RECYCLING: PROJECT SELECTION AND DESIGN

by

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Rehabilitation and maintenance of a country's transportation system is costly, time consuming and material intensive. In the last five years reuse or recycling of existing pavement materials has emerged as a viable rehabilitation and maintenance alternative as it offers several advantages over the use of conventional materials and techniques (Figure 1). Among the major benefits are lower costs, conservation of aggregates, binders and energy, and preservation of the environment and existing highway geometrics.

Since the benefits of recycling appeared promising from a wide variety of viewpoints a number of agencies in the United States including the National Cooperative Highway Research Program (NCHRP) have sponsored research (1, 2). NCHRP Synthesis 54, "Recycling Materials for Highways" was the first comprehensive summary of recycling information (1). Federal Highway Administration sponsored programs include: Demonstration Project No. 39, "Recycling Asphalt Pavement" (3, 4); Demonstration Project No. 39, "Recyclying Portland Cement Concrete Pavement" (5); National Experimental and Evaluation Program (NEEP) Project No. 22 (6); Implementation Package 75-5 (7); Office of Research studies on "Softening or Rejuvenating Agents for Recycled Bituminous Binders," "Tests for Efficiency of Mixing Recycling Asphalt Pavements," Data Bank for Recycled Bituminous Concrete Pavement" and "Materials Characterization of Recycled Bituminous Paving Mixtures" and HPR and special state studies (8, 9). Other government sponsored studies have been performed by the Corps of Engineers (10) and the Navy (11).

Associations and Institutes that have contributed to the collection and distribution of recycling information include the American Concrete Paving Association, Asphalt Emulsion Manufacturers Association, Asphalt Reclaiming and Recycling Association, The Asphalt Institute (12), National Asphalt Pavement Association (13), (14), Portland Cement Association (15) and West Coast User-Producer Group on Asphalt Specifications (16). In addition conference sessions and symposiums have been held on pavement recycling at the Transportation Research Board (17) American Society for Testing and Materials (18) and Association of Asphalt Paving Technologists meetings. (19)

Definitions

The term pavement recycling has not been formally defined. However, most individuals concerned with roadway rehabilitation use the term to indicate "the reuse (usually after some processing) of a material that has already served its first-intended purpose in a roadway: (20).

Definitions for recycling categories have been prepared by the Federal Highway Administration Demonstration Project No. 39 Technical Advisory Committee (3), a joint National Asphalt Pavement Association-Asphalt Institute Committee (21), Asphalt Recycling and Reclaiming Association (22), National Cooperative Highway Research Program (1, 2), U. S. Army Engineers Waterway Experiment Station (10), and Navy Civil Engineering Laboratory (11). Although formal definitions for recycling categories have not been developed those advanced by a joint National Asphalt Pavement Association, The Asphalt Institute and Federal Highway Administration committees are the most widely accepted and are given below:

Asphalt-Pavement Surface Recycling. One of several methods where the surface of an existing asphalt pavement is planed, milled, or heated in-place. In the latter case, the pavement may be scarified, remixed, relaid, and rolled. Additionally, asphalts, softening agents, minimal amounts of new asphalt hot-mix, aggregates, or combinations of these may be added to obtain desirable mixture and surface characteristics. The finished product may be used as the final surface or may, in some instances, be overlayed with an asphalt surface course.

Cold-Mix Asphalt Pavement Recycling. One of several methods where the entire existing pavement structure including, in some cases, the underlying untreated base material, is processed in-place or removed and processed at a central plant. The materials are mixed cold and can be reused as an aggregate base, or asphalt and/or other materials can be added during mixing to provide a higher strength base. This process requires that an asphalt surface course or surface seal coat be used.

Hot-Mix Asphalt Pavement Recycling. One of several methods where the major portion of the exlisting pavement structure including, in some cases, the underlying untreated base material, is removed, sized, and mixed hot with added asphalt cement at a central plant. The process may also include the addition of new aggregate and/or a softening agent. The finished product is a hot-mix asphalt base, binder, or surface course.

Portland-Cement Concrete Pavement Recycling. A process by which an existing portland cement concrete pavement is processed into aggregate and sand sizes, then used in place of, or in some instances with additions of conventional aggregates and sand, into a new mix and placed as a new portland cement concrete pavement. This process is a phase of the econo-crete concept in that the broken concrete is considered to be a local aggregate.

The major advantages and disadvantages of the defined recycling techniques are shown on Table 1. It is important that the engineer understand these basic advantages and disadvantages prior to selection of pavement rehabilitation alternatives.

SELECTION OF RECYCLING ALTERNATIVES

If the engineer is to select the most appropriate recycling alternative for a particular project, he must describe or characterize the conditions of the existing facility. Aside from historical facts and known conditions, (Table 2) the present condition must be measured on some rational basis and compared to standard criteria. Key factors that influence the decision include the following: (1) surface conditions, (2) structural conditions, (3) roughness, and (4) skid resistance. These factors together with a summary of key data describing the existing facility are discussed in the following.

Existing Facility

Particular data are required to describe adequately the existing facility for the purpose of rehabilitation decision-making. These factors are summarized in Table 3 in a form for easy reference. Specific items noted are as follows: (1) location and size of project, (2) roadway class, (3) existing pavement cross section, (4) geometrics, (5) traffic, and (6) subgrade characteristics. The contribution of the factors, in terms of a selection process for recycling, are briefly described next.

Location and Size of Project. The location and size of a project may be such that only certain techniques would be cost effective. For example, projects located in remote areas will have to be large in size to justify the transportation of the equipment associated with central plant recycling. In-place recycling is a cost effective approach for pavement rehabilitation in remote areas where small projects with low traffic volumes are under consideration.

Roadway Class. Generally, the roadway can be classed in broad categories as: Interstate and Urban Freeway, Rural Primary (U.S. and state signed routes), Rural Secondary (farm and ranch-to-market, park roads, etc.), and Urban Streets (arterial, collector, local). Roadway class dictates criteria for determining the need for pavement rehabilitation as well as general criteria for selection of an appropriate recycling alternative.

Existing Pavement Cross Section. The date of original construction together with a listing of the thickness and types of materials used will be important in judging the general serviceability of the pavement. Subsequent history of rehabilitation and maintenance activities, such as seal coats, overlays, patching, crack sealing, etc., will influence the determination of a viable recycling alternative. Thickness of each layer of different material, as well as the type of material and its condition, should be obtained from project records. Reliance on memory for the information is often risky. A few carefully located core samples will provide confidence in the information.

The type or nature of the existing materials will influence the recycling method selected for a given project. If the bound materials, such as multilayers of seal coats and overlays are variable, both vertically and horizontally, it may be difficult to make a uniform recycled mixture without adding large quantities of aggregate and/or binder to dilute these undesirables. Asphalt modifiers and/or additional asphalt may also be needed. If the structural strength of the pavement must be increased, several options exist that include removing the pavement materials and stabilizing the subgrade before remixing and replacing the pavement, or using all existing pavement materials stabilized as a base course and then overlaying.

Geometrics. The geometric features of a roadway, such as horizontal and vertical alignment, are often constraints to conventional rehabilitation techniques such as asphalt overlays. For example, the drainage line at curbs and gutters can not be altered without considerable expense. Therefore, an overlay must be constructed at the appropriate thickness in the driving lanes and then tapered to near zero thickness at the gutter. Multiple overlays can cause havoc, resulting in excessively high crowns at the centerline and steep cross slopes. Other features such as drainage inlets and manholes also cause problems of a similar nature. Recycling of existing pavement materials offers a solution to some of these problems.

Vertical clearance for trucks and other special vehicles at bridges and overhead signals and signs is often critical and can not be reduced as would be the case if overlays were used. Recycling offers a further benefit here.

On multilane highways, the truck or travel lane often deteriorates before the passing lane. Overlaying only one of the lanes would be impractical, but recycling of that lane alone or to strengthen it before adding a general overlay would provide a more acceptable solution. Similarly, super-elevation could be preserved or altered as needed without disturbing adjacent lanes.

Changing the horizontal alignment or adding new features, such as shoulder widening or a new shoulder and lane widening or a new lane, may also be opportunities to use recycling techniques. Often, these features may not need the full design strength of adjoining lanes and could be stabilized in-place, or the existing aggregate base could be used to make asphaltic concrete without the need for new materials or for wasting existing materials.

Traffic Characteristics. The speed and volume of traffic, to a large extent, determine the traffic control problems associated with pavement rehabilitation activities. The use of recycling on high traffic volume urban facilities should be geared toward those activities that can provide low roadway occupancy time, can be performed with single lane blockage, and can use materials with rapid strength gain after placement.

The volume and axle weight distribution of traffic are important from a pavement design standpoint. For pavement design purposes, traffic should be converted to average daily equivalent 18,000-lb axle-load repetitions that are representative for the design period. It is suggested that the AASHTO procedures be used for this conversion.

Subgrade Characteristics. Pavement failures due to factors outside the pavement layers often need to be considered. For example, a subgrade that contains a swelling clay may need to be improved before recycling the pavement materials would be effective. Another environmentally influenced problem related to volume change is frost heave. For both of these problems, recycling may offer a reasonable solution in that the pavement materials would need to be removed in any event in order to remove or improve the poor subgrade. While removing the materials, they could be reprocessed and replaced after the subgrade has been prepared.

In summary, all known information about the pavement materials and background needs to be summarized and used in the decision process. Surprises at the time of construction can be avoided usually by proper testing, evaluation, planning and design.

Surface Condition

Each potential recycling project should be surveyed for surface defects that can be used not only to assess the cause of distress but perhaps to also suggest corrective action. Several agencies have devised methods to estimate pavement distress. Once the survey is made, the results can be summarized and entered on the first line of Table 3. This table has all the usual types of distress displayed across the top and major recycling alternatives listed along the left margin. In order to use this table, the engineer should systematically look at each distress marked on the first line and estimate which recycling methods would correct that distress, and indicate this assessment by placing a check mark in the appropriate box. Note that a number of boxes are shaded; this indicates that these recycling options would not be appropriate. For example, a pavement with severe alligator cracking over 30 percent of the area would not be improved by using a heater planer (A1) alone. Similarly, other surface methods would not be applicable unless a thick overlay followed the operation. Further, one can note on Table 3 that some methods of in-place recycling and central plant recycling would also not be particularly beneficial for certain types of distress.

Once the viable recycling alternatives for improving surface condition are identified, they can be summarized in Table 6.

Structural Condition

The structural adequacy or structural condition of the roadway under consideration is determined by the thickness of the overlay required. Overlay requirements should be determined by an appropriate deflection-based procedure. Certain recycling alternatives defined in this report can be eliminated, depending on the thickness of the overlay required (Table 4). For example, if the overlay required is greater than 2 in., only those recycling alternatives providing a major structural improvement would be considered adequate (A5, A8, B3, B7, C3, and C8). For overlay requirements less than 2 in., those recycling alternatives providing minor structural improvements are suggested for use (Table 4). Those recycling alternatives identified as appropriate for improving the pavement from a structural adequacy standpoint should be entered in Table 6.

Roughness

The smoothness of ride may be a deciding factor for rehabilitation of many roadways. Occasionally, a rough surface may be the only significant problem and surface recycling would be the solution. If a pavement is rough, but also has other deficiencies that require more extensive reworking, the roughenss should be taken care of automatically in that operation. Therefore, the need for surface recycling based on ride measurements (serviceability index, SI) can be estimated as noted in Table 5. As in previous discussion, some methods would not be appropriate and have been blocked out. For example, it is not recommended that very rough primary highway (SI less than 2.4) be surface recycled without an appropriate overlay (methods A1, A2, A3, A4, and A6). Those methods that are considered appropriate should be noted on Table 5 and the result summarized in Table 6.

Skid Resistance

Many pavements may perform adequately from a structural standpoint, but simply be deficient in skid resistance because of excess asphalt cement or perhaps because of polishing aggregate. As part of the overall pavement testing scheme, skid resistance can be measured by using any one of several test methods, but preferably by the so-called ASTM skid trailer. It is noted that all recycling methods are appropriate for improving skid resistance with the possible exception of the heater planer without additional aggregate (A1) or heater scarifier only (A3). The acceptable recycling methods to improve skid resistance should be entered in Table 6.

