NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
SYNTHESIS OF HIGHWAY PRACTICE **30**

BITUMINOUS EMULSIONS FOR HIGHWAY PAVEMENTS

RESEARCH SPONSORED BY THE AMERICAN ASSOCIATION OF STATE HIGHWAY AND TRANSPORTATION OFFICIALS AND THE FEDERAL ENERGY ADMINISTRATION IN COOPERATION WITH THE FEDERAL HIGHWAY ADMINISTRATION

AREAS OF INTEREST:
- PAVEMENT DESIGN
- BITUMINOUS MATERIALS AND MIXES
- CONSTRUCTION
- MAINTENANCE, GENERAL

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL
WASHINGTON, D.C. 1975

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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

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PREFACE

There exists a vast storehouse of information relating to nearly every subject of concern to highway administrators and engineers. Much of it resulted from research and much from successful application of the engineering ideas of men faced with problems in their day-to-day work. Because there has been a lack of systematic means for bringing such useful information together and making it available to the entire highway fraternity, the American Association of State Highway and Transportation Officials has, through the mechanism of the National Cooperative Highway Research Program, authorized the Transportation Research Board to undertake a continuing project to search out and synthesize the useful knowledge from all possible sources and to prepare documented reports on current practices in the subject areas of concern.

This synthesis series attempts to report on the various practices without in fact making specific recommendations as would be found in handbooks or design manuals. Nonetheless, these documents can serve similar purposes, for each is a compendium of the best knowledge available concerning those measures found to be the most successful in resolving specific problems. The extent to which they are utilized in this fashion will quite logically be tempered by the breadth of the user's knowledge in the particular problem area.

FOREWORD

By Staff
Transportation Research Board

This synthesis will be of special interest and usefulness to highway design, construction, materials, and maintenance engineers seeking technical information on the use of emulsified asphalts in highway and street construction and maintenance. Detailed information is presented on structural design, mixture design, materials selection, and construction and maintenance techniques for using emulsified asphalts in pavements. Construction problems that have been faced in the past, along with solutions that have been found to be workable, are described.

Administrators, engineers and researchers are faced continually with many highway problems on which much information already exists either in documented form or in terms of undocumented experience and practice. Unfortunately, this information often is fragmented, scattered, and unevaluated. As a consequence, full information on what has been learned about a problem frequently is not assembled in seeking a solution. Costly research findings may go unused, valuable experience may be overlooked, and due consideration may not be given to recommended practices for solving or alleviating the problem. In an effort to resolve this situation, a continuing NCHRP project, carried out by the Transportation Research Board as the research agency, has the objective of synthesizing and reporting on common highway problems—a synthesis being identified as a composition or combination of separate parts or elements so as to form a whole greater than the sum of the separate parts. Reports from this endeavor constitute an NCHRP report series that collects and assembles the various forms of information into single concise documents pertaining to specific highway problems or sets of closely related problems.

Syntheses research normally is conducted with support coming entirely from the state highway and transportation departments sponsoring the NCHRP. In this special instance, major support was received also from the Federal Energy Administration.

Emulsified asphalts have been available and used in highway construction for many years. In 1974, all state highway and transportation agencies had specifications covering one or more grades. Although quantities used have been substantial, they have never equaled those of the more popular cutback liquid asphalts and asphalt cements for which an emulsified asphalt might be considered as an alternative. Reaction to disappointing performance due primarily to construction inexperience undoubtedly has been a major factor in the slower acceptance of emulsified asphalts. Unfortunately, expertise in the use of cutback asphalts and asphalt cements has been found to be no guarantee of success in the use of emulsified asphalts. In this day of great need to conserve energy and reduce air pollution, the special contribution that emulsified asphalts can make in this regard as compared with alternative materials suggests that efforts to make proper use of them be approached with new intensity.

This report of the Transportation Research Board describes current practices in the use of emulsified asphalts that experience has shown to be successful. Step-by-step procedures that should result in quality construction are described. Research needs in the area are identified.

To develop this synthesis in a comprehensive manner and to ensure inclusion of significant knowledge, the Board analyzed available information assembled from many highway and transportation departments and other agencies concerned with various facets of highway planning, design, construction, operations, and maintenance. A topic advisory panel of experts in the subject area was established to guide the researchers in organizing and evaluating the collected data, and to review the final synthesis report.

This synthesis is an immediately useful document that records practices that were acceptable within the limitations of the knowledge available at the time of its preparation. Meanwhile, the continuing process of search for better methods should go on undiminished.

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Information on current practice was provided by many highway agencies and by the U.S. Forest Service. Their cooperation and assistance were most helpful.

BITUMINOUS EMULSIONS FOR HIGHWAY PAVEMENTS

SUMMARY

Bituminous emulsions are used widely in construction and maintenance of pavements ranging from high-traffic-volume highways and airports to low-volume rural roads and city streets. Although emulsions have been available since 1903 and used extensively since the 1930's, recent energy and environmental problems have focused attention on increased use of these materials. The use of emulsions can reduce energy requirements through reduction or elimination of the petroleum distillates that are used in liquid asphalts and through lower heating requirements compared to hot plant-mix asphalt concrete. The elimination of distillates also reduces air pollution.

There are two classes of asphalt emulsion in common use. Cationic emulsions have positively charged particles that adhere better to electronegative aggregates, such as silica and quartz; anionic emulsions (negatively charged particles) have better adhesion on limestone aggregates. However, there is such a wide variety of aggregates used in pavements that ionic characterization may be of secondary importance.

Some emulsion producers have provided technical service to the users. However, expanded use of emulsions requires additional training of engineers and technicians who may be familiar with other bituminous construction and maintenance but need more knowledge of emulsions.

Structural design of emulsion pavements by the AASHTO or Asphalt Institute methods involves using asphalt concrete design procedures and then applying a correction. In use of the AASHO Interim Guide an appropriate coefficient is selected for use with the structural number that was determined in the usual manner. In an adaptation of the AASHO Guide by the U.S. Forest Service, the coefficient depends on the materials and construction method to be used. The Asphalt Institute design method determines the thickness for asphalt concrete and multiplies this by a factor of 1.4 to obtain the thickness of emulsified-asphalt pavement layers.

A method developed by the Chevron Research Company is based on examination of the horizontal strain at the bottom of the treated layer and the vertical strain at the subgrade surface. The design takes into account climatic conditions that affect cure rate and strength. The pavement thickness is selected to ensure that the strains at the subgrade are within allowable limits for both early-cure and full-service conditions.

All three of these design methods are primarily applicable to dense-graded mixes, although the Forest Service adaptation provides for use of open-graded materials.

Spray applications of emulsified asphalt are widely used. Applications without cover material include: tack coats, to promote bond between layers; fog seals, to seal existing surfaces; and curing seals, to seal cement- or lime-treated bases.

Surface treatments and seal coats are spray applications of asphalt followed by an application of aggregate embedded by rolling. Multiple treatments are sometimes used. The aggregate is essentially a one-size material; the asphalt can be a rapid-setting emulsion. Application rates for emulsified asphalt and aggregate can be determined by the procedures given in The Asphalt Institute's *Manual MS-13*.

Slurry seals consist of a mixture of slow-setting or quick-setting mixing-type emulsion, fine aggregate, mineral filler, and water applied to a surface to serve as a

crack filler and wearing course. Design of slurry seals involves selection of optimum percentages of water and emulsion by testing specimens of various contents for abrasion in a submerged condition.

Emulsion-aggregate mix design must consider type and amount of asphalt emulsions, water content, mixing time, aeration, compaction, curing, and testing. It is important that the emulsion and aggregates used in trial mixes are representative of those to be used in the pavement. For dense-graded mixes, a preliminary estimate of emulsion content is made based on past experience or on the size and surface area of the aggregate. Sample mixes are then prepared in the laboratory and tested to determine optimum emulsion content for the mix. For open-graded mixes, a coating test is used to estimate the quantity of water to be used in mixing; little other testing is performed, although a runoff test has been proposed.

There is a wide variation in the properties of aggregates used in emulsion construction. For emulsion mixes the important properties are mineralogical composition, hardness, abrasion resistance, porosity, durability, particle shape, surface texture, surface chemistry, and gradation. The presence of deleterious materials affects an emulsion mix, particularly if degradation forms additional fines. Caution should be exercised with mixes using in-place aggregates that may have received chemical stabilization.

For quality construction, proper controls and good workmanship are required. Construction with emulsified asphalt involves different procedures from those used with cutbacks and asphalt cements. Care should be exercised in the storage and handling of emulsions to avoid breaking them. Emulsion mixes preferably are prepared in a central plant using a pugmill or drum mixer. Road mixing is also done; methods include traveling pugmill, in-place mixer, and blade mixing with a motor grader.

Some of the important hints for quality construction with asphalt emulsions include:

- Determine the proper type and grade of emulsion for use with available aggregates and the proposed method of construction.
- If necessary, consult the emulsion supplier on selection of the proper emulsion for the job.
- Do not use aggregates that are coated with clay or other dust.
- Use only as much mixing water as needed to disperse the emulsion and obtain workability.
- Mix only as long as necessary to disperse the emulsion throughout the aggregate.
- Placement of multiple thin layers of cold mix will allow faster curing than a single thick layer.

Cold-mix surface courses, especially dense-graded ones, should be sealed after construction but not so soon as to entrap mixing water.

Emulsions are also used for maintenance operations, such as crack repairs, pothole filling, skin patching, and overlays for skid resistance. Emulsions are also used as binders for mulch application on roadsides.

Although some research is under way, additional research is needed in several areas. Work is needed to develop materials and specifications for modified emulsions and emulsion residues. Studies and evaluation of field performance should result in improved construction techniques and procedures. Research is needed to define the role of emulsion-treated materials in improved structural design procedures.

CHAPTER ONE

INTRODUCTION

Bituminous emulsions—suspensions of minute globules of bituminous material in water—are recognized by most federal, state, and local agencies and authorities as an important bituminous material used in the construction and maintenance of pavements ranging from heavy-duty types for high-traffic-volume highways and airports to low-traffic-volume rural roads and city streets.

This report is a discussion of the state-of-the-art on the use of emulsified asphalts for construction and maintenance of the various types of pavements and surface applications. Because emulsified asphalts are becoming of greater importance in the partial solution of energy and environmental problems associated with the use of other bituminous materials, the advantages and disadvantages of using emulsions as replacements are discussed.

The development of emulsions, specifications, and test methods, and the apparent need for additional grades of emulsions and new test methods, are covered. Mix design and structural design methods that apply to emulsion base and surface courses are presented. Construction methods and equipment that may be unique to the use of emulsions also are reviewed. The need for training technicians and engineers in the selection, use, and control of emulsion applications, as well as proposed future training, is discussed. A glossary of terms is presented in Appendix A.

DEVELOPMENT OF EMULSIFIED ASPHALTS AND LIQUID ASPHALTS

The development and use of asphalt emulsions similar to those in current use began in the 1920's. The need for such materials was prompted by the rapidly increasing demand for all-weather, dust-free pavements brought on by the rapid growth in the use of automobiles. Prior to 1920 most of the bituminous pavements had been constructed in urban areas and were mainly hot plant mixtures using semisolid asphalt (asphalt cement). Because of the large mileage of highways to be built and the limited available funds, there was a need for developing materials for low-cost construction. Thus, the semisolid asphalts, in the form of asphalt emulsified with water and asphalt fluxed with petroleum distillates such as gasoline and kerosene, were developed and used for spray applications or as binders in mixtures at ambient (cold) or slightly warm temperatures.

Emulsified asphalts and liquid asphalts came into general use during the 1920's and 1930's. Three types of liquid asphalt materials were developed: Rapid Curing Cutback (RC), Medium Curing Cutback (MC), and Slow Curing Road Oil (SC) (*1*). During the same period, specifications for emulsified asphalts of rapid-, medium-, and slow-setting types came into use. Thus, two classes of asphalt materials came to the fore for cold applications and cold mixing processes.

Usually, new emulsified asphalts have been developed by emulsion manufacturers and recommended to the user for trial use in a local area, to provide better performance from the standpoint of the variability in aggregates, environment, and method of construction. If the new emulsions were proven to provide advantages, standard specifications were developed.

USE OF ASPHALT MATERIALS

There was a gradual but steady increase in the use of all liquid asphalt materials from 1930 to 1953. The use of asphalt materials during the period 1953 to 1973 is shown in Figure 1. The data shown are for shipments of asphalt cements, cutback asphalts, emulsified asphalts, and road oils as published by the U.S. Bureau of Mines (*2*).

Beginning in 1963 the use of rapid (RC) and medium (MC) curing cutbacks decreased and the use of emulsions increased. The quantity of road oil used also decreased slightly during the ten years 1953 to 1963. For the same period the consumption of asphalt cement for paving increased very rapidly, compared to the combined use of all liquid asphalts. The increase from 10.5 to 20.3 million tons (9.5 to 18.4×10^9 kg) of asphalt cement was due to the greater demand for high-type asphalt concrete pavements having better performance under the increased traffic demands.

ENERGY PROBLEMS

There is general recognition that the United States and most other nations are confronted with a severe energy problem. It is apparent that this problem is both short- and long-range and will require major adjustments in energy consumption practices.

The Federal Energy Administration has stressed the need for all segments of business, industry, and government to evaluate their energy use and to develop practical conservation measures. One area that shows some potential for reducing energy consumption is the substitution of emulsions for cutbacks and emulsion mixes for conventional hot mixes in highway construction and maintenance operations.

During the past ten years there has been a steady annual increase in the total consumption of asphalt materials for pavement construction and maintenance. However, in 1970 the asphalt industry experienced shortages of asphalt cement in certain areas of the country; these local shortages were attributed to a greater demand for the use of petroleum products as fuels.

Petroleum fuel prices increased, forcing a drastic increase in asphalt prices. In 1973, some aspects of the impact of the energy crisis on asphalt supply and the hot-mix paving industry were reported by the National Asphalt

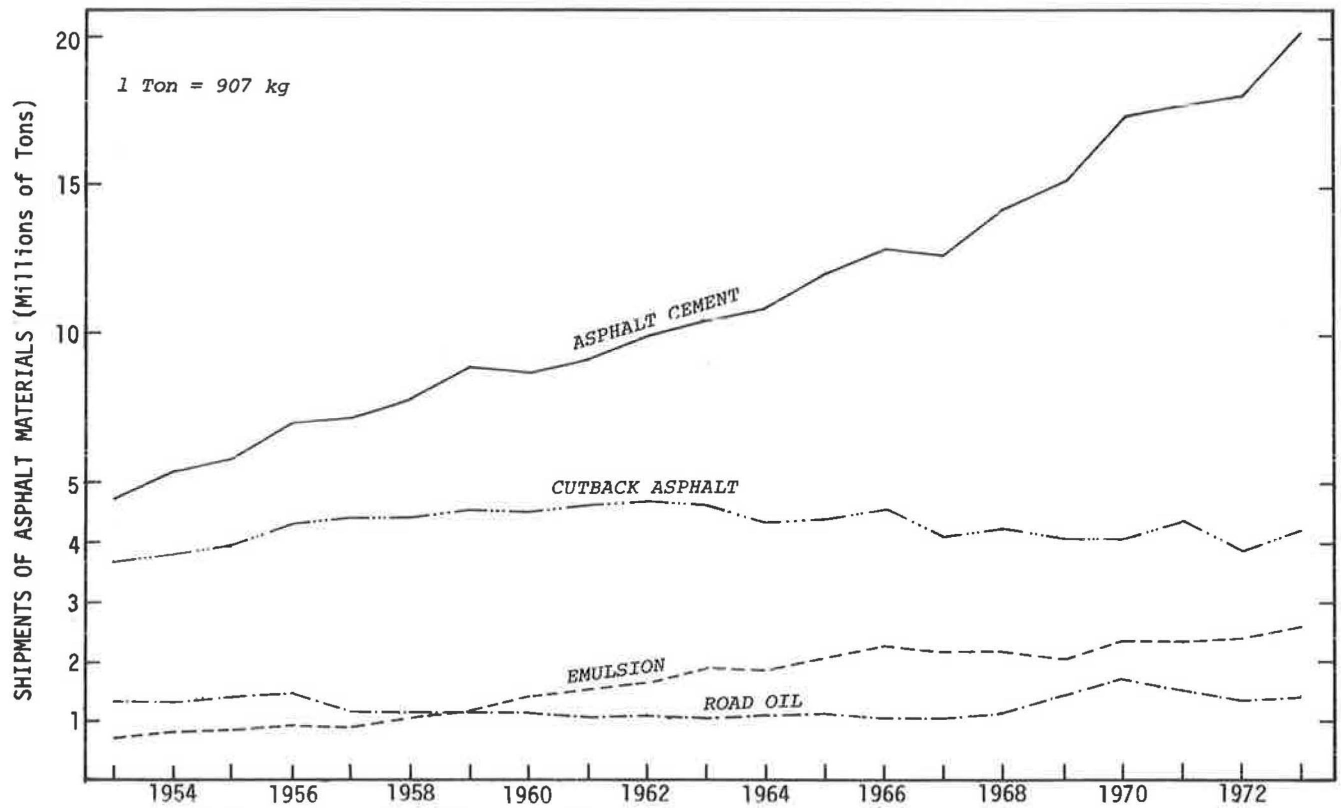


Figure 1. Use of asphalt paving materials, 1953 to 1973 (2).

Pavement Association (NAPA): the report concluded that material prices will be increasing and possibly some shortage could develop in some areas (*3*). Recently NAPA indicated a belief that the price of asphalt will stabilize around current rates and that, except for some geographical areas, the supply of asphalt appears adequate for road building materials (*4*).

The effect of the energy crisis on the supply and cost of asphalt paving materials, and the likelihood that the situation may become worse, resulted in initiation of several steps to improve the efficiency of highway operations with regard to fuel use and economy. Some of the organizations that initiated programs or are concerned with energy problems as they affect the supply and use of asphalt road materials are as follows:

American Association of State Highway and Transportation Officials (AASHTO)
Federal Highway Administration (FHWA)
Federal Energy Administration (FEA)
USDA Forest Service
Environmental Protection Agency (EPA)
Transportation Research Board (TRB)
National Asphalt Pavement Association (NAPA)
The Asphalt Institute (AI)
Asphalt Emulsion Manufacturers Association (AEMA)
American Society for Testing and Materials (ASTM)
American Road Builders Association (ARBA)
State highway agencies

The following are some of the more important actions taken that have a direct bearing on energy and relate to the use of emulsified asphalt. Other actions are of secondary importance but could have a long-range influence on their use.

In December 1973 FHWA issued a notice (*5*) concerning the conservation of fuel in highway construction programs involving federal funds. FHWA encouraged state officials to review and identify actions that could feasibly be taken under prevailing conditions to effect reduction in fuel use on ongoing and future federal-aid highway construction projects. Suggested actions included:

1. Minimize the use of cutback asphalts and road oils by substituting emulsions and other bituminous products.
2. Reduce mixing temperatures for plant-mixed bituminous mixes.

Also in December 1973 FHWA issued a second notice concerning fuel conservation, including guidelines for methods of conserving fuel on highway construction projects. In design, it was urged that consideration be given to the substitution of emulsions for cutback asphalts and road oils to the extent feasible for surface and base mixes, primes, seals, and stabilized bases. Use of fewer but thicker lifts in bituminous construction of black bases and surface courses was encouraged.

In January 1974 FHWA issued a third notice (*7*), directly concerned with the use of emulsified asphalts in lieu of cutback asphalts. This notice pointed out that, based on the total quantity of cutback asphalt used in the United States in 1972, 309 million gallons (1170×10^3 m^3), or approximately 1.28 million tons (1.16×10^9 kg), of petroleum products in critical supply could have been saved if emulsified asphalts had been used in lieu of cutbacks. An extension of the FHWA data indicates that in 1973 the quantity of distillates saved would have been about 336 million gallons (1270×10^3 m^3) or about 1.40 million tons (1.27×10^9 kg).

Criticism of the fuel waste in the use of cutbacks (RC and MC types) is not new. Because the naphtha (gasoline) and kerosene distillates were plentiful and reasonably cheap there was no great effort to stop their use (*8*). However, with the present energy problem, pressure is being brought on consumers and producers to stop using cutbacks so that the gasoline and kerosene distillates can be used as fuel.

Road oil (SC) should be considered as another source of fuel. However, the saving in light distillate fuels would be appreciably less compared with the amounts of distillates saved from the RC and MC cutback asphalts. Most specifications require that an SC-70 grade have 10 to 30 percent distillate. For comparison, specifications permit up to 45 percent (by volume) distillate for the RC-70 cutback. The SC-70 and SC-250 are very similar to residual refinery products that are used as heavy fuel oils (such as the bunker C or No. 6 fuel oils).

Hot Plant-Mix vs Cold Plant-Mix

Another potential source of energy savings is to substitute plant-mixed emulsified asphalt at ambient (cold) temperature for hot plant-mixes using asphalt cement. The primary energy saving in using emulsion is elimination of the fuel required to heat and dry the aggregate to provide good coating and workability of the asphalt cement mix.

Cold emulsified-asphalt concrete plant-mixes have been used since 1928. Some of the concepts for cold mixes are based on the use of emulsions formulated to result in more thorough coatings, formation of thicker films on aggregates in open-graded aggregate mixes, and less hardening of asphalt than in conventional hot plant-mixing processes (*9, 10*).

Another potential for saving fuel is to use emulsified-asphalt hot plant-mixes. Advocates of this process indicate that mixes can be produced at temperatures of 210 F (99 C) to 250 F (121 C) (*12*). ASTM Standard Specification for Hot-Mixed Hot-Laid Emulsified Asphalt Paving Mixtures, D 2629, specifies mixing temperatures of 220 to 260 F (104 to 127 C).

The Asphalt Institute has made an analysis of the energy requirements for hot and cold asphalt plant-mix pavements (*13*). Energy requirements were determined for producing asphalt cement, liquid asphalt, and emulsified asphalt. The variability in energy requirements based on different methods of production, processing, and handling of the various materials was recognized. Average values for typical asphalt materials are given in Table 1; these do not, however, include the energy potential of the base asphalt.

The high energy requirements for the cutbacks (RC, MC) and the road oils (SC) are due to the energy present in the distillates and the SC materials that can be used as fuels.

TABLE 1

ENERGY REQUIRED [a] TO PRODUCE ASPHALT MATERIALS [b]

TYPE OF MATERIAL	ENERGY REQUIRED (BTU/GAL)	GALLONS PER TON
Asphalt cement	2,500	235
Liquid asphalt:		
RC-250	46,200	249
MC-250	47,000	249
SC-250	58,100	249
Emulsified asphalt:		
RS-2	2,070	241
CRS-2	2,100	241
MS-2	2,100	241
CMS-2	2,100	241

[a] Does not include energy potential of base asphalt.
[b] Ref. *13*.

The Asphalt Institute estimated the energy requirements for the production of hot plant-mixed asphalt concrete and asphalt base, and emulsified asphalt base mixed at ambient temperature. The calculations include manufacture of the ingredients (asphalt and aggregate), their haul to the plant, plant operations (heating; drying, except emulsion mix; and mixing), hauling the mixture to the job, and placing and compacting the mix. Energy requirements are given in Table 2; calculations used to obtain these values are detailed in Appendix F. These estimates clearly indicate the potential saving in energy by using mixes prepared at ambient temperatures. However, in the structural design of cold-mix pavements, the required thickness is usually estimated to be more than the thickness of asphalt concrete.

A special report by NAPA on fuel conservation shows a number of items in the hot-plant-mix process where fuel savings could be made. For 1974 production of hot plant-mix an equivalent of 782 million gallons (2960×10^3 m^3) of No. 2 fuel oil would be needed; but by improved efficiency 173 million gallons (655×10^3 m^3) of fuel, equal to 22 percent, could be saved. The report indicates that a

TABLE 2

ESTIMATED ENERGY REQUIRED TO PRODUCE ASPHALT MIXES [a]

TYPE OF MIX	BTU REQUIRED PER SQ YD, 1-IN. THICK [b]
Hot plant-mix asphalt concrete	27,800
Emulsified asphalt plant-mix	15,600

[a] Ref. *13*.
[b] A 1-in. thick layer of each mix may not be structurally equivalent.

reduction in mixing temperature from 325 F (163 C) to 275 F (135 C) alone would reduce the fuel requirement by 11.4 percent (*14*).

NAPA reported that hot-mix production in 1974 was 365 million tons (331×10^9 kg) and the average total fuel used was 3.07 gal per ton (12.8 l/1000 kg) (*15*). The 3.07 value resulted from a study made by the Highway Equipment Committee of the Transportation Research Board (*16*).

NAPA also indicated that because of a number of factors use of emulsion in cold-mix construction does not appear to be an economical method of conserving fuel. They cite moisture problems related to curing, cost of emulsions, and extra pavement thickness as factors in their conclusion. However, further studies may result in at least partial if not full solution of these problems.

ENVIRONMENTAL PROBLEMS

In addition to the influence of energy on the production and use of asphalt materials in construction, environmental effects must be considered. Of most concern is use of cutback asphalts of the RC and MC grades containing volatile distillates that may evaporate in the air and add to air pollution. Attempts have been made to substitute distillates having lower photochemical reactivity as required under clean air regulations. The change was not feasible because of lack of sufficient distillates of the type needed and their high costs.

An estimate of the total potential contributions of distillates in cutback asphalts can be made. A summary of nationwide emissions for 1969 (*17*) shows that the total of air pollutants in the United States was 188.8 million tons (171×10^9 kg), of which 25.9 million tons (23.5×10^9 kg) were hydrocarbons. The distillates in RC and MC cutback asphalts can be considered as primarily hydrocarbon pollutants. Assuming that there is approximately 23 percent distillate in the combined total quantity of cutbacks of all types and grades used and that all of the distillate evaporated in the air, the amount would be about 783,000 tons (710×10^6 kg). This quantity is only about 3 percent of the hydrocarbon pollutants in the United States.

The amount of hydrocarbon emissions that would result from use of cutback asphalts (RC, MC) will vary appreciably with the type, grade, and amount of material and the type of construction and atmospheric conditions under which the material is used. Of the cutback asphalts, the rapid-curing RC-70 grade would produce the largest amount of air pollution for a given use and weather conditions and the MC-3000 would have the lowest emission. The slow-curing liquid asphalts (SC) lose volatile material more slowly and their contribution to air pollution would be very low. The replacement of cutbacks with emulsions would contribute appreciably to clean air.

Emulsified asphalts have one characteristic that can create an environmental hazard. Because the asphalt is suspended in water, the emulsion is susceptible to being washed off of aggregates or a road surface by rain if the emulsion is not sufficiently cured. Some unbroken emulsion may be carried into streams, lakes, springs, etc., causing contamination of the water. Some cities have rigid regulations on using emulsions or other bituminous materials in a watershed.

SAFETY

Another element of concern is the fire hazard associated with the production, storage, handling, and use of liquid asphalt materials, particularly the cutbacks of the rapid-curing type. Often the cutbacks are used in construction at temperatures exceeding their flash point. Numerous costly fires have occurred, resulting mainly in destruction of construction equipment and transports. The Department of Transportation has established a value of 80 F (26.7 C) for the flash point of rapid-curing cutbacks by the Tag Open Cup Method, ASTM D 1310, as a means of classifying liquids as flammable. Materials having a flash point at or below 80 F must be identified as flammable. Requirements for flash point in ASTM and AASHTO specifications are in most cases below suggested temperatures for spray application. For example, the minimum flash point of an RC-250 grade of rapid-curing asphalt is 80 F and suggested spray application temperatures are 165 F (74 C) to 220 F (104 C). Suitable safety precautions are mandatory at all times when handling, transporting, and applying the liquid asphalts of the RC and MC types.

Thus, because of the fire hazard associated with use of cutback asphalts, there is a desire to substitute alternate materials. The most logical alternates are emulsified asphalts.

HISTORY OF EMULSIONS

One of the earliest uses of bituminous emulsions in the United States was in 1903, when a residual "petroleum product" was emulsified and used as a dust preventative (palliative) to control the dust and surface erosion problems brought on by use of the automobile.

In 1907 the Office of Public Roads in the Department of Agriculture (now the Federal Highway Administration) constructed a series of road experiments that included oil emulsions (*18*).

In the experiments the oil emulsions were diluted with water and distributed over the road with a sprinkling cart. Further road experiments were constructed in 1910 using a material described as a "semiasphaltic oil emulsion," which was described as "fluid, sticky, and of piney odor" (*19*). The road experiments using emulsion were constructed to compare emulsion performance with the performance of residual petroleum products, semi-solid asphalts diluted with petroleum distillates, and in some cases concentrated waste sulfite liquor or mixtures of an emulsion with the sulfite liquor.

In 1914, mixing-grade asphalt emulsions were manufactured using clay as the primary emulsifying agents, and were used in dense aggregate mixtures. About 1928 the clay emulsions came into some disrespect because of their tendency to re-emulsify under the action of water and traffic, resulting in slippery pavements. A requirement for ash content by an ignition test was introduced in most specifications to restrict the use of clay emulsions.

By 1928, ASTM had devised some test methods and schemes of analysis (ASTM D 244-28T) to measure the properties of emulsified asphalt. The emulsions were classified for testing purposes as follows:

I. Emulsified light oils or liquid petroleum products for dust laying.
II. Emulsified asphaltic materials having asphalt contents of a suitable consistency for construction or repair of pavements. Two types were specified:
 (a) Containing little or no mineral matter;
 (b) Containing appreciable quantities of mineral matter.

The only tests specified were a stone coating test and a distillation test to determine the amount of water.

In 1934, ASTM issued tentative specifications for five grades of emulsified asphalt and recommendations for their use as follows:

ASTM D 397-34T—For open-graded coarse-aggregate plant mixtures.
ASTM D 398-34T—For open-graded coarse-aggregate for mix-in-place construction.
ASTM D 399-34T—For dense-graded bituminous concrete—summer use.
ASTM D 400-34T—For dense-graded bituminous concrete—winter use.
ASTM D 401-34T—For surface treatment and penetration macadam.

AASHTO adopted the same grades in 1935, designating them M 47, M 48, M 49, M 50, and M 51, respectively. The emulsion specifications adopted by ASTM and AASHTO were essentially for the anionic-class types, referred to in this report as anionic emulsions.

The tests used in 1935 by ASTM and AASHTO to identify, classify, and control the properties of emulsions (see Appendix B) were as follows:

Medium breaking: ASTM D 397 (AASHTO M 47)
(Now medium setting) ASTM D 398 (AASHTO M 48)
 Demulsibility, 50 ml 0.1 N $CaCl_2$
 Miscibility with water
 Stone coating test
 Settlement test, 5 days
 Sieve test
 Viscosity, Saybolt Furol, 77 F (25 C)
Slow breaking: ASTM D 399 (AASHTO M 49)
(Slow setting) ASTM D 400 (AASHTO M 50)
 Miscibility with water
 Stone coating test
 Freezing test ASTM D 400 (AASHTO M 50)
 Sieve test
Rapid breaking: ASTM D 401 (AASHTO M 51)
(Rapid setting)
 Demulsibility, 35 ml 0.02 N $CaCl_2$
 Settlement test, 5 days
 Sieve test
 Viscosity, Saybolt Furol, 77 F (25 C)

In addition to the foregoing tests, all specifications had requirements for percent residue by distillation and the following tests on the residues:

Penetration at 77 F (25 C)
Specific gravity at 77 F (25 C)
Ductility at 77 F (25 C), cm
Solubility in carbon disulfide, percent
Ash, percent

At the time these specifications were put into effect, emulsified asphalt for soil stabilization was a special grade differing from the other emulsions because it had to be capable of being mixed with soil containing appreciable amounts of material in the clay-size range. A mixing test with portland cement and a dehydration test were frequently used to ensure that the emulsion would have the desired properties.

By 1935, 13 states had adopted specifications for one or more grades of anionic emulsified asphalt. The tests used by the states were essentially the same as those in the ASTM and AASHTO specifications, but for a given grade the limits of the requirements often differed from these specifications (*20*).

By 1956, 45 states had emulsion specifications; by 1974, all states and the District of Columbia had approved specifications for one or more grades (*20, 21*).

Between 1935 and 1956, federal, state, and local agencies became more aware of emulsified asphalt and many of them wrote specifications adding new requirements or changing limits of the requirements in standard specifications such as ASTM and AASHTO. In 1948, ASTM combined the existing individual specifications into one specification, ASTM D 977. The classification system was changed to Rapid Setting (RS), Medium Setting (MS), and Slow Setting (SS) types of emulsion, with alternate grades of each type. About 30 of the 45 states using emulsion adopted the RS, MS, and SS classification, but not necessarily the same requirements. Several states included specifications for special emulsions and designations.

By 1956, 15 states and the District of Columbia had adopted specifications for water-in-oil emulsions (often referred to as "inverted" emulsions), in which minute droplets of water are dispersed in liquid asphalts with the aid of an emulsifying agent to keep the emulsion stable.

The water-in-oil or inverted emulsions are often used in place of cutbacks and slow-curing road oils with the objective to get better mixing, coating, and adhesion of the asphalt to the aggregate. Five of the 15 state specifications include requirements for adhesion or resistance to stripping. Inverted emulsions contain the same amounts of petroleum distillate as cutbacks and are part of the energy and air pollution problem, because their use is more closely related to cutback asphalts and SC road oils than to emulsified asphalts. However, total use of the inverted emulsions is quite small.

Cationic Emulsified Asphalt

In 1958, cationic emulsified asphalts were introduced into the United States. They were first developed in Europe to provide emulsions having better adhesion characteristics when used with gravels and siliceous aggregates. The concept of cationic emulsions and how they differ from anionic emulsions was first described in the United States by

Mertens and Wright at the 1959 Annual Meeting of the Highway Research Board (*22*). The authors reported that cationic emulsions were developed on the concept that the positively charged surface of the minute globules of asphalt would be strongly attracted to the surface of "electronegative" aggregates. Conversely, the negatively charged surface of the minute globules of asphalt in anionic emulsions would be attracted to the surface of "electropositive" aggregates. Thus, the cationic emulsion should develop a strong bond on silica and quartz aggregates and the anionic emulsion should develop good adhesion of the asphalt film to limestone aggregates. The proponents of cationic emulsion indicated they would solve field problems where anionic emulsions cannot be used because of unsatisfactory aggregate, cool weather, and wet weather conditions (*22, 23*). Present formulation technology has developed anionic and cationic emulsions suitable for both types of aggregates as well as intermediate types of mixtures.

Introduction of cationic emulsions in 1958 prompted ASTM, asphalt suppliers, and governmental agencies to develop specifications to define and control the properties of such materials. The first use of cationic emulsions in the U.S. was confined to the rapid-setting type used primarily in surface treatment and seal coat construction, and specifications were developed accordingly. Other uses of cationic emulsions, such as for mixing with open- and dense-graded aggregates and sand, came into use in the early 1960's. In 1965, ASTM issued a Tentative Specification for Cationic Emulsified Asphalt, D 2397, that included rapid-, medium-, and slow-setting types. The types and grades were comparable to those in ASTM Specification D 977 from the standpoint of application.

Table 3 gives the latest requirements of the Standard Specification for Emulsified Asphalt, ASTM D 977-73; Table 4 gives the latest requirements of Standard Specification for Cationic Emulsified Asphalt, ASTM D 2397-73. The similarity of the grading system for the two classes of asphalt emulsion, differing primarily in ionic character, is quite obvious. All of the grades in D 2397 are required to be cationic by virtue of the particle charge test requirement. There is no requirement for particle charge for the grades of emulsion in D 977 and, except for the demulsibility requirement for the rapid-setting (RS-1 and RS-2) grades, the emulsions could be of any ionic character—anionic, nonionic, or cationic. The theory has been advanced that, considering the wide variations in aggregates, ionic character is of secondary importance. However, the development of emulsifying agents has relied heavily on their ionic nature (*25*). Through such developments, newer cationic and anionic agents permit formulation of emulsions

TABLE 3

REQUIREMENTS AND TYPICAL APPLICATIONS FOR EMULSIFIED ASPHALT

(*1974 Annual Book of ASTM Standards*, Part 15 (1974) Table 2, p. 301)

Type	Rapid-Setting				Medium-Setting						Slow-Setting			
Grade	RS-1		RS-2		MS-1		MS-2		MS-2h		SS-1		SS-1h	
	min	max	min	max	min	max	min	max	min	max	min	max	min	max
Tests on emulsions:														
Viscosity, Saybolt Furol at 77°F (25°C), s	20	100			20	100	100		100		20	100	20	100
Viscosity, Saybolt Furol at 122°F (50°C), s			75	400										
Settlement,[a] 5-day, %		5		5		5		5		5		5		5
Storage stability test,[b] 24-h, %		1		1		1		1		1		1		1
Demulsibility,[c] 35 ml, 0.02N $CaCl_2$, %	60		60											
Coating ability and water resistance:														
Coating, dry aggregate					good		good		good					
Coating, after spraying					fair		fair		fair					
Coating, wet aggregate					fair		fair		fair					
Coating, after spraying					fair		fair		fair					
Cement mixing test, %												2.0		2.0
Sieve test, %		0.10		0.10		0.10		0.10		0.10		0.10		0.10
Residue by distillation, %	55		63		55		65		65		57		57	
Tests on residue from distillation test:														
Penetration, 77°F (25°C), 100 g, 5 s	100	200	100	200	100	200	100	200	40	90	100	200	40	90
Ductility, 77°F (25°C), 5 cm/min, cm	40		40		40		40		40		40		40	
Solubility in trichloroethylene, %	97.5		97.5		97.5		97.5		97.5		97.5		97.5	
Typical applications[d]	surface treatment, penetration macadam, sand seal coat, tack coat, mulch		surface treatment, penetration macadam, coarse aggregate seal coat (single and multiple)		cold plant mix, road mix, sand seal coat, crack treatment, tack coat		cold plant mix, coarse aggregate seal coat (single and multiple), crack treatment, road mix, tack coat, sand seal coat		cold plant mix, hot plant mix, coarse aggregate seal coat (single and multiple), crack treatment, road mix, tack coat		cold plant mix, road mix, slurry seal coat tack coat, fog seal, dust layer, mulch			

[a] The test requirement for settlement may be waived when the emulsified asphalt is used in less than 5 days time; or the purchaser may require that the settlement test be run from the time the sample is received until the emulsified asphalt is used, if the elapsed time is less than 5 days.

