recovered RAP binder to determine the critical intermediate temperature, $T_c(Int)$, based on pressure aging vessel (PAV) DSR.
   6.1 Determine the slope of the stiffness-temperature curve as $\Delta\,\text{Log}(G^*\sin\delta)/\Delta T$.
   6.2 Determine $T_c(Int)$ to the nearest 0.1°C using the following equation:

$$T_c(Int) = \left(\frac{\text{Log}(5000) - \text{Log}(G_1)}{a}\right) + T_1$$

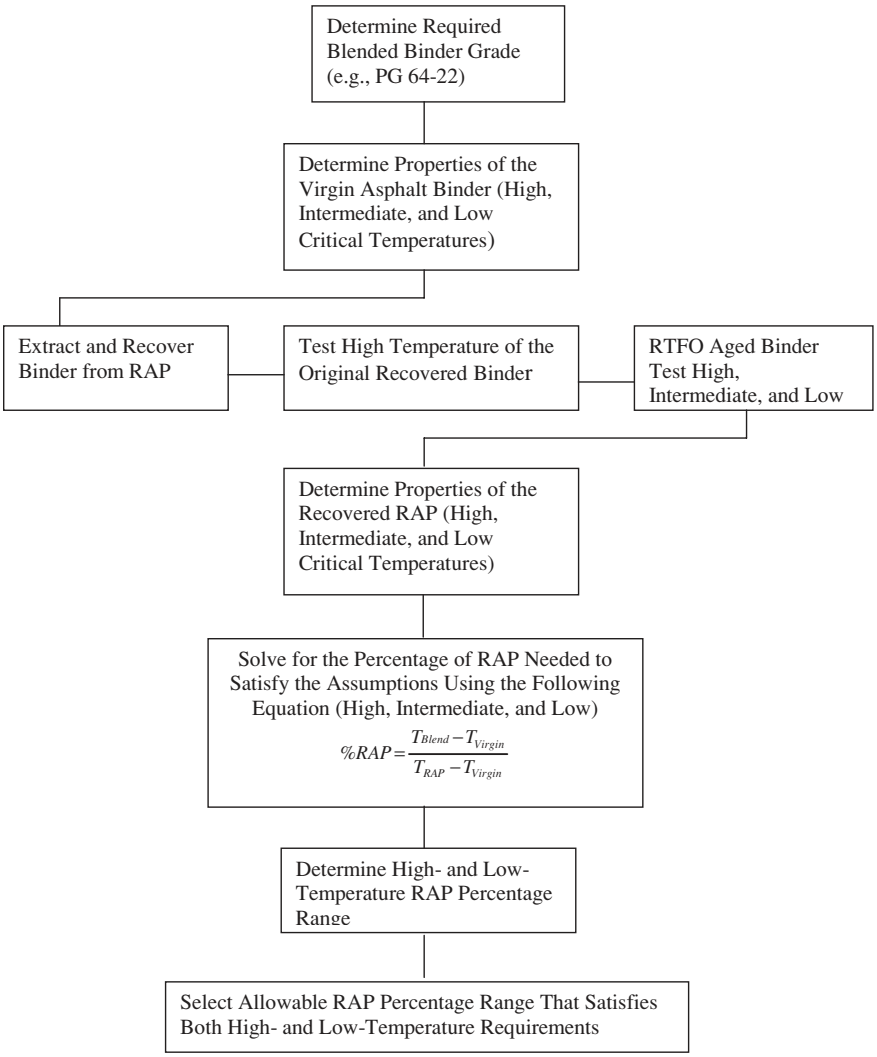

Figure 2. Method B: Blending a known virgin binder (RAP content unknown).

where

G_1 = the G^* sin δ value at a specific temperature, T_1; and
a = the slope of the stiffness–temperature curve described in 6.1.

Note: Although any temperature (T_1) and the corresponding stiffness (G_1) can be selected, it is advisable to use the G^* sin δ value closest to the criterion (5000 kPa) to minimize extrapolation errors.

7. Perform BBR testing on the RTFO-aged recovered RAP binder to determine the critical low temperature, $T_c(S)$ or $T_c(m)$, based on BBR stiffness or m-value.
   7.1 Determine the slope of the stiffness-temperature curve as $\Delta \text{Log}(S)/\Delta T$.
   7.2 Determine $T_c(S)$ to the nearest 0.1°C using the following equation:

$$T_c(S) = \left(\frac{\text{Log}(300) - \text{Log}(S_1)}{a}\right) + T_1$$

where

S_1 = the S-value at a specific temperature, T_1; and
a = the slope of the stiffness–temperature curve described in 7.1.

Note: Although any temperature (T_1) and the corresponding stiffness (S_1) can be selected, it is advisable to use the S-value closest to the criterion (300 MPa) to minimize extrapolation errors.

   7.3 Determine the slope of the m-value-temperature curve as Δm-value/ΔT.
   7.4 Determine $T_c(m)$ to the nearest 0.1°C using the following equation:

$$T_c(m) = \left(\frac{0.300 - m_1}{a}\right) + T_1$$

where

m_1 = the m-value at a specific temperature, T_1; and
a = the slope of the curve described in 7.3.

Note: Although any temperature (T_1) and the corresponding m-value (m_1) can be selected, it is advisable to use the m-value closest to the criterion (0.300) to minimize extrapolation errors.

7.5 Select the higher of the two low critical temperatures $T_c(S)$ and $T_c(m)$ to represent the low critical temperature for the recovered asphalt binder, $T_c(Low)$. Determine the low-temperature performance grade of the recovered RAP binder based on this single critical low temperature.

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

BINDER GRADE SELECTION

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

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

In some cases, you may know approximately how much RAP you would like to use in a mixture. For example, you may want to use all of the millings from a given project, or recycling may be most economical if a certain range of RAP contents is used. In other cases, the gradation or mix properties will limit the amount of RAP that can be used. There also may be specification limits that control how much RAP you can use. In these cases, you can choose a RAP content, then determine what binder grade you need to blend with the RAP to get a particular grade for the blend of old and new binder.

If the final blended binder grade, percentage of RAP, and recovered RAP properties are known, then the properties of an appropriate virgin asphalt binder grade can be determined. Consider the following example:

- The specifying agency requires a blended binder grade of PG 64-22 or better,
- The RAP percentage in the mixture is 30 percent, and
- The recovered RAP properties are as indicated in Table 2.

Using the following equation for the high, intermediate, and low critical temperatures separately, the properties of the virgin asphalt binder needed to satisfy the assumptions can be determined. (This general equation is a rearranged version of the earlier equations for critical temperatures.) These values are indicated in Table 3 and Figures 3 through 5.

$$T_{Virgin} = \frac{T_{Blend} - (\%\text{RAP} \times T_{RAP})}{(1 - \%\text{RAP})}$$

where

T_{Virgin} = critical temperature of the virgin asphalt binder;
T_{Blend} = critical temperature of the blended asphalt binder (final desired);
%RAP = percentage of RAP expressed as a decimal (i.e., 0.30 for 30 percent); and
T_{RAP} = critical temperature of recovered RAP binder.

As indicated in Table 3 and Figure 3, the minimum high-temperature grade of the virgin asphalt binder should be 54.3°C to satisfy the requirements of the blended grade (PG 64-22) using the RAP in Table 2 at 30 percent. This means that a PG 58-xx grade would be needed to ensure that the minimum required value of 54.3°C would be achieved.

Table 3 and Figure 5 indicate that the minimum low-temperature grade of the virgin asphalt binder should be –26.4°C (–16.4°C – 10°C factor in AASHTO MP1) to satisfy the

TABLE 2 Critical Temperatures of Recovered RAP Binder

Aging	Property	Critical Temperature, °C	
Original	DSR $G^*/\sin$	High	**86.6**
RTFO	DSR $G^*/\sin$	High	88.7
PAV*	DSR $G^*\sin$	Intermediate	**30.5**
	BBR S-value	Low	–4.5
	BBR m-value	Low	**–1.7**
	PG	Actual	PG 86-11
		MP1	PG 82-10

* Test RTFO-aged recovered RAP binder as if PAV-aged.

TABLE 3 Estimated Critical Temperatures of Virgin Asphalt Binder

Aging	Property	Critical Temperature, °C	
Original	DSR $G^*/\sin\delta$	High	**54.3**
RTFO	DSR $G^*/\sin\delta$	High	53.4
PAV	DSR $G^*\sin\delta$	Intermediate	**22.6**
	BBR S-value	Low	−15.2
	BBR m-value	Low	**−16.4**
	PG	Actual	PG 54-26
		MP1	PG 58-28

requirements of the blended grade (PG 64-22) using the RAP in Table 2 at 30 percent. This means that a PG xx-28 grade would be needed to ensure that the minimum required value of −26.4°C would be achieved.

From Table 3 and Figures 3 and 5, a PG 58-28 asphalt binder would be selected as the virgin asphalt binder for use in a mixture using 30 percent of the RAP described in Table 2.

To meet the intermediate temperature grade (G^* sin δ) in Figure 4, the virgin asphalt binder would need to have a critical intermediate temperature no higher than 22.6°C. Because the maximum critical intermediate temperature for a PG 58-28 binder is 19°C, the selected binder should easily meet all blended binder requirements.

It should be noted that the actual high-temperature grade required for the virgin asphalt binder is 54.3°C. It is possible that a PG 52-28 binder could be used, provided the actual high temperature was at least 54.3°C. However, material variability (e.g., RAP or virgin binder) and testing variability (e.g., Recovery and DSR testing) make this choice questionable.

DETERMINING RAP CONTENT

There may be cases in which you want to or have to use a particular virgin binder in a RAP mixture. The binder grade may be fixed based on economics and availability or on the specifications for a given project. In these cases, you need to determine how much RAP you can use with that specific virgin binder grade and still meet the final blended binder properties. The construction of a blending chart to determine the RAP content is described next.

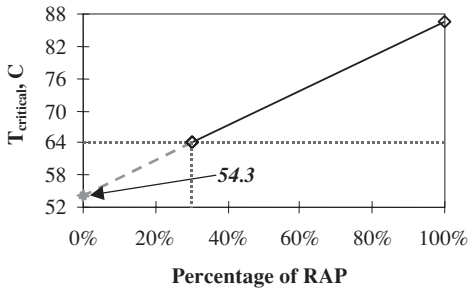

Figure 3. High-temperature blending chart (RAP percentage unknown).

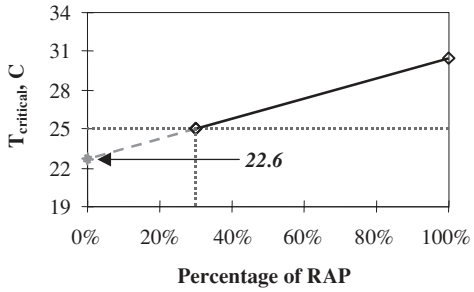

Figure 4. Intermediate-temperature blending chart (RAP percentage known).

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

If the final blended binder grade, virgin asphalt binder grade, and recovered RAP properties are known, then the appropriate amount of RAP to use can be determined. Consider the following example:

- The specifying agency requires a blended binder grade of PG 64-22 or better,
- The virgin binder grade is a PG 58-28 (critical temperatures in Table 4), and
- The recovered RAP is a PG 82-10 (critical temperatures in Table 4).

Using the following equation for the high, intermediate, and low critical temperatures separately, the percentage of RAP needed to satisfy the assumptions can be determined. These values are indicated in Table 5 and Figures 6 through 8. (Again, this equation is obtained by rearranging the earlier equations for critical temperatures.)

$$\%\text{RAP} = \frac{T_{Blend} - T_{Virgin}}{T_{RAP} - T_{Virgin}}$$

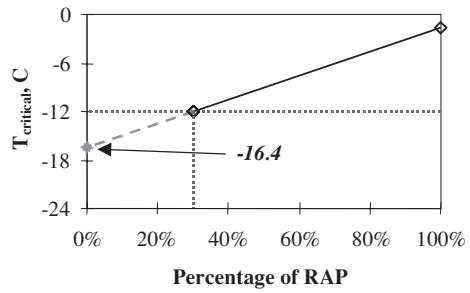

Figure 5. Low-temperature blending chart (RAP percentage known).

TABLE 4 Critical Temperatures of Virgin and Recovered RAP Binders

		Critical Temperature,˚C		
Aging	**Property**	**Temperature Range**	**Virgin Binder**	**RAP Binder**
Original	DSRG^*/sin	High	**60.5**	**86.6**
RTFO	DSRG^*/sin	High	61.0	88.7
PAV*	DSRG^*sin	Intermediate	**14.2**	**30.5**
	BBRS-value	Low	–22.2	–4.5
	BBRm-value	Low	**–19.0**	**–1.7**
	PG	Actual MP1	PG 60-29 PG 58-28	PG 86-11 PG 82-10

* Test RTFO-aged recovered RAP binder as if PAV-aged.

TABLE 5 Estimated Percentage of RAP to Achieve Final Blended Grade

			Percentage of RAP to Achieve	
Aging	**Property**	**Temperature**	**PG 64-22**	**PG 70-28**
Original	DSR G^*/sinδ	High	**13.4%**	**36.4%**
RTFO	DSR G^*/sinδ	High	10.8%	32.5%
PAV	DSR G^*sinδ	Intermediate	**66.3%**	—
	BBR S-value	Low	57.6%	23.7%
	BBR m-value	Low	**40.5%**	**5.8%**

where

T_{Virgin} = critical temperature of the virgin asphalt binder;
T_{Blend} = critical temperature of the blended asphalt binder (final desired);
%RAP = percentage of RAP expressed as a decimal (i.e., 0.30 for 30 percent); and
T_{RAP} = critical temperature of recovered RAP binder.

As indicated in Table 5 and Figure 6, a percentage of RAP between 14 percent and 36 percent should satisfy the high temperature requirements of the blended grade (PG 64-22) using the RAP and virgin asphalt binders in Table 4. Note that to achieve the minimum PG 64-xx grade, the percentage of RAP is rounded up. To achieve a maximum PG 64-xx grade (i.e., a PG 70-xx grade is not desired), the percentage of RAP is rounded down.

Table 5 and Figure 8 indicate that a RAP percentage between 6 percent and 40 percent should satisfy the low-temperature requirements of the blended grade (PG 64-22) using the RAP and virgin asphalt binders in Table 4. Note that to achieve the minimum PG xx-22 grade, the percentage of RAP is rounded down. To achieve a maximum PG xx-22 grade (i.e., a PG xx-28 grade is not desired), the percentage of RAP is rounded up.

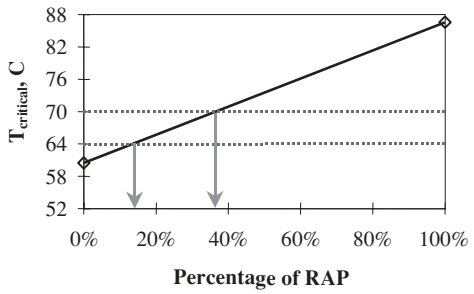

Figure 6. High-temperature blending chart (RAP percentage unknown).

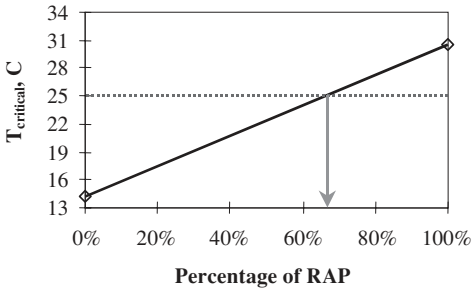

Figure 7. Intermediate-temperature blending chart (RAP percentage unknown).

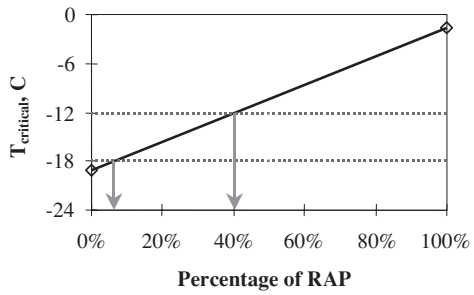

Figure 8. Low-temperature blending chart (RAP percentage unknown.)

From Table 5 and Figures 6 and 8, a RAP percentage between 14 percent and 36 percent would satisfy all the requirements of a blended PG 64-22 binder. If the maximum high-temperature grade were not a concern, the RAP percentage could be increased to 40 percent without changing the desired low-temperature grade of the blended asphalt binder.