After the above information has been collected and summarized, the potentially successful approaches should be analyzed with respect to cost and energy savings and the most viable recycling alternative determined. Thus, the basic steps required to select these preliminary alternatives are as summarized below.

1. List available information on existing roadway (Table 2).

2. Test existing pavement:

   a. Surface condition (Table 3)
   b. Structural condition (Table 4)
   c. Roughness (Table 5)
   d. Skid resistance

3. Evaluate other decision factors unique to the particular project.

4. Make preliminary cost and energy analysis of remaining options and rank accordingly.

5. Consider alternatives that appear most viable and continue evaluation (Table 6).

The above listed considerations will provide the engineer with several recycling alternatives. Detailed testing and analysis will have to be performed prior to the selection of the most appropriate recycling alternative for a particular roadway segment. Detailed mixture designs, pavement thickness design and detailed life cycle cost and energy considerations will have to be prepared. The proper use of recycling as a rehabilitation alternative requires more testing and analysis than does the use of conventional rehabilitation alternatives. Mixture design, pavement design and cost and energy information is presented below for asphalt pavement recycling only. Details for portland cement recyclying can be found in reference 2.

MIXTURE DESIGN

Surface, cold and hot recycling operations will often make use of chemical additives such as lime, portland cement, asphalt cement and/or recycling agents to improve the engineering properties of the recycled materials. Selection of this type of additive or stabilizer and the amount for a given recycling project is of concern to the engineer. This section of the report describes a soil stabilization index system (SSIS) which was developed for the U. S. Air Force by Texas A&M University (23), later modified by the Air Force Academy (24) and utilized in a FHWA soil stabilization manual (25). This index system can be used to select the type and amount of stabilizer to be used for a given recycled material.

Type of Stabilizer. Figure 2 provides a stabilizer selection procedure based on the percent passing the No. 200 sieve and the plasticity index (PI). Based on these criteria it is evident that the majority of the cold recycling projects utilizing stabilizers will use either lime or bituminous materials. The use of bituminous materials may involve selection of an appropriate recycling.

Lime Stabilization

The design sub-system for stabilization with lime is shown in Figure 3. Procedures for most entered tests are outlined in reference 2. Table 7 contains the minimum residual strength criteria that must be maintained.

Cement Stabilization

The modified SSIS cement design sub-system is as shown in Figure 4. The MacLean and Sherwood pH test discussed below is the only nonstandard test procedure employed. However, if a high sulfate content is suspected in the soil to be stabilized, a check on the amount of sulfate present should be made. An upper limit of 0.9 percent is set for sulfate content (23). The turbi-dimetric method used to determine sulfate content can be found in Reference 2. Because of the nature of the test it is only warranted when a high sulfate content is suspected.

After the soil cement mixture has been checked for deleterious organics content, standard PCA procedures are followed (27). In the base course procedure the wet-dry test is often much less severe than the well-established freeze-thaw test (24). Therefore, solely the PCA freeze-thaw weight loss criteria is suggested for use for base course design (Table 18).

Asphalt Stabilization

Asphalt binders present in recycled pavements often contain physical and chemical properties which make the "old" asphalt undesirable for reuse without modification. Materials have been developed to restore these old binders to a condition suitable for reuse. This concept is not new and has been the subject of a number of extensive studies during the last several years (28-36).

Materials used to alter properties of asphalt cements have been called softening agents, reclaiming agents, modifiers, recycling agents, fluxing oils, aromatic oils, etc. Suppliers of these oils market products under the names of Cyclogen, Dutrex, Paxole, Reclamite, and RejuAcote among others (2). The term "modifier" which has been used to designate this type of material originates from ASTM Subcommittee D) 4.37 (Modifier Agents for Bitumen in Pavements and Paving Mixtures). The general definition of modifier is "a material when added to asphalt cement will alter the physical-chemical properties of the resulting binder". A more specific definition has been developed by the Pacific Coast User-Producer Group for the term "recycling agent". A "recycling agent" is a hydro-carbon product with physical characteristics selected to restore aged asphalt to requirements of current asphalt specifications (36). It should be noted that soft asphalt cements, as well as speciality products, can be classified as recycling modifiers or agents.

The purpose of the modifier in asphalt pavement recycling is to;

1. Restore the recycled or "old" asphalt characteristics to a consistency level appropriate for construction purposed and for the end use of mixture.

2. Restore the recycled asphalt to its optional chemical characteristics for durability.

3. Provide sufficient additional binder to coat any new aggregate that is added to the recycled mixture and

4. Provide sufficient additional binder to satisfy mixture design requirements.

Methods must, therefore, be developed for the engineer to define the type and amount of modifier to use for a particular asphalt pavement recycling operation.

Mixture Design Method. A mixture design method for asphalt bound recycled materials is shown on Figure 5 (37). The design method allows the engineer to select the types and amount of bituminous modifiers to produce the desired mixture (37). The proposed method is applicable to surface, cold and hot recycling operations and includes modifiers such as softening agents, rejuvenators, flux oils and soft asphalt cements. The method consists of the following general steps:

1. Evaluation of salvaged materials

2. Determination of the need for additional aggregates

3. Selection of modifier type and amount

4. Preparation and testing of mixtures and

5. Selection of optimum combinations of new aggregates and asphalt modifiers.

The overall philosophy of this approach is to utilize the recycled materials, new aggregate and modifier to produce a mixture with properties as nearly like a new asphalt concrete mixture as possible. Standard test methods have been utilized where possible. The mixture design procedure is shown in Figure 5 and has been modeled after that suggested in References 28 to 37. The circled numbers on the flow diagram refer to the steps presented below.

Field Samples (1). Representative field samples should be obtained from the pavement to be recycled. A visual evaluation of the pavement should be made together with a review of construction and maintenance records to determine significant differences in the material to be recycled along the pavement section. Roadway sections with significant differences in materials should not be lumped together because uniformity and predictability of results will be impaired. Locations within a project can be determined on a random basis using the procedure outlined in Reference 37. At least 5 or 6 locations should be used as a minimum and a total composite sample of about 200 lbs. is recommended for laboratory evaluation. If desired, core samples may also be obtained and used for comparison of original and recycled properties such as stability and resilient modulus (M_R) (38).

Extract and Recover Asphalt and Aggregate (2). Extraction and Recovery tests should be performed at each location sampled. Results of these tests (penetration, viscosity, asphalt content) together with thickness measurements made from the cores should help determine the uniformity of the section under consideration for recycling. Sufficient asphalt should be recovered to permit blending with asphalt modifiers for further testing.

Aggregate Properties (3). Aggregate recovered from the samples in step (2) above should be tested for gradation, durability such as Los Angeles Abrasion and Polish Value if the recycled mixture is to be utilized as a surface course. These data can be used to establish project uniformity together with the recovered asphalt data obtained in step (2).

New Aggregate (4). New aggregate may have to be added to the mixture for one or more of the following purposes:

1. Satisfy gradation requirements

2. Skid resistance requirements for surface courses

3. Air quality problems associated with hot, central plant recycling

4. Thickness requirements and

5. Improved stability, durability, flexibility, etc.

Gradation requirements for recycled mixtures should be those presently required by the specifying agency or those in ASTM D3515.

To provide initial and long lasting skid resistance for the recycled bituminous surface course, it may be necessary to blend coarse non-polishing aggregate with the recycled pavement. It appears as if 40 percent by volume of the plus No. 4 fraction should be non-polishing to provide the desired skid performance on moderate to high traffic volume facilities.

Replacing the recycled pavement with a thicker section of asphalt stabilized material may be required from a structural pavement design standpoint. This can be accomplished by blending new aggregate with the recycled material or by the addition of layers of new asphalt stabilized materials.

Asphalt Demand (5). The asphalt demand of the proposed recycled material can be estimated from equations developed in reference 28.

The asphalt demand determined in this manner should be considered an estimate and can be used as a starting point for mixture design purposes. It should be noted that the asphalt demand will be satisfied by the modifier as specified in Tables 9 and 10 (39). These modifiers can be softening agents, asphalt cements or blends of softening agents and asphalt cements or emulsified products.

Asphalt Properties (6). Asphalt recovered from the samples in step (2) above should be tested for penetration at 77°F and viscosity at 140°F. Asphalt content, penetration and viscosity should be determined on all extracted samples. These data can be used to determine project uniformity.

Determine Type and Amount of Modifiers (7) (8). The type and amount of modifiers can be selected by utilizing Figure 5 and Tables 9 and 10 (39) together with a definition of the penetration or preferable viscosity of the binder in the processed recycled mixture and a knowledge of the asphalt demand of the recycled mixture. By use of Figure 6 the viscosity of the modifier can be approximated. The figure is entered with the volume percent of lower viscosity modifier (47%) and the desired viscosity of the recycled binder to locate Point A. Point A is connected with the viscosity of the recovered salvaged binder and the line projected to obtain the viscosity of the modifier. Table 9 indicates that modifier RA 5 would likely be suitable.

It should be noted that new asphalt cement and a softer modifier could be utilized to form the new binder provided air quality requirements can be met.

Modifier Tests (9). Samples of modifiers to be used on the job should be obtained and subjected to tests to establish their conformance to specifications (Table 9 or 10) as well as establish the viscosity of the modifier in order to obtain a more realistic modifier content (Figure 6).

Blend Modifier With Recovered Asphalt (10). The modifier which may consist of an asphalt cement and softener should be blended with the recovered asphalt and subjected to viscosity and penetration tests to determine if the predicted viscosity (penetration) of the blend was accurate. It is suggested that two blends, one 5% above and one 5% below the percent recycling agent determined in steps (7) and (8) be made. About 75 to 100 grams of recovered asphalt for each blend should be utilized. A third blend may be required to confirm the desired viscosity or penetration.

Some recycling base stock modifiers may not be compatible with the salvaged asphalt. Therefore, a thin film oven test should be performed on the selected recovered salvaged asphalt-modifier blend. A ratio of the aged viscosity to original viscosity of less than 3 will indicate that the recycling agent is likely to be compatible with the recovered salvaged asphalt.

Preliminary Mixtures (11). Five different mixtures of recycled aggregate, new aggregate if desired, and modifier should be fabricated. Three samples of each mixture should be fabricated and subjected to stability testing and tests to determine the air void content. These preliminary tests should vary the percent new asphalt cement and/or the type and amount of modifiers. It is helpful to have an experienced engineer present during the mixing and molding operation as subsequent trial mixtures may depend upon the appearance of the first few trial mixtures. It should be realized that the modifiers often have a delayed softening reaction.

Standard mixing and molding operations should be utilized. An oven curing procedure after mixing and prior to compaction such as that used in California appears to be desirable.

Detailed Mixture Evaluations (12). The three most promising mixtures evaluated in step (11) should be evaluated in detail for properties which can be used in pavement thickness design and for durability considerations such as water susceptibility. The testing plan as shown in Figure 7 can be used as a guide. The amount of testing will depend upon the capability of the agency considering the recycling project. However, the authors feel that extraction and recovery tests are important as well as resilient modulus tests.

Properties of the extracted and recovered bituminous material from the laboratory prepared and recycled mixture are an indication of the compatibility and durability of the recycling modifiers. Preliminary laboratory testing has indicated that extraction and recovery tests will identify potential problems between the "old" asphalt and the modifier that tests performed on the blend on "old" asphalt and modifier do not identify.

The resilient modulus appears to be the best single test to identify the effect of the modifier on the mixture. This test is sensitive to the properties of the binder and will help define the amount of modifier required to produce a binder of known consistency. Resilient modulus values of the order of 200,000 to 400,000 psi (measured at 77°F, 0.0 record load duration) are typical of recycled mixtures blended with modifiers to produce binders equivalent to AC-10 asphalt cements.

Select Optimum Mixture Design (13). The optimum mixture design should be based on results of steps (11) and (12) and economic and energy considerations. Reference 37 can be used as a general guide. In general, final mixture designs should be based on stability requirements and air void criteria; however, the resilient modulus versus temperature relationship should be considered. The resilient modulus should be below about 900,000 psi (77°F and 0.1 second load duration) experience has shown.

Mixture Containing Emulsified Modifiers. The above discussion has been primarily directed toward the use of recycling agents specified in Table 9 in cold operations. Recycling in central plants or in place with emulsified modifiers is also an alternative that is considered on a number of projects. The design of mixtures containing emulsions required special considerations as outlined below:

1. The properties of the base modifier should be used in step (7) to determine the type and amount of emulsified modifier to be used.

