STATE-OF-THE-ART COLD RECYCLING

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Cold recycling is desirable. Not much equipment is required and processing in-place enables structural and material problems to be corrected quickly without much disruption to traffic. Where an existing asphalt concrete course is pulverized and mixed together with the existing aggregate base, the residual asphalt acts as an excellent binder to help make the recycled base waterproof and less frost susceptible. The addition of new binder or chemical stabilizer may further upgrade the recycled base by reducing swell potential where active clays are present in the base, by reducing freeze-thaw potential, by waterproofing the base aggregate and/or by increasing the load-carrying capacity of the pavement structure. With an increased load-carrying capacity in the base course, the pavement structure may be constructed thinner. The ultimate decision as to application of in-place recycling is based on a total evaluation considering user utility, structural requirements, energy expenditures, and cost.

Rehabilitation and maintenance of our present 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 appear promising from a wide variety of viewpoints a number of agencies 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. 47, "Recycling 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 Recylcing 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, American Society for Testing and Materials (17) and Association of Asphalt Paving Technologists meetings.

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" (18).

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 (19), Asphalt Recycling and Reclaiming Association (20), 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 existing 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.

This conference is directed towards asphalt pavement recycling while this paper presents the state-of-the-art relative to cold-mix asphalt pavement recycling.

Cold-Mix Asphalt Pavement Recycling. As indicated by the definition cold-mix recycling involves the reuse of existing surface, base, subbase and/or subgrade materials. The material can be reprocessed in-place or it can be removed and processed in a central plant without the addition of heat. New binders such as lime, portland cement and bituminous materials can be used in the recycling process. After the roadway has been pulverized, mixed and placed, it will normally require a new wearing surface such as a surface treatment or asphalt concrete.

Cold recycling is an attractive pavement rehabilitation alternative. Equipment required for cold recycling is of basically a conventional nature, much the same as used in conventional soil or aggregate stabilization procedures. Thus, the equipment is readily available. The major advantages and disadvantes of in-place cold recycling operations are compared with surface and hot recycling operations on Table 1.

Advantages. Major advantages of cold recycling operations include:

1. Ability to achieve significant pavement structural improvements,
2. All types and degrees of pavement distress can be treated,
3. Reflection cracking can be eliminated if the depth of pulverization and reprocessing is adequate,
4. Frost susceptibility of subgrade and subbase soils can be improved by use of the process,
5. The pavement ride quality can be improved,
6. Skid resistance can be improved (depending upon type of surface placed on cold recycled section) and
7. Hauling costs can be minimized if processing takes place on grade.

Disadvantages. Cold recycling operations have several disadvantages when compared to other pavement rehabilitation operations. The disadvantages include:

1. Pulverization equipment is often in need of frequent repair and thus production can be low,
2. Traffic disruption can be greater than some other types of rehabilitation activities,
3. Portland cement concrete pavements cannot be recycled in-place,
4. Curing is normally required for strength gain,
5. Strength gain and construction is susceptible to climatic conditions including temperature and moisture and
6. Quality control for in-place operations is not as good as central plant operations.

Future of Cold-Mix Recycling. During the last 10 years highway construction, rehabilitation and maintenance costs have increased by a factor of nearly three. Funding at the federal, state and local level during this same time period has increased slightly. Therefore, it is critical that each available dollar be expended in the most cost-effective manner.

This funding situation which is expected to continue through the next few years is forcing governmental agencies to expend the available funds for roadways on rehabilitation and maintenance operations. Since recycling is a cost-effective rehabilitation and maintenance alternative, the future for all forms of pavement recycling is encouraging. Recycling will capture an increasing proportion of the estimated 34 billion dollars expended on highways in the United States.

Cold recycling will capture a significant share of those funds expended on recycling. The advantages listed above make cold recycling a prime candidate for roadways without surfaces and roadways with this asphalt bound wearing surfaces. Table 2 indicates that 48 percent of our nation's 3,884,761 miles of road are non-hard surfaced (21). An additional 28 percent of the roads are surfaced with thin layers of bituminous materials. Since several surface recycling operations can not be used on thin surfaced and non-hard surfaced pavements and since large scale hot-mix recycling operations may not be economical on thin surfaced and non-hard surfaced pavements, "the future for cold recycling is very promising."

Methods, Equipment and Quality Control

In-place recycling of old asphalt concrete and portland cement concrete pavement is not a new concept. Almost every state has used conventional construction equipment such as bulldozers, vibratory compactors, rollers, etc., to crush old pavement and combine it with a portion of the existing base or subbase to form a reconstituted structural layer. Development of pulverizing equipment and processing techniques are among the more important recent refinements of in-place recycling.

The various alternatives for in-place pavement recycling with no additional heat are shown in Figure 2. Stabilizers such as lime, cement, asphalt, and other chemicals have been used in these processes. Use of cement as stabilizers for recycled bases and surfaces dates to 1942 (22). Use of asphalt with recycled material probably dates to the early 1940's, although the most recent work indicates 1966 (23). States that have performed in-place recycling of the type described include Arkansas, California, Florida, Illinois, Indiana, Kansas, Kentucky, Louisiana, Maine, Michigan, Nebraska, Nevada, New Jersey, New York, Pennsylvania, Tennessee, Texas and Washington. Probably all states have recycled existing bases and surfaces without the addition of a stabilizer.

<u>Methods (In-Place)</u>. The basic sequence of operations for in-place surface and base recycling is shown in Figure 2. As noted the separation of techniques is based on the thicknesses of the surface course (stabilized material). When the thickness of the stabilized layer is approximately 2 inches or less, pulverization can be performed without a ripping and breaking operation. Pulverization of stabilized materials at depths greater than 2 inches can be performed economically with special equipment. Cold milling machines and specially altered soil stabilization equipment can pulverize to depths of about 5 to 7 inches economically.

The second separation of in-place recycling techniques is based on the use of a stabilizing agent. The stabilizer is most often an emulsified asphalt, lime, cement or fly ash in combination with lime or cement.

Experimental models of recently designed machines now make it possible to pulverize, add and mix a stabilizer and grade the surface in a single pass - single machine operation. The appearance of these types of machines in everyday practice will reduce costs and traffic disruption.

The literature indicates that a number of construction sequences have been utilized to complete the essential steps of pulverization, adding and mixing stabilizers and grading and compacting the recycled material. Figures 3 and 4 present typical operations. Figure 3 shows the recycling operation using no additional stabilizer but adding existing base and/or new aggregate to the processed bituminous bound material. Figure 4 shows the recycling operation using a stabilizer, the existing base and/or new aggregate. Note that a recycling agent or modifier has been added to the pulverized recycled bituminous bound material prior to the addition of the existing and/or new base.

With the advent of new equipment it is not unusual to pulverize with one machine in one pass and add stabilizer and mix with a second machine. Whatever the sequence of operation used in cold recycling the major operations consist of

1. Pulverization,
2. Adding and mixing stabilizers or water,
3. Fine grading,
4. Compaction and
5. Curing.

Equipment associated with these operations will be briefly discussed in another section of the report.

<u>Methods (Central Plant)</u>. Central plant cold recycling operations are very similar to those performed in-place. Pulverization of the recycled material can take place 1) on grade as part of the pavement removal operation, 2) on grade after initial ripping and breaking or 3) at the site of the central plant after initial ripping and breaking has taken place on-grade. Typical cold-central plant operations are shown in Figure 5.

Central plant mixing operations afford the best opportunity to produce uniform stabilized materials and can achieve close to 100 percent mixing efficiency as measured by the strength of the treated soil measured after field versus laboratory mixing. Of the two major types of central plants, the batch plant will normally have better uniformity and control than the continuous plant. However, continuous plants are used more often than batch type plants due to their high production capabilities.

<u>Equipment</u>. The types of equipment used for in-place recycling are very similar to those used for on-grade stabilization with lime, cement or asphalt. Generally, the only specialized equipment is that used to properly size bound materials prior to stabilization.

Typical soil stabilization construction equipment is identified in Figure 6 and identified with type of stabilizer in Table 3 (24). Excellent general summaries of soil stabilization construction equipment and construction operations can be found in References 25 and 26 for lime stabilization operations, References 27 and 28 for lime-fly ash, Reference 29 for cement stabilization and Reference 30 for asphalt stabilization (24).

As indicated above pulverization and pavement removal equipment developments have greatly contributed to the economic viability of cold recycling operations. John Wood's paper "Equipment for Cold Recycling" (31) presented at this conference summarizes equipment developments unique to cold recycling. A brief summary will be presented here for completeness.

Categorization of pavement removal and pulverization equipment commonly associated with cold recycling operations is shown in Figure 7 (1). It should be noted that the majority of this equipment is associated with either surface recycling or soil stabilization operations.

Heater-Planers and Heater-Scarifiers. Heater-planer and heater scarification is an outgrowth of equipment developed by Gibbons and Reed Contractors of Salt Lake City in the 1930's (32). Advancements in equipment technology have been made and now in excess of 10 companies have developed this type of equipment (1). Bituminous bound materials removed from heater-planer and heater-scarification equipment have been used without the addition of stabilizers on shoulder, as pavement base courses and for maintenance patching. This type of equipment is normally not used as a pavement removal process for cold recycling operations.

Hot-Millers. Hot-milling has not been used extensively in the United States. The process is limited to asphalt-surfaced roadways and has not been used extensively as a pavement removal process for cold recycling operations. Wirtgen and the Millars Company manufacture equipment.

Cold-Planing. Motorgraders have been used to plane asphalt pavements in the summer months. These materials have been reused to a limited extent.

A pavement planer capable of being used for cold recycling operations is under development by Envirodyne in Reno, Nevada (1). This planer removes pavement by use of the vibratory beam concept.

Cold-Milling. Cold-milling equipment has been used extensively for pavement removal and pulverization. Much of this equipment has been developed since 1973. Most of the larger units were not developed until after 1976. CMI, Barber-Greene and BARCO presently manufacture larger machines while BJD, Cutler, Galion, Payne, Reconeco and Sakai are some of the manufactures of smaller cold planers. One company is developing a machine capable of pavement removal, pulverization, adding stabilizer, mixing and laydown in a single pass.

Pavement Rippers. Typically pavement ripping is performed by crawler tractors pulling one to two ripper teeth. Large scale trenching tools have been used for pavement loading on at least one job in Nevada.

Traveling Hammer Mills. Traveling hammer mills have been developed and used for cold recycling operations by Pettibone and Independent Construction Company (1). This equipment is often used to pulverize the ripped and windrowed pavement.

Soil Stabilization Equipment. Some contractors have improved existing soil stabilization equipment with or without the cooperation of soil stabilization mixing equipment manufacturers. This equipment is capable of pavement removal and pulverization in a single pass. Pulverization can be obtained to depths of 5 inches in stabilized materials. Old P&H pulver-mixers, Koehring and Pettibone equipment has been upgraded by contractors and equipment manufacturers. Considerable detail on these commonly used cold recycling equipment items can be found in John Wood's paper.

Quality Control

The objective in cold recycling is to obtain a thorough mixture of a pulverized pavement (with or without new aggregate) with the correct quantity of stabilizer (if used) and sufficient fluids to permit maximum density during compaction. To achieve these ends equipment must be selected, operated and sequenced to provide the following:

1. Pulverization of recycled pavement material,
2. Proper water content (uniformly mixed),
3. Proper stabilizer content (uniformly mixed),
4. Attainment of some minimum specified density,
5. Favorable temperature and moisture conditions for strength development during the curing period and
6. Protection of the stabilized surface from traffic to prevent abrasion and to ensure adequate time for strength development.

