Federal Infrastructure Strategy Reports

This is the eleventh in a series of interim reports which will be published by the U.S. Army Corps of Engineers during the Federal Infrastructure Strategy program, a three-year effort to explore the development of an integrated or multi-agency Federal infrastructure policy. This report presents the technical description and documentation of a pavement technology transfer demonstration project performed by the U.S. Army Corps of Engineers Waterways Experiment Station.

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Local Public Finance Impact Model: User's Guide and Technical Documentation (IWR Report 94-FIS-10).

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The Federal Infrastructure Strategy Program

Technical Report Series

Nondestructive Testing, Evaluation, and Rehabilitation for Roadway Pavements: Warren County, Mississippi, Cincinnati, Ohio, and Berkeley, California

prepared by

Richard H. Grau and Don R. Alexander
Pavement Systems Division
Geotechnical Laboratory
U.S. Army Engineer Waterways Experiment Station

for

U.S. Army Corps of Engineers
Water Resources Support Center
Institute for Water Resources

July 1994

IWR REPORT 94-FIS-11

Federal Infrastructure Strategy Program

U.S. Army Corps of Engineers

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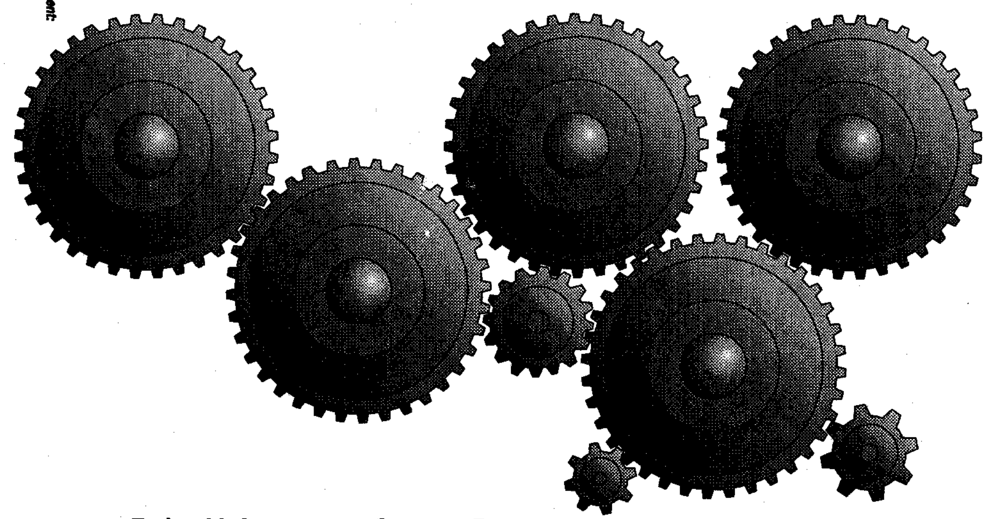

Federal Infrastructure Strategy Program

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PREFACE

This report was prepared for the U.S. Army Corps of Engineers Institute for Water Resources by the U.S. Army Engineer Waterways Experiment Station (WES) as part of the Federal Infrastructure Strategy (FIS) program. The FIS program was initiated as a budget initiative for Fiscal Year 1991. The U.S. Army Corps of Engineers (USACE) acted as program facilitator with various other government departments and agencies actively participating. The FIS program is overseen by the USACE Directorate of Civil Works, with detailed management responsibilities delegated to the Institute for Water Resources.

This project was selected in cooperation with the USACE Directorate of Research and Development by the USACE Infrastructure Task Force Subcommittee on Technical Transfer. The Waterways Experiment Station (WES) of the U.S. Army Corps of Engineers led this initiative.

As an integral part of this project, separate Cooperative Research and Development Agreements (CRDA's) were executed between WES and Warren County, MS; Cincinnati, OH; and Berkeley, CA. The CRDA's were approved by the Assistant Secretary of the Army (Research, Development, and Acquisition), Army Domestic Technology Transfer Program Manager.

The objective of the agreements was to acquaint municipal public works agencies with a process where they could use a guide specification to acquire vendor services to perform nondestructive assessments of their pavement's structural adequacy. The guide specification was employed to enable municipalities to contract for use of a Falling Weight Deflectometer (FWD) pavement evaluation system. The FWD system was used to assess the pavement structural adequacy and determine pavement material properties for each of the localities. These data were then used to design cost effective pavement rehabilitation strategies for the participating communities.

This project was planned and managed at WES from April 1992 to December 1993 by the Pavement Systems Division, Geotechnical Laboratory. Personnel of the Pavement Systems Division involved in this project were Dr. Albert J. Bush III, and Messrs. Don R. Alexander and Richard H. Grau. This report was prepared by Messrs. Grau and Alexander. The project was monitored by Messrs. James F. Thompson, Jr. and Robert A. Pietrowsky, Institute for Water Resources, Water Resources Support Center, Fort Belvoir, VA, who also prepared the Executive Summary.

Special recognition is given to Mr. Rhea A. Fuller, Road Manager, Warren County, MS, Mr. Douglas C. Perry, Department of Public Works, Cincinnati, OH, Mr. Paul Sachs, Metropolitan Transportation Commission, Oakland, CA, and Ms. Wendy P. Wong, Department of Public Works, Berkeley, CA who were points of contact and provided information required from each demonstration site to insure that this project was successful.

The project was conducted under the general supervision Dr. William F. Marcuson III, Director, Geotechnical Laboratory, and under the direct supervision of Drs. George M. Hammitt II, Chief, Pavement Systems Division, and Albert J. Bush III, Chief, Criteria Development and Applications Branch, Pavement Systems Division.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. The Commander of WES was Colonel Bruce K. Howard.

EXECUTIVE SUMMARY

Many of the nation's highways, roads, and streets managed by state and local governments require major rehabilitation. Traditionally, many of these pavements are repaired by applying a standard thickness of an asphalt overlay on top of the original pavement structure. For example, it is common practice in some areas to recommend applying a two-inch asphalt overlay to any pavement requiring rehabilitation.

Understandably, this is not always cost effective. Properly designing a durable and economical overlay requires knowledge of the pavement's structural capacity. A nondestructive evaluation procedure can often be utilized to assess the structural adequacy of a pavement and in determining the materials properties for use in designing cost-effective rehabilitation strategies.

OBJECTIVES

This report documents the results of one FIS technology transfer initiative: the demonstration of nondestructive pavement evaluation technology (NDT) to cooperating Federal and nonfederal partners. The demonstrations utilized Falling Weight Deflectometer (FWD) technology, a commercially available nondestructive procedure for determining the structural adequacy of a pavement system. Data obtained from FWD tests were combined with pavement material properties and estimated future traffic volumes to design rehabilitation strategies for the existing streets and roadways of three communities.

The specific objectives of the study were to:

- Evaluate and develop improvements to the initial guide specification used for contracting FWD technology.

- Evaluate the three analytical methods used by each contractor to develop the pavement repair strategies.

- Document and explain the differences in the results of the pavement evaluation methods.

- Document the benefits of FWD technology over other conventional techniques.

- Transfer nondestructive testing of pavements technology to non-federal partners, and demonstrate how analysis of the test results can be used to develop rehabilitation strategies for roadway pavements.

STUDY APPROACH

The technology transfer plan consisted of selecting three demonstration sites, awarding contracts to engineering firms to test, evaluate, and recommend rehabilitation strategies for the roadways, and conducting a seminar at each site for roadway planners, designers, and managers.

The demonstrations were undertaken in coordination with the Federal Highway Administration (FHWA) and the American Public Works Association (APWA). The three communities selected as demonstration sites were: Warren County, Mississippi, Cincinnati, Ohio, and Berkeley, California.

Separate Cooperative Research and Development Agreements were made between WES and the three local governments in order to acquaint them with a process for using guide specifications for obtaining vendor services to nondestructively test and assess their pavement's structural adequacy.

Each agency selected approximately twenty-five miles of local roads to be tested, with the roadways generally containing asphalt concrete (AC), portland cement concrete (PCC), and overlay pavements (asphalt concrete over portland cement concrete).

Specifications were prepared for testing the pavements, analyzing the test results, and developing rehabilitation strategies for each road. Contracts were awarded to two small businesses to perform the tasks required in the specifications: Dynatest Consulting, Inc. for Warren County and Cincinnati, and Engineering & Research International, Inc. (ERI) for Berkeley. Dynatest subsequently subcontracted the testing and evaluations for the Cincinnati site to Soil and Materials, Inc.

TECHNICAL CHARACTERISTICS

A total of 142 roadway sections ranging from 0.02 to 8.1 miles were included in the three tests (Table 1). Three different procedures were used to analyze data obtained from NDT and to provide overlay designs at each site.

These methods included the WES layered elastic procedure (an extensively tested, computerized methodology based upon multilayered elastic models and limiting stress/strain criteria), the American Association of State Highway and Transportation Officials (AASHTO) Guide for Design of Pavement Structures, and either Dynatest's or ERI's own methods (see Table 1).

Rehabilitation strategies were developed for each roadway section based on expected design lives of 5, 10, and 20 years. The recommendations were based on overlay thicknesses recommended by each analysis method, visual condition and amount of distress observed on the roadway, ride quality noted during a tour of each site, and the amount of traffic estimated for the time periods.

Recommendations were also based on engineering judgment and the constraints of typical construction and maintenance practices at the demonstration site. The tabulation of alternative rehabilitation strategies for each demonstration, tabulated by roadway section, is presented in Appendices F, H and K.

Table 1. Testing and Evaluation Data for Demonstration Sites

Site	No. Sections	Section Length (miles)	Test Equipment	Design Procedures
Warren County, MS	8	0.9-8.2	HWD[1]	AASHTO[2] ELMOD[3] WES[4]
Cincinnati OH	22	0.29-3.19	HWD	AASHTO ELMOD WES
Berkeley, CA	112	0.02-0.81	KUAB 2m-FWD[5]	AASHTO ERI[6] WES

SUMMARY OF RESULTS

Each method used to analyze the NDT data and determine overlay requirements for the roadway sections provided a different thickness. On average, the WES procedure produced overlay thicknesses that were within one-inch of the other methods for asphalt concrete (AC) pavements and three-inches higher for portland cement concrete (PCC) pavements. Average WES overlay thicknesses for composite pavements were within 2-inches of the AASHTO values and four to six-inches lower than the Dynatest/SME values. These comparisons are valid for the specific analysis methods used and assumptions made by the contractors for these specific pavements, and results should not be interpreted as typical or representative of the differences that can be encountered with other procedures or contractors.

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[1] Dynatest 8081 Heavy Weight Deflectometer Test System.

[2] American Association of State Highway and Transportation Officials Guide for Design of Pavement Structures.

[3] Dynatest's Evaluation of Layer Moduli and Overlay Design, and companion ELCON (ELmod for CONcrete).

[4] U.S. Army Waterways Experiment Station's Layered Elastic Procedure.

[5] KUAB Two Mass Falling Weight Deflectometer.

[6] Engineering & Research, Inc. evaluation procedure.

The differences between overlay thicknesses determined from the various evaluation methods can be attributed to a number of factors. The thicknesses recommended are directly related to the performance criteria selected. With layered elastic procedures, stresses and strains are computed at critical locations within the pavement system for the design vehicle. Limiting values of stress/strain are applied to translate from the analytical models to field performance. These limiting criterion are typically empirically derived from observed field performance or laboratory test results (WES, Dynatest/SME, and ERI performance criteria are presented graphically in Chapter 4, Figures 4-6).

For example, it is interesting to note that for flexible pavements the WES results will be more conservative for lower traffic levels (less than 500,000 vehicle coverage) and less conservative for higher traffic levels (greater than 500,000 coverage). It should also be noted that Dynatest/SME applies both a tensile stress criteria to the PCC and a stress criteria to the unbound layers. This stress criteria contributed significantly to the larger overlays reported for the composite pavements. In contrast, the asphalt strain criteria for flexible pavements is similar for each of the methods, with the WES procedure being slightly more conservative at the lower traffic levels.

When selecting an evaluation procedure, it is important to consider the type of performance criteria and how the criteria was developed. For example, if the anticipated traffic levels are extremely high, it may not be wise to select limiting criterion based on limited field or lab tests in which failures occurred at low coverage or repetition levels.

Another illustration of a criteria consideration is the method of analyzing composite pavements. In the WES computer programs, a composite pavement is analyzed using rigid pavement criteria. This does not mean, however, that all composite pavements should be treated as rigid pavements. If the modulus of the PCC layer is low (less than 1,000,000 psi), the pavement should be analyzed as a flexible pavement. In the case of very thick AC overlays, judgement is required to determine which failure mechanism is most likely to occur.

In addition to the criteria, the back-calculation procedures, methods of handling past fatigue damage, and other method-specific considerations can also cause a wide range of results. One of the first steps in the evaluation process, material characterization, is a difficult task that often requires a great deal of engineering judgement to obtain reasonable results. The assessment of damage that has already occurred in a pavement is also often difficult to define and incorporate into the analysis process.

Although the structural overlay requirements were found to vary significantly depending on the method used, no one method was found to be more accurate than another. However, it is recommended that a minimum of two methods always be used for determining overlay thicknesses so the designer has sufficient information for developing rehabilitation strategies.

Results from this study have shown that NDT is a viable technique for evaluating the structural capacities and overlay requirements for roads and streets. Analysis of the deflection test data has been shown to be a complex task with results depending on a number of factors including the selection of criteria, climate, and traffic considerations. Due to this complexity, results can vary significantly depending on the contractor and evaluation methodology. Thus, it is important to consider experience in selecting a contractor for conducting NDT analyses.

The WES procedures, which are well accepted methods with extensively documented performance-based criteria, have been presented and are available for use by local municipalities, counties, cities, or contractors. It is recommended that a well accepted method, such as the WES procedure, is specified for NDT analysis or required as a check if other new or less known procedures are used.

CONCLUSIONS

The demonstrations confirmed that the pavement related research performed at WES can be directly applied to roads, streets, and highways. Observations made during this project and comments/suggestions provided by personnel representing the three demonstration sites include the following:

- The methods used to analyze the data obtained with a FWD are dependent on traffic data; therefore, in order to obtain meaningful overlay designs, the traffic estimates must be accurate and realistic.

- The information obtained from construction and maintenance records was helpful, but was not always accurate. The thickness of each existing pavement layer within a pavement structure is a very important factor used when determining rehabilitation strategies. If historical data is not accurate, these data must be obtained by coring the pavement, which may significantly increase the cost of the procedure.

- In some cases, the rehabilitation procedures did not address the restricted curb and gutter and crown heights of many of the older roads and streets. Roadway design constraints peculiar to the local city/county must be provided in advance since this may impact on the rehabilitation strategies.

- A more detailed comparison of the cost for suggested maintenance procedures to a standard two-inch thick asphalt overlay would have been helpful. This comparison would have provided a cost analysis to determine the feasibility of NDT.

- The difference between the three methods used for analyzing the NDT results and providing rehabilitation strategies for each roadway are primarily attributed to the different procedures used by the design programs for analyzing the NDT results and accounting for the existing pavement thicknesses. In the future, the method used for determining overlay thicknesses should be specified in the guide specifications.

BENEFITS/SAVINGS

Rehabilitation requirements from NDT can be used effectively for formulating budget plans and prioritizing projects as an integral part of a comprehensive pavement management system. With the high cost of rehabilitation and the increasing traffic levels nationwide, pavement management systems are proving to be extremely cost effective, with benefits being realized within the first three years after implementation.

While no systematic comparison of benefits and costs accruing to users of this technology was made as part of these demonstrations, the analysis of such data for one particular case may be instructive. In Berkeley, California, contract costs for using the FWD amounted to $50,000. Berkeley officials reported that the use of the FWD technology enabled the city to revise their current and future pavement rehabilitation schedule, allowing the city to safely postpone a significant amount of the roadwork originally planned for the current year. This resulted in an estimated 1994 savings of $825,0000 in materials, and $125,000 in labor. Although such results do not reflect a rigorous time series analysis of future outlays, it provides an insight into the potential for using NDT to develop cost effective pavement rehabilitation strategies.

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of Measurement used in this report can be converted to SI units as follows:

Multiply	By	To obtain
feet	0.3048	meters
inches	2.54	centimeters
miles (U.S.statute)	1.609347	kilometers
tons (2,000 pounds, mass)	907.1847	kilograms

1. INTRODUCTION

STUDY OBJECTIVES

Falling Weight Deflectometer (FWD) technology is a commercially available nondestructive procedure for determining the structural adequacy of a pavement system. The data obtained from the FWD tests combined with pavement material properties and estimated future traffic volumes can be used to design rehabilitation strategies for existing streets and roadways. The objectives of this study were to:

a. Evaluate and develop improvements to the initial guide specification used for contracting FWD technology.

b. Evaluate the analytical methods used to develop the pavement repair strategies for three local jurisdictions.

c. Document and explain the differences in the results of the pavement evaluation methods.

d. Document the benefits of FWD technology over other conventional techniques.

e. Transfer nondestructive testing (NDT) of pavements technology to non-federal partners, and demonstrate how analysis of the test results can be used to develop rehabilitation strategies for roadway pavements.