2. The modifier sample tested in step (9) should be subjected to those tests required for specification compliance. Table contains example specifications for emulsified modifiers.

3. The base modifier should be used for the blends prepared in step (10). Tests should be performed as outlined in step (10).

4. Mixing and testing of recycled mixtures containing emulsified modifiers should be performed according to procedures outlined in Reference 40. Of the 11 methods identified in the reference it is suggested that The Asphalt Institue Method be utilized. Curing of the samples prior to testing is critical and should be closely followed and

5. Criteria for mixture designs are shown in Table 11. These criteria should be used on an interim basis.

PAVEMENT DESIGN

Design methods used for pavements containing recycled materials are those used for conventional pavements. Little research effort has been expected to characterize the local carrying ability of recycled materials in the laboratory or the field. Research performed at Texas A&M University (2) contains the majority of the existing information. These data are summarized below.

Dynaflect deflection measurements and pavement cores were obtained on pavements containing recycled materials. These data were utilized together with layered elastic computer programs and results from the AASHO Road Test to determine AASHTO strength coefficients and layer coefficients (stiffness equivalency). Data of the analysis method utilized can be found in references 2 and 41. Table 12 contains AASHTO structural layer coefficients computed for recycled surface courses while Table 13 contains AASHTO coefficients for base courses. A summary of typical AASHTO coefficients is shown on Table 14.

Material characterization parameters necessary for use with the more rational pavement design methods for the most part have not been estabilished. Resilient modulus, and limited flexural fatigue data have been developed at Texas A&M University. Additional research is under way at Ohio State University.

ECONOMICS AND ENERGY

Selection of the most appropriate rehabilitation or maintenance alternative for a particular project is largely dependent upon cost and energy comparisons. A method for selecting appropriate recycling operations for a given job has been outlined by Finn (42) while Halstead (43) has defined cost and energy considerations associated with project selection. Cost and energy data associated with recycling operations will be included in summary form for completeness.

Cost Considerations

The initial and recurring costs that an agency may consider in the economic evaluation of alternative rehabilitation strategies have been defined in Reference 44 and include the following:

1. Agency costs

   a. Initial capital costs of rehabilitation.
   b. Future capital costs of reconstruction or rehabilitation (overlays, seal coats, etc).
   c. Maintenance costs, recurring throughout the design period.
   d. Salvage return or residual value at the end of the design period.
   e. Engineering and administration and
   f. Costs of investments.

2. User costs

   a. Travel time
   b. Vehicle operation
   c. Accidents
   d. Discomfort and
   e. Time delay and extra vehicle operating costs during resurfacing or major maintenance.

3. Nonuser costs

Certainly all of these costs should be included if a detailed economic analysis is desired. However, definition of many of these costs is difficult while other costs do not significantly affect the analysis of alternative for a given roadway segment. For the sake of simplicity the method of analysis suggested for use in recycling operations should consider the following costs:

1. Initial capital costs of rehabilitation

2. Future capital costs of reconstruction or rehabilitation

3. Maintenance costs and

4. Salvage value.

It is suggested, however, that certain user costs such as time delay costs during rehabilitation be considered on high traffic volume facilities. The reader is directed to Reference 44 for additional detail.

Initial capital costs of various recycling operations are available from Reference 2 and are shown in Tables 15 and 16.

The cost figures given above are intended to be representative only. If cost data are available from the agency's historical records, they should be substituted appropriately.

Energy Considerations

Transportation of goods and services required 25 percent of the total 90 quadrillion (10^{15}) BTU (95,000 quadrillion J) annually consumed in the United States in 1977. This amount increases to 42 percent if the total amount of energy required for 1) the production of raw materials used in transportation vehicles, 2) manufacture of transportation vehicles and 3) the production of materials for construction, rehabilitation and maintenance of transportation facilities is considered.

Estimates of the energy consumed for highway construction are of the order of 1.7 percent of the total annual U. S. energy demand while maintenance and rehabilitation operations are estimated to require an additional 1.5 to 2.0 percent. Information developed by the author indicates that a reasonable energy estimate for routine pavement maintenance operations on our country's 3,800,000 mile highway system is 0.1 percent. Even with this relatively small percent of total energy consumption associated with highway construction and maintenance, it is, none-the-less, important that the engineer optimize these operations based on energy requirements just as he presently optimizes his operations based on cost.

Information given in Table 17 defines energy requirements for recycling operations. These energy requirements are intended to be representative only. If energy requirements for these operations are available from the agencies historical records, they should be substituted appropriately. Energy requirements for typical construction and reconstruction operations can be found in Reference 2.

SUMMARY AND CONCLUSIONS

Pavement recycling is a viable rehabilitation alternative. The major benefits of pavement recycling are lower costs, conservation of aggregates, binders and energy and preservation of the environment and existing highway geometrics.

In order to successfully utilize recycling, the engineer needs to be aware of the types of recycling, their advantages and disadvantages and methods available for mixture design, pavement thickness design and cost and energy analysis.

Realistic guidelines for the recycling of pavement materials have been developed and are briefly reviewed in the paper. The guidelines can be used by the practicing engineer and will provide the following information:

1. Point out the potential advantages of recycling.

2. Assist both in making a preliminary analysis of recycling as a pavement rehabilitation alternative and in identifying a suitable methodology.

3. Provide guidance and criteria for making a detailed analysis of cost, energy, material design, structural design, construction specifications, and quality control.

4. Recommend a methodology for evaluating project results so that recycling alternatives can be compared with conventional methods of rehabilitation.

The engineer is reminded that successful pavement recycling will require a larger amount of field and laboratory testing than that required for conventional rehabilitation alternatives.

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Table 1. Major advantages and disadvantages of recycling techniques

Recycling Techniques	Advantages	Disadvantages
Surface	• Reduces frequency of reflection cracking • Promotes bond between old pavement and thin overlay • Provides a transition between new overlay and existing gutter, bridge, pavement, etc. that is resistant to raveling (eliminates feathering) • Reduces localized roughness due to compaction • Treats a variety of types of pavement distress (raveling, flushing, corrugations, rutting, oxidized pavement, faulting) at a reasonable initial cost • Improve skid resistance	• Limited structural improvement • Heater-scarification and heater-planing has limited effectiveness on rough pavement without multiple passes of equipment • Limited repair of severely flushed or unstable pavements • Some air quality problems • Vegetation close to roadway may be damaged • Mixtures with maximum size aggregates greater than 1-inch cannot be treated with some equipment • Limited disruption to traffic
In-Place	• Significant structural improvements • Treats all types and degrees of pavement distress • Reflection cracking can be eliminated • Frost susceptibility may be improved • Improve ride quality • Improve skid resistance • Minimizes hauling	• Quality control not as good as central plant • Traffic disruption • Pulverization equipment in need of frequent repair • PCC pavements cannot be recycled in-place • Curing is often required for strength gain
Central	• Significant structural improvements • Treats all types and degrees of pavement distress • Reflection cracking can be eliminated • Improve skid resistance • Frost susceptibility may be improved • Geometrics can be more easily altered • Improved quality control if additional binder and/or aggregates must be used • Improve ride quality	• Potential air quality problems at plant site • Traffic disruption

After reference 2.

Table 2. Summary of existing pavement conditions

Feature	Value	Comment
Location		
Size of Project (Lane-Miles)		
Class of Roadway		
Existing Pavement Cross Section (include data, thickness and type of original pavement layers; date, thickness and type of subsequent rehabilitation and maintenance activities).		
GEOMETRICS (number of lanes, width, vertical clearance, other constraints)		
Traffic Characteristics ADT Average Dailey Eq. 18 kip (80 kN) axle loads		
Subgrade Characteristics		
Surface Condition (Pavement Rating Source, PRS)		
Structural Condition, (deflection, 0.001 inch) (.025 mm) overlay required		
Roughness (Serviceability Index)		
Skid Resistance (SN40)		
Other: Factors (distance to aggregate and binder source, available equipment and contractor experience)		

After reference 2.

Table 3. Selection of recycling techniques based on roadway conditions.

TYPE OF DISTRESS (■ = shaded cell)

	RECYCLING METHODS		RUTTING (% AREA)										RAVELING (% AREA)									
				1-15			16-30			30				1-15			16-30			30		
	CONDITION OF EXISTING PAVEMENT →		NONE	SLIGHT	MODERATE	SEVERE	SLIGHT	MODERATE	SEVERE	SLIGHT	MODERATE	SEVERE	NONE	SLIGHT	MODERATE	SEVERE	SLIGHT	MODERATE	SEVERE	SLIGHT	MODERATE	SEVERE
SURFACE	HEATER PLANER WITHOUT ADDITIONAL AGGREGATE	A1				■			■			■		■	■	■	■	■	■	■	■	■
	HEATER PLANER WITH ADDITIONAL AGGREGATE	A2				■			■			■		■	■	■	■	■	■	■	■	■
	HEATER SCARIFY	A3				■			■			■							■			■
	HEATER SCARIFY + THIN OVERLAY	A4																				
	HEATER SCARIFY + THICK OVERLAY	A5																				
	SURFACE MILLING	A6																				
	SURFACE MILLING + THIN OVERLAY	A7																				
	SURFACE MILLING + THICK OVERLAY	A8																				
IN PLACE	THIN ASPHALT CONCRETE - MINOR STRUCTURAL IMPROVEMENT WITHOUT NEW BINDER	B1																				
	THIN ASPHALT CONCRETE - MINOR STRUCTURAL IMPROVEMENT WITH NEW BINDER	B2																				
	THIN ASPHALT CONCRETE - MAJOR STRUCTURAL IMPROVEMENT WITHOUT NEW BINDER	B3																				
	THIN ASPHALT CONCRETE - MAJOR STRUCTURAL IMPROVEMENT WITH NEW BINDER	B4																				
	THICK ASPHALT CONCRETE - MINOR STRUCTURAL IMPROVEMENT WITHOUT NEW BINDER	B5																				
	THICK ASPHALT CONCRETE - MINOR STRUCTURAL IMPROVEMENT WITH NEW BINDER	B6																				
	THICK ASPHALT CONCRETE - MAJOR STRUCTURAL IMPROVEMENT WITHOUT NEW BINDER	B7																				
	THICK ASPHALT CONCRETE - MAJOR STRUCTURAL IMPROVEMENT WITH NEW BINDER	B8																				
CENTRAL PLANT	COLD PROCESS - MINOR STRUCTURAL IMPROVEMENT WITHOUT NEW BINDER	C1																				
	COLD PROCESS - MINOR STRUCTURAL IMPROVEMENT WITH NEW BINDER	C2																				
	COLD PROCESS - MAJOR STRUCTURAL IMPROVEMENT WITHOUT NEW BINDER	C3																				
	COLD PROCESS - MAJOR STRUCTURAL IMPROVEMENT WITH NEW BINDER	C4																				
	HOT PROCESS - MINOR STRUCTURAL IMPROVEMENT WITHOUT NEW BINDER	C5																				
	HOT PROCESS - MINOR STRUCTURAL IMPROVEMENT WITH NEW BINDER	C6																				
	HOT PROCESS - MAJOR STRUCTURAL IMPROVEMENT WITHOUT NEW BINDER	C7																				
	HOT PROCESS - MAJOR STRUCTURAL IMPROVEMENT WITH NEW BINDER	C8																				

