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GUIDELINES FOR RECYCLING ASPHALT PAVEMENTS

by

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GUIDELINES FOR RECYCLING ASPHALT PAVEMENTS

INTRODUCTION

In the past five years reusing or recycling pavement materials has become an important rehabilitation alternative. In order to provide order and direction to the promising area of pavement rehabilitation, NCHRP has sponsored a research project to provide guidelines to agencies who may wish to utilize recycling. This paper summarizes this two and one-half year research effort which has resulted in guidelines for pavement recycling.

The guidelines have been prepared to provide the following information for the engineer:

1. Point out the potential advantages for recycling.
2. Assist in making a preliminary analysis of recycling as a rehabilitation alternative and to identify suitable methodology,
3. Provide guidance and criteria for making a detailed analysis of cost, energy, mixture design, structural design, construction specifications and quality control and
4. Recommend a scheme for evaluation of results to see how well recycling compares to conventional methods of rehabilitation.

Five chapters and nineteen appendices were prepared in the NCHRP project to supply the needed information. Chapter I of the complete guidelines is an introductory chapter defining the scope, definitions associated with recycling and a general discussion of recycling as a pavement rehabilitation alternative. Chapter II addresses the recycling of asphalt pavements and contains information which allows the engineer to identify the most viable recycling method for a given project. Detailed analysis techniques are also presented together with mixture and structural design considerations, cost and energy considerations and ranking of recycling options for field implementation. Chapter III is similar to Chapter II but emphasis is on portland cement concrete pavements and will not be included in this paper. Chapter IV outlines the sampling and testing required to measure field performance of recycling pavements to provide general feedback for future recycling projects. Chapter V contains example problems which illustrate the use of the guidelines (1).

Appendices have been prepared and are contained in reference 1 on the following topics:

1. Surface condition evaluation of pavements,
2. Pavement deflection measurements,
3. Pavement roughness measurements,
4. Skid resistance measurements,
5. Volume change considerations for subgrade materials,
6. Stabilization and upgrading of unbound and recycled materials,
7. Mixture design for asphalt bound materials,
8. Portland cement concrete and econocrete mixture design,
9. Thickness design for flexible pavements,
10. Overlay thickness design,
11. Cost of construction, recycling and maintenance operations,
12. Energy considerations associated with recycling,
13. Model specifications,
14. Quality control considerations,

15. Economic analysis,
16. Equipment manufacturers and
17. Sample work sheets.

The guidelines are summarized in this paper with sufficient detail to allow the engineer to select the most promising recycling options.

It should be remembered, however, that recycling is only one of several rehabilitation alternatives, the selection of which depends upon the observed pavement distress, the establishment of the probable causes of distress based on field and laboratory study, and design input information such as the following factors (Figure 1): Figure 1

1. History of the pavement maintenance requirements and costs,
2. History of pavement performance,
3. Horizontal and vertical geometric controls,
4. Environmental factors, and
5. Traffic.

RECYCLING GUIDELINES

Types of Recycling

Recycling or reuse of existing pavement materials for pavement rehabilitation, reconstruction, and maintenance is not a new concept. A wide variety of recycling approaches has emerged since 1915. Categorization of recycling approaches is usually based on (a) the recycling procedure used, (b) the type of paving materials to be recycled and the end products they are to produce, or (c) the structural benefit to be gained from the recycling approach. Each of these categories has its own merit in describing the purpose and

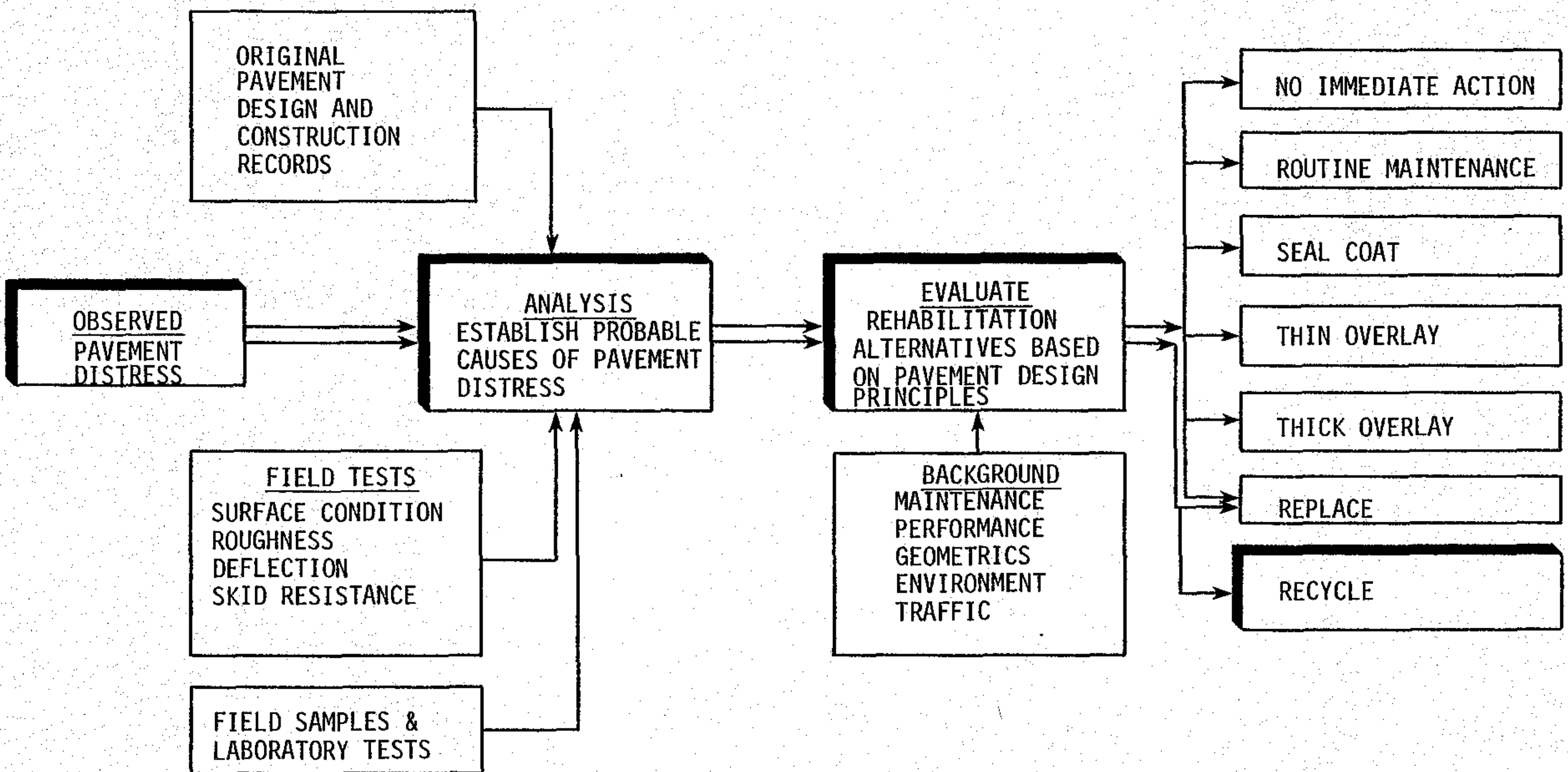

Figure 1. Recycling as a rehabilitation alternative.

applicability of a given type of recycling. A categorization based on the recycling procedure has been used in this paper.

Definitions for recycling categories have been prepared by the Federal Highway Administration Demonstration Project No. 39 Technical Advisory Committee (2), a joint National Asphalt Pavement Association - Asphalt Institute Committee (3), Asphalt Recycling and Reclaiming Association (4), National Cooperative Highway Research Program (5), U.S. Army Engineers Waterways Experiment Station (6), and the Navy Civil Engineering Laboratory (7). The following definitions are based on these suggestions together with those of the NCHRP panel members.

Surface recycling. Reworking of the surface of a pavement to a depth of less than about 1 in. (25 mm) by heater-planer, heater-scarifier, hot-milling, cold-planing, or cold-milling devices. This operation is a continuous, single-pass, multi-step process that may involve use of new materials, including aggregate, modifiers, or mixtures.

In-place surface and base recycling. In-place pulverization to a depth greater than about 1 in. (25 mm), followed by reshaping and compaction. This operation may be performed with or without the addition of a stabilizer.

Central-plant recycling. Scarification of the pavement material, removal of the pavement from the roadway prior to or after pulverization, processing of material with or without the addition of a stabilizer or modifier, and laydown and compaction to desired grade. This operation may involve addition of heat, depending on the type of material recycled and the stabilizer used.

Major advantages and disadvantages of these broad categories of recycling are shown in Table 1. More detailed recycling methods have been identified within each recycling category (Table 2). These methods and associated descriptions which have been formulated to aid in the selection of appropriate recycling options are based on the type of equipment utilized, the type of binder utilized and the degree of structural improvement afforded by the recycling option. Table 1 Table 2

Preliminary Analysis

For convenience the analysis technique has been divided into two parts. Part A is a preliminary analysis which identifies recycling methods which appear to be most suitable. Part B is a more detailed analysis based on laboratory and field data, cost and energy projections, and results in a prioritized list of alternatives with appropriate mixture and structural designs and construction specifications. The overall view of this preliminary analysis which results in a selection of recycling alternatives (Part A) is shown in Figure 2 and discussed below. Figure 2

The major elements of the preliminary analysis are as follows:

1. Description of existing conditions,
2. Testing of existing pavement,
3. Identification of feasible recycling alternatives,
4. Evaluation of preliminary cost and energy savings and
5. Selection of the most viable recycling alternatives.

