189

National Cooperative Highway Research Program

NCHRP Synthesis 189

Pavement Structural Design Practices

A Synthesis of Highway Practice

Transportation Research Board
National Research Council

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Synthesis of Highway Practice 189

Pavement Structural Design Practices

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Subject Areas
Pavement Design, Management, and Performance

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.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board of the National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as: it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; its relationship to the National Research Council is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the National Research Council and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are the responsibilities of the National Research Council and the Transportation Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

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The members of the technical committee selected to monitor this project and to review this report were chosen for recognized scholarly competence and with due consideration for the balance of disciplines appropriate to the project. The opinions and conclusions expressed or implied are those of the research agency that performed the research, and, while they have been accepted as appropriate by the technical committee, they are not necessarily those of the Transportation Research Board, the National Research Council, the American Association of State Highway and Transportation Officials, or the Federal Highway Administration of the U.S. Department of Transportation.

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PREFACE

A vast storehouse of information exists on nearly every subject of concern to highway administrators and engineers. Much of this information has resulted from both research and the successful application of solutions to the problems faced by practitioners in their daily work. Because previously there has been no systematic means for compiling such useful information and making it available to the entire highway community, 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 useful knowledge from all available sources and to prepare documented reports on current practices in the subject areas of concern.

This synthesis series reports on various practices, making specific recommendations where appropriate but without the detailed directions usually found in handbooks or design manuals. Nonetheless, these documents can serve similar purposes, for each is a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems. The extent to which these reports are useful will be tempered by the user's knowledge and experience in the particular problem area.

FOREWORD

By Staff
Transportation Research Board

This synthesis will be of interest to pavement, highway, and geotechnical engineers, and others interested in pavement structural design practices. Information is provided on flexible and rigid pavement design, design elements common to flexible and rigid pavement, and flexible and rigid pavement overlay design. Additionally, the synthesis discusses pavement research currently underway and recently completed in the United States and Canada.

Administrators, engineers, and researchers are continually faced with highway problems on which much information exists, either in the form of reports or in terms of undocumented experience and practice. Unfortunately, this information often is scattered and unevaluated, and, as a consequence, in seeking solutions, full information on what has been learned about a problem frequently is not assembled. Costly research findings may go unused, valuable experience may be overlooked, and full consideration may not be given to available practices for solving or alleviating the problem. In an effort to correct this situation, a continuing NCHRP project, carried out by the Transportation Research Board as the research agency, has the objective of reporting on common highway problems and synthesizing available information. The synthesis reports from this endeavor constitute an NCHRP publication series in which various forms of relevant information are assembled into single, concise documents pertaining to specific highway problems or sets of closely related problems.

The structural design of flexible and rigid pavements has evolved from the application of engineering judgement to include a variety of processes. This report of the Transportation Research Board describes the various methods for structural pavement design in the United States and several Canadian provinces. It focuses on the elements intended to provide strength and stiffness to the pavement. The objective is to present a summary of current practice and trends in the design of new pavements and overlays for several elements including, procedures to determine thickness, layer compositions, drainage treatments, characteristics of materials, mitigation of swelling and frost heave, and assessment of pavement residual strength and condition for overlay design.

To develop this synthesis in a comprehensive manner and to ensure inclusion of significant knowledge, the Board analyzed available information assembled from numerous sources, including a large number of state highway and transportation departments. A topic panel of experts in the subject area was established to guide the researcher 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. As the processes of advancement continue, new knowledge can be expected to be added to that now at hand.

CONTENTS

ACKNOWLEDGMENTS

This synthesis was completed by the Transportation Research Board under the supervision of Robert E. Skinner, Jr., Director for Studies and Information Services. The Principal Investigators responsible for conduct of the synthesis were Sally D. Liff, Senior Program Officer and Scott A. Sabol, Program Officer. This synthesis was edited by Linda Mason.

Special appreciation is expressed to Raymond A. Forsyth, who was responsible for collection of the data and preparation of the report.

Valuable assistance in the preparation of this synthesis was provided by the Topic Panel, consisting of George R. Cochran, Manager, Physical Research, Minnesota Department of Transportation; Newton Jackson, Pavement Design Engineer, Washington State Department of Transportation; Walter P. Kilareski, Associate Professor of Civil Engineering, Pennsylvania Transportation Institute, Pennsylvania State University; Roger M. Larson, Development Team Leader, Federal Highway Administration; Richard W. May, Principle Engineer, Asphalt Institute; Robert G. Packard, Manager, Paving and Transportation Department, Portland Cement Association; Gary W. Sharpe, Assistant Director, Division of Design, Kentucky Transportation Cabinet; and T. Paul Teng, Strategic Highway Research Program.

D. W. (Bill) Dearasaugh, Engineer of Design, Transportation Research Board, and Frank R. McCullagh, Senior Program Officer, Transportation Research Board, assisted the NCHRP 20-5 Staff and the Topic Panel.

Information on current practice was provided by many highway and transportation agencies. Their cooperation and assistance were most helpful.

PAVEMENT STRUCTURAL DESIGN PRACTICES

SUMMARY

A decline in funding for highway research in the United States, which began in the mid 1960s and reached forty percent by 1982, coupled with deterioration of the nation's highway system has since lead to research programs designed to effect improved highway products and processes.

Based on results from this continuing research, the structural design of flexible and rigid pavements has evolved from the application of engineering judgement to include a variety of processes. Although some pavements are still designed primarily on the basis of engineering judgement, drawing heavily on the expertise of an experienced pavement engineer, empirical, and to a lesser degree, mechanistic procedures predominate today.

This synthesis describes the various methods for structural design of pavements in use in the United States and several Canadian provinces. It considers only structural aspects of design (those intended to provide strength or stiffness to the pavement) and not functional aspects (such as skid resistance).

A comprehensive literature search, interviews of 54 North American pavement engineers, a questionnaire on agency pavement structural design practice conducted in 1990 and 1991, and follow-up comments by agencies were used to assemble information for this synthesis on structural design practice for new pavements and pavement overlays.

For flexible pavement, the information revealed that 51 agencies, the majority, employ empirical procedures, predominantly those in the AASHTO *Guide for Design of Pavement Structures*. Only a few agencies use mechanistic models, although nearly half indicated their intention to do so in the future. A significant trend in flexible pavement design is the movement to positive internal pavement drainage. Ten agencies routinely incorporate permeable bases into new pavements, while 12 are doing so experimentally. In addition, considerable movement to life-cycle cost analysis and resilient modulus testing was evident.

The majority of agencies design portland cement concrete pavement, either jointed plain, jointed reinforced, or continuously reinforced, using the AASHTO guide procedures while only a limited number employ the Portland Cement Association (PCA) method. Eight agencies use in-house mechanistic or empirical systems for the design of jointed plain pavement. Of those agencies that construct Reinforced Concrete Pavement (RCP) or Continuously Reinforced Pavement (CRCP), most use the 1972 or 1986 AASHTO procedures. The remainder employ the PCA or in-house mechanistic or empirical procedures for RCP and CRCP design.

As was the case with flexible pavement, a well-defined trend toward internal drainage of rigid pavement was noted. Twenty-eight agencies incorporate untreated or treated permeable bases into new rigid pavements with several others indicating their intent to do so in the future.

Seven agencies anticipate adoption of the 1986 AASHTO procedure for rigid pavement design while four others are considering a move toward mechanistic design in the future.

Flexible overlays of flexible pavement are designed by deflection analysis (28 agencies), judgement (26 agencies), and component analysis (26 agencies). Only six agencies presently use mechanistic models for flexible overlay design.

Use of Falling Weight Deflectometers (FWD) for nondestructive pavement testing increased dramatically between 1986 and 1991 (from 2 to 27). The Dynaflect is used by 16 states for this purpose.

Designs for flexible overlays of rigid pavement are based primarily on judgement or the use of standard thicknesses. Those agencies employing rigid overlays of rigid and flexible pavement use a combination of experience, judgement, component analysis, the 1986 AASHTO procedure, deflection analysis and, in a few instances, mechanistic models.

Pavement research has been greatly stimulated by the Strategic Highway Research Program (SHRP). The Long Term Pavement Performance (LTPP) portion of this massive research project involves approximately 2,500 in-service pavement test sections throughout the United States, Canada, and 10 other nations.

Pavement research underway as part of the FHWA-administered State Planning and Research Program (SPR) is concentrated in the areas of evaluation or modification of the 1986 AASHTO guide design procedure, development or modification of mechanistically based pavement design systems, and laboratory resilient modulus testing.

The pavement portion of the National Cooperative Highway Research Program, administered by the Transportation Research Board, has ongoing research projects for improvements in design, materials and construction quality control, maintenance, drainage, and training. A provision of the Intermodal Surface Transportation Efficiency Act of 1991 mandates that not less than 25 percent of SPR funding be dedicated to "research, development and technology transfer activities." Implementation of the ISTEA will approximately double SPR research funding, therefore augmenting pavement research funding.

The Federal Highway Administration contract research program has approximately doubled in the pavement area between 1989 and 1991. Much of this effort is concentrated on a variety of specific problems including those referred to above. In addition, considerable emphasis is being placed on the effects of truck-tire-pavement interaction and vehicle dynamics on pavement performance. Significant work is also underway to develop performance-related specifications for highway pavements.

Canada supports a large pavement-related research program. Eighty projects are either underway or have been recently completed (13 by national and 67 by local entities).

INTRODUCTION

In 1991, the Federal-aid highway system comprised more than 850,000 miles of pavements of various designs (Figure 1). It has been estimated that $20 billion is spent annually in the United States for pavement construction, maintenance, and rehabilitation (*1*). This being the case, the monetary implications of even a minor improvement in pavement performance could conservatively be described as substantial. Recognition of this fact by the highway community has proven to be a catalyst for research and experimentation in all phases of pavement technology, including pavement design.

Federal-Aid Interstate and Primary Systems						
	Paved[1]					Total
Highway Type	Low Type[2]	Intermediate Type	High Type			
			Flexible[3]	Composite	Rigid	
Rural Interstate Miles			16,329	5,826	11,522	33,677
Urban Interstate Miles			3,167	3,463	4,973	11,603
Rural Primary Miles	2,167	20,997	152,031	35,183	15,649	226,027
Urban Primary Miles	20	1,338	17,482	8,863	6,216	33,919

Federal-Aid Secondary Highway System							
	Unpaved[4]	Paved[1]					Total Miles
		Low Type	Intermediate Type	High Type			
				Flexible	Composite	Rigid	
Rural Secondary Miles	39,290	46,493	90,343	200,909	14,411	8,863	400,309
Urban Highway Miles	918	5,097	23,649	89,776	19,379	9,472	148,291

[1] Paved mileage includes the following categories:
- Low Type—an earth, gravel or stone roadway which has a bituminous surface course less than 1 in. thick, suitable for occasional heavy loads;
- Intermediate Type—a mixed bituminous or bituminous penetration road on a flexible base having a combined surface and base thickness of less than 7 in.;
- High Type Flexible—a mixed bituminous or bituminous penetration roadway on a flexible base with a combined surface and base thickness of 7 in. or more, also includes brick, block, or combination roadways;
- High Type Composite—a mixed bituminous or bituminous penetration roadway of more than 1 in. compacted material on a rigid base with a combined surface and base thickness of 7 in. or more; and
- High Type Rigid—a portland cement concrete roadway with or without a bituminous wearing surface of less than 1 in.

[2] Includes 36 unpaved rural primary miles in Montana.

[3] Includes a minor amount of intermediate type pavement in a few states.

[4] Unpaved mileage includes the following categories:
- Unimproved roads using the natural surface and maintained to permit passability;
- Graded and drained roadways of natural earth aligned and graded to permit reasonably convenient use by motor vehicles, and which have adequate drainage to prevent serious impairment of the road by normal surface water—surface may be stabilized; and
- Soil, gravel or stone, a graded and drained road with a surface of mixed soil, gravel, crushed stone, slag, shell, etc., surface may be stabilized.

Source of data: *Highway Statistics 1991*, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C.

FIGURE 1 Federal-aid highway systems, 1991 mileage by surface type.

The objective of this synthesis is to provide a snapshot of current practice and an indication of trends in the design of new pavements and overlays for the following elements:

- Procedures to determine thickness,
- Layer compositions and configurations,
- Drainage treatments,
- Traffic characterization,
- Material characterization,
- Mitigation of swelling and frost heave,
- Miscellaneous design features, and
- Assessment of pavement residual strength and condition for overlay design.

This synthesis includes information based on pertinent literature on state pavement design practice, communication with and assistance from Federal Highway Administration (FHWA) personnel, and a questionnaire (see Appendix A) on agency pavement design practice distributed to the 50 states and seven Canadian provinces. For the questionnaire, 54 responses with backup material were received. After analysis of the agency responses, designated representatives of each agency were contacted for clarification and, with respect to overlay design, updating. An effort has been made not only to provide basic information on agency pavement design practice, but also to identify regional trends throughout the United States.

Chapter Two of this synthesis begins with a brief background of the development of flexible pavements, citing the first known use and the various tests that evolved through time and experience. The second part of the chapter presents the design methods and procedures used by those highway agencies which responded to the questionnaire. These same topics, as they relate to rigid pavement design, are discussed in Chapter Three. Life-cycle cost analysis, traffic loading, and other design elements common to both pavement types are noted in Chapter Four. Increasing the structural capacity of pavement through the application of flexible and rigid overlays is the focus of Chapters Five and Six, respectively. Both chapters present the evolution of overlay methods and describe current highway agency practice. Chapter Seven highlights research projects related to pavement design that are currently underway.

FLEXIBLE PAVEMENT DESIGN

Background

The earliest written reference to a flexible pavement as we define it today is an inscription on a brick found in ancient Babylon (circa 604–625 B.C.) which refers to a "road glistening with asphalt and burnt bricks" (*2*).

Flexible pavement thickness design, however, is a relatively new and rapidly changing technology. As recently as 50 years ago, most flexible pavements were designed on the basis of experience and "engineering judgement." In his comprehensive two-volume work on American highway practice published in 1942 (*3*), L.J. Hewes makes no reference to flexible pavement thickness design, although a chapter is devoted to the design of concrete pavement slabs.

In the 1920s, recognizing that the engineering properties of subgrade soils were a critical factor in pavement performance, highway engineers began to develop soil classification systems and later initiated the practice of varying pavement thickness based on subgrade soil classification. Two of the most widely used of these systems were introduced by the Highway Research Board (*4*) and the U. S. Bureau of Public Roads (*5*).

In the 1930s, research was underway on the development of laboratory soil strength tests to provide the basis of flexible pavement thickness design. This approach received considerable impetus with the advent of World War II. In 1942, the California Bearing Ratio (CBR) test and pavement design procedure (*6*) were adopted by the U.S. Army Corps of Engineers for the design of airfield pavements and were soon thereafter applied to flexible highway pavements. The CBR procedure gained world-wide acceptance due, in no small part, to the modifications developed by the U.S. Army Corps of Engineers (*7*). The CBR procedure is, to this day, the most commonly used flexible pavement design procedure in the world.

A number of empirical flexible pavement design procedures based on soil strength tests were introduced after World War II including the North Dakota cone, triaxial compression, Florida bearing, and the Hveem stabilometer.

The postwar period also saw a rapid increase in the number of heavy axel loadings accompanied by accelerated deterioration of the nation's pavements. Recognition of the problem and concern within the pavement community led to one of the most comprehensive and costly pavement research programs ever initiated, the American Association of State Highway Officials (AASHO) Road Test of 1958–60.

Among the specific objectives of the test as stated by the advisory committee in 1957 were: "To develop the significant relationships between the number of repetitions of specified axle loads of different magnitude and arrangement and the performance of different thicknesses of uniformly designed and constructed asphaltic concrete, plain portland cement concrete, and reinforced portland cement concrete surfaces on different thicknesses of base and subbase when on a basement soil of known characteristics" (*8*).

The road test involved two years of massive effort and the expenditure of $27 million. Analysis of the data led to the publication, in 1961, of the *AASHO Interim Guides for Design of Rigid and Flexible Pavements* (*9*). After several years of use, the guide was revised in 1972, the new version being titled the *AASHTO Interim Guide for Design of Pavement Structures* (*10*).