	RECYCLING METHODS		FLUSHING (% AREA)										CORRUGATIONS (% AREA)									
				1-15			16-30			30				1-15			16-30			30		
	CONDITION OF EXISTING PAVEMENT →		NONE	SLIGHT	MODERATE	SEVERE	SLIGHT	MODERATE	SEVERE	SLIGHT	MODERATE	SEVERE	NONE	SLIGHT	MODERATE	SEVERE	SLIGHT	MODERATE	SEVERE	SLIGHT	MODERATE	SEVERE
SURFACE	HEATER PLANER WITHOUT ADDITIONAL AGGREGATE	A1							■		■	■							■		■	■
	HEATER PLANER WITH ADDITIONAL AGGREGATE	A2										■							■		■	■
	HEATER SCARIFY	A3				■		■	■		■	■				■			■		■	■
	HEATER SCARIFY + THIN OVERLAY	A4																				
	HEATER SCARIFY + THICK OVERLAY	A5																				
	SURFACE MILLING	A6																				
	SURFACE MILLING + THIN OVERLAY	A7																				
	SURFACE MILLING + THICK OVERLAY	A8																				
IN PLACE	THIN ASPHALT CONCRETE - MINOR STRUCTURAL IMPROVEMENT WITHOUT NEW BINDER	B1																				
	THIN ASPHALT CONCRETE - MINOR STRUCTURAL IMPROVEMENT WITH NEW BINDER	B2																				
	THIN ASPHALT CONCRETE - MAJOR STRUCTURAL IMPROVEMENT WITHOUT NEW BINDER	B3																				
	THIN ASPHALT CONCRETE - MAJOR STRUCTURAL IMPROVEMENT WITH NEW BINDER	B4																				
	THICK ASPHALT CONCRETE - MINOR STRUCTURAL IMPROVEMENT WITHOUT NEW BINDER	B5																				
	THICK ASPHALT CONCRETE - MINOR STRUCTURAL IMPROVEMENT WITH NEW BINDER	B6																				
	THICK ASPHALT CONCRETE - MAJOR STRUCTURAL IMPROVEMENT WITHOUT NEW BINDER	B7																				
	THICK ASPHALT CONCRETE - MAJOR STRUCTURAL IMPROVEMENT WITH NEW BINDER	B8																				
CENTRAL PLANT	COLD PROCESS - MINOR STRUCTURAL IMPROVEMENT WITHOUT NEW BINDER	C1																				
	COLD PROCESS - MINOR STRUCTURAL IMPROVEMENT WITH NEW BINDER	C2																				
	COLD PROCESS - MAJOR STRUCTURAL IMPROVEMENT WITHOUT NEW BINDER	C3																				
	COLD PROCESS - MAJOR STRUCTURAL IMPROVEMENT WITH NEW BINDER	C4																				
	HOT PROCESS - MINOR STRUCTURAL IMPROVEMENT WITHOUT NEW BINDER	C5																				
	HOT PROCESS - MINOR STRUCTURAL IMPROVEMENT WITH NEW BINDER	C6																				
	HOT PROCESS - MAJOR STRUCTURAL IMPROVEMENT WITHOUT NEW BINDER	C7																				
	HOT PROCESS - MAJOR STRUCTURAL IMPROVEMENT WITH NEW BINDER	C8																				

	RECYCLING METHODS		ALLIGATOR CRACKING (% AREA)										LONGITUDINAL CRACKING (LIN FT PER STA/LN)									
				1-5			6-25			25				10-99			100-199			200		
	CONDITION OF EXISTING PAVEMENT →		NONE	SLIGHT	MODERATE	SEVERE	SLIGHT	MODERATE	SEVERE	SLIGHT	MODERATE	SEVERE	NONE	SLIGHT	MODERATE	SEVERE	SLIGHT	MODERATE	SEVERE	SLIGHT	MODERATE	SEVERE
SURFACE	HEATER PLANER WITHOUT ADDITIONAL AGGREGATE	A1		■	■	■	■	■	■	■	■	■		■	■	■	■	■	■	■	■	■
	HEATER PLANER WITH ADDITIONAL AGGREGATE	A2		■	■	■	■	■	■	■	■	■		■	■	■	■	■	■	■	■	■
	HEATER SCARIFY	A3			■	■	■	■	■	■	■	■		■	■	■	■	■	■	■	■	■
	HEATER SCARIFY + THIN OVERLAY	A4				■		■	■	■	■	■				■		■	■	■	■	■
	HEATER SCARIFY + THICK OVERLAY	A5																				
	SURFACE MILLING	A6		■	■	■	■	■	■	■	■	■		■	■	■	■	■	■	■	■	■
	SURFACE MILLING + THIN OVERLAY	A7			■	■	■	■	■	■	■	■										
	SURFACE MILLING + THICK OVERLAY	A8																				
IN PLACE	THIN ASPHALT CONCRETE - MINOR STRUCTURAL IMPROVEMENT WITHOUT NEW BINDER	B1				■		■	■	■	■	■										
	THIN ASPHALT CONCRETE - MINOR STRUCTURAL IMPROVEMENT WITH NEW BINDER	B2				■		■	■	■	■	■										
	THIN ASPHALT CONCRETE - MAJOR STRUCTURAL IMPROVEMENT WITHOUT NEW BINDER	B3																				
	THIN ASPHALT CONCRETE - MAJOR STRUCTURAL IMPROVEMENT WITH NEW BINDER	B4																				
	THICK ASPHALT CONCRETE - MINOR STRUCTURAL IMPROVEMENT WITHOUT NEW BINDER	B5				■		■	■	■	■	■										
	THICK ASPHALT CONCRETE - MINOR STRUCTURAL IMPROVEMENT WITH NEW BINDER	B6				■		■	■	■	■	■										
	THICK ASPHALT CONCRETE - MAJOR STRUCTURAL IMPROVEMENT WITHOUT NEW BINDER	B7																				
	THICK ASPHALT CONCRETE - MAJOR STRUCTURAL IMPROVEMENT WITH NEW BINDER	B8																				
CENTRAL PLANT	COLD PROCESS - MINOR STRUCTURAL IMPROVEMENT WITHOUT NEW BINDER	C1				■		■	■	■	■	■										
	COLD PROCESS - MINOR STRUCTURAL IMPROVEMENT WITH NEW BINDER	C2				■		■	■	■	■	■										
	COLD PROCESS - MAJOR STRUCTURAL IMPROVEMENT WITHOUT NEW BINDER	C3																				
	COLD PROCESS - MAJOR STRUCTURAL IMPROVEMENT WITH NEW BINDER	C4																				
	HOT PROCESS - MINOR STRUCTURAL IMPROVEMENT WITHOUT NEW BINDER	C5				■		■	■	■	■	■										
	HOT PROCESS - MINOR STRUCTURAL IMPROVEMENT WITH NEW BINDER	C6				■		■	■	■	■	■										
	HOT PROCESS - MAJOR STRUCTURAL IMPROVEMENT WITHOUT NEW BINDER	C7																				
	HOT PROCESS - MAJOR STRUCTURAL IMPROVEMENT WITH NEW BINDER	C8																				

	RECYCLING METHODS		TRANSVERSE CRACKING (NO. PER STA)										PATCHING (% AREA)									
				1-4			5-9			10				1-5			6-15			15		
	CONDITION OF EXISTING PAVEMENT →		NONE	SLIGHT	MODERATE	SEVERE	SLIGHT	MODERATE	SEVERE	SLIGHT	MODERATE	SEVERE	NONE	SLIGHT	MODERATE	SEVERE	SLIGHT	MODERATE	SEVERE	SLIGHT	MODERATE	SEVERE
SURFACE	HEATER PLANER WITHOUT ADDITIONAL AGGREGATE	A1		■	■	■	■	■	■	■	■	■		■	■		■	■	■	■	■	■
	HEATER PLANER WITH ADDITIONAL AGGREGATE	A2		■	■	■	■	■	■	■	■	■		■	■		■	■	■	■	■	■
	HEATER SCARIFY	A3		■	■	■	■	■	■	■	■	■		■	■		■	■	■	■	■	■
	HEATER SCARIFY + THIN OVERLAY	A4				■		■	■	■	■	■				■		■	■	■	■	■
	HEATER SCARIFY + THICK OVERLAY	A5																				
	SURFACE MILLING	A6		■	■	■	■	■	■	■	■	■		■	■		■	■	■	■	■	■
	SURFACE MILLING + THIN OVERLAY	A7				■		■	■	■	■	■				■		■	■	■	■	■
	SURFACE MILLING + THICK OVERLAY	A8																				
IN PLACE	THIN ASPHALT CONCRETE - MINOR STRUCTURAL IMPROVEMENT WITHOUT NEW BINDER	B1																	■		■	■
	THIN ASPHALT CONCRETE - MINOR STRUCTURAL IMPROVEMENT WITH NEW BINDER	B2																	■		■	■
	THIN ASPHALT CONCRETE - MAJOR STRUCTURAL IMPROVEMENT WITHOUT NEW BINDER	B3																				
	THIN ASPHALT CONCRETE - MAJOR STRUCTURAL IMPROVEMENT WITH NEW BINDER	B4																				
	THICK ASPHALT CONCRETE - MINOR STRUCTURAL IMPROVEMENT WITHOUT NEW BINDER	B5																	■		■	■
	THICK ASPHALT CONCRETE - MINOR STRUCTURAL IMPROVEMENT WITH NEW BINDER	B6																	■		■	■
	THICK ASPHALT CONCRETE - MAJOR STRUCTURAL IMPROVEMENT WITHOUT NEW BINDER	B7																				
	THICK ASPHALT CONCRETE - MAJOR STRUCTURAL IMPROVEMENT WITH NEW BINDER	B8																				
CENTRAL PLANT	COLD PROCESS - MINOR STRUCTURAL IMPROVEMENT WITHOUT NEW BINDER	C1																	■		■	■
	COLD PROCESS - MINOR STRUCTURAL IMPROVEMENT WITH NEW BINDER	C2																	■		■	■
	COLD PROCESS - MAJOR STRUCTURAL IMPROVEMENT WITHOUT NEW BINDER	C3																				
	COLD PROCESS - MAJOR STRUCTURAL IMPROVEMENT WITH NEW BINDER	C4																				
	HOT PROCESS - MINOR STRUCTURAL IMPROVEMENT WITHOUT NEW BINDER	C5																	■		■	■
	HOT PROCESS - MINOR STRUCTURAL IMPROVEMENT WITH NEW BINDER	C6																	■		■	■
	HOT PROCESS - MAJOR STRUCTURAL IMPROVEMENT WITHOUT NEW BINDER	C7																				
	HOT PROCESS - MAJOR STRUCTURAL IMPROVEMENT WITH NEW BINDER	C8																				

After reference 2.

TABLE 4. SELECTION OF RECYCLING TECHNIQUES TO IMPROVE STRUCTURAL STRENGTH BASED ON PAVEMENT REFLECTION.

Recycling Methods			Thickness of Required Overlay		
			None	Less Than 2 inches	Greater Than 2 inches
Heater Planer	A1	Without additional aggregate			
	A2	With additional aggregate			
Heater scarify	A3	Heater scarify only			
	A4	Heater scarify plus thin overlay or aggregate			
	A5	Heater scarify plus thick overlay			
Surface milling or grinding	A6	Surface milling only			
	A7	Surface milling plus thin overlay			
	A8	Surface milling plus thick overlay			
Asphalt concrete surface less than 2-inches	B1	Minor structural improvement without new binder			
	B2	Minor structural improvement with new binder			
	B3	Major structural improvement without new binder			
	B4	Major structural improvement with new binder			
Asphalt concrete surface greater than 2-inches	B5	Minor structural improvement without new binder			
	B6	Minor structural improvement with new binder			
	B7	Major structural improvement without new binder			
	B8	Major structural improvement with new binder			
Cold mix process	C1	Minor structural improvement without new binder			
	C2	Minor structural improvement with new binder			
	C3	Major structural improvement without new binder			
	C4	Major structural improvement with new binder			
Hot mix process	C5	Minor structural improvement without new binder			
	C6	Minor structural improvement with new binder			
	C7	Major structural improvement without new binder			
	C8	Major structural improvement with new binder			

1 inch = 25.4 mm

After reference 2.

TABLE 5. SELECTION OF SURFACE RECYCLING TECHNIQUES BASED ON ROUGHNESS

Recycling Methods \ Type of Facility / Serviceability Index		Interstate Urban Freeway				Primary				Secondary				Urban Streets			
		+3.0	2.5-2.9	2.0-2.4	-2.0	+3.0	2.5-2.9	2.0-2.4	-2.0	+3.0	2.5-2.9	2.0-2.4	-2.0	+3.0	2.5-2.9	2.0-2.4	-2.0
Heater Planer Without Additional Aggregate	A1		■	■	■			■	■				■			■	■
Heater Planer With Additional Aggregate	A2		■	■	■			■	■				■			■	■
Heater Scarify	A3		■	■	■			■	■				■			■	■
Heater Scarify and Thin Overlay	A4			■	■				■								■
Heater Scarify and Thick Overlay	A5																
Surface Milling	A6			■	■				■								
Surface Milling and Thin Overlay	A7				■												
Surface Milling and Thick Overlay	A8																

After reference 2.