To meet the intermediate-temperature grade (G^* sin δ) in Figure 7, the RAP percentage would need to be less than 66 percent.

CHAPTER 4

DEVELOPING THE MIX DESIGN

This chapter describes the step-by-step mix design process. An example of a mix design will be shown in Chapter 5.

One major decision that must be made early in the process is the approximate amount of RAP that you would like to try to use. This decision is made based on the prevailing state specifications, the aggregate gradation and properties, economics, and, sometimes, the binder properties. The amount of RAP to include in the new mixture may be limited by many different factors, including

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

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

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

Overall, however, the situation when using RAP in Superpave mixtures is similar to the situation when using RAP in Marshall or Hveem mixtures. The blend of materials has to meet certain properties, and the plant must be capable of drying and heating the materials. Many of the techniques used to evaluate the RAP are similar to previous techniques. Other techniques, particularly the binder evaluations described in Chapter 3, are quite different.

DETERMINING COMBINED AGGREGATE GRADATION

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

The Superpave mix design procedure recommends that at least three trial blends be evaluated. When RAP is used, these blends may include different percentages of RAP or may be different combinations of virgin stockpiles with a set percentage of RAP. The proposed aggregate blends must meet the gradation requirements as well as the consensus aggregate properties. In addition, the final blend selected must meet the required volumetric properties (i.e., VMA, VFA, dust proportion, and densification properties) at 4 percent air voids. An example of blending is included in the example mix design in Chapter 5.

Verifying Aggregate Properties

As mentioned above, the trial blends must meet the consensus aggregate properties. These properties vary for different traffic levels, but they always apply to the total combined aggregate blend. Coarse aggregate angularity, flat and elongated particle content, and sand equivalent content can be calculated as a weighted average based on individual stockpile data, if available. It is recommended, however, that fine

aggregate angularity actually be measured for the final blend. Because this property depends on how individual aggregate particles slide past each other, a simple weighted average may give erroneous results, especially if the bulk specific gravities of the different stockpiles vary.

HANDLING RAP IN THE LAB

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

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

MODIFICATIONS TO STANDARD MIX DESIGN PROCEDURES

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

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

With these exceptions, the procedure is basically the same with or without RAP, as detailed below.

RAP BATCHING

When batching out the RAP aggregates, it is important to remember that part of the weight of the RAP is binder. It is necessary to increase the weight of RAP and decrease the amount of new binder added to take the presence of this RAP binder into account.

Normally, the recommended practice for batching is to split each aggregate stockpile down into various size fractions then recombine them in the proper proportions. To do this, you take the total batch weight of aggregate times the stockpile percentage times the percent of material of each size range in that stockpile. Breaking each stockpile down into the various size fractions and recombining may seem like a lot of work, but doing so provides much better control of the gradation and ensures that each stockpile is properly represented in the final aggregate batch.

Batching a RAP mixture is, perhaps, best illustrated by an example. Let's say we are preparing a 5000-g batch of aggregate for a mix design. The trial blend includes 24 percent RAP, 16 percent coarse aggregate, 48 percent manufactured sand, and 12 percent natural sand. The gradations of each stockpile are shown in Table 6. The fine fraction of the RAP (–4.75 mm) has a binder content of 6.0 percent, and the coarse fraction (+4.75 mm) has a binder content of 4.0 percent.

When batching the RAP, the weight of the RAP will include both aggregate and binder. For a 5000-g aggregate batch weight, we would want 24 percent of 5000 g (1200 g) to be the RAP aggregate weight. The weight of dry RAP that would provide a given weight of RAP aggregate is

TABLE 6 Stockpile Gradations for Batching Problem

Sieve	RAP	Coarse Aggregate	Manufactured Sand	Natural Sand
Percentage in Trial Blend	24% (Agg)	16%	48%	12%
25.0 mm	100%	100%	100%	100%
19.0 mm	90%	98%	100%	100%
12.5 mm	75%	75%	100%	100%
9.5 mm	60%	35%	90%	100%
4.75 mm	50%	15%	70%	100%
2.38 mm	40%	5%	60%	90%
1.16 mm	35%	4%	40%	80%
0.600 mm	26%	3%	20%	70%
0.300 mm	17%	2%	15%	40%
0.150 mm	11%	1%	10%	27%
0.075 mm	8%	0.2%	4%	18%

$$M_{dryRAP} = \frac{M_{RAPAgg}}{(100 - P_b)} \times 100$$

where

M_{dryRAP} = mass of dry RAP,
M_{RAPAgg} = mass of RAP aggregate, and
P_b = RAP binder content.

This formula can be used to determine how much RAP to batch out.

If we split the RAP on the 4.75-mm sieve for the mix design, 50 percent of the RAP passes the 4.75-mm sieve, and 50 percent is retained. Therefore, we would want 50 percent of 1200 g (600 g) of fine RAP aggregate and 600 g of coarse RAP aggregate. To get those amounts, we would weight out

1. Fine RAP:

$$M_{dryRAP} = \frac{600 \text{ g}}{(100 - 6.0)} \times 100 = 638.3 \text{ g}$$

2. Coarse RAP:

$$M_{dryRAP} = \frac{600 \text{ g}}{(100 - 4.0)} \times 100 = 625.0 \text{ g}$$

The fine RAP would contain 38.3 g of binder (638.3 g of RAP – 600.0 g of RAP aggregate), and the coarse RAP would contain 25.0 g of binder (625.0 g – 600.0 g). The total weight of RAP binder would be 38.3 g + 25.0 g = 63.3 g. The total batch weight would be the weight of aggregate plus the weight of RAP binder: 5000 g aggregate + 63.3 g binder = 5063.3 g of RAP.

The rest of the materials would be batched as usual. The preferred method is illustrated in Table 7.

STEP-BY-STEP MIX DESIGN PROCEDURE

The following steps are required when doing a Superpave mix design with RAP. This is based on the recommended steps in a Superpave mix design (*3*). The steps outlined here are based on the 1999 AASHTO specifications, which require compacting specimens to N_{design} (design number of gyrations) rather than to N_{max} (maximum number of gyrations). Only for the final mix design is N_{max} verified. Please note that not all states have adopted these revisions yet.

I. Selection of Materials

A. Evaluate RAP, Determine RAP Properties
   1. Extract RAP and determine binder content (P_b). Follow the extraction process described in Chapter 3 if you anticipate testing the RAP binder properties.
   2. Determine RAP aggregate gradation. The RAP may be split into two fractions on, for example, the 4.75-mm (No. 4) sieve and analyzed as two separate fractions.
   3. Determine RAP consensus properties if desired (recommended but optional at this point). Properties include coarse aggregate angularity, fine aggregate angularity, and flat and elongated particles.

TABLE 7 Batching Weights

Fraction (mm)	Weight, g	Cumulative Batch Weight, g
Coarse Aggregate	Total amount in batch: 16% (5000 g) = 800 g	
25.0 – 12.5	25% (800) = 200	200 g
12.5 – 9.5	40% (800) = 320	520
9.5 – 4.75	20% (800) = 160	680
4.75 – 2.36	10% (800) = 80	760
–2.36	5% (800) = 40	800
Manufactured Sand	Total amount in batch: 48% (5000 g) = 2400 g	
25.0 – 9.5	10% (2400) = 240	1040
9.5 – 4.75	20% (2400) = 480	1520
4.75 – 2.36	10% (2400) = 240	1760
–2.36	60% (2400) = 1440	3200
Natural Sand	Total amount in batch: 12% (5000 g) = 600 g	
4.75 – 2.36	10% (600) = 60	3260
–2.36	90% (600) = 540	3800
RAP		
Fine (–4.75)	638.3 g RAP*	4438.3
Coarse (+4.75)	625.0 g RAP*	5063.3

* Includes weight of RAP binder. RAP aggregate weight is 600 g fine and 600 g coarse, as determined previously.

4. Estimate desired RAP content and test RAP binder properties as outlined in Chapter 3, if required (see Table 1).
5. Measure maximum theoretical specific gravity (G_{mm}) of the RAP according to AASHTO T209.
6. Estimate RAP aggregate specific gravity using the effective specific gravity (G_{se}) or calculate the bulk specific gravity (G_{mb}) based on assumed asphalt absorption. (See Appendix A of *NCHRP Web Document 30*.)

B. Select Virgin Asphalt Binder
1. Determine project weather conditions using weather database.
2. Select reliability.
3. Determine design temperatures.
4. Verify asphalt binder grade.
5. If required based on desired RAP content and Table 1, decrease high- and low-temperature grade of virgin binder by one increment or develop blending charts as described in Chapter 3.
6. Determine temperature–viscosity relationship for lab mixing and compaction based on virgin binder grade.

Note: Steps B-1 through B-3 may be done by the specifying agency, and desired binder grade may be specified in the contract documents.

C. Selection of Virgin Aggregates
1. Measure consensus properties—recommended, but optional.
   a. Combined gradation,
   b. Coarse aggregate angularity,
   c. Fine aggregate angularity,
   d. Flat and elongated particles, and
   e. Clay content.
2. Determine source properties by measuring specific gravities and other source properties as required by the specifying agency.

II. Selection of Design Aggregate Structure

A. Establish Trial Blends
1. Select trial percentage(s) RAP aggregate.
2. Develop three blends (minimum).
3. Evaluate combined aggregate consensus and source properties. The combined aggregate bulk and apparent specific gravities will be based on the RAP aggregate specific gravity estimated in Step I-A-6 above.

B. Compact Trial Blend Specimens
1. Establish trial asphalt binder content.
   a. Superpave method, or
   b. Engineering judgment method.
   c. Decrease amount of binder added to account for RAP binder content.
2. Establish trial blend specimen size as usual.
3. Determine $N_{initial}$ (initial number of gyrations), N_{design}, and N_{max} based on design traffic level.
4. Batch trial blend specimens. When batching the RAP aggregate, it is important to remember that part of the RAP weight is binder. Decrease the weight of new binder added by the weight of RAP binder.
5. Compact specimens and generate densification tables as usual.
6. Determine mixture properties (G_{mm} and G_{mb}) as usual.

C. Evaluate Trial Blends
1. Determine $\%G_{mm}$ @ $N_{initial}$ and N_{design} as usual.
2. Determine % Air Voids and % VMA. The VMA calculation will be based on the G_{sb} as determined in Step II-A-3 above.
3. Estimate asphalt binder content to achieve 4 percent air voids.
4. Estimate mix properties at estimated asphalt binder content as usual.
5. Determine dust-to-asphalt ratio as usual.
6. Compare mixture properties to criteria as usual.

D. Select most promising design aggregate structure for further analysis.

III. Selection of Design Asphalt Binder Content

A. Compact Design Aggregate Structure Specimens at Multiple Binder Contents.
1. Batch design aggregate structure specimens, keeping in mind that part of the RAP weight is binder. Reduce the amount of new binder added by the weight of the binder provided by the RAP.
2. Compact specimens and generate densification tables as usual.

B. Determine Mixture Properties versus Asphalt Binder Content as Usual.
1. Determine $\%G_{mm}$ @ $N_{initial}$ and N_{design}.
2. Determine volumetric properties.
3. Determine dust-to-asphalt ratio.
4. Graph mixture properties versus asphalt binder content.

C. Select Design Asphalt Binder Content.
1. Determine asphalt binder content at 4 percent air voids.
2. Determine mixture properties at selected asphalt binder contents.
3. Compare mixture properties to criteria.

IV. Verify Mix Design as Usual

A. Evaluate moisture sensitivity using AASHTO T283.
B. Verify that $\%G_{mm}$ @ N_{max} is less than 98 percent.

(Appendix B of *NCHRP Web Document 30* includes a checklist showing the basic information needed to do a mix design with RAP. Appendix C, also in *NCHRP Web Document 30*, contains suggestions for how to increase the VMA, if none of your trial mix designs meets the VMA requirements.)

CHAPTER **5**

MIX DESIGN EXAMPLE

You are asked to design a 25.0-mm mixture for use on an interstate. The design traffic volume is 15 million equivalent single axle loads (ESALs). The mixture will be within the top 100 mm of the pavement structure. The required final binder grade is a PG 70-22. Experience with local materials indicates that the RAP binder would likely grade as a PG 82-16.

SELECTION OF MATERIALS

One source of RAP is available. It is separated into fine and coarse fractions by splitting on a 4.75-mm sieve. Each fraction is then analyzed for binder content and gradation.

- RAP Asphalt Content (P_{sb} = salvaged binder content) determined by extraction or ignition:

  +4.75 mm = 4.50 percent

  –4.75 mm = 6.10 percent

Determine Stockpile Gradations

Four aggregate stockpiles are available. The gradations of each stockpile and the fine and coarse RAPs are determined by sieve analysis and are shown in Table 8.

Determine Stockpile Properties

The consensus properties and specific gravity are determined for each stockpile. Results are shown in Table 9. These values are so good that the trial blends should all easily meet the specifications. Therefore, consensus properties will only be checked on final mix design.

Estimate RAP Specific Gravity

To estimate RAP specific gravity, either use effective specific gravity (G_{se}) or assume P_{ba} and calculate G_{sb}.

- Coarse RAP:

$$G_{mm\,(RAP)} = 2.545 \qquad G_{b\,(RAP)} \cong 1.020$$
$$P_{b\,(RAP)} = 4.50 \text{ percent}$$

$$G_{se} = \frac{100 - P_b}{\frac{100}{G_{mm}} - \frac{P_b}{G_b}} = \frac{100 - 4.50}{\frac{100}{2.545} - \frac{4.50}{1.020}} = 2.738$$

$$G_{sb} = \frac{G_{se}}{\left(\frac{P_{ba} G_{se}}{100 G_b} + 1\right)} = \frac{2.738}{\left(\frac{1.5 \times 2.738}{100 \times 1.020} + 1\right)} = 2.632$$

where

G_{mm} = theoretical maximum specific gravity;
$G_{b(RAP)}$ = specific gravity of RAP binder;
$P_{b(RAP)}$ = the RAP binder content;
G_{se} = effective specific gravity of aggregate;
G_{sb} = bulk specific gravity of aggregate; and
P_{ba} = absorbed binder, percent by weight of aggregate.

Estimate $P_{ba} \cong 1.5$ percent *based on familiarity with local aggregates*.

- Fine RAP:

$$G_{mm(RAP)} = 2.481 \qquad G_{b(RAP)} \cong 1.020$$
$$P_{b\,(RAP)} = 6.10 \text{ percent}$$

$$G_{se} = \frac{100 - P_b}{\frac{100}{G_{mm}} - \frac{P_b}{G_b}} = \frac{100 - 6.10}{\frac{100}{2.481} - \frac{6.10}{1.020}} = 2.736$$

Estimate $P_{ba} \cong 1.5$ percent *based on familiarity with local aggregates*.

$$G_{sb} = \frac{G_{se}}{\left(\frac{P_{ba} G_{se}}{100 G_b} + 1\right)} = \frac{2.736}{\left(\frac{1.5 \times 2.736}{100 \times 1.020} + 1\right)} = 2.630$$

The estimated G_{sb} values for the coarse and fine RAP fractions are also shown in Table 9.

TABLE 8 RAP and Aggregate Stockpile Gradations

Sieve Size mm (No.)	RAP +4.75	RAP –4.75	Coarse Aggregate	Intermed. Aggregate	Chips	Crusher Fines
25.0 mm (1 in.)	100.0	100.0	97.5	100.0	100.0	100.0
19.0 mm (3/4 in.)	99.9	100.0	73.2	100.0	100.0	100.0
12.5 mm (1/2 in.)	92.9	99.9	24.6	76.2	100.0	100.0
9.5 mm (3/8 in.)	78.4	99.2	3.5	15.4	91.5	100.0
4.75 mm (No. 4)	42.8	79.3	1.6	1.6	13.9	90.5
2.36 mm (No. 8)	27.1	54.2	1.5	1.3	3.3	51.1
1.18 mm (No. 16)	20.0	38.7	1.4	1.2	2.6	28.2
0.600 mm (No. 30)	16.5	28.8	1.3	1.2	2.3	15.1
0.300 mm (No. 50)	12.8	22.2	1.2	1.1	2.1	8.2
0.150 mm (No. 100)	10.0	17.3	1.2	1.1	2.0	4.7
0.075 mm (No. 200)	8.1	12.2	1.1	1.0	1.9	3.5

TABLE 9 Properties of RAP and Aggregate Stockpiles

Stockpile	RAP + 4.75	RAP –4.75	Coarse Aggregate	Intermed. Aggregate	Chips	Crusher Fines
Coarse aggregate angularity	94%		94%	94%	93%	
Fine aggregate angularity		47%				48%
Flat and elongated	0.0%		3.6%	4.5%	5.7%	
Sand equivalent value		—				85%
LA abrasion*			16%			
G_{sb}	*Below*	*Below*	2.645	2.647	2.652	2.612
G_{sa}			2.730	2.735	2.745	2.748

* State highway agency–required source property.