Specifications. Guide specifications have been prepared for and are contained in Reference 1 for the following cold recycling operations (1):

1. In-Place Recycling of Existing Asphalt Surface and/or Existing Base (Subbase) Without Chemical Stabilization.
2. In-Place Recycling of Existing Asphalt Surface and/or Existing Base (Subbase) Employing Lime Stabilization.
3. In-Place Recycling of Existing Asphalt Surface and/or Existing Base (Subbase) Employing Portland Cement Stabilization.
4. In-Place Recycling of Existing Asphalt Surface and/or Existing Base (Subbase) Employing Asphalt Stabilizers.

Other specifications can be obtained from references cited in this report or from governmental agencies conducting cold recycling operations as identified herein.

A review of the specifications contained in the literature will indicate that they were largely developed from soil stabilization specifications and quality control guides. At present sufficient data are not available to develop statistically based quality assurance specifications for recycling operations. Potential quality control problem areas associated with cold recycling operations are:

1. Depth of pavement removal,
2. Degree of pulverization,
3. Control of additional binder,
4. Control of recycling agent, and
5. Distribution of additional binder and/or stabilizers.

Climatic and Safety Considerations. The use of lime, lime-fly ash, portland cement, cement-fly ash and asphalt stabilizers in cold recycling operations have certain climatic limitations and construction safety precautions. These limitations and precautions are listed on Table 4. Climatic limitations include minimum temperatures of about 40°F and sufficient time before the first freeze to prevent damage to newly stabilized layers. Flash and fire points should be considered when handling bituminous materials and protective clothing worn at all times when lime and portland cement are utilized.

Mixture Design

In-place and central plant cold 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 (33), later modified by the Air Force Academy (34) and utilized in a FHWA soil stabilization manual (24). 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 8 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 agent (softening agent).

After an appropriate stabilizer or appropriate stabilizers are selected, design sub-systems can be used to select the amount of stabilizers. Appropriate test methods and criteria are briefly outlined for each type of stabilizer. Detailed information can be found in Reference 24. Design sub-systems for lime, portland cement and asphalt stabilization follow. Design sub-systems for lime-fly ash and cement-fly ash are contained in Reference 24.

Lime Stabilization. The design sub-system for stabilization with lime is shown in Figure 9. The procedures for the nonstandard tests are outlined in Reference 2.

The design curve for the freeze-thaw test and a correlation curve between three-cycle freeze-thaw strength and vacuum immersion strength are shown in Figures 10 and 11, respectively. The purpose of Figure 10 is to allow the interpolation of the freeze-thaw strength loss after a predicted number of freeze-thaw cycles from three freeze-thaw cycles in the laboratory.

The family of design curves in Figure 10 was developed from an extensive testing program (34). These curves showed that the additional strength loss after 7 cycles was negligible.

In using Figure 10, first determine the expected number of freeze-thaw cycles during the first winter after rehabilitation then interpolate along the appropriate design curve from the laboratory strength loss after 3 cycles to that after the appropriate number of freeze-thaw cycles (strength loss is the difference between the reactivity test strength and the strength after the freeze-thaw cycle).

Figure 11 allows use of vacuum immersion in lieu of freeze-thaw. The strength loss is determined as described above. Table 5 contains the minimum residual strength criteria that must be maintained.

Cement Stabilization. The modified SSIS cement design sub-system is as shown in Figure 12. 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 (33). The turbidimetric 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 (36). In the base course procedure the wet-dry test is often much less severe than the well-established freeze-thaw test (34). Therefore, solely the PCA freeze-thaw weight loss criteria is suggested for use for base course design (Table 6).

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 (37-44).

Materials used to alter properties of asphalt cements have been called softening agents, reclaiming agents, modifiers, recycling agents, fluxing oils, extender oils, aromatic oils, etc. Most of the major oil companies market products of this type will be used to designate this type of material in this report and originate from ASTM Subcommittee D4.37 (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 hydrocarbon product with physical characteristics selected to restore aged asphalt to requirements of current asphalt specifications (45). It should be noted that soft asphalt cements, as well as specialty products, can be classified as recycling agents or modifiers.

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 purposes and for the end use of the 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.

The design method outlined below allows the engineer to select the types and amount of bituminous modifiers to produce the desired mixture (46).

The proposed method is applicable for both hot and cold 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 aggretates 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 13 and has been modeled after that suggested in References 37 to 42. 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 46. 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) (47).

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 the following equation:

$$D_T = V_R D_R + V_N D_N \quad (1)$$

where:

$$D_R = D_{CKE} - A_R \quad (2)$$

and

D_R = asphalt demand for salvaged or recycled aggregate, percent

D_{CKE} = CKE derived Oil Ratios for salvaged or recycled aggregate, percent

A_R = asphalt content of salvaged or recycled aggregate

D_N = CKE derived Oil Ratios for new aggregate, percent

V_R = volume of recycled aggregate in mixtures

V_N = volume of new aggregate in mixtures

It should be noted that if new aggregate is not utilized, Equation 1 becomes Equation 2.

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 7 and 8. 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 14 and Tables 1 and 2 (48) 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 which was obtained in step (5), Equation 1. For example, assume the following:

1. CKE Oil Ratios on extracted salvaged or recycled aggregate, $D_{CKE} = 5.0\%$
2. Percent asphalt in salvaged or recycled material, $A_R = 4.0\%$
3. Viscosity of aged asphalt 20,000 poises
4. Additional new aggregate, $V_N = 30\%$
5. CKE Oil Ratio of new aggregate, $D_N = 6.0\%$
6. Desired viscosity of recycled asphalt = 2,000 poises

From Equations 1 and 2 the following asphalt demand can be calculated:

$$D_T = V_R D_R + V_N D_N \quad (1)$$

$$D_R = D_{CKE} - A_R \quad (2)$$

$$D_R = 5.0 - 4.0 = 1.0$$

$$D_T = (.70)\ (1.0) + (.30)\ (6.0)$$

$$D_T = 2.5\%$$

The maximum predicted percent modifier by weight of total binder in the recycled mixture is therefore:

$$\frac{D_T}{V_R A_R + D_T} \times 100$$

$$= \frac{25}{(.70)\ (4.0) + 2.5} \times 100$$

$$= 47\%$$

By use of Figure 14 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 1 indicates that modifier grade 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 7 or 8) as well as establish the viscosity of the modifier in order to obtain a more realistic modifier content (Figure 14).

Blend Modifier With Recovered Asphalt (10). The modifier which may consit of an asphalt cement and softener should be blended with the recovered asphalt and subjected to viscosity and penetration tests to determine if the precicted 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 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 15 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 of "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 46 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 shoul be considered. 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).

Mixture Containing Emulsified Modifiers. The above discussion has been primarily directed toward the use of recycling agents specified in Table 7 in cold operations. Recycling in central plants or in place with emulsified modifiers is also an alternative that is considered one 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 containes an example specification 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 49. Of the 11 methods identified in the reference it is suggested that The Asphalt Institute 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 9. These criteria should be used on an interim basis.

Pavement Design

Pavements containing cold recycled layers should be designed using methods which are capable of considering the load carry capability of stabilized materials. Design procedures advanced by the American Association of State Highway and

Transportation Officials (AASHTO) (50), U. S. Forest Service (51), The Asphalt Institute (52), Arizona, California, Illinois, Louisiana, New Mexico, Ohio, Texas, Utah (53) and Wyoming have developed procedures in which pavement layer coefficients are utilized for thickness determination.

Layered elastic approaches can also be utilized for the design of pavements containing cold recycled materials. Methods available for use in manual form include those developed by Chevron (54), Shell (55) and the Federal Highway Administration. Reference 56 contains descriptions of these methods and is a good reference for pavement design.

Because of its general widespread acceptability and use the AASHTO method of pavement design has been utilized in this paper. A brief description of the method follows.

AASHTO Method. The AASHTO design procedure is based on the AASHTO Road Test in Ottawa, Illinois, and on latter satellite programs. The "AASHTO Interim Guide for Design of Pavement Structures, 1972" (50) along with National Cooperative Highway Research Program (NCHRP) Report 128 which reports on data accumulated by State Highway Departments since 1961 (57) and Highway Research Board Special Report 73 (58) form the background for the procedure.

Figure 16 shows the nomograph solution to the pavement design equations resulting from the AASHTO Road Test and with terminal serviceability index values (P_E) values of 2.0 and 2.5. The nomograph solution is obtained by first finding the unweighted structural number ($\overline{SN}$) on the center scale for a given soil support value (S) and total equivalent 18-kip single axle loads (W_{t18}). The unweighted structural number value is then corrected by the regional factor (R) to determine the required design structural number (SN). The structural number can then be utilized to calculate pavement layer thicknesses. A description of each term associated with the nomographic and the method used to determine pavement layer thicknesses follows.

Terminal Serviceability. As noted in the design nomograph, commonly used values of the terminal serviceability are 2.0 and 2.5. The p_t value is the lowest serviceability that will be tolerated on the road at the end of the traffic analysis period before resurfacing or reconstruction is warranted. For major highway facilities a value of 2.5 is recommended while a $p_t = 2.0$ is suggested for lesser traffic volume roads. Normally it is recommended that the p_t value selected should never be less than 2.0. For minor highways, the approach is to keep $p_t = 2.0$ but reduce the traffic analysis time period.

Soil Support Value (S). The arbitrary manner in which the soil support scale was introduced into the AASHTO design procedure is discussed in the literature (57, 58). Because this input value (S) cannot be directly obtained by testing, each design agency using the guide must establish correlations between standard soil tests (e.g., CBR, R, triaxial strength) and soil support value. Figure 17 illustrates such a correlation. Figure 17a is based on a Utah study while 17b is based on a layered elastic study (57). A close examination of these two studies shows that even though the two are in fairly good general agreement, differences in (S) for a given soil test procedure do occur. This fact illustrates the obvious necessity to use as much engineering judgement as possible with the selection of the soil support value.

Equivalent Wheel Load Repetition (W_{t18}). For the AASHTO design method, mixed traffic within a given period of time (termed the traffic analysis period) is accounted for by equivalent damage factors relative to the standard 18-kip single-axle load (see Reference 56, Chapter 4).

Traffic may be equated to daily 18-kip load applications if a common 20-year traffic analysis period is selected or it may be expressed as the total 18-kip load applications within the traffic analysis period. Equivalency factors, and hence W_{t18} applications, are a function of p and SN. For most design problems, an SN value of 3.0 may be assumed for the equivalency analysis. This value will normally result in an overestimation of the W_{t18} but in general, the resulting error will be insignificant.

Regional Factor. The regional factor was placed into the AASHTO design procedure to allow for its use in climatic environments other than the one that existed during the Road Test. In its present form, the R value constitutes a fairly significant input value but unfortunately is one that, at present, is not well documented. Based upon an analysis of the Road Test results dealing with the rate of loss of serviceability during various climatic periods during various climatic periods during the testing, typical values of R were developed by the AASHTO guide. These values are shown in Table 10. Based on an NCHRP state evaluation study of the AASHTO design guide (57), a generalized R value contour map has been developed for the U. S. (Figure 18). In most cases, the selection of the proper R value must be based upon the local conditions of the highway in combination with the judgement of an experienced engineer. The recommended range in R by the AASHTO design guide for U. S. conditions is from 0.5 to 4.0.