TABLE 6. SUMMARY OF PRELIMINARY RECYCLING ALTERNATIVES.

Recycling Methods				Surface Condition	Deflection	Roughness	Skid Resistance
Surface	Heater Planer	Without additional aggregate	A1				
		With additional aggregate	A2				
	Heater scarify	Heater scarify only	A3				
		Heater scarify plus thin overlay or aggregate	A4				
		Heater scarify plus thick overlay	A5				
	Surface milling or grinding	Surface milling only	A6				
		Surface milling plus thin overlay	A7				
		Surface milling plus thick overlay	A8				
In Place	Asphalt concrete surface less than 2-inches	Minor structural improvement without new binder	B1				
		Minor structural improvement with new binder	B2				
		Major structural improvement without new binder	B3				
		Major structural improvement with new binder	B4				
	Asphalt concrete surface greater than 2-inches	Minor structural improvement without new binder	B5				
		Minor structural improvement with new binder	B6				
		Major structural improvement without new binder	B7				
		Major structural improvement with new binder	B8				
Central Plant	Cold mix process	Minor structural improvement without new binder	C1				
		Minor structural improvement with new binder	C2				
		Major structural improvement without new binder	C3				
		Major structural improvement with new binder	C4				
	Hot mix process	Minor structural improvement without new binder	C5				
		Minor structural improvement with new binder	C6				
		Major structural improvement without new binder	C7				
		Major structural improvement with new binder	C8				

1 inch = 25.4 mm

Table 7. Tentative Short-Term Soil-Lime Mixture Compressive Strength Requirements.

Anticipated Use	Residual Strength Requirement, PSI
Modified Subgrade	20
Subbase	
Rigid Pavement	20
Flexible Pavement	
Thickness of Cover	
10 Inches	30
8 Inches	40
5 Inches	60
Base	100

After reference 26.

Table 8. Criteria for Soil-Cement as Indicated by Wet-Dry and Freeze-Thaw Durability Tests

AASHTO Soil Group	Unified Soil Group	Max. Allowable Weight Loss - Percent
A-1-a	GW, GP, GM, SW, SP, SM	14
A-1-b	GM, GP, SM, SP	14*
A-2	GM, GC, SM, SC	14
A-3	SP	14
A-4	CL, ML	10
A-5	ML, MH, CH	10
A-6	CL, CH	7
A-7	OH, MH, CH	7

*10% is maximum allowable weight loss for A-2-6 and A-2-7 soils.

Additional Criteria:

1. Maximum volume changes during durability test should be less than 2 percent of the initial volume.
2. Maximum water content during the test should be less than the quantity required to saturate the sample at the time of molding.
3. Compressive strength should increase with age of specimen.

After reference 25.

Table 9. Proposed Specifications for Hot Mix Recycling Agents[1].

	ASTM Test Method	RA 5 Min.	RA 5 Max.	RA 25 Min.	RA 25 Max.	RA 75 Min.	RA 75 Max.	RA 250 Min.	RA 250 Max.	RA 500 Min.	RA 500 Max.
Viscosity @ 140°F, cSt	D 2170 or 2171	200	800	1000	4000	5000	10000	15000	35000	40000	60000
Flash Point COC, °F	D 92	400	-	425	-	450	-	450	-	450	-
Saturates, wt. %	D 2007	-	30	-	30	-	30	-	30	-	30
Residue from RTF-C Oven Test @ 325°F	D 2872[2]										
Viscosity Ratio[3]	-	-	3	-	3	-	3	-	3	-	3
RTF-C Oven Weight Change ± %	D 2872[2]	-	4	-	4	-	2	-	2	-	2
Specific Gravity	D 70 or D 1298	Report		Report		Report		Report		Report	

1. The final acceptance of recycling agents meeting this specification is subject to the compliance of the reconstituted asphalt blends with current asphalt specifications.

2. The use of ASTM D 1754 has not been studied in the context of this specification, however, it may be applicable. In cases of dispute the reference method shall be ASTM D 2872.

3. $\text{Viscosity Ratio} = \dfrac{\text{RTF-C Viscosity at 140°F, cSt}}{\text{Original Viscosity at 140°F, cSt}}$

After Reference 39.

Table 10. Interim Specifications for Emulsified Modifiers.

Property	Function and Purpose	Test Method	Specifications
Viscosity @ 77°F, SFS	Ease of Handling	ASTM D 244-76	15-85
Pumping Stability	Prevention of Premature Breaking	G.B. Method(2)	Pass
Emulsion Coarseness, Percent	Optimal Distribution	Sieve Test, ASTM D 244-76 (MOD(3)	0.1 Max.
Sensitivity to Fines, Percent	Adequate Mixing Life	Cement Mixing, ASTM D 244-76	2.0 Max.
Particle Charge	Preferential affinity to Asphalt	ASTM D 244-76	Positive
Concentration of Oil Phase, Percent	Assurance of Oil Content and for Calculations	ASTM D 244-76 (MOD)(4)	60 Min.

1. Oils used for emulsions must meet specifications listed in Table 9.

2. Pumping stability is determined by charging 450 ml of emulsion into a one-liter beaker and circulating the emulsion through a gear pump (Roper 29,B22621) having 1/4" inlet and outlet. The emulsion passes if there is no significant oil separation after circulating ten minutes.

3. Test procedure identical with ASTM D 244 except that distilled water shall be used in place of two percent sodium oleate solution.

4. ASTM D 244 Evaporation Test for percent of residue is modified by heating 50 gram sample to 300°F until foaming ceases, then cooling immediately and calculating results.

After Reference 39.

Table 11. Test Methods.

Test Method		Base or Temporary Surface: Dense Graded	Base or Temporary Surface: Open Graded	Permanent Surface: Dense Graded	Permanent Surface: Open Graded
Coating, %		50 min.	50 min.	75 min.	75 min.
Run-off, % Residual Asphalt		N. A.	0.5 max.	N. A.	0.5 max.
Wash-off, % Residual Asphalt		N. A.	0.5 max.	N. A.	0.5 max.
Combined (Run-off and Wash-off), %		N. A.	0.5 max.	N. A.	0.5 max.
Resistance R_t-Value @ 73 ± 5°F (23 ± 2.8°C)	Early Cure*	70 min.	N. A.	N. A.	N. A.
	Fully Cured + Water Soak**	78 min.	N. A.	N. A.	N. A.
Stabilometer S-Value @ 140 ± 5°F** (60 ± 2.8°C)		N. A.	N. A.	30 min.	N. A.
Cohesiometer C-Value @ 73 ± 5°F (23 ± 2.8°C)	Early Cure*	50 min.***	N. A.	N. A.	N. A.
	Fully Cured + Water Soak**	100 min.***	N. A.	N. A.	N. A.
Cohesiometer C-Value @ 140 ± 5°F** (60 ± 2.8°C)		N. A.	N. A.	100 min.	N. A.

*Cured in the mold for a total of 24 hours at a temperature of 73 ± 5°F (23 ± 2.8°C).

**Cured in the mold for a total of 72 hours at a temperature of 73 ± 5°F (23 ± 2.8°C) plus vacuum disiccation.

***Applicable to temporary wearing surface only.

Note: Besides meeting the above requirements, the mix must be reasonably workable (i.e., not too stiff or sloppy).

After Reference 40.

Table 12. AASHTO structural layer coefficients computed for the recycled surfaces evaluated.

Project	Computed Structural Layer Coefficient, a_1,' Based on the Response Criterion of W_s *	$\varepsilon_{ac}(N_{18})$ **	a_1' Selected
Interstate 8, Gila Bend, Arizona	0.44	0.46	0.44
U.S. Highway 666, Graham County, Arizona	0.46	0.49	0.46
Kossuth County, Iowa	0.43	0.46	0.43
Trunk Highway 94, Minnesota	0.42	0.42	0.42
Interstate 15, Henderson, Nevada	0.57	0.60	0.57
Hillsboro to Silverton Highway, Woodburn, Oregon	0.49	0.54	0.49
Interstate 20, Roscoe, Texas	0.44	0.44	0.44
U.S. Highway 36, Burleson County, Texas	0.54	0.65	0.54
U.S. Highway 54, Dalhart, Texas	0.43	0.44	0.43
U.S. Highway 277, Abilene, Texas	0.44	0.44	0.44
Loop 374, Mission, Texas (Section 1)	0.45	0.48	0.45
Loop 374, Mission, Texas (Section 2)	0.46	0.48	0.46

(Continued)

Table 12 - Continued.

Project	Computed Structural Layer Coefficient, a_1' Based on the Response Criterion of		
	W_s	$\varepsilon_{ac}(N_{18})$	a_1' Selected
Loop 374, Mission, Texas (Section 3)	0.39	0.38	0.39
U.S. Highway 50, Holden, Utah	0.54	0.66	0.54
Blewitt Pass, Washington	0.46	0.46	0.46
Rye Grass, Washington	0.47	0.51	0.47

* W_s = subgrade deformation

** N_{18} = number of 18 kip (80.1 KN) load applications to failure based on relationship between tensile strain in recycled AC layer, ε_{ac}, and N_{18}.

After reference 2.

Table 13. Structural layer coefficients computed for the recycled bases evaluated.

Recycled Base	Description of Recycled Base	Reference Base Thickness Inches,	Structural Layer Coefficient of Recycled Base, a_2'
18th Avenue, Lemoore, California	Crushed AC + 3.5% cyclogen	14 10 6	0.40 0.42 0.46
Russel Avenue, California	Crushed AC + 1.1% cyclogen HE	14 10 6	0.36 0.40 0.42
Highway 45, Yolo, California	Crushed AC + existing base and native sub-grade stabilized with lime	14 10 6	0.40 0.42 0.46
U.S. Highway 56, Kansas (Section 2)	Crushed AC+ 1.5% cement and 3.8% water	14 10 6	0.45 0.49 0.56
U.S. Highway 56, Kansas (Section 3)	Crushed AC + 1% MC-800	14 10 6	0.41 0.45 0.50
U.S. Highway 56, Kansas (Section 4)	Crushed AC + 1.5% cement, 1.5% AC-7 and 4% water	14 10 6	0.44 0.49 0.55
TH 94, Minnesota	Crushed AC + existing base + 2.5% AC	14 10 6	0.46 0.51 0.54
U.S. Highway 50, Nevada	Crushed AC + existing base + cement	14 10 6	0.25 0.27 0.31

Table 13 - Continued.

Recycled Base	Description of Recycled Base	Reference Base Thickness, Inches	Structural Layer Coefficient of Recycled Base, a_2'
U.S. Highway 93, Nevada	Crushed AC + existing base + cement	14 10 6	0.53 0.56 0.61
Ponderosa Avenue, Inclined Village, Nevada	Crushed AC + existing base + cement	14 10 6	0.25 0.27 0.31
Interstate 20, Roscoe, Texas	Crushed AC + existing base + 2.8% AC-3	14 10 6	0.41 0.43 0.46
Russel Avenue, California	Crushed AC + 1.1% cyclogen HE	14 10 6	0.36 0.40 0.42
U.S. Highway 84, Texas (Section 1)	Crushed AC + base + 5% asphalt emulsion	14 10 6	0.52 0.56 0.62

1 inch = 2.54 cm

After reference 2.

Table 14. Typical AASHTO Structural Layer Coefficients

Type of Recycled Material	Layer Used as	Range of a_i Computed	Average a_i	Number of Test Sections	a_i for Corresponding Layer and Material at AASHTO Road Test
Central Plant Recycled Asphalt Concrete Surface	Surface	0.37-0.59	0.48	14	0.44
Central Plant Recycled Asphalt Concrete Base	Base	0.37-0.49	0.42	3	0.35
In-Place Recycled Asphalt Concrete Stabilized with Asphalt and/or an Asphalt Modifier	Base	0.22-0.49	0.39	6	0.35
In-Place Recycled Asphalt Concrete and Existing Base Material Stabilized with Cement	Base	0.23-0.42	0.33	4	0.15-0.23
In-Place Recycled Asphalt Concrete and Existing Base Stabilized with Lime	Base	0.40	0.40	1	0.15-0.30
In-Place Recycled Asphalt Road Mix Stabilized with Asphalt	Surface	0.42	0.42	1	

After reference 2.