Select Desired RAP Content

In selecting desired RAP content, use about 25 percent RAP in the mix.

Select Virgin Binder Grade

At this RAP content and with a RAP binder grade of about 82-16, this mixture will fall in the second tier. No binder testing is required. Because the desired final grade is a PG 70-22, a PG 64-28, which is one grade lower on the high- and low-temperature grades, will be used.

SELECTION OF DESIGN AGGREGATE STRUCTURE

Establish Trial Blends

Determine trial blend percentages (a minimum of three) based on RAP and aggregate stockpile gradations. Trial blend proportions are shown in Table 10. The resulting blend gradations are listed in Table 11 and are shown graphically in Figures 9 through 13.

Estimate Trial Binder Content (Total)

Select the total trial binder content based on experience or Superpave method. We will use the Superpave method. The data and assumed values needed to use the Superpave method to estimate the trial binder content are shown in Table 12. The resulting trial blend properties, shown in Table 13, are determined based on information in Table 12 and the on following equations:

$$G_{se} = G_{sb} + \text{Absorption Factor } x\,(G_{sa} - G_{sb})$$

$$V_{ba} = \frac{P_s \times (1 - V_{a)}}{\left(\dfrac{P_b}{G_b} + \dfrac{P_s}{G_{se}}\right)} \times \left(\frac{1}{G_{sb}} - \frac{1}{G_{se}}\right)$$

TABLE 10 Stockpile Percentages for Trial Blends

Blend	RAP (+4.75)	RAP (–4.75)	Coarse Aggregate	Intermed. Aggregate	Chips	Crusher Fines	Total %
#1	12.0	13.0	22.0	13.0	25.0	15.0	100
#2	12.0	13.0	17.0	15.0	21.0	22.0	100
#3	12.0	13.0	12.0	12.0	25.0	26.0	100
#4	12.0	13.0	15.0	10.0	20.0	30.0	100
#5	12.0	13.0	10.0	10.0	15.0	40.0	100

TABLE 11 Trial Blend Gradations

Sieve Size mm (No.)	Blend #1	Blend #2	Blend #3	Blend #4	Blend #5
25.0 mm (1 in.)	99.5	99.6	99.7	99.6	99.8
19.0 mm (3/4 in.)	94.1	95.4	96.8	96.0	97.3
12.5 mm (1/2 in.)	79.5	82.7	87.2	85.4	89.2
9.5 mm (3/8 in.)	63.0	66.4	73.4	72.7	77.9
4.75 mm (No. 4)	33.1	38.8	42.8	45.8	54.1
2.36 mm (No. 8)	19.3	22.7	24.7	26.6	31.5
1.18 mm (No. 16)	12.8	14.6	15.7	16.7	19.4
0.600 mm (No. 30)	9.0	9.9	10.5	11.0	12.4
0.300 mm (No. 50)	6.6	7.0	7.4	7.6	8.2
0.150 mm (No. 100)	5.1	5.3	5.4	5.5	5.9
0.075 mm (No. 200)	3.9	4.1	4.2	4.3	4.5
Bulk specific gravity	2.638	2.636	2.635	2.633	2.629
Apparent specific gravity	2.750	2.750	2.751	2.751	2.752

NOTE: Some of these gradations violate the restricted zone, but this is permitted in state specifications.

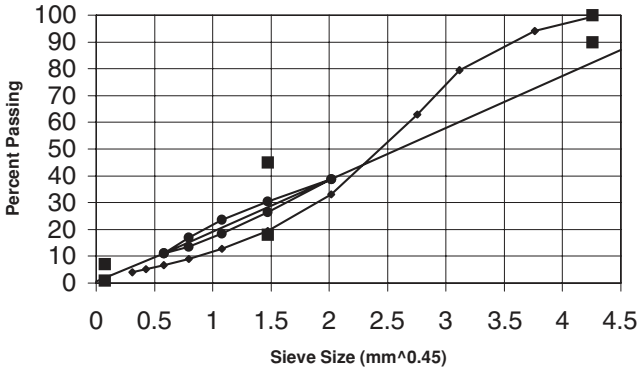

Figure 9. Gradation of trial blend #1.

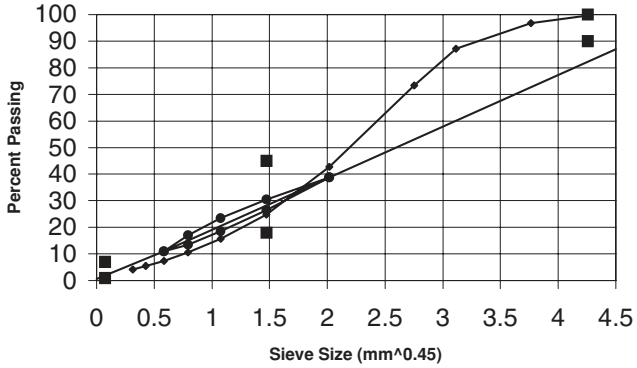

Figure 11. Gradation of trial blend #3.

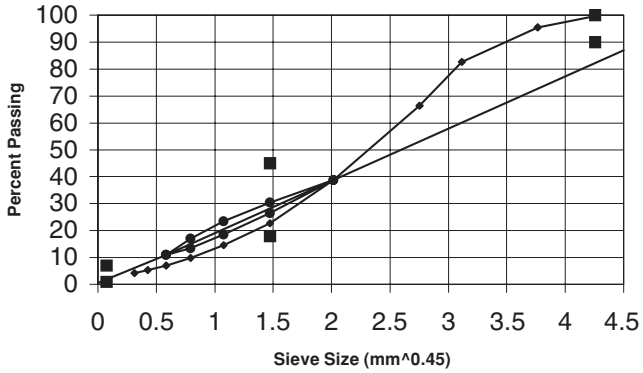

Figure 10. Gradation of trial blend #2.

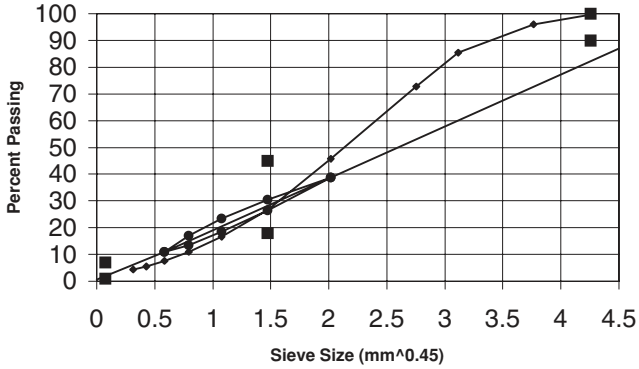

Figure 12. Gradation of trial blend #4.

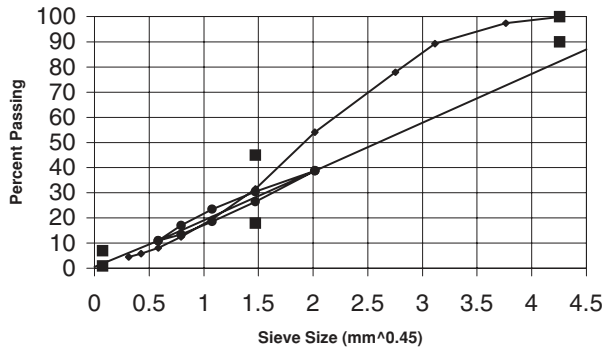

Figure 13. Gradation of trial blend #5.

$$V_{be} = 0.081 - 0.02931\ (\ln S_n)$$

$$W_s = \frac{P_s \times (1 - V_a)}{\left(\frac{P_b}{G_b} + \frac{P_s}{G_{se}}\right)}$$

$$P_{bi} = \left[\frac{G_b(V_{be} + V_{ba)}}{(G_b \times (V_{be} + V_{ba})) + W_s}\right] \times 100\%$$

where

G_{se} = effective specific gravity of the combined aggregate;
G_{sb} = bulk specific gravity of the combined aggregate;
G_{sa} = apparent specific gravity of the combined aggregate;
V_{ba} = volume of absorbed binder;
P_s = aggregate content;
V_a = volume of air voids;
P_b = binder content;
G_b = binder specific gravity;
V_{be} = volume of effective binder;
S_n = nominal maximum sieve size of the largest aggregate in the aggregate trial blend;
W_s = mass of the aggregate; and
P_{bi} = estimated initial trial binder content, percent by weight of total mix.

Calculate Batch Weights

Batch weights are then calculated for both the gyratory specimens and the maximum theoretical specific gravity samples. Typically, gyratory specimens need about 4600 to 4700 g of material to provide the proper specimen height. This weight can be adjusted based on experience with local materials or trial batches. In this case, an aggregate batch weight of 4650 g is assumed. Determination of the maximum theoretical specific gravity requires a sample size of about 2000 g.

TABLE 12 Data and Assumed Values Used to Calculate Trial Blend Properties

Absorption Factor (0.8 typical)	0.8
Assumed Total Binder Content (P_b)	4.0%
Assumed Percent Aggregate ($P_s = 100 - P_b$)	96.0%
Design Air Voids, V_a	4.0%
Binder Specific Gravity (G_b)	1.020
Nominal Maximum Aggregate Size, mm (S_n)	25.0 mm

The aggregate batching sheets are developed based on the individual stockpile percentages in each trial blend, the gradations of each stockpile, and the required batch weights for the samples. The aggregate batching sheets are shown in Tables 14 through 18 for the gyratory samples and Tables 19 through 23 for the maximum theoretical specific gravity samples. The mixture batching sheets showing the calculations for the amount of binder to add are shown in Table 24 for the gyratory samples and in Table 25 for the maximum theoretical specific gravity samples.

Mix and Compact Trial Blend Specimens

Two specimens of each blend should be prepared for compaction and two for the maximum theoretical specific gravity test. Gyratory samples are prepared and compacted in the gyratory. Maximum theoretical specific gravity samples are prepared, but not compacted because that test is run on loose mix. Mixture properties are analyzed as usual to determine which blend is preferred.

Compactive Effort

For the design traffic volume (15 million ESALs), the gyration levels are $N_{initial} = 8$; $N_{design} = 100$; and $N_{max} = 160$.

TABLE 13 Calculated Trial Blend Properties

Blend	#1	#2	#3	#4	#5
Combined G_{se}	2.727	2.727	2.728	2.728	2.728
Volume of Absorbed Binder (V_{ba})	0.0291	0.0300	0.0306	0.0310	0.0323
Volume of Effective Binder (V_{be})	0.082	0.082	0.082	0.082	0.082
Mass of Aggregate (W_s), g	2.356	2.356	2.356	2.356	2.356
Initial Trial Binder Content (P_{bi})	4.50	4.54	4.56	4.58	4.63

TABLE 14 Aggregate Batching Sheet—Trial Blend #1, Gyratory Samples

Sieve Size (mm)	Coarse Agg.	Cumu-lative	Interm. Agg.	Cumu-lative	Chips Agg.	Cumu-lative	+ #4 RAP	Cumu-lative	– #4 RAP	Cumu -lative	Crush Fines	Cumu-lative	Com-bined
25.000	25.6	25.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	25.6
19.000	274.2	0.0	0.0	0.0	0.0	0.6	0.6	0.0	0.0	0.0	0.0	0.0	249.2
12.500	497.2	771.4	143.9	143.9	0.0	0.0	39.1	39.7	0.6	0.6	0.0	0.0	660.8
9.500	215.9	987.3	367.5	511.4	98.8	98.8	80.9	120.6	4.2	4.8	0.0	0.0	767.3
4.750	19.4	1006.7	83.4	594.8	902.1	1000.9	198.6	319.2	120.3	125.1	66.3	66.3	1390.1
2.360	1.0	1007.7	1.8	596.6	123.2	1124.1	87.6	406.8	151.7	276.8	274.8	341.1	640.1
1.160	1.0	1008.7	0.6	597.2	8.1	1132.2	39.6	446.4	93.7	370.5	159.7	500.8	302.7
0.600	1.0	1009.7	0.0	597.2	3.5	1135.7	19.5	465.9	59.8	430.3	91.4	592.2	175.2
0.300	1.0	1010.7	0.6	597.8	2.3	1138.0	20.6	486.5	39.9	470.2	48.1	640.3	112.5
0.150	0.0	1010.7	0.0	597.8	1.2	1139.2	15.6	502.1	29.6	499.8	24.4	664.7	70.8
0.075	1.0	1011.7	0.6	598.4	1.2	1140.4	10.6	512.7	30.8	530.6	8.4	673.1	52.6
PAN	11.3	1023.0	6.1	604.5	22.1	1162.5	45.3	558.0	73.9	604.5	24.4	697.5	183.1
	1023		604.5		1162.5		558		604.5		697.5		183.1
RAP *								584.3		643.8			

* Actual weight of RAP to add to provide proper weight of RAP aggregate.

TABLE 15 Aggregate Batching Sheet—Trial Blend #2, Gyratory Samples

Sieve Size (mm)	Coarse Agg.	Cumu-lative	Interm. Agg.	Cumu-lative	Chips Agg.	Cumu-lative	+ #4 RAP	Cumu-lative	– #4 RAP	Cumu-lative	Crush Fines	Cumu-lative	Com-bined
25.000	19.8	19.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	19.8
19.000	192.1	211.9	0.0	0.0	0.0	0.0	0.6	0.6	0.0	0.0	0.0	0.0	192.7
12.500	384.2	596.1	166.0	166.0	0.0	0.0	39.1	39.7	0.6	0.6	0.0	0.0	589.9
9.500	166.8	762.9	424.1	590.1	83.0	83.0	80.9	120.6	4.2	4.8	0.0	0.0	759.0
4.750	15.0	777.9	96.3	686.4	757.8	840.8	198.6	319.2	120.3	125.1	97.2	97.2	1285.2
2.360	0.8	778.7	2.1	688.5	103.5	944.3	87.6	406.8	151.7	276.8	403.1	500.3	748.8
1.160	0.8	779.5	0.7	689.2	6.8	951.1	39.6	446.4	93.7	370.5	234.3	734.6	375.9
0.600	0.8	780.3	0.0	689.2	2.9	954.0	19.5	465.9	59.8	430.3	134.0	868.6	217.0
0.300	0.8	781.1	0.7	689.9	2.0	956.0	20.6	486.5	39.9	470.2	70.6	939.2	134.6
0.150	0.0	781.1	0.0	689.9	1.0	957.0	15.6	502.1	29.6	499.8	34.8	975.0	82.0
0.075	0.8	781.9	0.7	690.6	1.0	958.0	10.6	512.7	30.8	530.6	12.3	987.3	56.2
PAN	8.6	790.5	6.9	697.5	18.5	976.5	45.3	558.0	73.9	604.5	35.7	1023.0	188.9
	790.5		697.5		976.5		558		604.5		1023		4650.0
RAP *								584.3		643.8			

* Actual weight of RAP to add to provide proper weight of RAP aggregate.

TABLE 16 Aggregate Batching Sheet—Trial Blend #3, Gyratory Samples

Sieve Size (mm)	Coarse Agg.	Cumu-lative	Interm. Agg.	Cumu-lative	Chips Agg.	Cumu-lative	+ #4 RAP	Cumu -lative	– #4 RAP	Cumu-lative	Crush Fines	Cumu -lative	Com-bined
25.000	14.0	14.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	14.0
19.000	135.6	149.6	0.0	0.0	0.0	0.0	0.6	0.6	0.0	0.0	0.0	0.0	136.2
12.500	271.2	420.8	132.8	132.8	0.0	0.0	39.1	39.7	0.6	0.6	0.0	0.0	443.7
9.500	117.7	538.5	339.3	472.1	98.8	98.8	80.9	120.6	4.2	4.8	0.0	0.0	640.9
4.750	10.6	549.1	77.0	549.1	902.1	1000.9	198.6	319.2	120.3	125.1	114.9	114.9	1423.5
2.360	0.6	549.7	1.7	550.8	123.2	1124.1	87.6	406.8	151.7	276.8	476.3	591.2	841.1
1.160	0.6	550.3	0.6	551.4	8.1	1132.2	39.6	446.4	93.7	370.5	276.9	868.1	419.5
0.600	0.6	550.9	0.0	551.4	3.5	1135.7	19.5	465.9	59.8	430.3	158.4	1026.5	241.8
0.300	0.6	551.5	0.6	552.0	2.3	1138.0	20.6	486.5	39.9	470.2	83.4	1109.9	147.4
0.150	0.0	551.5	0.0	552.0	1.2	1139.2	15.6	502.1	29.6	499.8	42.3	1152.2	88.7
0.075	0.6	552.1	0.6	552.6	1.2	1140.4	10.6	512.7	30.8	530.6	14.5	1166.7	58.3
PAN	5.9	558.0	5.4	558.0	22.1	1162.5	45.3	558.0	73.9	604.5	42.3	1209.0	194.9
	558		558		1162.5		558		604.5		1209		4650.0
RAP *								584.3		643.8			

* Actual weight of RAP to add to provide proper weight of RAP aggregate.