HISTORY

Pavement design and evaluation methods for flexible and rigid pavements were developed from numerous performance tests, theories, and studies beginning in 1926 for rigid pavements with the Westergard analysis and 1947 for flexible pavements with full-scale test pavement using actual aircraft loadings. The procedures that resulted from the study and interpretation of these performance tests were used to design and evaluate several hundred military airfield pavements throughout the world and are documented in numerous reports. The first generation evaluations depended on direct sampling of pavement layers to determine either the modulus of subgrade reaction (k) from plate bearing tests on rigid pavements or the California bearing ratio (CBR) on flexible pavements.

Nondestructive test procedures for pavement evaluation have been developed by WES through years of research sponsored by the Army, Air Force, and Federal Aviation Administration (FAA). WES started vibratory testing of pavements in search of NDT procedures in the mid-1950's. Initial work in

NDT was concentrated in the area of airport pavements. During the 1950's and 60's, accepted methods for evaluating the load-carrying capacity of airport pavements required direct sampling techniques that were both costly and time-consuming. Often, direct sampling required the closing of a pavement facility to traffic operations, which in turn necessitated the rerouting and/or rescheduling of aircraft.

With substantial increases in traffic operations (that is, takeoffs and landings), closing a pavement facility, even briefly, could result in delay of a mission and higher costs to air carriers. Increasing aircraft loads and aging pavement systems made accurate and frequent evaluations of both civil and military pavements extremely important to the airport owner/operator since many facilities would need strengthening or rehabilitation to meet increased demands.

These considerations dictated the need for test equipment, data collection techniques, and evaluation methodologies to satisfy the requirement for a rapid NDT procedure for valuating the load-carrying capacity of pavements with a minimum of disturbance to normal operations. Even though the early work dealt with airport pavements, similar procedures were later applied to NDT of roads and streets.

Early work (pre-1967) suggested that deflections caused by vibratory loadings on pavement could be used in an evaluation procedure if properly correlated with the performance of pavement. The test sections of the WES full-scale multiple-wheel heavy gear load study conducted during 1969-1970 were used to validate the pavement performance to deflection. Tests to determine load-deflection relations (dynamic stiffness modulus (DSM) values and wave propagation results) were conducted periodically during this study. An analysis of the results showed that the DSM values correlated well with the performance data while wave propagation results were erratic. Further studies of the correlation between DSM and pavement performance were conducted at military airfields by applying vibratory loadings and comparing the resulting DSM with allowable loadings determined using existing evaluation criteria. A 16-kip vibrator was then constructed to produce peak vibratory loadings up to 15,000 lbs at frequencies ranging from 5 to 100 Hz, thus producing a combined static plus peak dynamic load of 31 kips, approximately equal to one wheel load of the C-5A aircraft.

WES 16-KIP VIBRATOR - DSM EVALUATION PROCEDURE

In 1972, the FAA sponsored a study to develop a workable nondestructive evaluation procedure for airport pavements. Based upon available data, the use of the DSM-pavement performance method was selected as the most applicable procedure to be developed at that time. The most important phase of the study was the development of correlations between the nondestructive test results and the evaluation of the load-carrying capacities of the pavement by direct sampling procedures. Available pavement performance data from full-scale accelerated traffic tests and condition surveys of airports conducted over a 30-year period were used in this phase of the study. The correlation was made by performing both nondestructive and direct sampling tests at the same locations on several airport pavements representing a range of pavement conditions. The NDT data collected included DSM values, deflections for frequency sweeps from 5 to 100 Hz, deflection basin measurements, and wave propagation data. Direct sampling data collected included the thicknesses of all layers of material comprising the pavement, foundation strength values (CBR or k), concrete flexural strengths, and material properties.

The convenience and desirability of nondestructive pavement evaluation had led to the development of several types of nondestructive testing devices capable of measuring load-deflection responses of pavements. However, since the characteristics of these devices vary, different measurements on the same test site can be expected from each. Therefore, the WES 16-kip vibrator was selected as the standard vibrator for the comparison tests because it was readily available and it had been developed to produce a range of loadings including the largest vibratory load possible with any of the transportable equipment.

Several obvious shortcomings of the DSM procedure were realized. The empirical nature of the procedure (correlations between DSM and allowable load) somewhat limited the applicability to conventionally constructed pavement structures. Another disadvantage was that the procedure was inherently tied to one particular device, the 16-kip vibrator.

In the early 1980's, the Army funded a project to develop a DSM procedure for evaluating roads and streets based on NDT results for a small vibratory device, the Road Rater. The procedure was published in 1984 and has been used by the Army.

LAYERED ELASTIC PROCEDURE

Growing acceptance and convenience of NDT led to widespread use of various NDT devices and procedures to evaluate the load-carrying capability of pavements for air carrier and highway pavements in the late 1970's. During this time, the FAA sponsored a study to evaluate commercially available NDT devices for use on light aircraft pavements and develop a methodology for evaluation of light aircraft pavements based upon multilayered elastic models and limiting stress/strain criteria.

From this work, it was determined that the deflection basin produced by applying a load to the pavement with an NDT device gives input parameters to the system analysis that can be used to derive the stiffness parameters of the pavement layers. A computer program was developed utilizing a layered elastic system to determine a set of modulus values that provide the best fit between a measured deflection basin and a computed deflection basin when given an initial estimate of the modulus values, a range of modulus values, and a set of measured deflections.

The original work, presented for evaluation of light aircraft pavements using a small vibratory NDT device, has been expanded to include the evaluation of all airport and highway type pavements using NDT results from a variety of vibratory or impulse type equipment. Limiting stress/strain criteria were extracted from design procedures developed under joint FAA-Army funding. The layered elastic criteria has been calibrated with earlier performance based criteria. The layered elastic procedure provides several advantages that make it a desirable alternative to the DSM procedure. One major factor is that it provides a rational approach for characterizing and analyzing pavement structures. This allows for consideration of a variety of material types including stabilized layers, new materials, etc. Also, material properties for all layers in a pavement system can be better defined in terms of modulus. Evaluation techniques and computer software have been developed in conjunction with the layered elastic evaluation methodology.

CURRENT STATUS

The DSM procedure based on NDT with the WES 16-kip vibrator was adopted by the FAA and Army in the late 1970's for evaluation of airport pavements. NDT was performed at approximately 150 FAA airports between 1970 and 1985 and 48 Army airfields were evaluated between 1982 and 1987.

Use of this equipment and procedure has been phased out in favor of the newly developed layered elastic procedure which can make use of NDT results from smaller, less costly test equipment.

The WES layered elastic procedure has been finalized and extensive associated computer software developed. A layered elastic pavement evaluation procedure was presented to the Navy in 1986. The procedure, utilizing NDT results from a falling weight deflectometer (FWD), was adopted for use by the Air Force in 1986 and is now being used for Army airfield evaluations. The Army has also funded a project to expand the layered elastic procedure to include evaluation of Army roads and streets.

The elastic layer procedure has been evaluated, along with a number of commercially available NDT devices, under a jointly funded Army, Air Force, Navy, and FAA NDT comparative study that began in late 1987. This effort involved side-by-side NDT on a range of pavement types and thicknesses. Direct sampling was conducted on each of the pavement sections and undisturbed samples of the subgrade materials obtained for laboratory resilient modulus testing. Variability of test equipment and evaluation results was evaluated. The data and equipment calibration results have been published in a Phase I report (1989). Results from all NDT devices were used to evaluate each section with the layered elastic procedure. A Phase II report will include an evaluation of the equipment and procedures.

BENEFITS/SAVINGS

The major benefit of improved NDT techniques from an Army viewpoint is obviously that it provides a safer and more reliable military pavement system which is of great importance to National defense. Several benefits are realized from the operations side. First, NDT provides rapid and reliable determinations of load-carrying capacities and overlay requirements needed to support current or anticipated traffic. NDT is essential to the effective utilization of a pavement management system. For example, timely structural evaluations will indicate the need for minor maintenance or rehabilitation efforts as compared to much more costly alternatives that can result from allowing the pavement to deteriorate to a failed condition. Increased efficiency due to more compact and computer controlled equipment results in substantial cost savings. NDT can be conducted with minimal disturbance to normal traffic flow, thus detailed evaluations can be conducted safely and economically.

A list of publications that document the development and evaluation of NDT technology and equipment is provided in the Bibliography. The publication by Van Cauwelaert, F. J. et al, 1989 describing a computer program developed for back-calculating pavement layer moduli from measured surface deflections, and the publication by Bentsen, R. A. et al, 1989 describing the evaluation of seven NDT pavement testing devices will provide the reader a general background of the technology.

STUDY APPROACH

Separate Cooperative Research and Development Agreements were made between WES and three local public works agencies to acquaint the agencies with a process for using guide specifications to obtain vendor services to nondestructively test and assess their pavement's structural adequacy. Each agency selected approximately twenty-five miles of local roads to be tested. Specifications were prepared for testing the roads, analyzing the test results, and developing rehabilitation strategies for each road. Contracts were awarded to small businesses to perform the tasks required in the specifications. After the contractors completed their work, they participated in seminars that included a presentation of their results, rehabilitation strategies, and a demonstration of their equipment to local personnel responsible for designing and maintaining roads.

PROBLEM STATEMENT

Many of the highways, roads, and streets managed by state and local governments across the United States require major rehabilitation. Most of these pavements are repaired by applying a standard thickness of an asphalt overlay on top of the original pavement structure. For example, it is common practice in some local government organizations to recommend applying a 2 inch asphalt overlay to any pavement requiring rehabilitation. This is not cost effective. Some pavements are structurally sound and a much less expensive surface treatment would provide the rehabilitation required. Some pavements are severely overloaded and a 2 inch overlay only lasts 6 months before rutting and/or cracking reoccurs. Designing a durable and economical overlay requires knowledge of the pavement's structural capacity. With a nondestructive evaluation procedure using a FWD, the structural adequacy of a pavement can be assessed, and materials properties can be determined for use in designing rehabilitation strategies that will reduce life cycle costs.

During preparation of the contract and statement of work/specifications (Appendix A) for obtaining the FWD technology/ services, several problems incurred that had to be resolved. WES had a list of sixteen engineering and consultant firms that were experienced in providing the required services, but this was not inclusive of recently formed companies that were qualified to perform the services requested. A notice was published in the Commerce Business Daily to alert interested companies of the technology transfer project and request solicitations for bid. Twenty-three companies responded to the published notice. Since this contract was set aside for small businesses (average annual sales receipts equal no more than $2.5 million per year for the previous three years), only eight companies submitted proposals to our solicitation for bid. For this demonstration, we wanted to limit the type of equipment used and define the test procedures for evaluating the pavements. To accomplish this, an American Society for Testing and Materials (ASTM) standard test method was specified to define the acceptable equipment and an ASTM standard guide was specified to define the level of work required.

In order to eliminate contractors who were definitely not qualified to perform the requested work, four factors were used to evaluate each proposal. These factors included equipment characteristics and calibration, similar work experience by the firm, ability to complete the work within a short time period, and employee experience/qualifications were listed in the solicitation package. A statement was included in the package that all proposals would be evaluated using these four factors. This is discussed in detail in section two of this report.

COOPERATIVE RESEARCH AND DEVELOPMENT AGREEMENTS

Three Cooperative Research and Development Agreements (CRDA's) were obtained during this project. They were executed between WES and Warren County, MS, Cincinnati, OH, and Berkeley, CA. The purpose of the CRDA's was to demonstrate and transfer the WES-developed technology of NDT and evaluation of roadways to state and local governments. The local governments agreed to provide WES a prioritized list of streets and roads that required rehabilitation based on their pavement management system. After this list was approved by WES and the local governments, WES agreed to awarded contracts to commercial firms to test, evaluate, and develop rehabilitation strategies for each of the streets. A copy of the CRDA between WES and Cincinnati, OH is provided as Appendix B.

These CRDA's were the first to be obtained by WES and there seemed to be some caution by the local Office of Counsel in developing the agreements and obtaining final approval from the Assistant Secretary of the Army (Research, Development, and Acquisition), SARDA. After the initial draft of the CRDA with Warren County, MS was submitted to the local Office of Counsel, five months elapsed before it was finalized and forwarded to SARDA for their review and comments. One and one half months were required to obtain approval from SARDA. Warren County officials approved and signed the final CRDA within one week.

While the initial CRDA with Warren County was being approved by the appropriate U.S. Government agencies, CRDA's were sent to representatives of Cincinnati, OH and Berkeley, CA for their review and comments. Their comments were received within two weeks and incorporated into the documents. These revised CRDA's were then forwarded to Cincinnati and Berkeley for approval by their local officials. The signed CRDA's were received from each city within two weeks. During this time, SARDA informed WES that additional statements should be incorporated into these last two agreements. Therefore, these locally approved agreements were revised and forward to Cincinnati and Berkeley for final approval. This process required two additional weeks. After the agreements were signed by officials from WES and the two cities, five weeks were required to obtain final approval from SARDA. The purpose of the two previous paragraphs is not to criticize anyone, but to sensitize the reader to the relatively lengthy approval process required to obtain a CRDA. The approved CRDA provided in Appendix C should provide an example for future agreements and hopefully decrease the time required to develop and obtain final approval for a CRDA.

None of these CRDA's were developed and approved in the same manner, therefore, it is not clear exactly how this process should proceed in the future. A suggested schedule of milestones and events would be helpful for those preparing a CRDA.

2. TECHNOLOGY TRANSFER PLAN

The plan for informing local governments how to use NDT technology to help manage their pavements consisted of selecting three demonstration sites, awarding contracts to engineering firms to test, evaluate, and recommend rehabilitation strategies for the roadways, and conducting a seminar at each site for roadway planners, designers, and managers.

DEMONSTRATION SITE SELECTION

During the initial stages of this project, personnel from WES met with representatives from the Federal Highway Administration (FHWA) and the American Public Works Association (APWA) to coördinate the project and obtain their suggestions and assistance. The FHWA suggested that three demonstration sites should be selected, and these should be located in urban, suburban, and rural areas. They also suggested using the American Association of State Highway and Transportation Officials (AASHTO) Guide for Design of Pavement Structures as one of the methods for analyzing the FWD data and determining overlay requirements.

Three government agencies responsible for construction and maintenance of roadways in their local areas were selected as partners in this technology transfer process. The partners included representatives from Warren County, MS; Cincinnati, OH, and Berkeley, CA. Selection of the partners was based on receptiveness of the agencies, use of a pavement management system, pavements requiring rehabilitation, and funds that could be applied to the roadway rehabilitation strategies that would be recommended. The APWA assisted WES in selecting Berkeley, CA and Cincinnati, OH as the demonstration sites that represented urban and suburban areas, respectively.

Each agency was responsible for providing a prioritized list of roads for evaluation. The prioritization was based on a pavement management system currently being used. WES requested that the list contain asphalt concrete (AC), portland cement concrete (PCC), and overlay pavements (asphalt concrete over portland cement concrete), and that the total length of roadways be approximately 25 miles. Included in the list was the length of each road, number of lanes, location, type construction, average daily traffic (ADT), and estimated ADT's for the next 5, 10, and 20 years. The agencies were also responsible for furnishing all pavement design data, and maintenance and rehabilitation records that were available for the roadways.

CONTRACTOR SELECTION

After the demonstration sites were selected, WES prepared a statement of work/specifications (Appendix A) that was included in the solicitation for bid. The responsibilities of the government agencies and the contractor were listed in detail.

WES was responsible for providing the contractors with a computer program for evaluating the test data and determining rehabilitation methods for roads. WES also provided instructions to the contractor on how to use the program. As previously discussed, each city/county was responsible for providing a prioritized list of roads for evaluation. The contractor was responsible for conducting the FWD tests, determining pavement thicknesses, traffic control, liability due to accidents, analysis of the data, recommended rehabilitation strategies, a final report, and conducting a seminar that explained the NDT process and demonstrated their NDT equipment at the demonstration site. The PREMEETING listed as item 5 of the appendix proved to be beneficial to both the contractor and representatives from the demonstration site. During this meeting, such things as color of marking paint, local traffic control requirements, peculiar traffic conditions, availability of rehabilitation methods, and accommodations for the seminar were discussed.