Structural Number (SN). The SN is defined as an index number derived from an analysis of traffic, road-bed soil conditions, and regional factor that may be converted to thickness of various flexible-pavement layers through the use of suitable layer coefficients related to the type of material being used in each layer of the pavement structure. The layer coefficient (designated by a_1, a_2, and a_3, for surface, base and subbase, respectively) is the empirical relationship between SN for a pavement structure and layer thickness, which expresses the relative ability of a material to function as a structural component of the pavement (50).

Analytically, the SN is given by

$$SN = a_1D_1 + a_2D_2 + a_3D_3$$

where the D_1 values are the respective layer thicknesses.

At the AASHTO Road Test, four types of basic materials were used in the study: crushed stone, gravel, cement-treated gravel, and bituminous-treated gravel. Based upon the results of the study along with an estimation from results of special base studies at the test, layer coefficients were established by the AASHTO Committee on Design and are shown in Table 10.

Since the initial publication of the layer coefficients, several state highway departments and trade agencies have developed their own layer coefficients for materials commonly used by their respective agencies. Based upon the NCHRP evaluation study of the AASHTO design guide (57), nomographic solutions of the layer coefficients have been proposed from a combined analysis of individual state highway results and a theoretical multi-layered elastic analysis. These nomographs are shown in Figure 19 and are presented as guides in assessing relative changes in the a_1 values as the measured test response of the material varies.

Since the solution of the AASHTO equation in a design, SN, it should be realized that any combination of layer thicknesses and material types satisfies the design equation. However, Van Til, et al. (57) have advocated that, since the flexible pavement is a layered structure, each layer must be checked to insure that an adequate thickness of proper material is provided as cover. This logic parallels that of the CBR design method in which the thickness of pavement above any specific layer must be such that excessive stresses (greater than the strength) do not occur in that layer.

Figure 20 illustrates the suggested procedure for checking the pavement design on this layered concept. In essence, the procedure is to select appropriate S_1 values for each layer and then compute the required SN_1 value from the design equation or nomograph. By using the differences in SN between the computed SN required over each layer, the minimum allowable thickness of any given layer must be obtained.

Minimum Layer Thicknesses. The suggested minimum layer thicknesses for surface, base and subbase course are 2, 4 and 4-inches, respectively. These minimums are based primarily upon construction and maintenance considerations. Obviously, the minimum thickness for the subbase layer is only applicable when such a layer is used in the pavement structure.

Coefficients for Recycled Materials. From the above discussion it is apparent that determination of layer coefficients for cold recycled materials is important if pavement structures are to be designed properly. Since cold recycling produces materials very similar to those produced by conventional stabilization operations, a summary of coefficients has been prepared for stabilized materials and is shown in Table 12. Layer coefficients for recycled materials have been recently calculated at Texas A&M University (2, 59, 60, 61). Table 13 presents a summary of these data obtained for various types of recycling operations. Structural coefficients for cold recycled materials containing bituminous binders are shown in Table 14. These coefficients were determined from laboratory measured properties of field cores according to the method explained in References 2 and 20.

Table 15 contains structural coefficients for cold recycled materials containing lime, cement, asphalt and SA-1 binders. These coefficients were determined from in-situ deflection testing according to the methods explained in References 2 and 20. Structural ratios based on stiffness of cold recycled materials are shown in Table 16 (2, 60).

It should be recognized that the structural layer coefficient is not only dependent on the material properties of the layer in question but also on the material properties of the other layers in the system, the thicknesses of the other layers and the material properties of the subgrade. In turn, since the elastic material properties of the other layers may be either stress sensitive, temperature sensitive or both, the structural coefficients are also a function of the type and magnitude of loading and the climate.

Properties of Cold Recycled Materials. Typical properties of cold recycled materials are available in the literature and unfortunately have been reported on a job by job basis. Preparation of a summary table of these data would be almost meaningless because of the variety of molding, curing and testing techniques utilized by the various agencies. Data are, however, being generated at Chevron, Purdue University and Witco Chemical (among others) for a wide range of materials. Comparison of these data which are not available in the literature indicates that cold recycling materials can be produced which meet the commonly accepted criteria used for stabilized soils.

Resilient moduli data have been obtained on a number of core samples obtained from cold recycled pavements in California, Kansas and Texas. These data were obtained over a temperature range and are reported in Reference 2. Figures 21 to 25 illustrate typical results for cement, cut-back and emulsion stabilized projects. It is interesting to note that low percentages of cement introduced into mixtures does not greatly effect the temperature dependence of the resulting recycled mixture.

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 (62) at this conference while Halstead (63) 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 64 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 alternatives 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 64 for additional detail.

Initial capital costs of various recycling operations are available from Reference 2 and are shown in Tables 17 and 18. Costs of common construction and rehabilitation operations are shown in Tables 19 and 20.

The cost figures given above are intended to be representative only. If cost data are available from the agencies 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 21 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.

Case Histories and Example Project

Case Histories. Cold recycling case histories will be presented in papers prepared by Canessa (48) and Spelman (65). In addition Reference 1 contains a summary of over 10 cold recycling projects located throughout the United States, performed with a variety of different types of equipment and utilizing several different construction operation sequences. A partial list of recycling projects together with appropriate references are given in Table 22. Review of this literature will be encouragement for those individuals planning their first cold recycling project.

Example Project. An existing highway in central Nevada presently carries 50 daily equivalent 18-kip single axle loads. The pavement has extensive alligator cracking in the wheel path and transverse and longitudinal cracks. The pavement was constructed in 1954 with a six-inch crushed gravel base and two inches of asphalt concrete. The R value of the subgrade material is 8.

Deflection measurements have been made along the 6-mile project and samples of the material have been obtained. Overlay design methods based on deflection measurements indicate that a 4-inch asphalt concrete overlay is required.

The pavement is located a considerable distance from a central hot mix plant and cold recycling with an asphalt emulsion is being considered.

Based on Figure 16 and with the following assumptions;

1. Soil support = 4 (Figure 17a)
2. Daily equivalent 18-kip axle loads = 50 (given)
3. Regional factor = 1 (Figure 18)
4. Terminal serviceability index = 2.5 (assumed)

a structural number (SN) of 3.1 can be calculated. An acceptable cold recycled pavement section that will provide this structural number is given below:

1. Surface treatment (chip seal)
2. Nine inches of cold recycled surface, base and new aggregate

The structural layer coefficient has been assumed to be 0.35 (Table 13) for the recycled material; thus, the structural number provided by the section is 3.15 (9 x 0.35).

The anticipated cost of the recycled pavement section is

Surface treatment = 0.45 (Table 19)
Recycled material (9 x 0.60) = 5.40 (Table 17)
Total = 5.85 per square yard

Due to the remote location and the long haul required for the aggregates, hot mix is expected to cost \$30 per ton in-place. The cost of the 4-inch overlay would be \$6.00 per square yard. In addition, it is expected that the shoulder work required for the overlay would be equivalent to adding another \$1.50 per square yard to the cost of the job.

Energy requirements associated with the two alternatives can be calculated as shown below:

Cold Recycling Alternative
Surface treatment = 4,000 (Reference 2)
Recycled material 9 x 17,000 = 153,000 (Table 21)
Total = 157,000 Btu per square yard

Overlay Alternative
Asphalt concrete 4 x 28,000 = 112,000 (Reference 2)
Shoulder work = 42,000 (estimated)
Total = 154,000 Btu per square yard

It is important to realize that the comparison of alternatives based on cost should be over their life. Life cycle costing techniques are defined and worksheets are available in Reference 2.

Mixture designs using emulsions can be performed as outlined in this paper. As stated above Reference 49 is an excellent guide to assist in selection of the emulsion content. Since the amount of binder in the old surface is small compared to the total binder requirements for the 9-inch recycled layer it is doubtful if the hardness of the old asphalt should be considered in the selection of the emulsion.

Conclusion

Cold recycling offers several advantages. Equipment required for the process is minimal and processing in-place affords the opportunity to correct structural and material problems quickly and, therefore, without prolonged disruption of traffic. Where an existing asphalt concrete course is pulverized and mixed together with the existing aggregate base, the residual asphalt acts as an excellent binder to help make the recycled base waterproof and less frost susceptible. The addition of new binder or chemical stabilizer, such as lime or cement, may further up-grade the recycled base by reducing swell potential where active clays are present in the base, by reducing freeze-thaw potential, by waterproofing the base aggregate and/or by increasing the load carrying capacity of the pavement structure.

With an increased load-carrying capacity in the base course, the pavement structure may be constructed thinner. A thinner pavement structure could mean less total materials required and, therefore, a savings of "virgin," select materials. Another advantage is that any material generated as waste due to grade requirement of the new surface course can be sold or stockpiled for future use.

Generally the equipment required for in-place recycling is of the basic road building type and is, therefore, available at almost any location. Furthermore, since in-place recycling is quite versatile in terms of the equipment required and the construction sequence, the engineer can tailor the operation to handle any peculiarities of the project. Since the equipment required is widely used, equipment operators are readily available.

The binders most widely used to upgrade the existing base aggregate (i.e., liquid asphalt, lime, cement, and fly ash) are usually acquired economically. In addition, the agencies associated with these products (The Asphalt Institute, the National Lime Association, the Portland Cement Association) provide detailed construction procedures and suggestions for optimizing the benefits from the use of these binders.

Major items of present concern should be recognized. These are stated very briefly below:

1. Reliability and productivity of pulverization and mixing equipment.
2. Uniformity of distribution of stabilizers and/or recycling agents.
3. Uncertain strength gain associated with cold recycled materials.
4. Rate of softening of the old asphalt cement by the emulsified recycling agents.

Obviously many of these concerns are common to soil stabilization.

The ultimate decision as to the application of in-place recycling is based on a total evaluation considering user utility, structural requirements, energy expenditures, and cost.

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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. Road and Street Mileage in the United States Classified by Type of Surface-1978.

Type of Surface		Mileage	Percent of Total Mileage
Non-Hard Surfaced	Unimproved	283,976	7.3
	Graded and Drained	397,986	10.2
	Soil and Rock	1,192,052	30.7
	Total	1,874,052	48.2
Hard Surfaced	Bituminous Low Strength	1,078,382	27.8
	Bituminous High Strength	811,553	20.9
	PCC*	120,812	3.1
	Total	2,010,747	51.8
Total Mileage		3,884,761	100.0

*Portland cement concrete with or without asphalt concrete overlay

After reference 21.

Table 3. Equipment Typically Associated with Mixed-In-Place Subgrade Stabilization Operations.