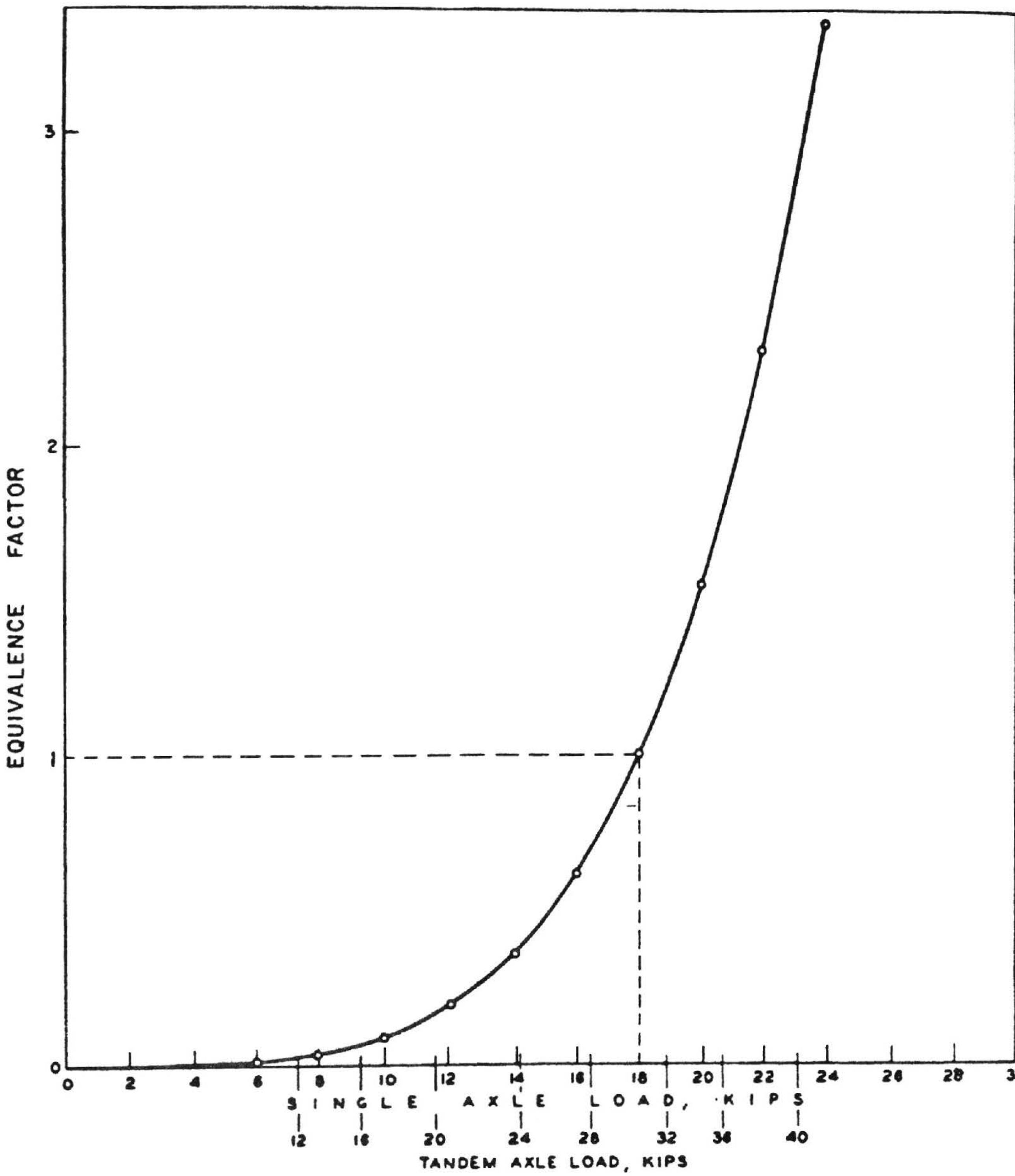
As with any purely empirical design procedure based on accelerated test track performance, it had a number of basic deficiencies including:

- The short duration (two years) of the road test did not allow an evaluation of the effect on pavement performance of surface aging.
- The road test was limited to a single subgrade condition and environment.
- The road test did not incorporate pavement features and materials which have since become or are becoming standard.
- The truck loading applied at the road test did not include tridem or quadrum axles, "super single" tires, or the relatively high truck tire pressures now prevalent.

In spite of these shortcomings, the design guidelines resulting from this carefully controlled experiment were used throughout the world and were adopted, to some degree, by 35 states and the Federal Highway Administration (FHWA).

The most significant single product of the AASHO Road Test was the development of a relationship characterizing the relative destructive effect of varying axle loads in terms equivalent to 18 kip single axle loads (ESAL) shown by Figure 2. In a paper presented at a conference on the road test in 1962 (*11*), Scrivner and Dozan discussed two methods of introducing mixed traffic loading into the pavement performance equations resulting from the analysis of road test data. One method was the use of "mixed traffic theory." This approach results in a multiload equation in the form of a complex integral which is somewhat cumbersome to apply.

The other method, termed the "equivalent application approach," which was much simpler in application, involved converting the number of applications of each axle load found in mixed traffic to an equivalent number of applications of a selected axle load so that the single-load equations developed at the road test could be used directly. This method generated results that agreed closely with those obtained using the more rigorous "mixed traffic theory" in four of the five cases studied by the authors. In almost every comparison of the two methods, the equivalent applications approach resulted in a pavement life prediction slightly greater than that obtained with the mixed traffic theory. However, the pavement thicknesses dictated by each of the two approaches were essentially identical. Thus, the less rigorous applications approach (ESAL) was incorporated into the AASHO pavement design procedure. The relationship characterizing the relative destructive effect of varying axle loads in terms of equivalent 18 kip axle loads (ESAL), sometimes referred to as the "Fourth Power Rule", has subse-



Relation between axle loads and equivalence factors, based on terminal serviceability index of 2.2, and on average equivalence factors for both rigid and flexible pavement.

FIGURE 2 Relation between axle loads and equivalence factors (*11*).

quently been independently verified by the research of a number of entities including Pennsylvania (*12*), Canada (*13*), and California (*14*).

The pace of change in pavement design practice since the AASHO Road Test was reflected by the 1986 revision of the AASHTO *Guide for the Design of Pavement Structures* (*15*) which included:

- Internal pavement drainage design criteria,
- "Reliability" factors,
- Replacement of soil support with resilient modulus (Mr),
- An overlay design procedure for flexible and rigid pavements based on backcalculation of the resilient moduli of the elements of the existing pavement section,
- Extension of load equivalence factors to include heavier loads and tridem axles,
- The addition of sections on life-cycle cost analysis and pavement management, and
- An overview of mechanistic pavement design.

In recent years, the pavement design community has been moving from empirical procedures to the use of mechanistic models for the design of both flexible and rigid pavements. Elements of the pavement structural section are modeled as elastic or visco-elastic layers on elastic or visco-elastic foundations to calculate stress, strain, and deflection due to pavement loading. Application of a mechanistic procedure requires that these values be correlated to pavement performance.

Mechanistic models, which are based on known properties of materials used, permit a qualitative evaluation of the effect of unusual loadings, wheel configurations, new materials, or structural section designs on pavement response without the neccesity of constructing field test sections.

Examples of mechanistic procedures currently being used for flexible pavement design include that of the Kentucky DOT (*16*), the Illinois DOT (*17*), Asphalt Institute Method (*18*), and the Shell International procedure (*19*). A National Cooperative Highway Research Program (NCHRP) project (1-26) is currently underway with the objective of providing a fully implementable mechanistic design procedure for the AASHTO Pavement Design Guidelines.

AGENCY PRACTICE

Design Procedures

A review of agency input, summarized in Table 1, revealed that a number of agencies use two or more flexible pavement design procedures. Empirical design procedures, including the 1972 and 1986 AASHTO procedures (*17,18*), are used by 51 agencies. Ten agencies have developed their own, usually empirically based, systems ("Other"). Four agencies presently employ mechanistic models for flexible pavement design while five use the Asphalt Institute procedure (*18*) which is mechanistically based.

Use of these procedures in the United States is shown in Figure 3. The 1972 AASHTO procedure is favored by the Rocky Mountain, Southern, and New England states, while the 1986 AASHTO procedure predominates in the Midwest.

The "Other" category consists primarily of in-house empirical procedures commonly used on the Pacific coast. Forty-two of the responding 54 agencies use a 20-year design period for primary highways. The remaining 12 agencies use the following design periods:

Number of Agencies	Design Period (Years)
1	10
1	12
4	15
1	15–20
5	30

All but five of the responding agencies use the same design period for both primary and secondary highways.

Internal Drainage of Flexible Pavement

As shown by Figure 4, agency questionnaire response revealed a definite movement toward rapid positive internal drainage of flexible pavement in the United States, primarily in the Pacific Coast and East Central regions. Ten states and one Canadian province (Ontario) are incorporating unbound or treated permeable materials into flexible pavement on a routine basis. Twelve states, mainly in the Southwest and Midwest are doing so on an experimental basis.

Twenty agencies employ collector and outlet pipes for removal of water collected in the permeable layer while seven extend the permeable layer to "daylight" for this purpose. A typical flexible pavement section with an internal drainage system consisting of treated permeable base with collector and outlet pipes is shown in Figure 5.

As shown by Table 2, those agencies using untreated permeable material (UPM) are, almost without exception, assigning to it an AASHTO layer coefficient comparable to aggregate base for pavement design purposes. With respect to asphalt treated permeable material (ATPM), which is now being commonly referred to as asphalt stabilized permeable material (ASPM), 10 of 17 agencies assign an AASHTO layer coefficient significantly higher (0.2–0.3) than that for aggregate base, while the remainder give it a value equivalent to that for gravel (0.12–0.14). This represents a significant shift in design policy for states using ATPM (ASPM) since, as recently as early 1990, the responses to a National Asphalt Pavement Association (NAPA) questionnaire on ATPM usage revealed that 11 of 27 states assigned no structural value to ATPM. Six agencies assign AASHTO layer coefficients ranging from 0.12 to 0.34 (approximately) to cement treated permeable material (CTPM).

Shoulder Design

Twenty-three agencies reported using standard shoulder designs while 22 construct shoulders with the same structural section as the pavement, i.e., "full depth." Twelve agencies base shoulder design on a percentage of the traffic loading assumed for pavement design.

Figure 6 illustrates that full-depth shoulder design predominates in the Rocky Mountain states, whereas shoulder designs based on traffic loading are more common in the Pacific Coast and East Central states. The survey indicated that five of 12 agencies assume

TABLE 1
FLEXIBLE PAVEMENT DESIGN PROCEDURES

Agency	Design Procedure(s)	Shoulder Design
Alabama	AASHTO (1986)	
Alaska	Alaska	Standard Thickness
Arizona	AASHTO (1986)	Full Depth
Arkansas	AASHTO (1986)	Standard Thickness
California	Caltrans	2% Mainline Traffic
Colorado	AASHTO (1986) with Colorado	Full Depth
Connecticut	AASHTO (1986)	Full Depth
Delaware	AASHTO (1986)	2.5% Mainline Traffic
Florida	AASHTO (1972)	Standard Thickness
Georgia	AASHTO (1972)	Standard Thickness
Hawaii	Caltrans	Full Depth
Idaho	Caltrans	Full Depth
Illinois	AASHTO (1972), Mechanistic (full depth)	Standard Thickness
Iowa	AASHTO (1986), AASHTO (1972)	Standard Thickness
Kansas	Asphalt Institute	10% Mainline Traffic
Kentucky	Kentucky (mechanistic)	10-20% Mainline Traffic
Louisiana	AASHTO (1972)	Standard Thickness
Maine	AASHTO (1972)	Standard Thickness
Maryland	AASHTO (1986) modified	10% Mainline Traffic
Massachusetts	AASHTO (1972)	Full Depth
Michigan	AASHTO (1972)	Full Depth
Minnesota	Mn DOT (AASHTO (1986), Asphalt Institute used as checks)	Standard Thickness (rural), Full Depth (urban)
Missouri	AASHTO (1986)	Standard Thickness, Full Depth
Montana	AASHTO (1972) Back Calc. Mr	Full Depth
Nebraska	AASHTO (1986)	Standard Thickness
Nevada	AASHTO (1972)	Full Depth
New Hampshire	AASHTO (1972)	Standard Thickness
New Jersey	AASHTO (1972), AASHTO (1986)	Full Depth, 10% Mainline Traffic

TABLE 1 (*Continued*)

Agency	Design Procedure(s)	Shoulder Design
New Mexico	AASHTO (1972)	20% Mainline Traffic
New York	NYSDOT	Standard Thickness, Full Depth
North Carolina	AASHTO (1972)	3% Mainline Traffic
North Dakota	AASHTO (1972)	Standard Thickness
Oklahoma	AASHTO (1986)	Full Depth
Ohio	AASHTO (1986)	Standard Thickness
Oregon	AASHTO (1986), Asphalt Institute, Mechanistic	Full Depth
Pennsylvania	AASHTO (1972)	Standard Thickness
Rhode Island	AASHTO (1986)	Full Depth
South Carolina	AASHTO (1972)	Standard Thickness
South Dakota	AASHTO (1986)	Standard Thickness
Tennessee	AASHTO (1972)	2% Mainline Traffic
Texas	Texas FPS	Full Depth
Utah	AASHTO (1972)	Full Depth
Vermont	AASHTO (1972)	Standard Thickness
Virginia	AASHTO (1972), VDOT	2.5% Mainline Traffic
Washington	WSDOT (mechanistic), AASHTO (1986)	10% Mainline Traffic
West Virginia	AASHTO (1986)	Full Depth
Wisconsin	AASHTO (1972)	Standard Thickness, Full Depth
Wyoming	AASHTO (1972)	Full Depth
Alberta	RTAC Prototype Method, Asphalt Institute	Full Depth
British Columbia	Canadian Good Roads Association	Standard Thickness
Nova Scotia	Asphalt Institute	Standard Thickness
Ontario	Ontario Pavt. Anal. of Cost (OPAC)	Standard Thickness
Quebec	AASHTO (1986)	Full Depth
Saskatchewan	Shell (mechanistic)	10% Mainline Traffic

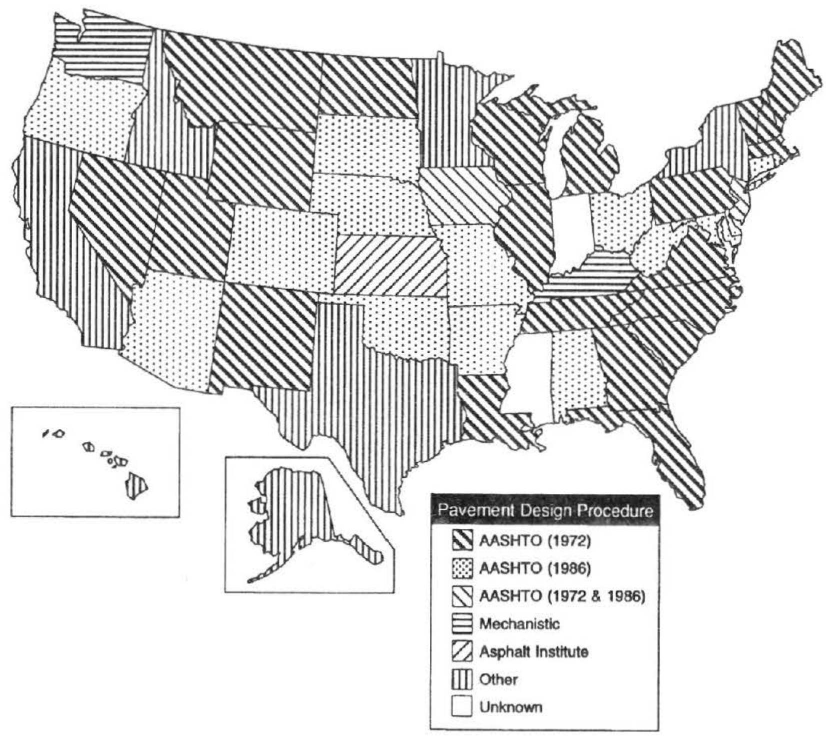


FIGURE 3 Flexible pavement design procedures.