A brief description of each of these elements follows:

The existing conditions need to be adequately described for the purposes of rehabilitation decision making. These factors are summarized on Table 3 in a form for easy reference. Specific items Table 3

TABLE 1 - MAJOR ADVANTAGES AND DISADVANTAGES OF RECYCLING TECHNIQUES

Recycling Techniques	Advantages	Disadvantages
Surface	• Reduces 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 • Treats a variety of types of pavement distress (raveling, flushing, corrugations, rutting, oxidized pavement, faulting) at a reasonable cost • Improved skid resistance • Minimum disruption to traffic	• 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
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	• Quality control not as good as central plant • Traffic disruption • Pulverization equipment repair requirement • Cannot be easily performed on PCC pavements
Central	• Significant structural improvements • Good quality control • Treats all types and degrees of pavement distress • Reflection cracking can be eliminated • Improved skid resistance • Frost susceptibility may be improved • Geometrics can be more easily altered • Better Control if addition binder and/or aggregates must be used • Improve ride quality	• Increased disruption to traffic • May have air quality problems at plant site

TABLE 2 - OPTIONS FOR BITUMINOUS PAVEMENT RECYCLING

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

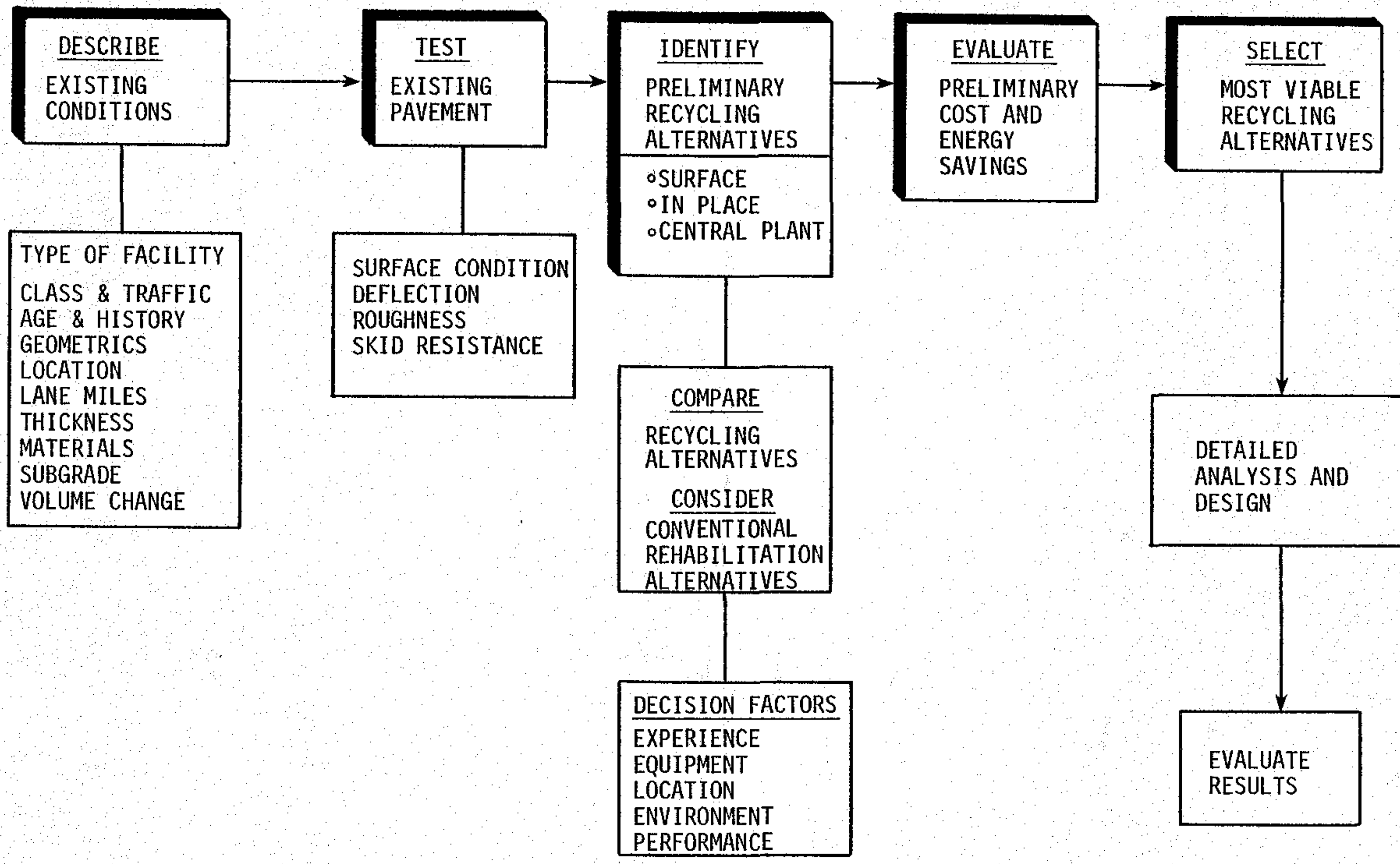

Figure 2. Preliminary analysis and selection of most suitable alternatives.

TABLE 3 - SUMMARY OF EXISTING PAVEMENT CONDITIONS

Feature	Value	Comment
Location	15 miles west of Pecos	
Size of Project (Lane-Miles)	36	
Class of Roadway	Interstate	
Existing Pavement Cross Section (date, thickness and type of original pavement layers; date, thickness and type of subsequent rehabilitation and maintenance activities).	4" AC - 1965 2 course ST - 1963 12" Aggregate Base - 1963 CBR 8 Subgrade	
GEOMETRICS (number of lanes, width, vertical clearance, other constraints)	4-12' lanes Paved Shoulders - 8' No vertical constraints	
Traffic Characteristics ADT Average Daily E. 18 kip axle loads	100	
Subgrade Characteristics	CBR = 8	
Surface Condition (Pavement Rating Source, PRS)	-	Slight alligator cracking, >200 ft of moderate long cracks 100 severe transverse cracks
Structural Condition, (deflection, 0.001 inch) overlay required		
Roughness (Serviceability Index)	2.3	
Skid Resistance (SN 40)	41	
Other: Factors (distance to aggregate and binder source, available equipment and contractor experience)	60 mile haul to aggregate source Contractors not familiar with in-place recycling	

noted are as follows:

1. Location and size of project,
2. Roadway class,
3. Existing pavement cross section,
4. Geometrics,
5. Traffic, and
6. Subgrade characteristics.

Testing of the existing pavement establishes the overall condition of the pavement which is needed to evaluate potential rehabilitation options. Surface conditions, structural capacity (deflection), roughness and skid resistance need to be determined.

A pavement condition survey such as that shown on Table 4 should be made to determine the type, degree and extent of distress (8). Table 4 has all the usual types of distress displayed across the top and major recycling alternatives listed along the left margin. In order to use this table, the engineer should systematically look at each distress marked on the first line and estimate which recycling methods would correct that distress, and indicate this assessment by placing a check mark in the appropriate box. Note that a number of boxes are shaded; this indicates that these recycling options would not be appropriate. For example, a pavement with severe alligator cracking over 30 percent of the area would not be improved using a heater planer (A1) alone. Similarly, other surface methods would not be applicable unless a thick overlay followed the operation. Further, one can note on Table 4 that some methods of in-place recycling and central plant recycling also would not be particularly beneficial for certain types of distress.

Table 4

TABLE 4. SELECTION OF RECYCLING TECHNIQUES BASED ON SURFACE CONDITION OF ASPHALT CONCRETE.

(■ = shaded cell)

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

TYPE OF DISTRESS (continued)

	RAVELING										FLUSHING										CORRUGATIONS									
		% AREA 1-15			16-30			30				% AREA 1-15			16-30			30				% AREA 1-15			16-30			30		
	NONE	SLIGHT	MODERATE	SEVERE	SLIGHT	MODERATE	SEVERE	SLIGHT	MODERATE	SEVERE	NONE	SLIGHT	MODERATE	SEVERE	SLIGHT	MODERATE	SEVERE	SLIGHT	MODERATE	SEVERE	NONE	SLIGHT	MODERATE	SEVERE	SLIGHT	MODERATE	SEVERE	SLIGHT	MODERATE	SEVERE
CONDITION	X										X										X									
A1		■	■	■	■	■	■	■	■	■							■		■	■							■		■	■
A2		■	■	■	■	■	■	■	■	■										■							■		■	■
A3							■			■				■		■	■		■	■				■			■		■	■
A4																														
A5																														
A6																														
A7																														
A8																														
B1																														
B2																														
B3																														
B4																														
B5																														
B6																														
B7																														
B8																														
C1																														
C2																														
C3																														
C4																														
C5																														
C6																														
C7																														
C8																														

TYPE OF DISTRESS (continued)

	ALLIGATOR CRACKING										LONGITUDINAL CRACKING									
		% AREA 1-5			6-25			25				LIN FT PER STA/LN 10-99			100-199			200		
	NONE	SLIGHT	MODERATE	SEVERE	SLIGHT	MODERATE	SEVERE	SLIGHT	MODERATE	SEVERE	NONE	SLIGHT	MODERATE	SEVERE	SLIGHT	MODERATE	SEVERE	SLIGHT	MODERATE	SEVERE
CONDITION			X																	X
A1		■	■	■	■	■	■	■	■	■		■	■	■	■	■	■	■	■	■
A2		■	■	■	■	■	■	■	■	■		■	■	■	■	■	■	■	■	■
A3			■	■	■	■	■	■	■	■		■	■	■	■	■	■	■	■	■
A4				■	■	■	■	■	■	■				■		■	■	■	■	■
A5																				
A6		■	■	■	■	■	■	■	■	■		■	■	■	■	■	■	■	■	■
A7			■	■	■	■	■	■	■	■										
A8																				
B1				■		■	■	■	■	■										
B2				■		■	■	■	■	■										
B3																				
B4																				
B5				■		■	■	■	■	■										
B6				■		■	■	■	■	■										
B7																				
B8																				
C1				■		■	■	■	■	■										
C2				■		■	■	■	■	■										
C3																				
C4																				
C5				■		■	■	■	■	■										
C6				■		■	■	■	■	■										
C7																				
C8																				

TYPE OF DISTRESS (continued)

	TRANSVERSE CRACKING										PATCHING									
		NO. PER STA 1-4			5-9			10				% AREA 1-5			6-15			16		
	NONE	SLIGHT	MODERATE	SEVERE	SLIGHT	MODERATE	SEVERE	SLIGHT	MODERATE	SEVERE	NONE	GOOD	FAIR	POOR	GOOD	FAIR	POOR	GOOD	FAIR	POOR
CONDITION										X			X							
A1		■	■	■	■	■	■	■	■	■		■	■		■	■	■	■	■	■
A2		■	■	■	■	■	■	■	■	■		■	■		■	■	■	■	■	■
A3		■	■	■	■	■	■	■	■	■		■	■		■	■	■	■	■	■
A4				■		■	■	■	■	■				■		■	■	■	■	■
A5																				
A6		■	■	■	■	■	■	■	■	■		■	■		■	■	■	■	■	■
A7				■		■	■	■	■	■				■		■	■	■	■	■
A8																				
B1																	■		■	■
B2																	■		■	■
B3																				
B4																				
B5																	■		■	■
B6																	■		■	■
B7																				
B8																				
C1																	■		■	■
C2																	■		■	■
C3																				
C4																				
C5																	■		■	■
C6																	■		■	■
C7																				
C8																				

Once the viable recycling alternatives for improving surface condition are identified, they can be summarized on Table 7.

The structural adequacy or structural condition of the roadway under consideration can be determined by the thickness of the overlay required. Overlay requirements should be determined by an appropriate deflection based procedure (9, 10). Certain recycling alternatives defined in this manual can be eliminated depending upon the thickness of the overlay required (Table 5). For example, if the overlay required is greater than 2 inches, only those recycling alternatives which provide a major structural improvement would be considered adequate (A5, A8, B3, B7, C3, C7, and C8). For overlay requirements less than 2 inches, those recycling alternatives providing minor structural improvements are suggested for use (Table 5). Those recycling alternatives identified as appropriate for improving the pavement from a structural adequacy standpoint should be entered on Table 7.