STABILIZER	CONSTRUCTION OPERATION				
	SOIL PREPARATION	STABILIZER APPLICATION	PULVERIZATION AND MIXING	COMPACTION	CURING
Lime [1]	•Single-shaft rotary mixer (flat type) •Motor grader •Disc Harrow •Other agricultural-type equipment	•Dry-bagged •Dry bulk •Slurry •Slurry thru mixer	•Single- and multi-shaft rotary mixers •Motor graders •Other agricultural-type equipment	•Sheep's foot •Pneumatic •Steel wheel	•Asphalt membrane •Water sprinkling
Lime or cement, Fly ash [2]	•Single-shaft rotary mixer (flat type) •Motor grader •Disc harrow •Other agricultural-type equipment	•Separate application •Lime--dry or slurry •Fly ash--conditioned •Combined application •Dry-bagged •Dry bulk	•Same as lime	•Steel wheel •Pneumatic •Vibratory	•Asphalt membrane •Water sprinkling
Cement [3]	•Single-shaft rotary mixer (flat type) •Motor grader •Disc harrow •Other agricultural-type equipment	•Dry-bagged •Dry bulk	•Same as lime	•Sheep's foot •Pneumatic (clay soils) •Vibratory (granular soils)	•Asphalt membrane •Water sprinkling
Asphalt [4]	•Motor grader •Single-shaft rotary mixer (flat type)	•Asphalt spray distributor •During mixing process	•Single- and multi-shaft rotary mixer (flat type) •Motor grader	•Pneumatic •Steel wheel •Vibratory	•Volatiles should be allowed to escape and/or the pavement to cool

	COMMENTS	SAFETY PROCEDURES
1	Double application of lime may be required to facilitate mixing. The soil and air temperature should be greater than 40°-50°F to insure adequate strength gain. Construction should be completed early enough in summer or fall so that sufficient durability will be gained to resist freeze-thaw action.	Lime spreading should be avoided on windy days. Proper clothing should be worn so that workmen can avoid skin contact with quicklime. Workmen should avoid prolonged contact with lime and breathing lime dust.
2	Fly ash must be conditioned with moisture prior to distribution to prevent dusting. Mixing and compaction should be completed shortly after stabilizer application. The soil and air temperature should be greater than 40°-50°F to insure adequate strength gain. Construction should be completed early enough in summer or fall so that sufficient durability will be gained to resist thaw-freeze action.	Fly ash, lime and cement spreading should be avoided in windy days. Workmen should avoid prolonged contact with the stabilizers and breathing the stabilizers.
3	Mixing and compaction must be completed shortly after stabilizer application. The soil and air temperatures should be greater than 60°F to insure an adequate rate of strength gain. Construction should be completed early enough in summer or fall so that sufficient durability will be gained to resist freeze-thaw action.	Cement spreading should be avoided on windy days. Workmen should avoid prolonged contact with cement and breathing the cement dust.
4	Proper soil moisture content must be achieved to aid distribution and mixing. Stabilized material should be properly aerated prior to compaction. The soil and air temperature should be above 40°F to allow for proper curing and sufficient time for compaction if hot mix processes are utilized. Thick lifts of hot, asphalt cement stabilized materials can be placed below 32°F.	Proper clothing should be worn so that workmen can avoid skin contact with quicklime.

After reference 24.

Table 4. Climatic Limitations and Construction Safety Precautions.

Type of Stabilizer	Climatic Limitations	Construction Safety Precautions
Lime and Lime-Fly Ash	Do not use with frozen soils Air temperature should be 40 F (5 C) and rising Complete stabilized base construction one month before first hard freeze Two weeks of warm to hot weather are desirable prior to fall and winter temperatures	Quicklime should not come in contact with moist skin Hydrated lime [$Ca(OH)_2$] should not come in contact with moist skin for prolonged periods of time Safety glasses and proper protective clothing should be worn at all times.
Cement and Cement-Fly Ash	Do not use with frozen soils Air temperature should be 40 F (5 C) and rising Complete stabilized layer one week before first hard freeze	Cement should not come in contact with moist skin for prolonged periods of time Safety glasses and proper protective clothing should be worn at all times
Asphalt	Air temperature should be above 32 F (0 C) when using emulsions Air temperatures should be 40 F (5 C) and rising when placing thin lifts (1-inch) of hot mixed asphalt concrete Hot, dry weather is preferred for all types of asphalt stabilization	Some cutbacks have flash and fire points below 100 F (40 C) Hot mixed asphalt concrete temperatures may be as high as 350 F (175 C)

1 in. = 2.54×10^{-2} mm.

After reference 24.

Table 5. 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 35.

Table 6. 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 24.

Table 7.- 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. $\text{Viscosity Ratio} = \frac{\text{RTF-C Viscosity at 140°F, cSt}}{\text{Original Viscosity at 140°F, cSt}}$

After Reference 48.

Table 8. 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 7.

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 48.

Table 9. 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 13.

Table 10. Regional Factors[a]

Condition	R Value
Roadbed materials frozen to depth of 5 in. or more	0.2-1.0
Roadbed materials dry, summer and fall	0.3-1.5
Roadbed materials wet, spring thaw	4.0-5.0

[a]From AASHTO Interim Guide (50).

Table 11. Structural Layer Coefficients Proposed by AASHO Committee on Design,[a] October 12, 1961

Pavement Component	Coefficient[b]
Surface course	
Roadmix (low stability)	0.20
Plantmix (high stability)	0.44*
Sand asphalt	0.40
Base course	
Sandy gravel	0.07[c]
Crushed stone	0.14*
Cement-treated (no soil-cement)	
Compressive strength @ 7 days	
650 psi or more[d]	0.23[c]
400 psi to 650 psi	0.20
400 psi or less	0.15
Bituminous-treated	
Course-graded	0.34[c]
Sand asphalt	0.30
Lime-treated	0.15-0.30
Subbase course	
Sandy gravel	0.11
Sand or sandy clay	0.05-0.10

*Established from AASHO Road Test data

[a]From AASHO Interim Guide (50).

[b]It is expected that each state will study these coefficients and make such changes as experience indicates necessary.

[c]This value has been estimated from AASHO Road Test data, but not to the accuracy of those factors marked with an asterisk.

[d]Compressive strength at 7 days.

Table 12. Structural Layer Coefficients Developed from Various Sources.

STABILIZER	LAYER	MATERIAL	COEFFICIENT (note)
Asphalt	[a]Surface	Road mix (low stability) Plant mix (high stabil.) Sand asphalt	0.20(a) 0.15(k) 0.44(B) 0.30(h) 0.25 - 0.34(i) 0.30(k) 0.40(a,d,n) 0.20(h) 0.25(e) 0.28(g)
	[b]Base	Bituminous treated coarse graded sand asphalt Sand gravel Asphalt stabilized	0.175 - 0.21(g) 0.34(a,b) 0.24(m) 0.30(d) 0.30(a) 0.25(d) 0.25 - 0.34(e) 0.10(f)
Untreated	[b]Base	Sandy gravel Crushed stone	0.17(a,b) 0.14(*)
	[c]Subbase	Sandy gravel Sand or sandy clay	0.11(*) 0.05 - 0.10(a)
Lime	[b]Base	Lime-treated	0.15 - 0.39(a,n) 0.15 - 0.20(h)
	[c]Subbase	Lime-treated clay-gravel Lime-treated soil	0.18(c) 0.14 0.11(p)
Lime - Fly ash	[b]Base	Lime - Fly ash base	0.25 - 0.30(c)
Cement	[b]Base	7-day compressive strength: 650 psi or more 400-650 psi 400 psi or less Soil cement Gravel Cement-treated	 0.23(a,b,n,k) 0.20(a,n) 0.17(k) 0.15(a,n) 0.12(k) 0.20(f,ℓ) 0.17(j) 0.15 - 0.25(p)

1 psi = 6.89×10^3 Pa

Notes for Table 12

* Established from AASHO Road Test

a From AASHO Interim Guide, 1972 (50)

b This value has been estimated from AASHO Road Test data, but not to the accuracy of those marked with an asterisk.

c NCHRP Synthesis of Highway Practice, No. 37, "Lime-Fly Ash-Stabilized Bases and Subbases." (57)

d Alabama (from a above)

e Arizona (from a above)

f Deleware

g Minnesota

h Montana

i Nevada

j New Hampshire

k New Mexico

ℓ Pennsylvania

m South Dakota

n Wisconsin

p Wyoming

Table 13. Typical AASHTO Structural Layer Coefficients

Type of Recycled Material	Layer Used as	Range of a_1 Computed	Average a_1	Number of Test Sections	a_1 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 60.

Table 14. Structural Coefficients of Recycled Bases Where the Recycled Bases were Stabilized with a Bituminous Binder (Characterized by Diametral Resilient Modulus versus Temperature).

Recycled Base	Description of Recycled Base	Reference Base Thickness, Inches	Compute a_2	
18th Avenue, Le Moore, California	Crushed AC + 3.5% Cyclogen (Rejuvenator)	4 8 12 avg.	0.46 0.42 0.38	 0.38
Russel Avenue, Fresno County California	Crushed AC + 1.1% Cyclogen (Rejuvenator)	4 8 12 avg.	0.42 0.38 0.36	 0.35
U.S. Highway 56, Pawnee Co., Kansas (Section 2)	Crushed AC + 1.6% Cement and 3.8% Water	4 8 12 avg.	0.43 0.38 0.34	 0.34
U.S. Highway 56, Pawnee Co., Kansas (Section 3)	Crushed AC + 1% MC - 800	4 8 12 avg.	0.39 0.36 0.32	 0.33
U.S. Highway 56, Pawnee Co., Kansas (Section 4)	Crushed AC + 1.5% Cement + 1.6% AC - 7 and 4% Water	4 8 12 avg.	0.40 0.39 0.33	 0.33
Trunk Highway 94, Minnesota	Crushed AC + Existing Base + 2.6% AC	4 8 12 avg.	0.60 0.45 0.41	 0.42
I20, Roscoe, Texas	Crushed AC + Existing Base + 2.8% AC - 3	4 8 12 avg.	0.45 0.40 0.36	 0.37
U.S. Highway 84, Snyder, Texas	Crushed AC + Base + 5% Asphalt Emulsion (Section 1)	4 8 12 avg.	0.56 0.51 0.48	 0.49

After reference 2.

Table 15. Structural Coefficients of Recycled Bases Where the Recycled Layer was Characterized by In-Situ Dynamic Testing.

Recycled Base	Description of Recycled Base	In-Situ Dynamic Modulus, psi	Reference Base Thickness, Inches	Computed a_2
Ponderosa Avenue, Inclined Village, Nevada	Crushed AC + Existing Base + Cement (Approx. 4%)	190,000	4 8 12 Avg.	0.34 0.31 0.27 0.26
U.S. Highway 50, Dayton, Nevada	Crushed AC + Existing Base + Cement (Approx. 2.6%)	120,000	4 8 12 Avg.	0.29 0.26 0.23 0.23
U.S. Highway 93, Wells, Nevada	Crushed AC + Existing Base + Cement (Approx. 2.6%)	700,000	4 8 12 Avg.	0.49 0.46 0.42 0.42
Highway 45, Yolo, California	Crushed AC + Existing Base and Some Native Subgrade + Approx. 4% Lime	600,000	4 8 12 Avg.	0.47 0.43 0.39 0.40
Elkhart, Indiana County Road 3	Crushed AC + Existing Base Stabilized with SA-1 Stabilizer	140,000	4 8 12 Avg.	0.31 0.28 0.25 0.26
Flint, Michigan Interstate 69	Crushed AC + Existing Base Stabilized with Asphalt (used as Shoulders	116,000	4 8 12 Avg.	0.27 0.24 0.22 0.22

After reference 2.

Table 16. Structural Stiffness Ratios for Recycled Layers.

Project	Description of Layer	Reference Layer	Stiffness Ratio Recycled/Reference
11th Avenue, Hanford, California	Recycled Asphalt Road Mix Surface	Conventional Road Mix Surface	1.00
Russell Avenue, Fresno, California	Recycled Asphalt Stabilized Base	Conventional Road Mix Base	3.44
18th Avenue, LeMoore, California	Recycled Asphalt Stabilized Base	Conventional Aggregate Base	2.40
Highway 45, Yolo, California	Recycled Lime Stabilized Base	AC Surface	1.24
U. S. 56, Pawnee County, Kansas	Recycled Cement Stablized Base	AC (full depth)	1.12
U. S. 50, Dayton, Nevada	Recycled Cement Stabilized Base	AC Surface	0.42
U. S. 93, Wells, Nevada	Recycled Cement Stabilized Base	AC Surface	1.15
Ponderosa Avenue, Inclined Village, Nevada	Recycled Cement Stabilized Base	AC Surface	0.56

After reference 2.