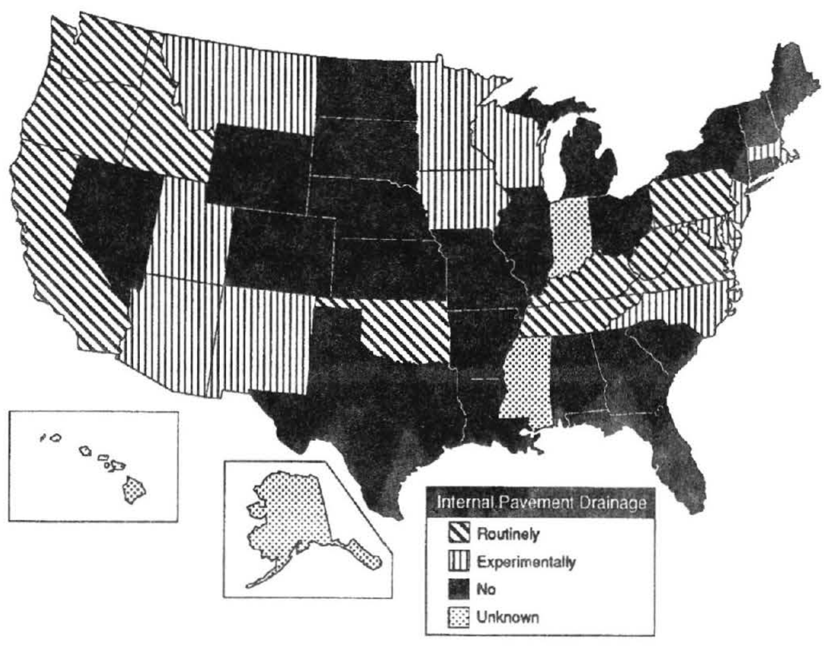


FIGURE 4 Internal drainage of flexible pavement.

three percent or less of the main line traffic loading for shoulder design, five use 10 percent and three use 10–21 percent.

Anticipated Modifications in Flexible Pavement Design Practice

Anticipated changes in state flexible design practice are summarized in Figure 7. As shown, 22 agencies indicated an eventual shift to the use of mechanistic models. Twelve agencies will use resilient modulus testing for materials characterization while 10 will adopt the 1986 AASHTO Pavement Design Guidelines. Six agencies indicated their intention to incorporate permeable bases into flexible pavement. Other anticipated modifications cited by four agencies each included life-cycle cost analysis for pavement type selection and the incorporation of falling weight defectometer test data into the pavement design process. Research on flexible pavement design is discussed in Chapter Seven.

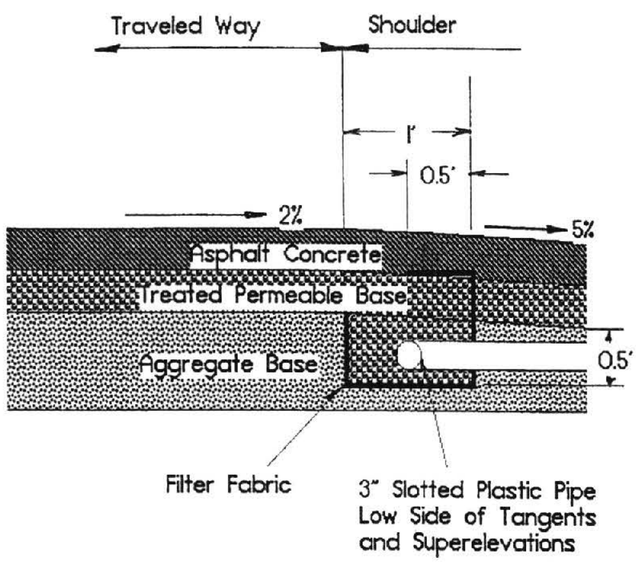


FIGURE 5 Flexible pavement internal drainage detail (from *Highway Design Manual*, California Department of Transportation, Sacramento (1990).

TABLE 2
ASSUMED STRUCTURAL CONTRIBUTION OF PERMEABLE MATERIAL

State	AASHTO Layer Coefficient		
	Asphalt Treated/ Stabilized	Cement Treated	Untreated
Arizona	0.28	NA	NA
California	1.4[1]	1.7[1]	1.1[1]
Hawaii	1.4[1]	NA[2]	1.1[1]
Kentucky	0.2	NA	0.14
Maryland	0.14	NA	0.14
Massachusetts	NA	NA	0.14
Minnesota	0.22	NA	0.14
Montana	NA	NA	0.14
New Jersey	0.14	NA	0.14
New Mexico	0.12	0.12	0.1
Oklahoma	0.14	500,000[3]	NA
Oregon	0.2	NA	0.1-0.14
Pennsylvania	0.3	NA	0.11
Tennessee	0.3	NA	NA
Utah	NA	NA	0
Virginia	0.10	0.18	0.15
West Virginia	0.30	NA	NA
Wisconsin	0.2-0.3	0.15-0.25	0.14
British Columbia	0.14-0.21	NA	0.14
Ontario	0.14	0.14	0.14

[1]Gravel Factor.
[2]Not Applicable.
[3]Resilient Modulus.

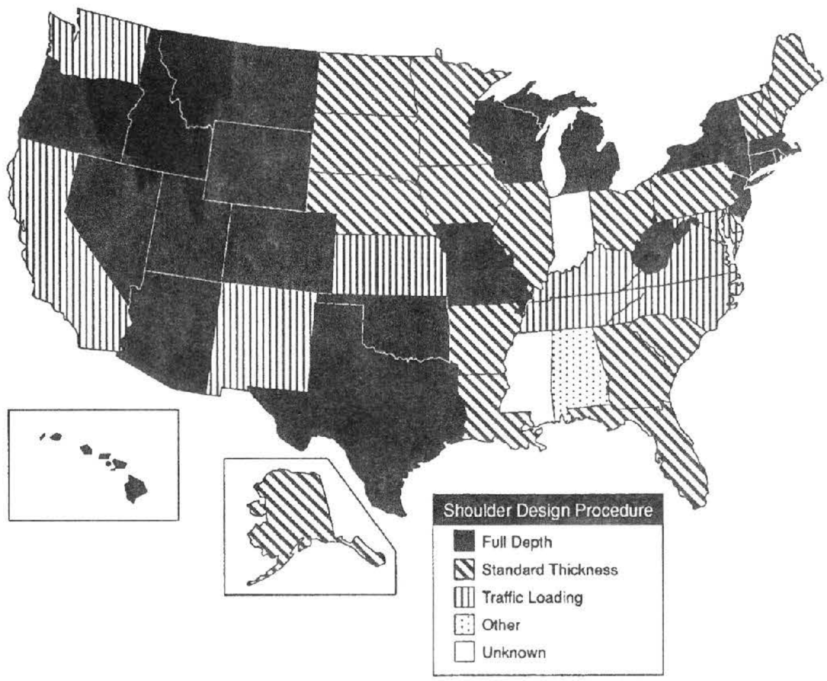


FIGURE 6 Flexible pavement shoulder design.

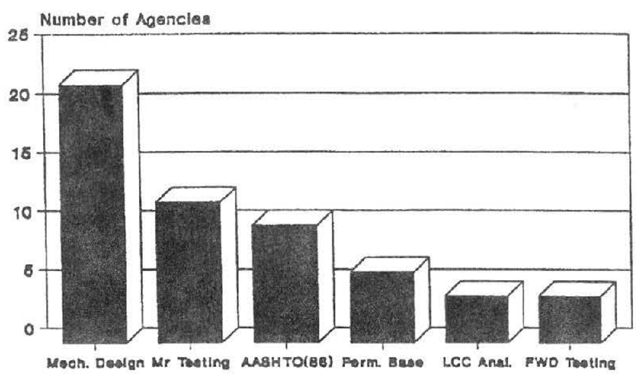


FIGURE 7 Anticipated changes in flexible design.

RIGID PAVEMENT DESIGN

BACKGROUND

The first portland cement concrete pavement in the United States consisted of a 10-ft wide by 220-ft long slab constructed in Bellefontaine, Ohio in 1891. Early concrete pavements were normally of a 6–7-in. uniform thickness placed directly on the subgrade. With time, it became apparent that subgrade type played a significant role in pavement performance.

Beginning in the 1920s, a number of researchers became involved in the study of stresses and strains developed in concrete pavements under load. The work of Westergaard, initially published in 1925 (*19*), provided the basis for a rational concrete pavement design procedure that was ultimately introduced by the Portland Cement Association (*18*) and was based on the prevention of premature fatigue cracking. Westergaard's method for computing stresses in concrete pavement was based on two assumptions. The first was that the subgrade acts as a Winkler foundation. The pressure between slab and subgrade is proportional to deflection, which he referred to as the modulus of subgrade reaction (k). Winkler also assumed that the slab and subgrade were in full contact, although the results of the Arlington Road Test (*20*) revealed that this was not the case even for flat slabs with no temperature differential between the slab top and bottom.

Accordingly, Westergaard's equations were modified to conform to the results of field measurements made by a number of researchers including Spangler (*21*) and Pickett (*22*). The results of the test tracks at Bates, Illinois and Pittsburg, California (1920–1922) demonstrated the efficacy of thickened slab edges. This design feature, shown in section in Figure 8, became virtually standard after 1930 and remained so for approximately 20 years.

The effect of steel reinforcement on concrete pavement performance was also studied at the Bates and Pittsburg test tracks where it was found to be only marginally beneficial. A more positive assessment of this feature was made in a comprehensive report presented at the 5th annual meeting of the Highway Research Board in 1925 by C. A. Hogentogler (*23*). He concluded that steel reinforcement served to delay the appearance of cracks and hold the fractured slabs together resulting in improved ride quality. An early design procedure for reinforced concrete pavements was published by Grinter (*17*) in 1931.

The Bates Test Road also demonstrated the benefits of longitudinal joints, which have been used routinely since the 1920s. The use of transverse joints in the form of weakened plane contraction joints dates from the same period.

The reduction of edge stresses through the use of dowels for improved load transfer was recognized by Westergaard who presented a procedure for its calculation at the 8th annual meeting of the Highway Research Board in 1928 (*24*). Dowel design with respect to faulting progression has been largely by experience, although a microcomputer program, PFAULT, and other faulting models have been developed to predict faulting of doweled and undoweled jointed pavements (*25*).

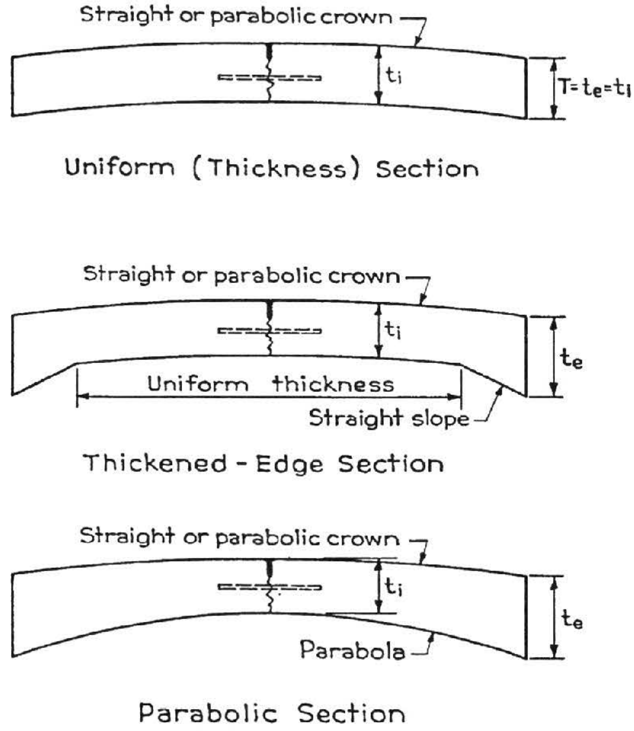


FIGURE 8 PCC pavement typical sections (*24*).

Tranverse expansion joints were commonly used on early concrete pavements to provide space for movement when concrete slabs lengthen as a result of temperature changes. Vertical openings filled with a mastic were placed at 30- to 150-ft intervals for this purpose. The use of expansion joints was virtually standard practice by the mid 1930s, but has since been found to be unnecessary except where the pavement abuts a structure.

The Maryland Test Road (1949) involved accelerated testing of a 1.1-mile section of a 9-7-9 in. concrete pavement with 40-ft contraction joints (doweled) and a 120-ft expansion joint spacing. Significant findings of the test included the effects of various axle loads and configurations on pavement performance. The test results indicated that damage was related to the occurrence of pumping, and that pumping was found to be much more severe on fine-grained as opposed to granular subgrades. Pavement stress and deflection were significantly affected by temperature, warping, and truck speed. These findings were to have considerable influence on the development on future concrete pavement design procedures.

The AASHO Road Test of 1958–1960 included 156 rigid pavement test sections (See Chapter Two on the background of flexible pavement design for more information). The principal variables were PCC slab thickness, reinforcement, subbase thickness, and traffic loading. The performance equations developed as a result of two years of testing pavement loading, thickness, and serviceability. Based on the results, the Portland Cement Association (PCA) revised its design procedure in 1966 (*26*).

The first continuously reinforced concrete pavement (CRCP) was constructed by the state of Indiana in 1938. Built with continuous longitudinal reinforcement, CRCP has no contraction or expansion joints. Cracks develop at random and remain tightly closed, which minimizes the ingress of water or soil fines. As was the case with JPCP and JRCP, early CRCP was constructed directly on subgrade. Problems with edge pumping eventually resulted in the use of aggregate and, ultimately, stabilized bases where appropriate.

Designs of early CRCP projects were based primarily on experience. In time, a number of rational design procedures evolved (*7,27,28,29*). The 1972 AASHTO *Pavement Design Guidelines* included CRCP through a modification of load transfer factors used for reinforced pavements. In recent years, a number of mechanistic models have been developed for the design of concrete pavements (*30,31,32*), one of which, the Illinois procedure (*33*), has been adopted as a standard by the Illinois Department of Transportation.

In 1984, the PCA revised its design procedure (*34*) to include erosion (pumping and faulting) in addition to traditional stress/fatigue design criteria.

In 1986, AASHTO revised the 1972 interim pavement design guidelines (*11*). While the basic rigid pavement algorithms of the AASHO Road Test were retained, the procedure was expanded to include reliability, internal drainage, environmental conditions, tied shoulders, and pavement management considerations.

AGENCY PRACTICE

The 54 individual agency responses on rigid pavement and shoulder design, shown by Table 3, reveal that a number of agencies employ more than one design procedure for the three basic types of rigid pavement.

Jointed Plain Concrete Pavement (JPCP)

As shown in Figure 9, the 1986 AASHTO procedure is favored by 21 states, primarily in the Midwest, while the 1972 version is widely used (12 states) in other areas. Three states employ in-house empirical systems, while two have adopted mechanistic models.

Reinforced Concrete Pavement (RCP)

A summary of the agency responses with respect to RCP design is shown by Table 3. Figure 10 illustrates that although RCP is used sparingly in the western and southeastern United States, it is commonly used in the Midwest and Northeast. The 1986 AASHTO procedure is employed by a plurality of agencies (11) followed by the 1972 AASHTO procedure (four agencies), the PCA procedure (three agencies), and in-house empirical procedures (two agencies).

Continuously Reinforced Concrete Pavement (CRCP)

We see in Figure 11 that CRCP is used more in the South and East Central regions of the continental United States than in other regions.

The 1986 AASHTO procedure is favored by the majority of states for the design of CRCP (14 states) followed by the 1972 AASHTO procedure (four states) and the PCA procedure (three states).

The design periods employed by the responding agencies for all three rigid pavement types are summarized below.

Number of Agencies	Design Period (years)
1	12–20
30	20
2	20–25
8	30
1	20–30
1	35
1	40

Rigid Pavement Shoulder Design

Tied concrete shoulders are used routinely by 33 of the responding agencies and by 9 agencies on an experimental basis. Almost without exception, concrete shoulders are tied to the pavement slab.

As shown by Figure 12, 26 agencies use full-depth designs for rigid pavement shoulders while 10 use standard thicknesses for shoulder sections. Seven agencies taper concrete pavement thickness at the pavement-shoulder interface (full-depth taper). Four agencies design the shoulder structural section based on an assumed percentage of mainline traffic ranging from 2 to 10 percent.

Figure 13 shows that full-depth shoulders are favored for rigid pavements by the majority of states west of the Mississippi River (17 of 22). Standard thicknesses for rigid pavement shoulders are commonly used in the Northeast and upper Midwest.

Four agencies indicated the use of widened lanes, a relatively recent innovation aimed at reducing edge and corner slab stresses, thus improving pavement performance. As reported in a recent FHWA publication (*35*), there has not been sufficient time to evaluate the effectiveness of this design feature.

Internal Drainage of Rigid Pavement

As was the case with flexible pavement, responses to the 1990 TRB questionnaire on pavement design practice revealed a well-defined movement to internal drainage of rigid pavement. The responses, which are summarized in Table 4, reveal that 17 agencies are incorporating untreated permeable material into rigid pavement and 16 are adding treated permeable material.

Permeable base use under rigid pavement in the United States (see Figure 14) reveals a trend toward internal pavement drainage in those states with heavy traffic loading but not necessarily those with severe weather conditions. It is widely used in the Great Lakes area, East Central, and Pacific Coast states. It is uncommon, however, in the Plains, Rocky Mountain, and Southern states. With respect to the removal of free water from treated permeable material, the preponderance of agencies (14 of 16) use pipe collector and outlet systems. Of the 17 employing untreated permeable material, 10 use "daylighting" for free water removal and 12 use pipe collector and outlet systems for this purpose.