Table 5

The smoothness of ride (11, 12) may be a deciding factor for rehabilitation of many roadways. Occasionally, a rough surface may be the only significant problem and surface recycling would be the solution. If a pavement is rough, but also has other deficiencies that require more extensive reworking, then the roughness should automatically be taken care of in that operation. Therefore, the need for surface recycling based on ride measurements (serviceability index, SI) can be estimated as noted on Table 6. As in previous discussions, some methods would not be appropriate and have been blocked out. For example, it is not recommended that very rough primary highway (SI less than 2.4) be surface recycled without an appropriate overlay (Methods A1, A2, A3, A4, and A6). Those methods

TABLE 5 - SELECTION OF RECYCLING TECHNIQUES TO IMPROVE STRUCTURAL STRENGTH BASED ON PAVEMENT REFLECTION.

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

TABLE 6 - SELECTION OF SURFACE RECYCLING TECHNIQUES BASED ON ROUGHNESS

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

that are considered appropriate should be noted on Table 6 and the results summarized on Table 7. Table 6

Many pavements may perform adequately from a structural standpoint, but simply be deficient on skid resistance due to flushing or bleeding or perhaps due to polishing aggregate. As part of the overall pavement testing scheme, skid resistance can be measured using any one of several test methods, but preferably by the ASTM skid trailer (13). All recycling methods are appropriate (provided non-polishing aggregates are used) for improving skid resistance with the possible exception of the heater planer without additional aggregate (A1) or heater scarifier only (A3). Table 7

As discussed earlier, the preliminary analysis is a guideline for selection of several reasonable, viable alternatives for recycling asphalt pavements. Referring to Figure 2, one can not that after all preliminary information is collected, the potentially successful approaches can be analyzed with respect to cost and energy savings and the most viable surivivors determined.

The steps required in order to reach these conclusions are summarized below:

1. List available information on existing roadway — Table 3
2. Test existing pavement
    a. Surface condition — Table 4
    b. Structural condition — Table 5
    c. Roughness — Table 6
    d. Skid resistance
3. Evaluate other decision factors unique to the particular project

TABLE 7 - SUMMARY OF PRELIMINARY RECYCLING ALTERNATIVES.

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

4. Make preliminary cost analysis of remaining options and rank accordingly — Table 8
5. Consider alternatives that appear most viable and continue evaluation.

Detailed Analysis

The organization of the detailed analysis is shown on Figure 3 and contains information on equipment and methods, application, mixture designs, pavement structural design, cost, energy, construction specifications and quality control. Figure 3

Equipment and Methods. References 1, 2, 5, 6, 7, 14, 15, 16, 17, 18, 19, 20, 21, 22 and 23 define in considerable detail recycling equipment and methods that have been used to rehabilitate pavements. Surface recycling techniques which were first developed in the early 1930's (2) are shown on Figure 4. Heater-scarification is a common form of surface recycling and many variations have been developed as shown on Figure 5. Figure 4

In-place surface and base recycling is not a new concept. Almost every state has used conventional construction equipment such as bull-dozers, 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 using travelling hammer-mills for recycling asphaltic concrete is among the more important recent refinements of in-place recycling. Typical in-place recycling techniques are shown on Figure 6. Figure 5 Figure 6 Table 8

Recycling of asphalt paving surfaces into asphalt concrete using

TABLE 8 - REPRESENTATIVE COSTS FOR PAVEMENT RECYCLING OPERATIONS

TYPE	OPERATION	OPTION OR EXPECTED RESULTS		REPRESENTATIVE COSTS PER SQ.YD AVERAGE	RANGE	ASSUMPTIONS
A. Surface	Heater Planer	Without Additional Aggregate	A1	0.50	0.35 - 0.90	heat, plane, clean-up, haul, traffic control
		With Additional Aggregate	A2	0.45	0.30 - 0.80	spread aggregate, heat, roll, traffic control & clean-up
	Heater Scarify	Heater scarify only	A3	0.50	0.25 - 0.80	heat, scarify, recompact, traffic control (3/4 inch scarification)
		Heater scarify plus thin overlay of aggregate	A4	1.10	0.80 - 1.40	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	3.30	2.60 - 4.00	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	0.60	0.35 - 1.20	milling, cleaning, hauling, traffic control, (1 inch removal)
		Surface milling plus thin overlay	A7	2.60	2.00 - 3.00	milling, cleaning, hauling, 200 lbs of asphalt concrete, traffic control (1 inch removal)
		Surface milling plus thick overlay	A8	4.60	3.75 - 5.75	milling, cleaning, hauling, 400 lbs of asphalt concrete, traffic control (1 inch removal)
B. In-Place	Asphalt Concrete surface less than 2 in.	Minor structural improvement without new binder	B1	2.80	2.20 - 3.40	rip, pulverize and remix to 4 inch depth with 2 inches of asphalt concrete, traffic control

TABLE 8 - CONTINUED

TYPE	OPERATION	OPTION OR EXPECTED RESULTS		REPRESENTATIVE COSTS PER SQ YD		ASSUMPTIONS
				AVERAGE	RANGE	
B. In-Place	Asphalt Concrete Surface less than 2 in.	Minor structural improvement with new binder	B2	2.40	1.90 - 2.90	rip, pulverize and remix with stabilizer to 4 inch depth with 1 inch of asphalt concrete, traffic control
		Major structural improvement without new binder	B3	5.20	4.10 - 6.30	rip, pulverize and remix to 6 in depth with 4 inches of asphalt concrete, traffic control
		Major structural improvement with new binder	B4	4.10	3.30 - 4.90	rip, pulverize and remix with stabilizer to 6 inch depth with 2 inches of asphalt concrete, traffic control
	Asphalt Concrete surface greater than 2 inches	Minor structural improvement without new binder	B5	3.00	2.40 - 3.60	rip, pulverize and remix to 4 inch depth with 2 inches of asphalt concrete, traffic control
		Minor structural improvement with new binder	B6	2.60	2.10 - 3.10	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	5.50	4.40 - 6.60	rip, pulverize and remix to 6 inch depth with 4 inches of asphalt concrete, traffic control
		Major structural improvement with new binder	B8	4.40	3.50 - 5.30	rip, pulverize and remix with stabilizer to 6 inch depth with 2 inches of asphalt concrete, traffic control
C. Central Plant	Cold Mix Process	Minor structural improvement without new binder	C1	3.60	2.90 - 4.30	remove, crush, and replace to 4 inch depth with 2 inches of asphalt concrete, traffic control
		Minor structural improvement with new binder	C2	3.00	2.40 - 3.60	remove, crush, mix, and replace to 4 inch depth with 1 inch of asphalt concrete, traffic control

TABLE 8 - CONTINUED

TYPE	OPERATION	OPTION OR EXPECTED RESULT		REPRESENTATIVE COSTS PER SQ YD		ASSUMPTION
				AVERAGE	RANGE	
C. Central Plant	Cold Mix Process	Major structural improvement without new binder	C3	6.40	5.10 - 7.70	remove, crush and replace to 6 inch depth with 4 inches of asphalt concrete, traffic control
		Major structural improvement with new binder	C4	5.00	4.00 - 6.00	remove, crush, mix and replace to 6 inch depth with 2 inches of asphalt concrete, traffic control
		Minor structural improvement without new binder	C5	3.90	3.10 - 4.70	remove, crush, and replace to 4 inch depth with 1.5 inches of asphalt concrete, traffic control
	Hot Mix Process	Minor structural improvement with new binder	C6	3.30	2.60 - 4.00	remove, crush, mix and replace to 4 inch depth with 1/2 inch of asphalt concrete, traffic control
		Major structural improvement without new binder	C7	6.60	5.30 - 7.90	remove, crush and replace to 6 inch depth with 3 inches of asphalt concrete, traffic control
		Major structural improvement with new binder	C8	5.20	4.20 - 6.20	remove, crush, mix and replace to 6 inch depth with 1 inch of asphalt concrete

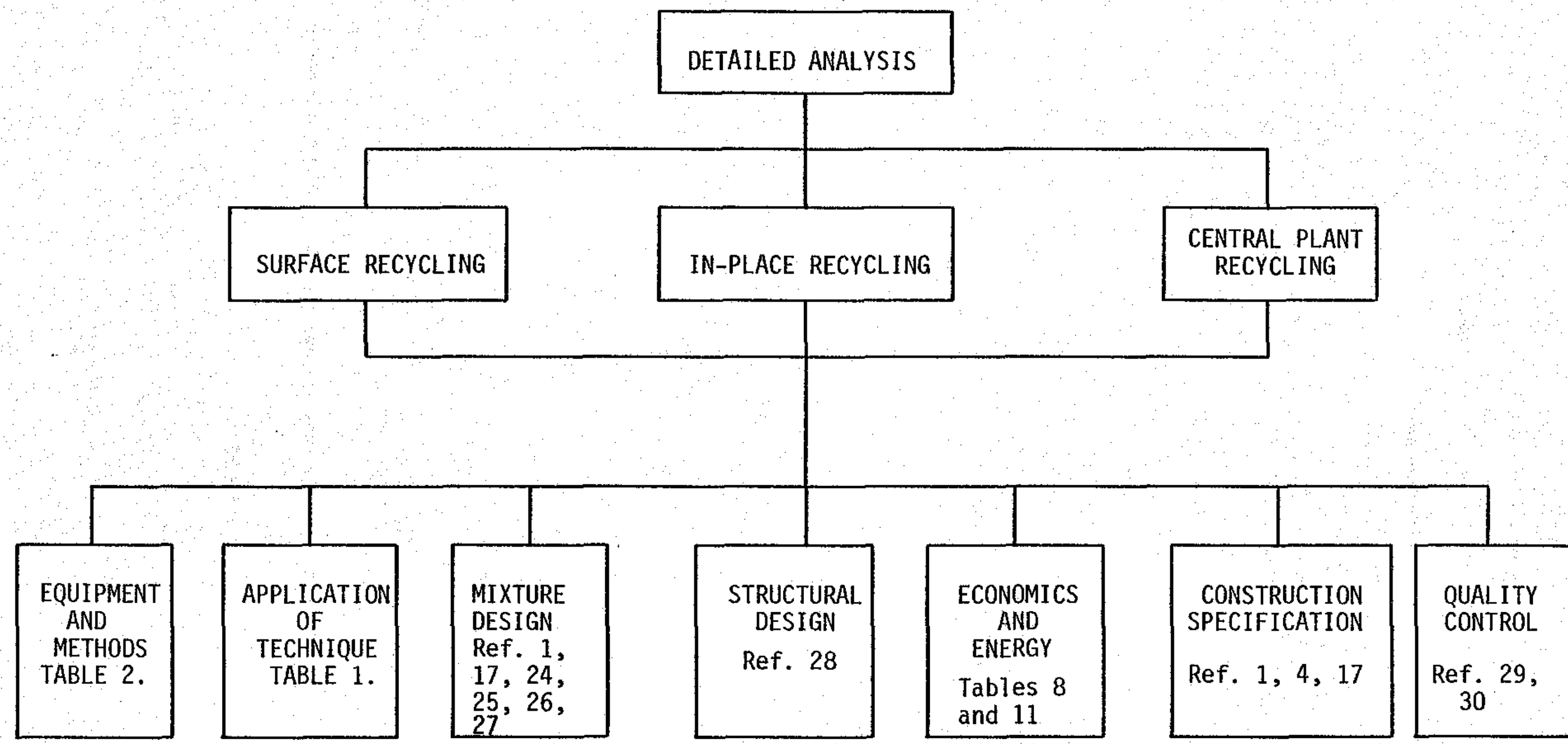

Figure 3. Detailed analysis and selection of most suitable recycling alternative.