[b] The 24-h storage stability test may be used instead of the 5-day settlement test.

[c] The demulsibility test shall be made within 30 days from date of shipment.

[d] These typical applications are for use only as a guide for selecting and using the emulsion for pavement construction and maintenance.

TABLE 4

REQUIREMENTS AND TYPICAL APPLICATIONS FOR CATIONIC EMULSIFIED ASPHALT

(1974 Annual Book of ASTM Standards, Part 15 (1974) Table 2, p. 590)

Type	Rapid-Setting				Medium-Setting				Slow-Setting			
Grade	CRS-1		CRS-2		CMS-2		CMS-2h		CSS-1		CSS-1h	
	min	max	min	max	min	max	min	max	min	max	min	max
Test on emulsions:												
Viscosity, Saybolt Furol at 77°F (25°C), s									20	100	20	100
Viscosity, Saybolt Furol at 122°F (50°C), s	20	100	100	400	50	450	50	450				
Settlement,[a] 5-day, %		5		5		5		5		5		5
Storage stability test,[b] 24-h, %		1		1		1		1		1		1
Classification test[c]	passes		passes									
or												
Demulsibility,[d] 35 ml 0.8 % sodium dioctylsulfosuccinate, %	40		40									
Coating, ability and water resistance:												
Coating, dry aggregate					good		good					
Coating, after spraying					fair		fair					
Coating, wet aggregate					fair		fair					
Coating, after spraying					fair		fair					
Particle charge test	positive		positive		positive		positive		positive		positive	
Sieve test, %		0.10		0.10		0.10		0.10		0.10		0.10
Cement mixing test, %										2.0		2.0
Distillation:												
Oil distillate, by volume of emulsion, %		3		3		12		12				
Residue, %	60		65		65		65		57		57	
Tests on residue from distillation test:												
Penetration, 77°F (25°C), 100 g, 5 s	100	250	100	250	100	250	40	90	100	250	40	90
Ductility, 77°F (25°C), 5 cm/min, cm	40		40		40		40		40		40	
Solubility in trichloroethylene, %	97.5		97.5		97.5		97.5		97.5		97.5	
Typical applications[e]	surface treatment, penetration macadam, sand seal coat, tack coat, mulch		surface treatment, penetration macadam, coarse aggregate seal coat (single and multiple)		cold plant mix, coarse aggregate seal coat (single and multiple), crack treatment, road mix, tack coat, sand seal coat		cold plant mix, hot plant mix, coarse aggregate seal coat (single and multiple), crack treatment, road mix, tack coat		cold plant mix, road mix, slurry seal coat, tack coat, fog seal, dust layer, mulch			

[a] The test requirement for settlement may be waived when the emulsified asphalt is used in less than 5 days time; or the purchaser may require that the settlement test be run from the time the sample is received until the emulsified asphalt is used, if the elapsed time is less than 5 days.

[b] The 24-h storage stability test may be used instead of the 5-day settlement test.

[c] Material failing the classification test will be considered acceptable if it passes the demulsibility test.

[d] The demulsibility test shall be made within 30 days from date of shipment.

[e] These typical applications are for use only as a guide for selecting and using the emulsion for pavement construction and maintenance.

that result in improved aggregate coatings highly resistant to the stripping action of water.

In the development of recent ASTM specifications, considerable effort went into the use of functional tests and requirements that would distinguish one type or grade of emulsion from the others. The stone coating and water resistance test in D 977 and D 2397 indicates that the emulsions are capable of being mixed with open-graded aggregates; use of the cement mixing test indicates that the emulsion can be mixed with aggregates containing appreciable amounts of material passing the No. 200 sieve. However, to pass the cement mixing requirement the emulsion may be too stable and will not coalesce and form satisfactory films on aggregate particles. The foregoing mixing tests serve to identify the grade of emulsion. When used with the job aggregate, the stone coating and water resistance test can provide information to help select the best emulsion for that particular aggregate. The medium-setting grades of cationic emulsion in ASTM D 2397 permit use of oil distillates up to 12 percent of the emulsion to provide for better mixing and aggregate coating. A CMS-2S grade used by some agencies permits up to 20 percent oil distillate. More recently, in order to eliminate the use of distillates that usually are similar to those used in the rapid- and medium-curing cutbacks, a CMS-3 grade has been proposed that contains not more than 4 percent oil distillate.

Demulsibility tests are used to distinguish the rapid-setting types of emulsion in ASTM Specifications D 977 and D 2397. However, for the cationic emulsion, D 2397, a classification test that is a more functional-type test, is specified, with the demulsibility test as an alternate. Improvements in specifications to use more functional tests to define and control setting characteristics are needed to advance the use of emulsions to ultimately replace the use of cutbacks.

Characteristics of Asphalt in Emulsions

Since the first standard specifications adopted in the 1930's, the character of the asphalt in emulsions has been determined by tests on the residue from a distillation test to 500 F (260 C). Penetration and ductility at 77 F (25 C), and solubility in trichloroethylene, are usually specified. With few exceptions, the penetration requirements on the distillation residues have been 100-200 for the anionic emulsions and 100-250 for cationic emulsions. In 1965 additional grades were added to the medium-setting (MS and CMS) and slow-setting (SS and CSS) emulsions, specifying residues of 40 to 90 penetration and designated as MS-1h, CMS-1h, etc. With few exceptions, the consistency of the residues from emulsion has not been specified to correspond to the penetration grades of asphalt cement in AASHTO Specification M 20.

Indiana was one of the first states to specify grades of emulsion having residues of several ranges in consistency. In 1935 the Indiana specification contained penetration requirements for residues from distillation of 50-80, 80-140, 100-300, 200+, and 300+. Table 5 gives the present Indiana specification. The penetration limits for the AE-60, AE-90, and AE-150 grades have been widened to 50-100, 100-250, and 200+, respectively. In addition to the usual ductility and solubility tests, Indiana specifies a minimum float value of 1,200 sec at 140 F (60 C) on the AE-60, AE-90, AE-150, and AE-300 grades. These are designated as "high-float" residues and the emulsions are known as "high-float" emulsions.

High-Float Emulsions

The concept of high-float emulsions or residues is based on using the emulsification process to modify the base asphalt to improve its properties for certain uses. By this process the asphalt may be made to be less temperature-susceptible, to have improved characteristics at high and low temperatures, and to have high penetration but be resistant to flow. The float test was selected because it is simple and convenient. In this application the float test is being used to identify a material that does not flow under low stress at 140 F (60 C) (*26*).

One of the advantages of high-float emulsions is that they will coat the surface of aggregate in open-graded mixes with thick films that will not flow at high pavement temperature. This makes the emulsion particularly useful in open-graded plant mixes such as premix macadam, mixed seal coats, and friction courses. Proponents of the high-float emulsions have indicated that the addition of petroleum distillates may be desired to obtain improved coating of aggregates, improved workability of the emulsion mixtures for immediate use, or for stockpiling. Also, in hot plant-mixing, the high-float material provides a means of using softer asphalts without detrimental effects caused by drainage and instability (*26*).

Indiana first used high-float emulsions in 1954; now, about 20 states have adopted specifications for one or more grades having the high-float characteristics. Many of the states have included high-float requirements as alternates to the regular anionic emulsions. The estimated quantity of high-float emulsions used in 1973 is 210 million gallons (795×10^6 liters).

ASTM has action under way to add high-float requirements as alternates to the present requirements on the residues of the MS-1, MS-2, and MS-2h grades of emulsion in ASTM Specification D 977.

Emulsions for Slurry Seal

Emulsions for slurry seal mixtures have been the slow-setting SS and CSS types. The aggregate usually is of dense grading and may contain up to 20 percent passing the No. 200 (75 μm) sieve. The emulsion must be capable of being mixed with the fine aggregates, and cure as rapidly as possible after the slurry seal is spread on the surface of

TABLE 5

INDIANA SPECIFICATIONS FOR ASPHALT EMULSIONS

	RS-2 (1), (2)	AE-60 (1)	AE-90 (2)	AE-150 (1), (2)	AE-150-L (9)	AE-300 (1)	AE-T (1), (7)	AE-P
Furol-Viscosity at 77°F. (Sec.)		50+	50+	50+		50+		
at 122°F. (Sec.)	75–300							15–150
The distillate per cent by weight when distilled to 260°C. (500°F.)	32—	32—	32—	32—		32—		35—
Oil portion of distillate (vol. meas.) (expressed as a percentage of the emulsion) shall not exceed (3)	4.0		4.0	7		7		25
Settlement, 5 days, not more than (%) (4)	5	5	5	5		5		5
Demulsibility (%)								
35 ml. $CaCl_2$, 0.02N	30+							
50 ml. $CaCl_2$, 0.10N		75+	75+					
Stone coating, shall pass		(5)	(5)	(6)		(6)		
Tests on residue distilled to 260°C. (500°F.)								
Float test at 122°F.								200—
Float test at 140°F.		1200+	1200+	1200+		1200+		
Penetration at 25°C. (77°F.)	100-200	50–100	100–250	200+				
Solubility in organic solvents (8)								
Natural asphalt (%)		95+	95+					
Oil asphalt (%)	97.5+	97.5+	97.5+	97.5+		97.5+		97.5+
Ductility at 77°F. (cm.) (8)	40+	40+	40+					

Notes: (1) Pumpable. (2) Sprayable. (3) The oil distillate shall conform with ASTM D 396, Table I, Grade 1. (4) This requirement is waived if the emulsion is used within 5 days. (5) See 902.09, 21b(1). (6) See 902.09, 21b(2). (7) AE-T shall consist of 80% approved AE-60 or AE-90 and 20% water containing not more than 8 grains of hardness per gallon. A Certificate of Compliance will be required. (8) The test may be waived by the Engineer. (9) AE-150-L used for light applications such as required for sand seal coats shall meet the requirements of AE-150 except the viscosity at 77°F. shall be 15 to 100 seconds and the per cent of distillate shall be 40—.

the road. Many of the emulsions used in the past cured slowly, resulting in traffic delays, and the slurry was subject to being washed out by rain . Emulsions of the slow-setting type that cure faster or are rapid curing are available. Specifications for the quick-curing, slow-setting emulsions for slurry seal applications are in the development stage by ASTM. The International Slurry Seal Association has published a guide specification for design and construction of emulsion slurry seal applications that provides for either anionic, cationic slow-setting, or "quick set" emulsions as alternates (*27*).

Rubberized Emulsions

Synthetic and natural rubber latex has been used for several years to modify emulsified asphalt, primarily for use in surface treatments and slurry seal applications. Anionic and cationic emulsions containing a minimum of 3 percent rubber based on the weight of the asphalt in the emulsion are usually used. The rubber is usually in the form of an emulsion (rubber in water) and can be added to the emulsified asphalt during the emulsification process or may be added to the emulsion on the job by adequate stirring or pumping to get good dispersion.

There are no material specifications for rubberized emulsions, although some work has been initiated in ASTM to determine what standard tests can be used and whether new tests are needed for use in specifications.

EMULSIFIED ASPHALT NEEDS FOR THE FUTURE

The Bureau of Mines data for all asphalt paving materials, exclusive of road oils, used in 1973 show approximately 27.11 million tons (24.6×10^9 kg) including 20.27 million tons (18.4×10^9 kg) of asphalt cement, 4.24 million tons (3.8×10^9 kg) (15.6%) cutback, and 2.60 million tons (2.4×10^9 kg) (9.6%) emulsion.

In April 1974, AASHTO made a survey of asphalt needs for highway construction and maintenance for 1974. The survey pointed out that of the 1.7 million miles (2.7×10^6 km) of paved highways in the United States, 93 percent have asphalt surfaces. Maintenance ranging from filling potholes to complete resurfacing requires the use of asphaltic products. In addition, new construction relies heavily on the use of asphalt for bases and surface courses.

The AASHTO survey of state and county agencies gave quantities of asphalt road materials that were needed during 1974 for construction and maintenance (Table 6). Based on the AASHTO data, the estimated quantity of asphalt needed for all road applications in 1974 was about 24.8 million tons (22.5×10^9 kg).

Because the AASHTO survey did not include estimates for city streets, airports, private developers, and other miscellaneous uses, the total amount needed would be greater than indicated.

A survey conducted by the FHWA in September 1974 indicated that 42 highway departments are substituting emulsified asphalts for other asphalt materials, or that this substitution is allowed. An earlier survey on March 1, 1974, showed that only 29 highway departments allowed this substitution (*32*).

If it is assumed that there will be substantial replacement of the use of the RC and MC cutbacks with emulsified asphalts, the demand for emulsions will more than double in the next ten years. Add the potential substitution of emulsions for some slow-curing road oils on low-volume roads and substitution of cold or warm emulsion plant mixes for hot asphalt cement plant mixes and the future demand for emulsions will be even greater.

TABLE 6

QUANTITIES OF ASPHALT ROAD MATERIALS NEEDED IN 1974

STATE HIGHWAY AGENCIES	Construction (1,000 Tons)	Maintenance (1,000 Tons)
Asphalt Cement	6,173	1,673
Asphalt Cutbacks	613	662
Asphalt Emulsions (Base)	479	470
COUNTIES		
Asphalt Cement, Cutbacks, and Emulsions	7,017	7,298
FEDERAL AGENCIES		
Asphalt Cement, Cutbacks, and Emulsions	295	86
Total	14,577	10,189
	24,766	

SELECTION OF TYPE AND GRADE OF EMULSION FOR OPTIMUM USE

A recent survey of state highway agencies showed the present uses of anionic and cationic emulsions given in Table 7 (*28*). Responses were received from all 50 states. Some states indicated that only one type of emulsion was used; others indicated that all types were used, but the quantity for each application was not determined. The states indicated that emulsions were used in the following major construction items:

Surface treatments and seal coats .... 42 states
Soil stabilization .... 6 states
Base course mixes .... 15 states
Surface course mixes .... 13 states
Other (includes slurry seals, patching mixes, etc.) .... 14 states

In 1972 *Rural and Urban Roads* published the results of

TABLE 7

STATE USE OF EMULSION BY CLASS AND TYPE (*28*)

ANIONIC		CATIONIC	
Type Used	No. of States	Type Used	No. of States
RS	26	CRS	35
MS	13	CMS	16
SS	35	CSS	20

a survey of state use of emulsions showing the following items (*31*):

Subbases	8 states
Base mixes	15 states
Cold-mix surfacing	10 states
Shoulders	20 states
Primes	30 states
Surface treatments and seal coats	38 states
Slurry seal treatments	24 states
Cold or hot patching mixes	15 states

Numerous attempts have been made to write "recommended practices" that would assist a user in selecting an emulsion type and grade for each application. Recommended practices of this nature have been written and published for other types of bituminous materials, such as the Standard Recommended Practice for Application of Liquid Asphalts, ASTM Designation D 2399-68, and the Standard Recommended Practice for Paving Uses and Application Temperatures for Road Tar, ASTM Designation D 2728-72. Each of these standards includes definitions and descriptions of uses, with only a brief description of pertinent characteristics of aggregates and construction procedures. The selection of a particular grade depends on local practice, equipment availability, bituminous material (asphalt or tar) availability, traffic, and environmental conditions for the particular construction project being considered.

In 1970, ASTM initiated a study to develop a recommended practice for the use of emulsified asphalt. The format would have been similar to the recommended practices D 2399 for liquid asphalts and D 2728 for tar. After considerable work, the subcommittee in charge of the study voted not to adopt a recommended practice because it could not provide criteria to select the optimum type and grade of material that would result in the best behavior during construction and best performance in service. However, typical applications are given in ASTM D 977 and D 2397 (Table 3 and 4).

A number of organizations have developed tables showing recommended uses of asphaltic materials. The 1974 Pacific Coast User-Producer Conference adopted an Interim Guide for Use of Emulsified Asphalt (Table 8). This guide includes paving asphalts, two grades of liquid asphalt, four grades of anionic and seven grades of cationic emulsion. It is interesting that the medium-setting anionic emulsions are not included, although they are used extensively by eastern states.

A guide developed for this synthesis is given in Table 9. It is based on a consensus of the best information available at this time, but may not include some special applications developed for use in specific areas. Where multiple choices are given, an evaluation of the aggregate-emulsion system and other factors should be made.

One of the most important factors in selection of an emulsion is the type and grading of aggregate that must be used. The compatibility of the aggregate-emulsion system must be determined on the basis of coating ability, rate of curing, workability, resistance to stripping by water action, and mixture strength properties. The influence of many of these variables is covered in later sections on aggregates and aggregate-emulsion design procedures.

CONSTRUCTION SPECIFICATIONS

Few national construction specifications have been written specifically for use of emulsions. ASTM has a Standard Specification for Hot-Mixed, Hot-Laid Emulsified-Asphalt Paving Mixtures, Designation D 2629, and emulsions are included in ASTM Standard Recommended Practice for Quantities of Materials for Bituminous Surface Treatments, ASTM Designation D 1369.

The AASHTO Guide Specifications for Highway Construction (*29*) permit the use of emulsified asphalts, but in all construction items they are listed as alternate materials to liquid asphalts and road tars. The type and grade of material used would be specified in the contract.

Some highway agencies include emulsions as alternates in construction items. Indiana probably has the most complete coverage of the use of emulsions in construction. In some agencies special emulsions, such as those having high-float characteristics, and priming materials are specified. Separate specifications for hot asphalt-emulsion pavement are provided.

Several of the major emulsion suppliers have prepared construction specifications and manuals covering detailed requirements for grading and quality of aggregate, mix design, emulsion grade(s), construction procedures, limitations on weather and temperature, and, in some cases, precautions on use of emulsions.

TECHNICAL SERVICE

Some of the emulsion producers have provided technical service to the user or contractor, including evaluation of aggregates and recommendations on the grade of emulsion that should be used. In other cases the producer has resolved problems concerning the behavior of an emulsion during construction by adjusting the formulation of the emulsion.

TECHNICAL TRAINING ON USE OF EMULSIFIED ASPHALT

If there is an expanded program to use emulsified asphalt in lieu of liquid asphalts and asphalt cements, training of engineers and technicians in the laboratory, at the plant, and on construction is essential. Engineers and technicians may be fully qualified to handle the various aspects of bituminous pavement construction and maintenance using liquid asphalts and asphalt cements. But the use of emulsions in the same type of construction requires further knowledge and training. In the past some of the emulsion producers have partially fulfilled the training needs by conducting training courses for emulsion users. More recently The Asphalt Institute has held one-day training sessions for numerous groups throughout the United States. The training included:

1. Emulsions—definitions, manufacture, types, properties, handling, and general uses.

TABLE 8

INTERIM GUIDE FOR USE OF EMULSIFIED ASPHALT
(Adopted by Pacific Coast User-Producer Conference, May 1974)

Type	Paving Asphalts					Liquid Asphalts		Emulsified Asphalts											
								Anionic					Cationic						
Grade	AR-1000	AR-2000	AR-4000	AR-8000	AR-16000	SC-250	SC-800	RS-1	RS-2	SS-1	SS-1h		CRS-1	CRS-2	CMS-2	CMS-2S	CMS-2h	CSS-1	CSS-1h
SURFACE TREATMENTS																			
Dust Palliative										x^1	x^1							x^1	x^1
Tack Coat								x		x^1	x^1		x					x^1	x^1
Penetration						x7			———	See		Note	4	———					
Prime Coat (Temporary Traffic)						x7			———	See		Note	4	———					
Fog Seal (Light application without cover)										x^1	x^1							x^1	x^1
Curing Seal for CTB or lime Treated Bases										x	x							x	x
Sand Seal (Light application with sand cover)								x	x				x	x					
Chip Seal		x						x	x				x	x					
Slurry Seal										x	x							x	x
ASPHALT BASE COURSES																			
Asphalt Concrete Base		x^2	x	x															
Asphalt Treated Base[6]																			
Open Grade Aggregate - less than 5% passing No. 8			x												x		x		
Clean Sand - 100% ± passing No. 4, 0-10% passing No. 200			x							x	x							x	x
Graded Aggregate - up to 15% passing No. 200			x							x	x							x	x
Sandy Soil - up to 20% passing No. 200										x	x					x^5		x	x
ASPHALT SURFACE, COLD LAID																			
Graded Aggregate - up to 15% passing No. 200										x	x							x	x
Sandy Soil - up to 20% passing No. 200										x	x					x^5		x	x
Open Graded Surface Course - 3/8" max., up to 2.0% passing No. 200															x		x		
PATCHING MIX																			
Immediate Use		x^3								x	x							x	x
Stockpile						x7	x7		———	See		Note	4	———					
ASPHALT CONCRETE SURFACES																			
Industrial Floors				x	x														
Parking Areas			x	x	x														
Highways - Good Quality rough-textured aggregate	x^2	x	x	x															
Highways - Borderline quality aggregate			x	x															
Airports - Good Quality rough-textured aggregate		x^2	x	x															
Curbs				x	x														
Open Graded Surface Course - 3/8" max. up to 2.0% passing No. 200			x	x															

Notes: May, 1974

1 - Diluted with compatible water.
2 - Very cold climates.
3 - Any grade available is acceptable.
4 - The use of asphalt emulsions for this application has not been generally practiced. More experience is needed before specific grades can be recommended.
5 - This grade of emulsion is approximately the same as MC-800 in terms of solvent usage.
6 - Applies to asphalt treated bases mixed in a central plant, a travel plant, or mixed in place.
7 - SC grades have been shown where no alternates can be recommended. The SC grades are deemed a better choice to meet energy savings and air pollution consideration than similar MC grades.

2. Emulsion bases—advantages, asphalt-stabilization concepts, materials, mix design methods, thickness design, and construction.

3. Emulsion surfacings—uses, types, materials, and construction.

4. Summary—review of the most important aspects of emulsions.

This training course covers a period of about six hours, but could be expanded to two days for those directly involved with the use of emulsions.

Organizations that might be expected to participate in the training of engineers and technicians include The Asphalt Institute, the Asphalt Emulsion Manufacturers Association, the Federal Highway Administration, the Forest Service, other federal agencies, and emulsion manufacturers. The National Highway Institute was established to help in training programs such as this.

TABLE 9

GUIDE TO USE OF EMULSIONS

USE	EMULSIFIED ASPHALT												
	ANIONIC (AASHTO M 140 or ASTM D 977)							CATIONIC (AASHTO M 208 or ASTM D 2399)					
	Rapid Setting		Medium Setting			Slow Setting		Rapid Setting		Medium Setting		Slow Setting	
	RS-1	RS-2	MS-1	MS-2	MS-2h	SS-1	SS-1h	CRS-1	CRS-2	CMS-2	CMS-2h	CSS-1	CSS-1h
Plant Mix: Cold-Mixed, Cold-Laid													
Open-graded aggregate				x^1	x^1					x^1	x^1		
Dense-graded aggregate			x^1	x^1	x^1	x^1	x^1			x^1	x^1	x^1	x^1
Clean sand				x^1	x^1					x^1	x^1		
Sandy soil			x^1			x^1	x^1					x^1	x^1
Plant Mix: Hot-Mix, Hot-Laid				x^1	x^1					x^1	x^1		
Mix-in-Place or Travel Plant													
Open-graded aggregate			x^1	x^1	x^1					x^1	x^1		
Dense-graded aggregate			x^1	x^1	x^1	x^1	x^1			x^1	x^1	x^1	x^1
Clean sand				x^1	x^1					x^1	x^1		
Sandy soil			x^1			x^1	x^1					x^1	x^1
Patching Mix													
Immediate use				x^1	x^1					x^1	x^1		
Stock pile				x^1						x^1			
Slurry Seal						x	x					x	x
Surface Treatment or Seal Coat													
Chip, single and multiple	x	x		x	x			x	x	x	x		
With sand cover	x		x	x				x		x			
Fog Seal						x^2	x^2					x^2	x^2
Tack Coat			x^2	x^2	x^2	x^2	x^2			x^2	x^2	x^2	x^2
Prime Coat:													
Open surface				x^2	x^2	x^2						x^2	
Dense Surface (3)													
Penetration Macadam													
High voids		x			x				x		x		
Low voids	x		x		x			x			x		
Crack Filler			x	x	x					x	x		

1. Evaluation of emulsion - aggregate required.
2. Dilute with water if necessary.
3. Standard emulsion grades are not suitable for priming dense surfaces.

COST ANALYSIS OF CONSTRUCTION USING EMULSION

Only limited data are available that can be used to compare the relative costs of construction of base and surface courses using emulsions or cutback asphalt in cold plant-mixes and emulsions or asphalt cement in hot plant-mixes. The rapid increase in the costs of all asphaltic road materials, as well as the unstable supply and price during the last two years, also restricts an analysis of comparative material and construction costs.

A survey by FHWA on material supply and cost shows that asphalt shortages in March 1974 were moderate in 26 states, critical in 14 states, and severe in 4 states (*32*). In September the shortages were moderate in 23 states, critical in one, and no state had a severe shortage. Exceptionally high bids were reported by 40 states in March and

36 in September. FHWA reported that there is more concern at this time about inflation than about scarcities of fuels and materials.

A reasonable assumption can be made that material and construction costs using either emulsified asphalts or cutback asphalts in surface treatment and seal coat applications would be approximately the same. For both classes of asphalt materials the aggregates, equipment, and construction and control procedures are similar. A direct comparison of the total construction costs of cold plant-mixes using emulsion and hot plant-mixes using asphalt cement is difficult because of the differences in structural design, mix design, available construction equipment, construction procedures, and quality control during construction.

The United States Forest Service and FHWA have reported cost data on open-graded emulsion cold plant-mixes placed in Oregon and Washington and indicate that the cost per ton is less than hot plant-mix (*11, 30*). Douglas County, Oregon, has constructed appreciable mileage of similar open-graded plant-mix and also indicated that the cost is appreciably less than hot plant-mix.

A major factor that must be considered in substitution of emulsified asphalt for cutback or asphalt cement is the performance of the pavement in which they are used. There is a lack of available information on direct comparisons of the performance of emulsion with cutback asphalt and asphalt cements in the various types of construction.

However, based on general discussions and the continued growth in use of emulsions for certain applications, tentative conclusions can be made concerning the behavior and performance of emulsions in pavement construction. For example, the general performance of emulsion for surface treatments and seal coats can be considered better than the same construction with cutback asphalt. Also, many of the roads constructed with emulsions by the Forest Service in Oregon and Washington and by Douglas County have given good performance. Without doubt the large use of emulsions by Indiana and other states has resulted in high-quality construction.

CHAPTER TWO

STRUCTURAL DESIGN OF PAVEMENTS

GENERAL CONSIDERATIONS FOR STRUCTURAL DESIGN WITH EMULSION-TREATED MATERIALS

Structural design of pavements can be accomplished relatively simply by means of a process in which the thickness of a component is selected from a design relationship involving a direct correlation between the important parameters affecting pavement performance—usually considered to be traffic, environment, and subgrade soil—and thicknesses known to provide reasonable performance. Two such methods are described in this chapter. Alternatively, one could envision pavement design, as shown in Figure 2, as a process wherein the potential for distress is determined for a selected pavement section and if the particular distress mode is estimated to occur, the design is modified to insure that this distress is reduced to a tolerable level or precluded for the selected design period. One procedure using this approach is briefly summarized herein.

When the latter procedure is used, the question arises as to which distress modes are critical. From an extensive survey of pavements constructed with hot-mix asphalt concrete, Finn (*33*) has suggested that the distress mechanisms that appear to be most significant in contributing to a reduction in pavement serviceability are:

1. *Fracture* from repeated loading, termed fatigue.
2. *Distortion* that is traffic associated, termed rutting.
3. *Fracture* resulting from nontraffic-associated factors; e.g., low-temperature cracking.

To illustrate general methodology whereby the potential for occurrence of some of these distress modes may be estimated, a brief description of the general approach, together with some of the required information, is given in the following.

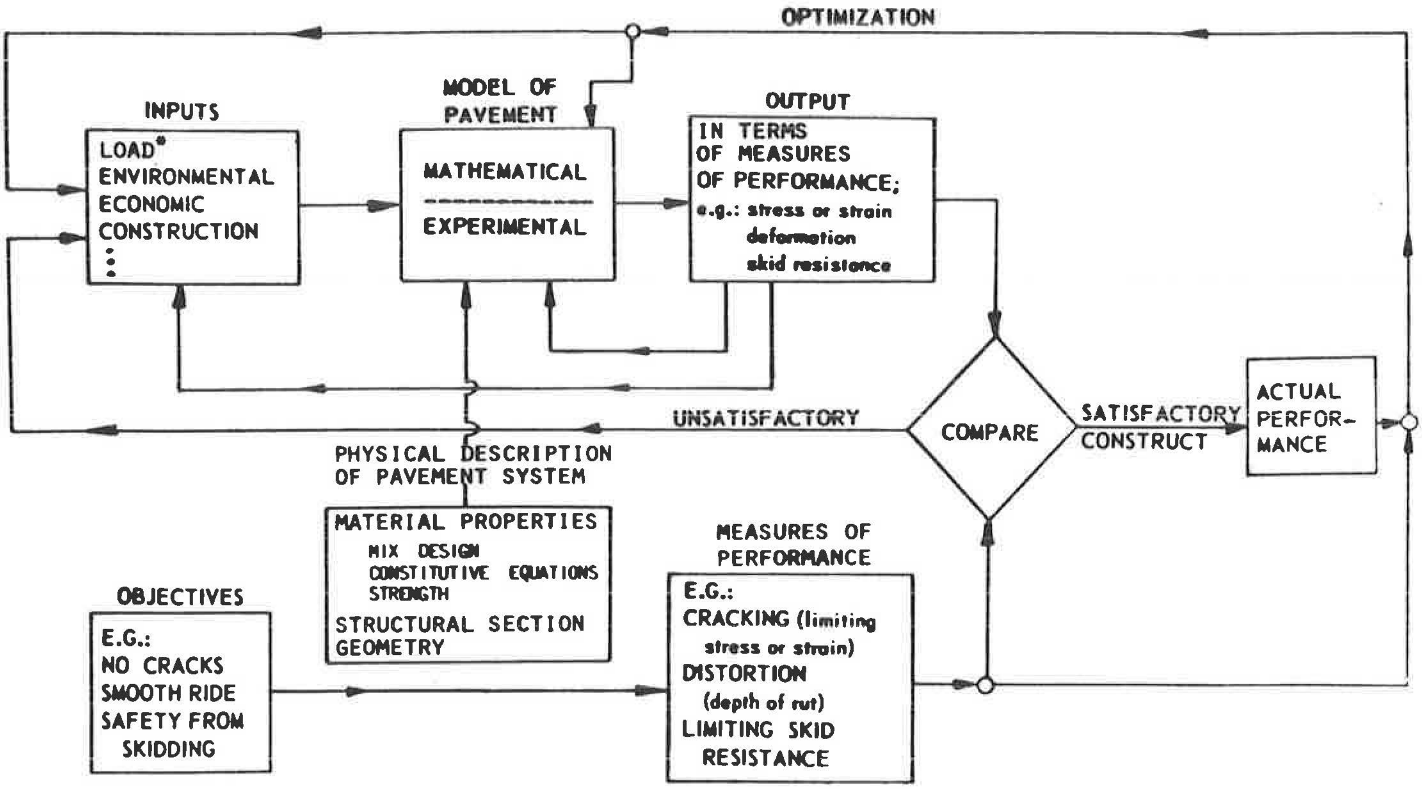
Resistance to Cracking from Repeated Loading—Fatigue

In a pavement system consisting of treated and untreated materials it would appear that load-associated cracking in the treated materials can be controlled by limiting the tensile strain on the underside of the treated layer to some prescribed value for specific material and loading conditions (*34*). Figure 3 shows schematically this controlling factor. Alternatively, if tensile strains can be estimated for a range in material and loading conditions, and if fatigue data for the material in question are available, usually in the form of log-log plots of tensile strain vs number of load repetitions, the potential for cracking can be estimated by use of a cumulative damage hypothesis such as the linear summation of cycle ratios. This procedure is illustrated in the Chevron design procedure presented subsequently.

Resistance to Permanent Deformation from Traffic—Rutting

Excessive permanent deformation in a pavement structure can be minimized by controlling the stresses or deformations at specific locations in the pavement cross section, by compaction control for both treated and untreated materials, and by mix design in the case of asphalt-treated materials.

In this synthesis some discussion of limiting vertical



*One can use the same system considering only one class of input, holding all others fixed; The objectives would have to be formulated accordingly.

NOTES: 1. It should be recognized that the pavement system is embedded in a larger system.
2. The formulation of the objective is a difficult and essential first step.
3. It is usually necessary to have more than one measure of performance and the system is required to satisfy them concurrently.
4. It should be recognized that all components of the system can be considered as functions of time.

Figure 2. Schematic representation of pavement system.

strain at the subgrade surface (Fig. 3) is included as a part of the Chevron design procedure. Such a criterion was first suggested by Shell (*34*) as a part of their pavement design procedure and is used by The Asphalt Institute for design of full-depth asphalt concrete airfield pavements (*35*).

Also included in the synthesis is a discussion of mix design procedures for emulsion-treated materials. One of the governing factors in selecting the quantity of emulsion is the ability of the material to withstand repeated loading without excessive permanent deformation, particularly prior to complete curing of the material.

Other Considerations

In design with asphalt-treated materials other factors may have to be considered: namely, (1) cracking from thermal stresses, (2) cracking from braking or tractive forces applied at the pavement surface, and (3) the influence of curing of emulsion-treated materials on the performance of the pavement during its early life.

Thermal (low temperature) cracking occurs because of a temperature differential through the treated layer. Generally, cracking of this type starts at the surface and progresses into the layer with time. To minimize this type of cracking, research has indicated that the stiffness of the asphalt in the mix must not exceed certain limits, depending on the environment (*36*). Table 10 (*37*) provides a guide. This, in the case of emulsion-treated materials, may require special considerations in low-temperature areas (e.g., use of emulsions that have been formulated with softer-base asphalts, resulting in softer residues upon curing).

Under some circumstances, if the treated layer is relatively thin, the tractive forces of braking or cornering vehicles may lead to cracking in the mix and a slippage failure. If the potential for this type of loading occurs, consideration should be given to use of a thicker treated layer and, possibly, an asphalt that will result in a stiffer mixture.

These factors can be considered as modifiers to the basic design procedures discussed in subsequent sections.

Mixes containing asphalt emulsions require some time to develop their stiffness characteristics after they have been compacted, the time required being dependent on the environment. Mixes placed in hot, dry climates such as the southwest United States can be expected to cure in a comparatively short time (approximately 6 months); those placed in colder environments and/or where the average rainfall is comparatively high will require longer times to reach the cured state. These curing influences may have some influence on the thickness requirements. The Chevron procedure to be discussed subsequently illustrates a procedure whereby such effects can be considered.

AASHTO DESIGN PROCEDURE

The AASHTO design procedure is based on data developed from the AASHO Road test and modified by other experience (*38*). Recently the AASHO Interim Guides (for both asphalt and portland cement concrete pavements) have been modified and updated (*39*); the material presented herein was obtained from the 1972 AASHO Interim Guide (*40*).

Principal Design Considerations

The design chart shown in Figure 4 (for a Terminal Serviceability Index of 2.5) is based on the assumptions that the equations developed from the AASHO Road Test:

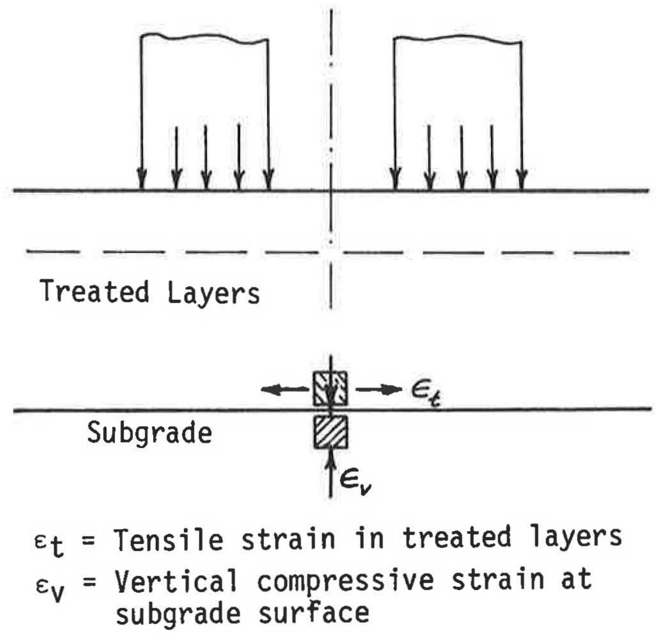


Figure 3. Controlling strain conditions considered to minimize cracking and rutting from repeated traffic loading.