Table 17. 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 18. Representative Costs for Pavement Recycling Operations - 1979.

Type	Operation	Option or Expected Results		Representative Cost Per Square Yard Average	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 18. Continued.

Type	Operation	Option or Expected Results		Representative Cost Per Square Yard: Average	Representative Cost Per Square Yard: 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 18. Continued.

Type	Operation	Option or Expected Results		Representative Cost Per Square Yard: Average	Representative Cost Per Square Yard: Range	Assumptions
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 19. Cost of Common Pavement Construction Operations - 1979.

Construction Operation	Representative Costs Dollars - Per Square Yard - Inch	
	Average	Range
Crushed Stone Base	0.60	0.30 - 0.75
Gravel Base	0.50	0.20 - 0.75
Lime Stabilized Subgrade	0.30	0.15 - 0.45
Cement Stabilized Subgrade	0.40	0.20 - 0.50
Cement Treated Base	1.00	0.60 - 1.40
Asphalt Treated Base	1.00	0.60 - 1.25
Lime--Fly Ash--Aggregate Base	0.90	0.60 - 1.00
Chip Seal	0.45*	0.20 - 0.55*
Asphalt Concrete	1.25	0.70 - 1.50
Portland Cement Concrete	1.65	1.00 - 2.50

*Price per square yard of surface.

$1 \text{ yd}^2 = 8.361 \times 10^{-1} \text{ m}^2$

$1 \text{ in.} = 2.54 \times 10^{-2} \text{ m}$

Table 20. Cost of Pavement Rehabilitation Operations - 1979.

Rehabilitation Operation	Approximate Thickness, Inch	Representative Cost Dollars - Per Square Yard	
		Average	Range
Chip Seal Coat	1/2	0.45	0.20 - 0.55
Fabric Interlayers	1/4	1.10	0.75 - 1.75
Asphalt-Rubber Interlayer	1/2	1.25	0.90 - 1.50
Open Graded Friction Course	5/8	1.50	1.00 - 2.50
Asphalt Concrete (Dense Graded)	1	1.50	1.00 - 2.50
Asphalt Concrete (Dense Graded)	2	2.60	1.80 - 4.50
Asphalt Concrete (Dense Graded)	3	3.30	2.40 - 6.00

$1 \text{ yd}^2 = 8.361 \times 10^{-1} \text{ m}^2$

$1 \text{ in.} = 2.54 \times 10^{-2} \text{ m}$

Table 21. 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

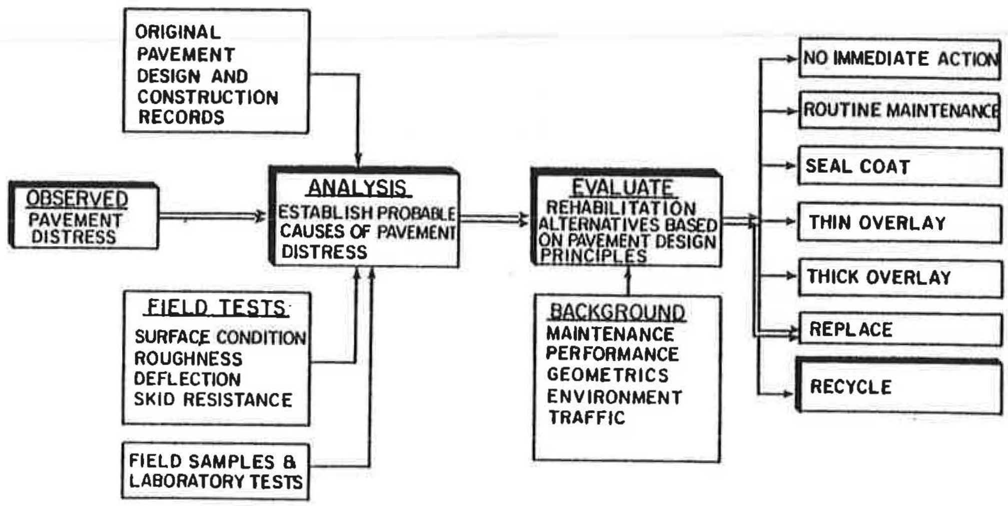
After Reference 2.

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

Table 22. Partial Listing of Cold Recycling Projects

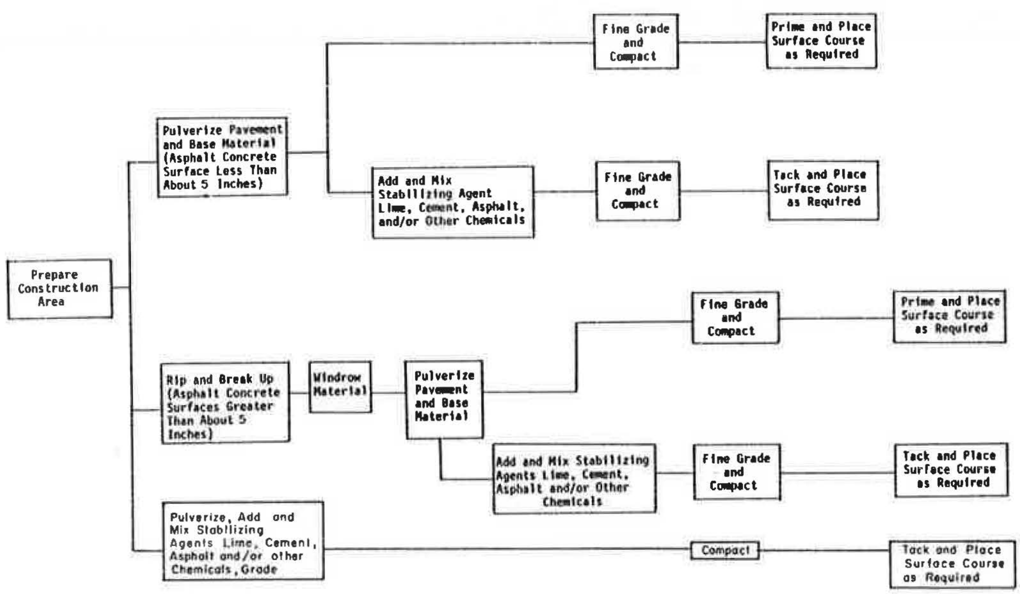
State	Recycled Material	Type of Agent	Reference
Alabama	Surface, Base	Cement	65
California	SubBase, Subgrade		2, 65, 71, 88, 92
Florida	Limerock Base		66
Illinois	Surface	Cement	65
Indiana	Surface, Base	None, Chemicals	83
Kansas	Surface, Base	Cement, Cutback, Emulsion, Bituminous Recycling Agent	2, 79, 82, 91
Louisiana	Surface, Base	Cement	91
Maine	Surface, Base		73, 74, 77, 86
Massachusetts	Surface, Base		75
Michigan	Surface and Base		67, 68, 71, 81, 89, 90
Misssouri	Surface, Base	Emulsion	87
Nevada	Surface and Base		2, 69, 91
New Mexico	Surface, Base	Cement	91
North Dakota	Surface	None	65
Texas	Surface		70, 76, 78, 80
Utah	Surface	Cement	65
Vermont	Surface, Base	Emulsion	85
Virginia	Surface, Base	Cement	65
Wisconsin	Surface, Base	None, Cement, Emulsion, Chemicals	84, 91
FHWA	Surface, Base	None, Emulsion, Chemical	65

Figure 1. Recycling as a rehabilitation alternative.



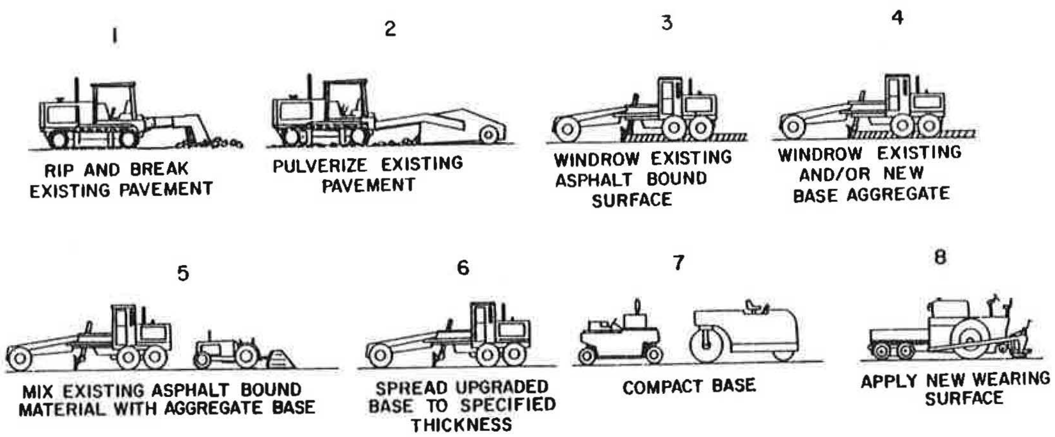
After reference 2.

Figure 2. Cold In-Place Surface and Base Recycling.



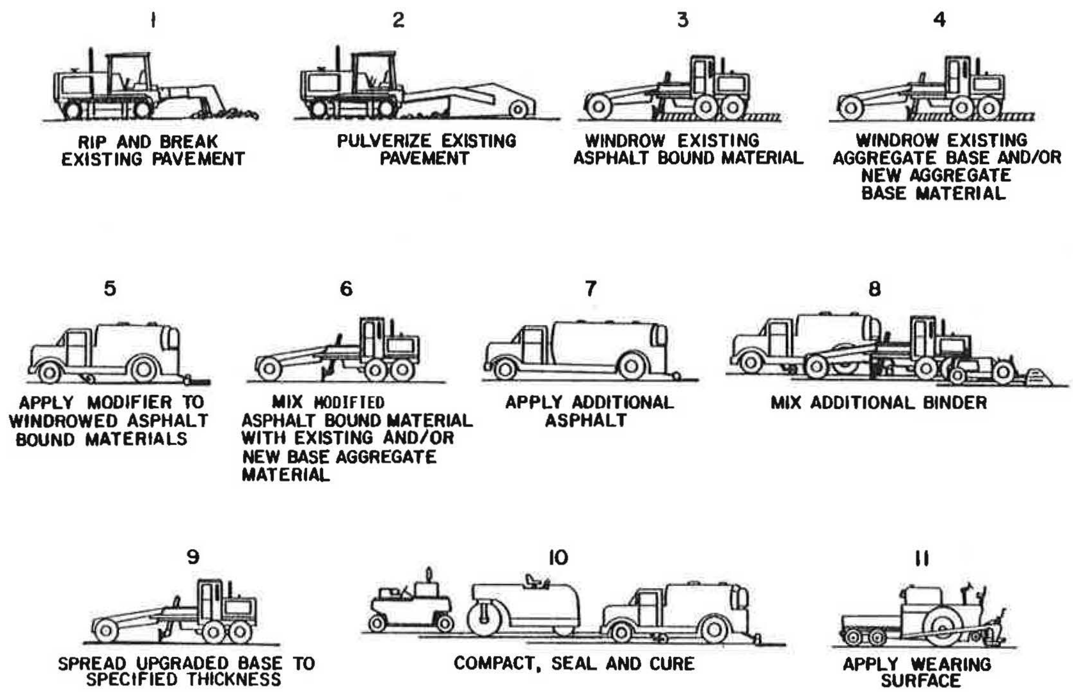
After reference 2.