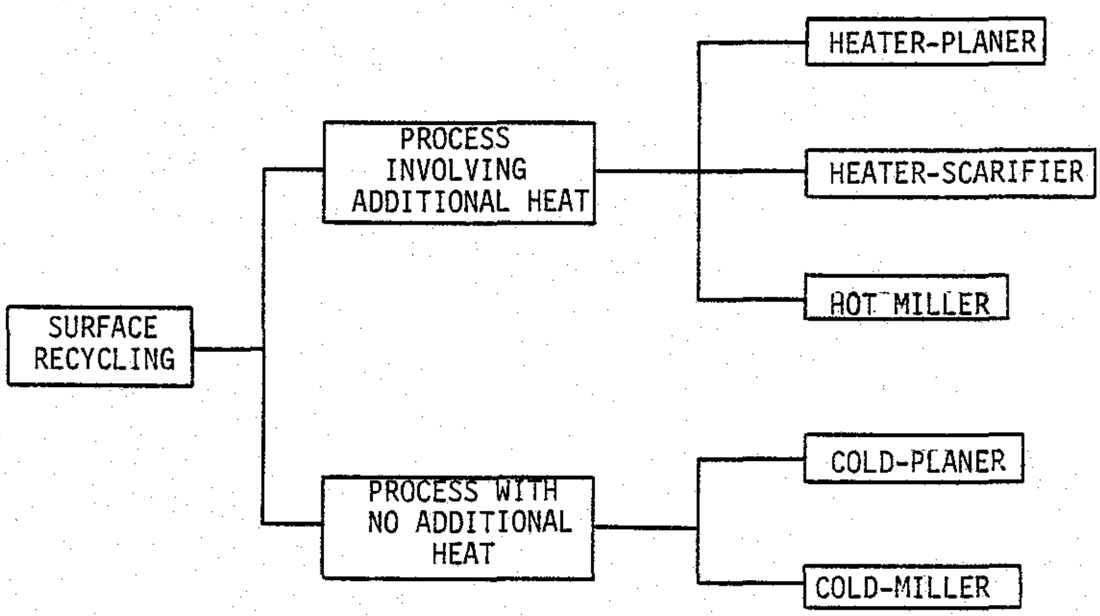

Figure 4. Surface recycling.

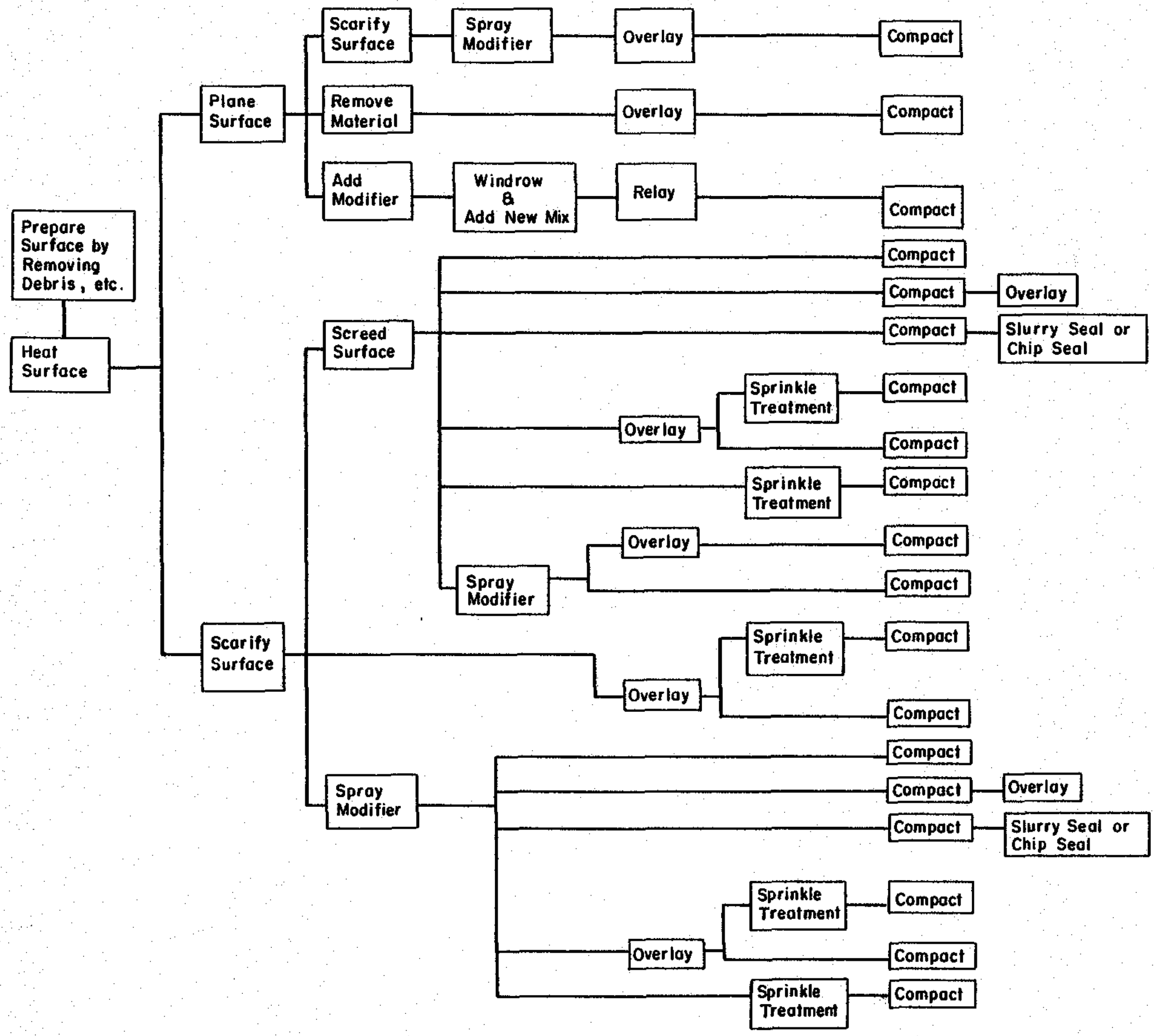

Figure 5. Recycling using the heater-scarifier.

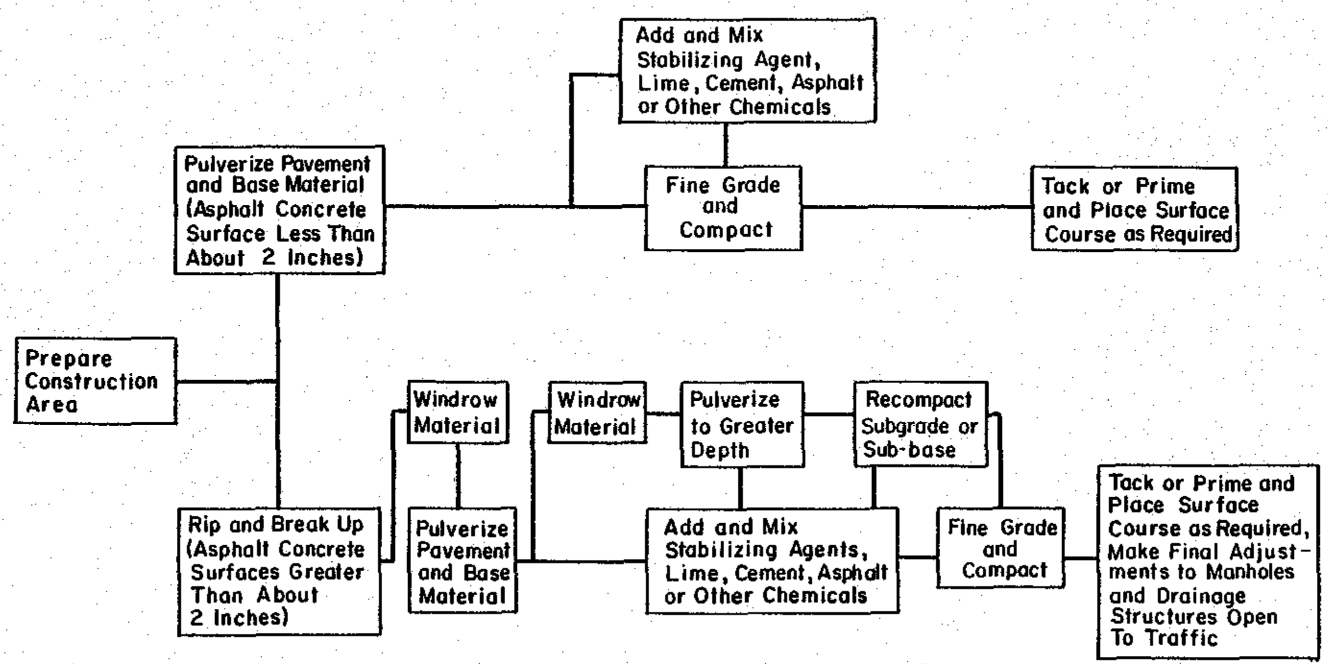

Figure 6. In-Place surface and base recycling alternatives.

central plant operations had an early history with Warren Brothers in 1915 (22), but very little experimentation was conducted from that time until 1974 (23). Equipment is now commercially available which can hot recycle asphalt pavements while satisfying air quality regulations. (Figure 7). Details of the type of equipment presently utilized can be found in Reference 5. Figure 7

Mixture Design. Mixture design techniques provide information for the selection of the type and amount of chemical or chemicals for recycling. Figure 8 is the basis for selection of a stabilizer to be used in a recycling operation (31). Figure 9 provides an outline for a mixture design method associated with using asphalts or asphalt modifiers (1, 17, 24, 25, 26, 27). 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: Figure 8 Figure 9 Figure 10

1. Evaluation of salvaged materials,
2. Determination of the need for additional aggregates,
3. Selection of modifier type and amount,
4. Preparation and testing of mixtures and
5. Selection of optimum combinations of new aggregates and asphalt modifiers.