A notice stating WES's intention to award contracts for NDT, evaluation, and subsequent rehabilitation strategies of roadways at three sites was published in the Commerce Business Daily (CBD). Solicitation packages were mailed to those firms that responded to the notice in the CBD and to engineering/consulting firms (Appendix C) that were known to own or have access to FWD equipment, and were experienced with NDT of pavements. A section was included in the package that stated that all proposals would be evaluated using four factors. The four factors were as follows:

a. Equipment characteristics and calibration: minimum output of 9 Kips, and calibration within the past 12 months at a Strategic Highway Research Program calibration site.

b. Documented experience of the firm in similar work on highways or airfields by either reports or references.

c. Ability to complete each/all jobs to include a final report by 15 August 1993 and seminar by 1 September 1993.

d. Experience/qualifications of employees that will conduct the work.

Initially, WES planned to award contracts to three separate firms, one for each demonstration site, so a broader picture of how the requirements of the contract were met could be obtained. Therefore, the contractors were requested to prepare separate bids for each demonstration site, and they were informed that it was WES's intention to award three separate contracts. Each demonstration site was divided into four bid items (the first item contained approximately ten miles of roadway and each of the other three items contained approximately five miles of roadway) so an item could be deleted if funds were not available for testing the entire 25 miles of roadway.

Eight firms provided proposals in response to the solicitation for bid. Dynatest Consulting, Inc. included Soil and Materials Engineers, Inc. in their proposal and explained that Soil and Materials Engineers, Inc. would test and evaluate the roadways at one demonstration site if they were awarded more than one site. A Board of Award was convened and the proposals were scored against the criteria above. Seven of the firms scored 70 percent or higher on the evaluation factors and were considered acceptable. Based on evaluation scores and to some extent bid price, only two firms were awarded contracts. Dynatest Consulting, Inc. was awarded contracts for Warren County, MS and Cincinnati, OH and Engineering & Research International, Inc. was awarded the contract for Berkeley, CA. Three firms were actually involved in the evaluations and demonstrations since Dynatest Consulting, Inc. subcontracted the testing and evaluation of roadways in Cincinnati to Soil and Materials Engineers, Inc.

3. TESTING AND EVALUATION

WARREN COUNTY, MS

Test Equipment. A Dynatest 8081 Heavy Weight Deflectometer (HWD) Test System was used to generate NDT load-deflection data that was analyzed for this project. Basically, the Dynatest HWD generates a transient, impulse-type load of 25-30 msec duration, at any desired (peak) load level between 6,500 and 54,000 lbf. For this project, test loads of approximately 9,000 lbf were used, corresponding to the effect of a standard 18,000 lbf single axle load, i.e., 9,000 lbf in each wheel path. In addition, one lower HWD load level was used at each test point as well as one higher level on the portland cement concrete sections. Information obtained by the different load levels may be used, if needed, to determine non-linear material behavior of the unbound materials.

Roadway Test Sections. Eight roadways sections that ranged in length from 0.90 - 8.20 miles were included in this project. The local pavement management system employed for selecting these sections was based on visual inspections of the pavement surfaces to determine the condition of each roadway. A table that includes the length, average daily traffic (ADT), and type of surface for each section is provided in Appendix D. Five of the roads were double bituminous surfaced treated rural county roads with ADT's between 505 and 1,986. Two of the roads were constructed of portland cement concrete, and their ADT's were 201 and 8,208. One road was constructed with portland cement concrete and overlaid with asphalt concrete. The ADT for this road was 6,415.

Methods of Analysis. As requested, three methods were used to analyze the data obtained with the HWD and provide overlay designs. Based on the structural condition of the pavements and estimated traffic volumes, these methods were also used to determine overlay thickness requirements. These methods include the WES developed evaluation procedures and software, the 1986 AASHTO Guide for Design of Pavement Structures, and Dynatest's ELMOD method. In addition, the MODULUS Program was used to compare back-calculation results. Descriptions of these methods are provided in Appendix E. Detailed descriptions of these methods are provided in the contractor's final reports, Briggs, R. C. et al, 1993 listed in the Bibliography. These reports are available for loan from the WES library and may be obtained through your local library.

Field Tests. As stated in the Statement of Work/Specifications, the interval of pavement deflection measurements conformed to the Type II level of testing effort as described in ASTM D 4695, Standard Guide for General Pavement Deflection Measurements, with the exception that the tests were conducted in the outside wheelpaths of the outside lanes only. The test intervals ranged from 100 to 500 feet for flexible pavements and was 100 feet for rigid pavements. Based on data obtained with the HWD, specific locations were selected where pavement cores were obtained.

Rehabilitation Strategies. Rehabilitation strategies were developed for each roadway, and in some cases, a roadway was treated as two separate items because of vast differences in types and amount of traffic. The recommendations were based on overlay thicknesses recommended by each analysis method, visual condition and amount of distress observed on the roadway, ride quality noted during a tour of each site, and the amount of traffic estimated for the time periods. The recommendations were also based on engineering judgement and the constraints of typical construction and maintenance practices at the demonstration site. A tabulation of rehabilitation strategies for each roadway section is shown in Appendix F.

As shown in Appendix F, repair strategies were provided for each roadway section based on expected design lives of 5, 10, and 20 years. These alternative designs provided the county with options to link their roadway repair plans to long term municipal growth and community expansion plans. The options also provided cost effective solutions and definite plans for disbursement of funds allotted for roadway repair.

Findings. Each method used to analyze the NDT data and determine overlay requirements for the roadway sections provided a different thickness. These differences usually ranged between 0.1 and 1.5 inches, and were considered insignificant when the minimum standard recommended thickness for an asphalt overlay is one inch. In general, the thickness requirements determine by the WES method were 30 to 50 percent greater that those determined by the AASHTO or ELMOD methods, but this was not always true. There was no consistency between the differences in thickness requirements when comparing the thicknesses determined by the AASHTO method to those determined by the ELMOD method. Based on engineer judgement and calculated thickness requirements, the recommended overlay thicknesses ranged between the smallest and largest calculated values.

Based on the results of these three methods for determining overlay requirements, no one method is more accurate than the other. However, a minimum of two methods should always be used for determining overlay thicknesses so the designer will have a greater amount of information for developing rehabilitation strategies.

After the tasks described in Appendix A were completed, representatives from Warren County and the contractor were requested to provided WES comments concerning the project and suggested improvements to Appendix A. The Warren County road manager was pleased with the project and said the results will give him an accurate assessment of what really needs to be done for pavement repair. He said he could use the results to identify the pavement problems before they really got bad. The contractor suggested that the number of lanes should be included in the list of streets to be tested. He also suggested that the analysis method should conform to either the AASHTO or Corps of Engineers procedures.

CINCINNATI, OH

Test Equipment. The test equipment was the same as that used in Warren County, MS.

Roadway Test Sections. Twenty-two roadway sections that ranged in length from 0.29 - 3.19 miles were included in this project. The selection of these sections was based on a recent visual survey and evaluation of roadways conducted by an engineering firm. A table that includes the length, ADT, and type of surface for each section is provided in Appendix G. Nine of the roads were constructed of asphalt concrete, five were portland cement concrete, and eight were portland cement concrete overlaid with asphalt concrete. The number of traffic lanes ranged from two to six, and the ADT for the roads ranged from 500 to 25,000.

Methods of Analysis. The methods of analysis were the same as those for the Warren County, MS project.

Field Tests. The pavement deflection measurements were obtained as required in the Statement of Work/Specifications, and cores were obtained on each roadway to confirm construction and maintenance records or determine the thicknesses of the pavement structure. For safety purposes, some of the high traffic roads were tested and cored during the night when the traffic was lighter.

Rehabilitation Strategies. Rehabilitation strategies were developed for each roadway, and in some cases, a roadway was treated as two separate items because of differences in types and amount of traffic, pavement structure, and pavement deflection recorded during the testing period. The recommendations were based on overlay thicknesses recommended by each analysis method, visual condition and amount of distress observed on the roadway, ride quality noted during a tour of each site, and the amount of traffic estimated for the time periods. The recommendations were also based on engineering judgement and the constraints of typical construction and maintenance practices at the demonstration site. A tabulation of rehabilitation strategies for each roadway section is shown in Appendix H.

As shown in Appendix H, repair strategies were provided for each roadway section based on expected design lives of 5, 10, and 20 years. These alternative designs provided the city with options to link their roadway repair plans to long term municipal growth and community expansion plans. The options also provided cost effective solutions and definite plans for disbursement of funds provided for roadway repair.

Findings. Each method used to analyze the NDT data and determine overlay requirements for the roadway sections provided a different thickness. These differences usually ranged between 0.1 and 0.5 inches, and were considered insignificant when the minimum standard recommended thickness for an asphalt overlay is one inch. In general, the thickness requirements determine by the ELMOD method were 1 to 3 inches greater that those determined by the AASHTO or WES methods for the concrete pavements that were overlaid with asphalt. Based on engineer judgement and calculated thickness requirements, the recommended overlay thicknesses ranged between the smallest and largest calculated values.

Based on the results of these three methods for determining overlay requirements, no one method is more accurate than the other. However, a minimum of two methods should always be used for determining overlay thicknesses so the designer will have a greater amount of information for developing rehabilitation strategies.

After the tasks described in Appendix A were completed, representatives from the City of Cincinnati and the contractor were requested to provided WES comments concerning the project and suggested improvements to Appendix A. Personnel from the Cincinnati Department of Public Works were pleased with the project and said the results will give them an accurate assessment of the pavements and suggested repair procedures. They said the corings obtained from many of the roadways will provide them with valuable information concerning the thicknesses of the pavement structure. The contractor suggested that a map marked with the location of all of the roads to be tested would have been very helpful, and the traffic estimates for each roadway should include both the number of automobiles and trucks. The contractor also suggested that the analysis method should conform to either the AASHTO or Corps of Engineers procedures.

BERKELEY, CA

Test Equipment. A KUAB Two Mass Falling Weight Deflectometer (KUAB 2m-FWD) which is an impulse loading device that exerts a force similar in magnitude to a moving truck wheel load was used to test the roadways at this demonstration site. The two-mass system was developed to provide a consistently smooth load pulse with a single peak located at the center of the total load duration (time scale). The magnitude of the dynamic load applied to the pavement can be varied from 3,000 to 33,000 lbs by varying the mass and height from which the mass is dropped. A drop sequence of a single load of 6,000 lbf followed by two drops of 9,000 lbf was selected for these tests. The load rise time (time to peak load) is approximately 17 milliseconds, corresponding to a load duration of 34 milliseconds. A load cell measures the magnitude of the dynamic load.

Roadway Test Sections. There were 112 roadway test sections included in this project. The selection of these sections was based on a pavement management system developed by the Metropolitan Transportation Commission located in Oakland, CA. The system is a pavement condition survey determined by visual inspection of the roadway surface and measurement of crack size to determine the severity level of pavement distresses. The length of the sections ranged from 0.02 to 0.81 miles, and the majority of the roadways contained two lanes, although there was one single lane road, and others contained three, four, or five lanes. Three of the roadways were constructed of portland cement concrete, seven were asphalt concrete, and the remainder of the roadways were asphalt concrete over portland cement concrete overlays. The ADT's for these roadways ranged from 500 to 46,000. A table that includes the length, ADT, and type of surface for each section is provided in Appendix I.

Methods of Analysis. Three design procedures were used for structural evaluation and overlay design of the roadways included in this project. These included the WES procedures, AASHTO procedures, and procedures developed by ERI. Descriptions of these procedures are provided in Appendix E. Detailed descriptions of these methods are provided in the contractor's final report, ERES International, Inc...., 1993 listed in the Bibliography. This report may also be obtained on loan from WES's library through your local library.

Field Tests. Tests were conducted in accordance with Type II level of testing as described in ASTM D 4695 with the exception that the tests were conducted in the right wheel path of the outer traffic lane. When necessary, test locations within a section were adjusted in order to avoid unnecessary obstructions to traffic, severely deteriorated pavement areas, or other safety hazards.

The historical records provided layer thickness information for only 9 of the 112 sections that were evaluated. Due to the limited information on the pavement thicknesses, ERI conducted a comprehensive boring program on the sections. A single boring location was chosen for each pavement section at a location determined to be representative of the overall pavement section according to the results of the NDT. Drilling was performed to the bottom of the granular base layer using a six-inch diameter bit. Six-inch diameter core samples were extracted from composite pavement sections and tested for compressive strength.

Results of a 1992 pavement condition survey of the roadways were provided ERI by the city of Berkeley. The pavement condition index (PCI) of the roadways ranged from 40 (fair) to 80 (very good) with the exception of one street that had a PCI of 100. Most of the streets were constructed in the 1950's and 1960's which indicates that the pavements have been in service for 30 to 40 years.

Rehabilitation Strategies. Rehabilitation strategies were developed for each roadway. If the NDT tests indicated major structural differences in a roadway, the roadway was divided into two separate items before strategies were developed. The engineering evaluations were based on results of the pavement condition survey, nondestructive and destructive testing, and estimated ADT's for 5, 10, and 20 year time periods. Engineering judgement and the constraints of typical construction and maintenance practices at the demonstration site were also considered. A summary of the maintenance and repair recommendations are shown in Appendix J.

Findings. Generally, the AASHTO method for determining overlay thicknesses for asphalt pavements produced thicker overlays than the WES or ERI methods. But, in most cases the differences ranged from 0.5 to 1.0 inch, and were considered insignificant when the minimum standard recommended thickness for an asphalt overlay is one inch. For composite pavements, the ERI method produced thicker overlay requirements than the AASHTO or WES methods. The contractor based their rehabilitation strategies on the results produced by the ERI method.

After the project was completed, representatives from the City of Berkeley and the contractor were requested to provide WES comments concerning the project and suggested improvements to Appendix A. Representatives from Berkeley said the cones, flagman, and arrow board were sufficient for traffic control on the streets tested, but on high traffic volume roads or highways a much more extensive method for traffic control will be required. They also said that since the police department had been alerted to the testing program, no major problems were encountered. They mentioned that since they had a comprehensive pavement management system, they were able to provide the contractor with accurate traffic volumes, pavement condition data, and unit construction costs, but they had minimal records on the pavement layer thicknesses. This necessitated an extensive boring program by the contractor.

Personnel from Berkeley's Department of Public Works were concerned with differing overlay thicknesses resulting from the three separate methods, especially when one method recommended 0.5 inches, another 2.0 inches, and the third 4.0 inches. They also mentioned that Berkeley like other older cities are restricted by existing curb and gutter and crown height, and no longer have sufficient curb height to receive another overlay, and the rehabilitation strategies did not address these problems. They were also concerned with some of the recommendations where the overlay thickness was less than the material milled from the existing pavement.

BERKELEY'S COMMENTS

Berkeley's general comments concerning the demonstration project were as follows:

a. NDT appears to be a valuable tool in designing overlays.

b. They received a large quantity of information that will be useful in terms of planning and design.

c. Based on the results, they will be able to eliminate certain streets from their current overlay program, thereby saving the City $950,000 ($826,000 in material costs and $124,000 in labor costs) that would have been wasted on unnecessary repair.

d. WES' guidelines on issuing a Request for Proposal (RFP) for nondestructive testing will be most helpful to local agencies.

e. A joint procurement project by several local agencies could possibly lower individual costs for NDT.

CONTRACTOR'S COMMENTS

Comments received from the contractor were as follows:

a. In some cases the city/county and the contractor may not be entirely familiar with NDT and design techniques, and there is a potential for large misunderstandings between what the two parties expect and the cost required to obtain the results. One way to avoid this is to specify the testing and design methods and guidelines to be followed.

b. A map showing the location of each test site should be provided.

c. The percentage of truck traffic should be provided with the ADT's.

d. All construction, maintenance, and repair records for the test sites should be provided. This should be made known at the time of the RFP since this will directly affect the quantity of coring, etc. required.

e. Design constraints such as curb and gutter restrictions, no surface treatments allowed, etc. should be made clean prior to the design phase.

f. Make a provision that test point locations may be adjusted to avoid conflicts with intersections, poor visibility, and utilities.

SEMINARS

After the contractor completed testing and evaluating the roadways at a demonstration site, a final report was furnished to the city/county and WES. The contractor was responsible for participating in a seminar at the site. The purpose of the seminar was to inform local personnel of the NDT technology and demonstrate how it can be used with a pavement management system to develop rehabilitation procedures for roads and streets. Pavement engineers, roadway managers, county/city administrators, and other personnel responsible for design and maintenance of roadways were invited to attend. Representatives from WES, the demonstration site, and the contractor each participated in a day-long seminar. The major topics presented at each seminar were as follows:

- History of NDT technology
- Description of local pavement management system
- Selection of roadway sections
- Test procedures and data collection
- Discussion of analysis procedures
- Results and recommended maintenance and rehabilitation techniques
- Proper application of NDT technology
- Demonstration of equipment

Approximately 45 people attended the seminars at Warren County and Berkeley, but only seven attended the seminar conducted at Cincinnati. The Cincinnati seminar was poorly attended because it was not widely publicized and another seminar concerning construction and maintenance of roads was conducted during the same time period. During the seminars, there seemed to be considerable interest from the attendees, and many of them requested copies of the final report.