TABLE 10

RECOMMENDATIONS FOR SELECTION OF ASPHALT CEMENT (*37*)

Thickness of Asphalt Concrete, in.[5]	Climate	Asphalt Cement Grade AASHO M20	Asphalt Cement Grade AASHO M226	Western States[4]
≤3	Cold[1] Moderate[2] Hot[3]	200-300 85-100 85-100	AC - 5 AC - 10 AC - 10	AR-1000 AR-4000 AR-4000
4-6	Cold Moderate Hot	120-150 85-100 60-70	AC - 5 AC - 10 AC - 20	AR-2000 AR-4000 AR-8000
>7	Cold Moderate Hot	120-150 60-70 40-50	AC - 5 AC - 20 AC - 40	AR-2000 AR-8000 AR-16,000

[1]Normal minimum daily temperature* of 10F or less; for extremely low temperatures special studies are recommended.

[2]Normal maximum daily temperature* of 90F or less.

[3]Normal maximum daily temperature* greater than 90F.

[4]As reported in Western Construction Magazine, October, 1972.

[5]Total thickness of asphalt concrete; surface plus base

*As per National Weather Service climatological reports.

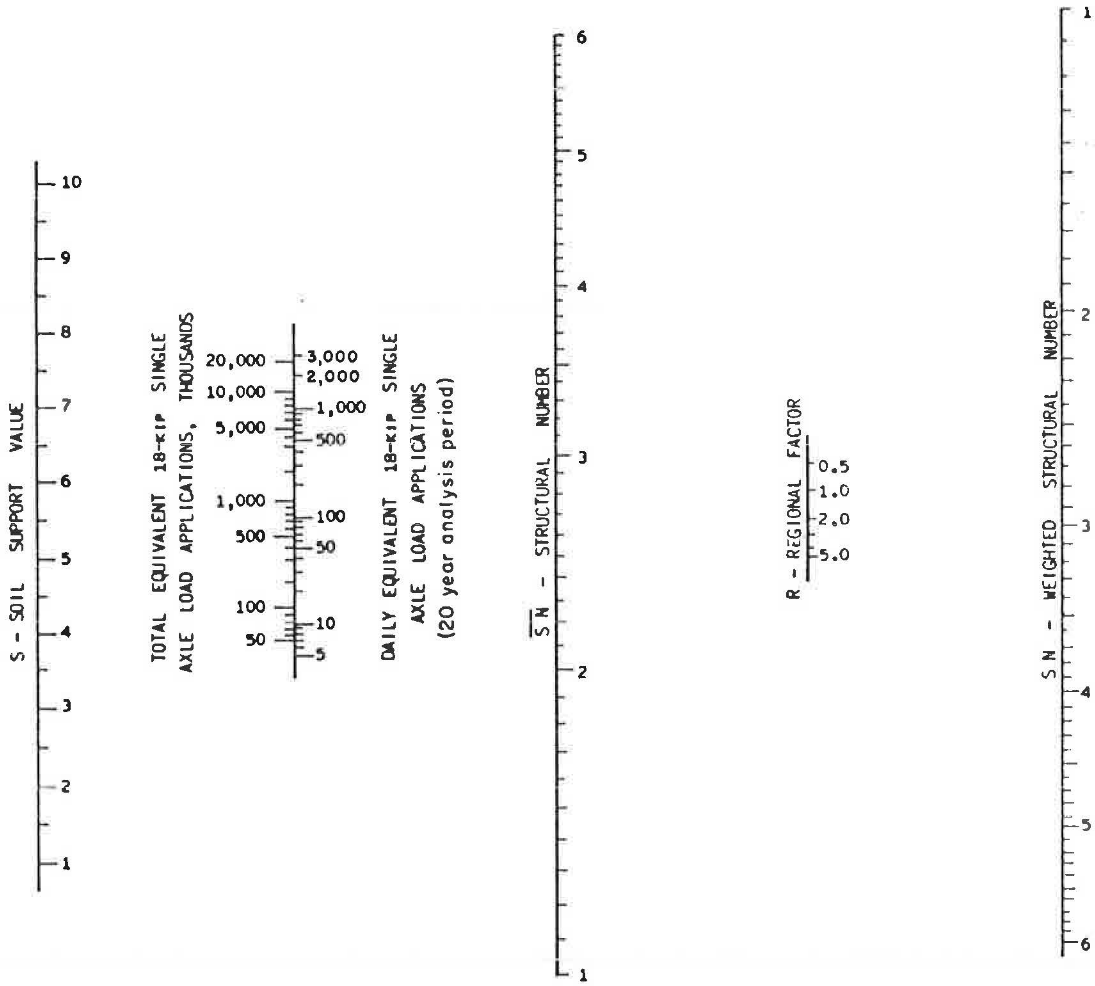


Figure 4. Design chart for flexible pavements, p_t*=2.5* (40).

1. Are a valid representation of the relationship between loss in serviceability, traffic, and pavement thickness.
2. For a single type of subgrade soil may be extended to apply to any subgrade by means of a soil support scale developed for this purpose.
3. For repeated applications of uniform traffic loads may be extended to apply to mixed traffic by conversion to equivalent 18,000-lb (8,200 kg) single-axle loads.
4. For a single environmental condition may be extended to apply to other environmental conditions by means of an appropriate regional factor.
5. For subbase, base, and surfacing materials used in constructing the test road may be extended to apply to other materials by assignment of appropriate layer coefficients (a_1, a_2, a_3).
6. For accelerated applications of traffic during the two-year test period may be extended to apply to repetitions of traffic during an extended period of time (up to 20 years).

Moreover, it is assumed that *uniform* and *high-quality* construction will be obtained.

Use of the design equations represented graphically in Figure 4 thus requires an evaluation of:

1. Terminal Serviceability Index, $P_t(= 2.5$ in Fig. 4).
2. Number of equivalent 18,000-lb single-axle loads anticipated during the design period.
3. Soil support value, *S*.
4. Regional factor, *R*.
5. Structural number, SN.
6. Layer coefficients, a_1, a_2, a_3.

Detailed discussion and appropriate developments of these factors for use in conjunction with the design chart (Fig. 4) are included in the AASHO Guide (*40*). In this synthesis only the structural number and layer coefficients are discussed with particular reference to the coefficients pertaining to pavements containing emulsion-treated materials.

The structural numbers, SN, for the entire pavement can be obtained from Figure 4 for a particular set of conditions. This number is represented by

$$(SN)_{total} = a_1 D_1 + a_2 D_2 + a_3 D_3 \qquad (1)$$

in which

a_1, a_2, a_3 = layer coefficients for surface, base, and subbase, respectively; and

D_1, D_2, D_3 = thickness, in inches, of surface, base, and subbase, respectively.

Values of layer coefficients obtained for the materials used in the factorial section of the AASHO Road Test are as follows:

Asphalt concrete surface course	0.44
Crushed stone base course	0.14
Sandy gravel subbase course	0.11

Coefficients for other materials are given in Table 11 as proposed by the AASHO Committee.

A number of agencies have modified these values somewhat in light of their own experiences. A summary of such practices is also included in the AASHO Guide (*40*).

Applicability to Pavements with Emulsion-Treated Layers

To use the Interim Guide for pavements with emulsion-treated layers requires determination of the structural number from Figure 4 and use of an appropriate coefficient a_1 if the entire section is an emulsion-treated section, or appropriate coefficients a_1, a_2, and a_3 if different materials are contemplated.

United States Forest Service Adaptation

The United States Forest Service has adapted the AASHO Guide to the structural design of roads in National Forests (*41*). Tables 12 and 13 have been included to illustrate the

TABLE 11

STRUCTURAL LAYER COEFFICIENTS PROPOSED BY AASHO COMMITTEE ON DESIGN, OCTOBER 12, 1961 (*40*)

Pavement Component	Coefficient[3]
Surface Course	
Roadmix (low stability)	0.20
Plantmix (high stability)	0.44*
Sand Asphalt	0.40
Base Course	
Sandy Gravel	0.07[2]
Crushed Stone	0.14*
Cement-Treated (no soil-cement)	
Compressive strength @ 7 days	
650 psi or more[1]	0.23[2]
400 psi to 650 psi	0.20
400 psi or less	0.15
Bituminous-Treated	
Coarse-Graded	0.34[2]
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

[1] Compressive strength at 7 days.

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

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

TABLE 12

COEFFICIENTS FOR DENSE-GRADED COLD BITUMINOUS PAVEMENTS
(U.S. Forest Service; *41*)

See Footnote when total 18 kip equivalent axles are >1,000,000 1/
Do not use when total 18 kip equivalent axles are from 350,000 to 1,000,000 without additives
Use base coefficient of 0.17 when total 18 kip equivalent axles from 120,000 to 350,000
Use base coefficient of 0.19 when total 18 kip equivalent axles from 60,000 to 120,000
Use base coefficient of 0.21 when total 18 kip equivalent axles from 10,000 to 60,000
Use base coefficient of 0.23 when total 18 kip equivalent axles are < 10,000

Add to Base Coefficient	Mixing	Asphalt	Grading		P.I.	Additives Cement, Lime, etc.	Aggregate Quality		2/
			Passing No. 200	Passing No. 4			% Wear LAA	% Loss $NaSO_4$	Additional Considerations
0.00	Blade Mix	> 100 Pen. Cutbacks	< 2 > 10	< 35 > 60	> 2		> 35	> 9	Marginal
0.01		< 100 Pen.	2-10	35-60	≤ 2	Improved Curing	25-35	6-9	Good
0.02	Travel Plant					25-50% Strength Increase	< 25	< 6	Excellent
0.03	Central Plant					50% Strength Increase			

1/ When the equivalent axles are 350,000, a relatively high standard road is justified. To assure a high probability of success, tighter controls are needed than are normally required in cold mix specifications. An economic analysis will almost always reveal an additive or hot mix are justified.

2/ Includes such things as curing conditions, experience level of both inspectors and contractors, aggregate uniformity requirements, etc.

TABLE 13

COEFFICIENTS FOR OPEN GRADED COLD BITUMINOUS PAVEMENTS
(U.S. Forest Service; *41*)

See footnote when total 18 kip equivalent axles >350,000 [1/]
Use base coefficient of 0.18 when total 18 kip equivalent axles from 120,000 to 350,000
Use base coefficient of 0.20 when total 18 kip equivalent axles from 60,000 to 120,000
Use base coefficient of 0.22 when total 18 kip equivalent axles from 10,000 to 60,000
Use base coefficient of 0.24 when total 18 kip equivalent axles are < 10,000

Add to Base Coefficient	Asphalt	P.I.	Aggregate Quality		Additional Considerations [2/]
			% Wear LAA	% Loss $NaSO_4$	
0.00	> 100 Pen.	> 2	> 35	> 9	Marginal
0.01	< 100 Pen.	≤ 2	25-35	6-9	Good
0.02			< 25	< 6	Excellent

1/ When the equivalent axles are 350,000 a relatively high standard road is justified. To assure a high probability of success, tighter controls are needed than are normally required in cold mix specifications. An economic analysis will almost always reveal a dense graded cold mix with additive or hot mix are justified.
2/ Includes such items as curing conditions, experience level of both inspectors and contractors, stockpile or aggregate uniformity requirements, etc.

NOTE: Open graded mixes with a single seal coat are extremely free draining. Practically all rainfall passes through the mix to the layers below. This may result in weakening the base layers or subgrade and must be considered in the design.

Silt and clay materials have low wet strength and the degree of weakening may be dramatic when they exist in the subgrade, the use of open graded mixes as surfacing is questionable.

When using open graded mix as surfacing, paving should extend full width and include shoulders. Untreated dense aggregate will trap water within the roadway and open graded untreated aggregate is so unstable it will be displaced by traffic as well as create a safety hazard. Open graded mixes are not recommended when tire chain use is expected.

range in coefficients being used for dense-graded and open-graded materials. These values represent a range for the coefficient a_2 (or a_1) of Eq. 1. Their use in Eq. 1 is as indicated in the previous section.

To illustrate the use of Table 12, assume: (1) 18-kip (8200 kg) equivalent axles are in the range 10,000 to 60,000; (2) central plant mixing; (3) the base asphalt will be harder than 100 penetration; (4) the aggregate grading is such that 2 to 10 percent passes the No. 200 (75 μm) sieve and the percent passing the No. 4 (4.75 mm) sieve is in the range 35-60; (5) the plasticity index of the fines is less than 2; (6) sufficient cement is added to provide a 50 percent increase in strength; (7) aggregate quality is such that the material exhibits less than 25 percent loss in the Los Angeles abrasion and less than 6 percent loss in the Na_2SO_4 soundness tests; and (8) excellent construction and curing conditions exist. For these ideal circumstances the resulting coefficient for a_2 (or a_1) is 0.37; from a comparison with Table 11 it can be seen that this material is comparable to an asphalt concrete in structural equivalency.

ASPHALT INSTITUTE PROCEDURE

The Asphalt Institute method was developed from analyses of data from the AASHO Road Test (*42*); however, data from the WASHO Road Test, various British test roads, previous Asphalt Institute design considerations, together with a range of existing design experiences from throughout the United States, influenced development of the present procedure (*42, 43*) first published in 1963 (*44*) and revised slightly in 1970 (*45*).

Principal Design Considerations

Adequacy of a structural section design is defined in terms of the Present Serviceability Index (PSI) of the pavement, with a terminal value set at 2.5.

As in the AASHTO procedure, the number of applications of various wheel loads are expressed in terms of an equivalent number of 18,000-lb (8,200 kg) single-axle load applications:

$$\frac{W_{18}}{W_L} = 10^{0.118(L-18)} \qquad (2)$$

in which

L = single-axle load or 0.57 × tandem-axle load (must be >10 kips);
W_{18} = repetitions of 18-kip wheel load; and
W_L = wheel load of magnitude L.

Further

$$\text{DTN} = \frac{W_{18}}{7{,}300} \tag{3}$$

in which DTN is the design traffic number and represents the average daily equivalent 18,000-lb single-axle load applications for a design period of 20 years.

Thickness of asphalt concrete, T_A, may be determined from either

$$T_A = \frac{9.19 + 3.97 \log \text{DTN}}{(\text{CBR})^{0.4}} \tag{4}$$

in which CBR is the design California Bearing Ratio of the subgrade

or

$$T_A = 6.37 + 2.75 \log \text{DTN} - 0.0893\ \text{DTN}^{0.119}(R\text{-}12) \quad \text{for DTN} < 20 \tag{5a}$$

$$T_A = 6.37 + 2.75 \log \text{DTN} - 0.117\ \text{DTN}^{0.0279}(R\text{-}12) \quad \text{for DTN} > 20 \tag{5b}$$

in which R is the stabilometer R-value (*46*). Design charts representing Eq. 4 and Eq. 5 are shown in Figures 5 and 6.

For convenience, in the western United States an approximate relationship between DTN and Traffic Index (TI) has been established and thicknesses of asphalt concrete for a range in R-values, DTN's, and TI's are given in Table 14.

To use the procedure with emulsion-treated materials, the thickness of asphalt concrete to be replaced with emulsion-treated base is increased by the factor 1.4 to obtain the desired thickness.

The procedure requires, however, a minimum thickness of hot-mix asphalt concrete as surface course, with the thickness being dependent on traffic and aggregate gradation.

Material Properties

Characteristics of the subgrade soil may be determined by either the CBR or R-value procedure. No determinations of the properties of the other pavement components are made, although the assumption is made that all structural section components meet certain minimum quality standards normally specified for these materials.

CHEVRON DESIGN PROCEDURE

Recently the Chevron Research Company has developed a thickness design procedure for pavement structures constructed with asphalt concrete, dense-graded emulsion-treated mixes, or cement-modified emulsion-treated mixes (*47*). Although this procedure has only recently been developed and has not had the use of the two methods described previously, it has a number of desirable features that provide it with the potential for more effective use of emulsion-stabilized materials. Hence, it has been included as a part of the synthesis.

Like the Shell pavement design procedure (*34*), two critical strains—estimated by elastic layer theory—are examined in determining proper pavement thickness. These are the horizontal tensile strain, ϵ_t, at the bottom of the treated layer and the vertical compressive strain, ϵ_v, at the surface of the subgrade (Fig. 3).

Two locations are checked for the critical strains under a standard 9,000-lb (4100 kg) wheel load (18,000-lb axle load) on dual tires used for design, one midway between the wheels and the other directly under one of the wheels, the latter occurring in thin structures.

Allowable values for horizontal tensile strain are based on fatigue data determined from laboratory tests on asphalt concrete, emulsion-stabilized, and cement-modified emulsion mixes. Figures 7 and 8 show data for mixes with an air void content, V_v, of 5 percent. In addition, these curves were developed for mixes with an asphalt content, V_B, of 11 percent (expressed on a volumetric basis). To obtain fatigue data for other void or asphalt contents the data of Figures 7 and 8 can be adjusted by the ratio $V_B/(V_v + V_B)$* in

$$N_C = N_f \cdot 10^M \tag{6}$$

in which

N_C = corrected number of repetitions to failure;
N_f = number of repetitions to failure at a particular strain level, Figures 7 and 8; and

$$M = 4.84\left(\frac{V_B}{V_v + V_B} - 0.69\right).$$

Vertical strain criteria for the subgrade, shown in Figure 9, have been selected to minimize surface rutting caused by overstressing the subgrade.

One of the distinctive features of this design procedure is the use of a recently developed diametral resilient modulus device (*48*) to define the stiffness characteristics of the treated materials used in the structural pavement section. In the design procedure an emulsion mix is characterized at two temperatures and two cure levels to reflect its response over a range of in-service conditions.

The steps in the design procedure are illustrated by the flow diagram of Figure 10 and are briefly summarized in the following sections.

Traffic

Traffic is expressed in terms of the average daily equivalent 18,000-lb single-axle loads expected during the selected design life of the structure.

Material Characteristics

The *subgrade stiffness,* expressed as a modulus, can be determined from repeated-load triaxial compression tests (*49*), estimated from conventional tests (e.g., E (psi) = 1,500 CBR) (*34*) or predicted from a soil classification (*45, 50, 51*). Frost is accounted for by reducing the subgrade stiffness by 50 percent during the thaw period. This reduction in subgrade stiffness is based on results reported by Bergan and Monismith (*52*) obtained from laboratory repeated-load tests on soil specimens subjected to cycles of alternate

* The fatigue data of Figures 7 and 8 were developed for a ratio of 0.69.

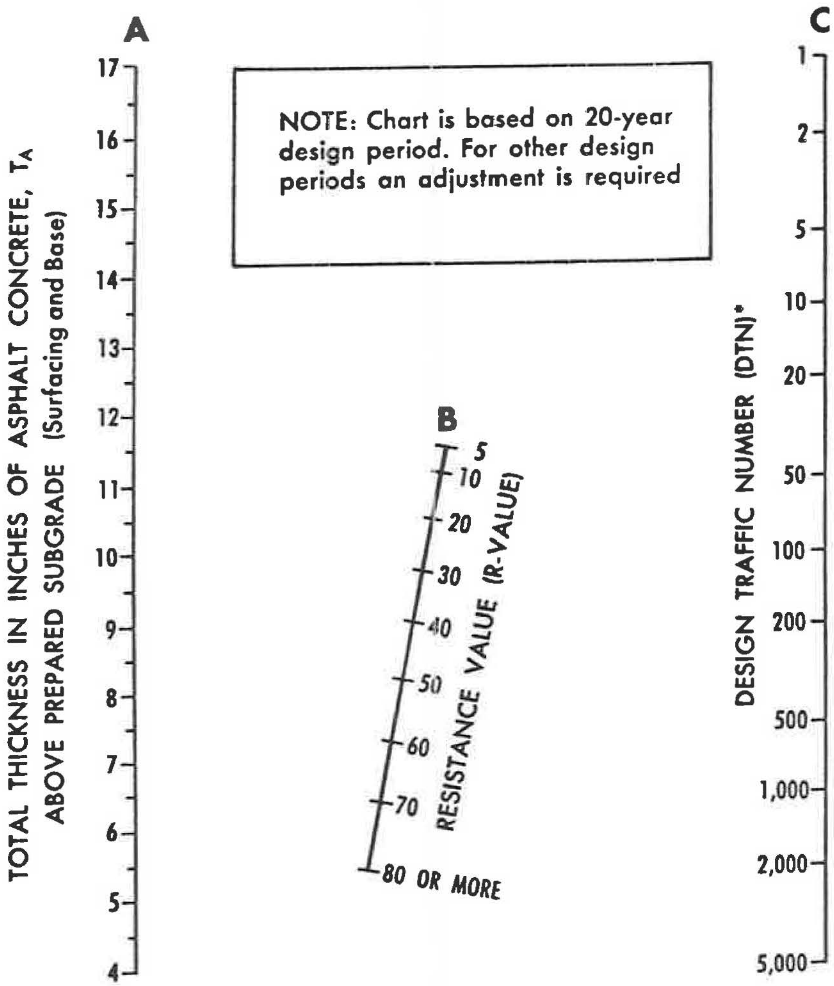


Figure 5. Thickness design chart using subgrade soil R-*value* (45).

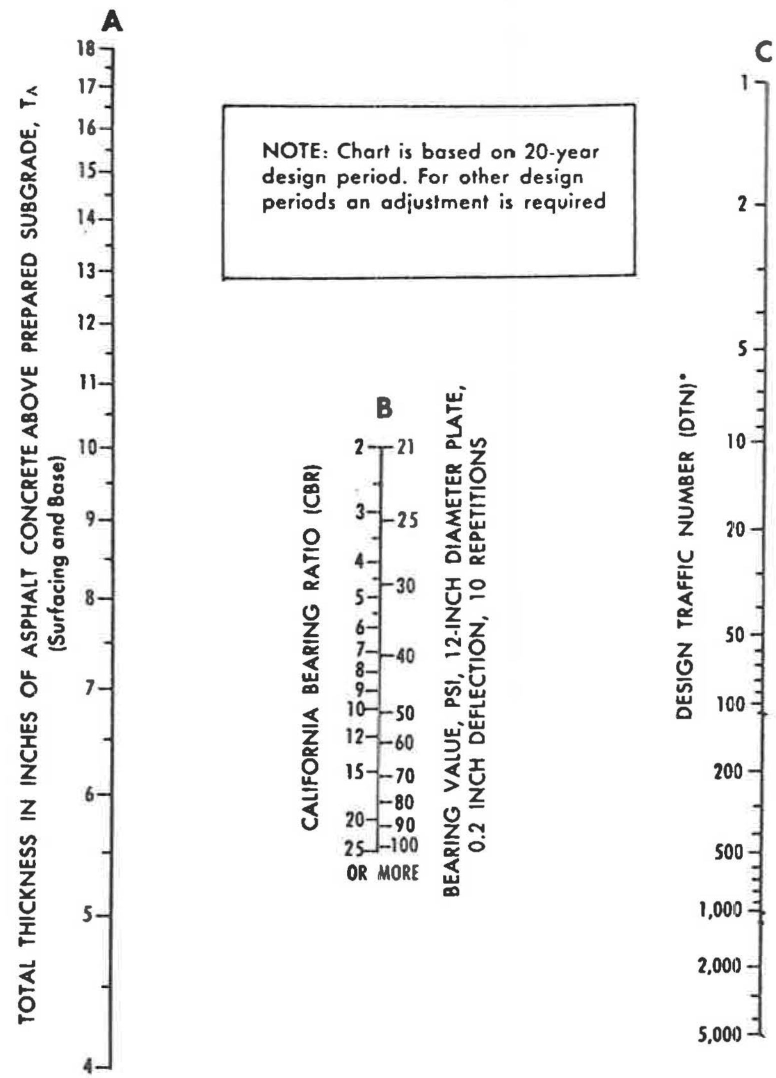


Figure 6. Thickness design chart using subgrade soil CBR or plate-bearing values (45).

TABLE 14

ASPHALT CONCRETE THICKNESS (FT) DERIVED FROM ASPHALT INSTITUTE MS-1 (*45*)

DESIGN TRAFFIC NUMBER (A1)	TRAFFIC INDEX (CA)	R VALUE (CALIFORNIA) OF UNDERLYING SOIL															
		5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80
0.14	4.0	0.40	0.40	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
0.39	4.5	0.50	0.50	0.45	0.40	"	"	"	"	"	"	"	"	"	"	"	"
0.95	5.0	0.60	0.55	0.50	0.50	0.45	0.40	0.40	"	"	"	"	"	"	"	"	"
2.11	5.5	0.70	0.65	0.60	0.55	0.50	0.50	0.45	0.40	"	"	"	"	"	"	"	"
4.40	6.0	0.75	0.70	0.65	0.60	0.60	0.55	0.50	0.45	0.40	"	"	"	"	"	"	"
8.62	6.5	0.85	0.80	0.75	0.70	0.65	0.60	0.55	0.50	0.45	0.40	"	"	"	"	"	"
16.08	7.0	0.90	0.85	0.80	0.75	0.70	0.65	0.60	0.55	0.50	0.45	0.40	0.40	0.40	0.40	0.40	0.40
29	7.5	0.95	0.90	0.85	0.80	0.75	0.70	0.65	0.60	0.55	0.50	"	"	"	"	"	"
49	8.0	1.0	0.95	0.90	0.85	0.80	0.75	0.70	0.65	0.60	0.50	0.45	"	"	"	"	"
82	8.5	1.05	1.00	0.95	0.90	0.85	0.80	0.75	0.70	0.60	0.55	0.50	0.45	0.45	0.45	0.45	0.45
133	9.0	1.10	1.05	1.00	0.95	0.90	0.85	0.80	0.70	0.65	0.60	0.55	0.50	"	"	"	"
209	9.5	1.15	1.10	1.05	1.00	0.95	0.85	0.80	0.75	0.70	0.65	0.60	0.55	"	"	"	"
322	10.0	1.20	1.15	1.10	1.00	0.95	0.90	0.85	0.80	0.75	0.70	0.65	0.55	0.50	0.50	0.50	0.50
486	10.5	1.25	1.20	1.10	1.05	1.00	0.95	0.90	0.85	0.80	0.70	0.65	0.60	0.55	"	"	"
718	11.0	1.30	1.20	1.15	1.10	1.05	1.00	0.95	0.85	0.80	0.75	0.70	0.65	0.60	"	"	"
1043	11.5	1.30	1.25	1.20	1.15	1.10	1.00	0.95	0.90	0.85	0.80	0.75	0.65	0.60	0.60	0.60	0.60
1491	12.0	1.35	1.30	1.25	1.20	1.10	1.05	1.00	0.95	0.90	0.80	0.75	0.70	0.65	0.60	"	"
2101	12.5	1.40	1.35	1.25	1.20	1.15	1.10	1.05	0.95	0.90	0.85	0.80	0.75	0.65	0.60	0.60	0.60
2922	13.0	1.45	1.35	1.30	1.25	1.20	1.10	1.05	1.00	0.95	0.90	0.80	0.75	0.70	0.65	"	"
4150	13.5	1.45	1.40	1.35	1.25	1.20	1.15	1.10	1.05	0.95	0.90	0.85	0.80	0.70	0.65	0.60	"
5800	14.0	1.50	1.45	1.35	1.30	1.25	1.20	1.10	1.05	1.00	0.95	0.85	0.80	0.75	0.70	0.60	"

NOTE: To use Chart, use TI to left - R-Value across - at intersection, read thickness of asphalt concrete required.

When no further reduction in thickness is indicated, it may be assumed the minimum recommended thickness has been reached.

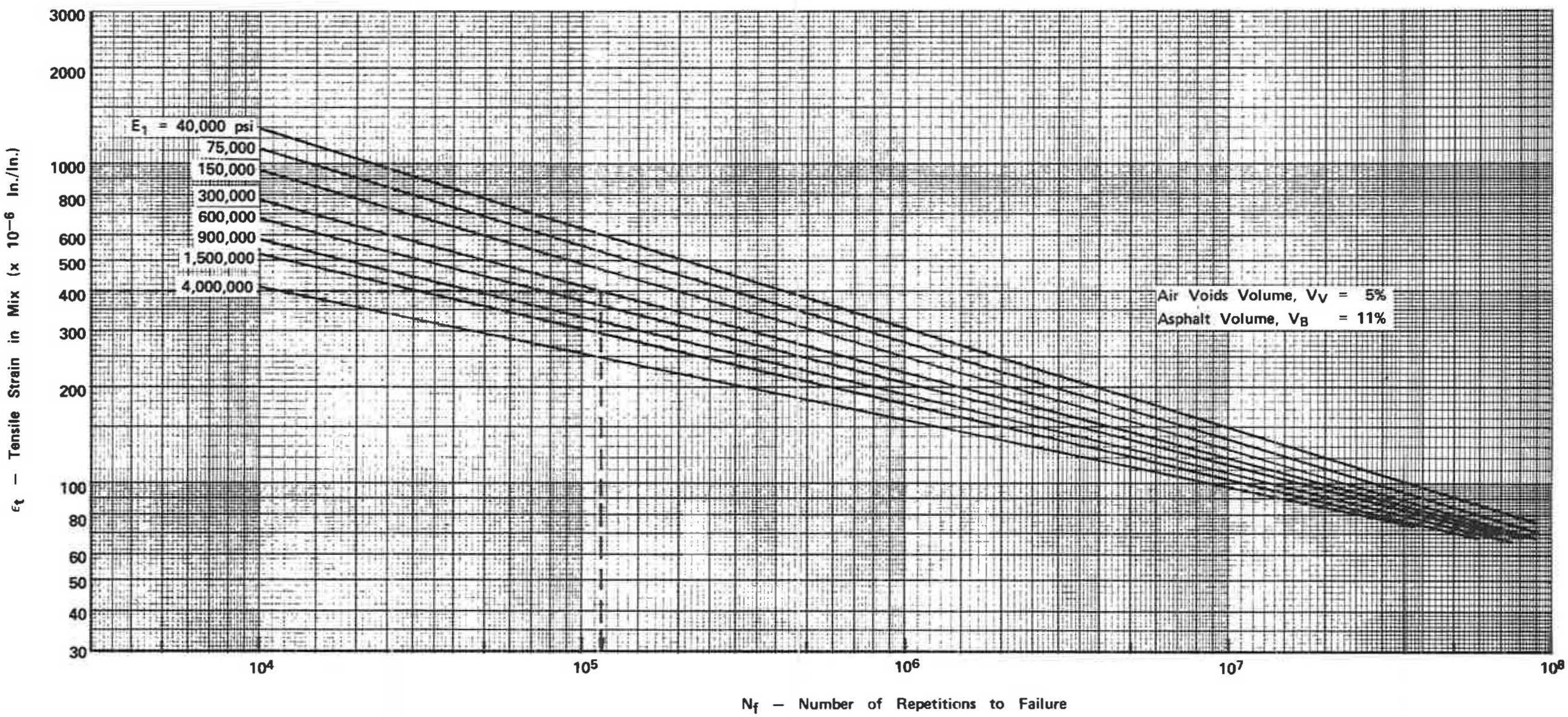


Figure 7. Fatigue criteria for asphalt and emulsion mixes.

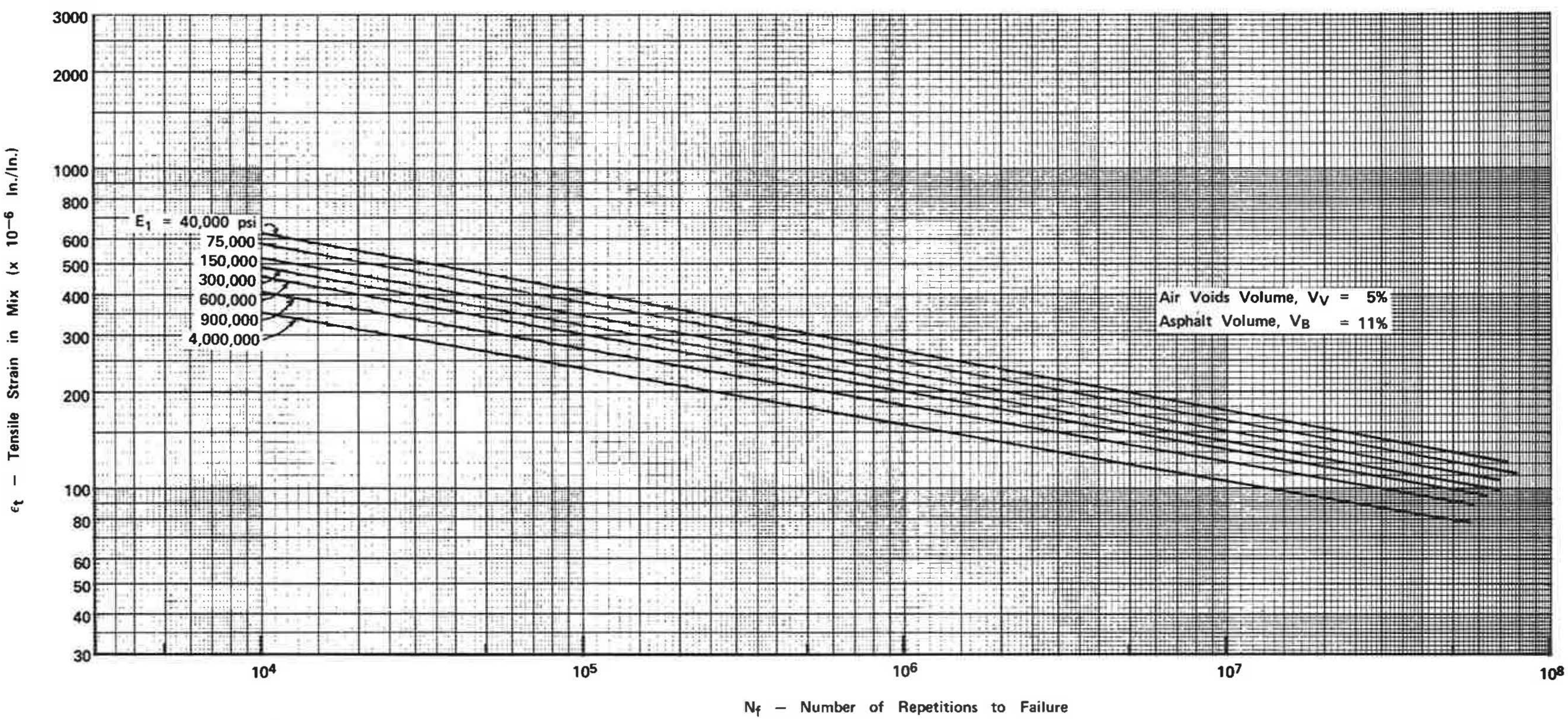


Figure 8. Fatigue criteria for cement-modified asphalt emulsion mixes.

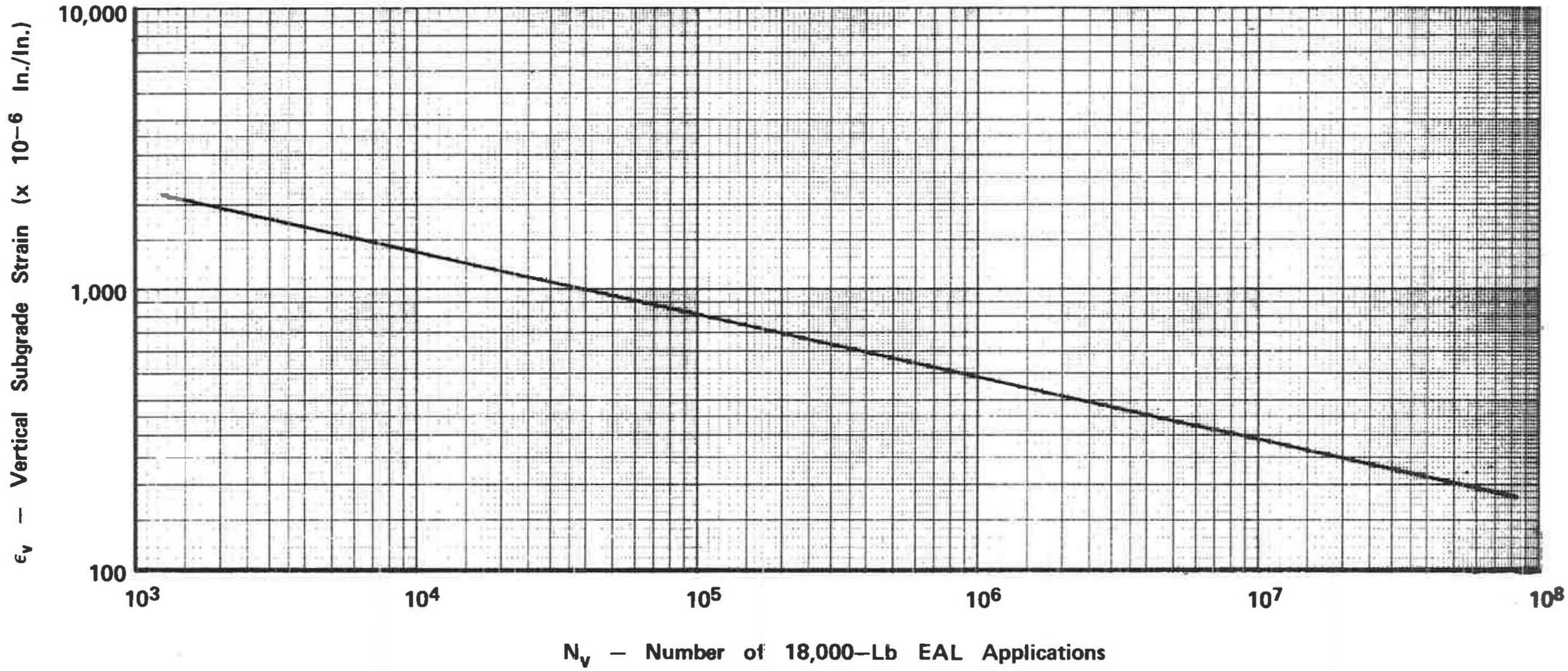


Figure 9. Subgrade strain criteria.