Figure 10 and Table 9 have proven to be useful for selection of the appropriate type and amount of asphalt modifiers required for a given recycling operation (20). Table 9

Structural Design. Structural design techniques suggested for use include the 1972 AASHTO Interim Guides (28) and layered elastic design procedures. Typical AASHTO layer coefficients have been

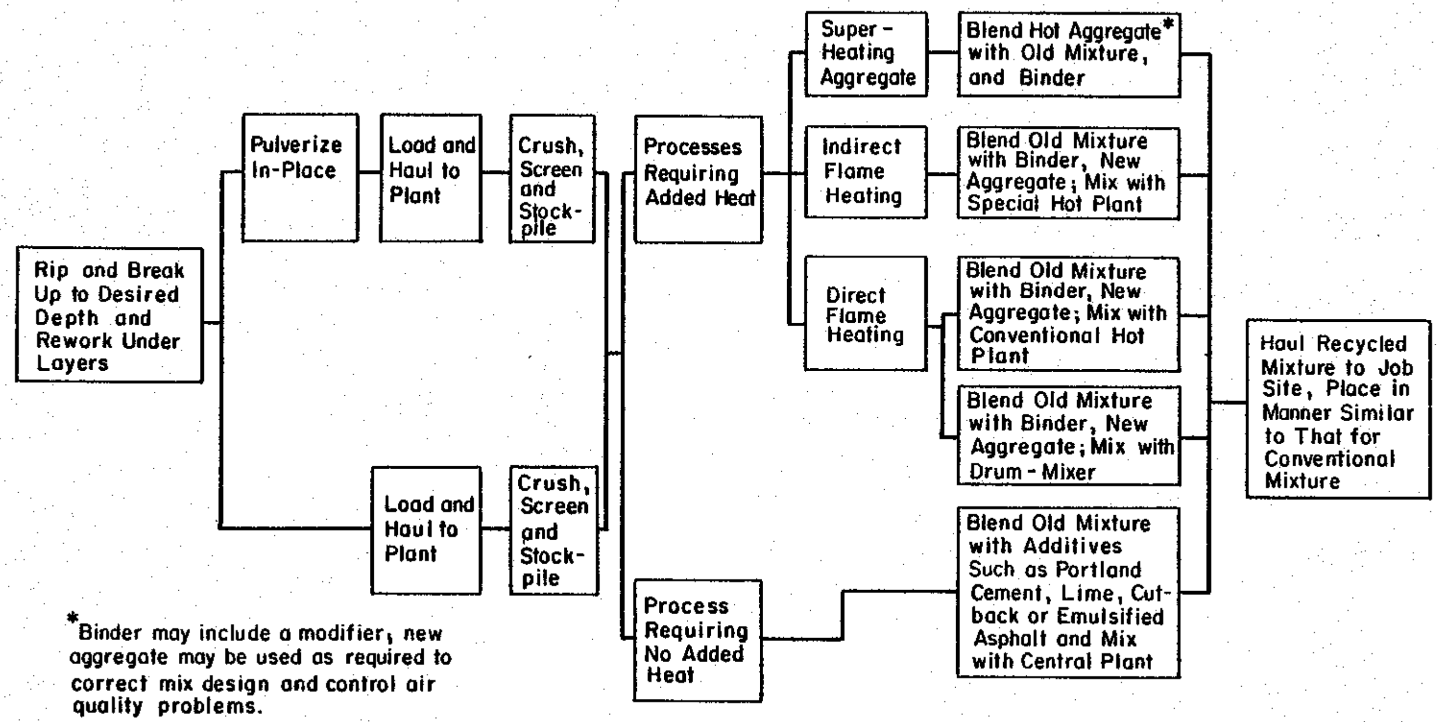

Figure 7. Central-plant recycling techniques.

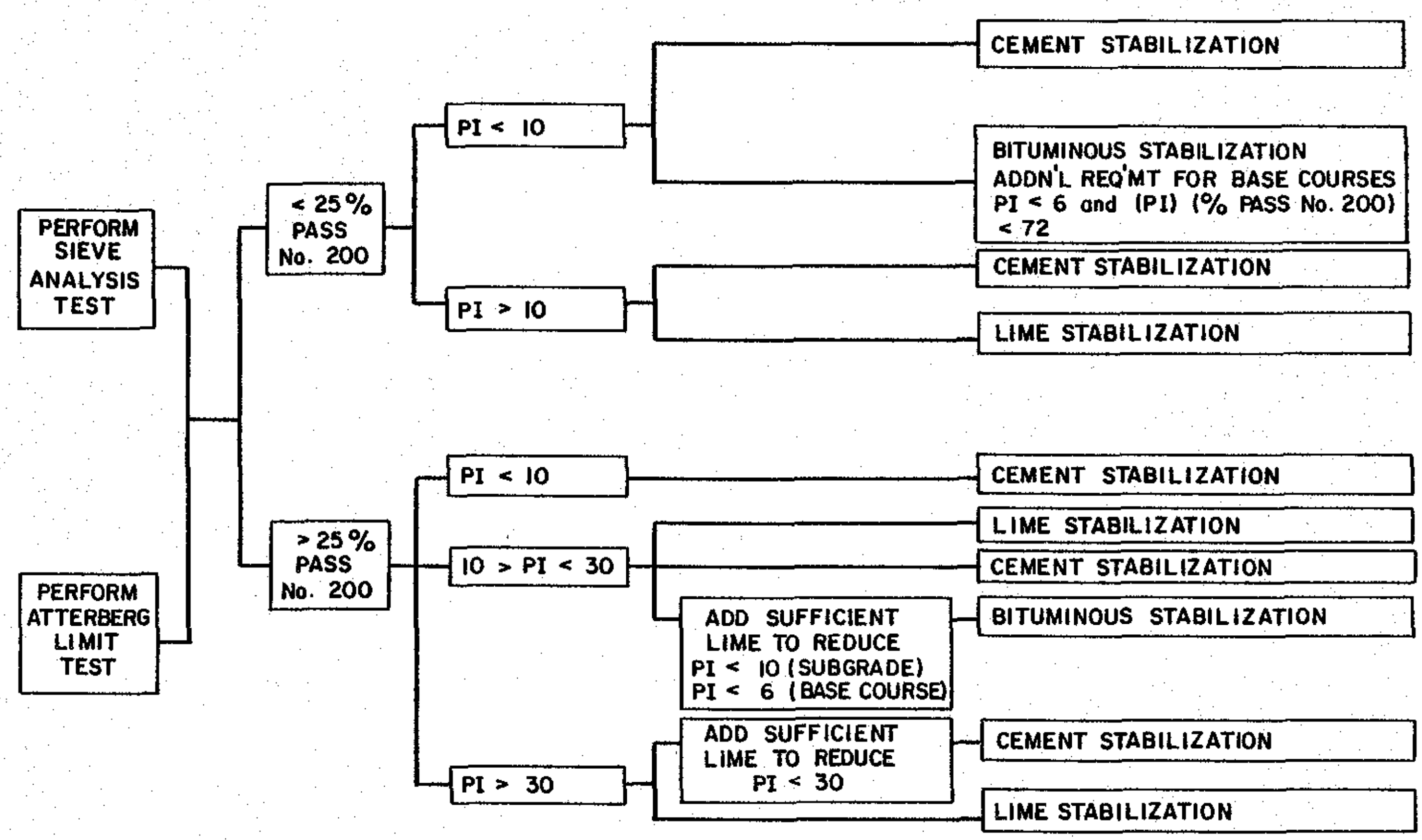

Figure 8. Selection of Stabilizer (after Dunlap, et al. - Ref. 31).

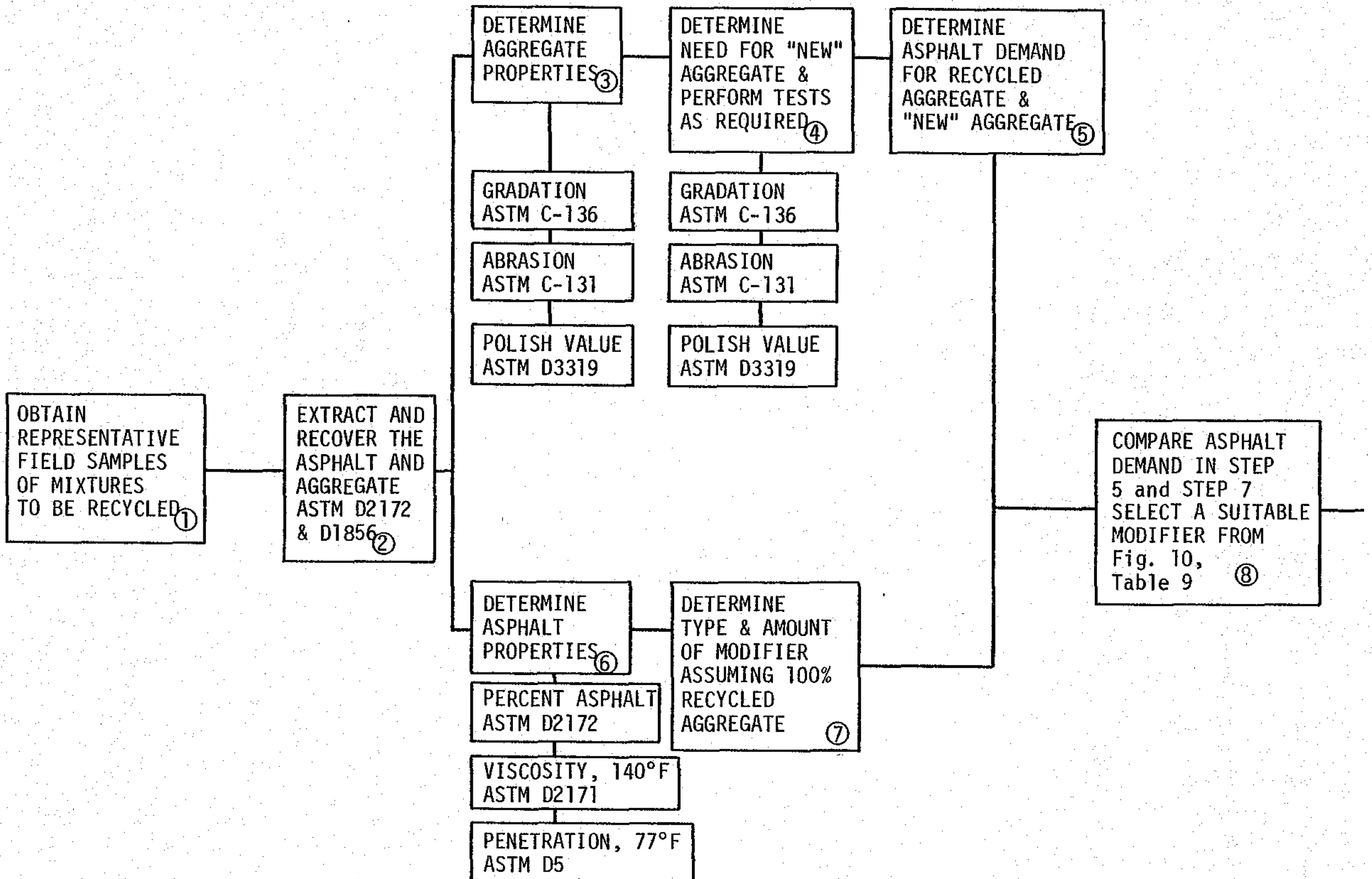

Figure 9. Mixture design procedure.