ANALYSIS

Observations made during this project and comments and suggestions provided by personnel who represented the three demonstration sites are as follows:

a. The methods used to analyze the data obtained with a FWD are dependent on traffic data; therefore, in order to obtain meaningful overlay designs, the traffic estimates must be accurate and realistic. If this information is not realistic, the calculated overlay requirements will be incorrect, and the rehabilitated road will be either under designed or over designed.

b. City/county street maps with the selected street segments marked provided an easy method to locate the test sites. During these demonstrations, some of the test sites were impossible to locate when only the beginning and end of the sites were provided in the tabulation of sites. When this occurred, personnel from the local office were required to physically show the contractor the location of the site.

c. The information obtained from the construction and maintenance records was helpful, but was not always accurate. The inaccuracies were partially due to the fact that many of the roadways were 30 to 50 years old, and some of the maintenance procedures conducted during the years were not entered into the records. The thickness of each existing pavement layer within a pavement structure is a very important factor used when determining rehabilitation strategies. If historical data is not accurate, these data must be obtained by coring the pavement. If the contractor is required to core the pavement, the cost of the contract will increase significantly.

d. Items discussed during the premeeting that helped the contractor proceed in a timely manner included discussion of local procedures for traffic control, roadway rehabilitation procedures, color of marking paint to use, and unusual traffic conditions on certain roadways.

e. In some cases, the rehabilitation procedures did not address the restricted curb and gutter and crown heights of many of the older roads and streets. At times, the recommended thickness of overlay would result in a pavement surface located above the top of the curb. Roadway design constraints peculiar to the local city/county should be made at the premeeting since this will effect the rehabilitation strategies.

f. A more detailed comparison of the cost for suggested maintenance procedures to a standard 2 inch thick asphalt overlay would have been helpful. This comparison would have provided a cost analysis to determine the feasibility of NDT.

g. Comparison of the three methods used for analyzing the NDT results and providing rehabilitation strategies for each roadway were confusing. In some cases, one method may require no overlay, whereas another method may require an overlay thickness of three inches. These differences are attributed to the different procedures used by the design programs for analyzing the NDT results and accounting for the existing pavement thicknesses. In the future, the method used for determining overlay thicknesses should be specified in the guide specifications.

h. The city and county representatives received a large quantity of information on their roadways. Not only was information such as thicknesses of the pavement layers obtained, but based on the results of these demonstration, some of the streets and roads originally scheduled for rehabilitation will not be repaired.

i. It would be cost effective to have one contractor evaluate the roadways of two or more adjacent communities during the same time period. Since it is expensive for a contractor to mobilize and bring his equipment into an area, it would be economically advantageous to have a contractor test roads in more than one community while his equipment is in the vicinity.

4. SUMMARY OF RESULTS

The purpose of this project was to introduce personnel at the city, county, and municipality levels to NDT technologies. They should be aware of the DOD/DOT research efforts conducted over the past decade. The pavement related research performed at WES can be directly applied to roads, streets, and interstate highways. Rehabilitation requirements from NDT can be used effectively for formulating budget plans and prioritizing projects as an integral part of a comprehensive pavement management system. With the high cost of rehabilitation and the increasing traffic levels nationwide, pavement management systems are proving to be extremely cost effective, with benefits being realized within the first three years after implementation. In the case of Berkeley, CA benefits were immediately realized, saving the city a one-year total of $950,000.00 ($826,000.00 in material costs and $126,000.00 in labor costs). With an initial contract cost of $50,000.00, the NDT technology provided a 19 to 1 return on investment.

Each contractor analyzed the selected pavements using the WES procedures, AASHTO procedures, and their own methods. Based on NDT and visual condition assessments, rehabilitation alternatives were provided for 5-, 10-, and 20-year traffic projections. Structural overlay requirements were found to vary significantly depending on the analysis method used. The AC overlay thicknesses for Warren County, Cincinnati, and Berkeley are shown in Figures 1-3. The Dynatest/SME and AASHTO overlays, plotted in Figures 1 and 2, are actually the mean plus one standard deviation, which is the contractor's recommendation for these sections. WES values are based on a representative data set for each pavement section which should provide a value near the mean. AASHTO values are based on a reliability level of 50 percent. On the average, the WES procedure produced overlay thicknesses that were within ± 1 inch of the other methods for asphalt concrete (AC) pavements and 3 inches higher for portland cement concrete (PCC) pavements. Average WES overlay thicknesses for composite pavements were within ± 2 inches of the AASHTO values and 4-6 inches lower than the Dynatest/SME values. These comparisons are valid for the specific analysis methods used and assumptions made by the contractors for these specific pavements, and results should not be interpreted as typical or representative of the differences that can be encountered with other procedures or contractors.

The differences between overlay thicknesses determined from the various evaluation methods can be attributed to a number of factors. The required thicknesses are directly related to the performance criteria selected. With layered elastic procedures, stresses and strains are computed at critical locations within the pavement system for the design vehicle. Limiting values of stress/strain are applied to translate from the analytical models to field performance. These limiting criterion are typically empirically derived from observed field performance or laboratory test results. WES, Dynatest/SME, and ERI performance criteria are presented graphically in Figures 4-6. Direct comparisons of the strain-based and stress-based criteria may be difficult, however, although the plots do illustrate why different results are obtained from each method.

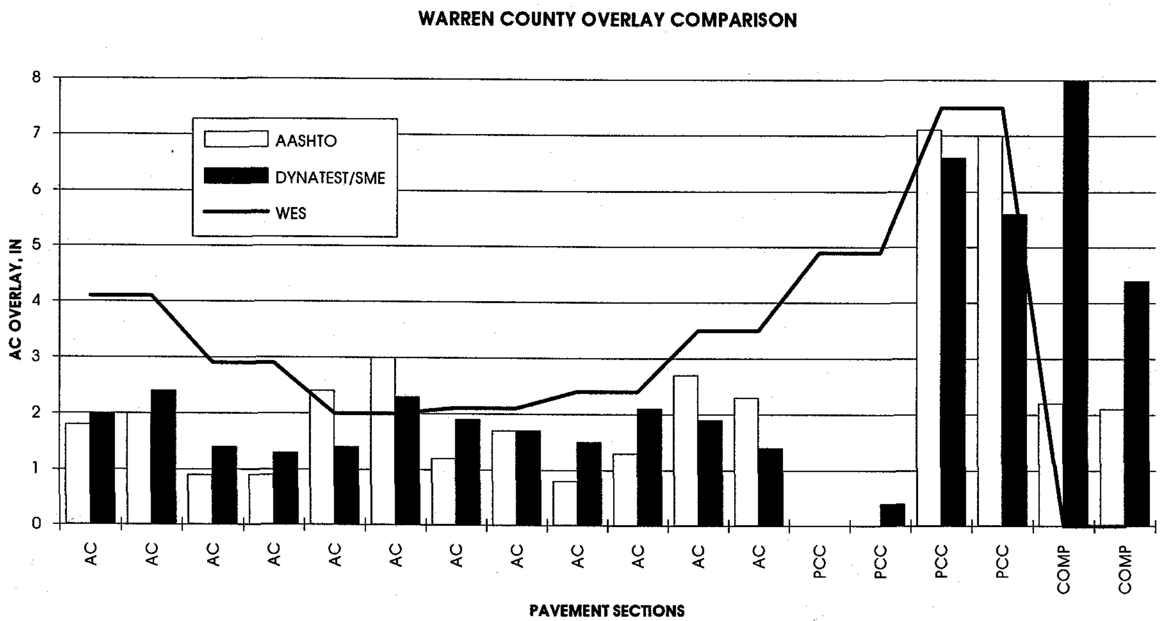

Figure 1. AC overlay thicknesses computed for the Warren County, Mississippi pavements (AASHTO and Dynatest/SME values = mean + 1 standard deviation).

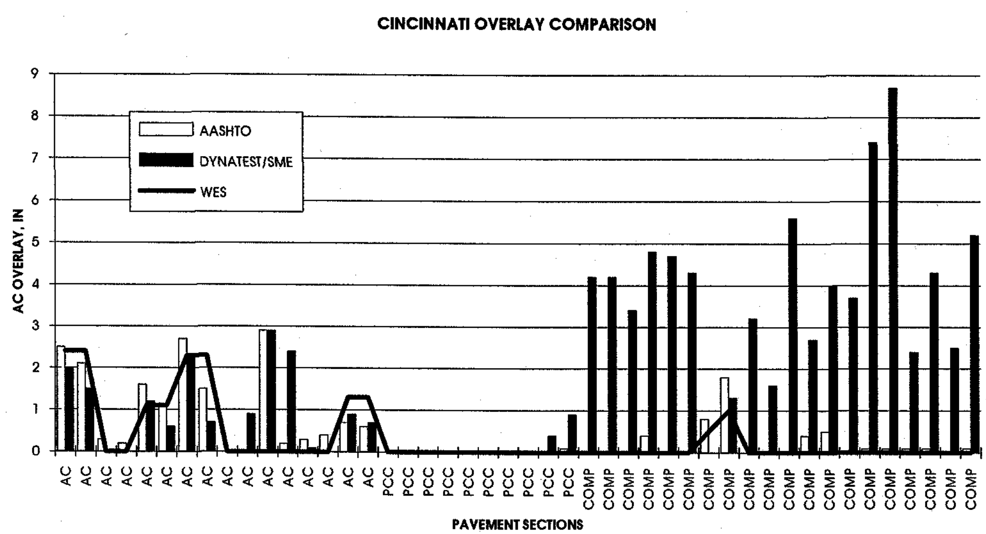

Figure 2. AC overlay thicknesses computed for the Cincinnati, Ohio pavements (AASHTO and Dynatest/SME values = mean + 1 standard deviation).

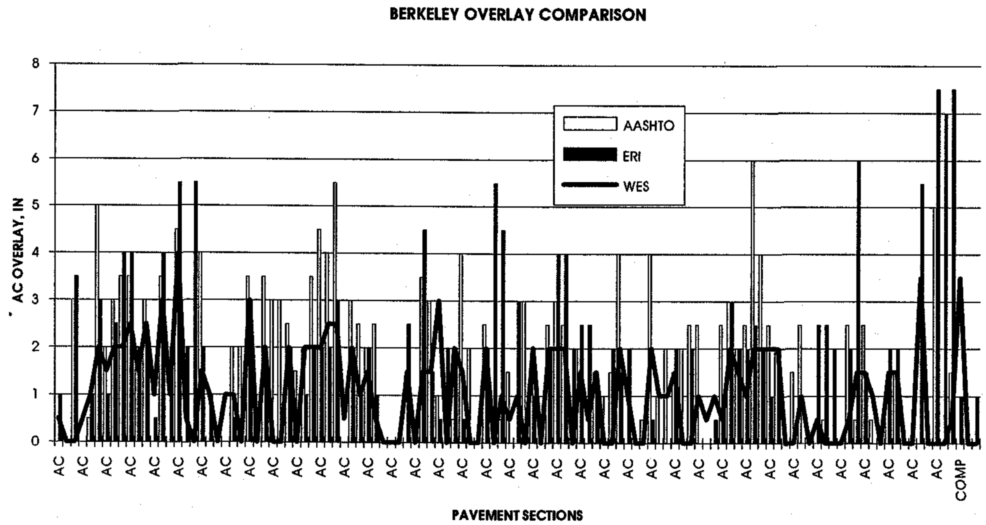

Figure 3. AC overlay thicknesses computed for the Berkeley, California pavements.

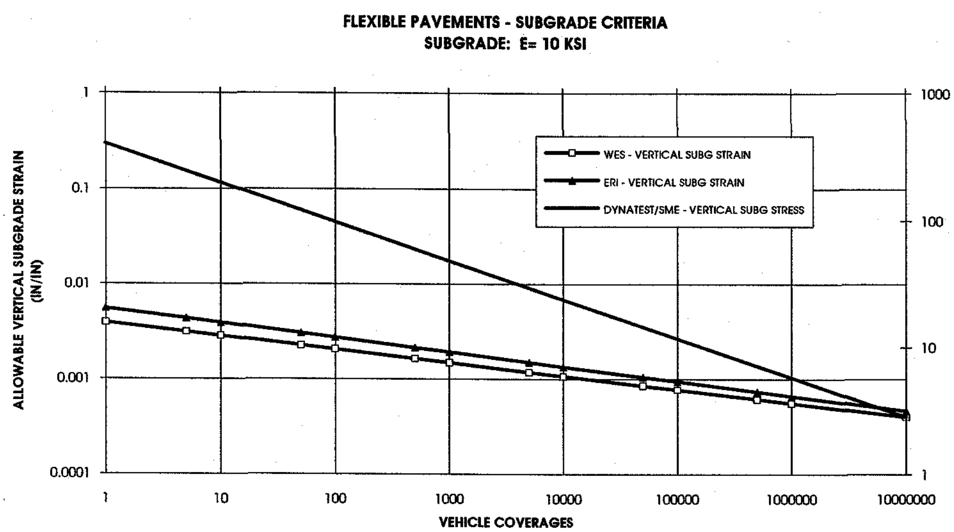

Figure 4. Comparison of subgrade stress and strain criteria used for evaluating flexible pavements.

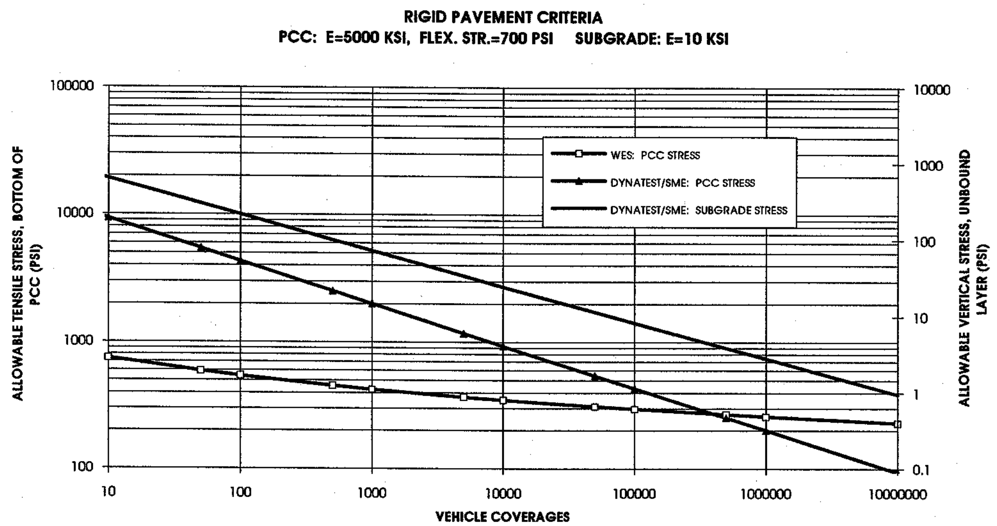

Figure 5. Comparison of stress criteria used for evaluating rigid and composite pavements.

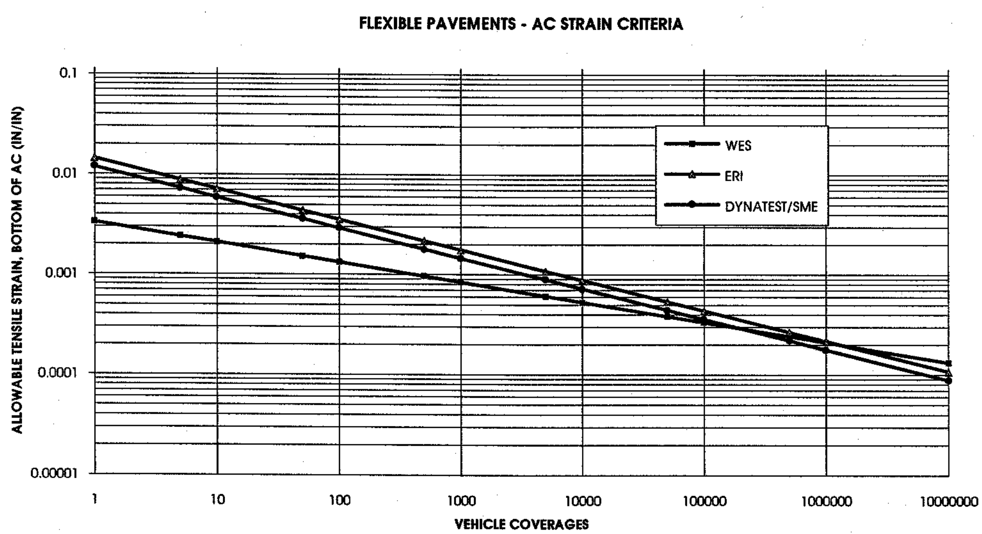

Figure 6. Comparison of asphalt tensile strain criteria used for evaluating flexible pavements.