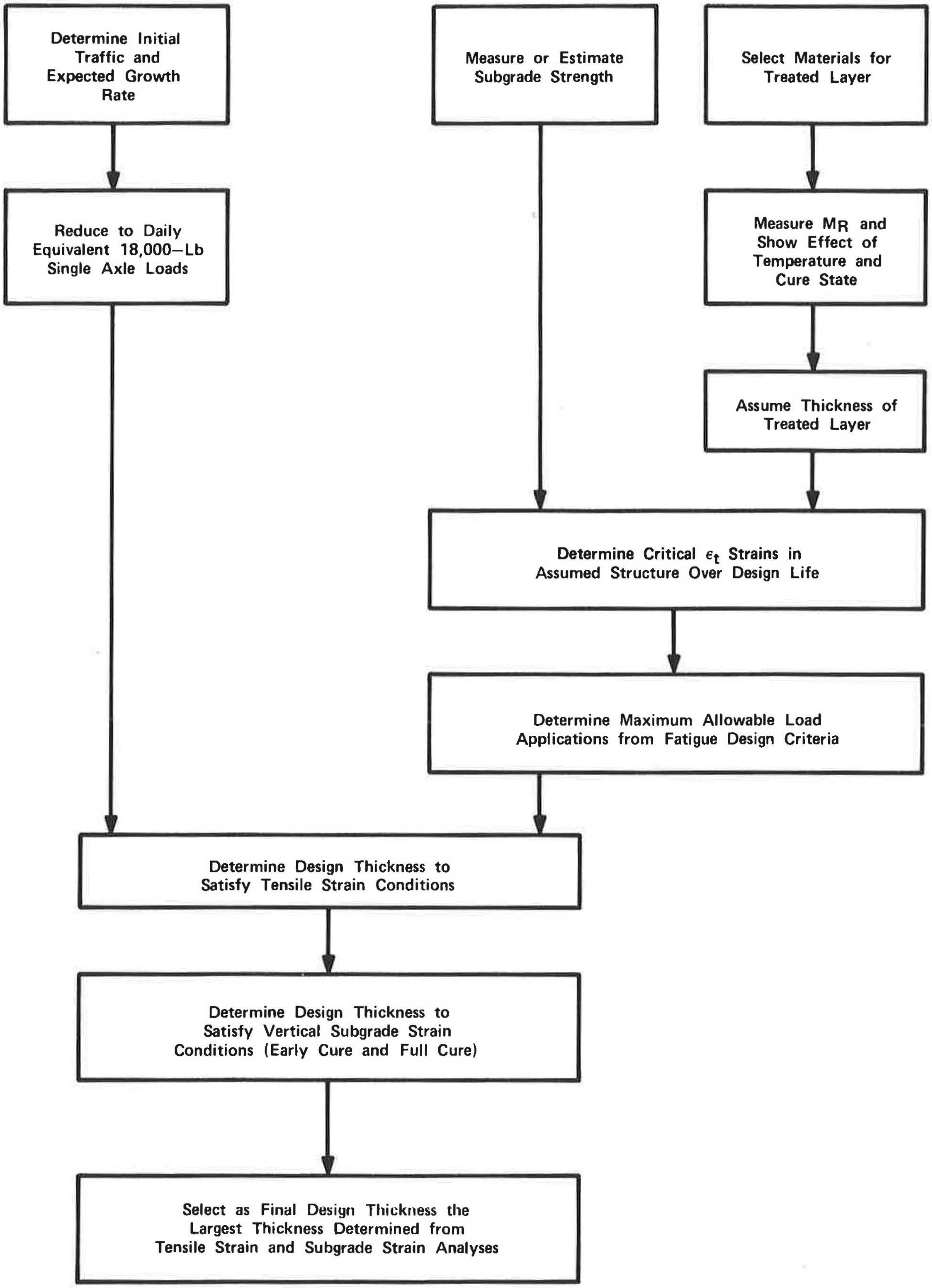


Figure 10. Flow diagram for structural design of asphalt pavement.

freezing and thawing and verified by analyses of the performance of an in-service pavement. Poisson's ratio is assumed to be 0.45.

Stiffness of the *asphalt-treated* material(s) is determined using the diametral M_R device. Temperature and, in the case of emulsion-treated materials, early-cure as well as final-cure conditions, are ascertained. For the emulsion-treated materials early cure is normally defined as one day at room temperature (73 F ± 3 F) (22.8 C ± 1.7 C) and final cure results after three days air cure plus four days vacuum dessication; the corresponding moduli are termed M_i and M_f, respectively. The final stiffness is also determined at an elevated temperature, normally 100 F (38 C). Measured values for a specific mix are shown in Figure 11.

The numbers next to the lines between M_i and M_f represent the months after construction. During the first month, the strength of the emulsion mix is depicted by the M_i line. In the case of an asphalt concrete mix, only the M_f curve would be developed.

The time for an emulsion mix to reach its final M_R in the field is also critical in determining its design thickness. Based in part on Chevron's field experience with emulsion mixes, the evapotranspiration map shown in Figure 12 has been selected as a guide for estimating emulsion mix cure periods. Emulsion mixes placed in parts of the southwest and most of Texas and Florida are expected to reach their ultimate design modulus in six months. A two-year cure period is assumed for emulsion mixes placed in the northern regions of the map.

The rate of strength development for an emulsion mix can be depicted in Figure 11 by using reduction factors given in Table 15 and the equation:

$$M_t = M_f - (M_f - M_i)(RF) \quad (7)$$

in which

M_t = total modulus for the specified time after construction, psi;

M_f = final modulus (measured at 73 F (23 C) after three-day air cure and four-day vacuum cure at room temperature), psi;

M_i = initial modulus (measured at 73 F after one-day air cure), psi;

RF = early cure reduction factor as defined subsequently.

This relationship assumes that the rate of cure of the mix is rapid initially and then levels out, reaching 95 percent of its final modulus in the specified time period (*53*).

Effect of Temperature

The effect of temperature on the modulus of asphalt-treated mixes is also shown in Figure 11. The temperature scale has been compressed in the lower regions so that straight lines can be used to approximate the modulus-temperature relationship. The M_f line between 32 F (0 C) and 140 F (60 C) is developed from the measured moduli at 73 F (23 C) and 100 F (38 C) on the job mix. The one-day air cure modulus at 73 F for emulsion-treated mixes is measured and plotted in Figure 11. It has been shown that the modulus-temperature curve for mixes containing water is parallel to the fully cured curve (*54*); hence, line M_i is drawn parallel to M_f in Figure 11. Similarly, parallel lines are constructed between M_i and M_f to represent the curing process taking place with emulsion-treated mixes. These lines are developed by locating M_R values at 73 F according to Eq. 6.

Below 32 F (0 C) the modulus-temperature relationship is similar for the fully cured and partially cured mix because any water in the mix becomes frozen. The approximate M_R for all mixes at —20 F (—29 C) is taken as 5×10^6 psi (34×10^6 kPa) in this analysis.

The temperature values indicated in Figure 11 are pavement temperatures. Pavement temperature can be estimated from air temperature using a relationship developed by Witczak (*55*). Witczak's original correlation between mean monthly air temperature and mean monthly pavement temperature was shown to be dependent on asphalt concrete thickness. However, the average line shown in Figure 13 is considered acceptable. Mean monthly air temperatures can be obtained from climatological data near the job location or estimated from the monthly air temperature maps, an example of which is shown in Figure 14. With the air temperature, the pavement temperature is determined from Figure 13. Figure 11 then represents a complete picture of the pavement temperature and early-cure effects on the modulus of an asphalt-treated mix. Selection of appropriate cure and temperature conditions for the job under design allows the engineer to estimate the critical strain conditions needed for thickness design.

Structural Design

With the foregoing data, a pavement thickness is selected to ensure that the vertical subgrade strain at the subgrade surface and horizontal tensile strain on the under side of the asphalt-treated layer satisfy the established criteria. The following steps are taken in the design for an emulsion-treated mix.

Tensile Strain Evaluation

1. Assume thickness of treated layer.

2. *Conduct early cure analysis* * by examining monthly variations in properties (cure period is estimated from Figure 12.)

(a) Determine from Figure 11 the appropriate M_R (E_1 in Figs. 15 and 16) for each month.

(b) Determine horizontal tensile strain, ϵ_t, from design charts like Figures 15 and 16.

(c) Determine N_f from fatigue data (e.g., Fig. 7).

(d) Calculate $1/N_f$ for each month and sum at end of analysis period.

(e) Determine predicted damage for early cure period (D_E) by multiplying $(\Sigma 1/N_f)_E$ by average monthly traffic (T_E).

3. Conduct *full-cure analysis* for remaining design life in same manner as in Step 2, except use mean annual air and pavement temperatures. Determine predicted damage for

* Early-cure analysis is eliminated with asphalt concrete mixes.

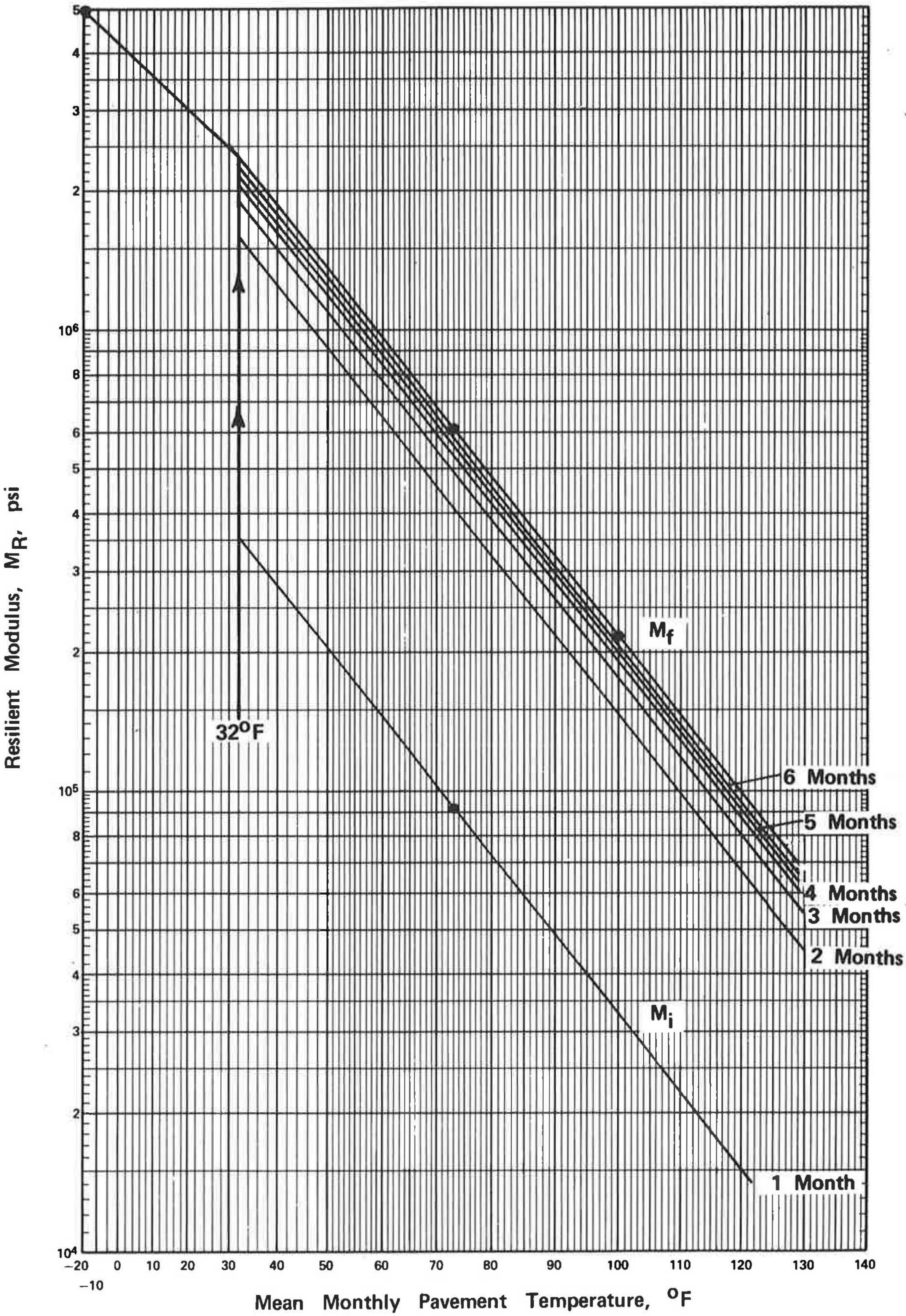


Figure 11. Modulus-pavement temperature relationships for emulsion mixes.

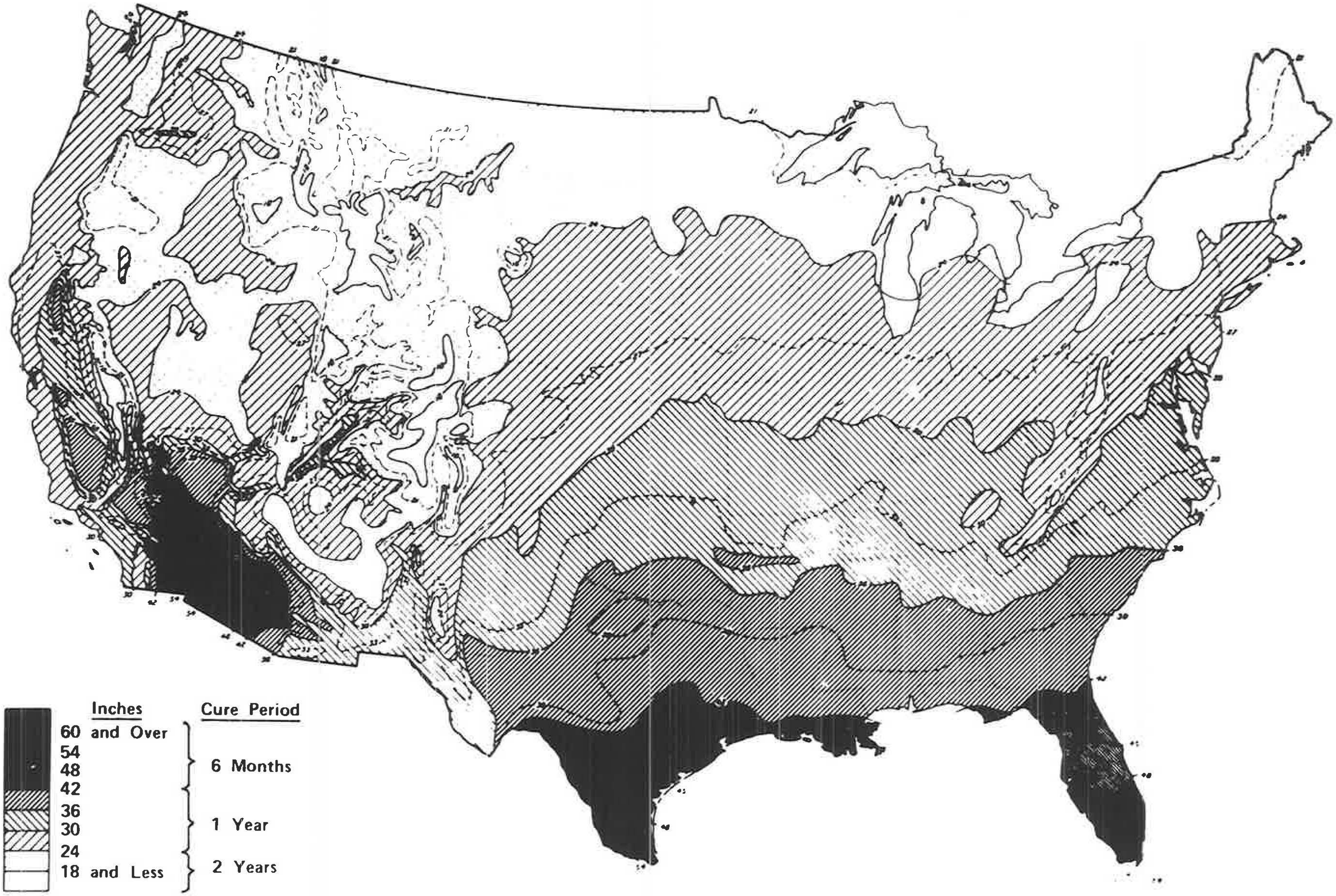


Figure 12. Field cure periods for emulsion mixes based on annual potential evapotranspiration map.

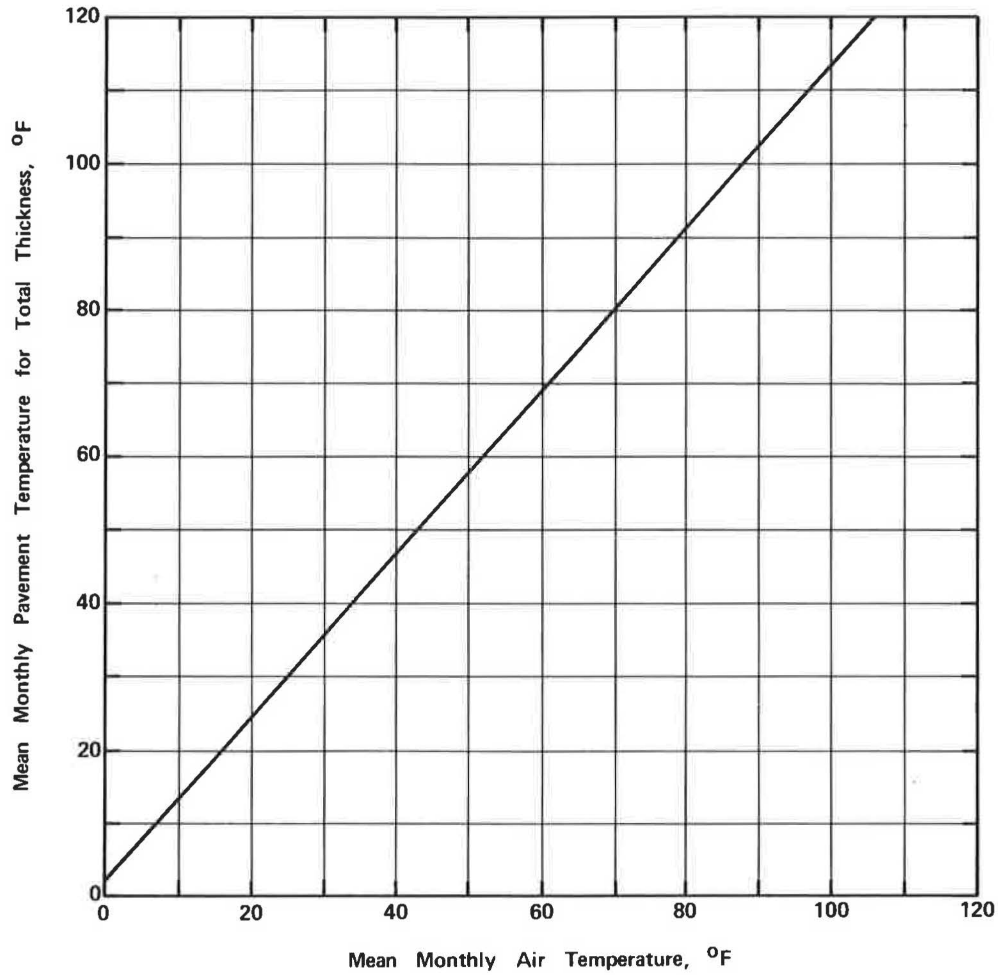


Figure 13. Prediction of pavement temperature from air temperature.

full-cure period (D_F) by multiplying ($\Sigma 1/N_f$) by average annual traffic.

4. Sum D_E and D_F to obtain total damage factor (DF).

5. Repeat Steps 1 through 4 using a different assumed thickness.

By plotting the total damage factor vs thickness for a series of trials, the pavement thickness corresponding to a damage factor of 1 can be selected.

Subgrade Strain Evaluation

6. Using the design thickness determined above, examine the *early-cure condition* * for subgrade strain.
   (a) Determine lowest or critical pavement modulus (normally first month after construction).
   (b) Calculate traffic for critical period.
   (c) Determine predicted subgrade strain, ϵ_v, with the aid of charts like Figures 17 and 18.
   (d) Compare with allowable ϵ_v from Figure 9. If:
      (1) Allowable ϵ_v is greater than predicted ϵ_v, design thickness is acceptable.
      (2) Allowable ϵ_v is less than predicted ϵ_v, increase design thickness until allowable ϵ_v = predicted ϵ_v.

7. Examine *full service conditions* for subgrade strain.
   (a) Use critical pavement modulus of 100,000 to 250,000 psi for full design life.
   (b) Calculate traffic for full design life.
   (c) Repeat Steps 6c and 6d.

* Early-cure condition is eliminated with asphalt concrete mixes.

The distress criteria shown in Figures 7 and 8 are based on the results of controlled-stress laboratory fatigue tests. Accordingly, for stiff subgrades the results of this design procedure may provide somewhat conservative estimates of pavement thickness.

DISCUSSION

Three methods have been presented for the structural design of pavements containing emulsion-stabilized layers. The AASHO Interim Guide and the Asphalt Institute procedures have as their basis the performance of pavements in the AASHO Road Test. No emulsion sections were included in the test road. Thus, extension of these procedures to pavements containing such materials through use of the "layer-equivalency" concept is based in part on

TABLE 15

EARLY-CURE REDUCTION FACTORS FOR STRENGTH DEVELOPMENT

Month	Reduction Factor Six Month's Cure	 One-Year Cure	 Two-Year Cure	Month	Reduction Factor Two-Year Cure
1	1.0	1.0	1.0	13	0.198
2	0.37	0.62	0.78	14	0.175
3	0.225	0.48	0.69	15	0.154
4	0.136	0.37	0.62	16	0.136
5	0.082	0.29	0.545	17	0.120
6	0.05	0.225	0.48	18	0.105
7	-	0.175	0.42	19	0.093
8	-	0.136	0.37	20	0.082
9	-	0.105	0.33	21	0.073
10	-	0.082	0.29	22	0.064
11	-	0.064	0.255	23	0.057
12	-	0.05	0.225	24	0.05

judgment and, as in the case of the U.S. Forest Service modification, in part on observation of field performance. In these procedures no cognizance is taken of the fact that emulsion-treated materials will exhibit different response characteristics or that climatic conditions, particularly as they influence the curing characteristics of these materials, may result in different performance characteristics. The Chevron design procedure is a step in this direction and, although requiring a few more tests than either of the first two procedures, provides the designer with a greater capability in effectively utilizing local materials. All three methods are primarily applicable to mixes containing dense-graded aggregates, although the Forest Service adaptation of the AASHO Guide provides for use of open-graded materials.

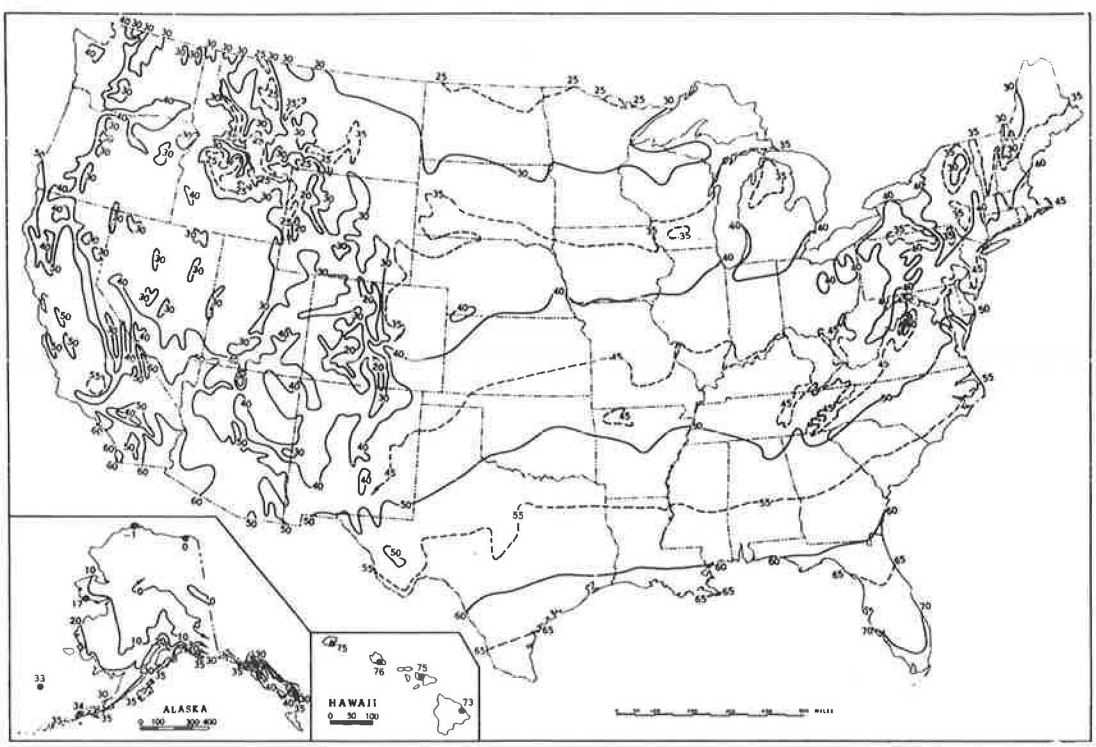


Figure 14. Normal monthly air temperature, °F (1931–60), November.

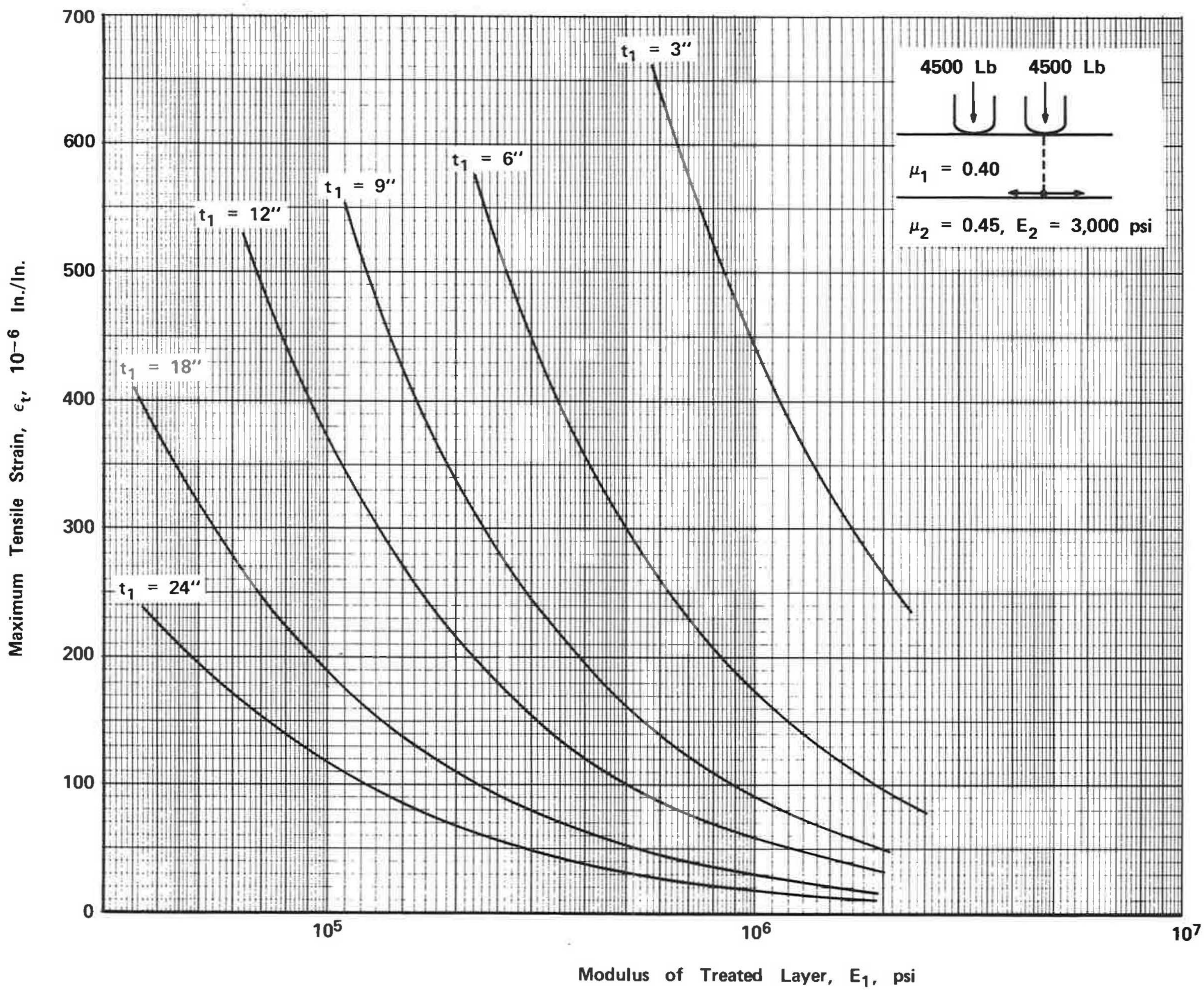


Figure 15. Maximum tensile strain under one tire of a dual assembly vs modulus of treated layer for a range in thicknesses.

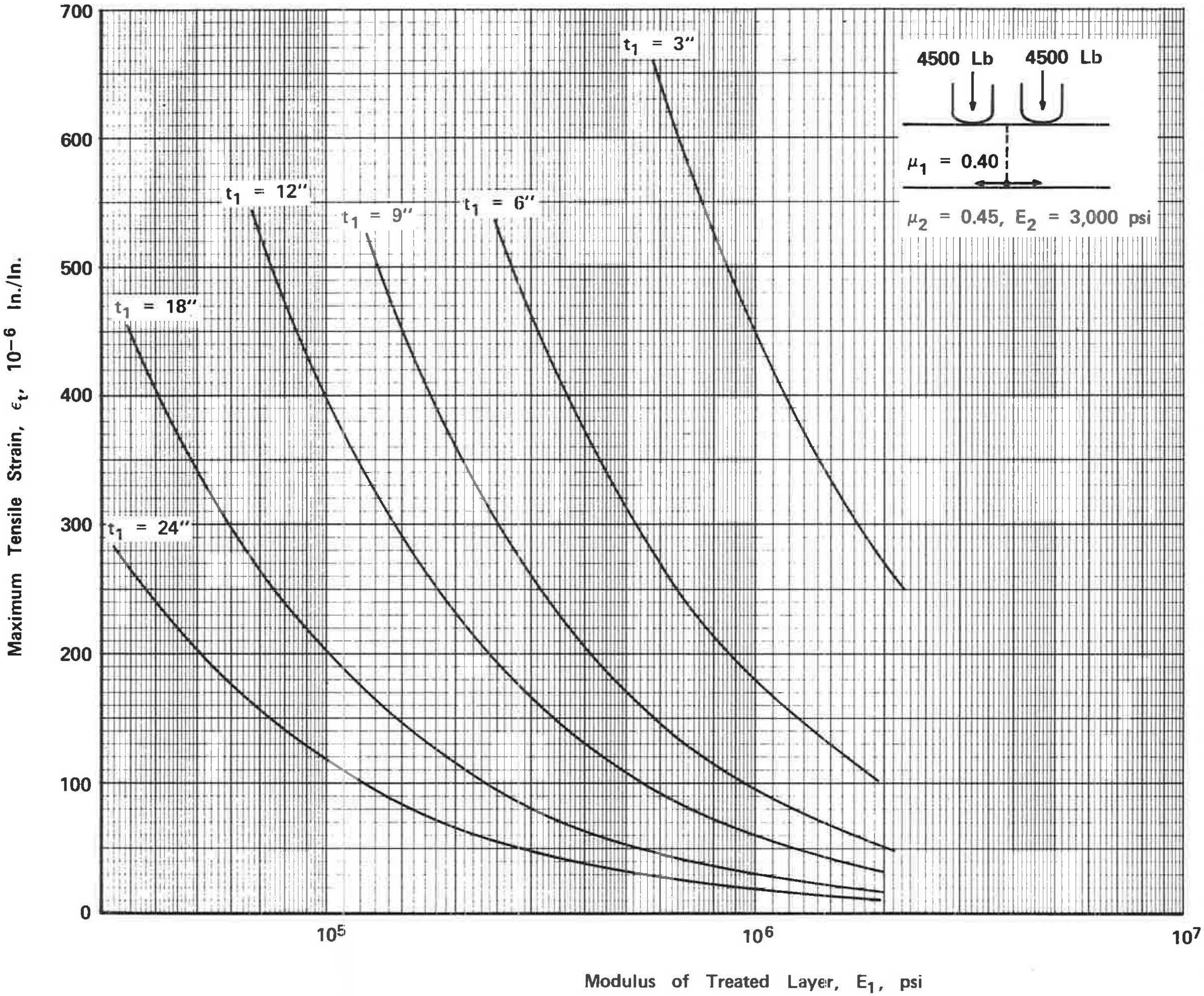


Figure 16. Maximum tensile strain between tires of a dual assembly vs modulus of treated layer for a range in thicknesses.

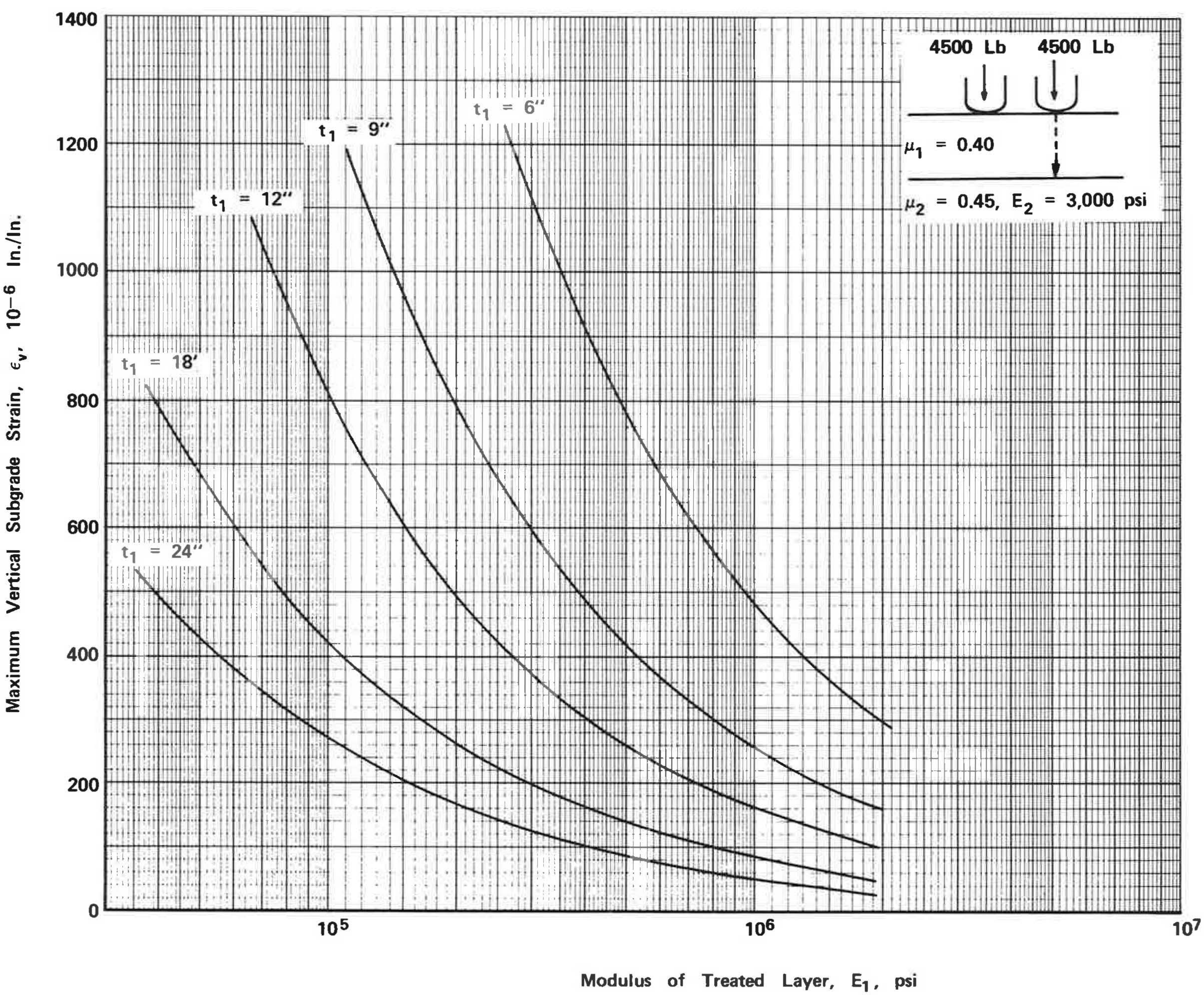


Figure 17. Maximum vertical compressive strain in subgrade under one tire of a dual assembly vs modulus of treated layer for a range in thicknesses.