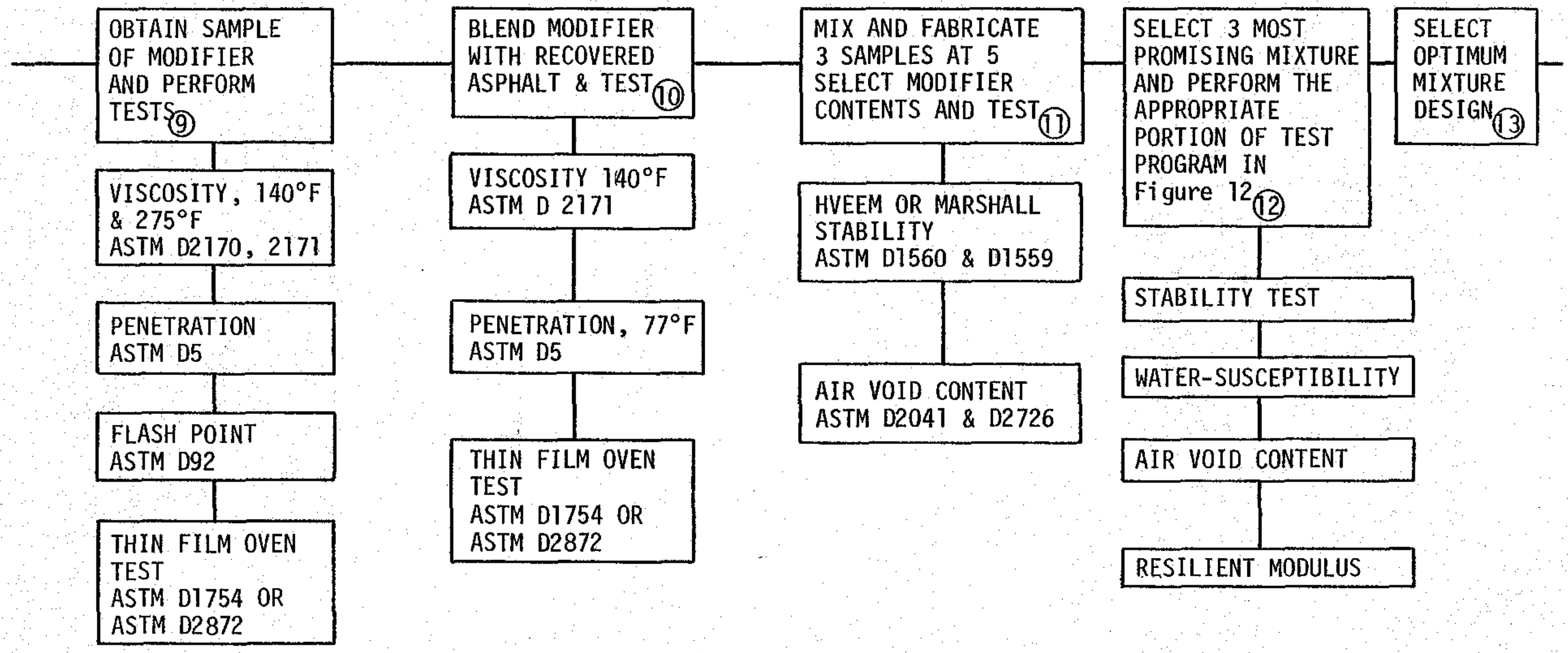

Figure 9 - Continued.

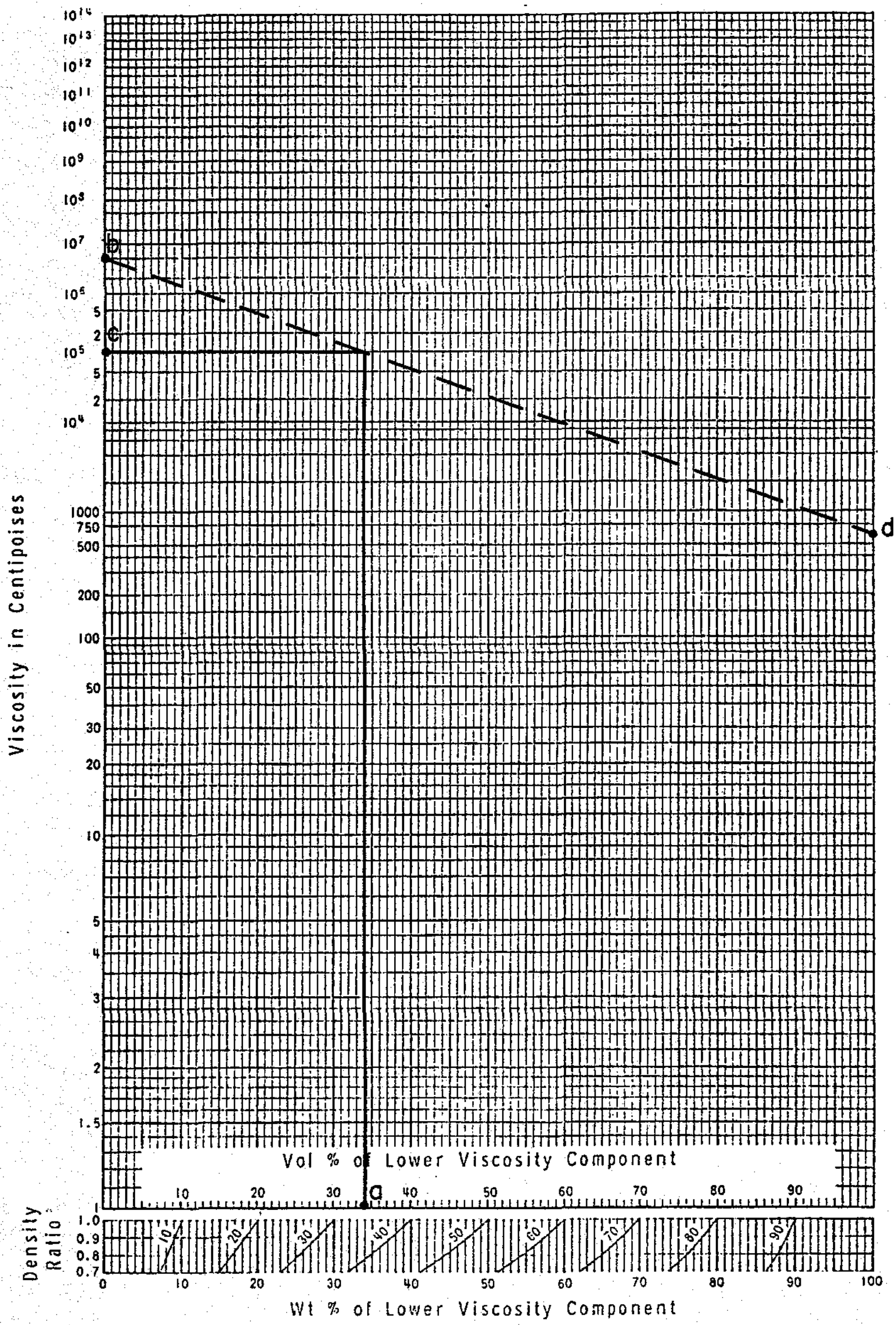

Figure 10. Viscosity Blending Chart (after Reference 20).

TABLE 9 - PROPOSED SPECIFICATIONS FOR HOT MIX RECYCLING AGENTS [1]

TEST	ASTM TEST METHOD	RA 5		RA 25		RA 75		RA 250		RA 500	
		min.	max.	min.	max.	min.	max.	min.	max.	min.	max.
Viscosity @140°F, cSt	D2170 or 2171	200	800	1000	4000	5000	10000	15000	35000	40000	60000
Flash Point COC, °F	D92	400	-	425	-	450	-	450	-	450	-
Saturates, wt. %	D2007	-	30	-	30	-	30	-	30	-	30
Residue from RTF-C Oven Test @325°F	D2872[2]										
Viscosity Ratio[3]	-	-	3	-	3	-	3	-	3	-	3
RTF-C Oven Weight Change, ±, %	D2872[2]	-	4	-	4	-	2	-	2	-	2
Specific Gravity	D 70 or D1298	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 D1754 has not been studied in the contest of this specification, however, it may be applicable. In cases of dispute the reference method shall be ASTM D2872.

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

After Reference 20

obtained on several field projects and are shown on Table 10 (32). Material properties suitable for use with layered elastic design procedures are available on only a few recycling projects (33).

Economics and Energy. Economic and energy comparisons among recycling and/or rehabilitation alternatives should be made on a 20- to 30-year life cycle basis. Summarized cost information is shown on Table 8 while representative energy consumption is shown on Table 11. Detailed cost and energy information for a wide range of construction, rehabilitation and maintenance operations can be found in Reference 1.

Table 10

Table 11

Guide Specifications. Guide specifications have been formulated for specific common recycling operations (1, 4, 17). The guide specifications are intended to supplement and/or provide input in order that agency specifications can be revised. Guide specifications are provided for the following recycling operations:

1. Planing Operations
2. Heater-Scarification Operations
3. In-Place Pulverization and Compaction Without Chemical Stabilizers
4. In-Place Pulverization and Lime Stabilization
5. In-Place Pulverization and Portland Cement Stabilization
6. In-Place Pulverization and Asphalt Stabilization
7. Central Plant Recycling - Asphalt Concrete

Quality Control. At the time of the preparation of these guidelines, quality control measures currently employed on pavement recycling jobs have been those typically used on similar types of construction by the performing agency. Sufficient data are not available to develop

TABLE 10 - TYPICAL AASHTO STRUCTURAL LAYER COEFFICIENTS

Type of Recycled Material	Layer Used as	Range of a_i Computed	Average a_i	Number of Test Sections	a_i for Corresponding Layer and Material at AASHTO Road Test
Central Plant Recycled Asphalt Concrete Surface	Surface	0.37-0.59	0.48	14	0.44
Central Plant Recycled Asphalt Concrete Base	Base	0.37-0.49	0.42	3	0.35
In-Place Recycled Asphalt Concrete Stabilized with Asphalt and/or an Asphalt Modifier	Base	0.22-0.49	0.36	6	0.35
In-Place Recycled Asphalt Concrete and Existing Base Material Stabilized with Cement	Base	0.23-0.42	0.31	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 32

TABLE 11 - TYPICAL ENERGY REQUIREMENTS FOR 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 Plan Recycling	20,000 - 25,000	1

1 BTU/yd^3 = 1381 J/m^3

statistically based quality assurance specifications for recycling operations (29, 30).

Evaluation of Results

Performance of pavements and determination of in-place material properties should be obtained in a uniform and continuous manner for a 20- to 30-year period. Project data collection should include preconstruction mixture design and structural design information, construction quality control records, properties of the materials after construction and performance of the pavement after construction. A Figure 11
similar performance evaluation program should be used to study the behavior of selected conventional construction and rehabilitation pro- Figure 12
jects for comparison purposes. These data should be utilized as feedback information to the design process described above and thereby form the basis for future selection of pavement rehabilitation alternatives.

A description of the types of information that should be considered for inclusion in this evaluation program are shown on Figure 11. During construction, samples of the loose mixtures should be obtained and the samples fabricated. The testing plan shown on Figure 12 is suggested for recycling jobs where asphalt is utilized as a binder. This testing plan has been formulated for research purposes and a particular agency may elect to perform a limited number of these tests.