Figure 3. Typical Cold In-Place Recycling Operation Without Restabilization.



After reference 2.

Figure 4. Typical Cold In-Place Recycling Operation with Modifier Agent and Additional Binder.



After reference 2.

Figure 5. Cold Central Plant Surface and Base Recycling.

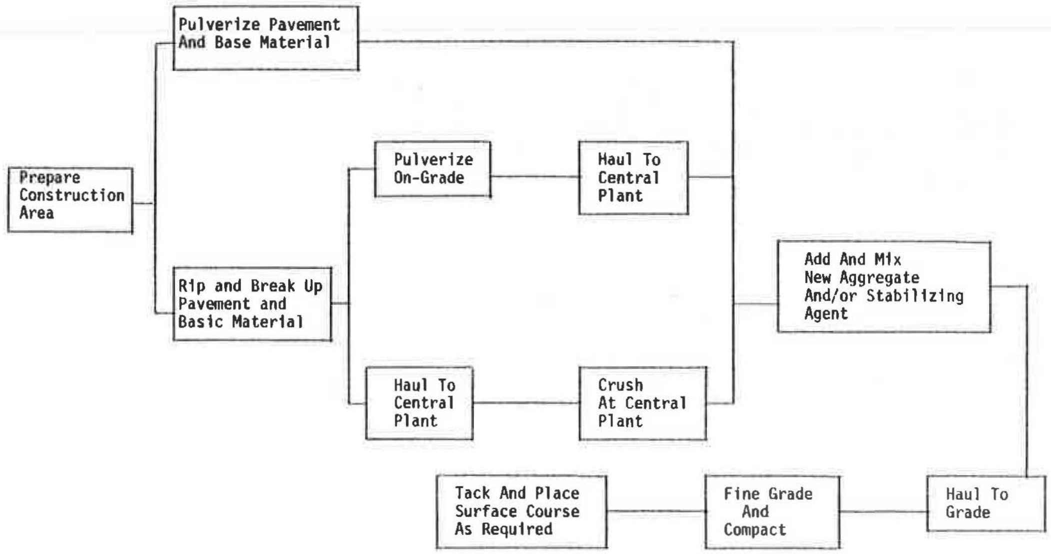
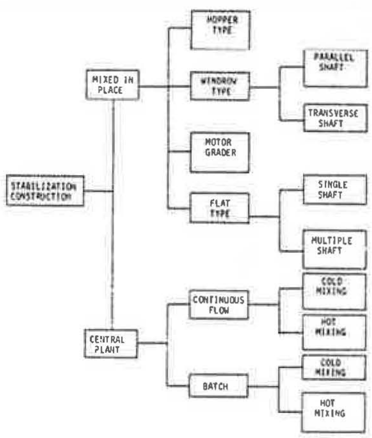
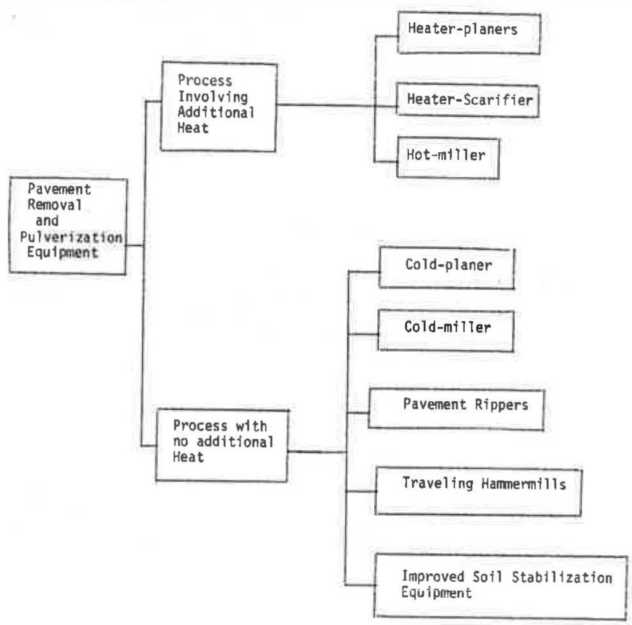


Figure 6. Soil Stabilization construction equipment.



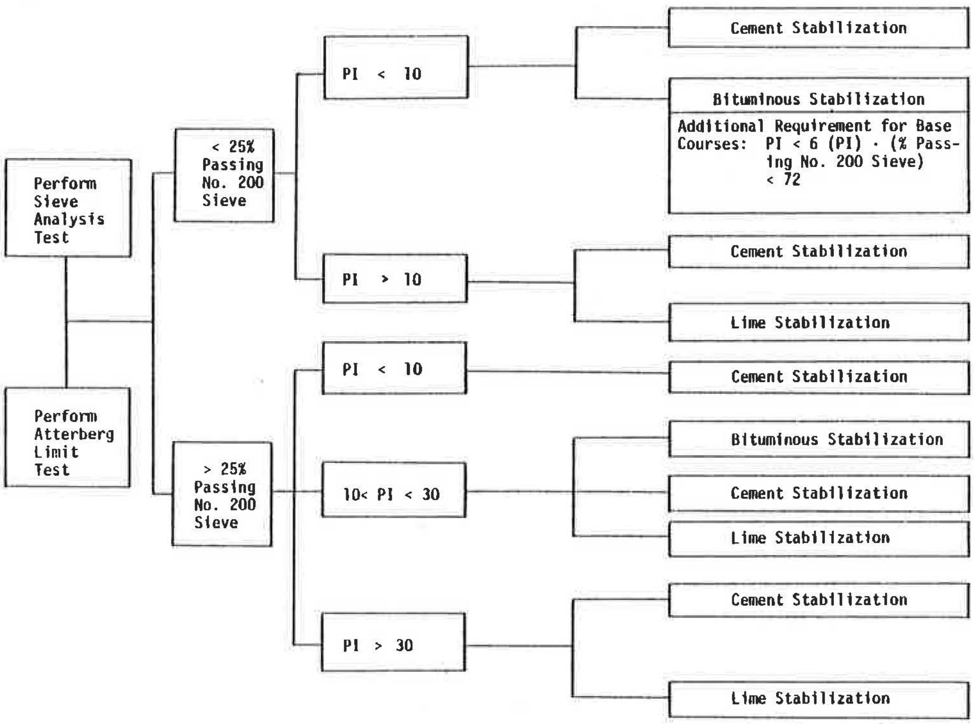
After reference 24.

Figure 7. Pavement Removal and Pulverization Equipment Associated with Cold Recycling Operations



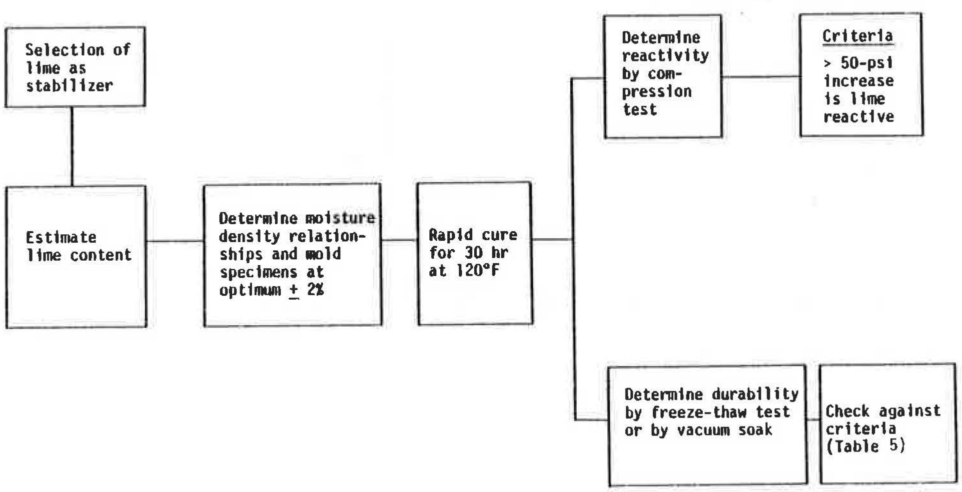
After reference 1.

Figure 8. Selection of Stabilizer.



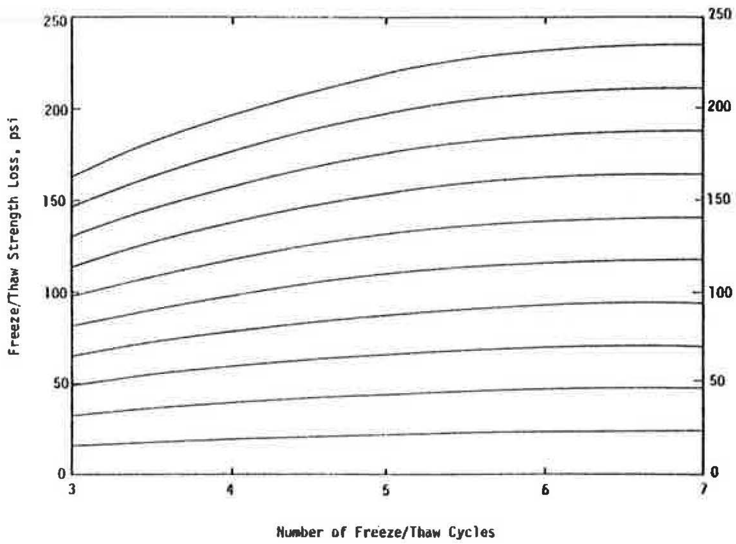
After reference 33.

Figure 9. Design Subsystem for Stabilization with Lime.



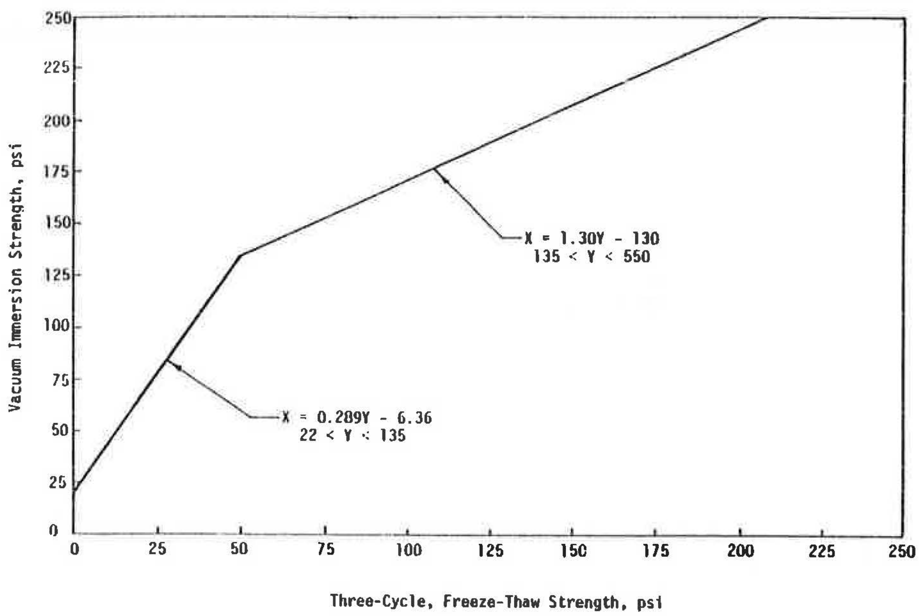
After reference 39.