In comparing the criteria, it is interesting to note the slopes of the various performance curves. It can be seen in Figure 4 that the slope of the Dynatest/SME tensile stress relationship is much steeper than the WES curve. This means that WES results will be more conservative for lower traffic levels (less than 500,000 vehicle coverage) and less conservative for higher traffic levels (greater than 500,000 coverage). It should also be noted that Dynatest/SME applies both a tensile stress criteria to the PCC and a stress criteria to the unbound layers. This stress criteria contributed significantly to the larger overlays reported for the composite pavements. The asphalt strain criteria for flexible pavements, shown in Figure 5, is similar for each of the methods, with the WES procedure being slightly more conservative at the lower traffic levels. The subgrade criteria for flexible pavements, presented in Figure 6, indicates that the WES and ERI criteria are very similar, and, in fact, the ERI criteria is based on previous Corps of Engineer research efforts. Dynatest/SME methods utilize a stress-based criteria for the unbound layers. When selecting an evaluation procedure, it is important to consider the type of performance criteria and how the criteria was developed. For example, if the anticipated traffic levels are extremely high, it may not be wise to select limiting criterion based on limited field or lab tests in which failures occurred at low coverage or repetition levels. The traffic levels for the roads and streets included in this study ranged from approximately 5,000 up to 2,000,000 equivalent single axle coverage.

Another criteria consideration is the method of analyzing composite pavements. In the WES computer programs, a composite pavement is analyzed using rigid pavement criteria. This does not mean, however, that all composite pavements should be treated as rigid pavements. If the modulus of the PCC layer is low (less than 1,000,000 psi), the pavement should be analyzed as a flexible pavement. In the case of very thick AC overlays, judgement is required to determine which failure mechanism is most likely to occur.

In addition to the criteria, the back-calculation procedures, methods of handling past fatigue damage, and other method-specific considerations can result in a wide range of results. One of the first steps in the evaluation process, material characterization, is a difficult task that often requires a great deal of engineering judgement to obtain reasonable results. The assessment of damage that has already occurred in a pavement is difficult to define and incorporate into the analysis process. Many procedures attempt to define the loss of pavement life in terms of the existing surface condition. When results are reported for the AASHTO method, it is important to know which AASHTO procedure has been used. AASHTO has both NDT and pavement condition methods. AASHTO overlay requirements are also specified in terms of reliability. Overlay requirements for an 80-percent reliability level will be significantly higher than those determined for 50-percent reliability. Some of the AASHTO overlay thicknesses, reported by ERI, doubled depending on the reliability level specified.

Results from this study have shown that NDT is a viable technique for evaluating the structural capacities and overlay requirements for roads and streets. Analysis of the deflection test data has been shown to be a complex task with results depending on a number of factors including the selection of criteria, climate, and traffic considerations. Due to this complexity, results can vary significantly depending on the contractor and evaluation methodology. Thus, it is important to consider experience in selecting a contractor for conducting NDT analyses. The WES procedures, which are well accepted methods with well documented performance-based criteria, have been presented and are available for use by local municipalities, counties, cities, or contractors. It is recommended that a well accepted method, such as the WES procedure, is specified for NDT analysis or required as a check if other new or less known procedures are used.

5. RECOMMENDATIONS REGARDING A SPECIFICATIONS TEMPLATE

Personnel from the three demonstration sites and attendees at the seminars were informed how NDT of their roadways can be used as a tool for developing rehabilitation strategies. At each site, the NDT equipment and testing procedures were demonstrated to the attendees.

Based on the results of this project, additional items have been suggested for the specification template used for requesting bid proposals to nondestructively test, evaluate, and develop rehabilitation strategies for roadways. These model specifications are provided in Appendix K. Additions to the original specification (Appendix A) are as follows:

a. In paragraph 1 (see Appendix K), the specifications were modified such that contractor is requested to provide rehabilitation strategies based on average daily traffic projections (ADT's) of 5,10,and 20 years. These strategies should provide the city/county with multiple alternatives that can be used to develop the most cost effective use of roadway maintenance funds.

b. Paragraphs 2.a. and 2.b. call for a more extensive description of the test sites and their location (including a location map) to provide the contractor with sufficient information required to prepare a bid proposal.

c. Paragraphs 2.c. and 3.b. concerning the collection of pavement layer thickness data were added because this data is required during the analysis and design of overlays for the roadway structures. If this data is not available, the contractor must include the collection of this data in his cost estimate. Collection of this data may become quite involved when underground utilities are present.

d. In paragraph 3.a., the level of testing effort should be selected by the city/county based on how the test data will be used. Three levels are provided in the model: limited testing for a general overview of the pavement condition, a routine analysis for overlay design projects, and a detailed analysis for evaluation of joint efficiency for portland cement concrete slabs.

e. Paragraph 3.e. was added because properties of the pavement materials are required for analyzing the test data.

f. The AASHTO and Corps of Engineers analysis and design methods are suggested in the template because they are well known accepted procedures.

g. Five specific items were added to the PREMEETING paragraph to ensure that the contractor obtains the historical records required to complete the tasks, and that design constraints and past construction costs are considered.

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ABBREVIATIONS AND ACRONYMS

AASHTO	American Association of State Highway and Transportation Officials
AC	Asphalt Concrete
ADT	Average Daily Traffic
ADTT	Average Daily Truck Traffic
APWA	American Public Works Association
ASTM	American Society for Testing and Materials
CBD	Commerce Business Daily
CBR	California Bearing Ratio
CRDA	Cooperative Research and Development Agreement
DSM	Dynamic Stiffness Modulus
ERI	Engineering and Research International
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FIS	Federal Infrastructure Strategy
FWD	Falling Weight Deflectometer
HWD	Heavy Weight Deflectometer
ISM	Impulse Stiffness Modulus
NDT	Nondestructive Testing
PCI	Pavement Condition Index
PCC	Portland Cement Concrete
RFB	Request for Bid
RFP	Request for Proposal
WES	Waterways Experiment Station
USACE	U.S. Army Corps of Engineers

Appendix A
Statement of Work/Specifications

1. GENERAL.

The contract shall provide all supplies, labor and equipment to conduct nondestructive tests (NDT) on roads in Warren County, MS, Cincinnati, OH, and Berkeley, CA. A report listing rehabilitation strategies for each road evaluated shall be provided. The contractor shall be required to make a presentation and demonstrate their NDT equipment to the city/county personnel responsible for construction and maintenance of their roadway system.

2. GOVERNMENT RESPONSIBILITIES.

a. The U.S. Army Waterways Experiment Station (WES) shall provide the contractor with the Corps of Engineers design/evaluation software to determine rehabilitation methods for the roads evaluated. WES shall also provide any training required to use the software.

b. The city/county shall furnish pavement design, maintenance and rehabilitation records for the roads selected for evaluation. Traffic estimates for the next 20 years for the selected roadways shall be provided to the contractor.

c. Liability associated with the pavement rehabilitation shall be accepted by the city/county and or the contractor performing the rehabilitation construction.

3. CONTRACTOR RESPONSIBILITIES

a. Field work. Test measurements shall be obtained with falling-weight type impulse load device that is in accordance with ASTM D 4694, Standard Test Method for Deflections with a Falling-Weight-Type Impulse Load Device. The testing effort shall conform to Type II level as described in ASTM D 4695, Standard Guide for General Pavement Deflection Measurements, with the exception that the tests shall be conducted in the outside wheelpaths only.

b. Pavement thickness. Pavement layer thicknesses shall be determined by reviewing construction records. Coring of the roadway structure may be necessary to determine and/or verify layer thicknesses when such data is questionable or unavailable. When required material property data is not available, the contractor shall collect samples and conduct laboratory tests to determine these properties (ie flexural strength of concrete).

c. Traffic control. The contractor shall be responsible for traffic control during the data acquisition process. Traffic control shall be in accordance with the Manual of Uniform Traffic Control Devices.

d. Any liability due to accidents associated with the field testing shall be covered by the contractor.

e. Analysis. The contractor shall analyze the pavement data using the government furnished software, the 1986 AASHTO Guide for Design of Pavement Structures, and his own methods. From these three analysis procedures, the contractor shall select the appropriate method based on engineering judgement. Recommendations for rehabilitation strategies shall be furnished based on 5 year, 10 year, and 20 year traffic estimates to allow the city/county to use stage construction based on budget constraints.

f. Report. The final report shall consist of a summary of test results, analysis of results, and the recommendations for maintenance and rehabilitation required to support the estimated future traffic.

g. After submission of the report, and approval by the contracting officer, a one day seminar will be conducted at the local area. City and county pavement engineers from the region will be invited. The contractor shall present his analysis at this seminar and demonstrate the operation of their falling weight deflectometer equipment. The date and exact location of the seminar shall be determined later.

4. AREAS TO BE TESTED.

A prioritized list of roads to be tested, their locations, and descriptions are provided in Appendices D, G, and I.

5. PREMEETING.

Prior to initiating the work, representatives from the WES, city/county, and contractor shall meet at work sites to coordinate the testing and evaluation of the pavements and determine when and where the seminar shall be conducted. There shall be three (3) seminars conducted, one at each site.

Appendix B
Cooperative Research and Development Agreement Between WES and the City of Cincinnati

WES AGREEMENT NO. WES-93-GL-002

COOPERATIVE RESEARCH AND DEVELOPMENT AGREEMENT (CRDA)
BETWEEN
U.S. ARMY ENGINEER WATERWAYS EXPERIMENT STATION
AND
CINCINNATI, OHIO

THIS AGREEMENT ENTERED INTO THIS 7th day of JUNE, 1993, by and between the U.S. Army Engineer Waterways Experiment Station represented by the Director, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi (hereinafter referred to as WES) and Cincinnati, Ohio (hereinafter referred to as Cincinnati), pursuant to the authority contained in the Federal Technology Transfer Act (15 USC 3710 et seq.) and Army Regulation 70-57.

WITNESSETH THAT:

WHEREAS WES desires to further test and demonstrate and to transfer the WES-developed technology of non-destructive testing (NDT) and evaluation of pavements to State and local governments; and

WHEREAS, Cincinnati is interested in cooperating with WES in the demonstration and further testing of the WES-developed technology of non-destructive testing and evaluation of pavements;

NOW THEREFORE, the PARTIES hereto do mutually agree as follows:

1. SCOPE OF WORK AND SCHEDULE:

The project shall include, the following:

a. Tasks to be performed by WES:

(1). Select roads to be evaluated from a prioritized list provided by Cincinnati, Ohio.

(2). Provide software, design methods, and coordinate the non-destructive testing of the roads identified in 1a(1) as well as the analysis of results and selection of proper rehabilitation procedures based on future traffic estimates.

(3). Provide Cincinnati with a written report of the results.

(4). Document the NDT with a video camera for use in future training workshops.

b. Tasks to be performed by Cincinnati:

(1). Provide WES a prioritized list of roads to be evaluated with the NDT process.

(2). Furnish available pavement design, maintenance, and rehabilitation records for the roads selected.

(3). Provide estimates of future traffic for the next twenty years for the roads selected.

(4). Notify WES of rehabilitation actions taken on the roads evaluated as a result of the study.

2. DATA AND RESULTS:

Each Party shall have the right to utilize and publish all data provided and results obtained.

3. TERM OF THE AGREEMENT:

The term of this CRDA shall be from the day and year first above written through 30 September 1996.

4. PATENT AND OTHER INTELLECTUAL PROPERTY RIGHTS:

It is not envisioned that any technology will be developed under this CRDA since the technology being employed by WES to perform its portion of the cooperative effort does not appear to be patentable. However, should there be any patentable technology developed hereunder, each PARTY shall retain title to the patent rights and other intellectual property rights in this or any foreign country in any invention developed solely by the PARTY's own employees. Should either PARTY elect not to retain title to an invention of one or more of its employees, the other PARTY to the agreement shall have the right to obtain title to the subject patent rights and other intellectual property rights and will grant to the other PARTY a non-exclusive, paid-up license to practice or have practiced each such invention throughout the world.

On inventions made jointly, either PARTY shall have the right to elect to file a joint patent or other intellectual property application in this or any foreign country by notifying the other PARTY within ninety (90) days after the invention is reported. The PARTY so electing to file shall pay the expense of preparation, filing and prosecuting the patent or other intellectual property application.

5. REPRESENTATIVES:

The following individuals have authority to act under this CRDA for their respective PARTIES:

Cincinnati: George Hartman, P.E.
Acting City Engineer
Division of Engineering
801 Plum Street
Room 440, City Hall
Cincinnati, OH 45202
Telephone: (513) 352-3401

WES: Dr. A. J. Bush III
Chief, Criteria Development & Applications Branch
U.S. Army Engineer Waterways Experiment Station
Geotechnical Laboratory
3909 Halls Ferry Road
Vicksburg, MS 39180-6199
Telephone: (601) 634-3545

6. LIABILITY:

a. Liability for Property. The U.S. Government shall not be responsible for damages to any property of Cincinnati provided to WES or acquired by either PARTY under this CRDA.

b. Liability for Injuries Under the CRDA. To the extent permitted by law, each PARTY assumes liability for the negligent actions of its employees or agents that are the cause of injuries or damages that occur during the performance of this CRDA.

c. No Warranty. Except as specifically stated herein, WES makes no express or implied warranty as to any matter whatsoever, including the conditions of the research or any invention or product, whether tangible or intangible, made or developed under this CRDA, or the ownership, merchantability, or fitness for a particular purpose of the research or any invention or product.

d. Force Majeure. Neither PARTY shall be liable for any unforeseeable event beyond its reasonable control not caused by the fault or negligence of such PARTY, which causes such PARTY to be unable to perform its obligations under the Agreement (and which it has been unable to overcome by the exercise of diligence), including, but not limited to flood, drought, earthquake, storm, fire, pestilence, lightning and other nature catastrophes, epidemic, war, riot, civic disturbance or disobedience, strikes, labor dispute, or failure, threat of failure, or sabotage of either PARTY's facilities, or any order of injunction made by a court or public agency.

In the event of the occurrence of such a force majeure event, the party unable to perform shall promptly notify the other PARTY. It shall further use its best efforts to resume performance as quickly as possible and shall suspend performance only for such period of time as is necessary as a result of the force majeure event.

7. OFFICIALS NOT TO BENEFIT:

No member of or delegate to Congress or resident commissioner shall be admitted to any share or part of this Agreement or to any benefit that my arise therefrom.

8. RELATIONSHIP OF PARTIES:

The parties to this CRDA act in their independent capacities in the performance of their respective functions under it, and neither PARTY is to be considered the officer, agent or employee of the other.

9. MISCELLANEOUS:

a. Drug-Free Workplace. During the performance of this CRDA, the PARTIES shall be required to comply with the intent of the Drug-Free Workplace Act of 1988, 41 U.S.C. § 701, et seq., which requires the establishment of a drug-free workplace.

b. Equal Employment Opportunity. During the performance of this CRDA, both PARTIES shall comply with Executive Order 11246, as amended, and the rules, regulations, and orders of the Secretary of Labor concerning equal employment opportunity.

c. Export Control Laws. The Parties understand that materials and information resulting from the performance of this Agreement may be subject to the export control laws (50 U.S.C. §

2401-2420) and that each Party is responsible for its own compliance with such laws.

d. Use of Name or Endorsements. The Government and the federal laboratory will not directly or indirectly endorse any product or service provided by the collaborating party as a result of the CRDA.

Cincinnati shall not use the name of the U.S. Army Engineer Waterways Experiment Station, or the U.S. Government on any product or service which is directly or indirectly related to either this CRDA or any patent license or assignment Agreement which implements this CRDA unless permission has been obtained from the Office of the Assistant Secretary of Defense for Public Affairs. The U. S. Army Engineer Waterways Experiment Station shall assist in obtaining such approval as appropriate. By entering into this CRDA the U. S. Army Engineer Waterways Experiment Station does not directly or indirectly endorse any product or service provided, or to be provided, by Cincinnati, its successors, assignees, or licensees. Cincinnati shall not in any way imply that this CRDA is an endorsement of any such product or service.

10. TERMINATION OF AGREEMENT:

Either PARTY may terminate this CRDA within 30 days written notice by the written approval of either PARTY.

11. MODIFICATION OF AGREEMENT:

This CRDA may be modified and its scope extended, subject to written approval of both PARTIES. All notices shall be in writing and sent by Registered Mail to the other PARTY.

12. DISPUTES:

Any dispute arising under this CRDA which cannot be readily resolved shall be submitted jointly to the signatories of this CRDA with each party agreeing to seek in good faith to resolve the issue through negotiation or other forms of non-binding alternative disputes resolution. A joint decision of the signatories, or their designees, shall be the disposition of such dispute.