TABLE 17 Aggregate Batching Sheet—Trial Blend #4, Gyratory Samples

Sieve Size (mm)	Coarse Agg.	Cumu-lative	Interm. Agg.	Cumu -lative	Chips Agg.	Cumu -lative	+ #4 RAP	Cumu -lative	– #4 RAP	Cumu-lative	Crush Fines	Cumu -lative	Com-bined
25.000	17.4	17.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	17.4
19.000	169.5	186.9	0.0	0.0	0.0	0.0	0.6	0.6	0.0	0.0	0.0	0.0	170.1
12.500	339.0	525.9	110.7	110.7	0.0	0.0	39.1	39.7	0.6	0.6	0.0	0.0	489.4
9.500	147.2	673.1	282.7	393.4	79.1	79.1	80.9	120.6	4.2	4.8	0.0	0.0	594.1
4.750	13.3	686.4	64.2	457.6	721.7	800.8	198.6	319.2	120.3	125.1	132.5	132.5	1250.6
2.360	0.7	687.1	1.4	459.0	98.6	899.4	87.6	406.8	151.7	276.8	549.6	682.1	889.6
1.160	0.7	687.8	0.5	459.5	6.5	905.9	39.6	446.4	93.7	370.5	319.5	1001.6	460.5
0.600	0.7	688.5	0.0	459.5	2.8	908.7	19.5	465.9	59.8	430.3	182.7	1184.3	265.5
0.300	0.7	689.2	0.5	460.0	1.9	910.6	20.6	486.5	39.9	470.2	96.3	1280.6	159.9
0.150	0.0	689.2	0.0	460.0	0.9	911.5	15.6	502.1	29.6	499.8	48.8	1329.4	94.9
0.075	0.7	689.9	0.5	460.5	0.9	912.4	10.6	512.7	30.8	530.6	16.7	1346.1	60.2
PAN	7.6	697.5	4.5	465.0	17.6	930.0	45.3	558.0	73.9	604.5	48.9	1395.0	197.8
	697.5		465		930		558		604.5		1395		4650.0
RAP *								584.3		643.8			

* Actual weight of RAP to add to provide proper weight of RAP aggregate.

TABLE 18 Aggregate Batching Sheet—Trial Blend #5, Gyratory Samples

Sieve Size (mm)	Coarse Agg.	Cumu-lative	Interm. Agg.	Cumu -lative	Chips Agg.	Cumu-lative	+ #4 RAP	Cumu -lative	– #4 RAP	Cumu -lative	Crush Fines	Cumu -lative	Com-bined
25.000	11.6	11.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	11.6
19.000	113.0	124.6	0.0	0.0	0.0	0.0	0.6	0.6	0.0	0.0	0.0	0.0	113.6
12.500	226.0	350.6	110.7	110.7	0.0	0.0	39.1	39.7	0.6	0.6	0.0	0.0	376.4
9.500	98.1	448.7	282.7	393.4	59.3	59.3	80.9	120.6	4.2	4.8	0.0	0.0	525.2
4.750	8.8	457.5	64.2	457.6	541.3	600.6	198.6	319.2	120.3	125.1	176.7	176.7	1109.9
2.360	0.5	458.0	1.4	459.0	73.9	674.5	87.6	406.8	151.7	276.8	732.8	909.5	1047.9
1.160	0.5	458.5	0.5	459.5	4.9	679.4	39.6	446.4	93.7	370.5	425.9	1335.4	565.1
0.600	0.5	459.0	0.0	459.5	2.1	681.5	19.5	465.9	59.8	430.3	243.7	1579.1	325.6
0.300	0.5	459.5	0.5	460.0	1.4	682.9	20.6	486.5	39.9	470.2	128.3	1707.4	191.2
0.150	0.0	459.5	0.0	460.0	0.7	683.6	15.6	502.1	29.6	499.8	65.1	1772.5	111.0
0.075	0.5	460.0	0.5	460.5	0.7	684.3	10.6	512.7	30.8	530.6	22.3	1794.8	65.4
PAN	5.0	465.0	4.5	465.0	13.2	697.5	45.3	558.0	73.9	604.5	65.2	1860.0	207.1
	465		465		67.5		558		604.5		1860		4650.0
RAP *								584.3		643.8			

* Actual weight of RAP to add to provide proper weight of RAP aggregate.

TABLE 19 Aggregate Batching Sheet—Trial Blend #1, Maximum Theoretical Specific Gravity Samples

Sieve Size (mm)	Coarse Agg.	Cumu-lative	Interm. Agg.	Cumu-lative	Chips Agg.	Cumu-lative	+ #4 RAP	Cumu-lative	– #4 RAP	Cumu-lative	Crush Fines	Cumu-lative	Com-bined
25.000	11.0	11.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	11.0
19.000	106.9	117.9	0.0	0.0	0.0	0.0	0.2	0.2	0.0	0.0	0.0	0.0	107.1
12.500	213.8	331.7	61.9	61.9	0.0	0.0	16.8	17.0	0.3	0.3	0.0	0.0	292.8
9.500	92.8	424.5	158.1	220.0	42.5	42.5	34.8	51.8	1.8	2.1	0.0	0.0	330.0
4.750	8.4	432.9	35.9	255.9	388.0	430.5	85.4	137.2	51.7	53.8	28.5	28.5	597.9
2.360	0.4	433.3	0.8	256.7	53.0	483.5	37.7	174.9	65.3	119.1	118.2	146.7	275.4
1.160	0.4	433.7	0.3	257.0	3.5	487.0	17.0	191.9	40.3	159.4	68.7	215.4	130.2
0.600	0.4	434.1	0.0	257.0	1.5	488.5	8.4	200.3	25.7	185.1	39.3	254.7	75.3
0.300	0.4	434.5	0.3	257.3	1.0	489.5	8.9	209.2	17.2	202.3	20.7	275.4	48.5
0.150	0.0	434.5	0.0	257.3	0.5	490.0	6.7	215.9	12.7	215.0	10.5	285.9	30.4
0.075	0.4	434.9	0.3	257.6	0.5	490.5	4.6	220.5	13.3	228.3	3.6	289.5	22.7
PAN	5.1	440.0	2.4	260.0	9.5	500.0	19.5	240.0	31.7	260.0	10.5	300.0	78.7
	440		260		500		240		260		300		2000.0
RAP *								251.3		276.9			

* Actual weight of RAP to add to provide proper weight of RAP aggregate.

TABLE 20 Aggregate Batching Sheet—Trial Blend #2, Maximum Theoretical Specific Gravity Samples

Sieve Size (mm)	Coarse Agg.	Cumulative	Interm. Agg.	Cumulative	Chips Agg.	Cumulative	+ #4 RAP	Cumulative	– #4 RAP	Cumulative	Crush Fines	Cumulative	Combined
25.000	8.5	8.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8.5
19.000	82.6	91.1	0.0	0.0	0.0	0.0	0.2	0.2	0.0	0.0	0.0	0.0	82.8
12.500	165.2	256.3	71.4	71.4	0.0	0.0	16.8	17.0	0.3	0.3	0.0	0.0	253.7
9.500	71.7	328.0	182.4	253.8	35.7	35.7	34.8	51.8	1.8	2.1	0.0	0.0	326.4
4.750	6.5	334.5	41.4	295.2	325.9	361.6	85.4	137.2	51.7	53.8	41.8	41.8	552.7
2.360	0.3	334.8	0.9	296.1	44.5	406.1	37.7	174.9	65.3	119.1	173.4	215.2	322.1
1.160	0.3	335.1	0.3	296.4	2.9	409.0	17.0	191.9	40.3	159.4	100.8	316.0	161.6
0.600	0.3	335.4	0.0	296.4	1.3	410.3	8.4	200.3	25.7	185.1	57.6	373.6	93.3
0.300	0.3	335.7	0.3	296.7	0.8	411.1	8.9	209.2	17.2	202.3	30.4	404.0	57.9
0.150	0.0	335.7	0.0	296.7	0.4	411.5	6.7	215.9	12.7	215.0	15.4	419.4	35.2
0.075	0.3	336.0	0.3	297.0	0.4	411.9	4.6	220.5	13.3	228.3	5.3	424.7	24.2
PAN	4.0	340.0	3.0	300.0	8.1	420.0	19.5	240.0	31.7	260.0	15.3	440.0	81.6
	340		300		420		240		260		440		2000.0
RAP *								251.3		276.9			

* Actual weight of RAP to add to provide proper weight of RAP aggregate.

TABLE 21 Aggregate Batching Sheet—Trial Blend #3, Maximum Theoretical Specific Gravity Samples

Sieve Size (mm)	Coarse Agg.	Cumulative	Interm. Agg.	Cumulative	Chips Agg.	Cumulative	+ #4 RAP	Cumulative	– #4 RAP	Cumulative	Crush Fines	Cumulative	Combined
25.000	6.0	6.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.0
19.000	58.3	64.3	0.0	0.0	0.0	0.0	0.2	0.2	0.0	0.0	0.0	0.0	58.5
12.500	116.6	180.9	57.1	57.1	0.0	0.0	16.8	17.0	0.3	0.3	0.0	0.0	190.8
9.500	50.6	231.5	145.9	203.0	42.5	42.5	34.8	51.8	1.8	2.1	0.0	0.0	275.6
4.750	4.6	236.1	33.1	236.1	388.0	388.0	85.4	137.2	51.7	53.8	49.4	49.4	612.2
2.360	0.2	236.3	0.7	236.8	53.0	53.0	37.7	174.9	65.3	119.1	204.9	254.3	361.8
1.160	0.2	236.5	0.2	237.0	3.5	3.5	17.0	191.9	40.3	159.4	119.1	373.4	180.3
0.600	0.2	236.7	0.0	237.0	1.5	1.5	8.4	200.3	25.7	185.1	68.1	441.5	103.9
0.300	0.2	236.9	0.2	237.2	1.0	1.0	8.9	209.2	17.2	202.3	35.9	477.4	63.4
0.150	0.0	236.9	0.0	237.2	0.5	0.5	6.7	215.9	12.7	215.0	18.2	495.6	38.1
0.075	0.2	237.1	0.2	237.4	0.5	0.5	4.6	220.5	13.3	228.3	6.2	501.8	25.0
PAN	2.9	240.0	2.6	240.0	9.5	9.5	19.5	240.0	31.7	260.0	18.2	520.0	84.4
	240		240		500		240		260		520		2000.0
RAP *								251.3		276.9			

* Actual weight of RAP to add to provide proper weight of RAP aggregate.

TABLE 22 Aggregate Batching Sheet—Trial Blend #4, Maximum Theoretical Specific Gravity Samples

Sieve Size (mm)	Coarse Agg.	Cumulative	Interm. Agg.	Cumulative	Chips Agg.	Cumulative	+ #4 RAP	Cumulative	– #4 RAP	Cumulative	Crush Fines	Cumulative	Combined
25.000	7.5	7.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.5
19.000	72.9	80.4	0.0	0.0	0.0	0.0	0.2	0.2	0.0	0.0	0.0	0.0	73.1
12.500	145.8	226.2	47.6	47.6	0.0	0.0	16.8	17.0	0.3	0.3	0.0	0.0	210.5
9.500	63.3	289.5	121.6	169.2	34.0	34.0	34.8	518.8	1.8	2.1	0.0	0.0	255.5
4.750	5.7	295.2	27.6	196.8	310.4	344.4	85.4	137.2	51.7	53.8	57.0	57.0	537.8
2.360	0.3	295.5	0.6	197.4	42.4	386.8	37.7	174.9	65.3	119.1	236.4	293.4	382.7
1.160	0.3	295.8	0.2	197.6	2.8	389.6	17.0	191.9	40.3	159.4	137.4	430.8	198.0
0.600	0.3	296.1	0.0	197.6	1.2	390.8	8.4	200.3	25.7	185.1	78.6	509.4	114.2
0.300	0.3	296.4	0.2	197.8	0.8	391.6	8.9	209.2	17.2	202.3	41.4	550.8	68.8
0.150	0.0	296.4	0.0	197.8	0.4	392.0	6.7	215.9	12.7	215.0	21.0	571.8	40.8
0.075	0.36	296.7	0.2	198.0	0.4	392.4	4.6	220.5	13.3	228.3	7.2	579.0	26.0
PAN	3.3	300.0	2.0	200.0	7.6	400.0	19.5	240.0	31.7	260.0	21.0	600.0	85.1
	300		200		400		240		260		600		2000.0
RAP *								251.3		276.9			

* Actual weight of RAP to add to provide proper weight of RAP aggregate.

TABLE 23 Aggregate Batching Sheet—Trial Blend #5, Maximum Theoretical Specific Gravity Samples

Sieve Size (mm)	Coarse Agg.	Cumulative	Interm. Agg.	Cumulative	Chips Agg.	Cumulative	+ #4 RAP	Cumulative	– #4 RAP	Cumulative	Crush Fines	Cumulative	Combined
25.000	5.0	5.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.0
19.000	48.6	53.6	0.0	0.0	0.0	0.0	0.2	0.2	0.0	0.0	0.0	0.0	48.8
12.500	97.2	150.8	47.6	47.6	0.0	0.0	16.8	17.0	0.3	0.3	0.0	0.0	161.9
9.500	42.2	193.0	121.6	169.2	25.5	25.5	34.8	51.8	1.8	2.1	0.0	0.0	225.9
4.750	3.8	196.8	27.6	196.8	232.8	258.3	85.4	137.2	51.7	53.8	76.0	76.0	477.3
2.360	0.2	197.0	0.6	197.4	31.8	290.1	37.7	174.9	65.3	119.1	315.2	391.2	450.8
1.160	0.2	197.2	0.2	197.6	2.1	292.2	17.0	191.9	40.3	159.4	183.2	574.4	243.0
0.600	0.2	197.4	0.0	197.6	0.9	293.1	8.4	200.3	25.7	185.1	104.8	679.2	140.0
0.300	0.2	197.6	0.2	197.8	0.6	293.7	8.9	209.2	17.2	202.3	55.2	734.4	82.3
0.150	0.0	197.6	0.0	197.8	0.3	294.0	6.7	15.9	12.7	215.0	28.0	762.4	47.7
0.075	0.25	197.8	0.2	198.0	0.3	294.3	4.6	220.5	13.3	228.3	9.6	772.0	28.2
PAN	2.2	200.0	2.0	200.0	5.7	300.0	19.5	240.0	31.7	260.0	28.0	800.0	89.1
	200		200		300		240		260		800		2000.0
RAP *								251.3		276.9			

* Actual weight of RAP to add to provide proper weight of RAP aggregate.