Figure 10. Design Chart for Freeze-Thaw Loss.



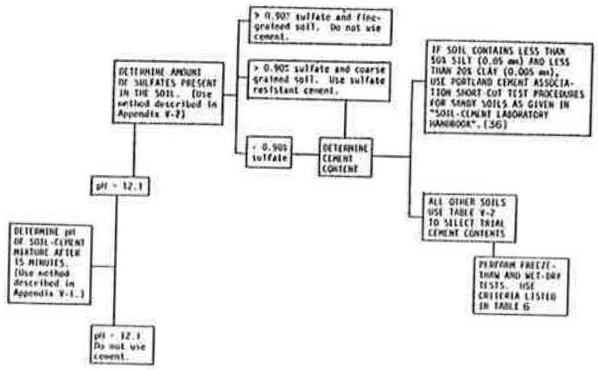
After reference 39.

Figure 11. Design Chart for Three-Cycle, Freeze-Thaw Strength from Vacuum Immersion Strength.



After reference 34.

Figure 12. Design Subsystem for Stabilization with Portland Cement.



After reference 24.

Figure 13. Mixture design procedure.

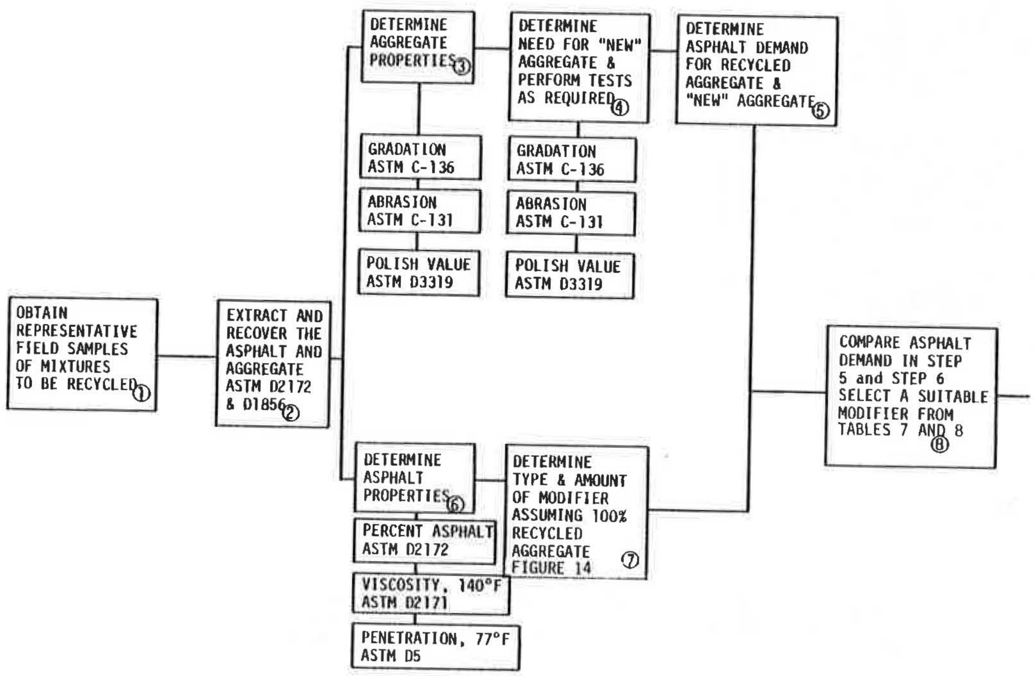


Figure 13. Continued

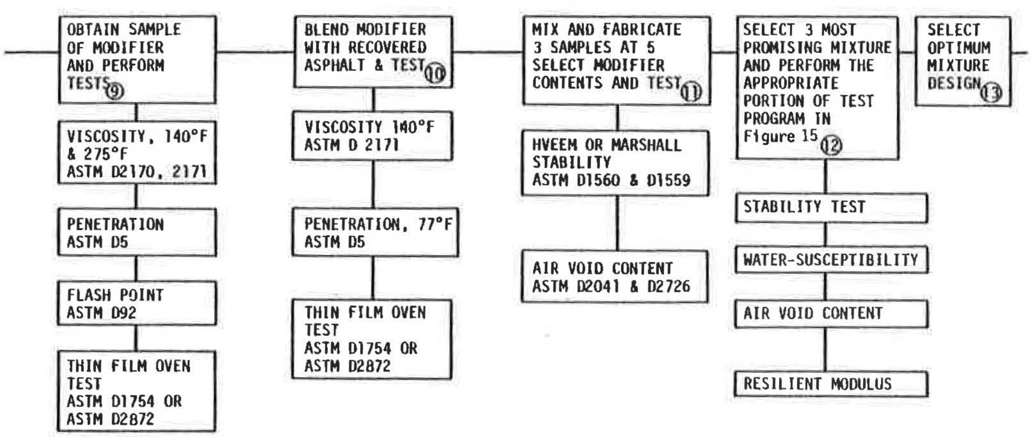
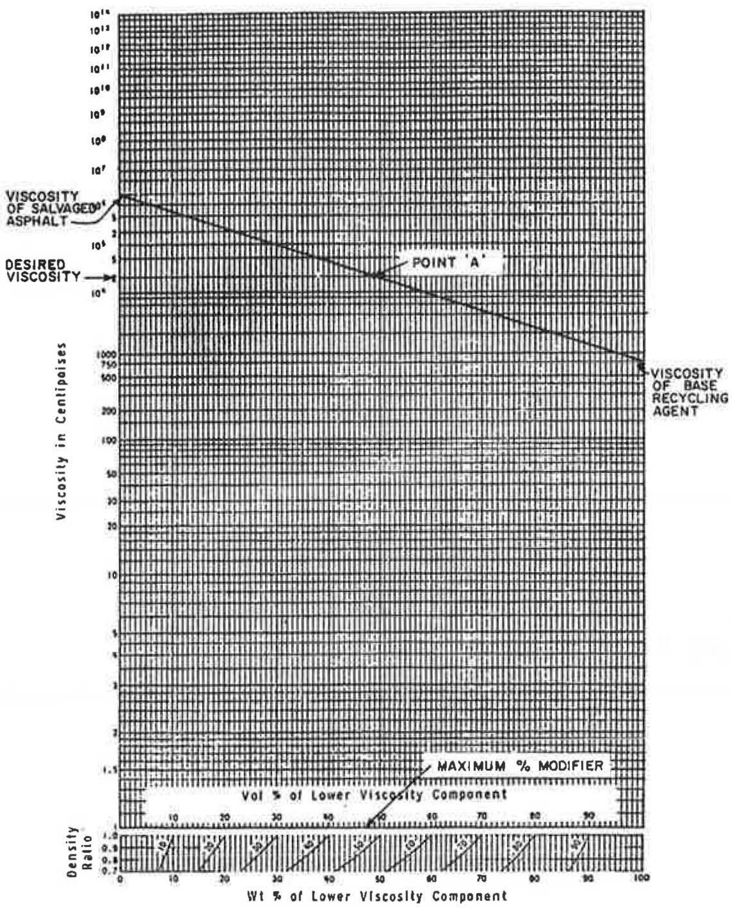


Figure 14. Viscosity Blending Chart.



After reference 39.

Figure 15. Test Sequence for Mixture Evaluation.

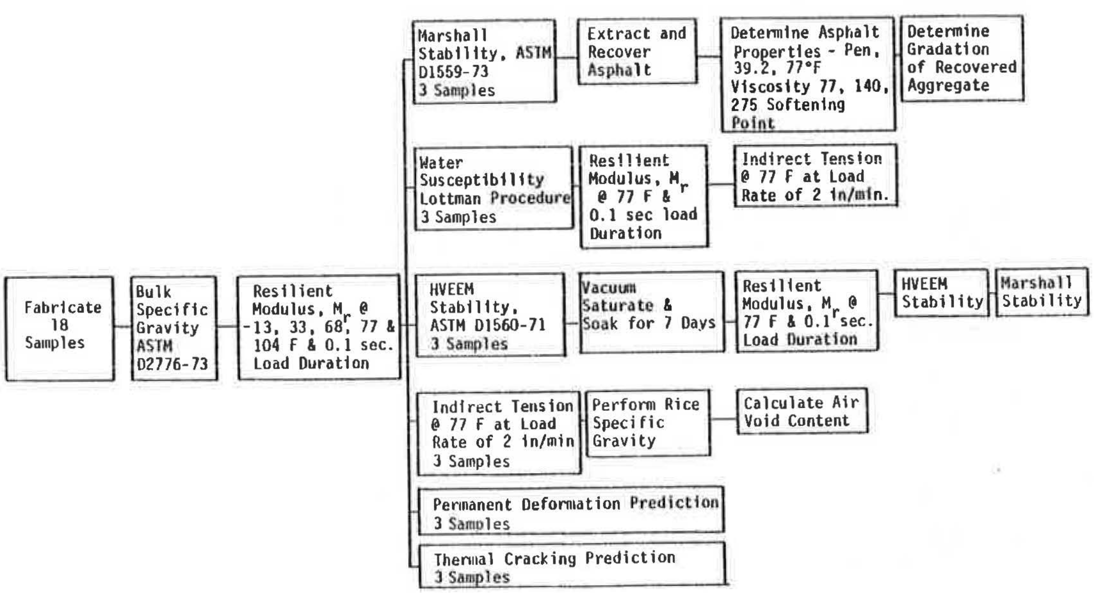
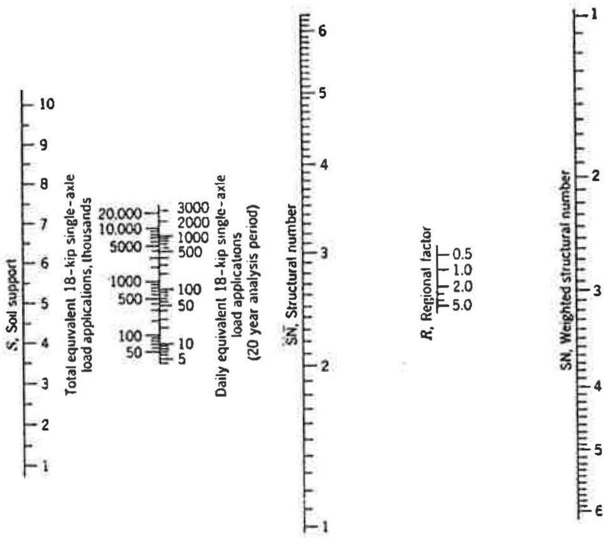
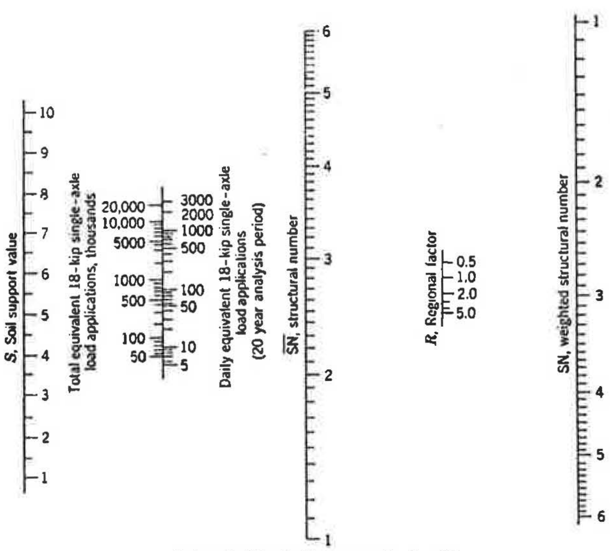


Figure 16. AASHO flexible-pavement design nomographs.