13. AGENCY REVIEW:

a. Authority. All prior reviews and approvals required by regulation or law have been obtained prior to the execution of this CRDA. The officials executing this CRDA have the requisite authority to do so. Notwithstanding the delegation of authority to execute this CRDA to the individual designated, the Secretary of the Army has reserved to the Assistant Secretary of the Army (Research, Development and Acquisition) the opportunity provided by 15 United States Code section 3710a(c)(5)(A), to disapprove or require the modification of this CRDA within 30 days of the date it is presented to him or her by WES.

b. Ratification. In the event that the Assistant Secretary of the Army (Research, Development and Acquisition) exercises the authority reserved by paragraph 12.1, Cincinnati shall have 30 days from notification of the required modification to ratify the modifications or terminate the CRDA.

IN WITNESS WHEREOF, the PARTIES hereto have executed this Agreement as of the day and year first above written.

FOR: THE U.S. ARMY ENGINEER WATERWAYS EXPERIMENT STATION

FOR [signature], COL
ROBERT W. WHALIN, PhD, PE
Director
U.S. Army Corps of Engineers
Waterways Experiment Station

FOR: CINCINNATI, OHIO

FADawson
FRANK A. DAWSON
Acting City Manager

APPROVED AS TO FORM:

[signature] 5/25/93
Assistant Solicitor

Appendix C
Solicitation Package Mailing List

ARE, Inc
2600 Dellana Lane
Austin TX 78746

BRE, Inc
102144 I.H. 35 North
Austin, TX 78753

PCS/Law Engineering
12240 Indian Creek Court
Suite 120
Beltsville, MD 20705-1242

ERI, Inc
1401 Regency Dr. East
Savoy, IL 61874

Pavement Consultants, Inc
7530 Roosevelt Way NE
Suite 300
Seattle, WA 98115-4221

D. A. Voss & Associates
12520 SE 14th Street
Bellevue WA 98005

Dynatest Consulting, Inc
P.O. Box 71
Ojai, CA 93023

Louis Berger International, Inc
100 Halsted Street
PO Box 270
East Orange, NJ 07019

Soil and Materials Engineers, Inc
43980 Plymouth Oaks Blvd.
Plymouth,MI 48170

ERES Consultants, Inc
8 Dunlap Court
Savoy, IL 61874

Pavement Services, Inc
2510 Southwest First Ave
Portland, OR 97201

Rajan, McQueen,and Assoc.
3112 Fox Den Lane
Oakton, VA 22124

Hadley & Hollingsworth Ltd
747 Sheridan Blvd
Unit 1E
Lakewood, CO 80214

Infrastructure Management Services
3350 Salt Creek Lane
Suite 117
Arlington Heights, IL 60005

Braun Pavement Technologies, Inc
1404 Concordia Ave
St. Paul, MI 55104

Crawford, Murphy & Tilly, Inc
2750 West Washington St
Springfield, IL 62702

Appendix D
Warren County, MS Test Sections

Warren County Mississippi
Highway Department
Streets to be Evaluated

PRIORITY	NAME OF STREET	BEGINNING	END	LENGTH, FT	AVERAGE DAILY TRAFFIC	SURFACE TYPE
1	Jeff Davis	US Hwy 61	Fisher Ferry	8.20	505	Asphalt
2	Nine-Mile Cutoff	Halls Ferry	China Grove	1.44	671	Asphalt
3	Redbone Road	Paces Bayou	Jeff Davis	2.82	1,267	Asphalt
4	US Hwy 80	State Maintenance	Big Black River	2.57	201	Concrete
5	Gibson Road	Hwy 27	Halls Ferry	3.66	1,986	Asphalt
6	Mt. Alban Road	Culkin	US Hwy 80	2.45	533	Asphalt
7	US Hwy 61 (2 Lane)	Haining	0.90 Miles North	0.90	6,415	Concrete Asphalt Overlay
8	US Hwy 61 (4 Lane)	1.74 Miles South	Haining	1.74	8,208	Concrete

Appendix E
Pavement Analysis

Test Requirements

The statement of work for this project required the use of nondestructive testing equipment in accordance with ASTM D 4694, Standard Test Method for Deflections with a Falling-Weight-Type Impulse Device (Appendix A). A Type 2 level test program was conducted at each of the three locations in accordance with ASTM D 4695, Standard Guide for General Pavement Deflection Measurements (with the exception that tests were conducted only in the outside wheelpaths for both flexible and rigid pavements. At the Type 2 level, tests are conducted at 100 to 500 ft intervals to provide enough detail for the purpose of overlay design. All pavements were analyzed using WES developed evaluation procedures and software, the 1986 or 1993 AASHTO Guide for Design of Pavement Structures, and one other method of the contractor's choice. Recommendations for rehabilitation were furnished for 5-, 10-, and 20-year traffic estimates. Each evaluation methodology utilized in this study is described below.

WES Procedure

Overview. Methodologies for structural evaluation of roads and streets by use of nondestructive testing (NDT) and layered elastic theory have been developed through years of research at WES. Procedures and computer software are available for data reduction, material characterization, and analysis of flexible, rigid, and composite (flexible over rigid) pavements using surface deflection measurements from commercially available NDT equipment (TM 5-826-5). The criteria included in these procedures were developed from data obtained by monitoring the response of experimental test sections due to a range of prototype loadings.

The structural deterioration of flexible pavements caused by traffic is normally evidenced by cracking of the asphalt concrete (AC) surface course and development of ruts in the wheel paths. The evaluation procedure handles these two modes of structural deterioration through limiting values of the strain at the bottom of the AC layer and at the top of the subgrade. Failure of rigid pavements due to the repeated application of loads (fatigue) is normally evidenced by cracking of the portland cement concrete (PCC) layer. Performance criteria for rigid pavements are based on limiting the tensile stress in the PCC slab to levels such that failure occurs only after the pavement has sustained a number of load repetitions.

The stresses and strains used for entering the criteria are computed by the use of Burmister's solution for multilayered elastic continua. The solution of Burmister's equations for most pavement systems will require the use of computer programs and characterization of pavement materials by the modulus of elasticity and Poisson's ratio. The computer code utilized in the WES procedures for computing pavement response is the five-layer linear elastic program WESLEA. When WESLEA is used, the following assumptions are made:

a. The pavement is a multilayered structure, and each layer is represented by a modulus of elasticity and Poisson's ratio.

b. The interface between layers is continuous; i.e., the friction resistance between layers is greater than the developed shear force.

c. The bottom layer is of infinite thickness.

d. All loads are static, circular, and uniform over the contact area.

<u>Supporting Data</u>. A considerable amount of basic information, in addition to the NDT test results, is necessary for conducting a nondestructive pavement evaluation. In some cases, much of this data can be obtained from construction and maintenance records or previous evaluation reports. However, in most instances, acquiring the following additional data elements will require a substantial effort on the part of the contractor and/or the city, county, or agency funding the project:

a. Construction and maintenance history including as-built drawings and dates of construction and overlay.

b. Pavement material profiles including thickness, material classification, and frost code of each pavement layer. These parameters can be determined from the construction records or by drilling small diameter holes through the pavement and measuring layer thicknesses and obtaining samples of each material for laboratory testing.

c. Temperature data for AC and composite pavements.

   (1) Five-day mean air temperature (for the 5 days prior to testing).
   (2) Pavement surface temperature at the time of testing.
   (3) Average daily maximum and average daily mean air temperature for each month.

   The stiffness of bituminous concrete is highly dependent on the temperature as shown in Figure E-1. Thus, the modulus determined for the AC from NDT may not be a good value for design, which should take the seasonal variation into account. Procedures are available for estimating the mean pavement temperature using the measured surface temperature and the mean air temperature for the five days prior to NDT testing. This can be used with Figure E-1 to predict the AC modulus at the time of testing. The design AC modulus that is used in the analysis and overlay design can be determined from a mean pavement temperature that is based on the design air temperature. This requires monthly temperature information that can be obtained from records of the National Oceanographic and Atmospheric Administration or other sources.

d. PCC flexural strength. The flexural strength of PCC pavements is a required input for evaluating rigid and composite pavements (which are evaluated using rigid pavement failure *criteria). The flexural strength can be determined from construction records or by testing 6-inch-diameter cores for tensile splitting strength using the procedure given in ASTM Test Method C 496. The flexural strength is then approximated as:

$$\textit{Flexural Strength, psi} = 210.5 + \textit{Tensile Splitting Strength (psi)}$$

e. Traffic information. The current daily traffic using the pavement should be determined and an estimate of anticipated traffic for the design period must be made. The current daily traffic can be determined from existing records or by conducting a traffic-volume study. The future traffic should be estimated from studies which include vehicle classification counts.

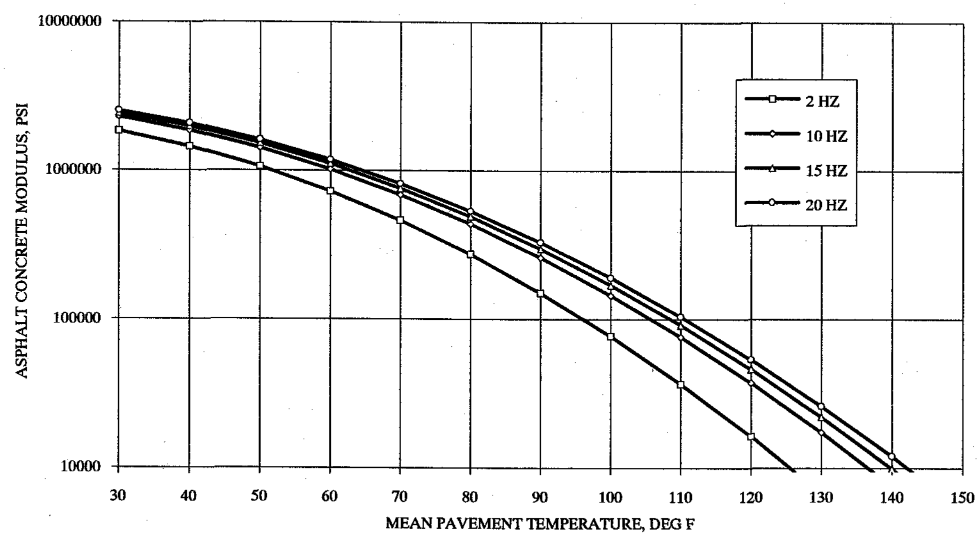

Figure E-1. Laboratory derived relationship showing AC modulus as a function of pavement temperature and loading frequency.

f. Pavement condition survey. A comprehensive evaluation of the present condition of the pavement surface should be made using the pavement condition index method (TM 5-623).

Data Reduction. As a first step in the evaluation process, pavement facilities are typically divided into features according to pavement type, construction, and traffic levels. TM 5-623 provides a method for dividing the pavements into branches and sections. A branch is any identifiable part of the pavement network that is a single entity and has a distinct function such as an individual street or parking lot. A section is a subdivision of a branch that contains consistent characteristics in regard to pavement structure, construction history, traffic, and condition.

The computer program BASIN is used to delineate uniform sections along the length of a project. BASIN computes an impulse stiffness modulus (ISM) from the FWD test results. The ISM is obtained by dividing the applied force by the deflection measured at the center of the FWD load plate. The ISM profile provides a qualitative stiffness comparison between test points and between pavement sections as illustrated in Figure E-2. NDT data are grouped into areas of equivalent ISM based on a visual inspection of the profile. Even if a pavement feature supposedly has a uniform structure and the same construction history, it should be analyzed as more than one pavement group if the strength characteristics in one section are significantly different from those in another section. The ISM profile can also be used to develop a cost effective coring program to obtain accurate pavement structure information or verify existing records.

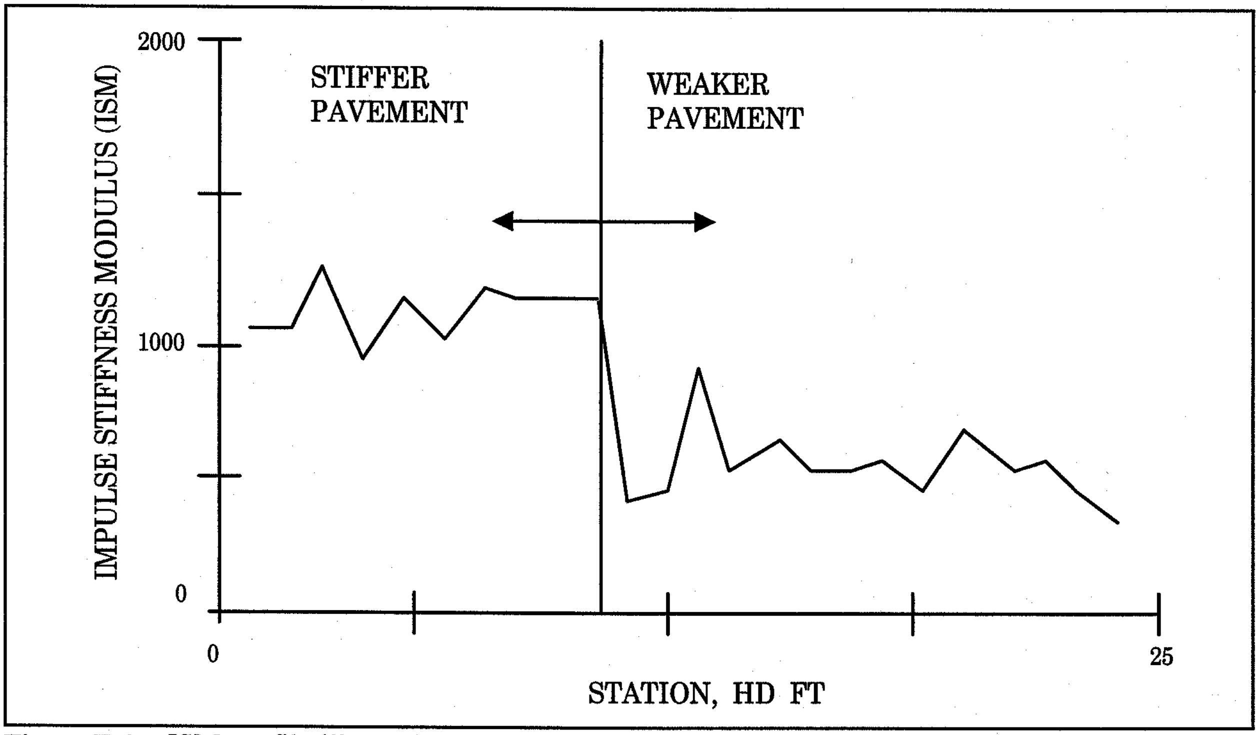

Figure E-2. ISM profile illustrating non-uniform strengths within a pavement section.

When a uniform section is identified, BASIN analyzes the ISM values, all measured deflections, and the area under each deflection basin to determine which data set is nearest to the averages for the section. The representative basin may then be used to determine material properties for analyzing the section. If the coefficient of variation for the ISMs is greater than fifteen percent, engineering judgement should be used to select an appropriate basin to represent the section or all test points may be used.

Material Characterization. Material characterization is the most important step in the evaluation process. It is also the most difficult step and often requires experience and judgement to achieve reliable results. The computer program WESDEF was developed to backcalculate layer moduli from surface deflections measured with an NDT device. To determine modulus values, the pavement structure is modeled as a layered system similar to that illustrated in Figure E-3. WESDEF uses the WESLEA linear, elastic program for computing surface displacements, which is capable of handling multiple loads, variable interface conditions, and up to five layers. WESDEF uses an iterative optimization procedure to determine a set of modulus values that provide the best fit between a measured and a computed deflection basin when given an initial estimate of the elastic modulus values, a range of modulus values, and a set of measured deflections. WESDEF contains default ranges for the modulus of various pavement materials. In analyzing the results from backcalculation, it is important to check the predicted modulus for a layer against the limits. If the modulus is outside a limit, engineering judgment is required to select one of the following:

a. Rerun WESDEF computing modulus values for fewer layers.