Eleven agencies use prefabricated edge drains, and 24 install

TABLE 3
RIGID PAVEMENT DESIGN PROCEDURES

Agency	JPCP	RCP	CRCP	Shoulder Design
Alabama	AASHTO (1986)	AASHTO (1986)	AASHTO (1986)	Full Depth
Arizona	AASHTO (1986)	AASHTO (1986)	AASHTO (1986)	Full Depth
Arkansas	AASHTO (1986)	AASHTO (1986)	AASHTO (1986)	Full Depth
California	Caltrans	NA	NA	2% Mainline Traffic
Colorado	AASHTO (1986)	NA	NA	Full Depth
Connecticut	AASHTO (1986)	PCA, ACPA	AASHTO (1986), PCA, ACPA	Full Depth
Delaware	AASHTO (1986)	AASHTO (1986)	NA	Standard Thickness
Florida	AASHTO (1972)	NA	NA	3% Mainline Traffic
Georgia	AASHTO (1972)	NA	AASHTO (1972)	Full Depth Taper
Hawaii	PCA	NA	NA	Full Depth
Idaho	AASHTO (1972)	AASHTO (1972)	AASHTO (1972)	Full Depth
Illinois	Illinois DOT	AASHTO (1972)	AASHTO (1972)	Full Depth Taper
Iowa	AASHTO (1986), PCA	NA	NA	Full Depth
Kansas	AASHTO (1986)	PCA	NA	Full Depth Taper
Kentucky	Mechanistic[1]	NA	NA	10%+ Mainline Traffic
Louisiana	AASHTO (1986)	NA	NA	Standard Thickness
Maine	AASHTO (1972)	NA	NA	Standard Thickness
Maryland	NA	AASHTO (1986)	AASHTO (1986)	Full Depth
Michigan	AASHTO (1986)	AASHTO (1986)	NA	Full Depth Taper
Minnesota	AASHTO (1972)	AASHTO (1972)	NA	Standard Thickness
Missouri	MHTD	MHTD	AASHTO (1986)	Full Depth
Montana	PCA	NA	NA	Full Depth
Nebraska	AASHTO (1986)	NA	NA	Full Depth
Nevada	AASHTO (1972)	NA	NA	Full Depth
New Jersey	NA	NA	Standard Thickness, AASHTO (1986), PCA	Full Depth 10% Mainline Traffic
New Mexico	AASHTO (1986)	NA	NA	Full Depth
New York	NYSDOT	NYSDOT	NA	Full Depth
North Carolina	AASHTO (1972)	NA	NA	Full Depth
North Dakota	AASHTO (1972)	NA	NA	Standard Thickness
Ohio	AASHTO (1986)	AASHTO (1986)	AASHTO (1986)	Full Depth
Oklahoma	AASHTO (1986)	AASHTO (1986)	AASHTO (1986)	Full Depth
Oregon	AASHTO (1986)	NA	AASHTO (1986)	Full Depth
Pennsylvania	AASHTO (1972)	AASHTO (1972)	AASHTO (1972)	Standard Thickness
Rhode Island	AASHTO (1986)	AASHTO (1986)	AASHTO (1986)	Full Depth
South Carolina	AASHTO (1972)	NA	NA	Standard Thickness
South Dakota	AASHTO (1986)	NA	AASHTO (1986)	Standard Thickness
Tennessee	AASHTO (1986)	NA	NA	Full Depth
Texas	AASHTO (1986)	AASHTO (1986)	AASHTO (1986)	Full Depth
Utah	AASHTO (1972)	NA	NA	Full Depth
Virginia	AASHTO (1986), PCA	AASHTO (1986), PCA	AASHTO (1986), PCA	Full Depth Taper
Washington	AASHTO (1986)	NA	NA	Full Depth
West Virginia	NA	AASHTO (1986)	NA	Standard Thickness
Wisconsin	AASHTO (1972)	NA	NA	Standard Thickness
Wyoming	AASHTO (1986)	NA	NA	Full Depth
Ontario	Ontario, PCA	NA	NA	Full Depth, Full Depth Taper
Quebec	PCA, AASHTO (1986)	NA	NA	Full Depth

[1]AASHTO (1986) for comparison.

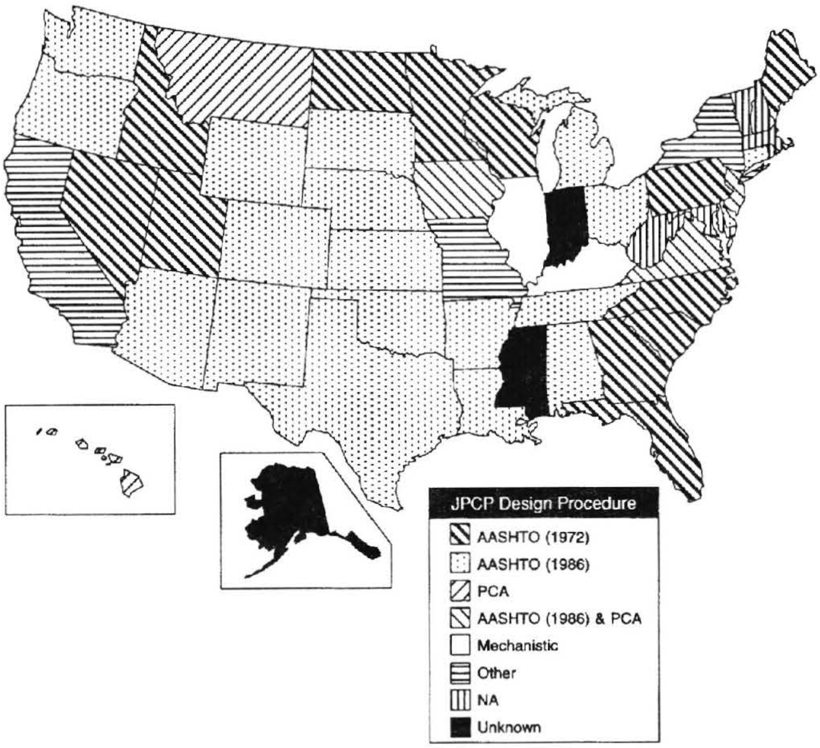


FIGURE 9 Jointed plain concrete pavement design.

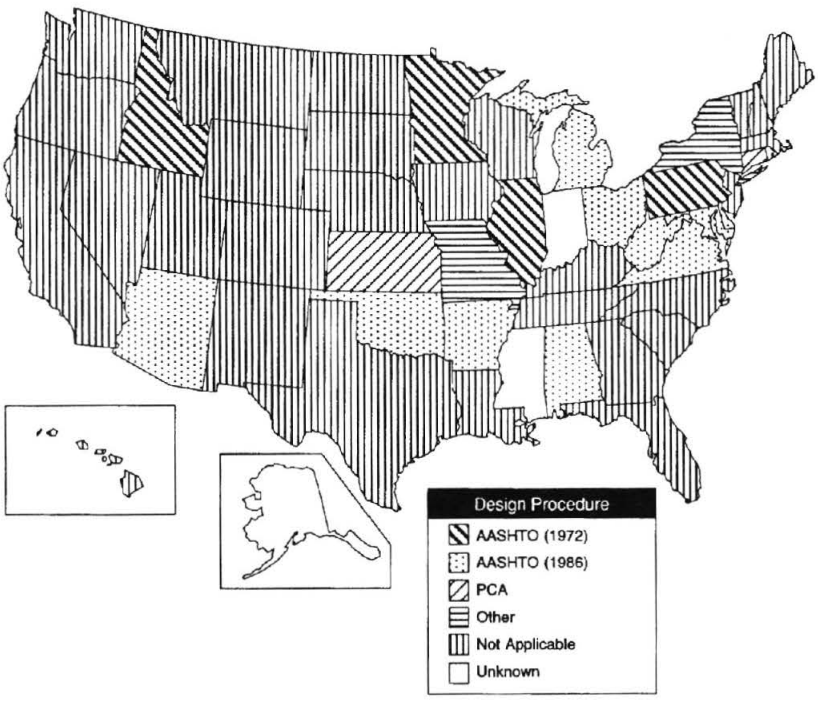


FIGURE 10 Reinforced concrete pavement design.

conventional edge drains. Typical rigid pavement sections with permeable base and collector and outlet pipes are shown by Figure 15.

Anticipated Modifications in Rigid Pavement Design Practice

Anticipated changes in rigid design practice are summarized in Table 5. As shown, seven agencies plan to incorporate permeable material into rigid pavements while six plan to adopt the 1986 AASHTO Pavement Design Guidelines. Other projected modifications in rigid pavement design practice by a significant number of agencies include resilient modulus testing (five agencies), use of mechanistic models for design (four agencies), life-cycle cost analysis for pavement type selection (four agencies), and the use of dowels (three agencies).

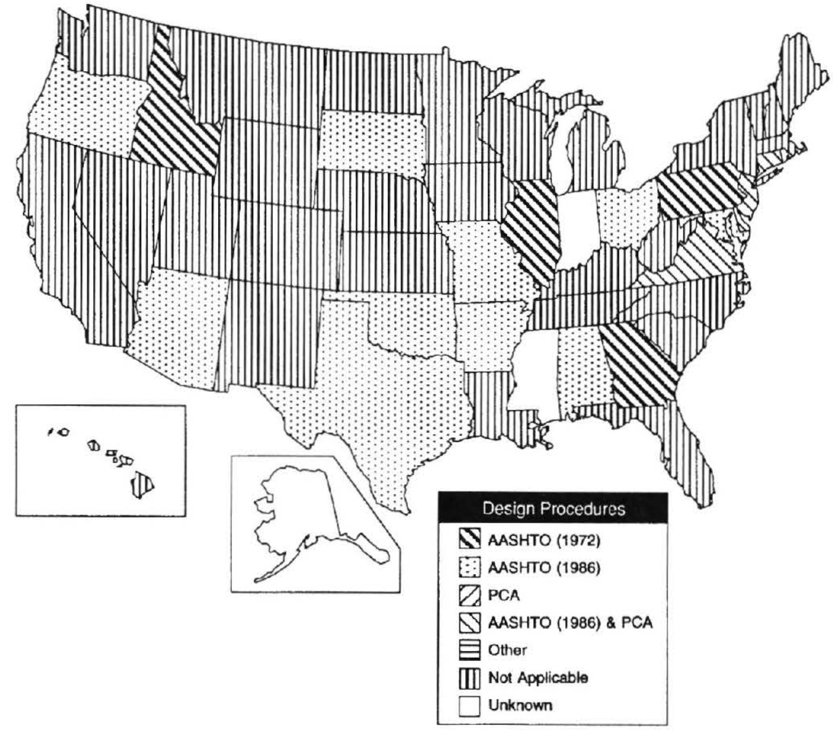


FIGURE 11 Continuously reinforced concrete pavement design.

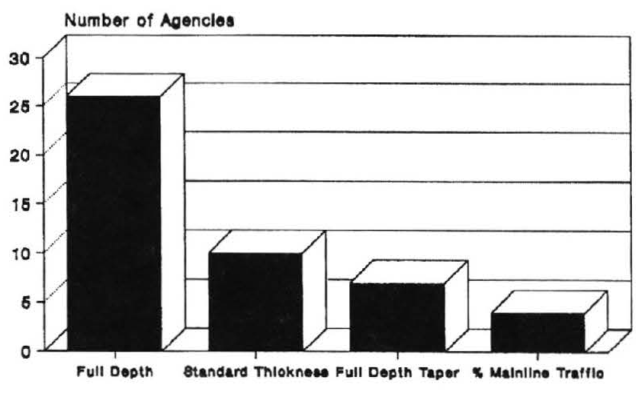


FIGURE 12 Rigid pavement shoulder design.

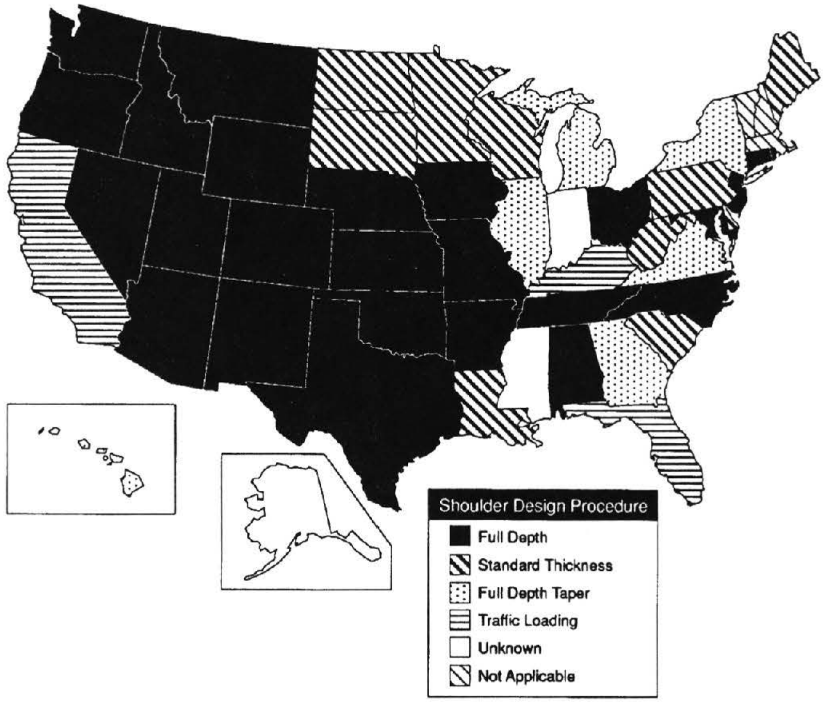


FIGURE 13 Rigid pavement shoulder design in the United States.