Recycling operations utilizing lime, portland cement (other than econocrete or portland cement concrete) or other types of binder should be sampled after mixing and just prior to compaction. These materials should be used to fabricate samples suitable for strength and durability testing. The types of tests that should be utilized

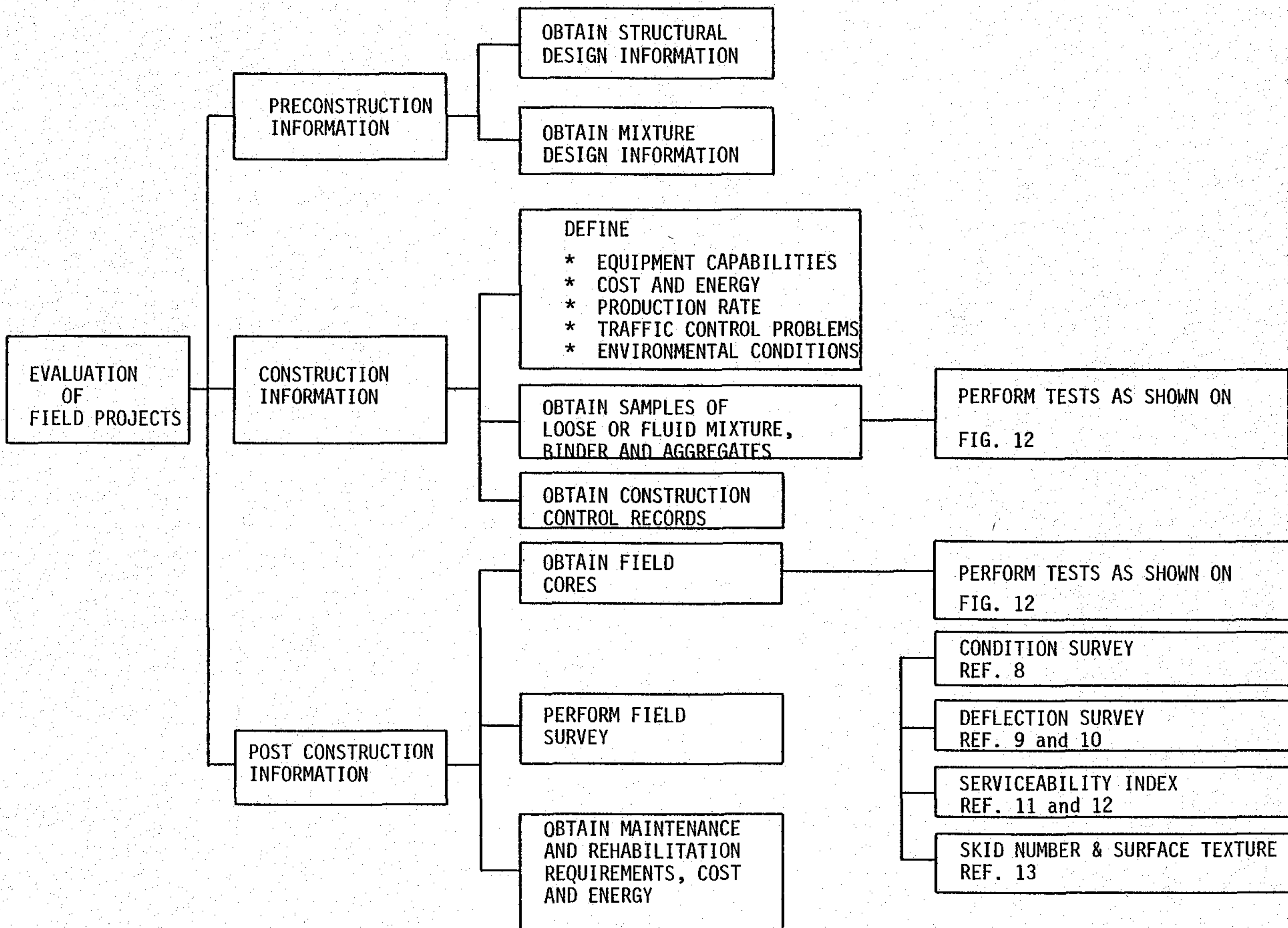

Figure 11. Evaluation of field projects.

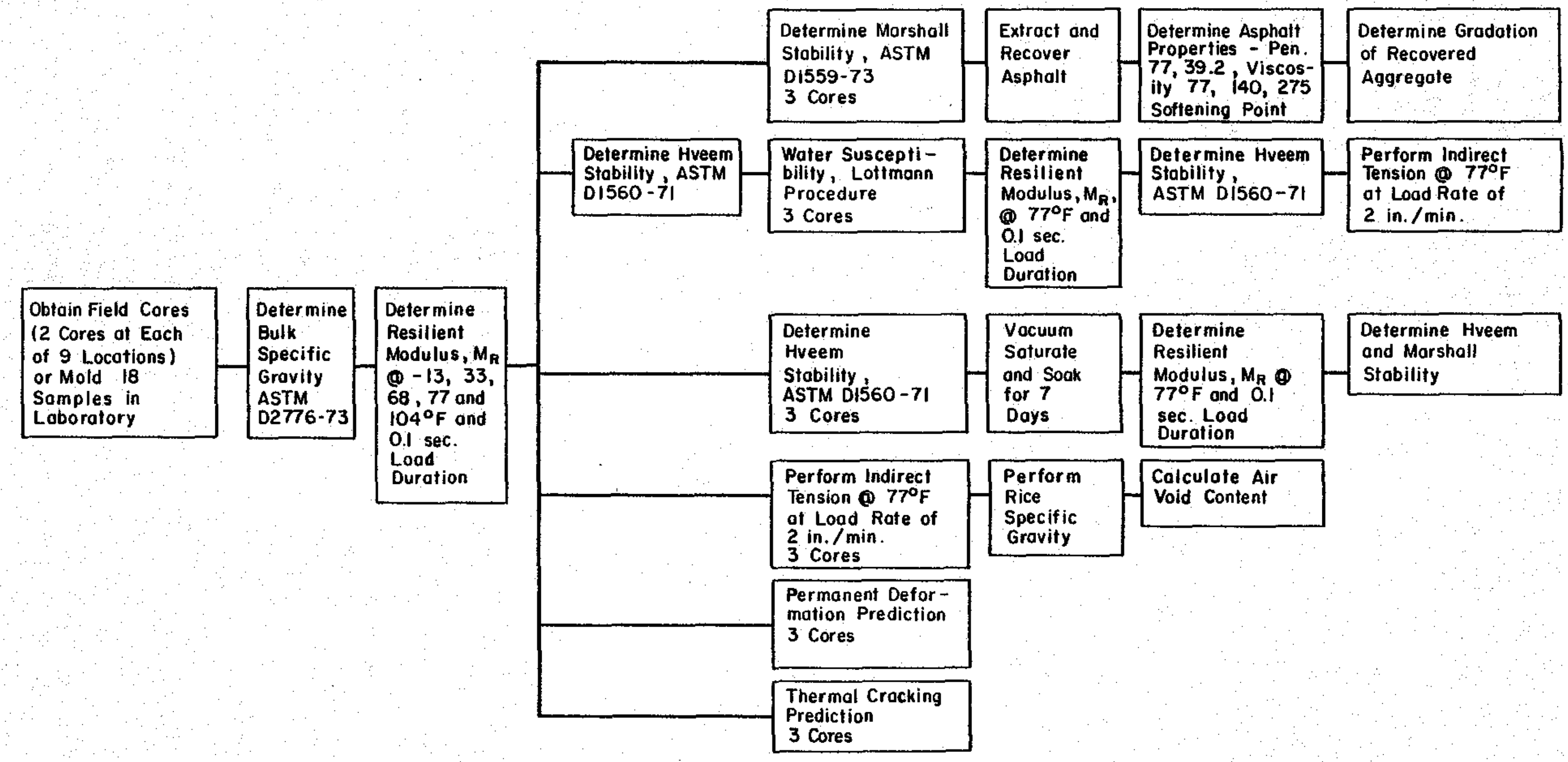

Figure 12. Suggested test sequence for field cores and laboratory molded samples - asphalt recycling.

are those presently specified by the agency performing the recycling operation or those tests suggested for design for these types of mixtures in Reference 31.

After construction, field cores should be obtained at various time intervals. Sufficient field cores or samples should be obtained to perform test plans shown on Figure 12, if asphalt is utilized as the binder. These testing plans have been formulated for research purposes and a particular agency may elect to perform a limited number of these tests.

The evaluation of a recycling job is an extremely important part of a recycling project. If the engineering community is to define the proper place for recycling in pavement rehabilitation, the types of data obtained in the field evaluations will have to be defined. In order to obtain the data outlined above, an agency or organization must be convinced of its usefulness and be willing to schedule these activities in order to make the necessary surveys, obtain field samples, perform laboratory tests and make the appropriate analysis. Perhaps the most effective way to make sure the data are collected in a uniform and continuous manner is to assign responsibility to a specific individual or organizational unit for a 10- to 15-year period.

EXAMPLE PROBLEM

An interstate highway in West Texas is in need of rehabilitation. The resident engineer would like to consider recycling as a rehabilitation alternative as aggregate supplies are not locally available (within 50-75 miles).

Preliminary Analysis

Information collected on this section of roadway is shown on Table 3. An inspection of the roadway indicated a minor amount of alligator cracking and large amounts of longitudinal and transverse cracking (Table 4). Based on results of Dynaflect tests and Reference 9, a two to two and one-half inch overlay will be required (Table 5). The Serviceability Index as determined with the Mays Ride Meter is 2.3 (Table 6). Tables 3, 4 and 5 were utilized to select preliminary recycling alternatives (Table 7). Based on this preliminary analysis the following recycling options appear feasible:

A5 - Heater-scarify plus thick overlay

A8 - Surface milling plus thick overlay

B7 - In-place recycling with major structural improvement and without new binder

B8 - In-place recycling with major structural improvement and with new binder

C3 - Central cold mix process with major structural improvements without new binder

C4 - Central cold mix process with major structural improvements with new binder

C7 - Central hot mix process with major structural improvement and without new binder

C8 - Central hot mix process with major structural improvement and with new binder.

Since local contractors were not familiar with in-place recycling alternatives, B7 and B8 were eliminated. Alternative C3 was eliminated due to the long haul distances required to obtain suitable material for the thicker sections. Alternative C4 was eliminated as the engineer preferred to use a bituminous binder rather than portland cement while lime is not a suitable stabilizer for the existing in-place material (Figure 8). Alternative C7 was not used because of the initial cost economics demonstrated in Table 8. Alternative A8 was not utilized as the millings, from an economic standpoint, would have to be recycled and thus Alternative C8 utilized. Thus, recycling Alternatives A5 and C8 together with conventional rehabilitation techniques were considered in a detailed analysis.

Detailed Analysis

Equipment and Methods. Figure 5 was utilized to select the heater-scarification recycling technique. The surface is to be heated and scarified to a minimum depth of 3/4 inch, the surface "screed" and a two-inch asphalt concrete overlay applied.