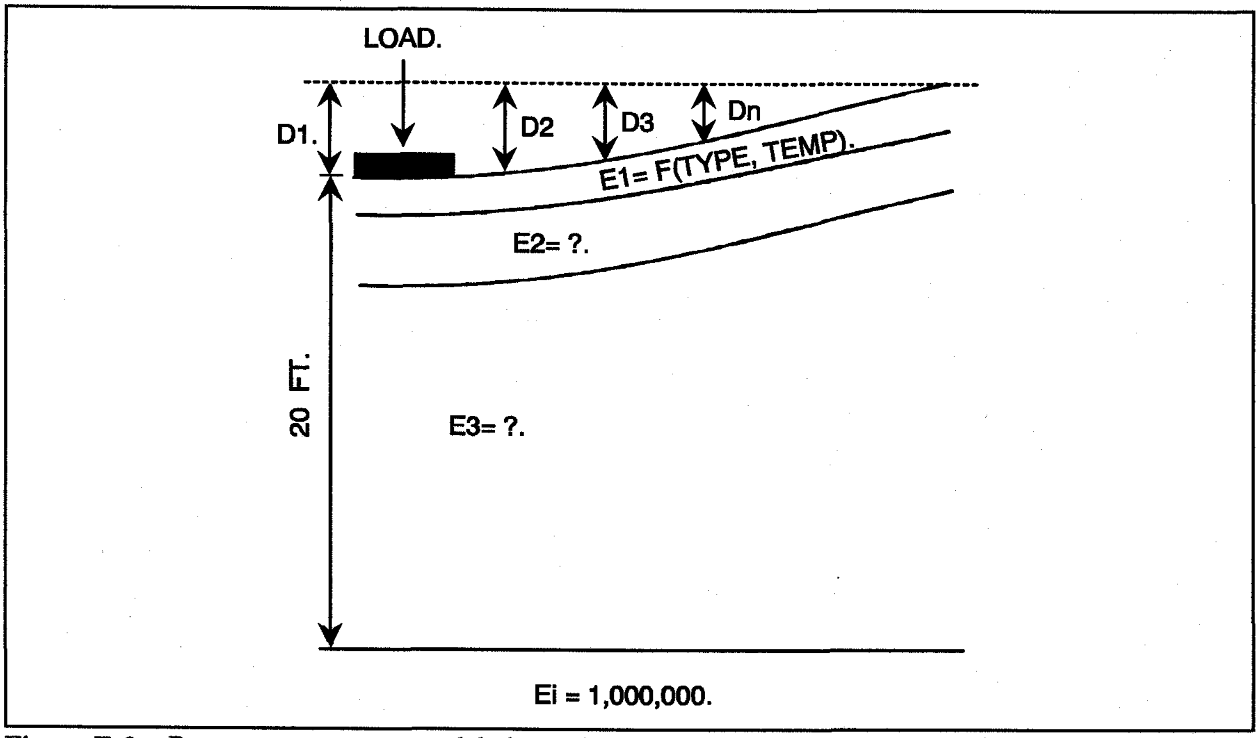

Figure E-3. Pavement structure modeled as a layered system with up to i layers (max=5) and n measured deflections (max=7).

Some options to be considered are as follows:

(1) Fix the modulus of an AC or PCC surface layer based on material type or temperature and condition at the time of testing rather than computing the modulus.
(2) Combine base and subbase into one layer and compute a composite modulus.
(3) Fix the subgrade modulus based on results of the preliminary run.

b. Rerun WESDEF with modified limits to include the predicted E (Values outside default ranges may be unrealistic.)

c. Accept the results of the WESDEF run as is realizing that the predicted values are outside the typical range for a particular material.

The following guidelines may be helpful in determining layer modulus values using WESDEF:

a. Do not attempt to compute the modulus values for more than three layers in a single WESDEF run. Limit the number of computed layer moduli to two if possible.

b. Do not attempt to compute the modulus of layers less than 3 inches thick. The modulus of a thin layer should be fixed based on material type, temperature, etc.; or else a thin layer should be combined with an adjacent layer and a composite modulus determined.

c. When computing the modulus of a PCC layer, it may be necessary to combine a base or subbase layer with the subgrade layer and determine a composite modulus for the material beneath the PCC slab.

d. Exercise caution when using modulus values outside the default ranges. Because the ranges are quite broad, values outside these limits may be unrealistic.

e. For NDT devices with circular loaded areas, the offset distance to the first measured deflection is input to WESDEF as one half of the radius of the loading plate to approximate the deflection at half the radius of a uniformly distributed circular loaded area.

Analysis and Overlay Design. Load carrying capacities and required overlay thicknesses are evaluated using the computer program WESROAD. The program can analyze up to 30 axles with different loading conditions in a single run. For the mixed traffic analysis, the number of load applications for each axle type must be specified. Axle types are selected from the vehicle data file ROADDATA, which contains the axle geometry needed for elastic layer calculations. For a given pavement, having modulus values determined from WESDEF, WESROAD computes the stresses (rigid and composite pavements) or strains (flexible pavements) that will be induced by each vehicle in the design traffic mixture. The allowable number of load applications is determined for each vehicle from empirically developed criteria and the damage is defined as:

$$\text{Total Damage} = \sum_{1}^{no.\,axles} \frac{\text{Design Load Applications}}{\text{Allowable Load Applications}}$$

$$\text{For:} \quad \text{Damage} > 1.0 \quad : \text{Overlay Required}$$

For analyzing flexible pavements, both the horizontal tensile strains at the bottom of the AC layer and the vertical subgrade strains at the top of the subgrade are considered. The allowable AC strain, shown graphically in Figure E-4, is:

$$\epsilon_{AC} = 10^{-\left[\frac{Log_{10}(N) + 2.665\ Log_{10}\left(\frac{E_{AC}}{14.22}\right) + 0.392}{5}\right]}$$

or:

$$N = 10^{-\left[5\ Log_{10}(\epsilon_{AC} + 2.665\ Log_{10}\left(\frac{E_{AC}}{14.22}\right) - 0.392\right]}$$

Where:

ϵ_{AC} = *Tensile Strain, Bottom of AC (in/in)*
N = *Vehicle Coverages*
E_{AC} = *AC Modulus, psi*

The allowable subgrade strain for flexible pavements, shown graphically in Figure E-5, is:

$$\epsilon_v = 10^{-[0.1408\ Log_{10}(N) + 2.408]}$$

or

$$N = 10^{-\left[\frac{2.408 + LOG_{10}(\epsilon_v}{0.1408}\right]}$$

Where:

ϵ_v = *Vertical Strain, top of Subgrade (in/in)*
N = *Vehicle Coverages*

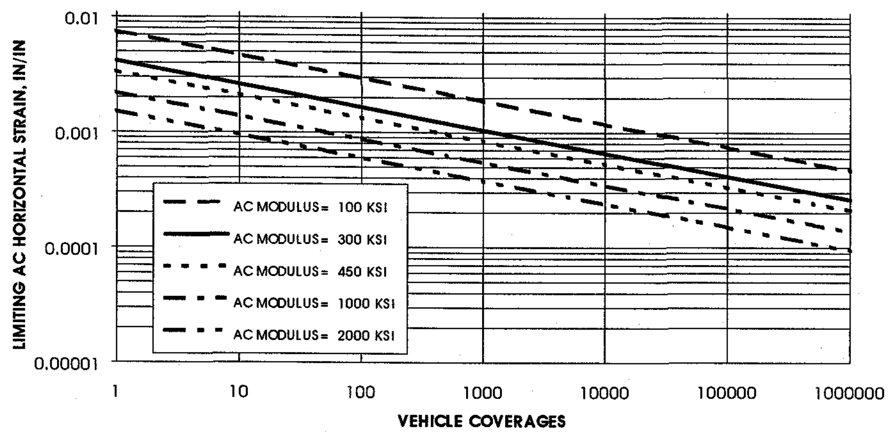

Figure E-4. Limiting criteria for horizontal tensile strain at the bottom of an AC surface layer, flexible pavement.

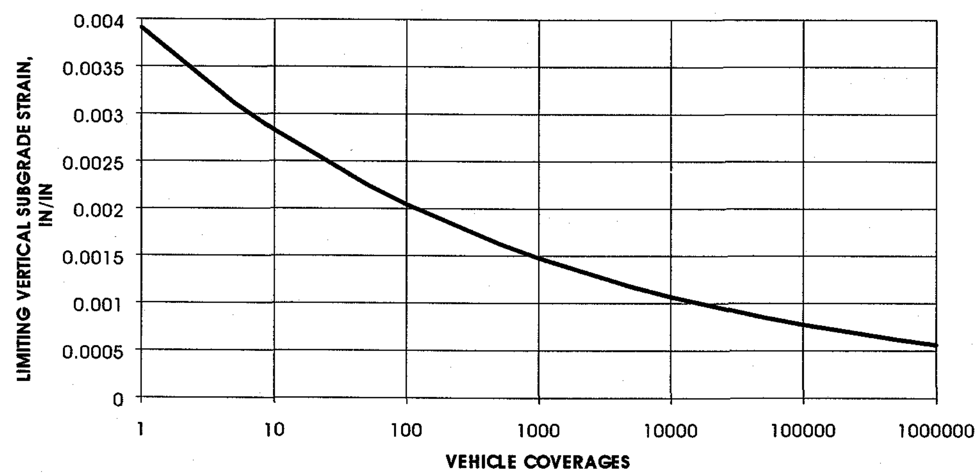

Figure E-5. Limiting criterion for vertical strain at the top of the subgrade, flexible pavements.

A composite pavement is an AC over PCC pavement structure that may be evaluated as a rigid or flexible pavement. If the modulus of the PCC layer determined using WESDEF is less than 1,000,000 psi, the pavement should be evaluated as a flexible pavement. The evaluation of rigid and composite pavements is based on the tensile stress at the bottom of the slab which is determined using the criteria shown in Figure E-6, for which failure is assumed when there are one or more structural cracks due to load in 50 percent of the trafficked slabs:

$$\sigma_{pcc} = \frac{PCC\ Flexural\ Strength,\ psi}{1.33(0.58901 + 0.35486\ Log_{10}(Coverages))}$$

or

$$N = 10^{\left[\frac{\frac{R}{\sigma_{pcc}} - 0.58901}{0.35486}\right]}$$

Where:

σ_{pcc} = *Allowable Stress, Bottom of PCC (psi)*
N = *Vehicle Coverages*

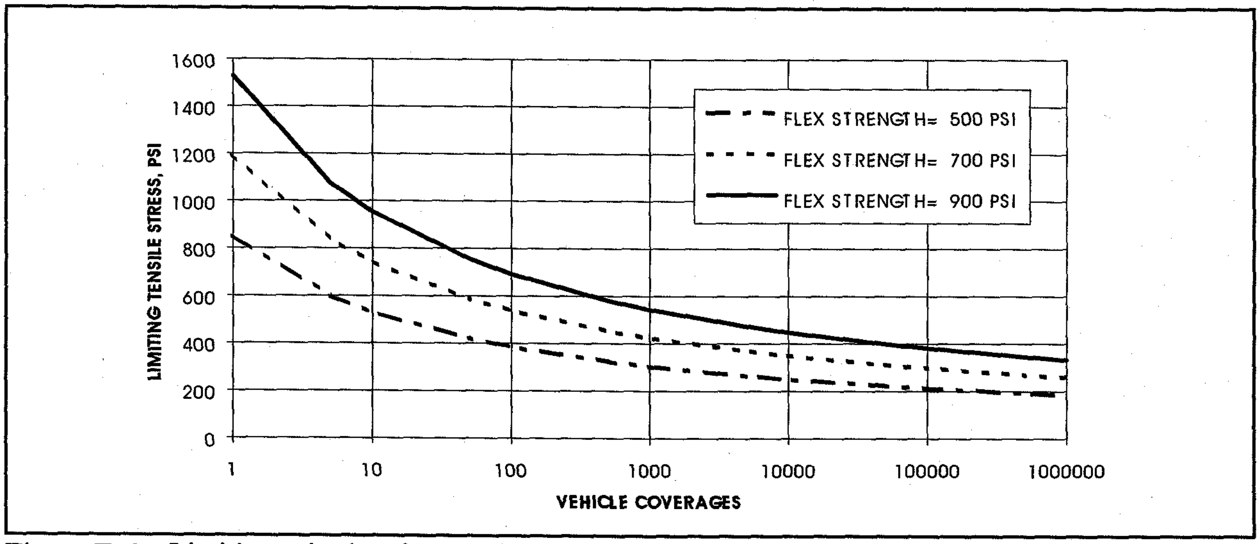

Figure E-6. Limiting criterion for tensile stress at the bottom of a PCC slab, rigid and composite pavements.

When the cumulative damage (sum of damage for all vehicles) exceeds one, WESROAD computes; the required AC overlay thickness for flexible pavements; the AC, partially bonded PCC, and unbonded PCC overlay thicknesses for rigid pavements; and the AC and unbonded PCC overlay thicknesses for composite pavements. For each case, the overlay calculations are based on the critical axle in the traffic mix. The number of axle loadings for the most severe vehicle is adjusted such that the total damage will be equivalent to the cumulative damage computed for the traffic mixture. The pavement thickness required to support the design vehicle at the design equivalent coverages is determined such that computed stresses/strains match the limiting criterion. WESROAD makes an initial estimate of the required surface layer thickness and uses an iterative procedure to close in on the actual thickness of the surface layer needed to support the vehicle under consideration. AC overlays on AC pavements are simply the difference between the required thickness and the existing AC thickness. Equations for computing overlay thickness requirements for rigid pavements are as follows:

$$AC\ overlay = 3.0\left(F\, h_d - C_b h \right)$$

$$PCC\ (unbonded) = \sqrt{(h_d)^2 - C_r(h)^2}$$

$$PCC\ (partially\ bonded) = \sqrt[1.4]{(h_d)^{1.4} - C_r(h)^{1.4}}$$

Where:

F = Factor which projects cracking ∈ PCC layer

h_d = Required thickness of new PCC pavement

C_b = Condition factor, (.5-1.0)

h = Thickness of existing PCC

C_r = Condition Factor, (0.35-1.00)

Composite pavements (AC over PCC) are evaluated as rigid pavements. For overlays, the required thickness of PCC is determined, and the existing AC is treated as a bond breaker.

A typical output from WESROAD is presented in Figure E-7. This is a rigid pavement example with the total damage for the three design axles being much greater than one. Overlays for 244,876 coverages of the 32 kip axle load are 10.7 inches (AC), 6.6 inches (PCC, partially bonded), and 7.4 inches (PCC, unbonded).

```
  AXLE ID  AXLELOAD  ALLOWABLE COVERAGE  AXLE COVERAGE     DAMAGE
     1        2.        .810880E+33       .104275E+05   .128595E-28

  AXLE ID  AXLELOAD  ALLOWABLE COVERAGE  AXLE COVERAGE     DAMAGE
     2        9.        .161166E+05       .320000E+05   .198553E+01

  AXLE ID  AXLELOAD  ALLOWABLE COVERAGE  AXLE COVERAGE     DAMAGE
    10       32.        .108687E+04       .242718E+06   .223318E+03


      THE TOTAL DAMAGE FOR ALL AXLES IS      .225303E+03

        THE CRITICAL AXLE ID IS           10
        THE EQUIVALENT COVERAGES=  244876.015679807500000

*************************************************************************
**********************"WESROAD" VERSION DRA-09.89.12*********************
**********************EXECUTED:  2- 6-1992 @ 14: 8***********************

                              PROBLEM NUMBER   1

      Example Problem, Rigid Base Pavement, Three axle loads.



                          PAVEMENT INPUT PARAMETERS
                          *************************

  LAYER                         FROST      MODULUS, PSI     THICK.  POIS  SLIP
   NO     MATERIAL TYPE         CODE      NDT       FROST     IN.   RAT.  VALUE
****** *****************     ******* ********* ********* ******** **** *****

   1         PCC                  0     4387500.  4387500.     6.00  .15 1000.
   2       SUBGRADE               0        6000.     6000.    10.00  .40    1.
   3       SUBGRADE               0        6000.     6000.    10.00  .40    1.
   4       SUBGRADE               0        6000.     6000.    10.00  .40
   5       SUBGRADE               0        6000.     6000. SEMI-INF  .40

                           PAVEMENT EVALUATION SUMMARY
                          (ALLOWABLE LOAD NOT APPLICABLE)
                                                               REQ'D OVERLAY,
                                                                    IN.
                               DESIGN        ALLOW-  ALLOWABLE **************
                          ****************    ABLE OPERATIONS OF          PCC
        DESIGN             LOAD EQUIVALENT  LOAD   DESIGN          PARTIAL  NO
        AXLE ID            KIPS  COVERAGE   KIPS     AXLE       AC  BOND  BOND
  ******************* ******  ********    ******  ********* **** ****  ****

          10               32.0   .244876E+06                   10.7   6.6   7.4
```

Figure E-7. Rigid pavement analysis and overlay design from WESROAD.

Dynatest Consulting, Inc. (Dynatest) and Soil and Materials Engineers, Inc. (SME)

The evaluations for Warren County, Mississippi and Cincinnati, Ohio were conducted jointly by Dynatest and SME using the WES procedures, AASHTO procedures, and their own ELMOD method. In addition, the MODULUS program was used to provide another comparison of backcalculation results. Tests were conducted using the Dynatest 8081 HWD Test System.