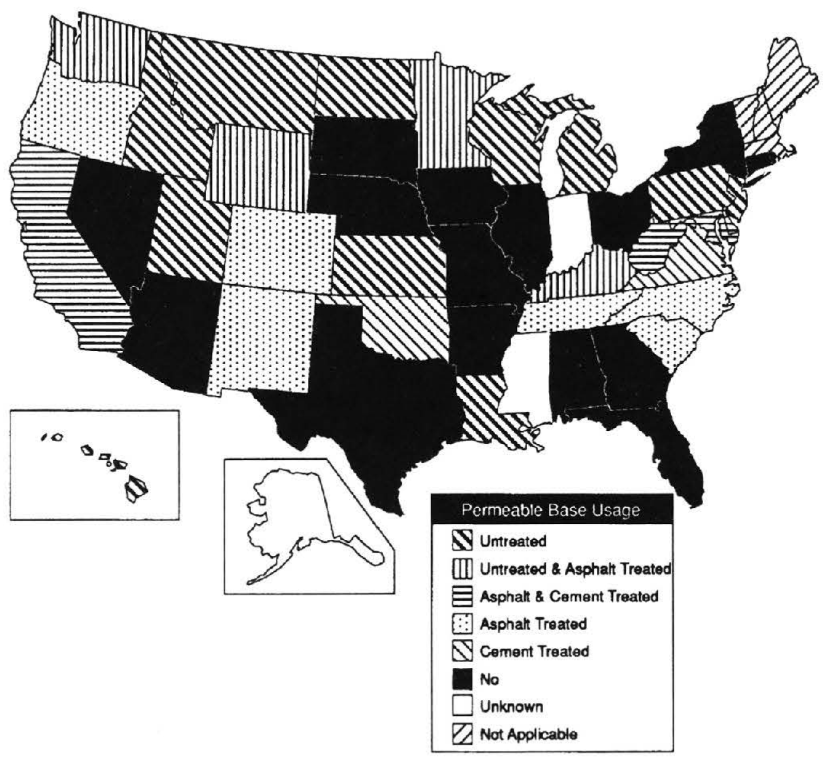
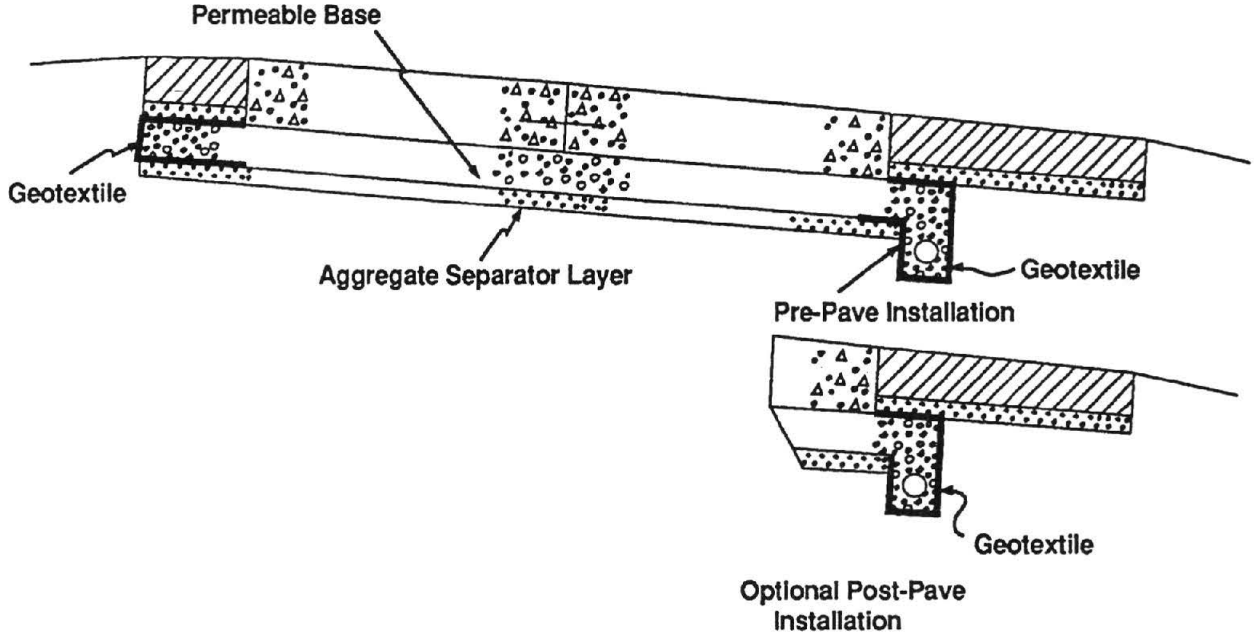
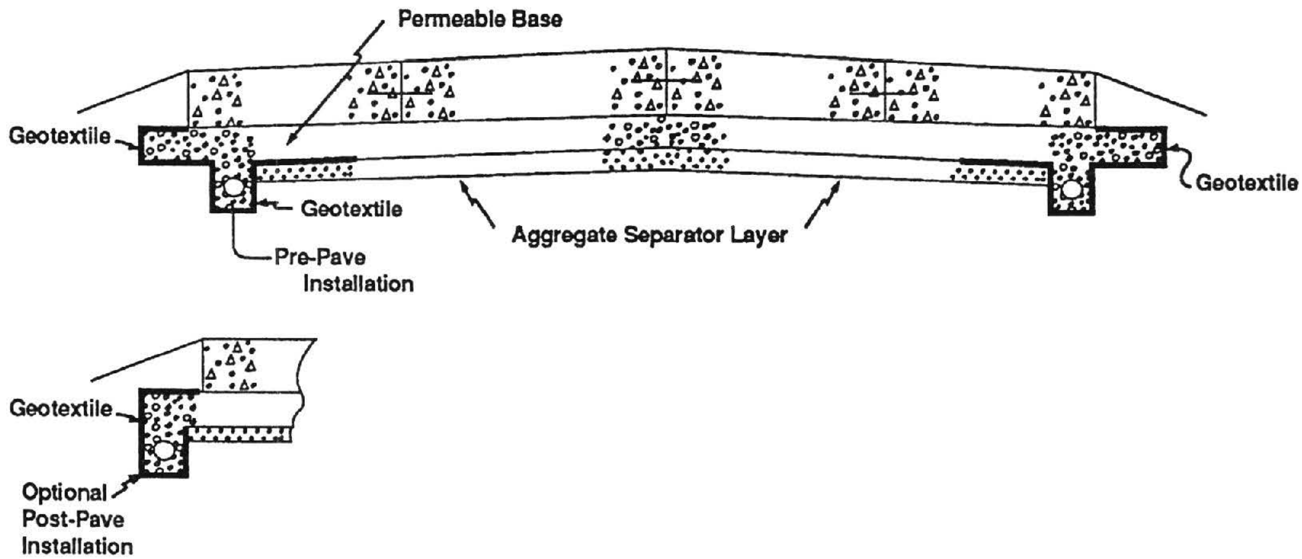


FIGURE 14 Internal drainage of rigid pavement.



Edgedrain Location for Concrete Pavement with Asphalt Concrete Shoulders



Edgedrain Location for Crowned Concrete Pavement with Tied Concrete Shoulders

FIGURE 15 Typical sections of internally drained rigid pavement (from "Drainable Pavement Sections," Participant Notebook, Demonstration Project 87, FHWA (1992)).

TABLE 4
INTERNAL DRAINAGE OF RIGID PAVEMENT

Agency	Untreated Permeable Material	Treated Permeable Material	Edge Drains: Conventional	Edge Drains: Prefab
Arkansas			X	X
California		X[2]	X	
Colorado		X[1]		
Connecticut			X	
Delaware		X[2]	X	
Florida				X
Hawaii	X[1,2]		X	
Idaho	X[1,2]			
Illinois			X	X
Iowa			X	
Kansas	X[2]			
Kentucky	X[1]	X[2]	X	
Louisiana	X[1]			X
Maryland		X[2]	X	
Michigan	X[2]		X	X
Minnesota	X[2]	X[2]	X	
Missouri				X
Montana	X[1]			
New Jersey	X[1,2]			
New Mexico		X[2]		
New York			X	
North Carolina		X[2]		
North Dakota	X[2]		X	
Ohio			X	X
Oklahoma		X[2]	X	
Oregon		X[2]	X	
Pennsylvania	X[2]		X	X
South Carolina		X[2]	X	X
Tennessee		X[2]	X	X
Utah	X[1,2]			
Virginia	X[1,2]	X[2]		
Washington	X[1]	X[1]	X	
West Virginia		X[2]		
Wisconsin	X[2]		X	
Wyoming	X[1]	X[1,2]	X	
Ontario	X[2]		X	X
Quebec			X	

[1] "Daylighted."
[2] Collector & Outlet.

TABLE 5
ANTICIPATED CHANGES—RIGID PAVEMENT

Number of Agencies	Anticipated Change
12	None
8	Use of Treated and Untreated Permeable Bases
7	Adopt 1986 AASHTO Design Guidelines
5	Adopt Resilient Modulus Testing
4	Use of Life Cycle Cost Analysis for Pavement Type Selection
4	Adopt Mechanistic Design Procedures
3	Use of Dowels
1	Use of Edge Drains
1	Use of Sealed and Tied Shoulder Joints
1	Introduce Reliability as a Factor in Pavement Design
1	Establish Quality Assurance/Quality Control Procedures
1	Improved Procedure for Calculating ESALs

Completed and ongoing research on rigid pavement design is described in Chapter 7, "Pavement Research."

CHAPTER FOUR

DESIGN ELEMENTS COMMON TO RIGID AND FLEXIBLE PAVEMENT

Several design considerations are common to both rigid and flexible pavements. These must be evaluated regardless of pavement type, and may be among the first items considered in a design. This is because their consideration may lead the designer to choose between a rigid or flexible pavement, and then to proceed with the detailed structural design of the selected option. Some design considerations common to both pavement types, however, cannot be considered until after a decision has been made regarding the use of a rigid or flexible pavement. The design elements common to flexible and rigid pavement include life-cycle cost analysis, traffic loading, serviceability loss due to frost heave and swelling, and materials characterization.

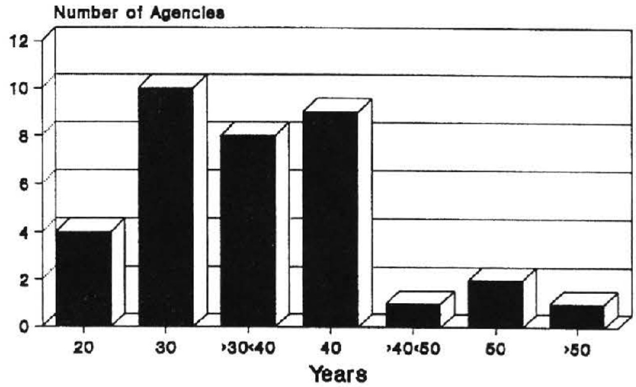


FIGURE 16 Life-cycle cost analysis periods.

Life-Cycle Cost Analysis

Life-cycle cost analysis can be defined as a procedure by which to select a pavement design alternative that will provide a satisfactory level of service at the lowest cost over time. The economic analysis methods used most commonly for this purpose include present worth, annualized cost, and rate of return. The analysis is most sensitive to the factors of inflation, discount rate, and analysis period. It is necessary to introduce into an economic analysis elements which can only be estimated and are subject to significant variation, including future maintenance and rehabilitation cost and frequency. To be effective, a life-cycle cost analysis procedure must be organized and consistent, such as those suggested by Dell'Isola and Kirk (*36*) and Chapter 3 of the AASHTO *Guide for the Design of Pavement Structures* (*11*). The FHWA, in issuing its 1989 pavement policy for highways, took a strong position on the use of life-cycle cost analysis as a standard part of the pavement design process. Section 626.9(c) of that policy was modified "to require an economic analysis for major rehabilitation projects as part of the pavement rehabilitation selection process which must be acceptable to the FHWA" (*37*). The requirement that the states use life-cycle cost in the state planning process for the design of "bridges, tunnels, and pavement" is an integral part of the Intermodal Surface Transportation Efficiency Act of 1991.

As of early 1991, thirty-four states were using life-cycle cost analysis for pavement type selection. As shown in Figure 16, the analysis periods range from 20 to more than 50 years. Most states use from 30 to 40 years for this purpose.

Traffic Loading

All but one of the responding agencies characterize traffic loading by equivalent 18 kip single axle loadings for the design of flexible pavement. The five agencies employing the PCA design procedure for the design of rigid pavements use average daily truck traffic (ADTT) and axle load spectra for this purpose. New York introduces traffic loading into both rigid and flexible pavement design with "Directional Design Hour Volume." A truck volume in excess of 10 percent of the total requires the selection of a pavement design in the "heavy" category from the New York State Department of Transportation *Design Manual,* Pavement Selection Guide.

Serviceability Loss Due to Frost Heave and Swelling

Nearly half (20) of the agencies responding to the questionnaire modify pavement designs to account for loss of serviceability due to frost heave or swelling (Table 6). Of these, five use the procedure contained in the 1986 AASHTO *Pavement Design Guidelines* or employ a regional factor with the 1972 version. Other commonly used mitigations for frost heave and swelling include encapsulation, removal and replacement of frost-susceptible and swelling soils, chemical stabilization including lime treatment, or increased pavement structural section thickness.

Materials Characterization

Agency input with respect to tests employed by the states for characterization of the most commonly used pavement materials is summarized by Table 7. It should be noted that the notation NA (Not Applicable) does not necessarily indicate nonuse of the material, but rather that the strength or "layer coefficient" is assumed for design purposes based on past experience or research.

As shown by Table 7, a clear plurality of responding agencies, 40, employ the Marshall Stability Test for asphalt concrete (AC)

TABLE 6
PAVEMENT DESIGN MODIFICATIONS FOR FROST HEAVE AND SWELL

State	Frost Heave/Thaw Weakening	Swelling
Alaska	Control -No. 200 sieve size material to a depth of 42"	NA
Arizona	Judgment	Encapsulate with rubber asphalt or fabric
California	NA	Lime treatment
Georgia	AASHTO (1972) Regional Factor	AASHTO (1972) Regional Factor
Idaho	Climatic Factor	200 psi exudation pressure Reduce compaction pressure
Illinois	Top foot of subgrade chemically modified or replaced	Top foot of subgrade chemically modified or replaced
Kansas	NA	Lime treatment
Maine	Minimum 36" of pavement and gravel based on degree days	NA
Massachusetts	Increase structural number	NA
Michigan	Replace to a depth of 5' from pavement surface	NA
Minnesota	Blend frost susceptible soils to frost depth (4-6')	Blend frost susceptible soils to frost depth (4-6')
Nebraska	AASHTO (1986)	AASHTO (1986)
New Mexico	AASHTO (1972) Regional Factor	AASHTO (1972) Regional Factor
Ohio	Frost susceptible material removed to a depth of 3' from pavement surface	Expansive soil removed to a depth of 3' from pavement surface
Pennsylvania	Additional strength requirement based on frost factor	NA
Texas	NA	Remove and replace, Texas FPS, vertical moisture barrier
Utah	Remove and replace frost susceptible material or increase pavement thickness	Remove and replace expansive soil or increase pavement thickness
West Virginia	AASHTO (1986)	AASHTO (1986)
Wisconsin	Design Group Index	Design Group Index
Ontario	Increase base and subbase thickness based on frost susceptibility of subgrade soils	NA

mixture design, while six employ the Hveem Stability Test for this purpose. Four agencies are using some form of elastic or resilient modulus (Mr) testing to characterize the structural contribution of AC. It should be noted that the Mr, while similar conceptually to the modulus of elasticity (E), differs in that it is determined from triaxial repeated load, as opposed to static testing. Only recoverable strain is considered in the calculation of the Mr.

Twenty-eight of the responding agencies employ some type of laboratory strength test (CBR, R-value, E, or Mr) to characterize aggregate base and subbase. Of these, 14 employ the CBR test.

TABLE 7
PAVEMENT MATERIALS CHARACTERIZATION

Agency	AC[1]	AB[2]	CTB[3]	LTS[4]	SC[5]	ATPM[6]	UPM[7]	SG[8]
Alabama	Marshall	CBR[9]	UC[10]	UC	NA[11]	NA	NA	CBR
Alaska	Marshall	Grading	NA	NA	NA	NA	NA	Grading
Arizona	Marshall	R-Value	UC	UC	UC	NA	R-Value	R-Value
Arkansas	Marshall	NA	NA	NA	NA	NA	NA	R-Value
California	Hveem	R-Value	UC	R-Value	NA	NA	NA	R-Value
Colorado	Eac[11]	R-Value	k[12]	k	NA	R-Value	R-Value	Mr[13]
Connecticut	Marshall	Grading	NA	NA	NA	NA	NA	Mr
Delaware	Marshall	CBR	UC	NA	UC	NA	NA	CBR
Florida	Marshall	CBR	NA	NA	UC	NA	NA	CBR
Georgia	Marshall	Grading	NA	CBR	NA	NA	NA	CBR
Hawaii	Hveem	R-Value	NA	NA	NA	NA	R-Value	R-Value
Idaho	Hveem	R-Value	UC	R-Value	R-Value	R-Value	R-Value	R-Value
Illinois	Marshall	CBR	UC	UC	UC	NA	NA	CBR
Iowa	Marshall	Grading	NA	NA	NA	NA	NA	R-Value, k
Kansas	Marshall	Grading	NA	NA	Esg[14]	NA	NA	Mr
Kentucky	Marshall	Grading	UC	UC	UC	NA	NA	CBR
Louisiana	Marshall	Grading	UC	NA	UC	NA	NA	R-Value
Maine	Hveem	CBR	NA	NA	NA	R-Value	CBR	CBR
Maryland	Marshall	CBR	UC	CBR	UC	NA	NA	CBR
Massachusetts	Marshall	NA	NA	NA	NA	NA	NA	CBR
Michigan	Marshall	Grading	NA	NA	NA	NA	NA	NA?
Minnesota	Marshall	Grading	NA	NA	NA	Grading	Grading	R-Value[14,26]
Missouri	DC[15]	NA	NA	NA	NA	NA	NA	Group Index
Montana	Marshall	R-Value	UC	NA	NA	NA	NA	R-Value
Nebraska	ST[16]	NA	NA	NA	NA	NA	NA	Mr
Nevada	Hveem	R-Value	UC	UC	NA	NA	NA	R-Value
New Hampshire	Marshall	NA	NA	NA	NA	NA	NA	NA
New Jersey	Marshall	Grading	NA	NA	NA	NA	NA	CBR (est.)