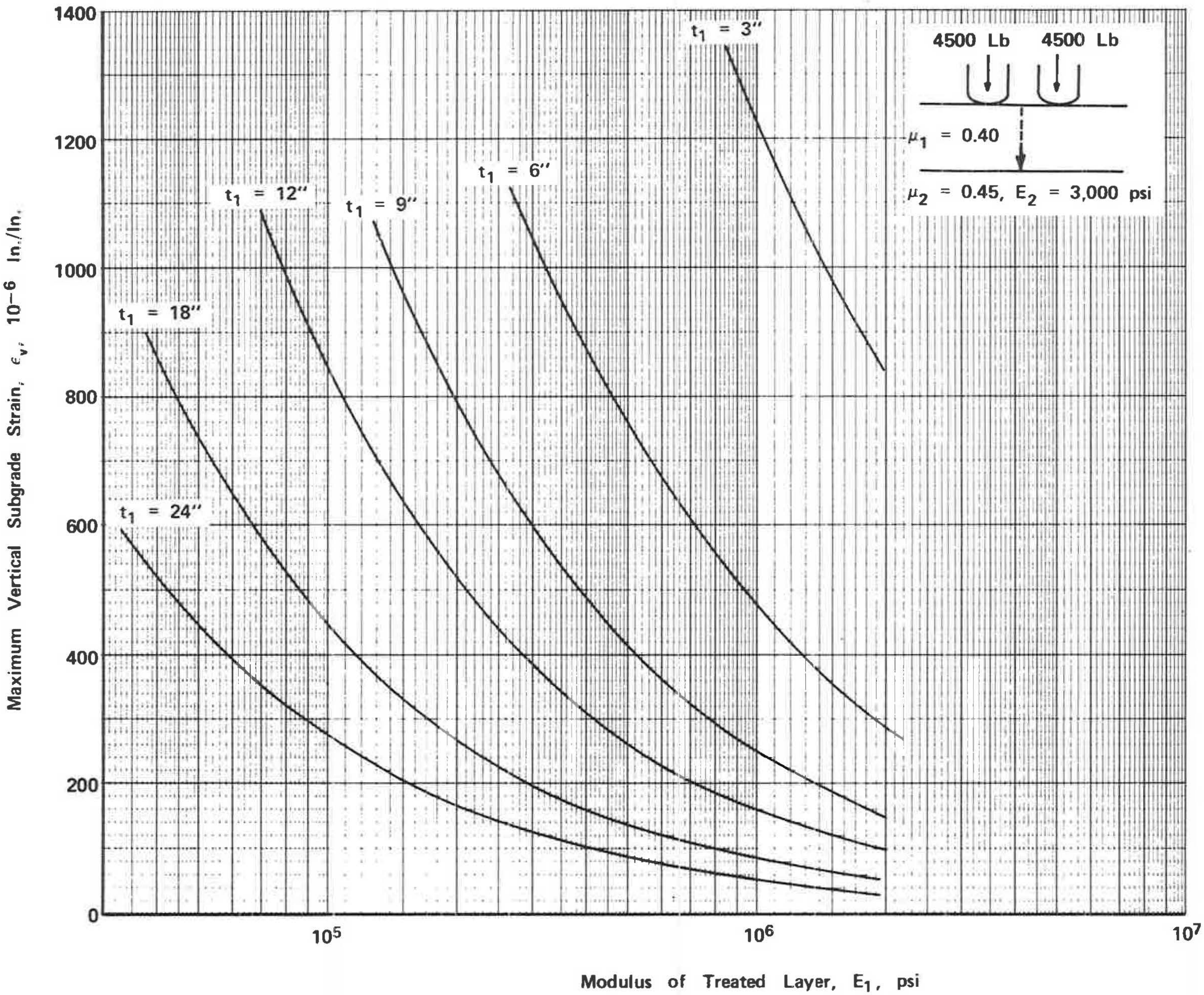


Figure 18. Maximum vertical compressive strain in subgrade between tires of a dual assembly vs modulus of treated layer for a range in thicknesses.

CHAPTER THREE

MATERIALS SELECTION AND MIX DESIGN

In this chapter general guidelines are suggested for use of emulsions in various portions of the pavement structure and, where appropriate, procedures are presented for selection of amounts of these materials to ensure reasonable performance of pavement structures.

Rather than summarizing all available methods, a few of the more widely used procedures have been included and represent the best available practice at this time.

SPRAY APPLICATIONS

Tack Coat

A tack coat is a light spray application of emulsion to an existing paved surface, either asphalt or portland cement concrete, the purpose of which is to promote bond between the existing surface and the subsequent course. An SS or CSS emulsion diluted with equal parts of water is recommended; the application rate should be less than 0.1 gal per sq yd (0.4 liter/m^2) of the diluted emulsion. Alternatively, MS or CMS emulsions that can be diluted with water may be used at comparable application rates. Some agencies have used RS-1 or CRS-1 emulsions during cool weather.

Fog Seal

A fog seal is a light spray application of emulsion to an existing asphalt pavement surface. Its purpose is to seal the existing surface to reduce raveling or to enrich a dry and weathered surface. Either an SS or a CSS emulsion diluted with equal parts of water is recommended at an application rate of about 0.1 gal per sq yd (0.4 liter/m^2) of the diluted material.

Curing Seal

A curing seal is a light spray application of emulsion to seal the surface of a cement- or lime-treated base. The resulting asphalt film acts as a membrane to retard water evaporation from the stabilized layer. Emulsified asphalts, both anionic and cationic, of the SS type are recommended for use at an application rate of about 0.2 gal per sq yd (0.9 liter/m^2).

Seal Coats and Surface Treatments

Seal coats and surface treatments consist of alternate applications of asphalt and aggregate with the aggregate firmly embedded in the asphalt layer by rolling. A seal coat is usually a single application of asphalt and aggregate; a surface treatment may consist of single or multiple applications of both materials placed one on the other. The thickness of the resulting layer corresponds, in the case of single applications, to the nominal aggregate particle size. In the case of multiple treatments the thickness is only slightly larger than the thickness of the first course because the maximum size of each successive aggregate application is usually one-half of the previous one.

These treatments provide a low-cost, all-weather, waterproof surface on a base; they are used to improve the skid resistance of existing pavements, to extend the life of a dry and weathered surface, or to seal the surface of a poorly compacted pavement to the entrance of air and water.

Aggregate

The aggregate should be essentially a one-size material; that is, the largest size should be no more than twice the smallest size with a reasonable tolerance (about 5 percent) for oversize and undersize. This requirement is perhaps the most important from an aggregate standpoint; if there is much difference in size, the smallest particles will be completely embedded, leading to "fat" spots, and the coarsest particles will be dislodged by traffic. In addition, the aggregate should be angular in shape and free of dust or clay coating. Suitable grading specifications for this type of construction are given in Appendix C.

For single treatments the maximum size should not exceed ½ in. (12 mm) to minimize noise (tire rumble). Generally, large-size aggregates are more difficult to adhere but are less critical with respect to asphalt quantity. Finer sizes tend to be more easily retained under fast heavy traffic.

Emulsion

The emulsion must be sufficiently fluid at the pavement temperature to wet and adhere to the pavement and to wet and adhere to the aggregate. After application it must develop sufficient consistency, before the surface is opened to traffic, to retain the aggregate at any subsequent pavement temperature.

Emulsions of the rapid setting (RS or CRS) type should be used for this type of construction, but should be applied only under dry conditions. Although the RS-1 or CRS-1 can be used on normal gradients and good alignment, the RS-2 or CRS-2 is preferred on projects with steep grades and superelevated curves. The higher proportion of residual asphalt in the grade 2 emulsion results in a higher viscosity, reducing the potential of runoff in the latter situations. The mineralogical composition of the aggregate will influence the choice of emulsion; e.g., anionic emulsions normally will be chosen for use with limestone aggregates.

Quantity Determination for Single Treatments

Two procedures recommended for determination of quantities of both asphalt and aggregate are presented in The Asphalt Institute's *Manual MS-13* (*56*). The first is applicable to one-size aggregates and is based on developments in New Zealand, Australia, and Canada; the second is for aggregates with slightly more oversize and undersize and is based on work developed in the United States and Canada. Approximate quantities given in Table C-2 provide an indication of the amounts of materials required, but for actual quantities the formulas in *MS-13* should be used.

The quantity of asphalt determined by The Asphalt Institute formulas is the amount of residual asphalt. When emulsions are used it is desirable to increase this amount in proportion to the actual amount of base asphalt in the emulsion so that when the water evaporates the computed quantity will remain. For example, assuming a CRS-2 were being used, the actual amount of emulsion to be applied would be:

$$\frac{\text{Calculated quantity from MS-13 formula}}{\text{Proportion of residual asphalt (e.g., 0.65)}}$$

A design procedure that is quite similar but specifically applicable to the use of emulsions can be found in McLeod (*84*).

Quantity Determination—Multiple Treatments

No unanimity exists as to the best procedure to use to estimate quantities for multiple treatments. McLeod (*57*) has suggested that the formulas in *MS-13* can be used to estimate the amount of aggregate and asphalt for each layer.

SLURRY SEALS

A slurry seal consists of a mixture of "quick" or slow-setting mixing-type asphalt emulsion, fine aggregate, mineral filler (such as portland cement, if required), and water applied to an existing surface to serve as a crack filler and a wearing course (*58*). The usual fine-graded slurry aggregates * should not be used for road surfaces carrying passenger car traffic at speeds in excess of about 40 mph (64 km/hr) under conditions conducive to hydroplaning. As with other surface courses, the slurry aggregate and thickness application should be designed to provide adequate skid resistance and protection against hydroplaning.

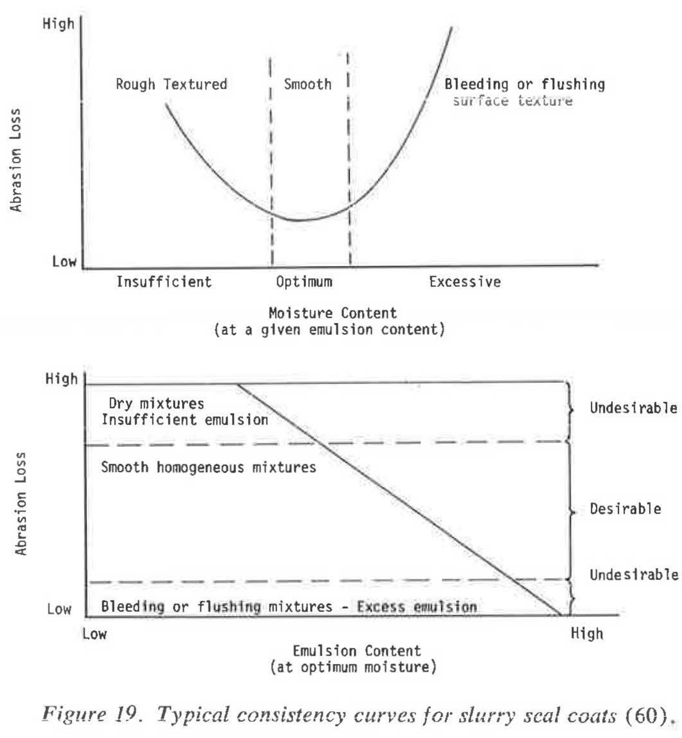


Figure 19. Typical consistency curves for slurry seal coats (60).

Materials

Aggregate

The aggregate consists of natural or manufactured sand, slag, crusher fines, or a combination thereof. Smooth-textured sand should not exceed 50 percent of the total combined aggregate. The International Slurry Seal Association has provided guide specifications for three different types of gradations (*27*); these are given in Appendix D. Also summarized in Appendix D are guidelines for the use of each gradation.

Emulsion

Generally the SS-type emulsions, both anionic and cationic, are used for slurry seals. Recently there have been introduced quick-set emulsion systems for slurry seals that consist of an emulsified asphalt with a special emulsifier requiring use of either a setting or retarding additive (*59*). These materials provide some advantages, compared to conventional slurry seals, if it is necessary to open the road to traffic relatively soon after application and the curing conditions preclude conventional slurries from developing the desired conditions within some prescribed time period.

Design Procedures

Design of a slurry seal involves selection of the optimum percentages of mixing water and emulsion for a specific aggregate, the grading of which is in the range noted in Appendix D. Figure 19 shows in a qualitative manner the basis for selection of both an optimum water content and a minimum emulsion content. The combination of materials should form a creamy-textured slurry that, when spread, will flow down into the pits and cracks in the pavement and fill them before the strike-off squeegee used in the application of the material passes. If the mixture is too stiff it will have a tendency to pile up immediately in front of the squeegee and not fill the cracks.

In this section two procedures for the design of slurry seals are briefly summarized, one developed by the Chevron Asphalt Company (*58*) and the other by the California Department of Transportation (*60*).

Chevron Method

The design procedure developed by the Chevron Asphalt Company (*58, 59*) involves two phases: (1) preparation of test specimen(s) and (2) subjecting the slurry to a wet track abrasion test.

Preparation of the test specimen involves, for a particular aggregate and emulsion content (usual range 15 to

* According to the International Slurry Seal Association guide specifications (*27*), Appendix D, Type I and Type II aggregate gradings would fall in this category.

25 percent of emulsion based on the dry weight of aggregate), first determining the proper amount of mixing water, usually by experience. When the proper mixture has been selected, the slurry is placed on a large (approximately 12 in.; 300 mm) disc of roofing felt and cured at 140 F (60 C) to constant weight (about 24 hr).

The cured specimen is then subjected to simulated abrasive forces of traffic in the wet track abrasion test, in which the specimen is abraded in a submerged condition. Following this test, the loss in material is determined and the data are plotted for a range in emulsions contents as shown in Figure 20. A maximum loss of 75 grams per square foot (810 g/m^2) is permitted in this test.

The recommended emulsion content is based primarily on this low wear value although other factors, such as lack of segregation of the materials and freedom from surface skinning and tackiness, also are considered. For slurries containing the quick-set emulsions, some additional tests are required, as described by Goodrich, et al. (*59*).

California Method

The procedure recently developed by the Transportation Laboratory of the State of California (*60*) is similar to the Chevron method.

The first step involves determination of an optimum water content for each emulsion content for the aggregate under investigation. This is accomplished by preparing slurries over a range of water contents (usually 9 to 15 percent of dry weight of material), curing them at 140 F (60 C), and selecting the highest water content that produces no visible free asphalt on the surface of the cured specimen. The procedure is repeated for a range of emulsion contents and a plot of "optimum" water content vs emulsion content is ascertained.

Specimens are then prepared over a range of emulsion contents (usually 10 to 20 percent) at the corresponding optimum water contents as determined, placed on roofing felt, cured at 140 F (60 C), and then subjected to abrasion with steel knurled wheels under water at 77 F (25 C). Loss in weight is determined and a relationship like that shown in Figure 20 is determined. The emulsion content corresponding to an abrasion loss of 75 g per sq ft (810 g/m^2) is noted and is recommended as the minimum emulsion content for use in the field.

EMULSION-AGGREGATE MIXES

Mixes of emulsion and aggregate can be used as subbase, base, and surface courses for pavements. Design of these mixes requires selection of the proper kind and amount of emulsion for a particular aggregate. Different design procedures have evolved for mixes containing dense-graded aggregates as compared to open-graded materials. These procedures are discussed in separate sections. Table 16 gives a summary of requirements for typical aggregates for use with emulsions (*61*); Table 17 gives a general guide to the selection of the type and grade of emulsion to be used.

General Design Framework

In selecting the amount of emulsion it is necessary that the mixes being tested are representative of those to be used in the pavement structure. Any testing procedure should thus embrace the following steps:

1. *Water content selection.* With some aggregates, in order for the emulsion to be properly mixed it is necessary that the aggregate contain some water (Fig. 21).

2. *Mixing.* A reasonable mixing time is necessary to insure proper coating of the aggregate. In the case of the

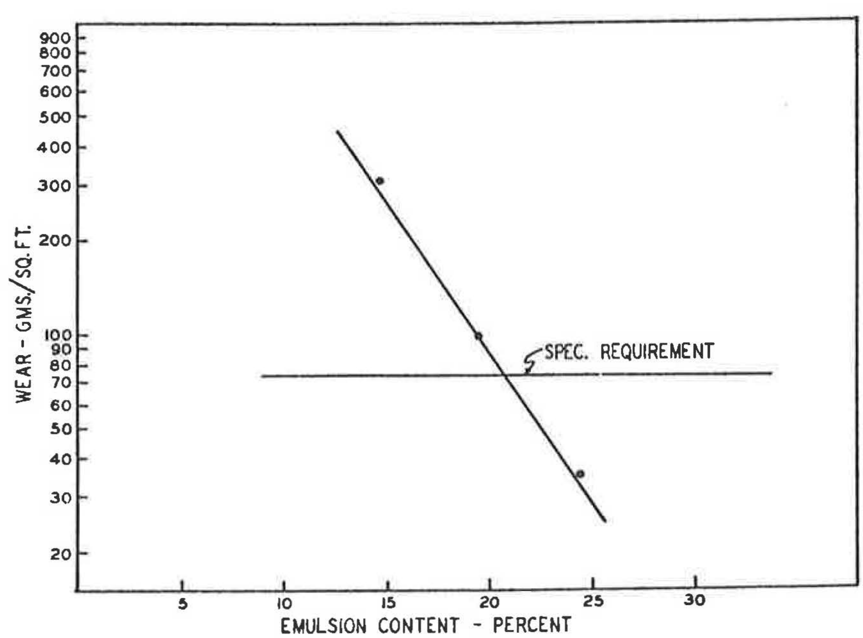


Figure 20. Effect of emulsified asphalt content on wear. (After Kari and Coyne; 58).

TABLE 16

TYPICAL EMULSION BASE MATERIALS AND METHODS

Category	Crushed Aggregate		Gravels		Sands		
	Dense	Open	Low Sand	High Sand	Well Graded	Poorly Graded	Silty Sand
Gradation, %Passing: 1-1/2"	100	100	100	100			
1	90-100	95-100	80-100	80-100			
3/4	65-90	-	-	-			
1/2	-	25-60	-	-	100	100	100
3/8	-	-	-	-	-	-	-
#4	30-60	0-10	25-50	50-85	75-100	75-100	75-100
8	-	0-5	10-30	30-75	-	-	-
16	15-30	-	-	-	35-75	-	-
50	7-25	-	-	-	15-30	-	-
100	5-18	-	-	-	-	-	15-65
200	4-12	-	3-8	3-15	5-12	0-12	12-25
Sand Equivalent, %, *min.*	30		30	30	30	30	30
L. A. Abrasion, 500 Revolutions, %, Max.	40	35	60	60	-	-	-
Crushed Faces, %, *min.*	65	65	-	-	-	-	-
Emulsified Asphalt Type SS	Yes	No	*	Yes	Yes	Yes	*
MS	*	Yes	Yes	*	*	*	Yes
Construction Method Central Mix	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Travel Plant In-Place Mixing	* (1)	No	Yes	*	*	Yes	Yes

* May be used but not preferred.

(1) Treatment of existing materials in unsurfaced roads is often accomplished by in-place mixing.

Adapted from Chevron Asphalt Company *(61)*.

TABLE 17

SUITABLE TYPES OF EMULSION FOR STABILIZATION

Type of Aggregate	Type and Grade of Asphalt Emulsion	Reason(s) for Selection
Open-graded aggregate	MS-2, CMS-2	Good retention by aggregate; ie, will not exhibit excessive "runoff" characteristics
Well-graded aggregate with little or no fine aggregate or material passing No. 200 sieve	MS-2, CMS-2 SS-1, CSS-1	Same as above
Aggregate containing a considerable percentage of fine aggregate and material passing No. 200 sieve	SS-1, SS-1h CSS-1, CSS-1h	Resists "balling" during mixing

After The Asphalt Institute *(62)*

MS-type emulsions, particularly, too long a mixing time will result in a reduction in coating (Fig. 21).

3. *Aeration.* To ensure proper densification of the mix during the compaction process it may be necessary to reduce the total fluids content somewhat below that required for mixing; thus, aeration may be required (Fig. 21).

4. *Compaction.* Compaction comparable to that expected in the field must be achieved in order that the properties, which are density-dependent, will reasonably reflect actual performance.

5. *Curing.* Laboratory curing conditions must reflect, in a comparatively short period of time, longer-term environmental influences to which the compacted mix will be subjected which, in turn, will influence the physical properties of the mix and, thus, pavement performance. This may require, at times, specimens being subjected to the action of moisture or moisture vapor.

6. *Testing.* This phase of the design procedures requires the conduct of tests that measure such desirable mix properties as stability, stiffness (or modulus), flexural strength, fatigue resistance, etc.

To minimize the amount of laboratory testing required, it is desirable to be able to estimate an asphalt content or asphalt contents that will approximate the final design value. One such method for dense-graded aggregate mixes is discussed later herein. Alternatively, experience with an aggregate in a specific area will also reduce the requirements for extensive testing.

Dense-Graded Aggregate Mixes

Mixtures of emulsions and dense-graded aggregates can be used as both base and surface courses in pavement structures. To date the majority of published design procedures are applicable to mixes to be used as base courses, although established design procedures for surface course mixes containing asphalt cements would probably be used for emulsion-aggregate mixes as well. Design of these mixes consists of: (1) selection of an aggregate with a gradation conforming to a set of specifications and with specific quality requirements such as limitations on the amount of plastic fines that the aggregate may contain; (2) selection of the type of emulsion and the amount, usually expressed as a proportion of the dry weight of aggregate; and (3) determination of the proper water content for the mix. In some instances design merely consists of selection of an emulsion content for a locally available material, provided some of the quality requirements are met; e.g., limitations on the plasticity of the fines.

Aggregate

For emulsion-stabilized base courses, an aggregate with less than 25 percent passing the No. 200 (75 μm) sieve and a sand equivalent greater than 30 or a material for which the product of the Plasticity Index and the percent passing the No. 200 sieve does not exceed 72 can be considered suitable (*63*).

Requirements for the maximum amount of material passing the No. 200 sieve and the amount of clay differ among various agencies. In some instances it may be possible to use aggregates in which the plasticity characteristics of the fines exceed the limits previously noted; if the addition of a small amount of lime reduces the plasticity characteristics to the suggested limits, the material will be considered suitable. Aggregates to be used in surface courses have more stringent requirements. (For more information, see Chapter Four).

Emulsion

Selection of the type and grade of asphalt emulsion will depend primarily on the aggregate (gradation) and the method of mixing the materials, including temperature. Table 16 provides a general indication of the type of emul-

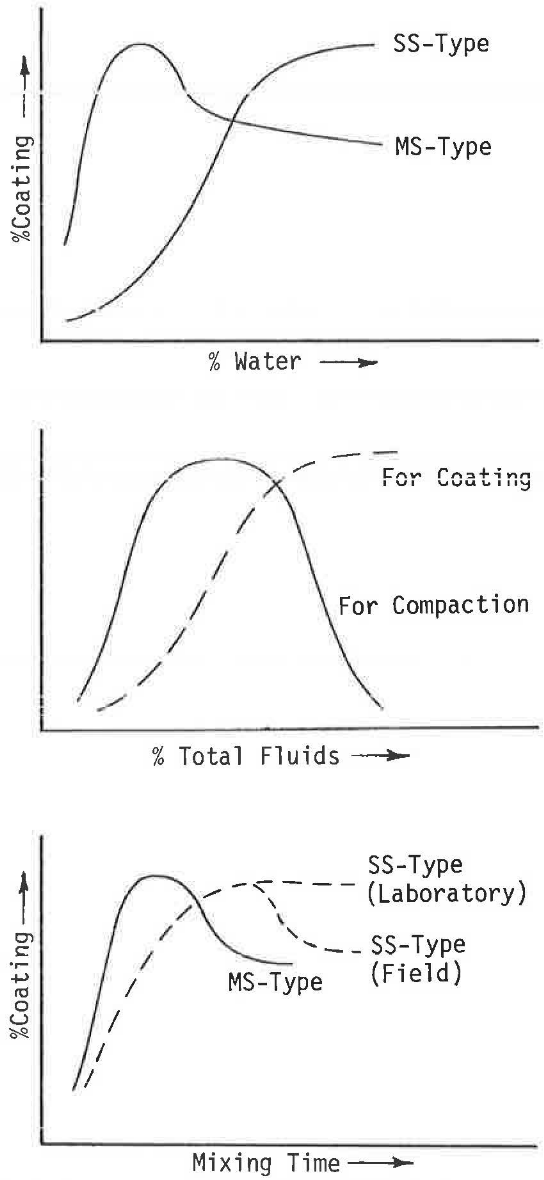


Figure 21. Emulsion mixing characteristics.

sion (MS or SS) that can be used, depending on the aggregate gradation. Table 17, adapted from material presented by The Asphalt Institute (*62*), gives more specific indications of the grades to be used.

Determination of the amount of asphalt is a function of the properties desired for the resulting compacted mix. As a general rule, as much asphalt as possible should be incorporated for a durable, fatigue-resistant structure, but not so much that the stability is reduced below some selected level consistent with the specific traffic requirements. This principle is followed in a number of the design procedures described subsequently.

Although it might be argued that one can use lower asphalt (emulsion) contents for mixes to be used as base courses because these materials are not subjected to loading conditions as severe as at the surface, one should balance the performance characteristics of these mixes as measured by cost (e.g., reduced fatigue resistance may lead to a thicker layer requirement) against mixes designed according to the principle noted in the preceding paragraph. The Chevron method of pavement design described previously permits this option.

Preliminary Estimate of Emulsion Content

To minimize the number of specimens to be tested in the mix design phase, it is desirable to have some preliminary estimate of the expected design asphalt (emulsion) content. This preliminary estimate may be based on previous experience with the material under investigation or it may be estimated from the size distribution and/or surface area of the aggregate.

One general form of the relationship between asphalt content and surface area is

$$A = 100\,(SA)\,t\,\gamma_a \tag{8}$$

in which

A = net asphalt content, percent;
SA = surface area of aggregate;
t = average asphalt film thickness; and
γ_a = unit weight of asphalt.

Although there have been a number of procedures developed to solve Eq. 8 relatively simply,* only the procedure developed by California is referred to in this section (*64*). In the California procedure it is necessary to measure the centrifuge kerosine equivalent (C.K.E.) and oil equivalent (O.E.) values for the fine and coarse aggregates.† With these values and the aggregate gradation and aggregate specific gravity, a preliminary emulsion content can be estimated, as illustrated in Appendix E.

It must be emphasized that the computation procedure serves as the starting point for the laboratory testing phase, from which the final design emulsion content is selected. The following section describes some of the available laboratory mix design procedures.

Laboratory Mix Design Procedures

Although there are many laboratory procedures available that have evolved over the years, only a few are discussed in this section. These methods involve equipment that is used to design conventional paving mixes containing asphalt cements.

All of the procedures described herein are applicable to materials that will be used as base courses. Different criteria are required should mixes be considered as surface courses.

Procedures Using the Stabilometer and Cohesiometer.—Three methods are briefly summarized that make use of test procedures developed by the California Division of Highways to measure specific mix properties.

Asphalt Institute Procedure (*65*).—For a particular aggregate the California C.K.E. corrected surface area pro-

* Epps, et al. (*63*) contains an excellent summary of these methods.

† These values provide a measure of the surface characteristics of an aggregate expressed as a percent of kerosine (C.K.E.) or percent of oil (O.E.) retained in the fine and coarse aggregates, respectively.

cedure (*24*) is used to estimate the preliminary emulsion content (Appendix E). Specimens are prepared at emulsion contents 1.1, 1.3, and 1.5 times the value determined by the C.K.E. procedure. Coating tests are then made to determine the type of asphalt emulsion and amount of mixing water required. Test specimens are prepared at the determined asphalt emulsion and water contents and compacted by means of the California kneading compactor; specimens are cured in a mold for three days at room temperature to simulate actual field curing conditions. To simulate the potential stripping and swelling effect of water in the base on stability, the specimens are vacuum soaked. The California stabilometer and cohesiometer (*64*) are used to determine a resistance value, termed the R_t-value, and computed from

$$R_t = R + 0.05\,C \qquad (9)$$

in which R is the stabilometer R-value and C is the cohesiometer value.

Suitability of the emulsified-asphalt mix is based on (1) ease of mixing and rapidity of curing (from observation during the coating test), and (2) mix stability and cohesion as measured by the R_t-value, which includes the influence of moisture pick-up in the cured mix. A suggested criterion is: resistance value, R_t, after vacuum soak = 78 min.

Chevron Procedure (*66*).—The Chevron procedure is very similar to the Asphalt Institute method previously described. Specimens are prepared at emulsion contents 1.1, 1.4, and 1.7 times that determined by the C.K.E. corrected surface area procedure. In addition to observing coatability, the stabilometer and cohesiometer tests are performed on specimens that have been cured in the compacted condition at room temperature for three days and then subjected to the vacuum saturation test (*64*). A satisfactory mix by this procedure is one that meets the following criteria:

1. Mixes easily. A mix that becomes stiff or tends to ball up on mixing is considered unsatisfactory; the emulsion should be well dispersed and the coated area should exceed that which is uncoated.
2. Meets minimum strength requirements. $R_t \geqq 78$.
3. Must be resistant to moisture pickup.
4. Have a minimum emulsion content of 4.5 percent by weight of dry aggregate.

In addition to selecting the asphalt content as described, the diametral modulus test is performed simultaneously on specimens containing an emulsion content of 1.4 times that estimated by the C.K.E. procedure to estimate the mix stiffness, M_R, for use in the structural design procedure described earlier. The initial M_R-value is measured after one-day air cure at room temperature (approximately 70 F; 21 C). Final stiffnesses are measured at both 73 F and 100 F (23 C and 38 C) after three days air cure and four days of vacuum desiccation.

California Procedure (*67*).—In the California procedure, developed to upgrade aggregates that are considered unsuitable in the untreated state, a series of specimens is prepared over a range in emulsion contents from 3 percent to 13 percent in 2-percent increments. As with the other methods, the proper mixing water content must be selected to ensure reasonable coating. Static compaction is used to prepare each specimen for test. Following compaction the specimen is subjected to a cure period consisting of 24 hr at 140 F (60 C) and 24 hr at room temperature (approximately 78 F; 26 C). Water pickup after five days soaking is determined by means of a capillary absorption test and the California cohesiometer test is then performed.

From the specimens tested, a mix is considered suitable if the moisture uptake is less than 5 percent and the cohesion value, C, exceeds 100. However, this has not been verified in the field and the 5 percent and 100 are somewhat arbitrary values.

Procedure Using Marshall Test Equipment.—Some agencies, such as Armak (*68*), have modified the Marshall procedure (ASTM D 1559) to design emulsion-treated mixes for use as base courses. In the modified procedure, mixing and compaction are conducted at room temperature. Curing is accomplished at room temperatures for varying periods ranging from 24 to 72 hr. The Marshall stability and flow values are determined at 100 F (38 C) on specimens that have been air cured and those air cured after water immersion, from which a wet/dry strength ratio can be determined. No specific criteria, such as those suggested in the other methods, are available as yet for this procedure.

Open-Graded Aggregate Mixes

Open-graded mixes with asphalt emulsions can be used for base and surface courses, special drainage layers, and porous friction courses. Recently, mixes of this type have also been used for full-depth structural sections for low-volume roads in the northwestern states (*30*). In the Forest Service modification of the AASHTO Interim Guide, layer equivalencies for this type of material have been suggested (Table 13).

Aggregate

An open-graded aggregate contains little or no fine aggregate or material passing the No. 200 (75 μm) sieve. Typical gradations are given in Table 18.* Coarse aggregate should be free of dust. The material should be rough textured to insure adequate stability and be resistant to degradation, usually expressed in terms of a maximum loss in the Los Angeles abrasion test on the order of 35 to 40 percent maximum. (For additional information on aggregates, see Chapter Four.)

Emulsion

Generally the MS-2, MS-2h, CMS-2, and CMS-2h emulsions are used for open-graded mixes.

Mix Design

As with dense-graded mixes, in the mix design process it is necessary to perform a coating test to estimate the quantity of water that should be used in the mixing process. Be-

* FHWA Implementation Package 74-3 (*30*) contains grading specifications for open-graded aggregates that have been used successfully in the Northwest and that tend to have fewer fines than those given in Table 18.

TABLE 18

AGGREGATE GRADATIONS, OPEN-GRADED MIXES

Sieve Size	Percent Passing			
1-1/2 in.	100			
1	95-100	100		
3/4	-	90-100		
1/2	25-60	-	100	
3/8	-	20-55	85-100	100
No. 4	0-10	0-10	10-30	85-100
No. 8	0-5	0-5	0-10	10-40
No. 16	-	-	0-5	0-10
No. 50	-	-	-	0-5
Asphalt emulsion content-percent, under normal conditions	4.8-6.4	5.2-7.2	6.0-8.0	6.0-8.0

yond this, little testing of a mix of this type is usually performed. Table 18 provides a guide to the approximate amount of emulsion required for each of the gradations. Chevron has proposed a runoff test in which the asphalt-coated aggregate is allowed to drain (*66*). The design asphalt content is that at which the asphalt runoff in the special test is not more than ½ percent (e.g., from 6.0% to 5.5% asphalt content).

Cement-Modified Asphalt Emulsion Mixes

The addition of small amounts of cement (approximately 1.5 percent by weight of aggregate) to emulsion-treated mixes assists in the development of early stiffness as compared to the same mix without cement. Data presented by Schmidt et al. (*69*) also indicate improvement in the resistance of some aggregate-emulsion mixtures to the action of water.

Care must be taken not to incorporate too much cement, otherwise brittle mixes may result. A ratio of cement content to emulsion content of the order of 1 to 5 appears appropriate to ensure adequate early stiffness without excessive embrittlement.

CHAPTER FOUR

AGGREGATES

In pavement construction with stabilized soils, bituminous-treated subbase material, asphalt base, binder and surface courses, and maintenance operations of surface treatments, seal coats, and patching, the aggregate represents from 90 to 97 percent by weight of the total paving material. For economy in such construction, there should be, and generally is, primary use of locally available construction aggregates rather than importing aggregates from long distances.

Aggregate materials are produced from rock quarries as manufactured stone or obtained from natural gravel or soil deposits. Metal ore refining and energy producing processes produce artificial aggregates as a by-product. Representative of these are blast-furnace slag, wet-bottom-furnace slag, cinders, and other slags resulting from extraction of metals from their ores. There is also a class of synthetic aggregates produced by calcination and partial fusion of raw soil and rock materials such as clay and shale. In the future it may be prudent both ecologically and economically to use as aggregate reprocessed construction materials reclaimed from building and pavement demolition.

Important properties of aggregate and soil materials from the standpoint of highway pavement construction are as follows (in the order discussed herein):

1. Mineralogical composition.
2. Hardness and abrasion resistance.
3. Density, porosity, and absorption.
4. Durability—freeze-thaw resistance, weathering.
5. Particle shape and surface texture.
6. Deleterious particles.
7. Surface chemistry.
8. Gradation.

MINERALOGICAL COMPOSITION

In asphalt technology, the coating of aggregate surfaces in the presence of water and the displacement (stripping) of such coatings by water are recognized problems related to optimum pavement performance. Generally, most inorganic minerals prefer wetting by water rather than by organic substances and are known as hydrophilic materials. Organic substances, such as asphalt, waxes, etc., are not readily wetted by water and so are known as hydrophobic materials. It was recognized early that the degree of wettability varied among materials, and attempts to express these differences by measuring the contact angle of a drop of liquid on the mineral surface were the subject of research studies in surface physical chemistry.

Coincident with such basic studies were similar studies in the coating and stripping of aggregates with asphalts by a number of investigators. These studies showed different surface energy levels with different materials. One theory postulated that these energy levels could be characterized by electropositive or electronegative surface charges capable of attracting cations or anions to promote coating. Other research utilized differences in the electrokinetic potential of different types of aggregates in predicting the interfacial reactions between the aggregate and asphalt coating.

In individual aggregate particles, the composition of mineral components as shown in Figure 22 qualitatively evaluates the surface chemistry as related to silica (SiO_2) content. Practically, a more complex system exists in aggregate materials used in highway construction. Transport of aggregates by water, ice, and wind, as well as solution and reprecipitation in sedimentary rocks, has resulted in the presence of both acid and basic chemical constituents influencing the surface chemistry of the aggregates. Further, blending of aggregates having different surface chemical properties is often required to meet specification or performance requirements.