TABLE 24 Mixture Batching Weights for Gyratory Samples

Material	Blend #1	Blend #2	Blend #3	Blend #4	Blend #5
RAP added	1229.2	1225.1	1225.4	1224.9	1225.7
Virgin aggregate added	3531.8	3531.7	3533.5	3528.7	3526.3
Target AC content	4.50	4.54	4.56	4.58	4.63
AC from RAP	65.5	65.3	65.3	65.3	65.4
Aggregate from RAP	1163.7	1159.8	1160.1	1159.6	1160.3
Total aggregate	4695.5	4691.5	4693.6	4688.3	4686.6
Total AC needed	221.3	223.1	224.3	225.0	227.5
Virgin AC to add	155.7	157.8	158.9	159.7	162.2

TABLE 25 Mixture Batching Weights for Maximum Theoretical Specific Gravity Samples

Material	Blend #1	Blend #2	Blend #3	Blend #4	Blend #5
RAP added	526.9	528.1	527.8	526.9	526.9
Virgin aggregate added	1516.7	1521.1	1518.9	1518.2	1520.9
Target AC content	4.50	4.54	4.56	4.58	4.63
AC from RAP	28.1	28.2	28.1	28.1	28.1
Aggregate from RAP	498.8	499.9	499.7	498.8	498.8
Total aggregate	2015.5	2021.0	2018.6	2017.0	2019.7
Total AC needed	95.0	96.1	96.4	96.8	98.1
Virgin AC to add	66.9	68.0	68.3	68.7	70.0

TABLE 26 Trial Blend Densification Data

Blend	Trial AC%	Est. AC%	$\%G_{mm}$ at $N_{initial}$	$\%G_{mm}$ at N_{design}	Est. VMA	Est. VFA	Eff. AC (P_{be})	Dust Proportion
#1	4.53	5.81	84.9	97.6	16.0	73.7	4.76	0.8
#2	4.54	5.42	84.9	97.8	15.3	71.6	4.35	0.9
#3	4.56	4.84	84.8	97.5	14.2	69.1	3.74	1.1
#4	4.58	4.54	84.8	97.4	13.4	66.9	3.42	1.2
#5	4.63	4.63	85.4	97.4	13.5	67.4	3.46	1.3
Specs			< 89	< 98	> 12	65–75		0.6–1.2

Table 26 summarizes the average densification data for each trial blend shown in the previous figures. Two replicates of each trial blend were made, compacted, and bulked. The results are also shown in Figures 14 through 18.

Evaluate Trial Blends

Now the trial binder content is adjusted to force the air voids to be 4.0 percent. The other mixture properties are estimated at this new binder content, as usual. The revised mixture volumetric properties are shown in Table 27.

Inspection of Table 27 shows Blend #5 has too high a dust proportion. All the other blends are acceptable. Blend #4 is selected as the design aggregate structure because it has the lowest binder content and is therefore the most economical.

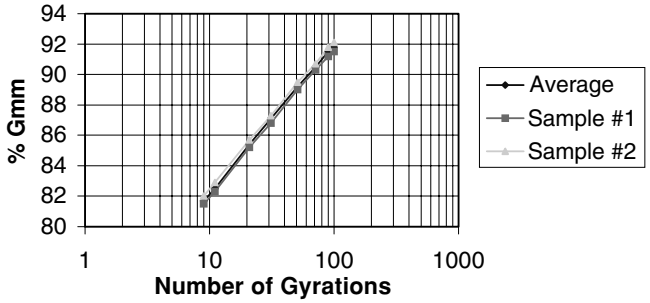

Figure 14. Densification of trial blend #1.

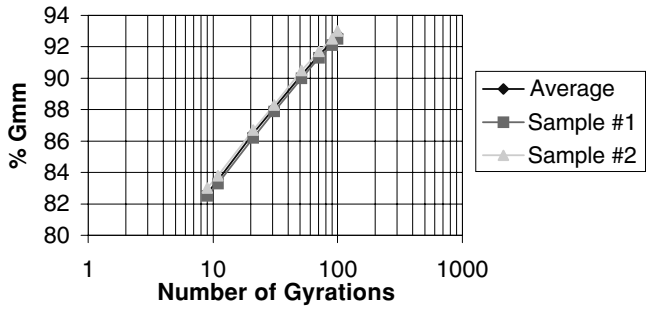

Figure 15. Densification of trial blend #2.

SELECTION OF DESIGN BINDER CONTENT

Compact Design Aggregate Structure Specimens at Various Binder Contents

Now samples of Trial Blend #4 are made at various binder contents (4.0, 4.5, 5.0, and 5.5 percent binder) to determine the optimum asphalt content, as usual. The aggregate batching

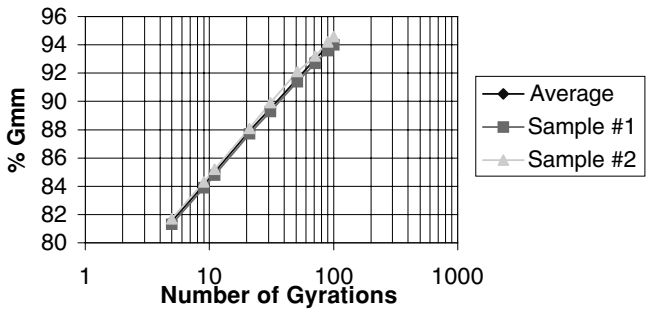

Figure 16. Densification of trial blend #3.

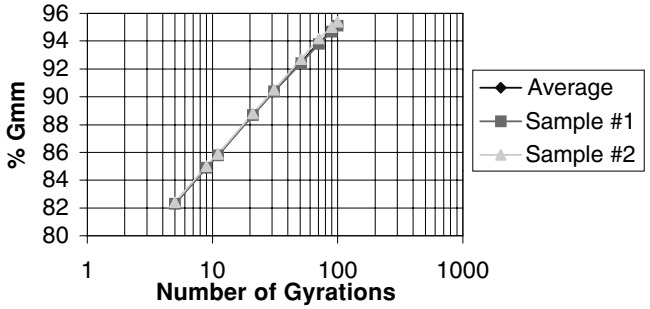

Figure 17. Densification of trial blend #4.

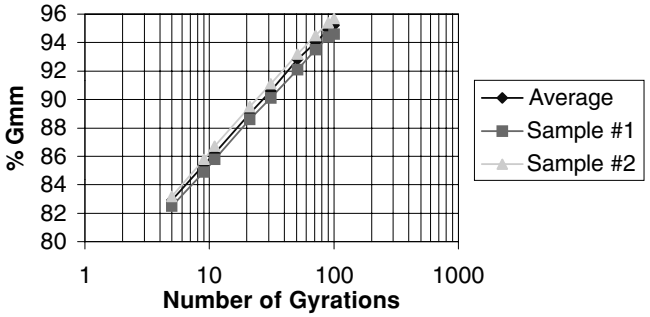

Figure 18. Densification of trial blend #5.

TABLE 27 Comparison of Trial Blends

Blend	Trial AC%	$\%G_{mm}$ at $N_{initial}$	$\%G_{mm}$ at N_{design}	% Air Voids	VMA at N_{design}
#1	4.53	81.7	92.8	7.2	15.2
#2	4.54	82.7	93.8	6.2	14.1
#3	4.56	84.1	95.3	4.7	13.0
#4	4.58	84.9	96.1	3.9	12.1
#5	4.63	85.4	96.0	4.0	12.3

TABLE 28 Aggregate Batching Sheet—Design Aggregate Structure, Gyratory Samples

Blend %	15		10	20		12		13		30			
Sieve Size mm	*Coarse Agg.*	*Cumulative*	*Chips Agg.*	*Cumulative*	*Chips Agg.*	*Cumulative*	*+ #4 RAP*	*Cumulative*	*– #4 RAP*	*Cumulative*	*Crush Fines*	*Cumulative*	*Combined*
25.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
19.000	167.7	167.7	0.0	0.0	0.0	0.0	0.6	0.6	0.0	0.0	0.0	0.0	168.3
12.500	335.3	503.0	109.5	109.5	0.0	0.0	38.6	39.2	0.6	0.6	0.0	0.0	484.0
9.500	145.6	648.6	279.7	389.2	78.2	78.2	80.0	119.2	4.2	4.8	0.0	0.0	587.7
4.750	13.1	661.7	63.5	452.7	713.9	792.1	196.5	315.7	119.0	123.8	131.1	131.1	1237.1
2.360	0.7	662.4	1.4	454.1	97.5	889.6	86.7	402.4	150.1	273.9	543.7	674.8	880.1
1.160	0.7	663.1	0.5	454.6	6.4	896.0	39.2	441.6	92.7	366.6	316.0	990.8	455.5
0.600	0.7	663.8	0.0	454.6	2.8	898.8	19.3	460.9	59.2	425.8	180.8	1171.6	262.8
0.300	0.7	664.5	0.5	455.1	1.8	900.6	20.4	481.3	39.5	465.3	95.2	1266.8	158.1
0.150	0.0	664.5	0.0	455.1	0.9	901.5	15.5	496.8	29.3	494.6	48.3	1315.1	94.0
0.075	0.7	665.2	0.5	455.6	0.9	902.4	10.5	507.3	30.5	525.1	16.6	1331.7	59.7
PAN	24.8	690.0	4.4	460.0	17.6	920.0	44.7	552.0	72.9	598.0	48.3	1380.0	212.7
	690.0		460.0		920.0		552.0		598.0		1380.0		4600.0
RAP *							578.0		636.8				

* Actual weight of RAP added to provide proper weight of RAP aggregate.

TABLE 29 Mixture Batching Weights—Design Aggregate Structure, Gyratory Samples

Material	4.0% Binder	4.5% Binder	5.0% Binder	5.5% Binder
RAP added	1224.5	1224.1	1226.6	1228.5
Virgin aggregate added	3486.5	3496.9	3495.0	3485.7
Target AC content	4.00	4.50	5.00	5.50
AC from RAP	65.3	65.3	65.4	65.5
Aggregate from RAP	1159.2	1158.8	1161.2	1163.0
Total aggregate	4645.7	4655.7	4656.2	4648.7
Total AC needed	193.6	219.4	245.1	4648.7
Virgin AC to add	128.3	154.1	179.7	205.1

TABLE 30 Mixture Batching Weights—Design Aggregate Structure, Maximum Theoretical Specific Gravity Samples

Material	4.0% Binder	4.5% Binder	5.0% Binder	5.5% Binder
RAP added	527.4	527.3	527.7	527.7
Virgin aggregate added	1515.8	1527.6	1518.1	1520.0
Target AC content	4.00	4.50	5.00	5.50
AC from rap	28.1	28.1	28.1	28.1
Aggregate from rap	499.3	499.2	499.6	499.6
Total aggregate	2015.1	2026.8	2017.7	499.6
Total AC needed	84.0	95.5	106.2	2019.6
Virgin AC to add	55.8	67.4	78.1	89.4

TABLE 31 Comparison of Design Aggregate Structure at Various Binder Contents

Binder Content	$\%G_{mm}$ at $N_{initial}$	$\%G_{mm}$ at N_{design}	% Air Voids	VMA, %	VFA, %	Dust Proportion
4.0%	83.1	93.9	6.1	14.1	56.7	1.2
4.5%	84.8	95.8	4.2	13.8	69.5	1.0
5.0%	85.7	97.0	3.0	13.4	77.6	0.9
5.5%	86.2	97.62.4	2.4	14.1	82.9	0.8
Specs	< 89	< 98	4	> 12	65–75	0.6–1.2

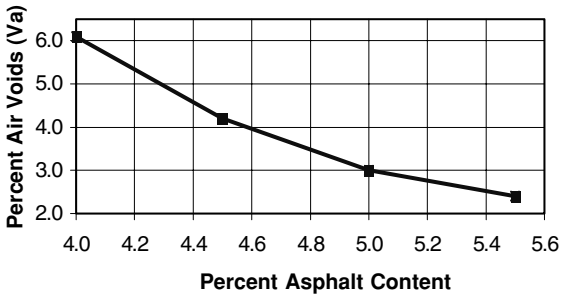

Figure 19. Air voids versus binder content.

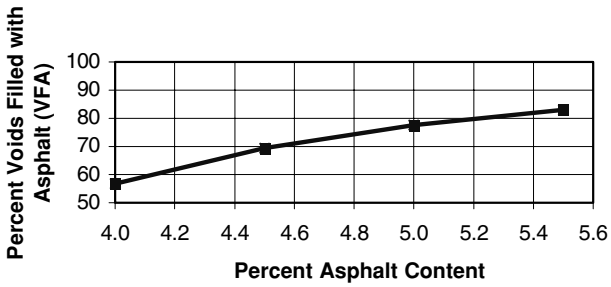

Figure 21. VFA versus binder content.

weights to provide a 4600-g sample are shown in Table 28. The mixture batching weights for four different binder contents are shown in Table 29 for the gyratory samples and Table 30 for the maximum theoretical specific gravity samples. Two replicate specimens should be compacted at each binder content.

The average densification data for each of the four binder contents is shown in Table 31. Graphs of the mixture volumetric properties versus binder content are shown in Figures 19 through 21. Inspection of Table 31 and Figures 19 through 21 shows that all the mixture properties are met at 4.5 percent binder, which is then selected as the design binder content.

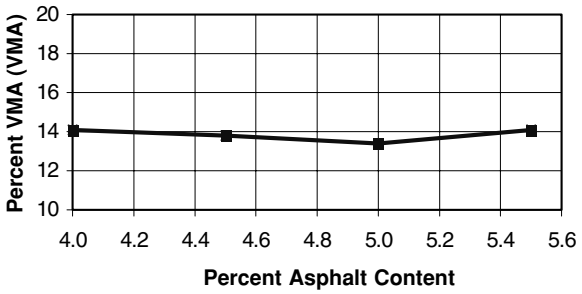

Figure 20. VMA versus binder content.

VERIFY MIX DESIGN

The final mixture design is checked to ensure that it is not susceptible to moisture damage and that it still has at least 2 percent air voids present after compacting to N_{max}.

- AASHTO T283: The tensile strength ratio, as determined by AASHTO T283, is 83.6 percent, which exceeds the required minimum value of 80 percent.
- Compaction to N_{max}: When two samples of the final mix design are compacted to N_{max}, the $\%G_{mm}$ at N_{max} is found to be 97.1 percent, which is less than the upper limit of 98 percent.

Trial Blend #4 with a binder content of 4.5 percent is found to be an acceptable mix design. This trial blend contains 25 percent RAP.

CHAPTER 6

FIELD QUALITY-CONTROL TESTING

FIELD TESTING OF RAP MIXTURES

This chapter discusses field testing of RAP mixtures. In most states, bituminous mixtures containing RAP are sampled and tested in the same way as virgin mixtures are sampled and tested. If there are any problems with the RAP, such as excessive moisture or variability, it is assumed that these problems will show up in the final mixture and be detected by the usual quality-assurance testing. Some additional testing of the RAP may be required by the state at the mix design stage or during construction. These requirements vary widely from state to state because they are based on each state's own experience and materials; therefore, it is important to know your state's requirements.

For example, you may be required to sample and test the RAP based on how much RAP is used—say, one sample for every 1000 Mg of RAP used. Typical tests that must be run include binder content, gradation, and moisture content tests. Consensus aggregate properties, such as coarse aggregate angularity, may also be required. Some states will waive this testing if the RAP stockpile is thoroughly tested prior to mix production.

Typical mixture acceptance tests include binder content, moisture content, gradation, voids, and VMA tests. These tests usually do not vary if RAP is included in the mixture. One exception to this rule is gradation. Some states allow the testing of belt samples or cold or hot bin samples for the aggregate gradation; with RAP mixtures, those states may choose to require the use of extracted gradations of the RAP aggregate.

ADDITIONAL QUALITY-CONTROL PROCEDURES WITH RAP MIXTURES

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

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

Good production quality-control practices may require extra testing to ensure that the RAP has not changed enough to throw the mixture properties out of compliance with the specification targets. Certainly, if problems begin to occur with the mixture properties, the RAP is one of the potential sources of the problem and should be checked.

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

The frequency of testing the RAP stockpile for quality-control purposes may vary, depending on many factors. A minimum frequency of testing is recommended, based either on the amount of RAP used (e.g., 1 test per 1000 Mg used) or on days of production (e.g., 1 test per day). Additional testing can then be performed if you suspect the RAP stockpile may be changing (e.g., you are getting into a wetter part of the pile); if problems begin to develop in the mixture properties; or for other reasons.

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

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7. Nady, R.M. "The Quality of Random RAP: Separating Fact from Supposition," *Hot-Mix Asphalt Technology*. National Asphalt Pavement Association: Lanham, MD (1997).

8. *Recycling Hot Mix Asphalt Pavements*. Information Series 123, National Asphalt Pavement Association: Lanham, MD (1996).

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GLOSSARY

BBR: bending beam rheometer.

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

DSR: dynamic shear rheometer.

ESALs: equivalent single axle loads.

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

$G^*/\sin\delta$: the viscous component of the binder shear stiffness, as measured by AASHTO TP5 and used as a specification parameter in AASHTO MP1.

G_1: the $G^*/\sin\delta$ value at a specific temperature (T_1).

G_b: specific gravity of binder.

G_{mb}: bulk specific gravity of compacted mix.

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

G_{sa}: apparent specific gravity of total aggregate.