TABLE 7 (*Continued*)

Agency	AC[1]	AB[2]	CTB[3]	LTS[4]	SC[5]	ATPM[6]	UPM[7]	SG[8]
New Mexico	Marshall	R-Value	UC	UC	UC	Mr	R-Value	R, Mr, CBR
New York	Marshall	NA	NA	NA	NA	NA	NA	NA
North Carolina	Marshall	NA	UC	UC	UC	NA	NA	CBR
North Dakota	Marshall	NA	NA	NA	NA	NA	NA	CBR
Ohio	Marshall	NA	NA	NA	NA	NA	NA	Mr[17]
Oklahoma	Hveem	NA	NA	NA	NA	NA	NA	Mr
Oregon	Mr	Mr	UC	Mr	UC	NA	Mr	Mr
Pennsylvania	Marshall	Grading	UC	NA	NA	NA	Gradation	CBR
Rhode Island	Marshall	CBR	NA	NA	NA	NA	CBR	CBR
South Carolina	Marshall	NA	NA	NA	NA	NA	NA	CBR, Esg
South Dakota	Marshall	CBR	NA	NA	NA	NA	NA	CBR
Tennessee	Marshall	CBR	CBR	CBR	CBR	NA	NA	CBR
Texas	Hveem	TT[18]	UC	UC	NA	NA	NA	DSC[19]
Utah	Marshall	CBR	UC	CBR	CBR	NA	NA	CBR
Vermont	Marshall	CBR	NA	NA	NA	NA	CBR	CBR
Virginia	Marshall	NA	UC	UC	UC	NA	NA	CBR
West Virginia	E[20]	E	E	E	E	E	E	Mr
Wisconsin	Marshall	CBR	UC	CBR	NA	CBR	CBR	DGI[21]
Wyoming	Marshall Hveem	R-Value	UC	NA	NA	NA	NA	R-Value
Alberta	Marshall	Proctor	NA	NA	Freeze-Thaw	NA	NA	CBR[22]
British Columbia	Marshall	23	24	NA	NA	Gradatio n	Gradation	25
Nova Scotia	Marshall	CBR	NA	NA	NA	NA	CBR	CBR
Ontario	Marshall	Grading		NA	NA	NA	Gradation	26
Quebec	27	CBR	NA	NA	NA	NA	CBR	CBR
Saskatchewan	28	Mr	NA	CBR	Mr	NA	CBR	CBR

[1]Asphalt Concrete.
[2]Aggregate Base & Subbase.
[3]Cement Treated Base.
[4]Lime Treated Subgrade.
[5]Soil Cement.
[6]Asphalt Treated Permeable Material.
[7]Untreated Permeable Material.
[8]Subgrade.
[9]California Bearing Ratio.
[10]Unconfined Compressive Strength.
[11]Not Applicable.
[12]Modulus of Subgrade Reaction.
[13]Resilient Modulus.
[14]Subgrade Modulus.
[15]Direct Compression.
[16]Split Tensile.
[17]Based on Group Index and CBR.
[18]Texas Triaxial Compression.
[19]Dynaflect Stiffness Coefficient.
[20]Elastic Modulus.
[21]Design Group Index.
[22]Backcalculated from performance.
[23]Gradation.
[24]Flexural Strength.
[25]Unified Soil Classification System.
[26]Particle Size, Atterberg Limits, Proctor Test.
[27]Stiffness Modulus estimated from Marshall Test.
[28]Stiffness Modulus.

TABLE 8
CONCRETE PAVEMENT STRENGTH SPECIFICATIONS

		Loading			
Agency	Flexural Strength (psi)	Mid point	3d point	Compressive strength[1] (psi)	Time (days)
Alabama	650		X		28
Arizona				5000	28
Arkansas				3000	28
California				3500	28
Colorado				3000	28
Connecticut	500		X		28
Delaware				3000	28
Florida				3000	28
Georgia	450		X		28
Hawaii	650		X		28
Idaho				4500	28
Illinois	650		X		28
Iowa	600 (AASHTO) 500 (PCA)		X		28
Kansas	600		X		28
Kentucky				3500	28
Louisiana	550	X			28
Maine	525-650		X		28
Maryland	350[2]				28
Michigan	700		X		28
Minnesota	500 (675 with AASHTO)		X		28
Missouri				3500	28
Montana	500	X			28
Nebraska				3000	28
Nevada	650	X			10
New Jersey				4080 or 4250	28
New Mexico	500		X		28
North Carolina	650		X		28
North Dakota	690		X		28
Ohio	700		X		28
Oklahoma	650		X		7
Oregon	625		X		28
Pennsylvania	440		X		28
Rhode Island				3000	3 to 5
South Carolina	550		X		14
South Dakota	550		X		28
Tennessee				3500	28
Texas	650	X			7
Utah				5210	28
Virginia	650	X			28
West Virginia	660		X		28
Wisconsin	650		X		28
Wyoming	560		X		28
Ontario				25 MPA	30
Quebec	580		X		

[1]Many states also specify a minimum cement content for durability.
[2]Tensile splitting test.

The remainder assure base and subbase strength by control of grading. Usually, the strength of lime- and cement-treated materials is established primarily by unconfined compressive strength testing.

With respect to subgrade materials, while 28 agencies employ the more traditional laboratory strength tests (CBR and R-value), eight now employ resilient modulus testing.

A summary of agency rigid pavement strength requirements is presented in Table 8. Twenty-eight of the 44 agencies specifying concrete strength have a flexural strength requirement ranging from 440 to 720 psi. Of these, only five agencies specify third point (as opposed to midpoint) loading. One state, Maryland, specifies concrete strength based on the tensile splitting test.

Fifteen agencies have a compressive strength requirement ranging from 3,000 to 5,210 psi. The majority specify a 28-day curing period for concrete test specimens.

CHAPTER FIVE

FLEXIBLE PAVEMENT OVERLAY DESIGN

BACKGROUND

The warrants for overlaying either a flexible or rigid pavement include:

- Poor ride quality,
- Low skid resistance,
- Excessive rutting within the AC surfacing, and
- Extensive pavement distress due to inadequate structural capacity.

Because the first three involve standard, usually functional treatments, they do not properly fall into the category of "structural pavement design." Primary emphasis in subsequent sections of the synthesis involving overlays will therefore be given to increasing pavement structural capacity to a desired level.

In the 1940s and 1950s, flexible pavement overlay design was based on engineering judgement or component analysis, although there was some interest and activity in the measurement of pavement structural capacity by nondestructive pavement testing (NDT).

In 1955, Francis Hveem of the California Division of Highways presented the results of pavement deflection research with permanently installed General Electric travel gauges, and later, linear variable differential transformer (LVDT) gauges (*38*). Based on an analysis of these measurements, begun in 1938 and involving more than 100 in-service pavements, Hveem suggested "tolerable" deflection levels for varying thicknesses of asphalt concrete, thus providing a basic framework for an overlay design procedure addressing the prevention of premature fatigue cracking.

A major breakthrough with respect to nondestructive pavement testing occurred with the introduction of a relatively simple and inexpensive device for pavement deflection measurement by A.C. Benkelman of the FHWA at the Western Association of Highway Officials (WASHO) Road Test (*39*) in Malad, Idaho (1954–56). This device, soon to be known as the "Benkelman Beam," made it possible for a three-man crew to obtain up to 300 individual pavement deflection measurements per day. Its introduction provided a tremendous stimulus to pavement deflection research, which ultimately resulted in the development of a number of deflection-based overlay design procedures.

The 1960s and 1970s saw the development of a number of increasingly sophisticated and reliable NDT pavement testing devices, including the Dynaflect, Traveling Deflectometer, Road Rater, Le Croix Deflectograph, and the Falling Weight Deflectometer (FWD). During this same period and up to the present, a number of mechanistically based analytical procedures for overlay design have evolved, including the Shell Research (*40*) and the FHWA-ARE (*41*) procedures. These systems have become readily accessible to pavement overlay designers as a result of advances in microcomputer technology.

Flexible pavement overlay design procedures presently fall into the following basic categories which, in some cases, tend to overlap each other.

Engineering Judgement

Still widely used, engineering judgement involves a subjective decision by the engineer with respect to overlay thickness based on experience, taking into account environmental conditions, traffic loading, subgrade soil type, and the nature and extent of distress. The breadth of experience necessary for its effective application is, unfortunately, not easily transferable to younger engineers.

Standard Thickness (Distress Identification)

In this variation of the engineering judgement approach, a standard overlay thickness is prescribed for a given pavement type, thickness, and traffic loading. It offers, in one sense, less flexibility than the engineering judgement method, since overlay thickness determination becomes policy rather than a subjective decision. In a variation, "distress identification," the overlay thickness is selected based on the nature and severity of distress.

Component Analysis

Using a thickness deficiency concept, this procedure involves a comparison of the structural capacity of the existing pavement with that required to carry the traffic loading estimated for the design life of the overlay. Samples of each component of the existing structural section are subject to appropriate laboratory strength or classification tests. A composite quantification of the strength of the existing section, i.e., structural number, is subtracted from that required for a new pavement to establish required overlay thickness.

An example of a component analysis procedure for overlay design is found in the 1972 AASHTO *Interim Guides for Design of Rigid and Flexible Pavements* (*7*), in which each layer of the structural section is assigned a structural coefficient based on experience. While some entities have developed guidelines for this purpose (*42,43*), the determination of adjusted layer coefficients is based primarily on judgement. The overlay design procedure presented in the 1986 revision of the AASHTO pavement guidelines (*12*) is a mechanistically based component analysis procedure in which the structural contribution of each layer is established from a resilient modulus backcalculation procedure using FWD test data from the existing pavement.

Deflection Analysis

Deflection-based overlay design procedures are currently used by a number of states, including California, Utah, Texas, and Louisiana. They are based on the premise that the fatigue life of a pavement is a function of deflection level as measured by an appropriate NDT device. An appropriate overlay thickness is determined to reduce the design deflection to a tolerable level for the estimated traffic loading during the design life of the overlay.

Empirical deflection-based procedures are applicable to the traffic loading conditions and the fatigue characteristics of the pavement materials for which they were developed. As an example, recent laboratory and field studies (*44,45*) indicate that the fatigue resistance of asphalt concrete may be improved with the use of a rubberized binder. In order to quantify the increase in tolerable deflection level possible with rubberized asphalt binder, additional field trials will be necessary. The results would offer the possibility of significant reductions in required overlay thickness.

Mechanistic Models

Mechanistic overlay design procedures are based on the assumption that the pavement structure will respond to load as a multilayer elastic solid. Layer stiffnesses of the existing pavement are determined by laboratory resilient modulus tests or analysis of the deflection basin developed by NDT testing. Using an elastic layer or finite element analysis, overlay thickness is determined by successive iterations so as to limit tensile strain at the base of the surfacing to avoid premature fatigue cracking for the anticipated traffic loading. Rutting is controlled by limiting subgrade compressive strain. Examples of overlay design procedures employing mechanistic modeling include the Shell Research and FHWA-ARE methods (*40,41*).

Use of mechanistic models for overlay design offers the advantage of predicting pavement response using a variety of pavement materials, structural section, and loading configurations once the elastic properties of the structural section elements have been established. It should be pointed out, however, that the validity of a mechanistically based procedure is very much dependent on the validity of the input to the analysis. Establishing the elastic properties of the pavement structural section elements by laboratory testing or backcalculation introduces the possibility of significant error, as these technologies are still evolving. It should be noted that there is a difference between static and dynamic moduli obtained from backcalculation procedures and this may affect the deflection analysis and subsequent design. Also, it is extremely difficult to predict the change in stiffness with age of a critical element of the pavement structural section, the asphalt concrete surfacing.

AGENCY PRACTICE

A primary resource with respect to overlay design practice by the individual states was a series of three reports published by the FHWA in August, 1986 (*46*). These comprehensive and thorough publications included detailed questionnaire responses by the states on every significant aspect of the subject. Another useful source of information on the subject was a summary of responses to a questionnaire developed by the AASHTO Joint Task Force on Pavements in 1988 to assess state usage of the 1986 revision of the AASHTO *Pavement Design Guidelines*. This information was supplemented by follow-up inquiries.

Flexible Overlays of Flexible Pavement

Many agencies use more than one of the basic categories of overlay design or employ a method that combines several. These agencies are identified in Table 9.

Figure 17 shows that deflection analysis is used in some form by 28 agencies, followed by engineering judgement and component analysis (26 each) respectively. Eleven agencies use standard thicknesses, while 10 others use or will adopt the 1986 AASHTO procedure. Six agencies employ mechanistic models for overlay design.

The falling weight deflectometer (FWD) is the most commonly used nondestructive testing (NDT) device, with 27 agencies employing it as indicated in Figure 18. Sixteen agencies use the Dynaflect while seven employ the Road Rater. Seven agencies use the Benkelman beam.

Flexible Overlays of Rigid Pavement

Design procedures for flexible overlays of rigid pavement fall into the same basic categories as for flexible over flexible, although deflection-based procedures are not as commonly used. The primary reason for this is that even severely cracked PCC pavement will distribute applied load such that conventional deflection measurement devices (e.g., the Dynaflect) will be unable to detect a significant response. The Asphalt Institute has a deflection-based procedure that requires deflection testing of the PCC slab edge, corners, joints, and cracks to establish the need for subsealing (*42*). AC overlays of sufficient thickness to preclude reflective cracking are selected based on slab length and temperature differential.

The U.S. Army Corps of Engineers, Waterways Experiment Station (WES) also employs a deflection-based overlay design procedure for AC overlays of rigid airfield pavements. The output of the testing device (WES heavy vibrator) is converted to a dynamic stiffness modulus (DSM) with which the structural capacity of the existing pavement is established. Based on projected future loading, overlay thickness is calculated using a component analysis procedure.

A primary consideration and concern, however, in the design of AC overlays of rigid pavements is reflection cracking as opposed to premature fatigue cracking, which is the normal controlling factor with respect to overlays of flexible pavement. This is reflected in the summary of responses to the 1986 FHWA questionnaire and the 1991 follow-up inquiry shown by Table 10 and Figure 19. As shown, only seven agencies reported using a deflection- or analytical-based procedure, while 25 employed judgement and 26 standard thickness or distress identification. Fourteen agencies employ component analysis while nine use the 1986 AASHTO procedure. Mechanistic models are used by three agencies for designing AC overlays of rigid pavement.

Reflective Crack Control

Reflection cracking can be defined as a process by which cracks in an existing pavement propagate through an asphalt concrete

TABLE 9
OVERLAY DESIGN PROCEDURES—FLEXIBLE ON FLEXIBLE

	Flexible on Flexible						
Agency	Judgment	Standard Thickness	Component Analysis	Mech. Model	Defl. Anal.	AASHTO (1986)	Distress Ident.
Alabama	X						
Alaska			X	X	X		
Arizona			X			X	
Arkansas			X			X	
California					X		
Colorado			X		X		
Connecticut	X	X				X	
Delaware	X	X					
Florida						X	
Georgia	X						
Hawaii			X				
Idaho	X		X				X
Illinois		X	X		X		
Iowa					X		
Kansas	X	X			X		
Kentucky	X			X	X		
Louisiana	X		X		X		X
Maine	X	X	X			X	
Maryland	X		X		X		X
Massachusetts			X				
Michigan	X						X
Minnesota	X		X		X		
Missouri		X					
Montana			X		X		
Nebraska					X		
Nevada	X	X	X			X	
New Hampshire	X		X				
New Jersey	X		X				X
New Mexico	X		X				
New York	X	X			X		
North Carolina			X		X		
North Dakota				X			
Ohio	X	X	X	X	X		
Oklahoma	X				X		
Oregon					X		
Pennsylvania			X		X		
Rhode Island		X					
South Carolina	X		X			X	
South Dakota					X		
Tennessee	X		X		X		
Texas	X				X		
Utah	X				X		
Vermont						X	
Virginia	X					X	
Washington			X	X			
West Virginia	X					X	
Wisconsin			X		X		
Wyoming			X		X		
Alberta					X		
British Columbia							
Nova Scotia					X		
Ontario	X	X					
Quebec				X	X		
Saskatchewan					X		

overlay in a relatively short period of time (in some cases, less than 24 hours) by load-induced vertical or temperature-induced horizontal movement of the original pavement. It is common to asphalt concrete overlays of both flexible and rigid pavement. Because reflective cracking can significantly reduce pavement life, its mitigation has been the subject of intensive study since 1932 (*47,48*).

A number of researchers have introduced mechanistically based design methodologies aimed at minimizing or preventing reflection cracks. McCullough and Seeds (*49*) published an analytical procedure with a computer program (RFLCR). Another mechanistic-empirical design procedure aimed specifically at predicting reflective cracks through flexible overlays of flexible pavements was suggested by Jayawickrama et al. in 1988 (*50*). To date, however, no such analytical procedure has been adopted for routine use, presumably due to concern over the variability of input quality.

Reflective cracking of AC overlays of flexible pavements has been addressed by a number of treatments with widely varying degrees of success. These include:

- Paving Fabrics,
- Stress Absorbing Membrane Interlayers (SAMI),
- Crack Arresting Interlayers (CAI) consisting of a granular layer sandwiched between the existing pavement and the overlay,
- Increased Overlay Thickness,
- Heater Scarification of Existing Surfacing, and
- Other (crack sealing, asphalt additives, fiber reinforcement, recycling, chip seals, cold planing and scarification, cold in-place recycling).

In its 1986 questionnaire on state practice, the FHWA asked the states to indicate their degree of success with these various treatments by classifying their performance as good, marginal, or poor. The ratings of reflective crack mitigation measures by the agencies providing input are summarized by Figure 20. As shown, increased overlay thickness was found to be the most effective mitigation, followed by crack arresting interlayers (CAI) and heater scarification. Paving fabrics and SAMIs provided marginal performance.