The central plant recycling technique will consist of ripping, loading and hauling to a central crushing operation followed by a direct flame hot recycling operation (Figure 7). Several contractors in the West Texas area have this type of recycling equipment and it can be used with 30 percent new aggregate to produce an acceptable recycled asphalt concrete while satisfying air quality regulations.

Mixture Design. Figure 9 was utilized as a basis to determine the amount of recycling modifier to be used in the hot central plant recycling operation. (A similar procedure could be used for the heater-scarifications operation; however, sampling and testing should be confined to the top 3/4 to 1-inch of the pavement.) The pavement was sampled at five locations and the asphalt extracted and recovered. Results of these tests indicated that the pavement could be considered homogeneous as the penetration ranged from 15 to 22 and the gradation of the recovered aggregate varied little. The average viscosity of the recovered asphalt cement was 50,000 poises at 140°F while the average penetration was 19 as measured under standard conditions at 77°F.

The aggregate gradation was satisfactory as recovered from the pavement; however, 30 percent new aggregate was added to help control air quality. The total estimated asphalt demand for the recycled mixture containing 70 percent recycled material and 30 percent new aggregate was 6.5 percent by dry weight or aggregate. The amount of asphalt in the mixture to be recycled was 6.2 percent. The anticipated additional amount of bituminous modifiers is therefore 2.2 percent as

$$6.5 - [(0.70 \times 6.2) + (.30 \times 0.0)] = 2.2$$

Figure 10 together with the following can be used to determine the approximate desired viscosity of the recycling agent (Step 8 of Figure 9).

a. The desired weight percent of recycling modifier is $\frac{2.2}{6.5} = .34$ or 34 percent of the total binder assuming the specific gravity of the modifier is equal to that of the recovered asphalt.
b. The viscosity of the recovered asphalt from the old pavement is 50,000 poises.
c. The desired binder in the recycled mixture is an AC-10.
d. The approximate viscosity of the modifier is 650-700 centipoises.

Table 9 indicates that an RA-5 recycling agent is suitable.

Tests performed on blends of recovered asphalt and modifier confirm that approximately 35 percent of the total binder should be an RA-5 designated recycling agent. Tests on mixtures prepared with 70 percent recycled asphalt concrete and 30 percent new aggregate indicate that adequate stability and air void contents can be obtained at 6.5 percent total binder. Water-susceptibility of the mixture is also adequate. The 70-30 blend with 6.5 percent total binder is the mixture which should be tried first in the field.

<u>Structural Design</u>. The structural design was performed according
to References 9 and 28 and resulted in the thickness requirements
associated with the various alternatives shown on Table 12. Table 12

<u>Economics and Energy</u>. Table 12 contains rehabilitation alter-
natives based on a detailed structural analyses as well as pavement Table 13
performance experience gained in the Southwest.

Anticipated life cycle costs are shown on Table 13 for a 20-year Table 14
period. Costs were based on information obtained by the local resident
engineer and shown on Table 14. Table 15 contains a summary of the Table 15
cost and energy requirements for these 10 rehabilitation alternatives. Both initial and life cycle costs and energies are shown. Life cycle costs in terms of present worth for rates of return of 0 and 8 percent are given. Equal annual life cycle costs (assuming an 8 percent rate of return) are of the order of 50 to 70 cents per square yard of pavement surface. Various hot recycling cost and timing options. (Plans 4, 5, 6, 7 and 8) were investigated to demonstrate the sensitivity of the assumptions made in the analysis.

The selection of the appropriate rehabilitation alternative will be based on the amount of money initially available for the project and if life cycle costs are to be considered the rate of return to be

TABLE 12 - REHABILITATION ALTERNATIVES DEFINED

Plan 1: Two-inch asphalt concrete overlay with maintenance on a 7-year cycle (asphalt concrete $25.00 per ton).

Plan 2: Chip seal plus 2-inch asphalt concrete overlay with maintenance (chip seal $0.55 per square yard, asphalt concrete $25.00 per ton).

Plan 3: Fabric reinforcement plus 2-inch asphalt concrete overlay with maintenance (fabric reinforcement $1.25 per square yard, asphalt concrete $25.00 per ton).

Plan 4: Recycle existing 4 inches of material and blend a selected aggregate into recycle mixture. A 2-inch overlay is scheduled after 5 years (recycling at $20.00 per ton and overlay at $25.00 per ton).

Plan 5: Recycling existing 4 inches of asphalt materials and 2 inches of asphalt concrete overlay with maintenance (recycling $16.00 per ton, asphalt concrete $25.00 per ton).

Plan 6: Recycling existing 4 inches of asphalt materials and 2 inches of asphalt concrete overlay with maintenance which includes a 2-inch overlay (recycling $16.00 per ton, asphalt concrete $25.00 per ton).

Plan 7: Recycling existing 4 inches of asphalt materials and 2 inches of asphalt concrete overlay with maintenance (recycling $20.00 per ton, asphalt concrete $25.00 per ton).

Plan 8: Delay recycling 4 years and then recycle and add 2 inches of asphalt concrete overlay with maintenance (recycling $16.00 per ton, asphalt concrete $25.00 per ton).

Plan 9: Heater-scarify to a depth of 1 to 1.5 inch and 2 inches of asphalt concrete overlay with maintenance (heater-scarification $0.90 per square yard, asphalt concrete $25.00 per ton).

Plan 10: Asphalt-rubber interlayer and 2 inches of asphalt concrete overlay with maintenance (asphalt-rubber interlayer $1.25 per square yard, asphalt concrete $25.00 per ton).

TABLE 13 - REHABILITATION ALTERNATIVES COST SCHEDULES *

Year	Plan 1 2" A.C. Overlay	Plan 2 Seal Coat +2" A.C. Overlay	Plan 3 Fabric Rein-force-ment +2" A.C. Overlay	Plan 4 Recycle	Plan 5 Recycle +2" A.C. Overlay	Plan 6 Recycle +2" A.C. Overlay	Plan 7 Recycle +2" A.C. Overlay	Plan 8 Recycle +2" A.C. Overlay	Plan 9 Heater-Scarify + 2" A.C. Overlay	Plan 10 Asphalt-Rubber Interlayer + 2" A.C. Overlay
1980	2.50	3.05	3.75	4.00	5.70	5.70	6.50	.15	3.40	3.75
1981								.15		
1982								.15		
1983	.08							.15		
1984	.13	.08	.08					6.50	.08	.08
1985	.15	.13		2.50						
1986	.15	.15	.13						.13	.13
1987	2.50	.15								
1988		.15	.15		.08	.08	.08		.15	.15
1989		2.50								
1990	.08		2.50		.13	.13	.13		2.50	2.50
1991	.13			.08				.08		
1992	.15	.08			.15	.15	.15			
1993	.15	.13	.08	.13				.13	.08	.08
1994	2.50	.15	.13		.15	2.50	.15		.13	.13
1995		.15	.15	.15				.15	.15	.15
1996		3.05	.15		.15		.15		.15	.15
1997	.08		.15	.15				.15	.15	.15
1998	.13		.15		.15	.08	.15		.15	.15
1999	.15		.15	.15				.15	.15	.15
2000	.15	.08	.15		.15	.13	.15		.15	.15

*Numbers represent costs per square yard.

TABLE 14 - COST DATA USED TO ANALYZE REHABILITATION STRATEGIES

Material or Operation	Cost	
	$ Per Ton	$ Per Sq. Yd.
Asphalt Concrete	25.00	1.25*
Recycle Asphalt Concrete	20.00	1.00*
Recycle Asphalt Concrete	16.00	0.80*
Chip Seal Coat		0.55
Fabric		1.25
Heater-Scarification		0.90
Crack Sealing		0.15
Asphalt Rubber Interlayer		1.25

*Cost per square yard for one-inch thickness.

TABLE 15 - COST AND ENERGY SUMMARY

Plan No.	Method	Energy, BTU/Sq.Yd. Initial	Energy, BTU/Sq.Yd. 20-Year Life	Cost, Dollars/Sq.Yd. Initial	Cost, 20-Year Life* 0 Percent	Cost, 20-Year Life* 8 Percent
1	2" AC Overlay	57,800	200,000	2.50	9.03	5.50
2	Seal Coat + 2" AC Overlay	61,700	203,000	3.05	9.85	5.80
3	Fabric + 2" AC Overlay	60,000	145,000	3.75	7.72	5.44
4	Recycle	119,600	190,000	4.00	7.16	5.91
5	Recycle + 2" AC Overlay	177,400	195,000	5.70	6.66	6.03
6	Recycle + 2" AC Overlay	177,400	244,000	5.70	8.77	6.76
7	Recycle + 2" AC Overlay	177,400	195,000	6.50	7.46	6.83
8	Recycle + 2" AC Overlay	2,200	201,000	0.15	7.76	5.52
9	Heater-Scarify + 2" AC Overlay	74,800	160,000	3.40	7.37	5.09
10	Asphalt Rubber Interlayer + 2" AC Overlay	64,000	149,000	3.75	7.72	5.44

*Equal annual costs assuming 0 and 8 percent rate of return.

expected on the monies available. The lowest first cost alternative is a 2-inch asphalt concrete overlay (Plan 1). (The "do nothing" alternative, Plan 8, has not been considered in making this statement.) Alternative Plan 5 has the lowest 20-year life cycle cost if 0 percent rate of return can be expected. For an expected 8 percent rate of return, Plan 9 is desirable. From a life cycle energy standpoint, Plans 3 and 10 are desirable. Table 15, therefore, forms a basis from which the decision can be made by the engineer. Local conditions and expected life cycles of the various alternatives must be considered in considerable detail before making the final decision.

Guide Specifications and Quality Control. Specifications utilized for hot central plant recycling in other Texas highway districts were reviewed together with information from other states and Reference 1. Quality control procedures followed those typically used for asphalt concrete surface courses.

SUMMARY

Information on pavement recycling has been collected and synthesized into realistic guidelines for the practicing engineer. The complete document provides the engineer with the following information in a single reference document:

1. Advantages and disadvantages of pavement recycling,
2. Identification of recycling techniques,
3. Assistance in making a preliminary analysis of recycling as a rehabilitation alternative.
4. Guidance and criteria for making a detailed analysis of cost, energy, mixture design, structural design, construction specifications and quality control and
5. Recommendations for evaluation of recycling projects so that comparison with conventional methods of rehabilitation can be made.

The criteria, cost data, energy data, etc. presented in this paper need to be improved. Criteria for selection of rehabilitation alternatives should be based on local conditions and local cost information should be used when possible. Performance of recycling projects needs to be defined and related to the type of distress corrected. Specifications and quality control for pavement recycling operations need to be improved. Improved specifications for pavement modifiers need to be established as well as the understanding of the compatibility of recycling modifiers and old recycled asphalts. Fatigue, permanent deformation and low temperature properties of recycled mixtures need to be defined for inclusion in mechanistic pavement design procedures.

The recycling guidelines presented in this paper provide a framework upon which change can be made as improved criteria are developed. Until these improved criteria are formulated, these guidelines will assist the practicing engineer in making his daily rehabilitation decisions.

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