Table 15. Representative Costs for Pavement Recycling Operations - 1979.

Type	Operation	Option or Expected Results		Representative Cost Per Square Yard: Average	Representative Cost Per Square Yard: Range	Assumptions
A. Surface	Heater Planer	Without additional aggregate	A1	0.60	0.45 - 1.15	Heat, plane, clean-up, haul, traffic control.
		With additional aggregate	A2	0.55	0.40 - 1.00	Spread aggregate, heat, roll, traffic control and clean-up.
	Heater Scarify	Heater scarify only	A3	0.60	0.35 - 1.00	Heat, scarify, recompact, traffic control (3/4 inch scarification).
		Heater scarify plus thin overlay of aggregate	A4	0.40	1.00 - 1.75	Heat, scarify, recompact, add 50 lbs. of asphalt concrete per square yard, compact, traffic control (3/4 inch scarification).
		Heater scarify plus thick overlay	A5	4.10	3.25 - 5.00	Heat, scarify, recompact, add 300 lbs. of asphalt concrete per square yard, compact, traffic control (3/4 inch scarification).
	Surface Milling or Grinding	Surface milling only	A6	0.75	0.45 - 1.50	Milling, cleaning, hauling, traffic control (1 inch removal).
		Surface milling plus thin overlay	A7	3.25	2.50 - 3.75	Milling, cleaning, hauling, 200 lbs of asphalt concrete, traffic control (1 inch removal).
		Surface milling plus thick overlay	A8	5.75	4.70 - 7.20	Milling, cleaning, hauling, 400 lbs. of asphalt concrete, traffic control (1 inch removal).

Table 15. Continued.

Type	Operation	Option or Expected Results		Representative Cost Per Square Yard Average	Range	Assumptions
B. In-Place	Asphalt Concrete Surface less than 5 inches	Minor structural improvement without new binder	B1	3.50	2.75 - 4.25	Rip, pulverize and remix to 4 inch depth with 2 inches of asphalt concrete, traffic control.
		Minor structural improvement with new binder	B2	3.00	2.40 - 3.70	Rip, pulverize and remix with stabilizer to 4 inch depth with 1 inch of asphalt concrete, traffic control.
		Major structural improvement without new binder	B3	6.50	5.10 - 7.90	Rip, pulverize and remix to 6 inch depth with 4 inches of asphalt concrete, traffic control.
		Major structural improvement with new binder	B4	5.10	4.10 - 6.20	Rip, pulverize and remix with stabilizer to 6 inch depth with 2 inches of asphalt concrete, traffic control.
	Asphalt Concrete Surface greater than 5 inches	Minor structural improvement without new binder	B5	3.75	3.00 - 4.50	Rip, pulverize and remix to 4 inch depth with 2 inches of asphalt concrete, traffic control.
		Minor structural improvement with new binder	B6	3.25	2.60 - 3.90	Rip, pulverize and remix with stabilizer to 4 inch depth with 1 inch of asphalt concrete, traffic control.
		Major structural improvement without new binder	B7	6.90	5.50 - 8.25	Rip, pulverize and remix to 6 inch depth with 4 inches of asphalt concrete, traffic control.
		Major structural improvement with new binder	B8	5.50	4.35 - 6.65	Rip, pulverize and remix with stabilizer to 6 inch depth with 2 inches of asphalt concrete, traffic control.

Table 15. Continued

Type	Operation	Option or Expected Results		Representative Cost Per Square Yard		Assumptions
				Average	Range	
C. Central Plant	Cold Mix Process	Minor structural improvement without new binder	C1	4.50	3.60 - 5.40	Remove, crush and replace to 4 inch depth with 2 inches of asphalt concrete, traffic control.
		Minor structural improvement with new binder	C2	3.75	3.00 - 4.50	Remove, crush, mix and replace to 4 inch depth with 1 inch of asphalt concrete, traffic control.
		Major structural improvement without new binder	C3	8.00	6.40 - 9.70	Remove, crush and replace to 6 inch depth with 4 inches of asphalt concrete, traffic control.
		Major structural improvement with new binder	C4	6.25	5.00 - 7.50	Remove, crush, mix and replace to 6 inch depth with 2 inches of asphalt concrete, traffic control.
		Minor structural improvement without new binder	C5	4.90	3.90 - 5.90	Remove, crush and replace to 4 inch depth with 1.5 inches of asphalt concrete, traffic control.
		Minor structural improvement with new binder	C6	4.10	3.25 - 5.00	Remove, crush, mis and replace to 4 inch depth with 1/2 inch of asphalt concrete, traffic control.
		Major structural improvement without new binder	C7	8.25	6.60 - 9.90	Remove, crush and replace to 6 inch depth with 3 inches of asphalt concrete, traffic control.
		Major structural improvement with new binder	C8	6.50	5.25 - 7.75	Remove, crush, mix and replace to 6 inch depth with 1 inch of asphalt concrete.

After reference 2.

Table 16. Costs of Common Recycling Operations - 1979.

Recycling Operation	Representative Cost Dollars - Per Square Yard - Inch*	
	Average	Range
Heat and Plane Pavement - 3/4 inch depth	0.30	0.15 - 0.60
Heat and Scarify Pavement - 3/4 inch depth	0.50	0.15 - 0.90
Cold Mill Pavement	0.85	0.30 - 1.25
Rip, Pulverize and Compact - Existing Pavement less than 5 inches of Asphalt Concrete	0.25	0.13 - 0.45
Rip, Pulverize, Stabilize and Compact - Existing Pavement less than 5 inches of Asphalt Concrete	0.45	0.20 - 0.50
Rip, Pulverize and Compact - Existing Pavement greater than 5 inches of Asphalt Concrete	0.30	0.15 - 0.50
Rip, Pulverize, Stabilize and Compact - Existing Pavement greater than 5 inches of Asphalt Concrete	0.50	0.25 - 0.60
Remove and Crush Portland Cement Concrete	0.60	0.30 - 0.90
Remove and Crush Asphalt Concrete	0.40	0.20 - 0.60
Cold Process - Remove, Crush, Place, Compact, Traffic Control - (Cold Process) without Stabilizer	0.50	0.30 - 0.75
Cold Process - Remove, Crush, Mix, Place Compact, Traffic Control - (Cold Process) with Stabilizer	0.60	0.35 - 0.90
Hot Process - Remove, Crush, Place, Compact, Traffic Control - without Stabilizer	0.75	0.45 - 1.20
Hot Process - Remove, Crush, Mix, Place, Compact, Traffic Control - with Stabilizer	0.90	0.50 - 1.25

*Costs are for a square yard inch except where listed.

1 yd = 8.361×10^{-1} m^2 1 in. = 2.54×10^{-2} m

After reference 2.

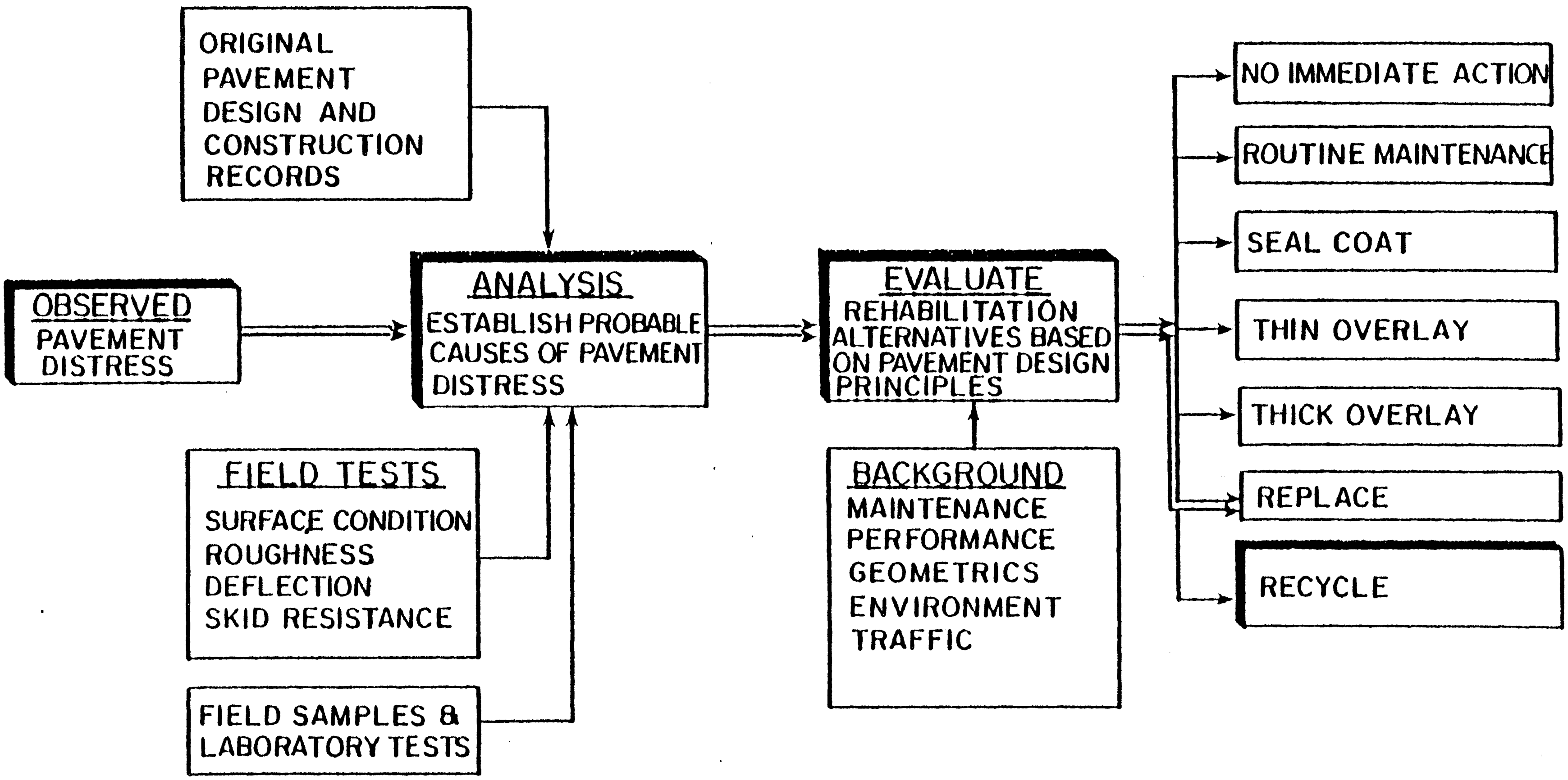
Table 17. Representative Energy Requirements for Pavement Recycling Operations.

Recycling Method	Btu/Yd^2	Thickness of Treatment, In.
Heater-Planer	10,000 - 20,000	3/4
Heater-Scarify	10,000 - 20,000	3/4
Hot-Milling	2,000 - 4,000	1
Cold-Milling	1,000 - 2,500	1
In-Place Recycling	15,000 - 20,000	1
Hot Central Plant Recycling	20,000 - 25,000	1

After Reference 2.