There is a rapidly developing technology in the emulsion field that is continuing to improve the performance of emulsions in highway applications. Newly formulated emulsifiers and surfactant stabilizers are being used to promote asphalt coating of aggregates through utilization of surface chemical reactions or forces. Common to all surface coating is the attempt to establish an electrochemical bond or ionic attraction between the aggregate surface and the coating material through the use of principles of surfactant chemistry.

Mineralogical components and structure also are related to other properties of aggregates. Therefore, an understanding and knowledge of the mineral aggregate types available in an area is important in their use for highway construction.

HARDNESS AND ABRASION RESISTANCE

A service requirement of bituminous pavements is that they resist abrasion and degradation under traffic forces and wear from tires. The hardness of the minerals and the cementation strength in case of sedimentary and metamorphic aggregates relate to the toughness and abrasion resistance. Generally, higher degrees of performance related to resistance to traffic abrasion of the surface and internal degradation of the aggregate particles are required of aggregates in surface courses as compared to base and subbase materials. Measurement of these properties now is commonly made by the Los Angeles abrasion test, although early rock technology used the standard Deval abrasion loss and toughness tests.

It is common practice to set the Los Angeles abrasion loss requirement at a value that will provide the most economical use of available aggregates. Generally, a higher abrasion loss can be tolerated in aggregates used in base courses than those for surface courses. An example of this is the AASHTO requirement of 40 percent maximum loss for surface course materials compared to 50 percent maximum loss in base course aggregates. Present knowledge does not indicate that special consideration should be given to abrasion loss requirements for aggregates used with asphalt emulsions compared to use with other asphalt materials.

The Los Angeles abrasion test is not entirely applicable to blast furnace slags; their abrasion resistance and toughness qualities are generally considered satisfactory if the slag aggregate satisfies a minimum density requirement, the value of which is based on performance. This also applies to synthetic aggregates, cinders, and other slag-type aggregates.

DENSITY, POROSITY, AND ABSORPTION

Although density itself is not a criterion for aggregate performance in emulsion mixes, it is related to porosity, which may have considerable influence. Porosity is characterized by macro- to micro-size pores in the aggregate. If the pores are very fine, or of very small diameter, they may be too small for the dispersed asphalt particles of an emulsion to enter. This may result in a filtering action sucking up only the water phase of the emulsion. If the emulsion has inadequate stability, this will tend to cause premature separation and coalesence of the asphalt in the emulsion before complete coating is attained. Formulation changes in the emulsion will correct this condition if it occurs. Porous sandstone and limestone aggregates could be subject to this phenomenon. Also, as in hot mixes, porosity increases the amount of binder required for optimum performance.

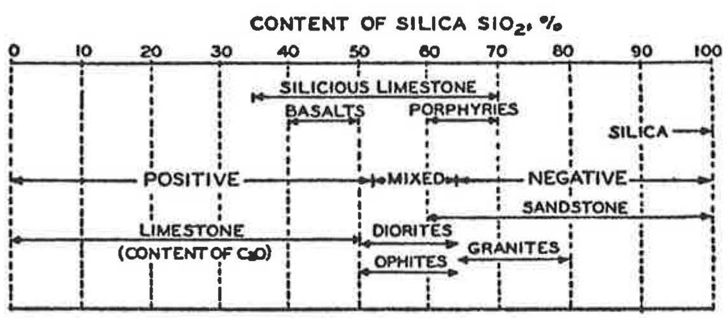


Figure 22. Classification of aggregates. (Adapted from Bellanger and Duriez (70).

Macro-sized pores, such as are found in slags, coarse-grained sandstones, and vuggy limestone formations, result in absorption of the emulsion from the mix; therefore, an increase in the emulsion content of the mix may be required, just as for conventional asphalt mixes. The porosity increases the surface area of the aggregate, which may require adjustment of the emulsifier content or type to satisfy the increased surface area to be coated.

Normally, the aggregate pores are saturated with water that is removed in hot asphalt mixing by drying and heating of the aggregate. In cold emulsion mixes, it is doubtful that this internally absorbed moisture is removed to any great extent. Therefore, the amount of asphalt binder required in cold emulsion mixes may be less than in hot mixes due to reduced absorption of the asphalt by the aggregate.

DURABILITY—FREEZE-THAW RESISTANCE, WEATHERING

The resistance of aggregates to freeze-thaw cycles is important to users where the road structure is subject to freezing conditions. This is usually measured by the sodium sulfate or magnesium sulfate accelerated soundness test or by actual freeze-thaw exposure of laboratory samples. In bituminous-treated aggregates, the freeze-thaw effect may be inhibited to some extent by the impermeability of the bituminous coating to water. However, in surface courses, where traffic abrasion removes the asphalt coating, or in seal coats, where the aggregate is only partially coated or imbedded in the asphalt applied, this factor must be considered to prevent excessive degradation from freezing action.

Certain structurally weak particles in the aggregate are usually easily recognized in petrographic examination. The deleterious effect of such nondurable particles is discussed in a later section. Other aggregates, because of their mineralogical character, will deteriorate or degrade due to repeated wetting and drying action. Certain basalts found in the northwestern United States are typical of such aggregates. Weakly bonded sedimentary limestone or limestone laminated with thin shale layers also may have poor durability. The use of such aggregates should be avoided in surface courses but might be considered in emulsion-treated subbase and base course mixes. Local experience with such materials in hot-mixed asphalt concrete should provide a clue to their behavior in emulsion-treated mixes.

In artificial aggregates, such as slag, certain impurities (such as coal, coke, and iron inclusions) may be detrimental in surfacing mixes. Open-hearth slag may contain aggregate particles of hard-burned calcium oxide and magnesium oxide. In asphalt mixes these slowly hydrate and react with carbon dioxide. The resulting explosive increase in volume causes surface cracking and formation of "bumps" in the surface. This has been noted even in base course asphalt mixes, where the reactive limes or magnesia were present as impurities in the open-hearth slag.

PARTICLE SHAPE AND SURFACE TEXTURE

In emulsion mixes, the same principles apply as in other asphalt mixes relative to particle shape. Higher stabilities or pavement strengths result from use of crushed or partially crushed aggregate particles. In seal coats, also, better aggregate retention is obtained with fractured particles. The presence of fractured faces on the aggregate particles increases the contact between such particles and promotes additional adhesion and cohesion. However, the rough texture of fractured surfaces also increases the surface area of the aggregate and requires an increase in the asphalt or emulsion content to optimize performance. The increased surface area (particularly with crushed sand or rock screenings) may also require adjustment of the emulsifier to obtain complete coating and workability.

Use of rounded or smooth-surfaced aggregates from locally available sources, however, may be more economically feasible, especially on local streets or low-traffic rural highways. This should be considered in single surface treatments or in asphalt base course mixes. Use of emulsions in which the asphalt is modified to produce non-Newtonian characteristics has been noted to improve the performance of such marginal aggregates in both surface treatments and base course mixtures.

Bank-run sands, poorly graded bank-run gravels, and dune sands treated with asphalt have shown good performance as subbase and base course layers where adequately confined by strong binder and surface course layers. The use of marginal materials provides an opportunity for the engineer and emulsion manufacturer to combine their knowledge to provide optimum performance from such materials. Mixing-grade emulsions of either cationic or anionic types have been specially formulated for such uses. Kansas and Indiana have made considerable application of such base stabilization construction.

DELETERIOUS MATERIALS

Deleterious particles in aggregates are those particles that may be structurally weak due to their mineral formation, subject to degradation by wetting-drying or freezing-thawing, subject to solution by water action, or subject to other breakdown in service.

Structurally weak particles are generally identified by softness and tendency to degrade purely by mechanical action during processing, or during construction, or under traffic. Soft sandstones, ochres, silt stones, coal, coke, weakly cemented particles, and shale are typical of this type of deleterious material. By their degradation, additional fines are formed in the aggregates. Such fines increase the surface area to be coated, requiring additional bitumen. In degrading in the road surface they cause pitting and raveling.

Shale, silt stones, and clay balls in the aggregate also are subject to degradation by alternate wetting and drying action. Reactive aggregate particles in slags (iron, hard-burned lime, magnesia) increase in volume due to slow hydration, oxidation, or formation of carbonate minerals.

The limit of deleterious particles has to be established on the basis of local experience as to what types are present in local aggregates, their effect on performance, and the economics of importing deleterious-free aggregate as replacement. Generally, higher amounts of deleterious particles can be tolerated in subbase and base course aggregates than in surface course layers. Maximum amounts of deleterious materials permitted in surface mix aggregates or seal coat aggregates range from 2 to 5 percent but may go as high as 10 percent for base course aggregates in areas where it is uneconomical to import higher-quality aggregates.

CONTAMINANTS

The use of dusty or dirty aggregates in seal coat construction with emulsions may be more critical than with cutbacks. The presence of dusty or dirty coating on the coarse aggregate prevents wetting of the stone surface by the rapid-setting emulsions and, actually, because of the high surface area of the dust, may cause premature separation of asphalt from the emulsion. If methods are not available for washing the aggregate, consideration might be given to precoating the aggregate with 0.5 to 1.0 percent of the mixing-grade emulsion prior to stockpiling for construction use. Precoating also has the advantage of eliminating subsequent dusting under traffic and there will be less loss of stone by traffic throw-off. Precoated aggregate is also found to have similar advantages when used in skin-patching maintenance operations.

In the use of in-place materials for road or travel mix, caution should be exercised if the in-place aggregate has received chemical dust-laying treatments or chemical salts as stabilizers. Typical of these are sodium chloride (salt), calcium chloride, chloride brines, and waste sulfite liquor. Such chemical treatments may react with the emulsifiers and cause premature separation of the asphalt prior to obtaining complete coating of the aggregate. Such treated aggregate material may require dilution with untreated aggregate, as well as special emulsifier formulation to correct for the presence of chemical salts in the aggregate.

SURFACE CHEMISTRY

The silica content of an aggregate determines whether its surface chemistry is acidic or basic. Silica mineral hydrates on its surface in the presence of moisture to form silicic acid, which is ionized in accordance with the following equation:

$$SiO_2 + H_2O \rightarrow H^+ + HSiO_3^-$$

Basic aggregates, such as limestone ($CaCO_3$), similarly hydrate but form basic ionic charges as follows:

$$CaCO_3 + H_2O \rightarrow Ca^{++} + HCO_3^-$$

Pure silica aggregates, such as quartzite, are difficult to coat with untreated asphalt films. However, when a coating aid, such as that in cationic emulsions, is used, the asphalt particles have a positive charge and are chemically attracted to the negatively charged silica surface. Similarly, negatively charged asphalt particles in anionic emulsions are attracted to positively charged aggregate surfaces, such as limestone.

Use of the principles of surface chemistry in promoting coating by cutbacks and asphalt cements is easily related to the emulsion chemistry and has resulted in building into both anionic and cationic emulsifiers active positive and negatively charged ions to promote electrochemical attraction of the asphalt to the mineral surface.

One approach to such formulation has led to use of the zeta potential theory for classification of cationic emulsifier (*71*). The zeta potential is related to colloidal chemistry and is the net electrical potential difference between the surface of the dispersed colloidal asphalt particle and the surrounding bulk aqueous solution. The zeta potential varies with the type and concentration of emulsifier and the pH of the solution. It controls the rate of break or plating out of the asphalt on the aggregate particles.

However, the mechanism of this deposition or plating out of the asphalt from either anionic or cationic emulsions on the aggregate particle surface is still in the development stage. For a clean pure-silica particle, the concept of attraction of the positively charged asphalt particles to the negatively charged surface appears correct. However, some basic or intermediate types of aggregate show similar attraction of the positively charged asphalt particles.

Surface chemistry is a complex subject in minerals and research has shown that different charges exist on the surface of aggregates. It has been shown that calcareous materials also have electronegative surface charges, which accounts for the fact that plating out or coating of limestone particles can be obtained with both anionic and cationic emulsions.

In hot mixes, workability and mixing require heat to fluidize the asphalt and permit coating of each individual particle. In emulsion cold mixes, the emulsion must be formulated to accomplish the same result. Because the surface chemistry of aggregates varies both locally and geographically, the emulsion manufacturer has to vary his components to be compatible with both the surface chemistry of the aggregates to be used and the particular construction procedure. Emulsions are generally manufactured in relatively small batches rather than in continuous processing, as is characteristic of asphalt refining, and variation in the formulation of the emulsion is feasible. Lending also to this feasibility is the wide distribution of emulsion plants, even to the extent of using portable emulsifying equipment at the construction site. Further, job changes in aggregate have been adjusted for by adding additional emulsifier or stabilizer to an emulsion at the construction site to correct setting and mixing properties.

To the surface chemistry concept, as influenced by mineral composition, must be added the effects of dust coatings, surface changes due to weathering, and possibly absorbed gaseous films. The net effect of this is that the electropositive-electronegative cation-anion theoretical relationships are frequently relegated to a nondeterminate position, solvable only by practical trial testing. Therefore, lines of communication between the user and the technical personnel of the emulsion producer should be utilized to the fullest extent.

GRADATION

The aggregate gradation is as important in all types of emulsion pavement construction as it is in construction using liquid asphalt and asphalt cements. In seal coat construction, control of the gradation to provide closely sized coarse aggregate is based on Hanson's basic seal coat theory (*72*) expanded by many agencies in developing the gradation requirement for the cover stone for such construction. A thorough discussion of these principles is found in McLeod's papers (*57, 73*) and in *HRB Special Report 96* (*74*). (See also Chapter Three.)

The use of emulsions in soil stabilization is restricted to fine granular soils, sands, and silty sands low in clay content. One-sized sands, such as dune sand or blow sands, perform better if mechanically stabilized with silt-sized fines before emulsion stabilization. The literature suggests that, where active clays are present, lime treatment prior to emulsion stabilization may be advantageous.

Emulsion treatment of in-place dry or water-bound macadam construction has been used for many years. Low-viscosity rapid-setting emulsions penetrate into the voids in the compacted stone layer providing cohesion between the crushed-stone particles. High-float emulsions leave a stiffer, nonNewtonian-type asphalt film between the stone particles. The aggregate gradation required is similar to that for conventional penetration macadam construction and gives an open-textured surface after compaction to permit thorough penetration of the emulsion into the interior voids of the compacted layer.

Emulsions can also be mixed cold with open-graded, intermediate-graded, and dense-graded aggregates. Both in-place and plant-mixed procedures may be used, but the emulsion should be formulated for construction use as well as aggregate surface chemistry and gradation.

Open-graded emulsion plant-mix construction has been reported by the Federal Highway Administration (*30*). Aggregates for these mixes contain less than 10 percent passing the No. 10 (2.00 mm) sieve and less than 2 percent passing the No. 200 (75 μm) sieve. They are composed of clean crushed-stone coarse aggregate and may contain up to 2½-in. (65 mm) maximum-sized particles but be well graded between the maximum size and No. 10 sieve. Such mixes, after curing and compaction, have a large volume of permeable voids and are considered to be free draining.

Intermediate-graded mixes contain a larger sand fraction, usually ranging from 10 to 20 percent passing the No. 8 (2.36 mm) or No. 10 (2.00 mm) sieve. They also must be well graded from coarse to fine and, although crushed-stone aggregate is preferred for maximum strength, partially crushed clean gravel may be used in low-cost base course construction. These gradations are sometimes known as open-graded binder gradation. A typical gradation is given in Table 19.

Dense-graded base, binder, and surface emulsion mixes may be composed of crushed stone, slag, crushed gravel, bank-run gravel, or mixtures thereof. They are well graded from coarse to fine, but should not contain more than 8 percent passing the No. 200 (75 μm) sieve. This fraction also should not contain clay fines. A typical gradation for a surface course mix is given in Table 20. Such mixes, after curing and compaction, *when properly formulated*, are relatively impermeable to water and usually will not require a surface treatment or seal coat, although sometimes a fog seal treatment may be specified. The open-graded and intermediate-graded base or binder mixes generally should receive a surface course, or at least a seal coat, to seal the surface to moisture and prevent raveling of the aggregate particles under traffic.

Open-graded, intermediate-graded, and dense-graded mixes may be either mixed in place (road mix) or plant mixed. The type of emulsion selected will vary with aggregate type, gradation, and mixing method. In the road-mix method some emulsions contain petroleum distillates to maintain workability during the mixing and laying process. However, some emulsifiers delay complete breaking of the emulsion during mixing without addition of petroleum distillates.

In some areas, dense-graded aggregate bases with as high as 25 percent passing the No. 200 (75 μm) sieve have been successfully mixed with asphalt emulsions, provided fines do not contain clay fractions in amounts that will affect performance. Aggregates with such a high fines content can be used, but their use should be weighed against their slower curing rate and reduced over-all structural capacity. In addition, they will require a higher asphalt content than dense-graded aggregates with lower amounts passing the No. 200 sieve. Further research should include the effect of the amount passing the No. 200 sieve, the clay content, and the formulation of emulsions to optimize performance.

Slurry seals represent a newer type of construction in which anionic emulsions were originally used. Recent developments in emulsion technology have produced cationic emulsions stated as having some advantages, particularly with highly siliceous-type sands (*71*). Presently, properly

TABLE 19

GRADATION FOR INTERMEDIATE-GRADED AGGREGATE

Sieve Size		% Passing
1"	(25.0mm)	100
3/4"	(19.0mm)	70-100
1/2"	(12.5mm)	30-70
No. 4	(4.75mm)	12-26
No. 8	(2.36mm)	8-18
No. 16	(1.18mm)	6-16
No. 50	(300μm)	0-8
No. 100	(150μm)	0-2

TABLE 20

GRADATION FOR DENSE-GRADED SURFACE COURSE

Sieve Size		% Passing
3/4"	(19.0mm)	100
1/2"	(12.5mm)	80-95
No. 4	(4.75mm)	50-65
No. 8	(2.36mm)	40-60
No. 50	(300μm)	10-25
No. 200	(75μm)	0-5

formulated emulsions, either anionic or cationic, will perform satisfactorily in slurry seals with the deposition or "plating out" of the asphalt on the fine-aggregate particles as curing occurs.

Aggregates for slurry seal treatments are well-graded fine aggregates containing an appreciable amount of material passing the No. 200 (75 μm) sieve. The aggregates may be crushed slag, crushed-stone screenings, or natural sands, or blends thereof. Typical gradations recommended by the International Slurry Seal Association are given in Appendix D.

Polished or smooth-surfaced sands from water-transported material tend to give unstable slurry seals; generally, the blended aggregate should not contain more than 50 percent of such material. Sands from crushing limestone rock may polish and develop low-friction surfaces under moderate to heavy traffic, but may be entirely satisfactory for parking lots, etc. Such limestone sands should not be used if local experience shows they are susceptible to polishing action. Also, aggregates containing excessive clay fines should not be used because of the detrimental properties of clay materials in asphalt mixtures. The sand equivalent test is suggested as a measure of the clay content; the recommended limit is a minimum value of 45.

In order to obtain stable slurry seals it is usually necessary to have at least 50 percent crushed particles content, generally provided by blending crusher screenings. The parent rock from which such screenings are produced should have low Los Angeles abrasion loss (under 35 percent) and less than 15 percent accelerated soundness test loss in order to provide durable aggregate characteristics.

To obtain the optimum amount passing the No. 200 (75 μm) sieve and to provide a workable slurry mix may require addition of fines or mineral filler. Natural fillers (such as loess, silt) and manufactured fillers (such as limestone or rock dust, fly-ash, portland cement) are used for this purpose. In some cases, portland cement may also be used to accelerate curing of the slurry seal.

Recent developments in improving the skid number or coefficient of friction of pavements have led to use of thin overlays of fine-aggregate mixes. The use of warm-mixed emulsion-treated sand mixes can be considered as a replacement for the hot-mixed sand-asphalt mixes for these friction courses. The aggregate for these mixes should be a high-silica-type coarse sand containing little or no material passing the No. 200 (75 μm) sieve. A typical grading of such a sand is given in Table 21.

The sand aggregate should be characterized as "sharp" with a fairly high percentage of rough-textured or crushed particles, although high mix stability is not required for the thin layers generally placed with this type of mix.

TABLE 21

GRADATION FOR SAND MIX

Sieve Size		%Passing
No. 4	(4.75mm)	100
No. 8	(2.36mm)	90-100
No. 16	(1.18mm)	60-80
No. 30	(600μm)	30-60
No. 50	(300μm)	5-15
No. 100	(150μm)	0-10
No. 200	(75μm)	0-5

Another recent development in providing open-textured nonskid surfaces is construction of open-graded, crushed-aggregate friction courses known sometimes as plant-mixed seals. The aggregates for such mixes are closely graded crushed stone with 90 to 100 percent passing the ⅜-in. (9.5 mm) sieve and 10 percent passing the No. 8 (2.36 mm) sieve. Properly designed, they provide, in addition to a high-friction surface, a porous open texture permeable to water. They are stated to reduce danger of "hydroplaning" through their surface-draining properties. Although asphalt cement has been used as binder in such mixes, they could readily be adapted to cold emulsion mix construction with the emulsions formulated for open-graded mixes. The use of open-graded surface construction in regions having considerable ice and snow cover has not been completely investigated for efficacy and durability under such environmental conditions.

DISCUSSION

In this chapter a review of aggregate properties and types for emulsion construction emphasizes the wide variations in properties of these materials. This points again to the necessity of giving basic engineering consideration to these properties as they relate to the emulsion they are to be mixed with in order to optimize the performance of the application. The fact that emulsion technology is developed to the extent that it is possible to evaluate the performance of the aggregate-emulsion system and modify either aggregate or emulsion, or both, makes it obligatory that the user work closely with the emulsion technologists in developing emulsion formulations, specifications, and construction methods to fully utilize this developing technology.

CHAPTER FIVE

CONSTRUCTION

Use of emulsified asphalt in pavement construction requires substantially different procedures from those used for cutback asphalts and asphalt cements. Selection of an emulsified asphalt for a specific type of construction depends on the emulsion-aggregate compatability, the type of application or mixing to be used, and the environment, including weather conditions and traffic. Because of these factors many emulsion suppliers maintain a technical representative who is capable in selecting the proper emulsion. In some instances this service leads to changes in the emulsion formulation to provide a material that will perform properly during construction. In addition, the contractor, the project engineer, and the technicians must be familiar with the behavior of the emulsion during handling, storage, and use in construction.

Quality construction and pavement performance depend on proper controls and good workmanship. In general, only those construction practices that are unique to the use of emulsions are given in this chapter. Insofar as possible, problems and their solutions are presented. Some "DO'S and "DON'TS" that pertain to construction with emulsified asphalts are included at the end of this chapter.

EMULSION STORAGE AND PUMPING SYSTEMS

Because emulsions differ in their storage stability and pumpability, project engineers and contractors should follow the advice of the emulsion producer or supplier on these matters.

Storage Systems

Different classes or types of emulsified asphalts should never be mixed in storage tanks. For example, if a cationic and an anionic emulsion were placed in the same tank the emulsions would immediately break. The tank would then contain a layer of water and a layer of asphalt. Preferably, the same type and grade of emulsion from different sources of supply should not be mixed.

Long-term storage of emulsified asphalts differs from that of other asphalt materials. Temperature should be kept between 50 F and 170 F (10 C and 76 C). Temperatures below 40 F (4 C) will cause separation of the water from the emulsion, leaving base asphalt. In general, it is considered prudent to provide adequately insulated storage facilities to prevent the temperature of the emulsion from dropping below 40 F.

Emulsions have a tendency to undergo some separation while in storage. There is little likelihood of causing stored emulsions to break if the material is circulated as needed by means of an in-tank propellor.

The surface of emulsions can skin over from exposure to air. However, the exposed surface area of stored emulsions can be minimized by use of vertical tanks instead of horizontal ones.

When emulsions containing rubber latex or other liquid additives are specified, the materials should be blended into the emulsion by the supplier. Recirculating storage arrangements become increasingly necessary when latex has been added to the emulsified asphalt.

Pumping Systems

Pumping systems should be specifically designed for use of emulsified asphalts. Because emulsions are sensitive to sliding friction, they can be broken when forced through close clearances. Most emulsion vane pumps have a slightly greater clearance for the pump vanes to prevent high pressures. Some form of mild heat, such as heating cable, is recommended for heating pumps and valves.

Metering pumps need a head to provide a uniform flow to the mixer and therefore should be located below the level of emulsion in the storage tank. A supply pump between the tank and the metering pump will provide a uniform pressure head to the metering device. A successful practice has been to set the supply pump at a pressure greater than required by the metering pump and to provide a bypass to return the excess to the storage tank. This arrangement has the side benefit of providing some circulation of the stored emulsions and serves as added insurance against separation of the emulsion components. A pressure head arrangement should not be set up without a bypass return to the tank because of the potential for pressure breaking of the emulsions and plugging of the supply lines.

AGGREGATE STOCKPILE MANAGEMENT

Handling of aggregate is as critical for emulsion mixes as for other asphalt mixes. Proper procedures in the construction of a stockpile are necessary to prevent segregation and the resultant need to adjust requirements for emulsion quantity. Some general information on handling aggregates can be found in *NCHRP Report 46* (*75*).

The materials should be incorporated into and removed from the stockpiles using methods that maintain gradations. Stockpiles with different gradations should be located a distance apart or separated by bulkheads. Loader operators should be aware of differing stockpiles and should avoid picking up contaminants from the bottom of the stockpile.

A stockpile located adjacent to an unsurfaced road can collect additional fines. The gradation of such a stockpile should be verified before it is used. The surface characteristics of weathered aggregates may differ from those freshly prepared and compatibility with the emulsion should be rechecked. (See Chapter Four for additional information.)

A long stockpile can accumulate water exceeding that specified in the design mix. This will result in an extended curing time with cold emulsion mixes or an increased consumption of fuel for drying and heating when used in a warm or hot mix. Under freezing conditions ice lenses can form, causing a nonuniformity of moisture content. Use of a relatively small stockpile will limit moisture uptake. Because open-graded aggregates are less susceptible to moisture retention, these might be selected for use in wetter areas.

PREPARATION OF EXISTING SURFACES

Prime Coats

Prime coats with low-viscosity cutbacks have been used to treat existing aggregate-surfaced roadways prior to overlay. Emulsions can be used as primes on permeable surfaces. There is a trend to omit the prime if the pavement to be placed exceeds 4 in. (100 mm) (*8*). Unprimed surfaces are normally watered ahead of the laydown operation to dampen the surface of the aggregate.

When emulsion primes are used, they are usually diluted between 1 and 3 parts water to 1 part emulsion. Emulsion types that are normally used are SS and CSS, but MS and CMS types that can be diluted with water can be used. The emulsion may be applied through a waterwagon equipped with a simple spray-bar or by a pressure distributor.

Application rates vary with the road surface condition. An open-graded surface will need and accept more material than will a dense, tight surface. Rates vary from 0.10 to 0.60 gal per sq yd (0.45 to 2.7 liter/m^2) of diluted emulsion applied.

Blade-and-Shape Treatments

Blade-and-shape treatments sometimes are used in lieu of prime coats. Diluted emulsion is introduced into the blading and shaping of the aggregate surface, resulting in a stabilized depth of material instead of an asphaltic "skin." The process developed from the recognition that water (fluid) was necessary in the blading, shaping, and compaction of the aggregate surface, and that the blade-and-shape operation and the prime operation could be combined. The blade-and-shape process provides a measure of increased strength and less chance of pickup from the surface.

Preparation of Bases and Pavements

The preparation of bases and pavements prior to receiving emulsion-aggregate overlay is essentially the same as for conventional hot-mix overlay.

Soil-cement and other stabilized-soil bases should be treated with a prime coat or tack coat prior to overlay.

Cement- and lime-treated aggregate bases usually will have a curing seal (see Chapter Three) applied as soon as they are constructed. No additional treatment is required prior to overlay.

Bituminous and PCC surfaces should be cleaned by power brooming and should receive a tack coat (see Chapter Three) prior to placing an overlay.

CENTRAL PLANT OPERATIONS

A central processing plant is generally preferred for mixing emulsion and aggregates.

Central plants available fall into two basic classifications: pugmill mixers (see Fig. 23) and drum mixers (see Fig. 24).

Mix control can be simple or increasingly complex for central plant operations. The degree of complexity is tied directly to the treatment of the aggregates. Some operations are conducted with single-gradation feed directly from the stockpile, whereas others separate materials according to screen size and blend them into the mixer to obtain improved uniformity.

The fewer number of components required to make emulsion mixes in a central plant could be an economic advantage to highway agencies and contractors. This is based on less control of aggregate proportioning and less heating and drying of aggregates compared to hot-mix plants.

On roads with little traffic, highly portable central mixing plants can provide quality mixes at costs comparable to or lower than blade mixing or travel plants.

Work Area Requirements

The requirements for a work area vary widely according to the mixer type and aggregate feed and storage requirements. Certain areas are common to any central plant operation with emulsions. These typically are:

- Mixer
- Feed bin(s)
- Aggregate stockpile(s)
- Emulsion storage
- Mix discharge (surge hopper or silo)
- Conveyors

Projects where water is added at the mixer also require either water storage capacity or a pipeline source. In addition, sufficient space is required for a truck turn-around area, scales, and service area for fueling and power plant.

For open-graded mixes only a single stockpile normally is required. For dense-graded mixes two or three stockpiles are frequently specified. With some processes the emulsion mix is stockpiled for a minimum of two weeks prior to placement. Projects of this type require sufficient area for storage and reloading.

Work area requirements for drum mixer plants are greater than for simple pugmill arrangements and less than for conventional hot plants. In general, the central plant work area requirements are less for emulsion mix operations than for conventional hot-mix operations.

Pugmill Mixing

In its simplest form, a continuous-mix pugmill is attached to a self-erecting conveyor system (Fig. 25a). Larger units are mounted on their own frames and require a separate conveyor unit to feed the aggregates (Fig. 25b). Conventional batch-mix plants also have been modified to produce cold emulsion mixes.

The pugmill consists of either a lined or unlined chamber in which the pugmill shafts rotate. The unlined chamber depends on the mix to form its own liner by the action of the pugmill. The shafts have paddles spaced along their length that are capable of being angled to advance or retard the movement of the mix through the mixing chamber.

Figure 23. Central plant, pugmill mixer.

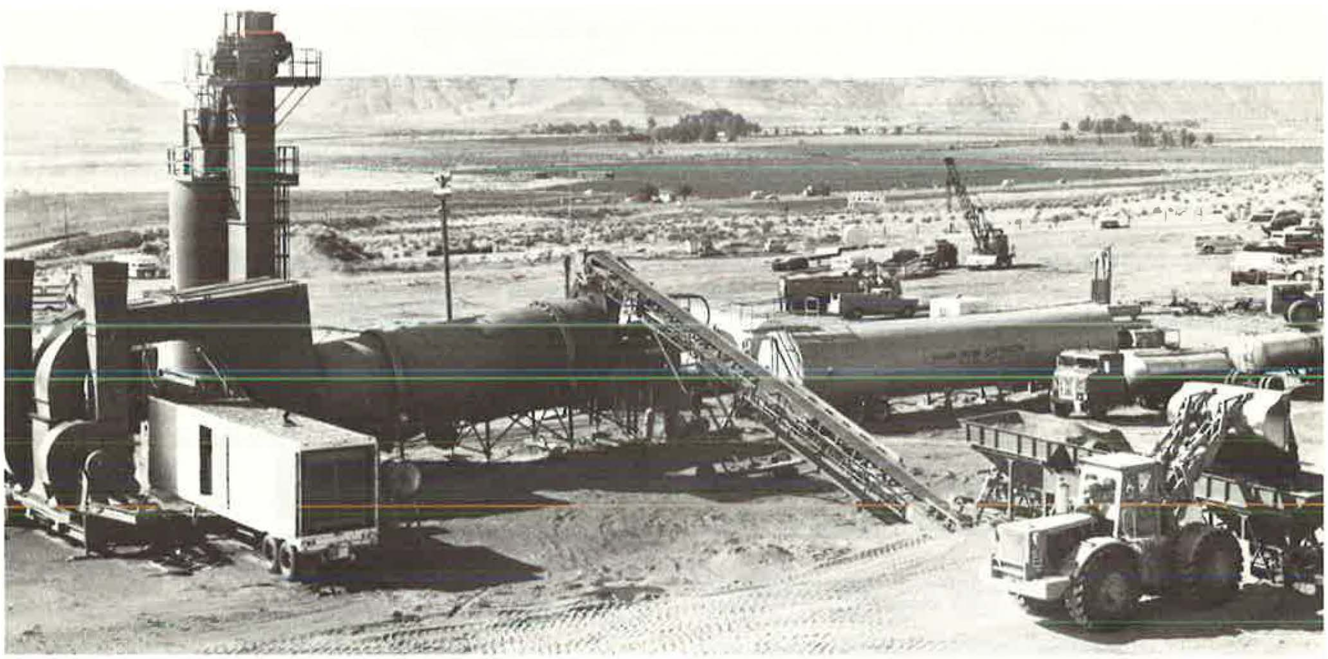


Figure 24. Central plant, drum mixer.

Some machines also incorporate an end dam that can be raised or lowered to alter the mixing time. Twin-shaft pugmills appear to provide a better mixing action than single-shaft units. A mixing chamber providing for flexibility in mixing times and the positioning of the spraybar units in the chamber is preferred.

Spraybars normally are mounted in the mixing chamber at the aggregate feed end, with the spraybar for water first if water is to be added. The emulsified-asphalt spraybar is mounted next to the water bar. A common practice is to angle the water spraybar toward the feed end of the pugmill, whereas the emulsion spraybar is set to spray slightly toward the discharge end. This allows a length in the mixing chamber to disperse the water prior to introduction of the emulsion.

A surge hopper at the discharge end allows a more con-

Figure 25. Pugmill mixers.

tinuous operation of the pugmill and thereby provides a better mix uniformity by decreasing the number of start-and-stop operations. The size of the surge hopper should be adequate to take the production of the pugmill between trucks.

Drum Mixing

Use of the drum mixer to mix emulsion-aggregate mixes has proved very efficient and versatile. The first drum mixers were modifications of the standard dryer unit, but they are now produced as standard construction equipment. Drum mixers come in all sizes and are advertised with capacities ranging from 50 to 700 tons per hour (45×10^3 to 635×10^3 kg). The cascading action within the drum is used to intermix the various components. Figure 24 shows one example of the drum mixer.

The drum mixer allows the preparation of cold (ambient, min. 50 F; 10 C), warm (140 F to 160 F; 60 C to 71 C), and hot (220 F to 260 F; 104 C to 127 C) mixes with emulsified asphalts. It is common practice to mix emulsions with moist or wet aggregate; however, for some aggregates and some moisture conditions, better mixes can be obtained with surface-dried aggregate mixed at warm or hot temperatures.

The emulsion is introduced in the drum mixer by spraybar. If heated emulsion mixes are produced in a drum mixer, the spraybar is positioned outside of the open flame cone to prevent flash hardening and modification of the asphalts. The need for dust collectors is dependent on the volume of air being forced through the mixer and the amount of fines in the aggregate, and may not be necessary with cold or wet mixes. The machines generally will need a dust collection system to meet air pollution emission standards.

Use of Additives

When hydrated lime or portland cement is specified in the mix the plant setup must incorporate the necessary storage bins and equipment for introducing the proper proportions. The bins for storage of these materials should be capable of air fluffing or other agitation to prevent variable delivery densities and the bridging of materials within the storage unit. The use of vibrators on the storage bin may be beneficial in providing a uniform delivery condition.

A screw, a rotating-vane meter, or an air delivery method may be selected. The screw or the rotating-vane meter is normally set to deliver the material onto the aggregate conveyor stream. An air system may need a discharge device to keep the material on the conveyor belt or may be discharged into the mixing chamber prior to the water spraybar.

Calibration of the Central Plant

The central plant is normally calibrated to the design mix by volumetric or by continuous belt weighing coupled with volumetric methods.

Volumetric calibration is accomplished by setting the aggregate feed device to a uniform feed volume. A simple gate device or reciprocating plate feeder can provide acceptable control. The aggregates are frequently fed dry through the mixer into a tared truck to determine the weight/time relationship. The correct amount of emulsion is computed and the meters set and interlocked with the aggregate feed. Another run is made and the amount of emulsion added is checked against the metered amount by the relationship of the initial weight run to the run with emulsion added. The same procedure is followed for the water if the addition of water is needed.

The calibration process is repeated until the proper settings of the aggregate feed, emulsion, and water are obtained. The plant controls are then interlocked to assure uniform introduction of all components at all times.

Control of Mixing Times

When the calibration process is completed the discharged mix is checked to determine the adequacy of the coating. It should be noted that open-graded cold emulsion mixes tend to have more greybacks (incomplete coating appearance) on the coarse aggregate than most dense emulsion or asphalt concrete mixes.

There is a greater tendency for emulsion mixes to be overmixed rather than undermixed. All that is required is for the aggregate-emulsion mixture to be mixed enough for the emulsion to be uniformly distributed through the aggregate mass.