With respect to reflective crack control of AC overlays of rigid pavement, the same means of mitigation have been used, plus the following:

- Crack and seat PCC slabs prior to overlay,
- Break and seat PCC slabs prior to overlay,
- Rubblize PCC slabs prior to overlay,
- Sawing and sealing joints in the AC overlay above those in the PCC pavement, and
- Other (crack seal, joint repair, fiber reinforcement, and recycling).

Agency evaluation in terms of good, marginal, and poor performance is summarized in Figure 21. By this measure of effectiveness, sawing and sealing the AC overlay above the PCC joints was the most effective mitigation with 14 of 15 states reporting good performance. The success ratios (ratio of good to poor performance) for crack arresting interlayers (CAI) and crack and seat (C&S) were 2.5 and 4.5 respectively. SAMIs and increased thickness were found to be marginally beneficial, while paving fabrics were rated as good by 3 of 33 states with 17 indicating marginal results.

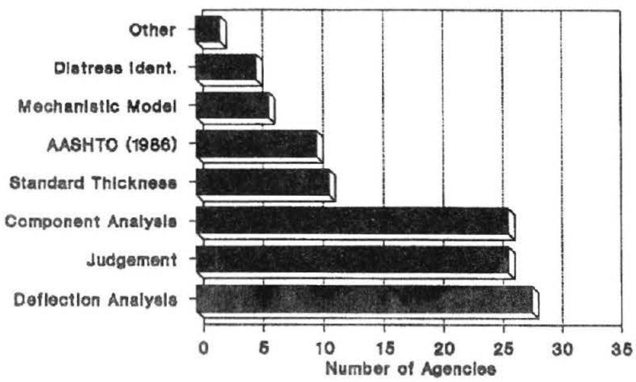


FIGURE 17 Design procedures for flexible overlays on flexible pavements.

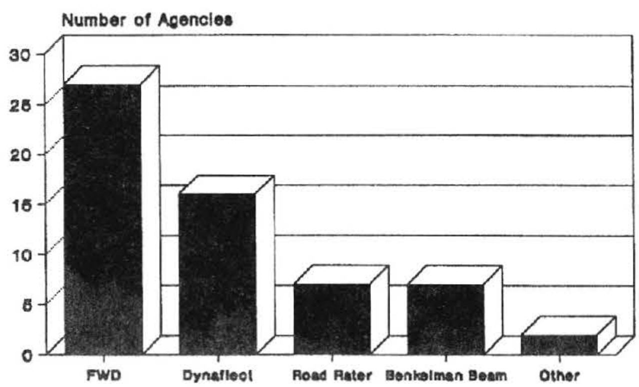


FIGURE 18 Deflection measurement devices.

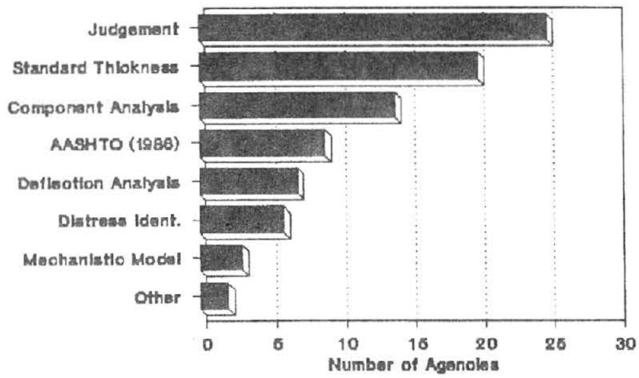


FIGURE 19 Design procedures for flexible overlay on rigid pavement.

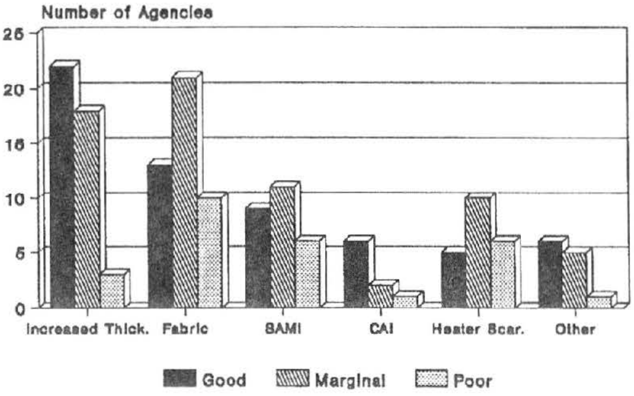


FIGURE 20 Reflective crack mitigation: flexible over flexible.

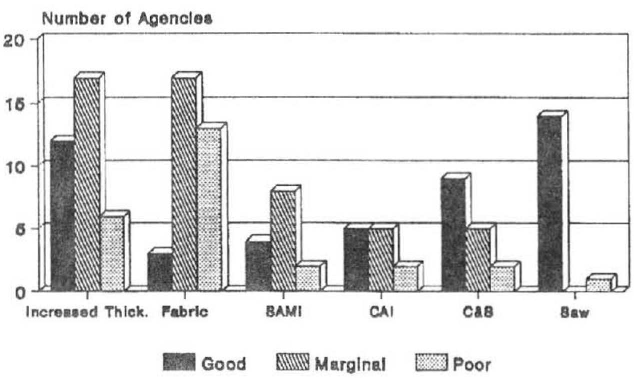


FIGURE 21 Reflective crack mitigation: flexible over rigid.

TABLE 10
OVERLAY DESIGN PROCEDURES—FLEXIBLE ON RIGID

	Flexible on Rigid							
Agency	Judgment	Standard Thickness	Comp. Anal.	Defl. Anal.	Distress Ident.	Mech. Model	AASHTO (1986)	Other
Alabama	X							
Arizona	X							
Arkansas			X				X	
California		X						
Colorado							X	
Connecticut	X	X					X	
Delaware	X	X						
Florida			X					
Georgia		X						
Idaho	X							AASHTO (1972)
Illinois		X	X					
Iowa		X		X			X	
Kansas	X							PCA
Kentucky	X			X	X	X		
Louisiana	X		X	X	X		X	
Maine		X						
Maryland	X	X	X					
Massachusetts	X							
Michigan	X				X			
Minnesota	X	X	X		X			
Missouri		X						
Montana		X						
Nebraska		X						
Nevada							X	
New Jersey	X				X			
New Mexico	X	X	X					
New York	X	X	X					
North Carolina			X	X				
North Dakota							X	
Ohio	X	X	X	X		X		
Oklahoma	X				X			
Oregon	X							
Pennsylvania			X					
Rhode Island		X						
South Carolina	X		X					
South Dakota	X							
Tennessee	X							
Texas	X							
Vermont							X	
Virginia	X		X					
Washington		X						
West Virginia	X			X			X	
Wisconsin		X	X	X				
Ontario	X	X						
Quebec		X						

CHAPTER SIX

RIGID PAVEMENT OVERLAY DESIGN

BACKGROUND

Portland cement concrete overlays are employed to strengthen existing pavements to support anticipated future traffic loadings or to improve ride quality. They have been used in the United States since 1913 (*51*). The thickness of early PCC pavements ranged from 4 to 6 in. As truck traffic increased in numbers and weight, local governments frequently added 4 to 6 in. of concrete to enhance load-carrying capacity and thus extend pavement life. Many PCC overlays were constructed with a separating layer over the existing pavement to reduce reflection cracking.

The backlog of pavement rehabilitation projects that accumulated during World War II resulted in a sizeable pavement rehabilitation program after the war. During this period, asphalt concrete was the preferred resurfacing material because of the widely held opinion that AC could be placed in lesser thicknesses than PCC, that it minimized reflective cracking and its placement was less disruptive to traffic, that it provided better ride quality and was more economical. PCC resurfacing was used extensively, however, to rehabilitate existing concrete airfield pavements made necessary by the rapid increase in aircraft weight and numbers.

In the years following construction of the Interstate system, AC overlays continued to be the favored means of pavement rehabilitation. However, the rigid pavement overlay option has become increasingly viable considering the following developments:

- The emergence of slip form paving, improved spreading and finishing equipment, and central-mix batch plants,
- Widespread rutting problems from application of marginal AC mixtures that were unable to withstand increasing truck tire pressures and the growing use of "super singles," and
- The increasing use of life-cycle cost analysis to select pavement type.

The design of a PCC overlay is affected by existing pavement conditions and the nature of the interface between the overlay and the original pavement.

Bonded Interface

This requires a thorough cleaning of the existing pavement surface and the application of a bonding agent (usually cement grout). It is used when the existing pavement is in structurally sound condition, since cracks will reflect through the bonded overlay. Transverse joints are normally sawed into the overlay to match those of the existing pavement.

Unbonded Interface

A separating layer is placed between the existing pavement and overlay to prevent bonding. This layer can consist of a thin AC layer, seal coat, gravel, or a wax base curing compound. Debonding minimizes reflection cracking. The most frequently used PCC overlays fall into the following general categories:

1. Jointed Reinforced or Jointed Plain Concrete Overlay (JRCP or JPCP)
    (a) unbonded
    (b) fully bonded
2. Continuously Reinforced Concrete Overlays (CRC)
    (a) unbonded only

Rigid pavement overlay design procedures fall into the same general categories as flexible overlays with the addition of empirical procedures. These procedures are closely related to the component analysis approach differing, primarily, in that their development was based on the results of full-scale accelerated tests.

Examples include those developed by the U.S. Army Corps of Engineers (*52*). The Corps of Engineers design equations for unbonded, partially bonded, and bonded overlays of rigid pavements are presented in summary form by Table 11. Development of the Corps procedures is described in a 1991 report (*53*).

AGENCY PRACTICE

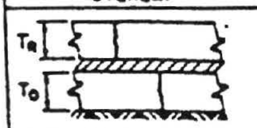
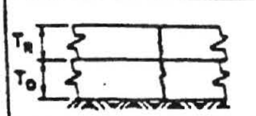
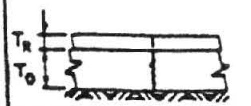
Rigid over Rigid

As was the case with flexible overlays, it should be pointed out that many agencies use more than one rigid pavement overlay design procedure. The agency responses to the 1986 FHWA questionnaire and the 1991 follow-up inquiry are summarized in Table 12. As shown, seven agencies indicate use of the 1986 AASHTO procedure which is, basically, a component analysis procedure in which the effective modulus of reaction (Kc) is established based on backcalculated values of E_{sg} and E_{sg} developed from NDT data. Six agencies explicitly employ judgement or component analysis procedures. Three agencies use deflection-based procedures, although one pavement engineer indicated that deflection measurements were used only to establish load transfer and to locate voids below the existing PCC pavement. Other procedures presently employed for the design of rigid overlays of rigid pavement include distress identification and those of PCA and the Corps of Engineers. Although a number of mechanistic procedures are available for the purpose of designing rigid overlays of rigid pavement (*54,55*), only three agencies employ them at this time.

Rigid over Flexible

Rigid overlay of flexible pavement is another rarely used rehabilitation strategy as shown in Table 13, which presents the results of the 1986 FHWA survey and 1991 follow-up inquiry on state practice. As shown, two states use component analysis, and four employ a deflection-based procedure, primarily to establish the modulus of subgrade reaction (k) based on a relationship between

TABLE 11
SUMMARY OF RIGID OVERLAY DESIGN EQUATIONS (U.S. ARMY CORPS OF ENGINEERS)

CONCRETE OVERLAYS ON CONCRETE PAVEMENT			
TYPE OF OVERLAY	UNBONDED OR SEPARATED OVERLAY 	PARTIALLY BONDED OR DIRECT OVERLAY 	BONDED OR MONOLITHIC OVERLAY 
PROCEDURE	CLEAN SURFACE DEBRIS AND EXCESS JOINT SEAL PLACE SEPARATION COURSE-PLACE OVERLAY CONCRETE.	CLEAN SURFACE DEBRIS AND EXCESS JOINT SEAL AND REMOVE EXCESSIVE OIL AND RUBBER-PLACE OVERLAY CONCRETE	SCARIFY ALL LOOSE CONCRETE, CLEAN JOINTS, CLEAN AND ACID ETCH SURFACE-PLACE BONDING GROUT AND OVERLAY CONCRETE.
MATCHING OF JOINTS IN OVERLAY & PAVEMENT — LOCATION	NOT NECESSARY	REQUIRED	REQUIRED
MATCHING OF JOINTS IN OVERLAY & PAVEMENT — TYPE	NOT NECESSARY	NOT NECESSARY	REQUIRED
REFLECTION OF UNDERLYING CRACKS TO BE EXPECTED	NOT NORMALLY	USUALLY	YES
REQUIREMENT FOR STEEL REINFORCEMENT	REQUIREMENT IS INDEPENDENT OF THE STEEL IN EXISTING PAVEMENT OR CONDITION OF EXISTING PAVEMENT	REQUIREMENT IS INDEPENDENT OF THE STEEL IN EXISTING PAVEMENT STEEL MAY BE USED TO CONTROL CRACKING WHICH MAY BE CAUSED BY LIMITED NON-STRUCTURAL DEFECTS IN PAVEMENT.	NORMALLY NOT USED IN THIN OVERLAYS IN THICKER OVERLAY STEEL MAY BE USED TO SUPPLEMENT STEEL IN EXISTING PAVEMENT
FORMULA FOR COMPUTING THICKNESS OF OVERLAY (T_r) NOTE: T IS THE THICKNESS OF MONOLITHIC PAVEMENT REQUIRED FOR THE DESIGN LOAD ON THE EXISTING SUPPORT C IS A STRUCTURAL CONDITION FACTOR T_R SHOULD BE BASED ON THE FLEXURAL STRENGTH OF	$T_r = \sqrt{T^2 - CT_0^2}$ OVERLAY CONCRETE	$T_r = \sqrt[1.4]{T^{1.4} - CT_0^{1.4}}$ OVERLAY CONCRETE	$T_r = \bar{T} - T_0$ NOTE: THE ABILITY OF THE OVERLAID SLAB TO TRANSFER LOAD AT THE JOINTS SHOULD BE ASSESSED SEPARATELY EXISTING CONCRETE
MINIMUM THICKNESS	6"	5"	1"
APPLICABILITY OF VARIOUS OVERLAY TYPES — STRUCTURAL CONDITION OF EXISTING PAVEMENT — NO STRUCTURAL DEFECTS C=1.0*	YES	YES	YES
APPLICABILITY OF VARIOUS OVERLAY TYPES — STRUCTURAL CONDITION OF EXISTING PAVEMENT — LIMITED STRUCT DEFECTS C=0.75*	YES	ONLY IF DEFECTS CAN BE REPAIRED	ONLY IF DEFECTS CAN BE REPAIRED.
APPLICABILITY OF VARIOUS OVERLAY TYPES — STRUCTURAL CONDITION OF EXISTING PAVEMENT — SEVERE STRUCT DEFECTS C=0.35*	YES	NO	NO
APPLICABILITY OF VARIOUS OVERLAY TYPES — SURFACE CRACKS, SCALING, SPALLING AND SHRINKAGE CRACKS — NEGLIGIBLE	YES	YES	YES
APPLICABILITY OF VARIOUS OVERLAY TYPES — SURFACE CRACKS, SCALING, SPALLING AND SHRINKAGE CRACKS — LIMITED	YES	YES	YES
APPLICABILITY OF VARIOUS OVERLAY TYPES — SURFACE CRACKS, SCALING, SPALLING AND SHRINKAGE CRACKS — EXTENSIVE	YES	NO	YES

* C-VALUES APPLY TO STRUCTURAL CONDITION ONLY, AND SHOULD NOT BE INFLUENCED BY SURFACE DEFECTS.

k value and deflection such as that developed from Canadian Good Roads Association data (Figure 22). This permits the design of the PCC overlay based on the PCA procedure. Five states use judgement or standard thickness to determine overlay thickness.

Only one state employs mechanistic modeling, which is somewhat illogical since the elastic properties of the primary structural element, the PCC overlay, are reasonably predictable and constant while those of the underlying flexible section can be established from available backcalculation procedures.

A more thorough discussion of current resurfacing for rigid overlays is being undertaken in NCHRP Synthesis Topic 23-10, *Portland Cement Concrete Resurfacing*.