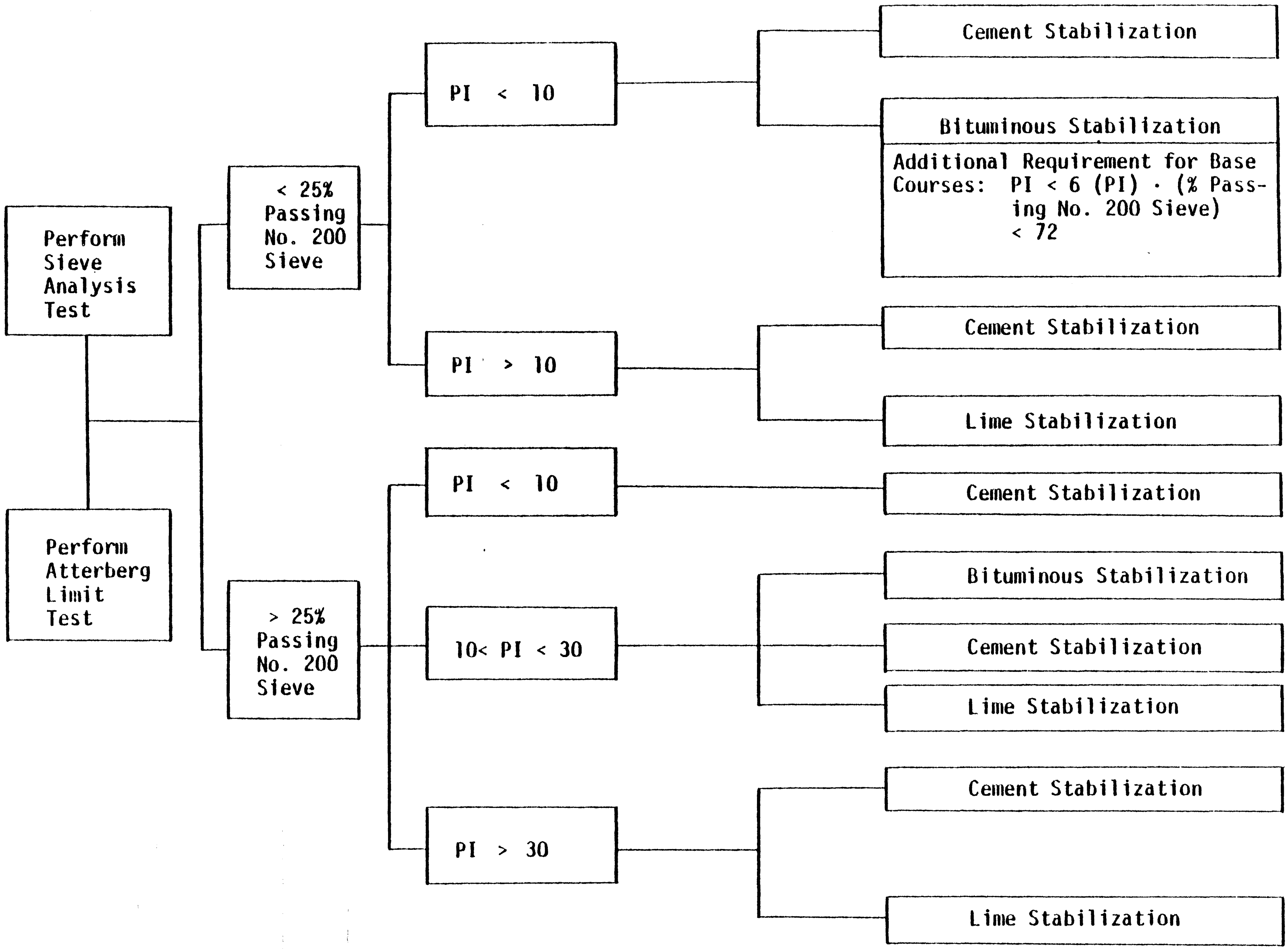
$$1\ Btu/Yd^3 = 1381\ J/m^3$$

Figure 1. Recycling as a rehabilitation alternative.



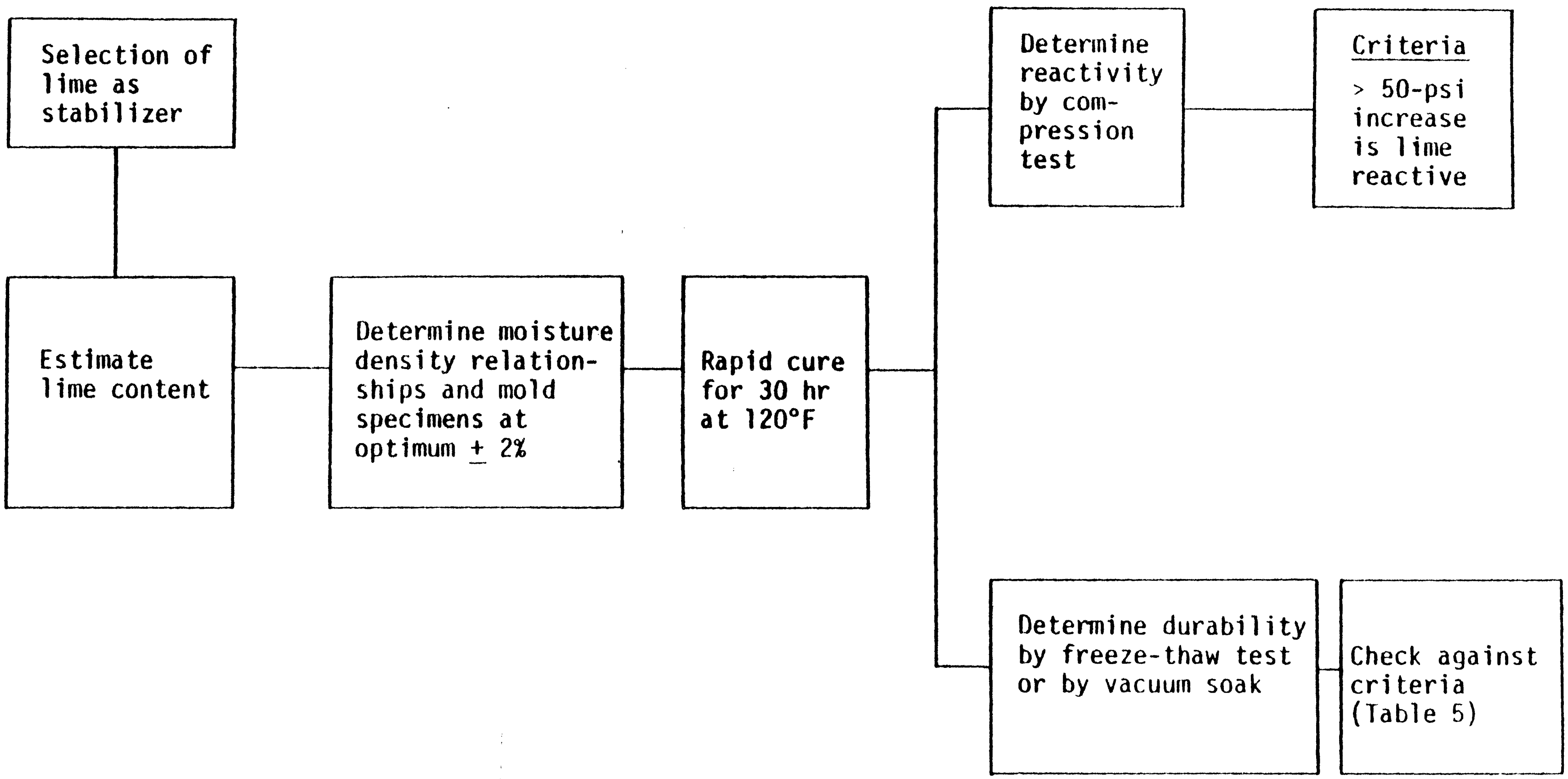
After reference 2.

Figure 2. Selection of Stabilizer.



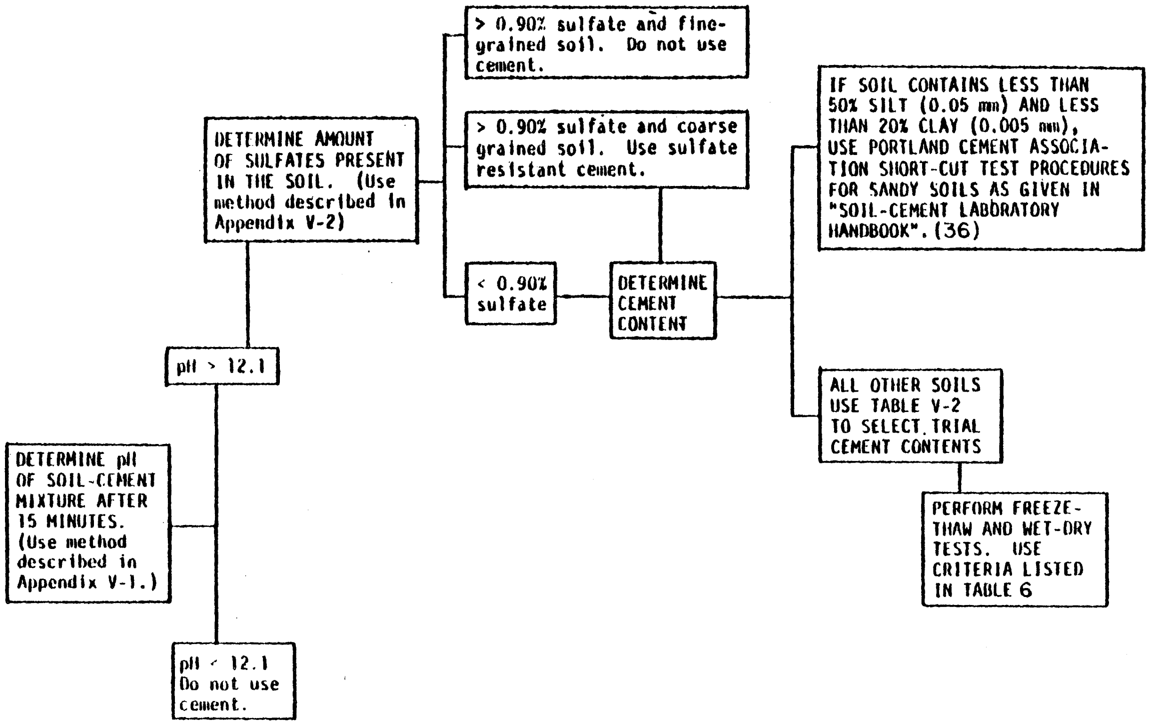
After reference 23.

Figure 3. Design Subsystem for Stabilization with Lime.



After reference 25.

Figure 4. Design Subsystem for Stabilization with Portland Cement.



After reference 25.

Figure 5. Mixture design procedure.