Excess or insufficient mixing causes different problems. Excess mixing time may strip the asphalt from the aggregates or may cause stiffness in the mix due to premature breaking of the emulsion and cause laydown problems. Insufficient mixing will generally result in inadequate coating of the aggregates.

In general, the paddles in a pugmill are inclined toward the discharge end of the machine. Should increased mixing be required the terminal paddles can be reversed or the end dam can be raised to retard the flow-through of the mix.

Drum mixing is controlled by the slope of the mixing drum, the position of the spraybar, and the rotational speed of the drum.

LAYDOWN OF CENTRAL PLANT MIXES

Laydown of central plant emulsion mixes may be accomplished with any of several methods ranging from motor grader to electronically controlled paving machine. The riding quality of the emulsion surfacing should become progressively better as the refinement of the laydown process increases. This is basically true provided each process incorporates quality workmanship. However, some excellent surfaces have been placed with tailgate spreaders and Jersey box spreaders pushed by a bulldozer. There have also been some poor surfaces placed with pavers having electronically controlled screeds. Workmanship must be stressed.

Cold Mixes

Cold-mixed and cold-laid emulsified-asphalt mixes need adequate fluid content for proper machine placement. A dry mix will tend to pull beneath the screed or strikeoff bar.

The solution to this problem is a slight increase of water in the mix. Heat should not be applied because this will increase the drying time and aggravate the pulling tendencies. In addition, many emulsions are heat sensitive and a heated screed will cause the emulsion to break into long strings of base asphalt.

Laydown of open-graded cold mixes used by the Forest Service is normally followed by application of aggregate passing the No. 4 (2.00 mm) sieve (choke stone) after initial rolling. The choke stone is spread uniformly over the fresh plant mix at a rate of 4 to 6 lb per sq yd (2.2 to 3.3 kg/m^2). The choke stone is used to prevent pickup, toughen the surface, and reduce porosity, and thus reduce the asphalt requirement for a chip seal. Uniform application is normally desired and chip spreaders are used; however, spreading has been done successfully with rotary-vane spreaders, such as used for sanding. Sometimes the choke stone is used only on the final surface layer.

Warm and Hot Mixes

Laydown of warm and hot mixes generally follows the procedures for hot-mix AC mats, inasmuch as the presence of heat is a key to their compaction. Warm- and hot-laid emulsions generally benefit from having a warm screed assembly. The screed unit generally gains sufficient heat from the mix to prevent pulling; however, use of screed heaters may be necessary when starting the day's laydown or when low temperature causes the screed to cool.

Warm mixes that are cold laid generally use the procedures given for cold mixes.

Placement

The sequence of placement normally calls for the first pass to be on the low side of the curve superelevation. In compound curve areas it is not always feasible to make this pass first because of the impracticality of shifting equipment from one side of the road to the other.

Of more importance in projects where traffic is allowed through the project area is the longitudinal joints. It is best to complete the full width of the surface daily, particularly when placing cold mixes directly after mixing. Traffic tends to deform the mat edges, so it is just good practice to have abutting panels placed so that compaction of the edges can be done by straddling them with the roller.

Transverse joints can be handled by blockouts placed as one would with standard asphalt concrete operations.

When a project calls for multiple layers of dense-graded cold mix, several factors must be considered in planning the project. The dense-graded cold-mix process relies on water to gain workability in the mix. Curing requires evaporation of the water from each layer. If a layer contains a high amount of mixing water at the time the next layer is placed, it is possible to seal the water in the lower layer and retard the curing process. Current experience with dense-graded cold mixes indicates that it is preferable to restrict layer placement to a nominal 2-in. (50 mm) compacted depth (see "Compaction" section for details). This allows exposure of the mix to the evaporative process. Subsequent layers can normally be placed within five days in summer months.

ROAD MIXING OF AGGREGATES

General Considerations

Several methods are available for the processing of in-place aggregates with emulsified asphalts; each depends largely on the characteristics of the in-place materials. In some cases, road mixing is done only with in-place materials, but in others aggregates are brought in—either to modify, improve, or supplement the in-place material, or to be used as the only aggregate material.

The aggregate materials should be analyzed to determine the representative gradation for the project, because gradation is a key factor in the selection of the proper emulsion to be used (see Chapter Four).

The mix design should determine that the selected emulsion will mix adequately, with sufficient coating and good adherence. The aggregate type and gradation may indicate the need for a special formulation of emulsion or the use of additives. The mix design also should determine the proper material and application rates for each of the components of the mixture, as follows:

Emulsified asphalt: type, grade, percentage
Water: percentage
Additives (when applicable): type, percentage

The variability of in-place aggregates normally is much greater than in well-controlled central plant operations. Accordingly, the mix design for road-mix projects should be checked at fairly frequent intervals along the project length to determine whether adjustments in emulsion or water content need to be made.

One inexperienced in emulsion mixes may initially encounter some problems in visualizing a desirable mix. The mix cannot be judged as one would a cutback mix because of the difference in color. The brown color tends to mislead the inexperienced user into adding a surplus of emulsion. Key points to consider in modifying mix composition are:

1. Increased fines will require increased emulsion.
2. Increased water may be necessary to aid dispersion of the emulsion.
3. Normal processing methods cause aeration of the mix and probable reduction in available water for processing.

Any increase of emulsion normally should be restricted to those cases where the aggregate has an increase of fines. Conversely, the emulsion content should be reduced only when the fines content is reduced.

Traveling Pugmills

The best method of incorporating aggregates with emulsified asphalts on the road is by use of the traveling pugmill. These machines take aggregate from the roadway or from a truck, introduce the various components into a pugmill, blend them, and place the mixture onto the roadway surface.

Equipment

There are various types of traveling pugmills: some pick up aggregate materials from a windrow; others have a hopper to receive aggregate from a dump truck. Some leave a processed windrow behind, whereas others have a laydown screed that places a mat ready to be compacted. Examples of traveling pugmills are shown in Figure 26.

Road Operations

The traveling pugmill normally is operated in conjunction with supply vehicles for emulsion, water, and aggregate. For machines that pick up material from the roadway, the aggregate is windrowed ahead of the machine. The windrow should be sized for the proper volume of aggregates that the machine can mix. Calibration of the machine is similar to that for central plant pugmills.

In-Place Mixing

In-place mixing refers to the process of mixing other components with the aggregate found in place on the roadway. The final cross section of the road surface will be essentially the same as it was before mixing.

Equipment

The development of in-place mixing equipment has evolved largely from the efforts associated with stabilization of subgrade soils. Many of these machines incorporate water pumps and meters (Fig. 27). The addition of emulsified-asphalt pumps and meters to these machines made them suitable for the in-place mixing of aggregate surfaces. The mixer uses one or more horizontal transverse rotating cross shafts on which are mounted tines to accomplish the mixing operation (Fig. 28). The depth of mixing is controlled by setting the vertical position of the shaft within the mixing hood.

The mixing hood provides the mixing chamber to contain the aggregate and the other mix components until the rotor assembly has blended them. The water and emulsion are introduced into the mixing chamber through a spraybar installation. The spray nozzles (snivvies) are placed under the hood and oriented toward the front of the rotor assembly. When the machine is fitted with individually controllable nozzles it is possible for a man walking behind the tailboard to sequentially open or shut off the emulsion flow, thus allowing the in-place mixing of tapers between varying surface widths.

The rear of the mixing hood should be hinged to provide a tailboard adjustable independently from the main hood. The tailboard should be set at the proper height to permit the completely mixed materials to exit at the rear of the mixing chamber, while retaining the partially agitated materials for further mixing.

Several tine patterns are available. Tines with 90-degree bends help provide a continuously uniform depth across the mixing width. Tines with other angles create a series of ridges beneath the mixed surface, thus contributing to variable compaction.

In-Place Mixing Operations

Preferably, the aggregate surface should be scarified to the full depth to be treated to avoid encountering any hard consolidated area.

The surface is then shaped to the desired final cross section prior to using the in-place mixer. If new aggregates are to be blended with the existing materials, the proper amount of the new materials is placed on the shaped roadway surface prior to the first mixing pass. The mixer then mixes the aggregate and incorporates the other mix components, leaving the combined mix in the same basic position but loosened or fluffed.

There are two application procedures for water and emulsion—simultaneous and separate. Simultaneous application requires two spraybars in the mixing chamber. A water tanker and an emulsion tanker are aligned in front of or beside the mixer and connected with hoses to the pumping/metering plumbing on the mixer. The separate application procedure begins with introduction of the proper water content and thorough mixing with the aggregates. The process is then repeated with the emulsion. For both procedures, control of application rates is accomplished by regulating the speed of the machine and the flow of water or emulsion.

If liquid tends to run ahead of the rotor assembly on steep grades, the applications should be split into two or more mixing operations. Depending on grades and materials, this situation may occur with a mixing depth of 4 in. (100 mm) or less and an emulsion content exceeding 6 percent, or when depth is greater than 4 in. and emulsion exceeds 4 percent.

If the design calls for addition of portland cement, the cement generally is added after introduction of the mixing water and preceding introduction of the emulsified asphalt. The cement is spread uniformly over the mixing width and mixed into the aggregates.

If lime is specified, it should be spread uniformly over the mixing area prior to introduction of any mixing water. The lime will be dispersed throughout the mix during the first mixing pass.

After the various components of the mix have been introduced and mixed, the in-place mixer makes additional passes as necessary to assure complete blending of the mix. The mixer should "break track" with the preceding mixing pathways by overlapping the joint lines.

The normal sequence of operations when water and emulsion are introduced separately and no additives (such as lime or cement) are specified would be:

1. Scarify and shape the road surface.
2. First pass—add water through the mixer and mix.
3. Second pass—add emulsified asphalt through the mixer and mix.
4. Third pass—Overlap the joints of preceding passes and mix without adding materials.
5. Fourth pass—Final remix if necessary.

Successful in-place mixing has been accomplished routinely in three passes of the mixer. The overlap of the third pass is necessary to offset any difference in the mix uniformity between mixing pathways.

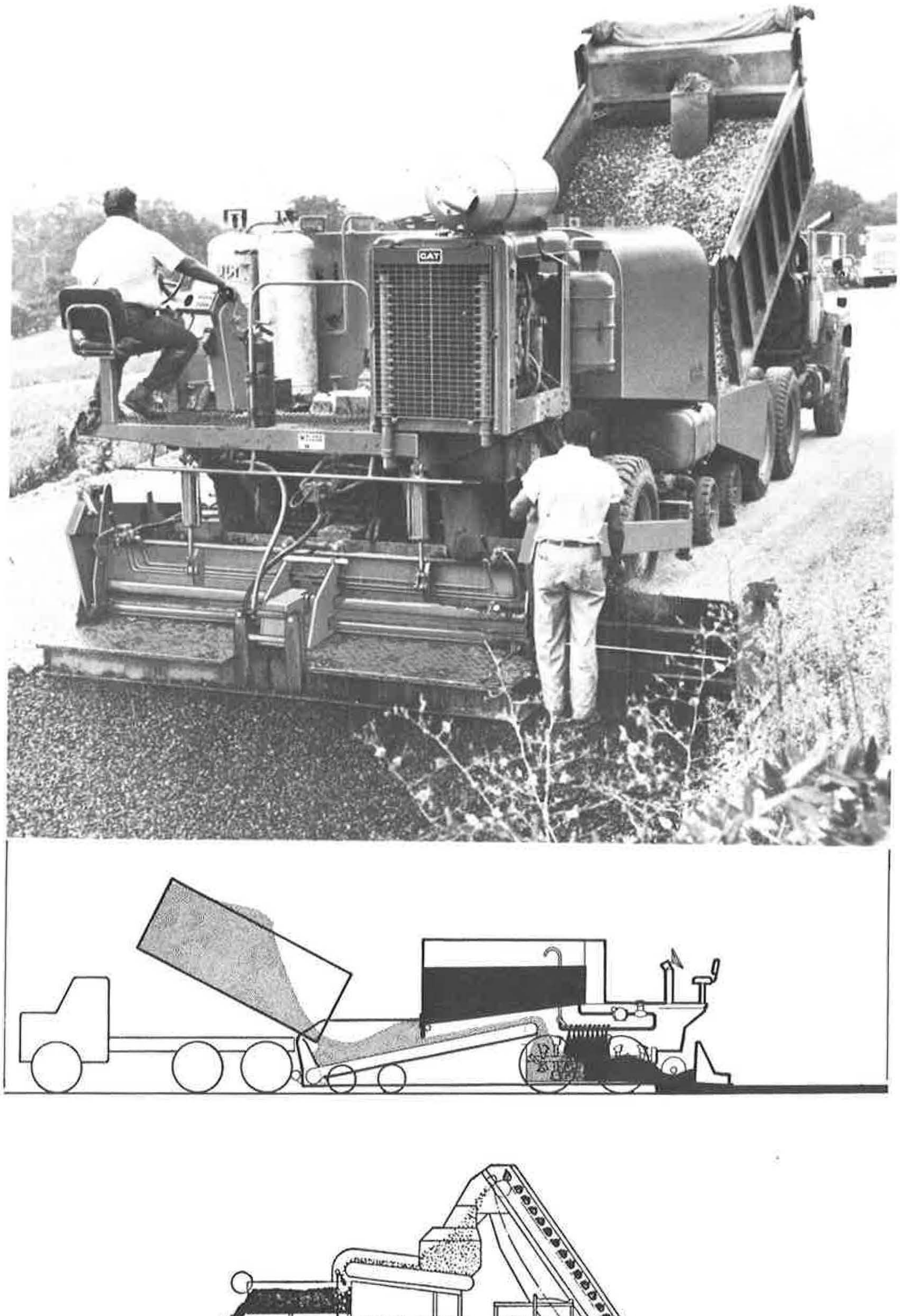


Figure 26. Traveling pugmills.

Figure 27. In-place mixers.

A cross-shaft in-place mixer should provide the following:

- Thorough single-pass mixing.
- Containment of the mixed materials at the mixed width.
- Easily replaced mixing tines.
- Capability to accurately control the application rates of water and emulsified asphalt into the mix.
- Adjustable mixing depth.

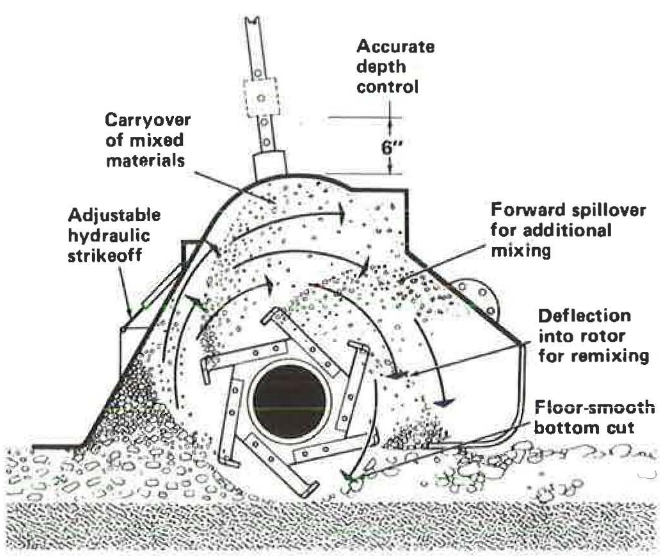


Figure 28. Cross section of in-place mixer.

- Adjustable tailboard.
- Individually controlled nozzles.

The in-place mixing operations provide a more consistently reproducible mix than is obtainable with blade mixing by any but the most highly skilled grader operator.

Blade Mixing

Use of the motor grader to process asphaltic mixes has decreased in direct proportion to the availability of experienced (skilled) operators. It is a valid method provided the necessary skills are available, but it is the least preferred method of road mixing.

Two basic requirements for blade mixing are:

1. There must be adequate surface width (mixing table) available to allow complete mixing of the materials.
2. The depth that can be mixed as a single layer is restricted by the capacity of the grader.

If the project requirements for mat depth exceed the moldboard capacity, it is necessary to windrow part of the materials at the edge of the mixing table for separate processing.

The motor grader used should have sufficient weight and power to move the windrow and should have a blade that is true with a smooth cutting edge.

The road surface is loosened by scarification and/or blading to the design depth. The materials to be mixed are initially windrowed to a uniform size. If addition of graded aggregates is specified, they are added to the windrow at this time. When lime or portland cement is specified, the normal practice is to meter and spread the material uniformly over the roadway prior to windrowing.

The mixing table should be tight prior to spreading a windrow. Some agencies prefer to use an emulsion and water mixture on the surface of the mixing table to hold the surface tightness.

Flattening the windrow prior to introducing water or emulsion provides uniformity of application and simplifies mixing. The distributor straddles the layer to apply the materials at the predetermined rates. Water is initially applied to the aggregates and the materials are processed with a rolling action off the moldboard (Fig. 29). The general practice has been to use slightly more water than the design mix indicates to allow for evaporation during processing. After the water is thoroughly mixed with the aggregates through normal blade mixing methods, the emulsion is added through the distributor. The emulsion usually is added in two or three increments, with blading after each application to disperse the fluids and assure uniformity of the end result.

When mixing has been completed, the suitability of the materials for immediate laydown should be determined. If the mixture has retained excess fluid content it is good practice to lay it out along the roadway (if space is available) until the desired fluid content is obtained. Continuous mixing to gain aeration may decrease aggregate coating substantially.

Key points to consider in the use of a blade mixing process are:

• The availability of skilled grader operator(s).
• Adequate road width available for mixing.
• Processing depth does not exceed moldboard capacity.
• The availability of the proper equipment in good condition.
• Aggregates that are suitable or can be modified for mixing.
• Windrows are kept to a known volume and uniform throughout the mixing area.
• Emulsion application rate is based on the known windrow volume and the designed mix. Modify the application rate to reflect changes in the fines fraction of the aggregates encountered.
• The water and emulsion are introduced separately into the aggregates to provide accurate control. Mixing the water and emulsion prior to application is discouraged because of a high potential for erring on the final emulsified-asphalt content.
• Weather conditions affect the break and cure of the mix.

Blade mixing should not be used on projects where the first four items cannot be satisfied.

COMPACTION OF EMULSION MIXES

Because of the wide variety of emulsions, aggregates, and weather conditions, it is not possible to describe any one optimum combination of equipment, sequence of operations, and rolling pattern for compacting emulsion mixes.

Generally, initial compaction is best achieved with light vibratory rollers or steel-wheeled rollers. If the mix is unstable, initial rolling patterns should keep the roller at least 8 in. (200 mm) from the edge of the mat until the materials have gained some strength, unless the design calls for rolled or flattened edges instead of vertical edge cutoffs. Intermediate rolling often is done with pneumatic rollers. Finish rolling is done with conventional steel-wheel rollers.

Compacting Dense Mixes

As shown in Figure 21, the amount of water needed in mixing to obtain coating is greater than that required for compaction. Typical total fluid contents (emulsion and water) would be 12 to 15 percent for mixing and 9 to 12 percent for compaction. Some excess water is seldom detrimental to mixing, but may cause a delay before compaction can begin.

Depending on the type of emulsion, some agencies recommend that the mix be allowed time to break before rolling and some recommend that compaction should start when total fluid content is optimum. Others begin compaction as soon as the mix appears stable under the roller. Rolling and compaction problems may be encountered in areas where trees shade portions of newly laid dense-graded mixes. The different cure rates necessitate delayed rolling on the shaded portions of the roadway.

When thick lifts (4 to 6 in.; 100 to 150 mm) do not cure or develop sufficient strength, multiple lifts of 2 to 3 in. (50 to 75 mm) should be used.

Use of portland cement to accelerate curing allows compaction to begin sooner after placement and lift thickness relative to curing is less critical. However, compaction should be completed within two hours of mixing to prevent destruction of cementing action.

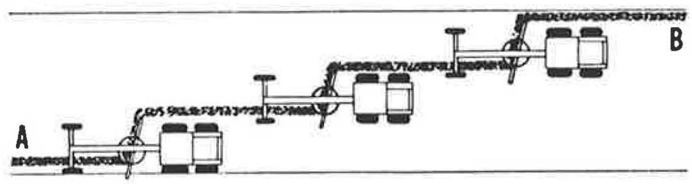


Figure 29. Blade mixing. Three passes of grader mixes windrow while moving it from side A to side B. Additional passes may be necessary to accomplish thorough mixing.

Compacting Open-Graded Mixes

Open-graded mixes should be placed at lift depths of greater than twice the maximum particle size. Lesser depths can result in poor compaction and fracture of the aggregate, exposing uncoated aggregate faces.

Rolling can follow immediately after laydown. Because of the large volume of voids in the compacted mix there is no danger of retarding cure.

Density Testing of Emulsion Mixes

End result density requirements for cold emulsion mixes are seldom specified because the test methods are difficult to perform.

Target densities on design mixes in the laboratory are based on dry weight of the compacted mix. At the time the laboratory compaction is performed, the mix would contain water and the true dry weight would be determined. To determine density in the field, ring or core samples or in-place methods could be used. If related to laboratory density, moisture correction will be required. Nuclear testing may be used to compare density with test strips, but careful control of moisture content is required.

Although such test methods are time consuming and difficult to perform in the field, one of the methods should be required in order to establish rolling patterns and equipment requirements for dense-graded mixes.

Because of the difficulty of measuring volume of open-graded specimens, procedure and equipment specifications, rather than end result specifications, may be necessary to control compaction.

CONTROL TESTS FOR EMULSION MIXES

Tests normally used for control and acceptance of bituminous mixes that are applicable to emulsion mixes include:

1. Extraction of bitumen from bituminous paving mixtures: AASHTO T 58; ASTM D 2172; California Method No. 310; Vacuum Extraction—proposed ASTM method.
2. Moisture or volatile distillates in bituminous paving mixtures: AASHTO T 110; ASTM D 1461.
3. Bulk specific gravity of compacted bituminous mixtures, using paraffin-coated specimens: AASHTO T 166; ASTM D 1188.

4. Bulk specific gravity of compacted bituminous mixtures, using saturated surface-dry specimens: ASTM D 2726.

5. Field coating test on emulsified asphalts: proposed ASTM method.

6. Density of soil in place by sand cone method: AASHTO T 191; ASTM D 1968.

7. Density of soil in place by rubber balloon method: AASHTO T 205; ASTM D 2167.

8. Density of bituminous concrete in place by nuclear method: ASTM D 2950.

9. Maximum specific gravity of bituminous paving mixtures: AASHTO T 209; ASTM D 2041.

10. Sampling bituminous paving mixtures: AASHTO T 168; ASTM D 140.

SPRAY APPLICATIONS

General

Spray applications, with or without aggregate cover, are designed and constructed for a variety of purposes. Basically, however, they are used to protect and extend the life of bituminous surfaces, and, except for fog seals, to improve surface texture for riding qualities and skid resistance. Additional information beyond that covered herein may be found in publications by The Asphalt Institute (*56*), by Chevron Asphalt Co. (*76*), and by McLeod (*73, 84*).

Aggregate Preparation

Fine dust on aggregate surfaces can cause the emulsion to break without achieving a bond with the cover aggregate. The best results are normally obtained with damp to wet aggregates. The presence of moisture counteracts some of the effect of dust and improves adhesion of the emulsion to the cover aggregate.

Equipment Considerations

The emulsions normally used with spraybar applications (except fog seals) are rapid-setting types that are less stable than the SS and MS mixing grades, and more susceptible to pressure and heat. Because of the pressure sensitivity, the pumps used with emulsions should have greater clearances to operate freely.

The distributor used for spraying emulsions in their undiluted form should be equipped with a full circulating system that includes spraybar units. Pressure generated when a noncirculating or unbypassed spraybar is shut off can cause the emulsion to break, plugging the assembly with asphalt. The full circulating spraybar and pressure bypass eliminate the excessive pressure. Constant circulation also will prevent heat concentrations that may cause the emulsion to break.

Weather Considerations

Spray applications should not be attempted during periods of rain or if the probability of rain exists. Unbroken emulsions subjected to rain can be further diluted and completely lost by runoff. A longer breaking or cure time should be anticipated during periods of high humidity. Pavement and air temperatures preferably should be above 60 F (16 C).

During hot, dry weather conditions, it may be advantageous to moisten the existing surface prior to application of emulsion.

Fog Seals

The least expensive seals are those consisting simply of a sprayed-on application of asphaltic material. These seals are often referred to as fog seals, flush seals, or black seals. They are used primarily to seal existing asphalt surfaces to reduce raveling, or to enrich dry and weathered surfaces. They should never be used on rich, unweathered surfaces.

Slow-setting emulsions (SS or CSS) are used for this purpose because they can be field diluted and applied uniformly with very light applications of residual asphalt. Normal application rates range from about 0.05 gal per sq yd (0.23 liter/m^2) to about 0.10 gal per sq yd (0.45 liter/m^2) of diluted emulsion (equal parts water and emulsion). Tests should first be made with a greater amount of water to determine the proper dilution. The emulsion should be diluted enough so that it can drain into the surface voids and interstices and leave the aggregate peaks practically uncoated.

The primary objection to the use of fog seals is that they may adversely affect the skid properties of the surface. Also, if traffic is allowed on the seal before the asphalt is properly cured, the tackiness causes pick-up and spray. For these reasons, provisions are sometimes made to sand or dust the fog seal before traffic is allowed on it.

Sand Seals

Sand seals consist of a spray application of emulsion covered with damp sand meeting certain gradation requirements and applied at predetermined rates. Rolling is also required in order to obtain embedment of the sand in the asphalt.

The emulsion application rate for sand seals is greater than for fog seals, permitting use of undiluted rapid- and medium-setting emulsions. Application rates range from 0.10 to 0.20 gal per sq yd (0.45 to 0.90 liter/m^2) for emulsion and 10 to 20 lb per sq yd (6.6 to 10.8 kg/m^2) for sand. Because of the heavier applications of asphalt and controlled cover coat material, sand seals are more effective, longer lasting, and generally have a better appearance than fog seals. They also do not create the tacky pick-up and spray problem sometimes associated with fog seals.

Seal Coats and Surface Treatments

Seal coats and surface treatments (often called chip seals) consist of alternate applications of asphalt and aggregate, with the aggregate firmly embedded in the asphalt layer by rolling. Design of these applications is covered in Chapter Three and typical application rates are given in Appendix C.

Cover coat material should be applied directly behind the distributor (within 2 min) and should be rolled immediately (Fig. 30). This will help prevent any loss of emulsion caused by run-off and will result in higher chip retention.

It is generally recommended that pneumatic rollers be used to roll the cover aggregate, particularly if the surface on which the seal coat is applied is fairly rough or uneven. Pneumatic rollers give uniform pressure over the entire area, whereas smooth, steel-wheel rollers hit only the high spots. Smooth, steel-wheel rollers have been successfully used on smooth, even surfaces; but care must be exercised to prevent crushing of the coarse aggregate particles.

It is essential to carefully control traffic by means of pilot cars until the emulsion has cured and the aggregate is firmly embedded in and bound by the asphalt.

Construction of multiple surface treatments is essentially the same as for single treatments. Each layer should be permitted to cure out before the succeeding layer is placed; otherwise, the lower courses may be unstable and prone to damage for a prolonged period of time.

Slurry Seals

The design methods for slurry seal and the materials normally used are covered in Chapter Three and aggregate gradations in Appendix D. For more complete coverage of slurry seals, the reader is referred to The Asphalt Institute's *Manual MS-13* (*56*) and a new manual on slurry seals to be published in 1975; to various publications of the International Slurry Seal Association, Shawnee, Oklahoma; and to the *Bituminous Slurry Surfaces Handbook* (*77*).

In the application of slurry seal treatments the following factors should be considered:

- The surface of the pavement should be clean. Remove extensive grease or oil spots. Tack coat concrete or brick pavements with 0.05 to 0.10 gal per sq yd (0.2 to 0.5 liter/m^2) of emulsion diluted in a ratio of 3 parts emulsion to 5 parts water.
- Preferably, use a continuous-mix slurry seal machine.
- Control traffic until the slurry is properly cured.
- Place the slurry seal under optimum weather conditions; 45 F (7 C) or higher and rising.

HINTS ON EMULSIFIED-ASPHALT CONSTRUCTION

- Know your local products—determine availability of emulsion types and grades in your area.
- Do not allow emulsions to freeze.
- Do not mix different emulsion types or grades in storage tanks.
- When pumping emulsion into a tank, do not let the material fall.
- Use proper pumps for handling emulsions.
- Do not heat emulsions above 170 F (76 C) in transports, storage tanks, or distributors.
- Determine type and grade of emulsion for use with available aggregates and proposed method of construction.
- If necessary, consult the emulsion supplier(s) on selection of proper emulsion for the job.
- Do not use aggregates that are coated with clay or other dust.
- Improved coating can usually be obtained with damp to wet aggregates.

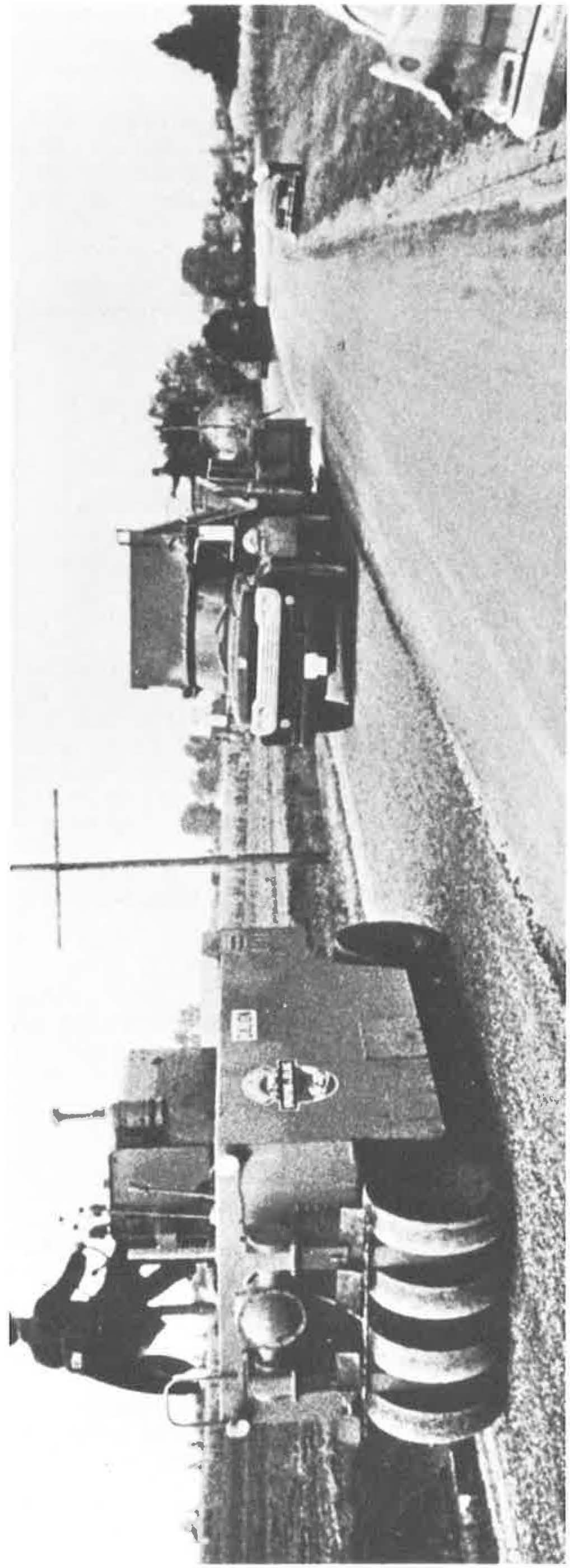


Figure 30. Construction of seal coat or surface treatment (84).

• Workability of cold mixes may be improved by addition of water during mixing. Use only as much mixing water as is needed to disperse the emulsified asphalt and obtain workability. Excess water may retard curing and delay compaction.

• Do not dilute rapid-setting emulsions (RS and CRS) with water. If medium-setting emulsions (MS and CMS) are to be diluted, determine their compatibility with water. For dilution, water should be added to the emulsion, not emulsion to the water.

• Mix only as long as necessary to disperse the emulsion throughout the aggregates. Overmixing may strip the emulsion from the aggregate or adversely accelerate the emulsion break.

• Portland cement added during mixing can accelerate curing of cold emulsion mixes.

• Placement of multiple layers of cold mixes, 2 to 3 in. (50 to 75 mm) thick, will allow faster curing than a single thicker layer.

• Cold-mix surface courses, especially dense-graded ones, should be sealed after construction, but not so soon as to entrap mixing water and distillates.

CHAPTER SIX

MAINTENANCE

The maintenance of roads has been variously defined, but most definitions include user safety and protection of the roadway from deterioration by the action of traffic and natural elements. There are many uses for emulsified-asphalt products in the maintenance of roads. Emulsions can replace much of the current use of cutbacks and hot plant-mix asphalt concrete in maintenance. More detailed information on the maintenance and repair of existing surfaces can be found in publications by The Asphalt Institute (*79*), Barenberg (*78*), and McConnaughay (*80*).

ASPHALT SURFACES

Maintenance procedures can be used to repair existing asphalt surfaces that have been damaged by weathering and traffic action. However, many surface problems are indicators of foundation failures. Treatment of these surface problems is only a treatment of the symptoms; correction of the foundation problems is the only cure.

Crack Repair

Limited cracking can be handled by treatment of the individual crack. If needed, the cracks are cleaned by air pressure or brooming prior to treatment, which consists of pouring emulsion into the cracks to seal them from the entry of surface water. MS-1 emulsions can be used where the cracks are narrow and MS-2 or CMS-2 where the cracks are relatively wide. The emulsion is poured into the crack by wand or sealing can. If the emulsion is squeegeed into the crack, the repair is improved structurally and has an improved riding quality. This not only forces the emulsion into the cracked mat, but also provides a smooth surface instead of a ridge. The repair is completed by sprinkling sand over the squeegeed emulsion.

Repair of large areas of cracking or alligatoring is best accomplished by application of a surface treatment, sand seal, or slurry seal as described in Chapter Four.

Pothole Repair

Potholes generally result from localized failure of the foundation or weak spots in the surface. The preparation of potholes for repair has been covered in many discussions but bears review. The edges of the hole should be cut vertically and all damaged or loose materials removed from the hole. All sides and the bottom of the prepared hole should be tacked with emulsion. The hole is then filled with patching mix and compacted.

Patching mixes should not be placed with an excess of mixing water present because that will extend the time before the patch can be opened to traffic. Use of warm emulsion mixes will provide the most rapid accessability to traffic. Because open-graded mixes in either the warm- or cold-mix processes have shown themselves to be the quickest to gain strength, it is suggested that the aggregate gradation for patching mixes be basically open-graded—less than 10 percent passing the No. 8 (2.36 mm) sieve.

Pothole patches generally result in a more open surface than abutting mats. This tends to allow surface water into the repaired area, with the potential to saturate the base materials. Therefore, patches should be sprayed with emulsion and sanded prior to leaving the location.

The availability of portable mixers at a repair site allows preparation and use of cold, warm, or hot emulsion mixes. They can also be used for special quick-setting emulsions that allow almost immediate use of the patch by traffic.

Emulsion patching mixes usually are made with SS, CSS, MS, or CMS emulsions. SS and CSS patching mixes are used soon after mixing because of their relatively short stockpile life. MS and CMS mixes generally have extended stockpile capability. Some patching mixes produced especially for extended stockpile life incorporate free diesel or other petroleum distillate in the emulsion. The prospective user is advised to confer with the supplier's technical representative for advice on the use of locally available emulsified asphalts or specialized formulations for use in patching mixes.

Skin Patching

Skin patches are generally used to relevel areas that have settled. Mixes prepared from MS or CMS emulsions with graded aggregates or sand and mixed cold or warm are suitable for skin patches. The edges of the area to be patched should be squared vertically or routed to prevent forming a slip plane at the interface of the old surface with the skin patch. The existing surface should be tacked with emulsion to assist the bonding of old to new materials.

Skid-Resistant Overlays

Overlays can be placed to improve the skid resistance of the road surface. The cold-mix choice for this purpose is an open-graded mix (See Chapter Four and Table 21) with an MS- or CMS-type emulsion. Because this combination allows passage of surface water through the mat, it will decrease surface moisture and hydroplaning tendencies. The moisture may, however, be a detriment to the subgrade unless the surface to be overlaid is impervious and has sufficient cross slope to drain the water. Lateral movement of water is necessary for the open-graded layer to function as intended. A dense or relatively impervious shoulder material should not be placed flush with the finished asphalt surface as it would cause a damming effect.

MAINTENANCE OF AGGREGATE SURFACES

Dust rising from aggregate road surfaces is a source of airborne particles. The use of emulsified products can either bind the dust particles together or make them sufficiently heavy so they will not become airborne.

Slow-setting emulsions in dilute form have been used to control dust with some success. The greatest factor in the use of emulsions is presence of material passing the No. 200 (75 μm) sieve. The greater the percentage of these materials the more the emulsion will form a surface skin.

The emulsion is normally diluted with water to 10 to 30 percent of original strength. The dilute mixture is applied in multiple applications to place from 0.10 to 0.35 gal of the full-strength emulsion per sq yd (0.45 to 1.6 liter/m^2) of road surface.

Several available emulsified products are formulated specifically for dust abatement. One such product has been developed by the U.S. Forest Service in California. It is called Dust Oil formulation 6 (DO-6). The DO-6 does not form a surface skin on the aggregate surface and provides a blade-maintainable surface.