TABLE 12
OVERLAY DESIGN PROCEDURE-RIGID ON RIGID

	Rigid on Rigid						
Agency	Judgment	Experimental	Component Analysis	Mech. Model	Defl. Anal.	AASHTO (1986)	Other
California		X					
Colorado						X	
Florida			X				
Georgia		X					
Illinois		X					
Iowa						X	
Kansas		X					
							X[1]
Kentucky				X		X	
Louisiana					X		
Maryland							X
Michigan	X						X
Minnesota	X		X			X	X[3]
							X[1]
New Mexico	X	X					
New York							X[2]
Ohio		X	X	X	X		
Oregon						X	X[1]
Pennsylvania							X[3]
Texas						X	
Utah			X				
Washington						X	
Wisconsin	X		X				
Wyoming	X	X	X				
Quebec	X						

[1]PCA
[2]Distress Identification
[3]Corps of Engineers

TABLE 13
OVERLAY DESIGN PROCEDURES-RIGID ON FLEXIBLE

		Rigid over Flexible					
Agency	Judgment	Standard Thickness	Comp. Anal.	Defl. Anal.	Mech. Model	PCA	AASHTO (1986)
Colorado							X
Iowa				X			
Montana						X	
Nebraska		X					
Ohio		X		X	X		
Oklahoma		X					
Oregon				X			
Texas	X			X			X
Utah			X				
Wisconsin	X		X				

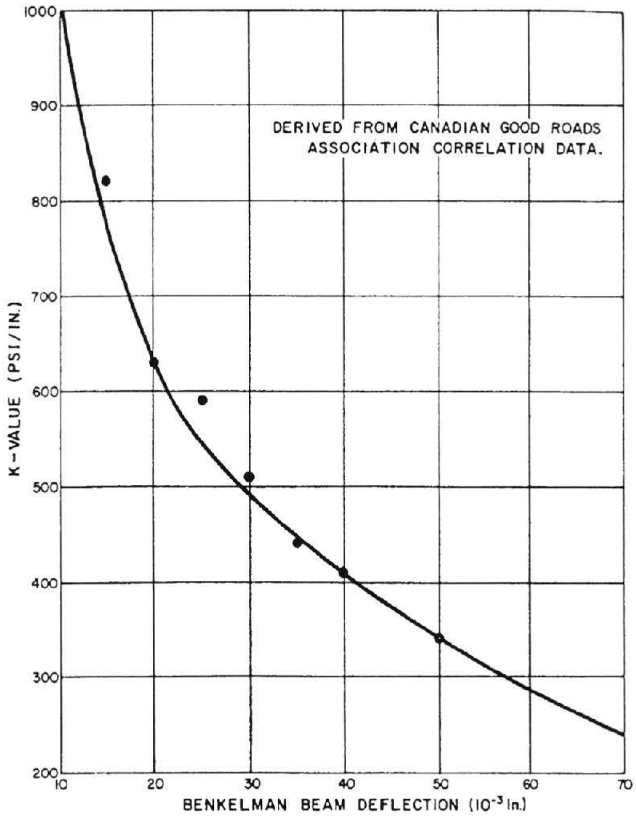


FIGURE 22 K value vs. deflection (from "K-Value-Deflection Relaitonship for AC pavements," Final Report, California Dept. of Public Works, Research Report 643449, Sacramento (1962)).

CHAPTER SEVEN

PAVEMENT RESEARCH

The Strategic Highway Research Program

Beginning in the late 1970s, the highway community in the United States became increasingly concerned with the decline in highway research funding (down 40 percent between 1965 and 1982) and America's "decaying infrastructure." To address the concern over the declining highway research program, in 1982 the FHWA sponsored an in-depth policy study by the Transportation Research Board of the country's highway-related research needs. The results of the study, published in 1984 (*1*) recommended implementation of the Strategic Highway Research Program (SHRP), a $150 million five-year research project focused on six specific problem areas considered to offer the greatest potential for timely and significant return. The heart of the program, described as the "trunk of the tree," was the Long Term Pavement Performance Study (LTPP), which would provide the mechanism for field testing of materials or systems developed in the five other study areas.

The LTPP, funded at $50 million, will ultimately include approximately 2,500 pavement test sections including both in-service pavements (General Pavement Studies) and pavements constructed specifically for the experiment (Specific Pavement Studies).

The basic objectives of LTPP as defined by its advisory panel are as follows:

- Evaluate existing pavement design procedures,
- Develop and improve methodologies and strategies for the rehabilitation of existing pavements,
- Develop improved design equations for new and reconstructed pavements,
- Determine the effects of (1) loading; (2) environment; (3) materials properties and variability; (4) construction quality; and (5) maintenance levels on pavement distress and performance,
- Determine the effects of specific design features on pavement performance, and
- Establish a national long-term pavement data bank to support SHRP objectives and future needs.

The LTPP program, in which all 50 states and several foreign countries are participating, represents the largest, most costly and complex pavement research experiment ever attempted. The expectation of the highway community is for improved predictive equations, design procedures, and a better understanding of pavement performance that will ultimately be reflected in lower life-cycle pavement costs. As was the case with the AASHO Road Test, data from the LTPP program will probably be analyzed for many years after completion of the experiment for purposes not even imagined at this time.

State Highway Planning and Research (SPR) Program

In addition to the massive research effort represented by SHRP, a review of the FHWA-funded and state-administered SPR program revealed more than 40 pavement-related research projects either underway or recently completed by state departments of transportation or their contractors. They are grouped by general category as follows:

- Evaluation or modification of the 1986 AASHTO pavement design procedure,
- Development or modification of mechanistically based pavement design procedures,
- Laboratory resilient modulus testing for pavement design input,
- Asphalt concrete mix design,
- Development of overlay design procedures based on nondestructive testing,
- Evaluate or maximize the reliability of portable weigh-in-motion devices, and
- Miscellaneous.

The level of research on the 1986 AASHTO pavement design procedure, mechanistic design, and resilient modulus testing by the states is consistent with the responses to the 1990 TRB questionnaire item on anticipated changes. The other SPR pavement-related projects, classified as "miscellaneous," are designed to address specific problems, including that of asphalt concrete rutting, which has increased with increases in axle loading and truck tire pressure. A significant provision of the Intermodal Surface Transportation Efficiency Act of 1991 mandates that not less than 25 percent of SPR funds be dedicated to "research, development and technology transfer activities." This will, in effect, nearly double SPR research funding since, historically, less than 15 percent of SPR (formerly HPR) funds have been used for this purpose.

National Cooperative Highway Research Program (NCHRP)

The National Cooperative Highway Research Program, administered by the Transportation Research Board, is a research arm of AASHTO. Major pavement-related projects in the program, either ongoing or recently completed include:

- Effects of Heavy Vehicle Characteristics on Pavement Response and Performance, Phase II
- Calibrated Mechanistic Structural Analysis Procedures for Pavements
- Video Image Processing for Evaluating Pavement Surface Distress
- Laboratory Determination of Resilient Modulus for Flexible Pavement Design
- Design and Evaluation of Large Stone Mixes

• Chip Seal Coats for High-Traffic Volume Asphalt Concrete Pavements

• Improved Surface Drainage of Pavements

• Support Under PCC Pavements

• Aggregate Tests Related to Performance

• Evaluation of PCC Overlays with Bond Breakers over PCC Pavement

Federal Highway Administration (FHWA)

The FHWA supports and administers a sizeable pavement-related contract research program. Funding for this purpose increased to more than $8 million for fiscal year 1991. As shown by Figure 23, that represented a significant increase in FHWA pavement-related research over recent years, which reflects the perception that pavement research has great potential for significant and rapid payout. The following is a listing of projects currently underway:

• Effects on Safety of Truck-Tire Interactions

• Effect of Different Tire Sizes and Pressures on Performance

• Impact of Truck Characteristics on Pavements Truck Load Equivalency Factors

• In-Situ Instrumentation for Resilient Moduli Measurement

• Concrete Joint Sawing Operations

• Cost Model for Truck Policy Analysis

• Operation of the Pavement Testing Facility (ALF)

• Support Services for the Pavements/Material Laboratories

• Dynamic Vehicle Forces on Pavements

• Using LTPP Data to Develop Mechanistic-Empirical Concepts for Deteriorated and Rehabilitated Pavements

• Performance Evaluation of Experimental Rigid Pavements, Photographic Distress Surveys

• Evaluation of Distress on Highway Pavements due to Combined Action of Heavy Traffic and Environmental Conditions

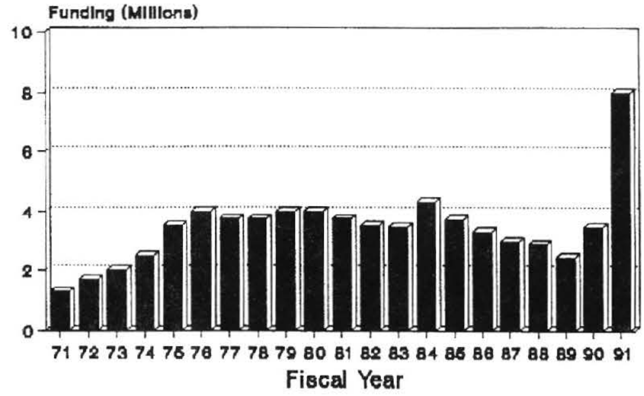


FIGURE 23 FHWA pavement research projects.

• Effects of Tire Pressure on Road Surface Life and Thickness Requirements

• Pavement Damage Prediction Models-Extension, Calibration, Verification

• Performance Related Specifications for Portland Cement Concrete: Laboratory Development and Accelerated Test Planning

Canadian Research Efforts

A recently completed survey (*56*) of ongoing and recently completed transportation research and development in Canada revealed that an extensive research program in the pavement area is underway in that country. Eighty separate pavement-related research projects were identfied as being underway or recently completed by federal or provincial transportation ministries, universities, and private firms. The following is a list of current pavement-related research projects sponsored by national rather than local entities:

PROJECT	SPONSOR
Priority Programming of Pavement Maintenance and Rehabilitation	Natural Sciences and Engineering Research Council of Canada; PMS Limited
Highway Cost Allocation	Natural Sciences and Engineering Research Council of Canada
Removal of Hazards Due to Ravelling of Granular Shoulder Material	Canadian Strategic Highway Research Program, Transportation Association of Canada
Open Graded Drainage Layers for Airfield Pavements	Department of National Defense
Interlocking Concrete Block Paving for Areas Subject to Traffic	Department of National Defense
Seasonal Variations in Pavement Responses	Transportation Association of Canada, Canadian Strategic Highway Research Program
Mitigation of Frost Effects on Pavements	Institute for Research in Construction, National Research Council of Canada; National Sciences and Engineering Research Council of Canada (NSERC)
Failure Prediction of Roadways	Institute for Research in Construction, National Research Council of Canada; Ontario Ministry of Transportation
Prediction of Moisture Damage Susceptibility in Asphalt Concrete Pavements	Institute for Research in Construction, National Research Council of Canada
Low Temperature Performance of Asphalt Concrete Pavements	Institute for Research in Construction, National Research Council of Canada

(*continued*)

Durability of Concrete to Physico-Chemical Action	Institute for Research in Construction, National Research Council of Canada
Measurement of Pore Size Distribution in Nonwoven Geotextiles	Natural Sciences and Engineering Research Council of Canada
Development of Construction Techniques for Asphalt Pavements	Institute for Research in Construction, National Research Council of Canada; Lovat Tunnel Equipment; Conwed Plastics
A New Asphalt Concrete Laboratory Compaction Method	Institute for Research in Construction, National Research Council of Canada
Development of Pavement Management Technology	Natural Sciences and Engineering Research Council of Canada
Corrective Measures for Surface Defects in Flexible Pavements	Canadian Strategic Highway Research Program, Transportation Association of Canada

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APPENDIX A
QUESTIONNAIRE

QUESTIONNAIRE

NCHRP Project 20-5, Topic 21-13

State Highway Pavement Design Practices

Flexible Pavement Design

1. What is the basis of your state's flexible pavement design procedure ?

   AASHTO Guidelines (1972) ____________

   AASHTO Guidelines (1986) ____________

   Asphalt Institute ____________

   Other (please indicate) ____________

2. If the answer to question 1 is "other" , is your state's procedure mechanistically based ? yes_____ no_______

3. What is the design period for primary highways ? _____ yrs.

   urban highways ? _______yrs

4. If your state uses life cycle cost analysis for pavement type selection, what service life is assummed ? _____ yrs

5. What strength or stiffness test or classification method is used to characterize the following materials for thickness design? (CBR, "R" value, etc)

   Asphalt Concrete____________

   Aggregate Base and Subbase____________

   Cement Treated Base ____________

   Lime Treated Subgrade ____________

   Soil Cement ____________

   Asphalt Treated Permeable Material ____________

   Cement Treated Permeable Material ____________

   Untreated Permeable Material____________

   Subgrade ____________

6. If the answer to question 1 was "other",how is traffic loading characterized by your state for flexible pavement design ?

   Equivalent 18 kip Single Axle Loading (ESAL) ____________

   Average Daily Traffic (ADT) ____________

   Average Daily Truck Traffic (ADTT) ____________

   Other (please indicate) ____________

   ____

7. Does your state's flexible pavement design procedure include consideration of serviceability loss due to frost heave ? _____ yes ____ no

   If so, briefly describe it.

   ____

8. Does your state's flexible pavement design procedure include consideration of serviceability loss due to roadbed swelling ? _____ yes ____no

   If so, briefly describe it.

   ____

9. Are open graded permeable materials (treated or untreated) for internal drainage being used in flexible pavement by your state ? routinely ___ experimentally____ not at all_____

10. What is the basis of the hydraulic design of your state's internal pavement drainage?

    FHWA Guidelines ___ AASHTO Guidelines_____ Not Applicable_____

    Other (please indicate)____________

11. If permeable material is being used by your state for internal pavement drainage, what structural contribution is assumed for pavement thickness design purposes ?

	AASHTO Layer Coef.	Other
treated permeable material — asphalt	________	________
cement	________	________
untreated permeable material	________	________

12. How is water removed from your state's flexible pavements containing a layer of permeable material ?

	Collector and Outlet pipes	"Daylighting"
Treated Permeable	________	________
Untreated Permeable	________	________

13. What is the basis of your state's asphalt concrete shoulder thickness design ?

Standard Thicknesses ________

Full Depth (same as pavement) ________

Traffic Loading ________

14. If shoulder thickness design is based on traffic loading, what level or volume is assummed ?

____

15. What changes in your state's flexible pavement design policy, procedures or methods of materials characterization do you envision in the forseeable future ?

____

____

____

____

Rigid Pavement

16. What design period is used for rigid pavements in your state ?

primary highways ________ yrs

urban highways ________ yrs

17. What is the basis of your state's rigid pavement design procedure ?

	Plain Jointed	Reinforced	Cont. Reinforced
AASHTO Guidelines(72)	________	________	________
AASHTO Guidelines (86)	________	________	________
Portland Cement Assoc.	________	________	________
Other (please indicate by pavement type)	________	________	________
	________	________	________
	________	________	________

18. If the answer to question 17 was "other", how is traffic loading characterized in your state's rigid pavement design procedure?

Equivalent 18 kip Single Axle Loading (ESAL) ________

Average Daily Traffic (ADT) ________

Average Daily Truck Traffic ________

Other (please indicate) ________

____

19. If the answer to question 17 was "other", does your state's rigid pavement design procedure include consideration of serviceability loss due to frost heave ?

______yes ______no

If so, briefly describe it. ________

____

____

20. If the answer to question 17 was "other", does your state's rigid pavement design procedure include consideration of serviceability loss due to roadbed swelling ?

______ yes ______ no

If so, briefly describe it. ______________________________________

____

____

21. Does your state use concrete shoulders ?

Routinely _______

Experimentally _____

Not at all ________

22. If concrete shoulders are used, are they tied to the pavement slab ?

Routinely _________

Experimentally ____

Not at all _____

23. What concrete strength is used for design ? _______psi at____days
If flexural, is it third point or midpoint ? _____________

24. What is the basis of your state's concrete shhoulder thickness design

Standard thicknesses _______

Full depth (same as pavement)

Other (please indicate)____

____

____

25. Internal drainage of rigid pavement is provided by:

Untreated permeable base, "daylighted"____ routinely ? yes____ no____

Untreated permeable base with collector and outlet pipes_____

routinely ? yes___ no ___

Treated permeable base, "daylighted" _____ routinely ? yes___ no___

Longitudinal (edge) drains ,prefabricated ____ routinely ? yes___no__

Longitudinal (edge) drains ,conventional*____ routinely ? yes___ no_

Other (please indicate)____

____

____

Not applicable _________

26. What changes do you envision in your state's rigid pavement design policy, details, procedure, and methods of materials characterization in the near future ?

____

____

____

____

____

Please indicate a contact person in your department for possible follow up questions.

Name____

Address____

____

Phone # (____)__________________________________

* Slotted or perforated collector pipe encased in permeable material

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