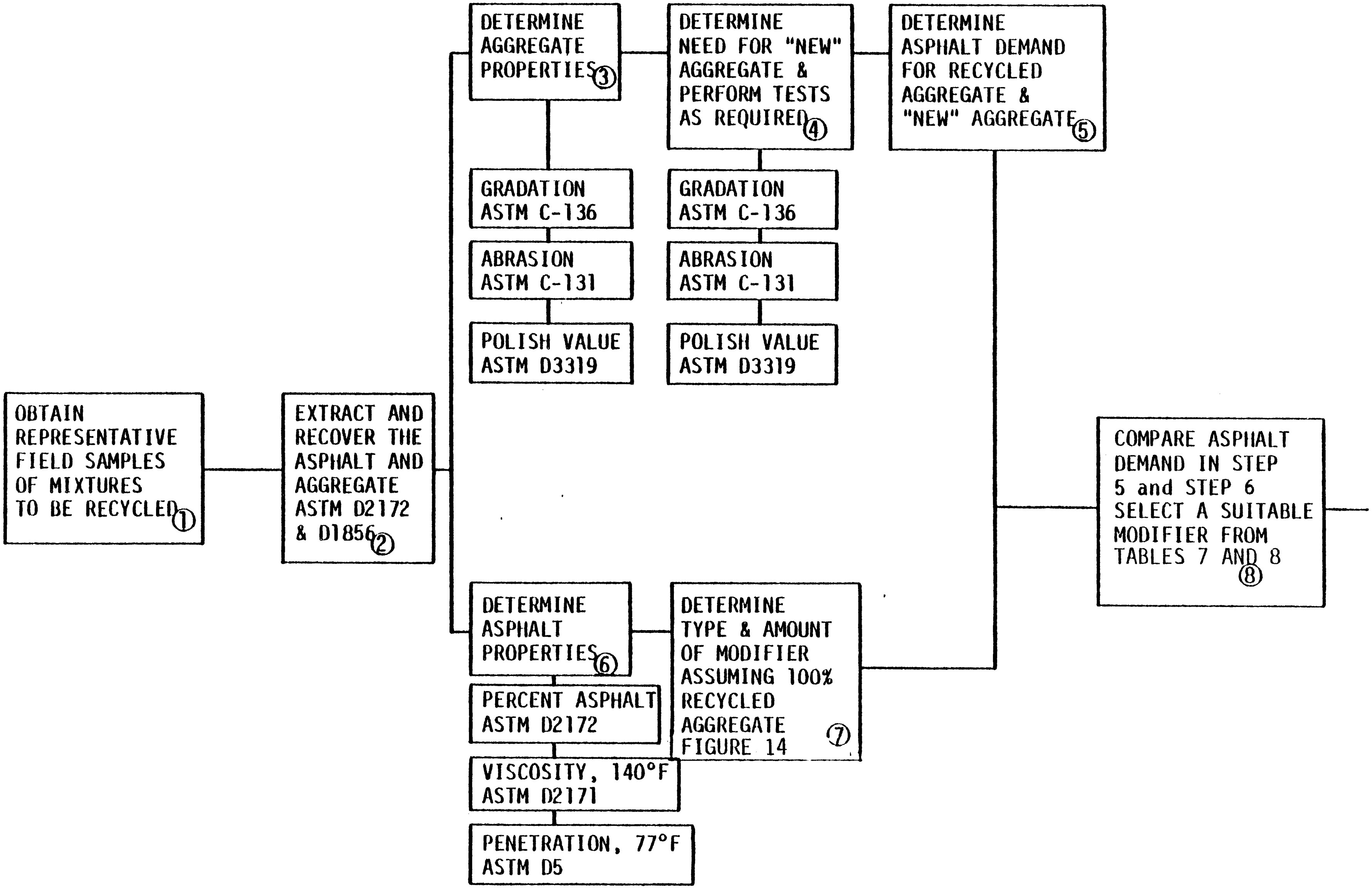
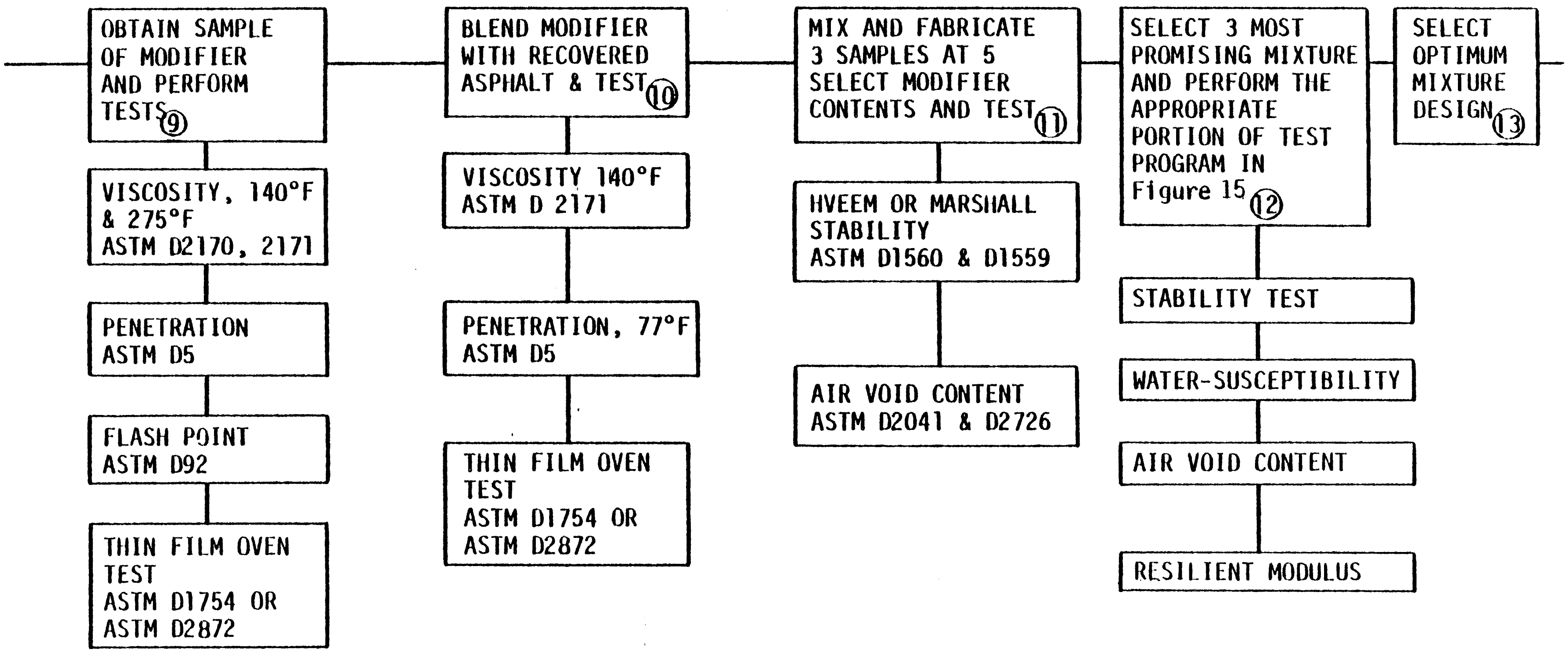
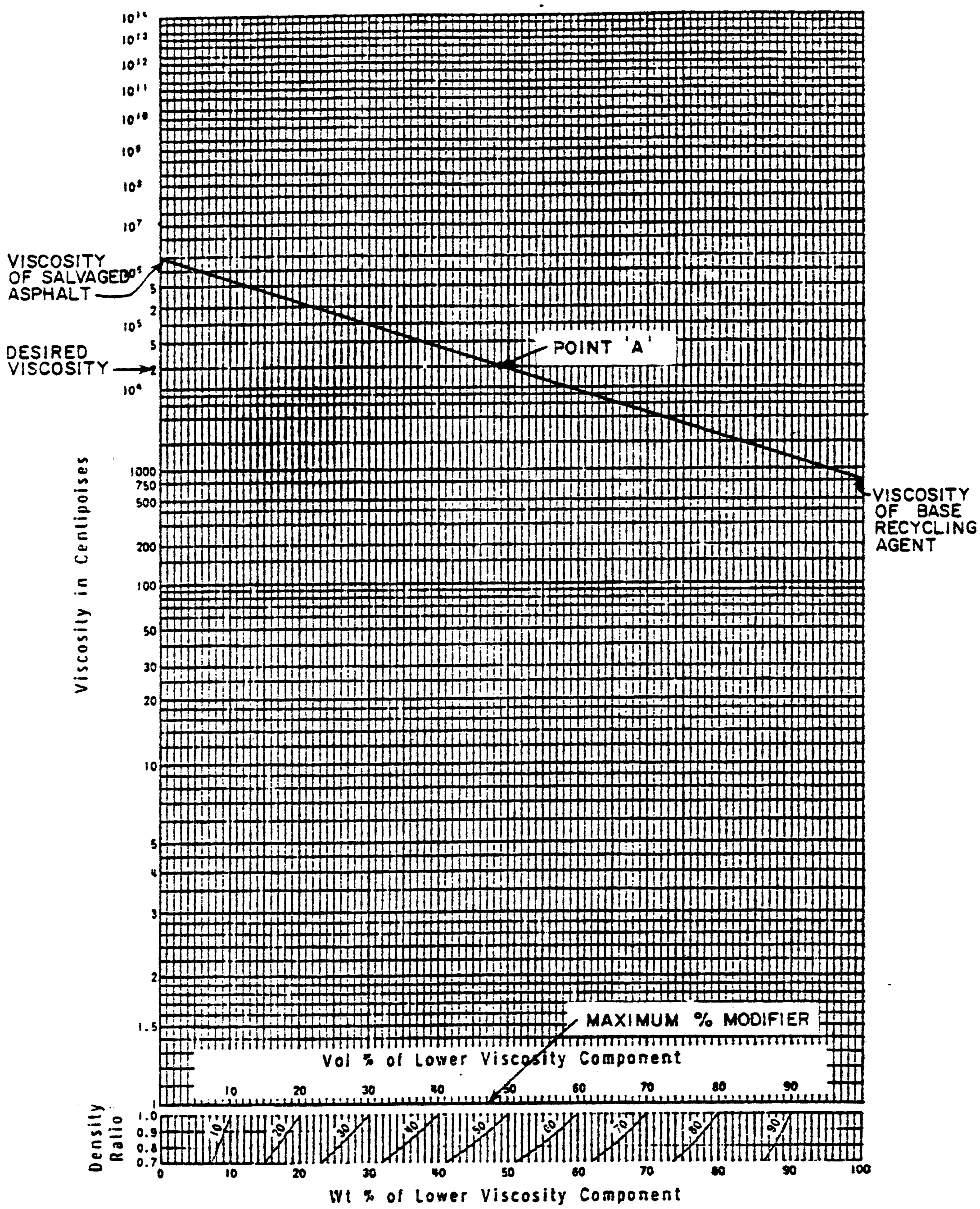


Figure 5. Continued



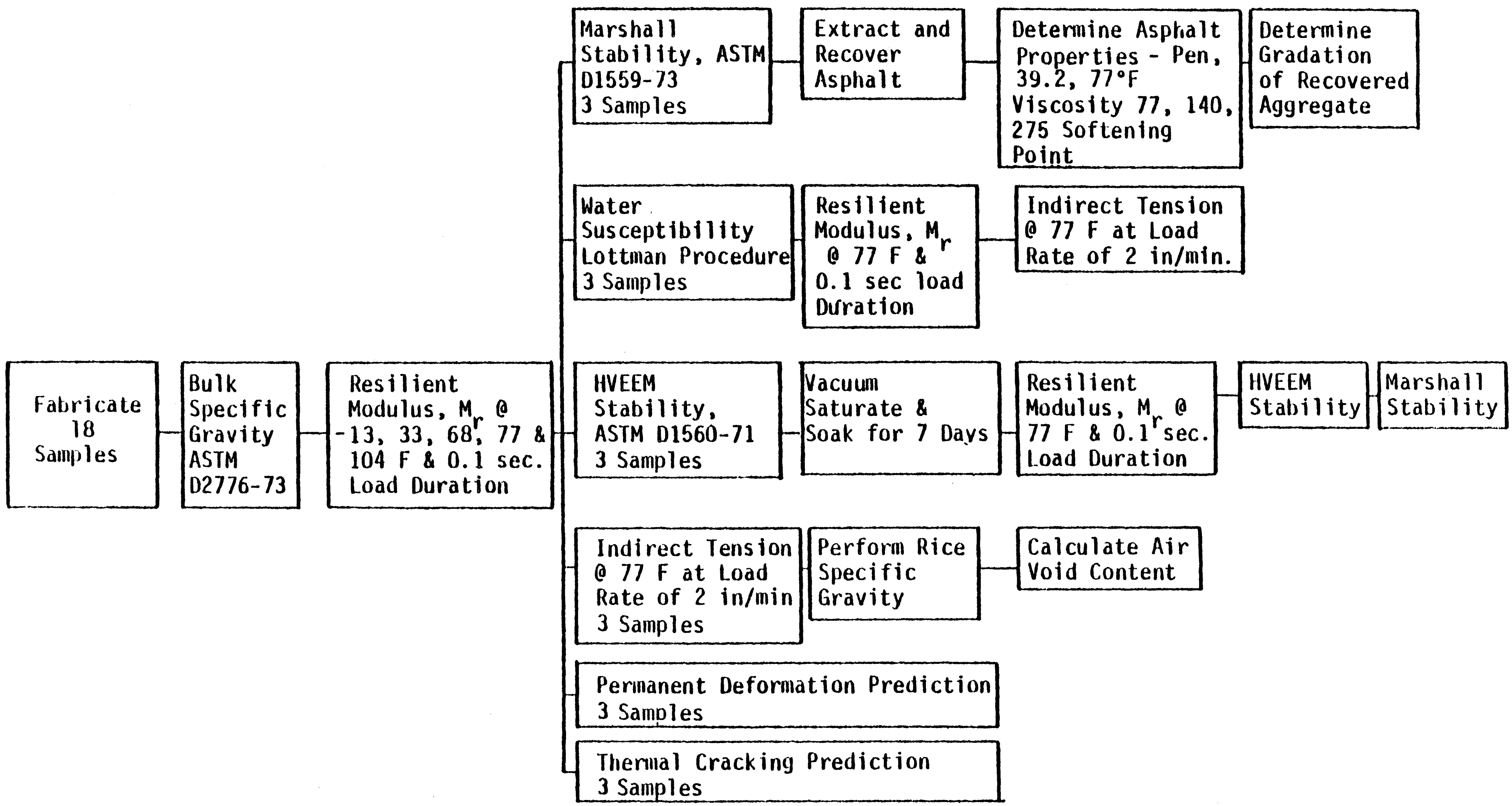
After reference 37.

Figure 6. Viscosity Blending Chart.



After reference 30.

Figure 7. Test Sequence for Mixture Evaluation.



After reference 2.