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

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

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

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

m_1: the m-value measured at a specific temperature (T_1).

Maximum aggregate size: one size larger than the nominal maximum aggregate size; this terminology and definition apply only to Superpave mix design.

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

N_{design}: in Superpave mix design, the design number of gyrations.

$N_{initial}$: in Superpave mix design, the initial number of gyrations.

N_{max}: in Superpave mix design, maximum number of gyrations.

Dust-to-binder ratio ($P_{0.075}/P_{be}$): by mass, the ratio between the percent passing the 0.075-mm (No. 200) sieve ($P_{0.075}$) and effective binder content (P_{be}).

PAV: pressure aging vessel as described in AASHTO PP1.

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

%RAP: percentage of RAP expressed as a decimal.

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

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

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

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

RTFO: rolling thin film oven.

***S*:** the creep stiffness measured by AASHTO TP1 and used as a specification parameter in AASHTO MP1.

***S_1*:** the value of the creep stiffness, *S*, at a specific temperature (T_1).

***S_n*:** nominal maximum sieve size of the largest aggregate in the aggregate trial blend; this terminology and definition apply only to Superpave mix design.

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

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

***T_c*(*High*):** critical high temperature.

***T_c*(*Int*):** critical intermediate temperature.

***T_c*(*Low*):** critical low temperature.

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

***V_{be}*:** effective asphalt volume; the volume of asphalt binder that is not absorbed into the aggregate.

VMA: voids in the mineral aggregate.

APPENDIX A
EQUATIONS FOR RAP SPECIFIC GRAVITY

Because the bulk specific gravity (G_{sb}) of the RAP aggregate cannot be measured directly, it is necessary to estimate it. There are two approaches that can be used to do this.

SUBSTITUTING G_{se}

In the past, some states have used the effective specific gravity (G_{se}) of the RAP aggregate instead of its bulk specific gravity. The effective specific gravity can be calculated from the RAP mixture maximum specific gravity, which can easily be determined by conducting AASHTO T209. The asphalt content of the RAP is determined by extraction or ignition; the binder specific gravity is assumed. The effective specific gravity is then calculated as

$$G_{se} = \frac{100 - P_b}{\frac{10}{G_{mm}} - \frac{P_b}{G_b}}$$

where

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

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

BACKCALCULATING G_{sb}

An alternative approach used by some states is to assume a value for the absorption of the RAP aggregate. On the basis of past experience with the same virgin aggregates, some states can estimate this value quite accurately. If the asphalt absorption can be estimated and G_{se} is determined as shown above, the G_{sb} of the RAP aggregate can be estimated by rearranging the equation for absorption and solving for G_{sb} as follows. Asphalt absorption is determined using

$$P_{ba} = 100 \times \frac{G_{se} - G_{sb}}{G_{sb}G_{se}} \times G_b$$

where

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

Rearranging this equation to solve for G_{sb} gives

$$G_{sb} = \frac{G_{se}}{\left(\frac{P_{ba}G_{se}}{100 \times G_b}\right) + 1}$$

When this equation is solved for G_{sb} for the RAP aggregate, that value can then be used to estimate the combined aggregate bulk specific gravity using the following equation:

$$G_{sb} = \frac{P_1 + P_2 + \cdots + P_N}{\frac{P_1}{G_1} + \frac{P_1}{G_2} + \cdots + \frac{P_N}{G_N}}$$

where

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

APPENDIX B
INFORMATION NEEDED FOR RAP MIX DESIGN

RAP ASPHALT CONTENT

Determine RAP asphalt content (P_{sb} = salvaged binder) from extraction or ignition.

+4.75 mm _____

–4.75 mm _____

GRADATIONS

Determine gradations of RAP and each aggregate stockpile.

Sieve Size mm (No.)	RAP +4.75	RAP -4.75				
25.0 mm (1 in.)						
19.0 mm (3/4 in.)						
12.5 mm (1/2 in.)						
9.5 mm (3/8 in.)						
4.75 mm (No. 4)						
2.36 mm (No. 8)						
1.18 mm (No. 16)						
0.600 mm (No. 30)						
0.300 mm (No. 50)						
0.150 mm (No. 100)						
0.075 mm (No. 200)						

STOCKPILE PROPERTIES

Determine stockpile properties.

Stockpile	RAP +4.75	RAP –4.75				
Course aggregate angularity						
Fine aggregate angularity						
Flat and elongated						
Sand equivalent value						
G_{sb}						
G_{sa}						

NOTE: Consensus properties on stockpiles are for information only, not for specification purposes.

RAP SPECIFIC GRAVITY

Either use G_{se} or calculate G_{sb} based on as assumed P_{ba}.

$G_{mm\,(RAP)}$ = _____ $G_{b\,(RAP)} \cong$ _____ $P_{b\,(RAP)}$ = _____

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

$P_{ba} \cong$ _____

$$G_{sb} = \frac{G_{se}}{\left(\frac{P_{ba} G_{se}}{100 G_b} + 1\right)} =$$

where

G_{mm} = theoretical maximum specific gravity;
$G_{b\,(RAP)}$ = specific gravity of RAP binder;
$P_{b\,(RAP)}$ = the RAP binder content;
G_{se} = effective specific gravity of aggregate;
G_{sb} = bulk specific gravity of aggregate; and
P_{ba} = absorbed binder, percent by weight of aggregate.

TRIAL BLENDS

Determine trial blend percentages (a minimum of 3) based on RAP and aggregate stockpile gradations.

Stockpile percentages:

Blend	**RAP (+4.75)**	**RAP (–4.75)**					**Total %**
#1					100		
#2					100		
#3					100		

Blend gradations:

Sieve Size mm (No.)	**Blend #1**	**Blend #2**	**Blend #3**		
25.0 mm (1 in.)					
19.0 mm (3/4 in.)					
12.5 mm (1/2 in.)					
9.5 mm (3/8 in.)					
4.75 mm (No. 4)					
2.36 mm (No. 8)					
1.18 mm (No. 16)					
0.600 mm (No. 30)					
0.300 mm (No. 50)					
0.150 mm (No. 100)					
0.075 mm (No. 200)					
Bulk specific gravity					
Apparent specific gravity					
Coarse aggregate angularity					
Fine aggregate angularity					
Flat and elongated					
Sand equivalent value					

TRIAL BINDER CONTENT (TOTAL)

Select trial binder content based on experience or on the Superpave method.

Superpave trial binder content calculations:

Absorption factor (0.8 typical)	
Assumed total binder content (P_b)	
Assumed percent aggregate ($P_s = 100 - P_b$)	
Design air voids (V_a)	4.0%
Binder specific gravity (G_b)	
Nominal maximum sieve size of largest aggregate in the aggregate trial blend, mm (S_n)	

Blend	#1	#2	#3		
Combined G_{se}					
Volume of absorbed binder (V_{ba})					
Volume of effective binder (V_{be})					
Mass of aggregate (W_s), g					
Initial trial binder content (P_{bi})					

where

$$G_{se} = G_{sb} + \text{Absorption Factor } x(G_{sa} - G_{sb})$$

$$V_{ba} = \frac{P_s \times (1 - V_a)}{\left(\frac{P_b}{G_b} + \frac{P_s}{G_{se}}\right)} \times \left(\frac{1}{G_{sb}} - \frac{1}{G_{se}}\right)$$

$$V_{be} = 0.081 - 0.02931(\ln S_n)$$

$$W_s = \frac{P_s \times (1 - V_a)}{\left(\frac{P_b}{G_b} + \frac{P_s}{G_{se}}\right)}$$

$$P_{bi} = \left[\frac{G_b(V_{be} + V_{ba})}{(G_b \times (V_{be} + V_{ba})) + W_s}\right] \times 100\%$$

where

G_{se} = effective specific gravity of the combined aggregate;
G_{sb} = bulk specific gravity of the combined aggregate;
G_{sa} = apparent specific gravity of the combined aggregate;
V_{ba} = volume of absorbed binder;
P_s = aggregate content;
V_a = volume of air voids;
P_b = binder content;
G_b = binder specific gravity;
V_{be} = volume of effective binder;
S_n = nominal maximum sieve size of the largest aggregate in the aggregate trial blend;
W_s = mass of the aggregate; and
P_{bi} = estimated initial trial binder content, percent by weight of total mix.

APPENDIX C

HOW TO INCREASE VMA

CHECKLIST OF POSSIBLE METHODS TO INCREASE VMA

The following checklist is based on "Guidelines to Increase VMA of Superpave Mixtures," which was prepared by an Ad Hoc Mix Design Task Group for the FHWA Superpave Mixtures Expert Task Group.

Methods to increase the VMA of recycled mixtures include all of the usual methods to increase VMA in any mixture, plus the option of changing the amount of RAP in the mixture. Varying the RAP content can be very effective in changing the VMA, especially if the RAP includes high fines contents or undesirable particles shapes. For convenience, a listing of the most common ways to increase VMA is shown below.

Possible Methods to Increase VMA

- Change aggregate gradation
  - Reduce the amount of fines (–0.075mm or P200)
  - Change or gap-grade the gradation
  - Change the RAP content
  - Rescreen the stockpiles to achieve different gradation
- Change aggregate surface texture
  - Increase manufactured sand
  - Increase crush count
  - Change RAP content
- Change aggregate shape
  - Change flat and elongated content

APPENDIX D

PROPOSED REVISED TP2, STANDARD TEST METHOD FOR QUANTITATIVE EXTRACTION AND RECOVERY OF ASPHALT BINDER FROM ASPHALT MIXTURES

Proposed Revisions to
Standard Test Method for the
Quantitative Extraction and Recovery of
Asphalt Binder from Hot Mix Asphalt (HMA)

AASHTO Designation TP2-94[1, 2] (Reapproved 1996)

1. Scope

1.1 This standard describes a procedure for the extraction and recovery of asphalt binder from asphalt mixtures (both hot mix asphalt (HMA) and reclaimed asphalt pavement (RAP)) which has a minimal effect on the physical and chemical properties of the asphalt binder recovered. It is intended for use when the physical or chemical properties or both of the recovered asphalt binder are to be determined. It can also be used to determine the quantity of asphalt binder in the HMA or RAP. Recovered aggregate may be used for sieve analysis.

1.2 This method is applicable to HMA sampled from the pavement, RAP sampled from the pavement or stockpile, HMA plant production, or laboratory fabricated HMA.

1.3 This procedure may involve hazardous materials, operations and equipment. This procedure does not purport to address all of the safety problems associated with its use. It is the responsibility of the user of this procedure to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

2. Referenced Documents

2.1 AASHTO Standards

M231	Specification for Standard Masses and Balances Used in the Testing of Highway Materials
T110	Moisture or Volatile Distillates in Bituminous Pavement Mixtures
T168	Method of Sampling Bituminous Paving Mixtures

2.2 ASTM Standards

D5361	Sampling Compacted Bituminous Mixtures for Laboratory Testing

3. Terminology

3.1 asphalt binder - an asphalt-based cement that is produced from petroleum residue either with or without the addition of non-particulate organic modifiers

4. Summary of Method - The asphalt mixture is repeatedly washed and filtered with solvent in an extraction/filtration apparatus. Each filtrate is distilled under vacuum in a rotary evaporator with the asphalt remaining in the flask. After recovery of the final filtrate, the solution is concentrated to about 300 mL and centrifuged to remove aggregate fines. The decanted solution is distilled under vacuum to remove the extraction solvents. Nitrogen gas is introduced during the final phase of distillation to drive off any remaining traces of solvents. The quantity of asphalt binder in the asphalt mixture is calculated (optional) and the recovered asphalt (distillation residue) sample is subjected to further physical and chemical testing as required. The recovered aggregate can then be used for sieve analysis, if desired.

5. Significance and Use - This method is used for obtaining recovered asphalt binder residue samples from asphalt mixture samples for further physical and chemical analyses, and for optional calculation of asphalt binder content.

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[1] This standard is based on SHRP Product 1004.
[2] Approved in October 1994, this provisional standard was first published in March 1995.

6. Apparatus

6.1 Extraction Vessel - The extraction vessel shall be a device as shown in Figure 1, and shall have a 130-mm long piece of 150-mm I.D. Schedule 80 aluminum pipe or Schedule 80, grade 304 stainless steel pipe (Figure 2) with removable top and bottom 13-mm thick aluminum or stainless steel plates. The top plate (Figure 3) shall have a mixing motor mount and 19-mm port for adding solvent. The bottom plate (Figure 4) shall be equipped with a quick connect fitting. Four 100-mm by 25-mm baffles (Figure 5) shall be mounted in the extraction vessel followed by 3-mm aluminum ring, 2-mm (#10) mesh screen, spacer (Figure 6), 0.3-mm (#50) mesh screen, another spacer, 0.075-mm (#200) mesh screen, then another 2-mm (#10) mesh screen, as shown in Figure 1.

Note 1 - Vessel available through Pass Industries Ph# (606)881-0205 has proven acceptable for these requirements.

6.2 In-line filter - The in-line filter apparatus shall be a cartridge type with 20-μm retention and at least 820-cm^3 effective filter area. The filter apparatus shall be able to be removed from the system to accommodate weighing before and after procedure. The filter shall be capable of withstanding heat up to 135°C without degradation in order to accommodate oven drying of the filter apparatus.

Note 2 - Whatman Polycap™ 75 HD Catalog number 6703-7521 or equivalent is a suitable filter.

6.3 Two (2) filtrate flasks with tubulation, 1000mL

6.4 Round bottom flask, 1000 mL and cork stand

6.5 Gas flowmeter, capable of indicating a gas flow up to 1000 mL/minute

6.6 Rotary evaporator device, with transfer and purge tubes, capable of holding a recovery flask in oil at a 15 degree angle and rotating at 40 r/min

Note 3 - The Buchi Rotavapor RE-120 has proven acceptable for these requirements.

6.7 Hot oil bath, capable of heating oil to 180°C

6.8 Single speed mixing motor, 150 W (1/5 hp), 30 r/min

6.9 Centrifuge, batch unit capable of exerting a minimum centrifugal force of 770 times gravity

6.10 Wide-mouth centrifuge bottles, 250 mL.

6.11 Oven, capable of maintaining a temperature of 110 ± 5°C

6.12 Balance, of suitable capacity meeting the requirements of M231 for Class G2 balances

6.13 Thermometer, having a range of 30 to 300°C

6.14 Utilities - Vacuum source and cooling water source.

6.15 Scale (optional) - having a capacity of 12 kg or more, sensitive to 0.1 g or less, and accurate within 0.1% of the test load at any point within the range of use for this test. Within any 100-g range of test load, a difference between readings shall be accurate within 0.1 g.

7. Materials and Reagents

7.1 6-mm diameter polypropylene tubing -- varying length, for transferring solution throughout the procedure

Note 4 - To avoid contamination of the sample due to solvent degradation of the tubing, do not substitute Nalgene or rubber tubing for the polypropylene tubing specified.

7.2 Copper tubing, of an amount and size adequate to connect the apparatus as shown in Figure 6.

7.3 Solvent

7.3.1 n-Propyl Bromide

7.3.2 or, Trichloroethylene, reagent grade

7.3.3 or, Toluene, reagent grade. If using Toluene, combine with Ethanol, absolute, in proportions of 85% Toluene and 15% Ethanol after the third wash (in section 12.2)

7.8 Nitrogen gas, at least 99.95 percent pure, in a pressurized tank, with a pressure-reducing regulator valve

8. Hazards - Use solvents only under a fume hood or with an effective surface exhaust system in a well-ventilated area and observe the manufacturer's recommended safety precautions when using compressed nitrogen.

9. Sampling - Obtain asphalt mixture samples in accordance with T168. When sampling from a compacted roadway, remove specimens from the roadway in accordance with ASTM D5361. When sampling RAP, refer to ASTM D75 for aggregate sampling.

10. Preparation of Apparatus

10.1 Preparing the Extraction Vessel - Install the baffles piece and other internal parts in the order shown in Figure 1. Tightly and evenly fasten the bottom piece (with quick connect) of the vessel with wing nuts or hexagonal nuts.

10.2 Preparing the Rotary Evaporator - Turn on the cooling water. Turn on the oil bath and set the temperature to 100 ± 2.5°C. Place six 3-mm glass boiling beads in a 1000 mL round bottom flask. Attach this recovery flask to the rotary evaporator and immerse approximately 38 mm of the flask into the oil bath. Set the angle of the recovery flask from the horizontal to the bath at 15 degrees. Set the flask rotation at 40 r/min. Clamp the empty condensate flask onto the condenser. Attach the transfer tube inside the neck of the rotary evaporator. Attach the filtrate transfer line to the external fitting on neck of rotary evaporator.