When the plans for a road envision retention of an aggregate surface, the best selection for dust abatement is a product specifically designed for this purpose. However, because some of these products are not compatible with asphalt, if the road will subsequently be paved with asphalt use of standard mixing-grade emulsions is preferred for dust abatement.

ROADSIDE USES OF EMULSIFIED ASPHALTS

Emulsions have been used successfully as binder for mulch applications in revegetative efforts. They have also been applied by spray application to provide a temporary membrane to control surface erosion on slopes and in ditches. A rather unusual application of emulsion was to provide a dark coloration on a fresh rock face along a stretch of scenic roadway.

Because emulsified asphalts are a liquid form of asphalt using water as one of the components, they are more compatible with plants and water purity than are the cutback formulations, which contain a high percentage of petroleum distillates. Emulsified-asphalt mixes have been used in reservoir liners for potable water storage and as mastic for natural and man-made fiber applications. It would appear that imagination is the prime limitation on the use of emulsified asphalts once their characteristics are understood.

CHAPTER SEVEN

RESEARCH

CURRENT RESEARCH

HRB Bibliography 35 (*81*) and its supplement, *Bibliography 40* (*82*), contain more than 1,100 references to published reports on bituminous materials from 1930 to 1966. Of these, only 26 concerned bituminous emulsions. During the period from 1966 to 1973 there probably were less than 10 additional publications concerning research on asphalt emulsions that contained significant information on their use and performance.

This lack of information, together with the demand to conserve energy by using emulsions in place of other bituminous materials, has greatly increased the interest and need for research on the properties, use, and performance of emulsions.

Several agencies are currently engaged in research on bituminous emulsions. These are identified in Table 22. In addition, several projects are under way on new mix design and test methods.

Mix Design Methods

In addition to the activities listed in Table 22, the following studies are under way to develop design methods for emulsion-aggregate mixes:

1. Use of Emulsified Asphalts in Base Course Mixtures—FHWA National Experimental and Evaluation Program (NEEP), Project No. 19 (*83*). The purpose is to encourage state and local agencies to participate in evaluation

TABLE 22

SUMMARY OF KNOWN RESEARCH ACTIVITY RELATED TO USE OF BITUMINOUS EMULSIONS

RESEARCH PROJECT TITLE	RESEARCH AGENCY	HRIP NO.
Highway Test Track Studies - Evaluation of Results	Washington State University	25 210673
Open Graded Emulsified Asphalt Pavements	Federal Highway Administration	25 234778
Use of Dilute Bitumen Emulsion in Base Course Construction	Murray-North Partners (New Zealand)	31 069292
Structural Evaluation of Asphalt - Aggregate Cold Mix Bases	University of Illinois	31 226001
Methods and Parameters for Use of Emulsified Asphalt Prime and Emulsified Asphaltic Concrete Utilizing Natural and Synthetic Lightweight Aggregates	ATL Testing Laboratories	31 226125
Cold Asphalt Concrete Surfacing	California Department of Transportation	31 226412
Emulsified Asphalt Slurry Seal Surface Treatment	U. S. Army Waterways Experiment Station	31 233464
Fracture Time of Anionic and Cationic Bitumen Emulsions	Karlsruhe Technical University (Germany)	31 600230
Improved Emulsified Asphalt for Bituminous Base Construction	North Dakota Highway Department	--
Criteria for Emulsified Asphalt Stabilization of Sandy Soils in Mississippi	University of Mississippi	082274

of laboratory mix design methods and experimental field studies in the design, construction, and performance of emulsified-asphalt base courses. The emulsion base courses would be compared with control sections consisting of cutback asphalt mixes and hot asphalt concrete.

2. Design procedure for emulsion-treated mixes and cement-modified emulsion-treated mixes using the resilient modulus. Work is under way at the Chevron Research Company, Richmond, California, to develop this design procedure.

Test Methods

Several methods of test have been proposed that have not become AASHTO or ASTM standards. Some are supported by sufficient data to be developed as standards and put into practice. Other methods need more supporting data and trial use prior to publishing as standards. Test methods in the research stage include:

1. Vacuum Recovery Distillation—Proposed by the Arizona Highway Department. The purpose of this method is to recover the asphalt from an emulsified asphalt by use of vacuum distillation. If perfected, the test would be used in place of the current atmospheric distillation. Work is continuing in some of the Pacific Coast states to determine the precision of the method.
2. Vacuum Dessication—Proposed by Chevron Research. The procedure is used to remove moisture from laboratory-compacted specimens and field pavement samples.
3. Wet-Track Abrasion—Used to evaluate the wearing qualities of slurry seals by measuring their resistance to abrasion under controlled conditions. The test, intended to be used to design slurry seal mixtures, is under study in ASTM.
4. Mixing and Setting Test to Identify "Quick-Set" Emulsified Asphalts—The test method covers determination of the ability of an asphalt emulsion to combine with a controlled aggregate system to (1) coat the aggregate uniformly and completely, (2) produce a slurry-consistency mix capable of being mixed for a specified time, and (3) set within a specified time. The test, to be used to identify a "quick-set" emulsion, is under study by ASTM.
5. Coating Test for Dense-Graded Aggregates—This test is being considered to provide performance characteristics of emulsions mixed with dense-graded aggregates containing more than 6 percent passing the No. 20 (75 μm) sieve, some of which could be clay.

NEEDED RESEARCH

It is generally accepted that emulsions should be used for highway pavements if they satisfy construction and performance requirements. Future research should be directed to improved performance, which in turn would give the user greater confidence in emulsions.

Additional research is needed in the following areas:

1. *Viscosity of distillation residues.* Procedures need to be developed for measuring the consistency of distillation residues in absolute viscosity units. The change from penetration grading to viscosity grading of asphalt cements will require study to determine the precision of viscosity determinations on residues from distillation.

2. *Modification of emulsions and emulsion residues.* In addition to the types and grades now included in AASHTO and ASTM specifications, emulsions are needed for mixes containing large amounts of fine aggregate and aggregates containing appreciable amounts of clay. Emulsions are needed for use as primes on dense-graded aggregate surfaces and other impermeable surfaces.

In line with the energy conservation program, emulsions should be developed to replace those containing petroleum distillate.

The increased use of the special "quick-set" emulsions and the "high-float" emulsions justifies the development of standard specifications for these materials.

3. *Field performance and evaluation studies.* Development of methods to measure density to control compaction of in-place emulsion cold mixes is needed.

A determination should be made as to how much uncoated aggregate can be tolerated in cold emulsion plant mixes. Evaluation should be made immediately after mixing and after spreading and compacting on the road.

Research is needed to determine the suitability of present extraction and recovery tests for emulsion mixes that contain moisture and petroleum distillates.

4. *Improved pavement design methods.* Research is needed on the role of emulsion-treated bases and emulsion surface courses in improved design procedures, either developed or under development. Mixes prepared hot, warm, and cold, with associated curing problems, should be included. Ultimately, the studies should develop strength-thickness relationships that can be used as controlled design variables. Although some studies are under way (e.g., Chevron Research), additional effort is required in this area.

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APPENDIX A

GLOSSARY—BITUMINOUS EMULSIONS

BITUMINOUS EMULSION—A suspension of minute globules of bituminous material in water or in an aqueous solution. The dispersion of asphalt in water is accomplished by a colloid mill that breaks down the hot bitumen into minute droplets in the presence of an emulsifier. The emulsifier keeps the finished emulsion stable and controls the rate of breaking.

ANIONIC EMULSION—A class of emulsion such that a particular emulsifying agent establishes a predominance of negative charges on the bituminous globules.

CATIONIC EMULSION—A class of emulsion such that a particular emulsifying agent establishes a predominance of positive charges on the bituminous globules.

NONIONIC EMULSION—A class of emulsion such that the emulsifying agent establishes neutral charges on the bituminous globules. [Note: In this report the nonionic emulsions have been classified with the anionic emulsions unless the distinction needed to be made.]

Each class of emulsion is available in three types—rapid, medium, and slow setting. Within types there are two or more grades.

BREAKING OR SETTING—The breaking or setting of emulsions is defined as the separation of the bitumen and the water and can be observed in the field by a marked color change from brown to black. The release of clear water can often be observed. With anionic emulsion it is believed that breaking occurs primarily by the evaporation of water with minor electrochemical action; with cationics evaporation speeds break but the electrochemical phenomenon is the primary action. The electrochemical action is due to the attraction of charged asphalt particles to the oppositely charged aggregate surfaces, and results in the deposition of asphalt on the aggregate. (For discussion of aggregate surface chemistry, see Chapter Four.)

CRACK FILLER—Emulsified asphalt used to fill and seal cracks in existing pavements.

DENSE-GRADED MIX—A mixture of emulsified asphalt and mineral aggregate containing fines or mineral filler which, after proper curing and compaction, normally has a void content of less than 10 percent. Some sand mixes may be exceptions to this criterion.

DUST PALLIATIVE—A light application of emulsified asphalt for the express purpose of laying and bonding loose dust.

INVERTED EMULSION—A suspension of minute globules of water or of an aqueous solution in a liquid bituminous material. Inverted emulsions usually contain 3 to 12 percent water. They actually are liquid asphalts of the rapid-, medium-, and slow-curing types containing water, and in some instances anti-strip additive, to improve wetting and adhesion characteristics.

MAINTENANCE MIX—A mixture of emulsified asphalt and mineral aggregate for patching holes, depressions, and distressed areas in existing pavements. These mixes are suitable for relatively small spot application hot or at ambient temperature using hand laying and compaction techniques. Includes mixes for immediate use or for stockpiling for future use.

Open-graded mix—A mixture of emulsified asphalt and mineral aggregate containing little or no fine material which, after proper curing and compaction, normally has a void content of more than 10 percent.

Penetration macadam—Pavement construction using essentially one-size coarse aggregate that is penetrated in place by an application of emulsified-asphalt binder. The emulsified-asphalt application may be followed by an application of finer aggregate to reduce the void space.

Plant mix, cold laid—A mixture of emulsified asphalt and mineral aggregate prepared in a central bituminous mixing plant and spread and compacted at the job site when the mixture is at or near ambient temperature.

Plant mix, hot mix—hot laid—A mixture of emulsified asphalt and mineral aggregate usually prepared in a conventional hot-mix plant or drum mixer at a temperature not more than 260 F (127 C) and spread and compacted at the job site at a temperature above 200 F (93 C).

Prime coat—An application of emulsified asphalt to an absorptive surface to penetrate and bind the aggregate surface and promote adhesion between it and the new superimposed construction.

Road mix (mix-in-place) and travel plant mix—A procedure by which the emulsified asphalt and mineral aggregate are mixed on the job site by means of travel mixers, motor graders, or other special road-mixing equipment.

Surface treatment—A bituminous surface that results from one or more successive alternate applications of emulsion binder and cover aggregate to a prepared consolidated gravel, crushed stone, waterbound macadam, earth, stabilized soil, or similar base. Multiple application of emulsified asphalt and mineral aggregates may be used.

Seal coat—A bituminous surface that results from one or more successive alternate applications of emulsion binder and cover aggregate to an existing paved surface.

Slurry seal—A uniform application of a mixture of emulsified asphalt, fine aggregate, mineral filler, and water to an existing pavement. Single or multiple applications may be used.

Tack coat—An application of emulsified asphalt applied to an existing surface to eliminate slippage planes and provide a bond between new surfacing and existing surface.

APPENDIX B

EMULSION TEST METHODS AND THEIR SIGNIFICANCE

Numerous test methods have been devised over the past 50 years to define the properties of emulsified asphalts and to control uniformity of production and compliance with specifications. The tests included here are those normally used in specifications for the anionic and cationic types and grades. There has been interest in developing more functional tests that can be applied to specifications to provide a classification system related to aggregates, construction, environment, and traffic.

Brief descriptions of the tests used in most specifications, as well as the significance of each test, are given in Standard Methods of Testing Emulsified Asphalt, ASTM D 244, AASHTO T 59, as follows:

Viscosity, Saybolt Furol—The efflux time, in seconds, for a 60-ml sample to flow through a calibrated orifice under specified methods of sample preparation and test temperature. For emulsified asphalts the test is used to determine whether an emulsion is of low or high viscosity. Emulsion viscosity can vary appreciably, depending on the asphalt used, the type of emulsion, asphalt content, and the handling history of the material.

Settlement Test—Determines the storage stability in respect to the asphalt particles settling out of the emulsion in five days. Most specifications waive the test if the emulsion is to be used in less than five days. The storage stability test may be used instead of the five-day settlement test.

Storage Stability Test—Determines the storage stability in respect to the asphalt particles settling out of the emulsion in 24 hours. Can be used in place of the settlement test.

Demulsibility—Determines the comparative stability or rate of breaking and is used to differentiate between the rapid-setting and medium- or slow-setting emulsions. In the test for anionic emulsions, calcium chloride solution is used to cause the asphalt and water to separate. For cationic emulsions a solution of dioctyl sodium sulfosuccinate is used in place of the calcium chloride solution.

Classification Test—Distinguishes the rapid-setting cationic-type emulsions from the medium- and slow-setting types of cationic emulsions. The emulsion is mixed with standard Ottawa sand and cement and, after one minute mixing, if there is an excess area of uncoated sand over the coated area the emulsion passes the test for rapid-setting cationic emulsion.

Coating Ability and Water Resistance Test—Determines the ability of an anionic or cationic asphalt emulsion to (1) coat an aggregate thoroughly, (2) withstand a mixing action while remaining as a film on the aggregate, and (3) resist the washing action of water after completion of the mixing.

Cement Mixing Test—Provides some indication of the ability of an emulsion to mix with a dense-graded aggregate containing appreciable amounts of fines passing the No. 8 (2.36 mm) and No. 200 (75 μm) sieves. Used for slow-setting emulsions.

Sieve Test—Determines the amount of coarse particles in an emulsion that will not pass a No. 20 (850 mm) sieve. The results indicate whether the emulsion was manufactured, stored, and sampled properly. Excess coarse particles may result in nonuniform spray applications.

Particle Charge Test—Identifies cationic emulsion electrically. Positively charged asphalt particles migrate to the cathode. At present the particle charge test is not used for anionic asphalt emulsions.

Residue by Distillation—Determines the amount of asphalt, petroleum distillates, and water in emulsified asphalts by distilling the emulsion. The residue is usually retained for testing to determine its characteristics.

Tests on Residue by Distillation—Most specifications determine the following tests on residues from emulsions obtained by distillation:

Penetration, 77 F (25 C) 100 g, 5 sec—ASTM D 5 AASHTO T 49

Ductility, 77 F (25 C) 5 cm/min—ASTM D 113, AASHTO T 51

Solubility in trichloroethylene—ASTM D 2042, AASHTO T 44

Optional Tests—There are several test methods given in ASTM D 244 (AASHTO T 59) that the consumer may wish to include to better control the emulsion for a given use and under certain conditions. These include:

Modified Miscibility with Water—Determining whether an emulsion can be diluted with no asphalt coagulation or settlement. The test should only be specified for use where the emulsion is to be diluted.

Freezing Test—Determines whether an emulsion can withstand freezing without separation and, if separated, can be rendered homogeneous by stirring at laboratory temperature.

APPENDIX C

GRADATIONS AND APPLICATION RATES FOR SEAL COATS AND SURFACE TREATMENTS

TABLE C-1

AGGREGATE GRADATIONS FOR SEAL COATS AND SURFACE TREATMENTS

NOMINAL SIZE SQUARE OPENINGS	PERCENT PASSING BY DRY WEIGHT, U.S. STANDARD SIEVES, SQUARE OPENINGS									PARTICLE SHAPE
	1 IN.	¾ IN.	⅝ IN.	½ IN.	⅜ IN.	¼ IN.	NO. 4	NO. 8	NO. 16	FLAKINESS INDEX, MAX.
¾ in.	100	95–100	—	0–20	0–5	—	—	—	0–0.5	35
⅝ in.		100	95–100	—	0–15	0–5	—	—	0–0.5	35
½ in.		100	—	95–100	0–30	0–5	—	—	0–0.5	35
⅜ in.				100	95–100	0–40	0–5	—	0–0.5	35
No. 4						100	95–100	0–40	0–0.5	35

TABLE C-2

APPROXIMATE QUANTITIES FOR SINGLE-APPLICATION SEAL COATS AND SURFACE TREATMENTS

APPROX. LAYER THICKNESS (IN.)	EMULSIFIED ASPHALT	EMULSION QUANTITY (GAL/SQ YD)	AGGREGATE SIZE	AGGREGATE QUANTITY (LB/SQ YD)
¼	RS-1 CRS-1	0.20 to 0.30	No. 4 to No. 16	15–20
⅜	RS-2 CRS-2	0.25 to 0.35	⅜ in. to No. 8	18–25
½	RS-2 CRS-2	0.35 to 0.45	½ in. to No. 4	25–35

APPENDIX D

AGGREGATE GRADATIONS FOR SLURRY SEALS

GUIDE SPECIFICATION A-105 [a]

SIEVE SIZE	PERCENT PASSING TYPE I	TYPE II	TYPE III
⅜ in. (9.5 mm)	100	100	100
No. 4 (4.75 mm)	100	90–100	70–90
No. 8 (2.36 mm)	90–100	65–90	45–70
No. 16 (1.18 mm)	65–90	45–70	28–50
No. 30 (600 μm)	40–60	30–50	19–34
No. 50 (300 μm)	25–42	18–30	12–25
No. 100 (150 μm)	15–30	10–21	7–18
No. 200 (75 μm)	10–20	5–15	5–15
Theoretical asphalt content (% dry aggregate)	10–16	7.5–13.5	6.5–12

[a] International Slurry Seal Association.

Type I. This aggregate blend is used to seal cracks, fill voids, and correct moderate surface conditions. An approximate application rate of 6 to 10 lb per sq yd (3.3 to 5.4 kg/m²) based on dry aggregate weight is used when standard aggregates are utilized. The fineness of this design provides it with maximum crack penetrating properties. A typical example of this type of slurry surface would be on airfields or other areas where only protection from the elements is desired.

Type II. This aggregate blend is used when it is desired to fill surface voids, correct severe surface conditions, and provide sealing and a minimum wearing surface. An approximate application rate of 10 to 15 lb per sq yd (5.4 to 8.1 kg/m²) based on dry aggregate weight is used when standard aggregates are utilized. A typical example of this type of slurry surface would be on pavements with medium-textured surfaces, which would require this size of aggregate to fill in the cracks and provide a minimum wearing surface. Another example would be placing a slurry on flexible base, stabilized base, or soil cement as a sealer prior to final paving.

Type III. This aggregate blend is used to give crown correction and a moderate wearing surface. It is applied at a rate of 15 lb per sq yd (8.1 kg/m²), or more, based on dry aggregate weight for normal aggregate. A typical example of this type of slurry surface is the first and/or second course of a two-course slurry treatment on flexible base, stabilized base, or soil cement. Another example of this type of slurry surface would be on pavements that have highly textured surfaces and require this size of aggregate to fill in the voids and provide a moderate wearing surface.

APPENDIX E

PRELIMINARY ESTIMATE OF ASPHALT EMULSION CONTENT USING SURFACE AREA PROCEDURE

California has developed a procedure that uses the surface area concept to estimate the quantity of asphalt for dense-graded aggregates (*24*). To use this procedure requires information on (1) aggregate gradation as determined by a sieve and wash analysis; (2) aggregate specific gravity; and (3) Centrifuge Kerosene Equivalent (C.K.E.) and Oil Equivalent (O.E.) values for the aggregate.

With this information, emulsion contents with which to prepare laboratory specimens are estimated as follows:

1. Using the surface area factors given in Table E-1, the surface area of the aggregate can be determined; an example is also included in this table. As seen in the example, the procedure consists of multiplying the percent passing each sieve by the surface area factor. The surface area for the aggregate is simply the sum of the resulting products. *Note:* The factors shown in Table E-1 can only be used with the sieve sizes shown and *all* sizes listed must be used.

2. With the surface area determined from Step 1 and the C.K.E. and O.E. values determined from laboratory tests, the amount of asphalt is estimated with the assistance of Figures E-1, E-2, E-3, and E-4.

3. To demonstrate the use of the charts, assume the following considerations apply:

Surface area of aggregate	= 29.6 sq ft/lb
C.K.E.	= 5.6
O.E. (% oil retained, coarse)	= 1.9
Sp. gravity, coarse aggregate	= 2.45
Sp. gravity, fine aggregate	= 2.64
Percent passing No. 4 sieve	= 60

a. From Figure E-1 determine k_f = 1.55

b. From Figure E-2 determine k_c = 0.8 (Note correction for specific gravity)

c. From Figure E-3 determine k_m = 1.35

d. From Figure E-4 determine the initial oil ratio as 5.7 percent

$$\left(\text{Note: Ave. sp. gr.} = \frac{100}{\dfrac{55}{2.45} + \dfrac{45}{2.64}} = 2.53\right)$$

4. Normally the emulsion content for trial mixes will be increased by some proportion.

TABLE E-1

SURFACE AREA FACTORS AND SURFACE AREA DETERMINATION

SIEVE SIZE [a]	SURFACE AREA FACTOR (1)	EXAMPLE: PERCENT PASSING (2)	EXAMPLE: SURFACE AREA [b] (1) × (2)
Max.	2	100	2.0
No. 4	2	60	1.2
No. 8	4	50	2.0
No. 16	8	30	2.4
No. 30	14	25	3.5
No. 50	30	15	4.5
No. 100	60	10	6.0
No. 200	160	5	8.0
			Σ=29.6

[a] U.S. Standard Sieve sizes.
[b] Square feet per pound.

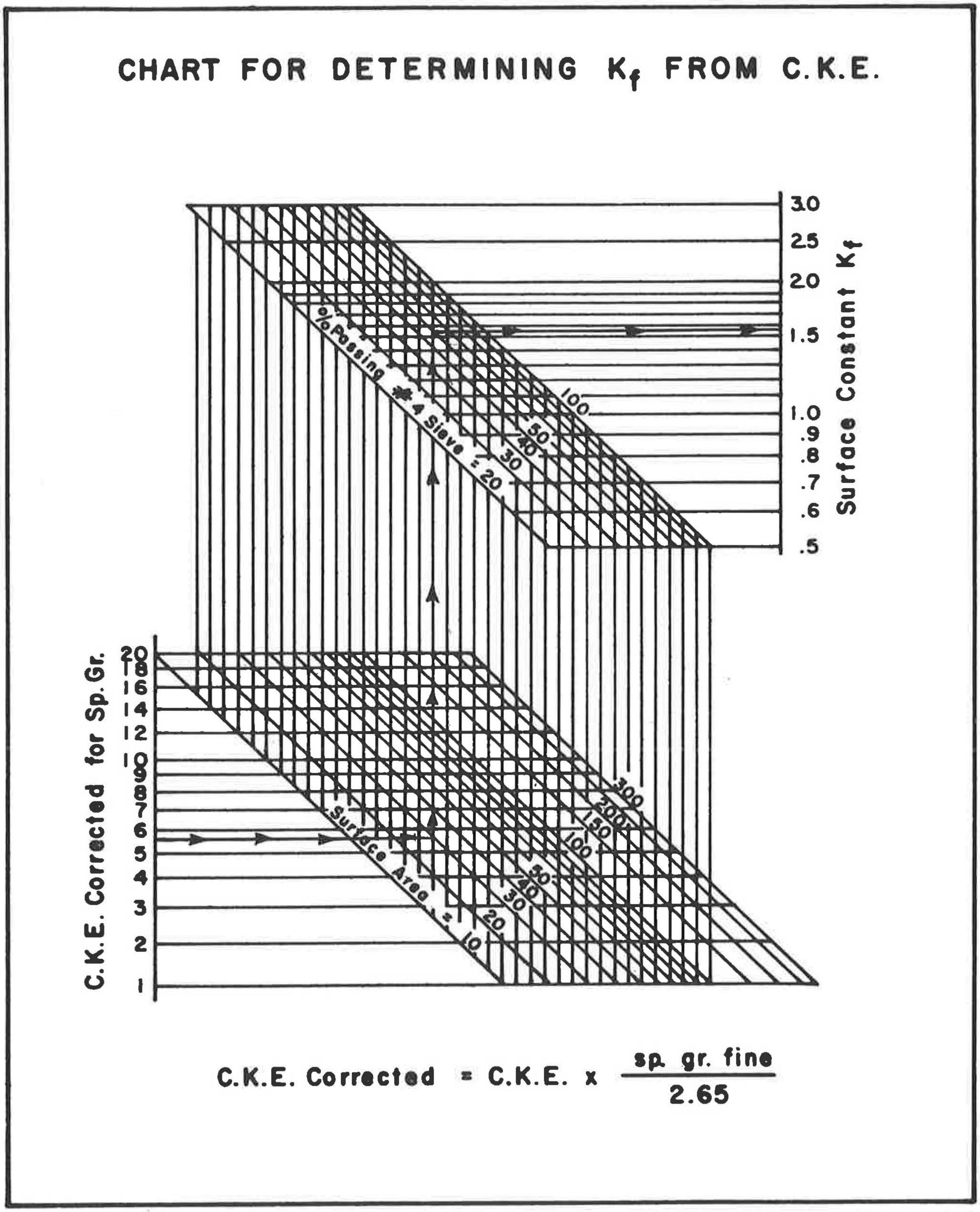

Figure E-1. Chart for determining surface constant for fine aggregate, K_f, from C.K.E. (From Test Method No. Calif. 303-F).

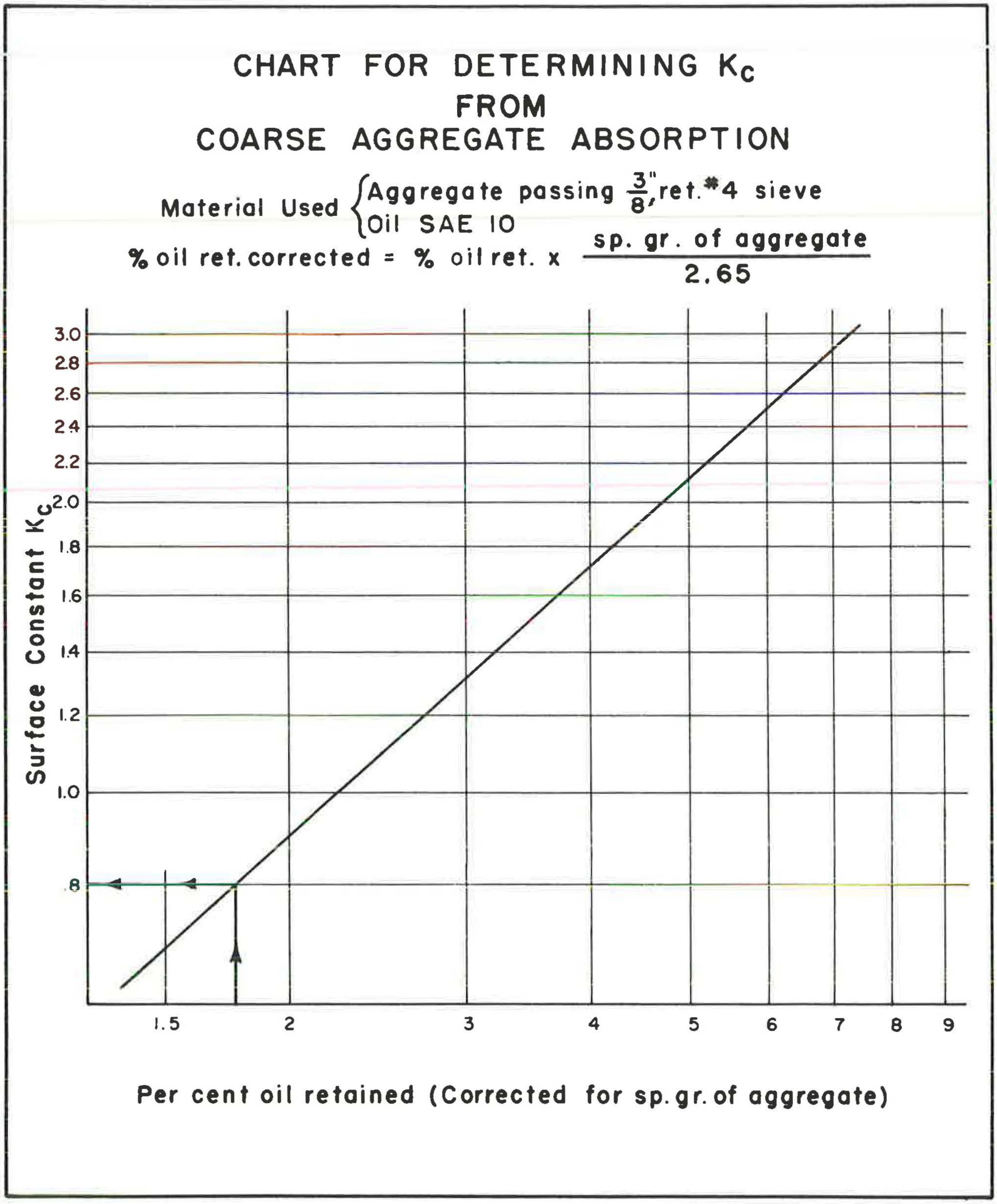

Figure E-2. Chart for determining surface constant for coarse aggregate, K_c, *from coarse aggregate absorption. (From Test Method No. Calif. 303-F).*

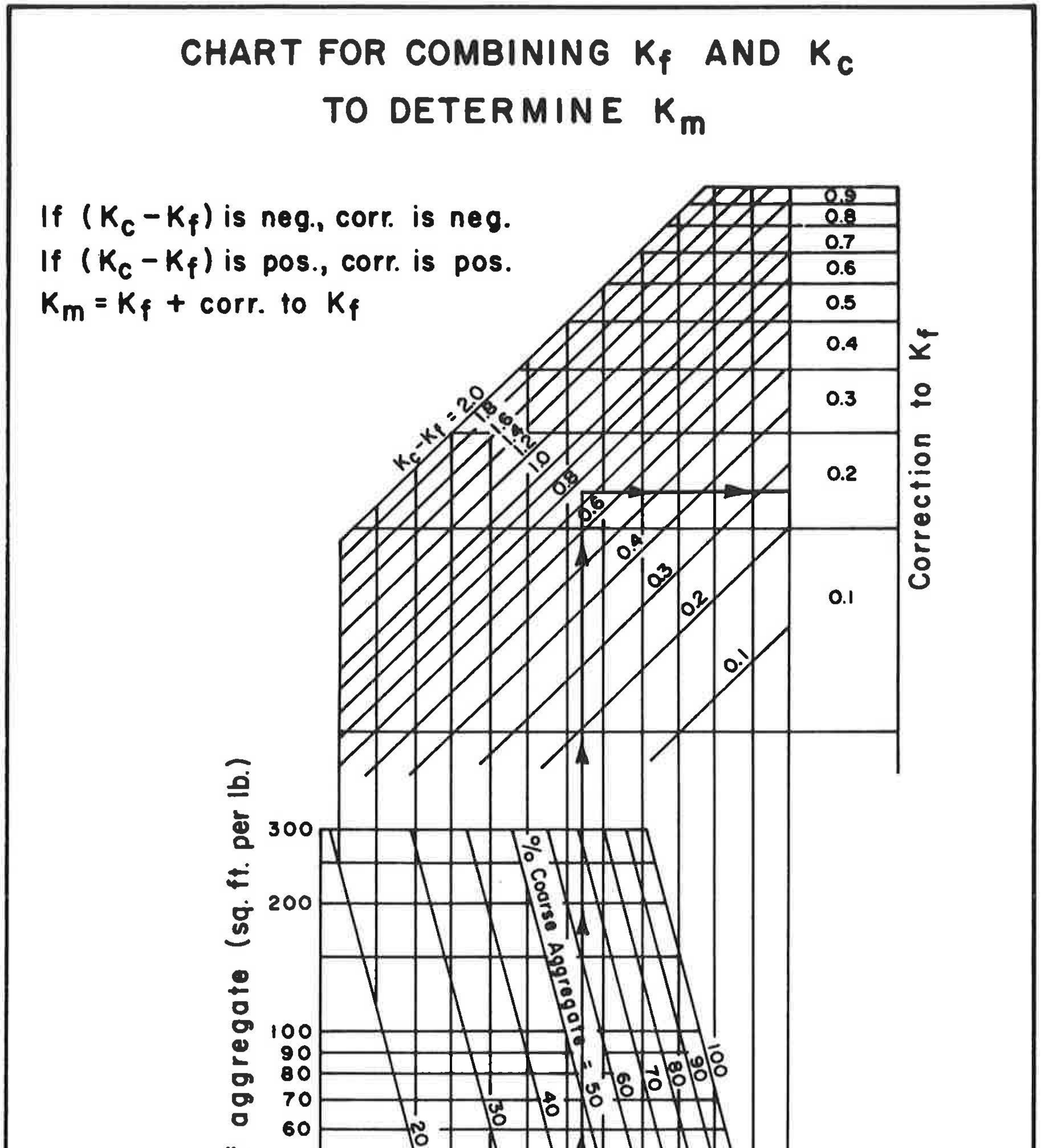

Figure E-3. Chart for combining K_f *and* K_c *to determine surface constant for combined aggregate,* K_m. *(From Test Method No. Calif. 303-F).*

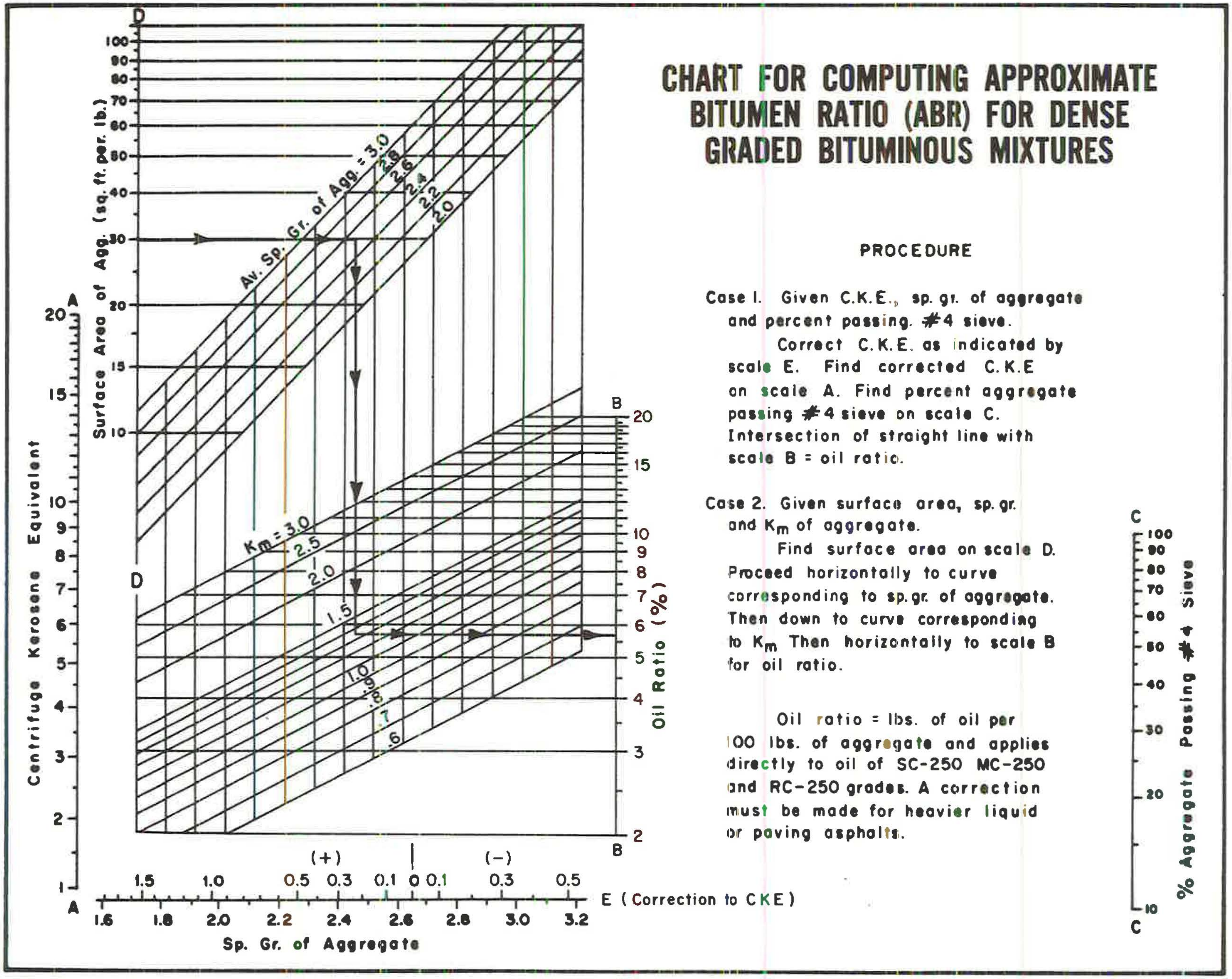

Figure E-4. Chart for computing approximate bitumen ratio (oil ratio) for dense-graded bituminous mixtures. (From Test Method No. Calif. 303-F).