Design chart for flexible payments, $P_t = 2.0$



Design chart for flexible pavements, $P_t = 2.5$

After reference 50.

Figure 17a. Soil support value correlations, (a) after Utah State Highway Department and (b) from reference 57.

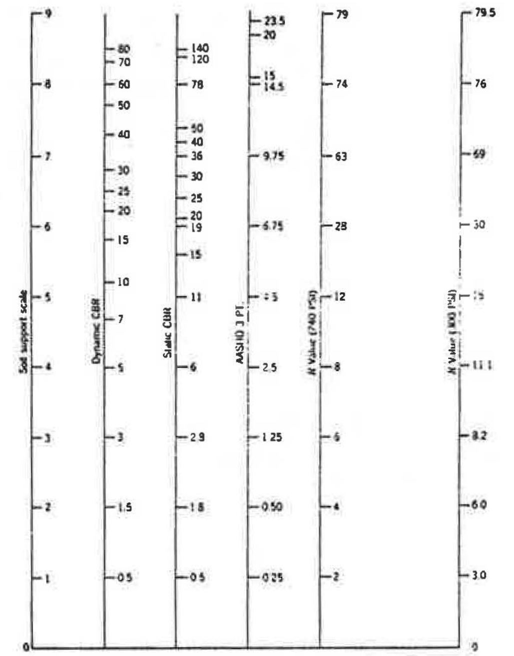


Figure 17b. Continued.

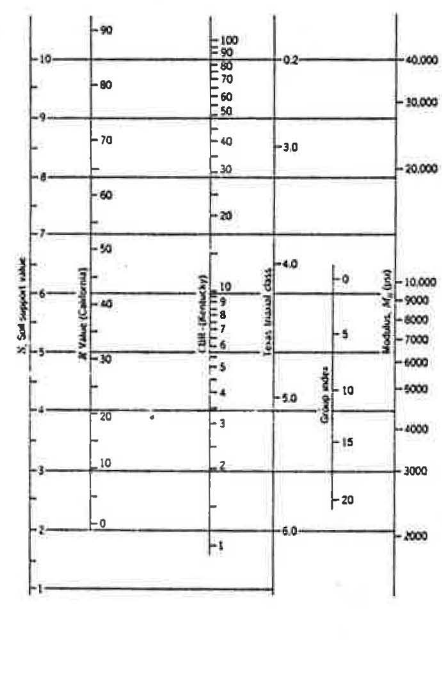
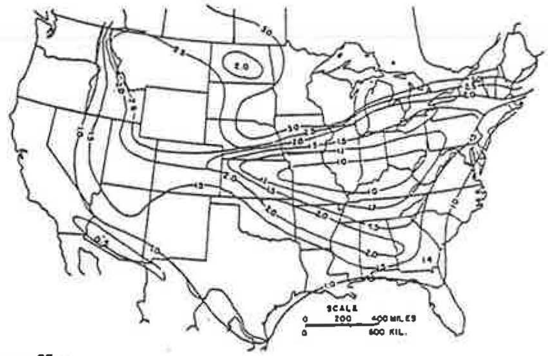
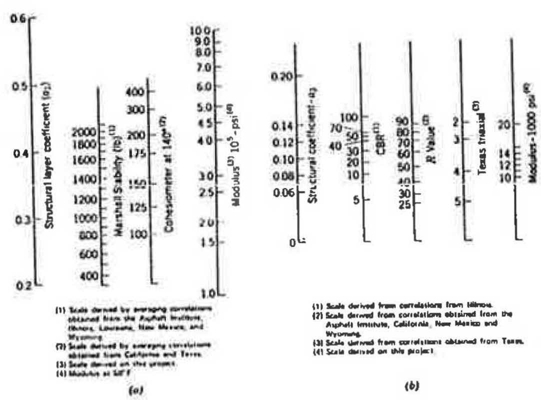


Figure 18. Generalized regional map of the United States.



After reference 57.

Figure 19. Suggested AASHO layer coefficient nomographs. (a) variation in a_1 with surface course strength parameters; (b) variation in a_2 for granular subbase and subbase strength parameters; (c) variation in a_2 for bituminous-treated bases with base strength parameters; (d) variation in granular coefficient a_2 with base strength parameters in a_2 for cement-treated base with base strength parameters.



After reference 57.

Figure 19. Continued

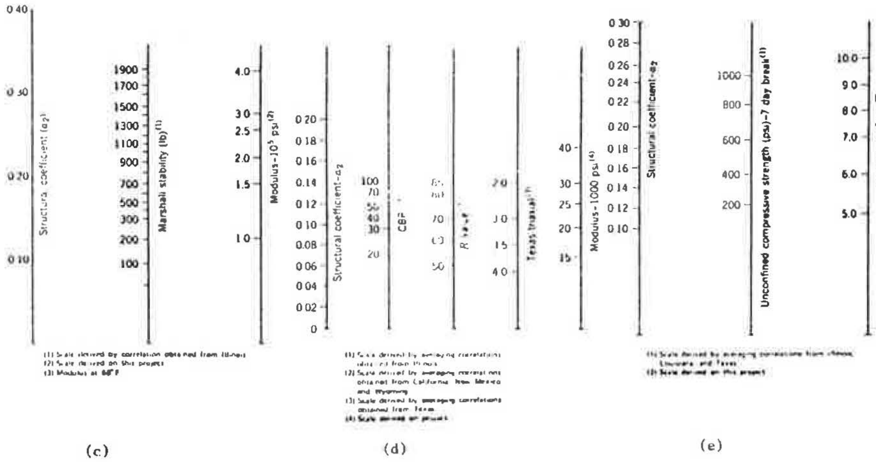
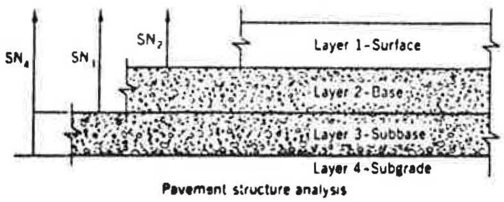
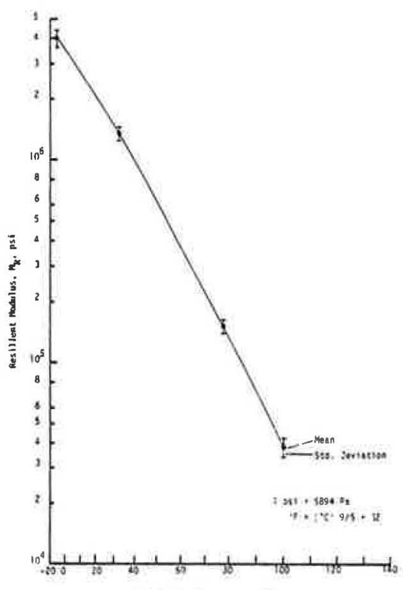


Figure 20. Alternate procedure for determining flexible-pavement layer thicknesses.



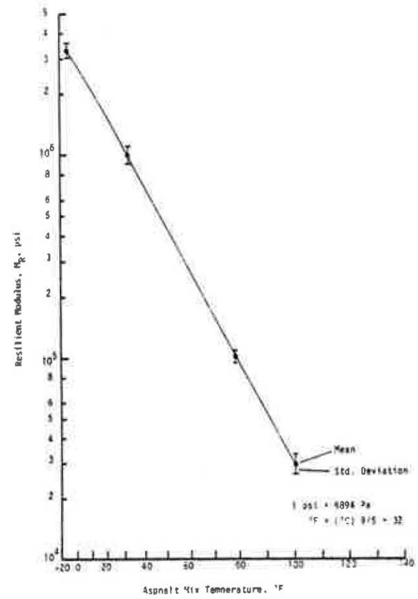
After reference 57.

Figure 21. M_R - temperature relationship for the recycled asphalt concrete, U.S. Highway 56, Kansas - Section 1. (Recycled asphalt Concrete with 20% cement).



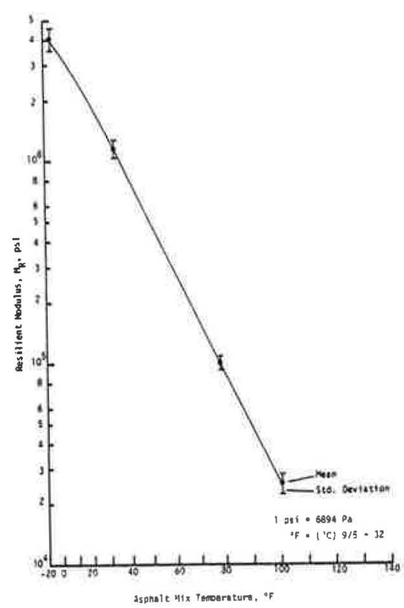
After reference 2.

Figure 22. M_R - temperature relationship for the recycled asphalt concrete, U.S. Highway 56, Kansas - Section 2. (Recycled Asphalt Concrete with 1.5% cement).



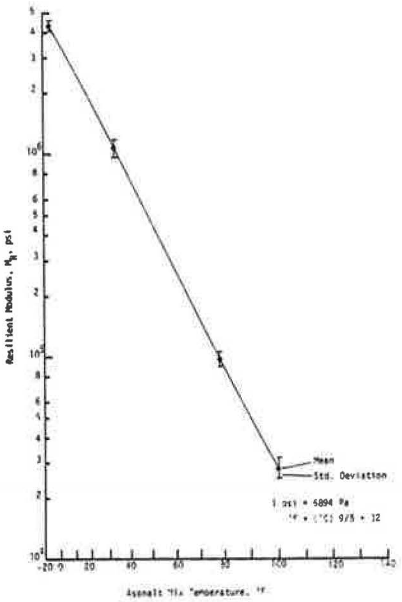
After reference 2.

Figure 23. M_R - temperature relationship for the recycled asphalt concrete, U.S. Highway 56, Kansas - Section 3. (Recycled Asphalt Concrete with 1% MC-8VV).



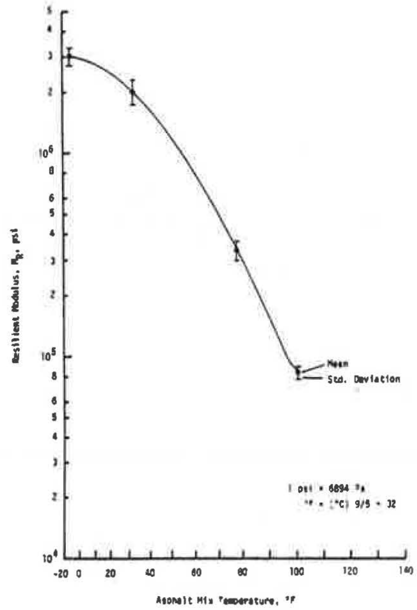
After reference 2.

Figure 24. M_R - temperature relationship for the recycled asphalt concrete, U.S. Highway 56, Kansas - Section 4. (Recycled Asphalt Concrete with 1.51. Cement and 1.5% AC-7).



After reference 2.

Figure 25. M_R - temperature relationship for the recycled asphalt concrete, U.S. Highway 277, Abilene, Texas. (Recycled Asphalt concrete with Emulsified Recycling Agent).



After reference 1.