11. Standardization

11.1 At least every six months, verify the calibration of the oil bath temperature detector by using a certified mercury in glass thermometer of suitable range that is accurate to ± 0.2°C. Immerse the thermometer in the oil bath close to the thermal detector and compare the temperature indicated by the certified thermometer to the temperature setting for the oil bath. If the temperature indicated by the thermal detector does not agree with the certified thermometer within ± 0.5°C, perform additional calibration or maintenance.

11.2 At least every six months, use a mercury manometer or other certified pressure measurement device to verify calibration of the vacuum indicator. If the vacuum indicator and the certified pressure measurement device do not agree within ± 0.1 kPa, perform additional calibration or maintenance.

11.3 At least every six months, verify the rotational velocity of the rotary evaporator.

11.4 At least every six months, verify the flow rate of the nitrogen flow meter.

12. Procedure

12.1 Sample Preparation

12.1.1 If a sample of asphalt mixture is not sufficiently soft to separate with a spatula or trowel, place the sample in
a large, flat pan and warm it in a oven at 110 ± 5°C only until it can be handled or mixed.

12.1.2 Split or quarter the loose asphalt mixture sample until an amount of the sample that will yield approximately 50 to 60 g of extracted asphalt binder is obtained (typically approximately 1000g of asphalt mixture).

> Note 5 - This procedure works best when recovering less than 60 g of asphalt binder. Therefore, if the asphalt binder content of the mix is already known, then the mass of the original sample required is that which yields about 50 to 60 g of asphalt binder.
>
> Note 6 - The maximum aggregate size in the test specimen will affect the calculated asphalt content. If the calculated results from this standard are used to represent the asphalt content in the asphalt mixture from which the sample was obtained, use a minimum mass of test specimens for calculations that will ensure that inclusion or removal of one maximum size particle will not change the calculated asphalt content by more than 0.05 percent. This may require testing multiple test specimens.

12.1.3 If the asphalt binder content is to be determined, obtain a separate test specimen from the asphalt mixture sample, determine the moisture

content in accordance with T110 and record the mass percent of water in the test specimen.

12.2 Extraction and Filtration

12.2.1 Place the asphalt mixture sample in the extraction vessel. Put the gasket and the upstream end piece on the vessel and fasten the wing nuts tightly and evenly, creating a secure seal.

12.2.2 Charge 600 mL of solvent through the 19-mm port on the upstream end of the extractor. Blanket the interior of the extraction vessel by injecting nitrogen through the upstream port at a rate of 1000 mL/min for 1 minute. Close the port with the threaded plug. Attach the extractor to the motor. Start the motor and mix for 5 ± 1 minutes at 30 r/min. Turn off the motor.

12.2.3 Remove the extractor, place it on a stand and attach the quick connect fitting to the first filtrate receiving flask. Make sure the filtrate transfer line is closed. Remove the upstream port plug and blanket the extractor with nitrogen at a rate of 400 mL/min while drawing the asphalt/solvent solution into the first flask. Apply 93.3 ± 0.7 kPa (700 ± 5 mm Hg) vacuum to the first filtrate receiving flask to draw the material from the vessel. Continue drawing the solution into the first flask until there is no noticeable amount of solution exiting the vessel. Turn off the vacuum.

12.2.4 Filtering through the in-line cartridge filter, switch the vacuum to the second filtrate receiving flask and apply 93.3 ± 0.7 kPa (700 ± 5 mm Hg) vacuum. Filter until there is no noticeable amount of solution remaining in the first flask or the filter. Turn off the vacuum.

12.2.5 After filtration, open the filtrate transfer valve on the second receiving flask and allow the solution to flow from the filtrate receiving flask to the recovery flask. Continue the transfer until the filtrate receiving flask is empty or the recovery flask is about 2/3 full, then, begin the primary distillation.

12.2.6 After the distillation is started, disconnect the extractor from the quick connect fitting. Repeat the extraction procedure. For the second wash use 400 ± 10 mL of solvent and mix/rotate for 10 ± 1 minutes. For all subsequent washes (Note 7), use 400 ± 10 mL of solvent and mix for 30 to 35 minutes.

> Note 7 - After the third wash, the condensate from the primary distillation step may be used for the extraction solvent. Recycling solvent in this manner allows the entire procedure to use approximately 1500 mL solvent.

12.2.7 Proceed to the final recovery step (12.4) when the filtrate flowing through the transfer tube, after a 30 minute wash, is a light brown color. A minimum of three washes is required.

12.3 Primary Distillation

12.3.1 Close the filtrate transfer valve line and distill solvent at 100 ± 2.5°C (oil bath temperature) and 93.3 ± 0.7 kPa (700 ± 5 mm Hg) vacuum.

12.3.2 If after the primary distillation step the condensate flask is over half full, empty the flask. Save this solvent for use in subsequent washes (Note 7). After primary distillation of each filtrate, maintain vacuum, temperature, flask rotation, andcooling water. Repeat the primary distillation after each filtration (Note 8).

> Note 8 - It is important to concentrate the asphalt in the recovery flask after each wash and at a low temperature. This minimizes the temperature and the time spent in dilute solution and, therefore, minimizes asphalt hardening in solvent.

12.4 Final Extraction and Recovery

12.4.1 Distill the contents of the recovery flask until it is about 1/3 full.

12.4.2 Turn off the vacuum, then clean and disconnect the recovery flask and pour the contents into the centrifuge bottles using a funnel and screen to prevent the boiling beads from entering the bottles. Fill the bottles so that their masses are equal. Wash any remaining residue from the recovery flask into the centrifuge bottles. Increase the oil bath temperature to 174 ± 2.5°C. Centrifuge the bottles at 3600 r/min for 25 minutes.

12.4.3 Empty the centrifuge bottles back into the recovery flask and add six 3-mm diameter glass boiling beads. Re-attach the flask to the rotary evaporator. Disconnect the transfer tube from the rotary evaporator and replace it with the gas purge tube. Disconnect the filtrate transfer line from the external rotary evaporator neck fitting and replace it

with the nitrogen gas line. Apply 93.3 ± 0.7 kPa (700 mm Hg) vacuum. Lower the flask approximately 38 mm into the oil bath.

12.4.4 Distill the solvent.

12.4.5 When the condensation rate falls below 1 drop every 30 seconds, introduce nitrogen gas at a rate of 1000 mL/minute. Maintain the gas flow, vacuum and bath temperature for 30 ± 1 minutes to reduce the residual solvent concentration to near zero. Complete removal of residual solvent is very important for obtaining accurate asphalt properties.

12.4.6 Shut down the oil bath, flask rotation, vacuum, gas flow, and cooling water. Remove the evaporating flask. If the asphalt binder content is to be determined, determine and record the mass of the recovered asphalt binder to the nearest 0.1 g. Pour the asphalt into a sample tin using a screen to prevent the boiling beads from entering the tin.

13. Determination of Asphalt Binder Content (Optional)

13.1 When a determination of asphalt binder content is desired, use the following procedure:

Before section 12.2.1:

- determine mass of mixture sample
- determine mass of cartridge filter
- determine mass of centrifuge bottles

After section 12.4.3:

- dry centrifuge bottles, in-line filter and opened vessel (including inserts) to constant mass
- determine mass of fine material in centrifuge bottles (dry - original)
- determine mass of fine material in filter (dry - original)
- determine mass of all aggregate material in vessel (scrape/brush all screens, etc.)

$$\text{Asphalt content } \% = \frac{\text{Original sample} - (\text{Recovered aggr} + \Delta\text{Bottles} + \Delta\text{filter})}{\text{Original sample}}$$

14. Report

14.1 Report the source of the test sample.

14.2 Report the following, if the asphalt binder content is to be determined:

14.2.1 the mass of test specimen to the nearest gram,

14.2.2 the mass percent of water in the companion test specimen to the nearest 0.01 percent,

14.2.3 the mass of asphalt binder in the test specimen to the nearest gram,

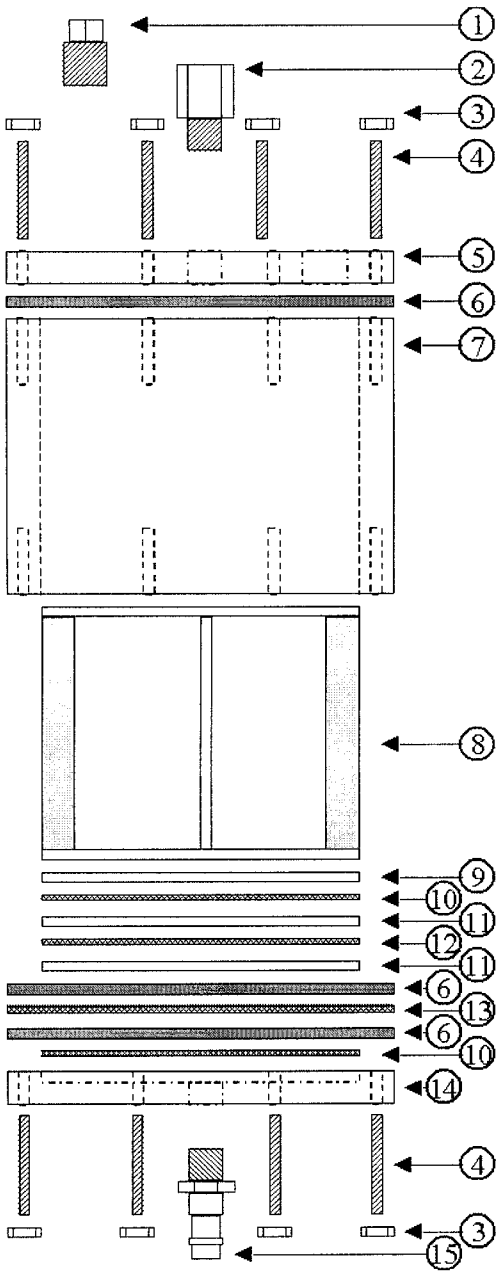
14.2.4 the percent asphalt binder in the test sample to the nearest 0.01 percent,

15. Precision and Bias

15.1 Precision - The research required to develop precision values has not been conducted.

15.2 Bias - The research required to establish the bias of this method has not been conducted.

16. Key Words - extraction, recovery, asphalt binder, rotary evaporator



1- 1- ISO 12RT (3/4 in. NPT) plug

2- ISO 8RT (1/2 in. NPT) fitting with I.D. hole for motor shaft

3- 12 M5 x 0.5 nuts

4- 12 M5 x 0.5 x 50 mm studs

5- extraction vessel top

6- 3 Viton gaskets 3 mm thick, 16 mm width with holes to fit over studs

7- extraction vessel housing

8- aluminum baffle

9- aluminum ring 3 mm thick 148 mm O. D., 10 mm width

10- stainless steel #10 screen

11- metal spacers

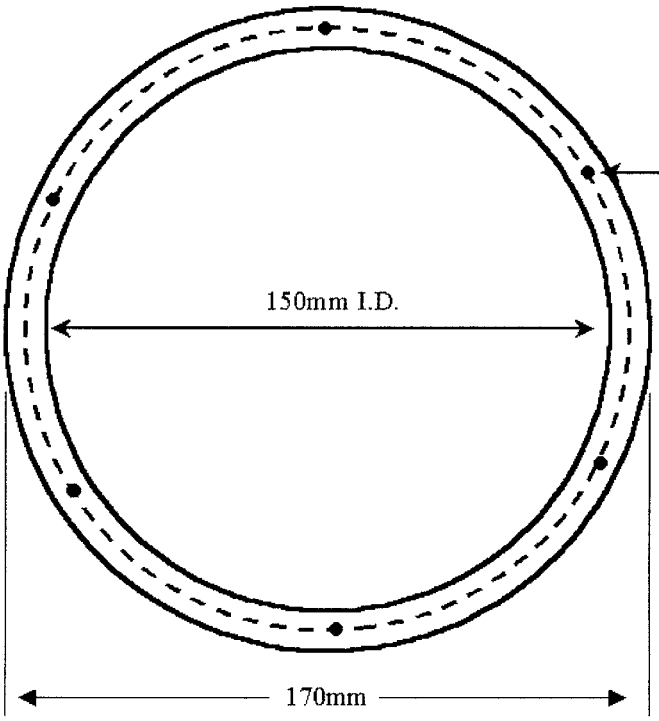
12- # 50 screen

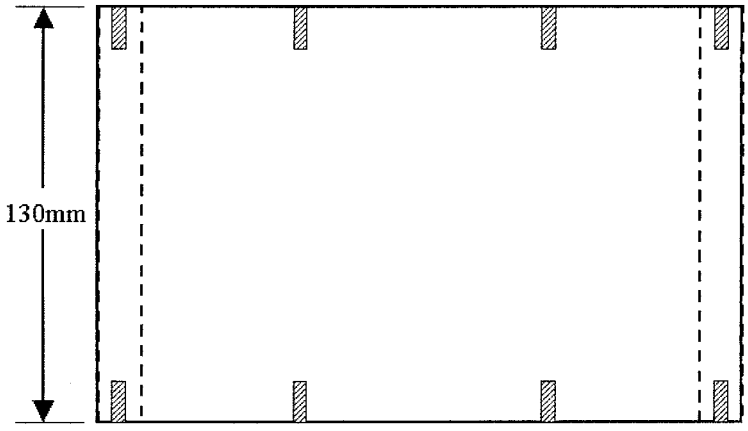
13- # 200 screen

14- extraction vessel bottom

15- ISO 4RT (1/4 in. NPT) quick connect fitting

Figure 1. Extraction vessel.





Notes:

All dimensions in mm

Not to scale

Unless otherwise indicated assume a tolerance of 0.2 mm

Schedule 80 Aluminum or Schedule 80 Stainless Steel, Grade 304

Figure 2. Extraction vessel housing.

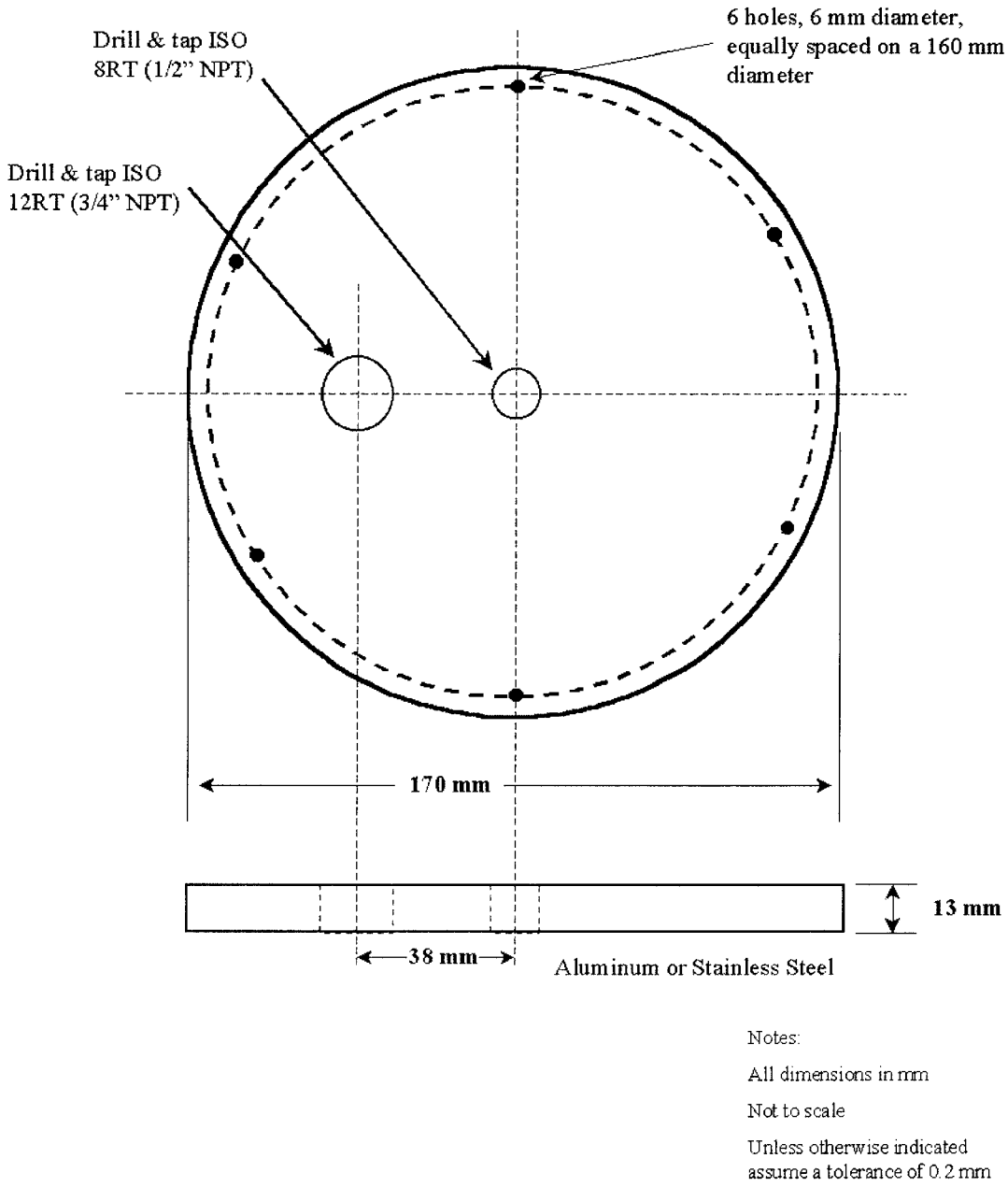


Figure 3. Extraction vessel top plate.

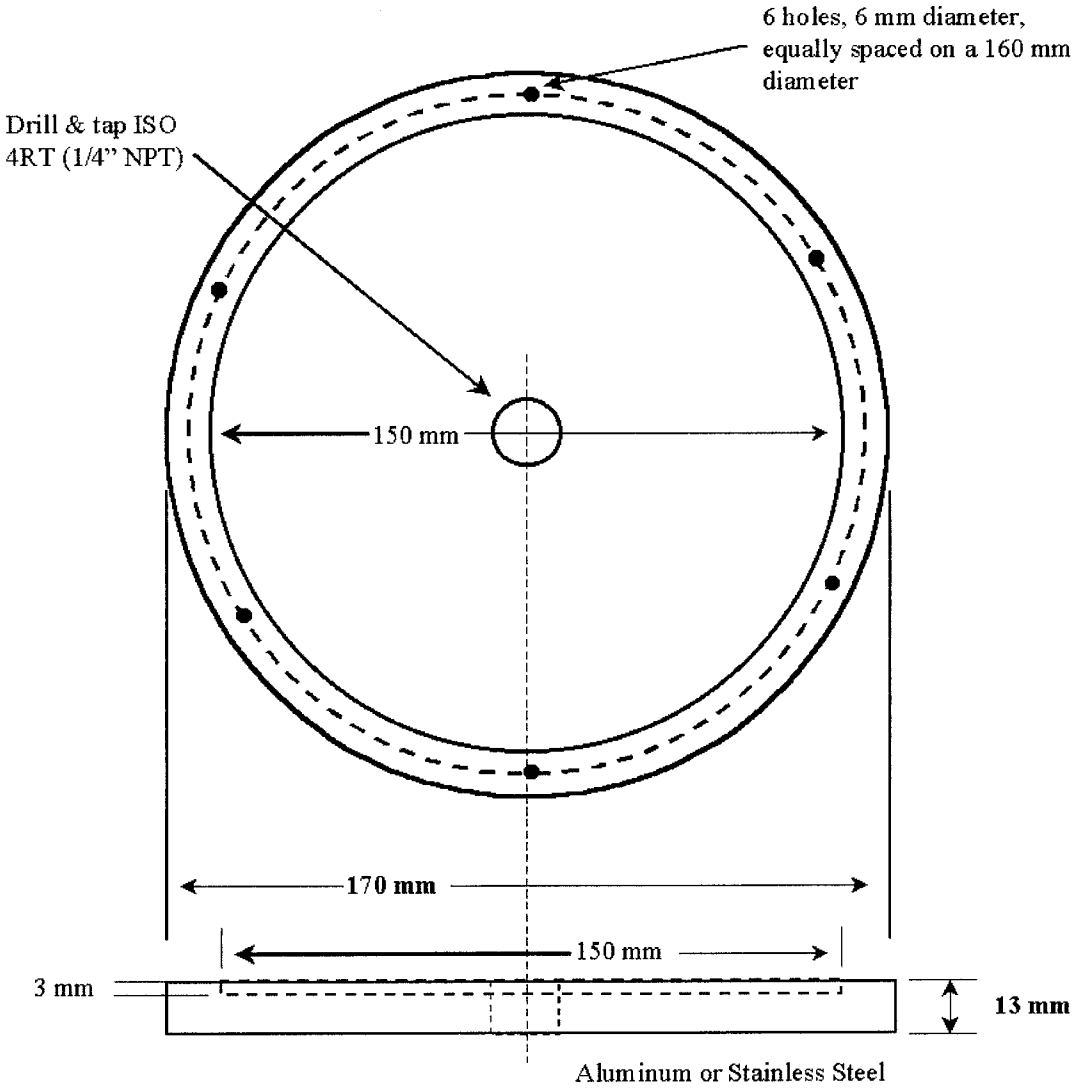


Figure 4. Extraction vessel bottom plate.

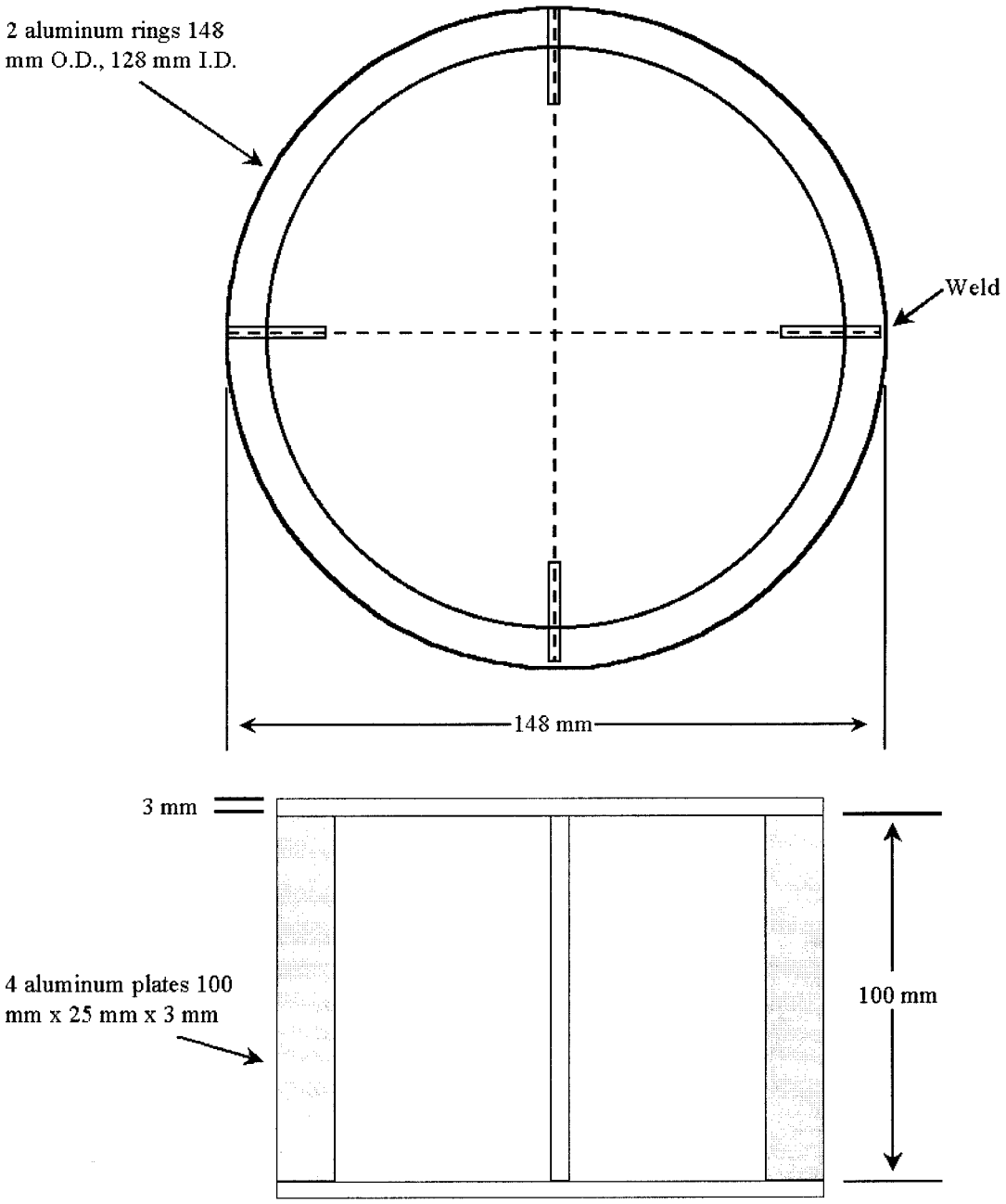


Figure 5. Extraction vessel baffle.

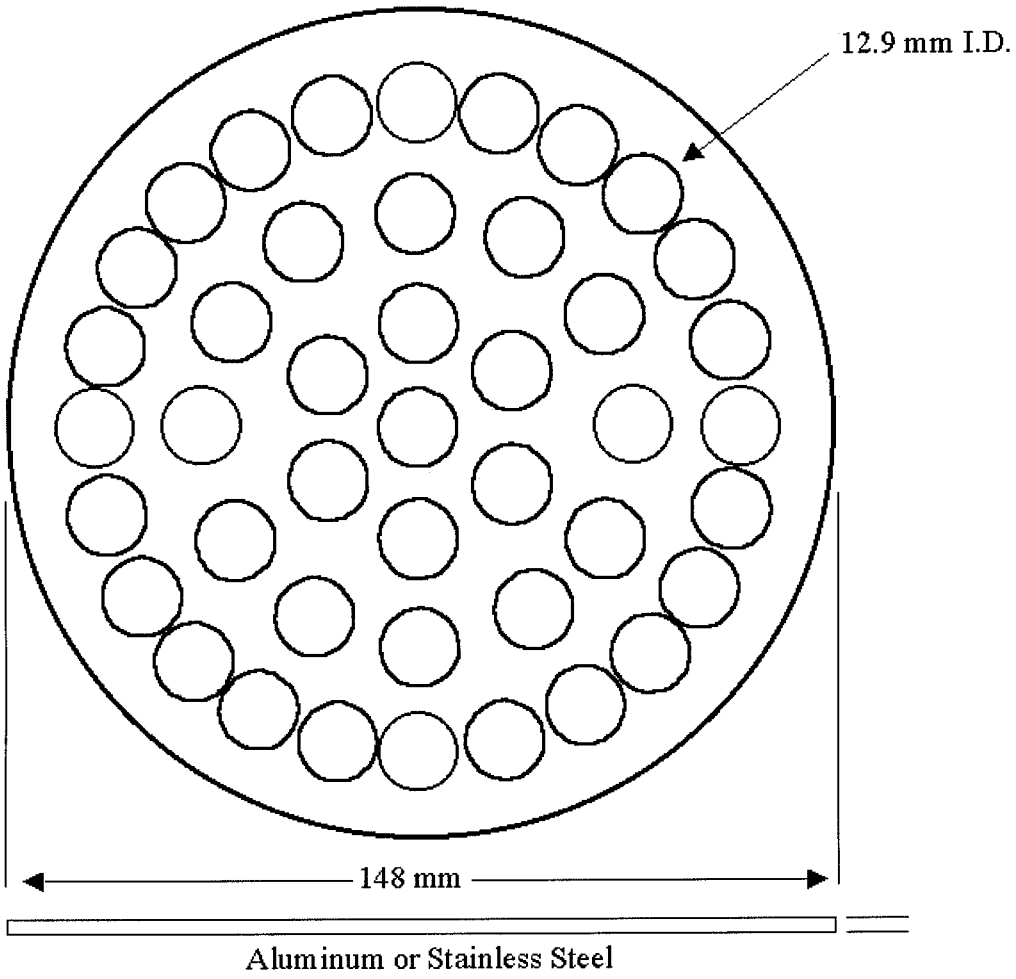


Figure 6. Extraction vessel spacer.

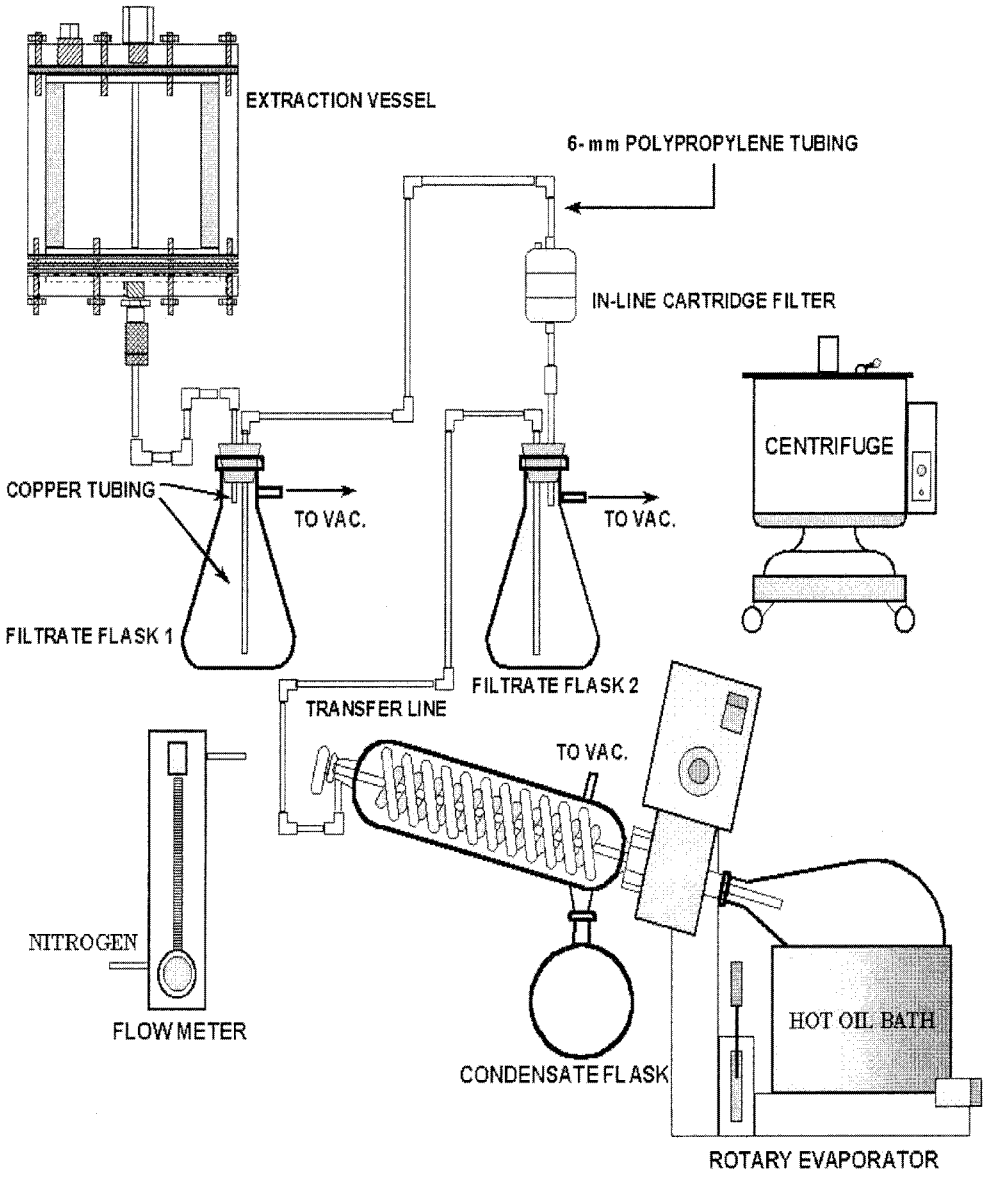


Figure 7. Extraction and recovery apparatus.

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Abbreviations used without definitions in TRB publications:

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ITE	Institute of Transportation Engineers
NCHRP	National Cooperative Highway Research Program
NCTRP	National Cooperative Transit Research and Development Program
NHTSA	National Highway Traffic Safety Administration
SAE	Society of Automotive Engineers
TCRP	Transit Cooperative Research Program
TRB	Transportation Research Board
U.S.DOT	United States Department of Transportation

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