ELMOD Method. Generally, Dynatest analyzes their project level load-deflection data through a specially developed software package. This method is based on a combined analytical and empirical approach. The system is analytical in the sense that actual, in-situ material properties and wheel load responses are derived through a reverse, layered analysis technique, as described below. It is still empirical, however, in the sense that the relationships between the load related response of these mechanistic and analytical properties and future pavement performance are based upon past experience (observed performance) and associated research. This software package, employed for analyzing the Warren County and Cincinnati data as discussed below, is called ELMOD.

ELMOD is an acronym for Evaluation of Layer Moduli and Overlay Design, and the program is used primarily for asphalt concrete and continually reinforced concrete pavement types. A companion procedure called ELCON (ELmod for CONcrete) was used for the concrete (PCC) sections as well. The first step in the program is a routine which backcalculates the mechanistic material properties of a uniaxial, semi-infinite pavement system (ie, the elastic moduli or E-values of each structural layer in the pavement). Based on these derived E-values (for each FWD test point), the design life and/or needed overlay to bring the pavement up to its design life standard is calculated. The program is able to assign various (user controlled) seasonal adjustments to the derived E-values (a lower rainy season subgrade modulus and a varying asphalt concrete modulus as a function of seasonal temperature), and then calculate the expected remaining service life of the pavement section, and an overlay design if the expected lifetime is inadequate, based on certain transfer functions (which are also user controlled). These transfer functions are primarily based on laboratory measured performance correlated with subsequent field observed performance obtained for various pavements. When the fundamental structural pavement properties (E-values) have been determined, the critical stress and strains in the structure may be calculated.

As indicated, the prediction of pavement performance (roughness or cracking) from the calculated pavement response (critical stresses and strains) is empirical. The empirical relationships between the derived mechanistic material properties and performance are, however, user controlled (variable inputs to ELMOD/ELCON). The program therefore may be used for any specific local environmental conditions if these relationships are known.

It should be noted that generally most of the measured magnitudes of deflection are due to the response of the subgrade. It is therefore very important that the subgrade modulus is accurately determined. A small error in the subgrade modulus will lead to a very large error in the derived asphalt concrete modulus. For this reason, it is necessary to consider any non-linearity of the subgrade, which can be done easily with the analytical-empirical method, using the highly accurate deflection data obtained.

Due to the large influence of the subgrade on the measured deflections, it is very important that the deflections are measured at a load level similar to that resulting from heavy truck wheels, and that the deflections measured at large distances from the loading center (> ~3 ft) are measured very accurately.

For purposes of the ELMOD analyses of the pavements in Warren County and Cincinnati, the most important equations and parameters assumed for the climatic zone and material conditions found in each region were as follows:

a. Four seasons assumed, 13 weeks each.

b. Maximum effective pavement temperature occurs during Week No. 31, at the beginning of August, ≈ 105 deg F (Warren County) and ≈ 95 deg F (Cincinnati). Minimum effective pavement temperature occurs during Week No. 7, in February, ≈ 40 deg F (Warren County) and ≈ 35 deg F (Cincinnati).

c. Seasonal variation of the modulus of the unbound materials is assumed to be sinusoidal. The ratio between the minimum and maximum unbound material E-values = 0.80, with the lower values occurring during the springtime in April.

d. The ratio between static and dynamic (effective) load = 1.2 (dynamic load factor, generally due to roughness).

e. Flexible pavement criterion:

1. Flexible pavement design fatigue failure criteria (structural failure, fatigue cracking in asphalt concrete):

$$\epsilon_{AC} = 0.07745\ N^{-0.304}\ E^{-0.259}$$

Where:

ϵ_{AC} = *tensile strain at bottom of AC*
E = *Modulus of AC*
N = *Equivalent 18-kip Axle Loads*

2. Permissible vertical stress (psi) on all unbound materials on flexible pavements (functional failure, roughness related):

$$\sigma_{1,p} = 1435 \left(\frac{E}{23.2}\right)^{C} N^{-0.307}$$

Where:

E = *Modulus of material*
C = 1 *for* $E > 23.2$ *ksi, or*
C = 1.16 *for* $E < 23.2$ *ksi*
N = *Equivalent 18-kip Axle Loads*

f. Rigid pavement criterion:

1. Rigid pavement design fatigue failure criteria (structural failure, fatigue cracking in PCC):

$$\sigma_{PCC} = 28000\ N^{-0.333} \left(\frac{E}{5080}\right)$$

Where:

σ_{PCC} = *tensile stress at bottom of PCC*
N = *Equivalent 18-kip Axle Loads*
E = *Modulus of PCC*

2. Permissible stress (psi) on all unbound materials on rigid pavements (functional failure, roughness related):

$$\sigma_{1,p} = 7800 \left(\frac{E}{23.2}\right)^{C} N^{-0.47}$$

Where:

E = *Modulus of material*
$C = 1$ *for* $E > 23.2$ *ksi, or*
$C = 1.16$ *for* $E < 23.2$ *ksi*
N = *Equivalent 18-kip Axle Loads*

g. Assumed design life = 5, 10, and 20 years
h. Design axle load = 18,000 lbf (9,000 lbf per dual wheel).
i. Design tire pressure = 110 psi.

Modulus. The MODULUS method consisted of using the MODULUS backcalculation program to determine the pavement layer moduli at each test location. This program is well suited to backcalculate layer moduli for a large number of FWD/HWD test locations since it utilizes a database search routine. Another advantage of this program is the capability of estimating the depth to a stiff layer which has been found to greatly influence the backcalculated moduli.

MODULUS was used on these projects for three purposes:

a. To determine the depth to a stiff layer and seed moduli for use in the WESDEF program.

b. To determine the variability of the layer moduli over the entire length of the project.

c. To check the backcalculated moduli obtained using the WESDEF and ELMOD methods.

Engineering & Research Int'l, Inc. (ERI)

The evaluation for Berkeley, California was conducted by ERI using the WES procedures, AASHTO procedures, and their own procedures. Tests were conducted using the ERI-KUAB Two Mass Falling Weight Deflectometer.

Backcalculation of Layer Moduli. For flexible pavements, the modulus of elasticity was determined for each structural layer of the flexible pavements at locations where both FWD tests and boring were done. The pavement was modeled as a multi-layered system based on boring results. Representative basins were used as inputs in an iterative scheme to backcalculate the layer moduli values. Representative deflection basins were determined by first calculating the mean plus one standard deviation of the maximum deflection recorded at each test point within a section. This weighted mean was then compared to all deflection basins within the section and the station with the maximum deflection closest to this value was selected as the representative basin. The ERI backcalculation program estimates the subgrade modulus based on the 1986 AASHTO guide. The estimated subgrade modulus is used in the ELSDEF87 program with other seed values to backcalculate the layer moduli values. During this process, measured deflections are compared to deflections calculated using a multi-elastic layer computer analysis program (ELSYM5) with various layer moduli sets. The layer moduli values that produce calculated deflection basins that best match field deflections are selected as the final moduli values of the in situ pavement layers. The hard rock was assumed a depth of 240 inches below the ground surface.

For composite pavements, the modulus of elasticity of the AC and PCC, and the foundation stiffness were determined. The composite pavement was modeled as a slab on grade with the maximum surface deflection corrected to account for compression in the AC layer. The subgrade was modeled as both dense liquid and elastic solid foundations, however, the dense liquid solution was utilized for overlay design.

Environmental Considerations. Environmental data is typically used to segregate the calendar year into design seasons. Design seasons are selected to maintain a consistency in temperature and moisture, both of which affect the pavement materials. The average monthly temperatures varied only slightly throughout the year and thus, there was no need to establish individual design seasons based on temperature. Precipitation data indicated increased moisture for the period between October and March. As such, two design seasons corresponding to the periods between April and September and between October and March would seem appropriate. However, the backcalculated modulus values for the base were low and any further reduction was not warranted. Therefore, a single design season was assumed for analysis and design purposes.

Temperature corrections were applied to the backcalculated asphalt moduli, rather than normalizing the deflection data prior to analysis. The following steps were taken:

a. Pavement design temperature was calculated using the following equation:

$$MMPT = 1.05\ (MMAT) + 5$$

Where:

MMPT = Mean Monthly Pavement Temperature
MMAT = Mean Monthly Air Temperature

The pavement design temperature was approximated, from climatological data, to be 70 deg F.

b. Pavement mid-depth temperature, at the time of FWD testing , was determined using the Asphalt Institute method.

c. The backcalculated asphalt moduli values were normalized for a design temperature of 70 deg F. The Asphalt Institute equation for the determination of temperature versus modulus relationship was solved for typical dense-graded asphalt mix parameters and the loading frequency of the FWD used for testing.

Traffic Analysis. Predicted future 18-kip ESALs in the design lane over the design period were computed for current average daily traffic (ADT), average daily truck traffic (ADTT), and 10- and 20-year projections of ADT provided by the City of Berkeley. Average traffic levels were projected to remain constant for the next 10 years and increase slightly in the following 10 years. It was assumed in the analysis that the percentage of truck traffic in ADT would remain constant over the next twenty years.

Structural Analysis, Flexible Pavements. The pavement layer thicknesses, normalized layer moduli values, and previous distress survey data were used in the structural evaluation of the existing pavements. The truck dual wheel load of 9000 lb-f was applied on two tires, with a center to center spacing of 13.5 inches. Critical strains in the asphalt and subgrade layers resulting from each loading were calculated. The allowable number of passes to failure of the pavement sections were determined using empirical fatigue equations with the calculated strains as inputs. Failure of the pavement section can be expressed as failure in either the asphalt surface or subgrade layer. Surface fatigue failure is typically defined as the point at which alligator cracking exceeds ten percent of the surface area. Subgrade failure is typically defined as the point at which subgrade rutting exceeds one-half inch. Surface fatigue failure was predicted using the following equation adopted from research work conducted for pavements in the State of Arizona:

$$Log\ (N) = -1.234 - 3.291\ Log\ (Strain) - 0.854\ Log\ (Modulus)$$

Where:

N = Number of coverages to failure
Strain = Maximum tensile strain , bottom of the asphalt
Modulus = Elastic modulus of asphalt concrete

Subgrade rutting was predicted using the following equation developed by the U. S. Army Corps of Engineers:

$$N = \left(\frac{0.005511}{\epsilon_v}\right)^{6.527}$$

Where:

N = Coverages to subgrade failure
ϵ_v *= Maximum vertical strain, top of subgrade*

The total fatigue damage at each pavement section was determined based on the past fatigue damage and future projected traffic for 5-, 10-, and 20- year planning horizons. The overlays were designed for pavement sections having total fatigue damage greater than 1.

Structural Analysis, Composite Pavements. The ERI approach to composite pavement overlay design is based on the calculation of critical stresses at increasing overlay thicknesses, and the decreasing effects on fatigue damage to the PCC slab. The pavement structure is modeled as a single slab-on-grade and in-situ, backcalculated layer moduli are used as the design values for slab and subgrade. A fatigue equation is applied to the inverse of the stress ratio, and the allowable loadings to failure are compared to the predicted traffic loadings to determine the required overlay thickness for a given design period. The design procedure contains the following steps:

a. Design values of PCC modulus and modulus of subgrade reaction are computed.

b. Existing asphalt overlays are converted to an equivalent concrete thickness, which is added to the existing concrete thickness.

c. The pavement is modeled as a slab on grade with the load applied to the edge of the slab at the midpoint between transverse joints.

d. Critical stresses are calculated using Westergaard equations.

e. PCC flexural strengths are estimated based on laboratory testing of concrete specimens and relationships between flexural strength and compressive strength or flexural strength and PCC modulus.

f. The ratio of flexural strength to critical tensile stress is computed and the allowable number of loadings are determined from a fatigue equation.

g. If the damage exceeds 1.0, an additional thickness of concrete is added to the existing system and the procedures are repeated until the total damage is equal to 1.0.

American Association of State Highway & Transportation Officials (AASHTO)

Dynatest & SME, Flexible Pavements. The AASHTO method used for analyzing the flexible pavements in Warren County and at Cincinnati is based on the maximum deflection measured at the center of the load plate (D0) and the deflection measured at the outermost sensor (D6). The deflection measured at D6 is used to estimate the subgrade strength. D0 and the estimated subgrade strength are then used to estimate the overall strength of the pavement which is expressed by the pavement's Structural Number (SN). The deflection measured at the center of the FWD/HWD load plate is corrected to a standard temperature of 70 deg F prior to determining the pavement strength.

The above method is described in detail in the 1986 AASHTO Pavement Design Guide. However, the following changes were made based on SME's experience and on published research papers regarding the use of the remaining life factor:

a. The subgrade modulus estimated using the AASHTO method generally result in unreasonably high subgrade moduli. This has been recognized by AASHTO and the 1993 method recommends that the backcalculated subgrade modulus be divided by 3. The 1993 method has not been thoroughly reviewed nor used extensively in the industry. Instead, the subgrade moduli for this project were estimated using the so-called Hogg model, which is well documented in the literature.

b. The remaining life factor (F_{rl}) is set equal to 1 rather than the factors recommended in the 1986 method. The 1993 method abandons the use of this factor when determining the required overlay thickness. Several research papers have been written regarding this issue, recommending the use of 1 for the F_{rl} factor.

Some of the composite pavements which exhibited relatively high deflections were also analyzed as flexible pavements. This condition was basically due to limitations in the rigid pavement analysis method.

Dynatest & SME, Rigid and Composite Pavements. The rigid pavement analysis method is described in detail in the 1993 AASHTO Pavement Design Guide. In summary, the deflections measured at the sensors located at 0, 12, 24 , and 36 inches from the center of the FWD/HWD load plate are used to compute the dynamic modulus of subgrade reaction (k-value) and the effective concrete layer modulus. The dynamic k-value is divided by 2 to obtain the static k-value normally used in rigid pavement design. The required slab thickness to carry the forecasted traffic is then estimated using this static k-value, the measured joint load transfer, the in-situ concrete moduli, the modulus of rupture estimated from the concrete layer moduli, and the drainage factor selected for the site.

The effective thickness of the slab is reduced based on the results of a visual condition survey. Factors to adjust for the condition of joints and cracks, the presence and extent of durability cracking, and the amount of fatigue damage are used to reduce the measured slab thickness to an effective thickness.

The difference between the thickness of the new slab and the thickness of the effective slab is used to estimate the thickness of the required overlay. A factor is used to transfer the required concrete thickness into an equivalent thickness of asphalt concrete.

The analysis of composite pavements is very similar to that of rigid pavements. However, different values are assigned to each of the factors discussed above which are used to calculate the effective thickness of the slab. Also, the deflection due to compression of the asphalt overlay is subtracted from the maximum measured deflection in order to evaluate the condition of the concrete slab. All other steps involved in the overlay analysis of composite pavements are similar to those discussed for rigid pavements.

ERI, Backcalculation. Composite pavements were modeled as a slab on grade with the maximum surface deflection corrected to account for compression in the AC layer. The subgrade was modeled as both dense liquid and elastic solid foundations, however, the dense liquid solution was utilized for overlay design. For the flexible pavements, the deflection at 36 inches from the load plate was used to backcalculate an in situ modulus for the subgrade. The deflection used to backcalculate the subgrade modulus must be measured far enough away that it provides a good estimate of the subgrade modulus, independent of the effects of any layers above, but also close enough such that it is not too small to measure accurately. The 36-inch sensor deflection met the test for adequate distance for all but two of the streets, and was used even for these streets, since the required distance was only slightly more than 36 inches. It should be noted that no temperature adjustment is needed in determining the in situ subgrade modulus since the deflection used is due only to subgrade deformation.

The effective pavement modulus E_p was estimated using the in situ subgrade modulus and the maximum deflection measured under the load plate D0. A correction factor was applied to the actual measured D0 values to adjust them to a standard temperature of 68 deg F.

ERI, Design. Overlay design by the AASHTO method is based on the concept of structural deficiency: if the existing pavement's structural capacity is insufficient to support the traffic loadings anticipated over some future design period, an overlay thickness can be determined which will compensate for this deficiency. The required overlay structural capacity can be correct only if the required future structural capacity and the assessment of the existing structural capacity are correct. The primary objective of the structural evaluation is to determine the effective structural capacity of the existing pavement.

Three methods are described for determining effective structural capacity: (1) an NDT method, in which the effective structural number is estimated directly from deflection analysis, (2) a condition survey method, in which the effective structural number is computed from reduced layer coefficients assigned to the pavement layers based on the amount and severity of load-related distress observed, and (3) a remaining life method, in which the structural number is estimated based on the ratio of actual past traffic to expected traffic capacity of the original pavement. The use of each of these methods depends on the availability of deflection, condition, or past traffic data. It is recommended that each of the methods for which the necessary data are available should be used, and the results compared.

The steps followed in analyzing the existing pavement sections are:

a. The required future structural number was determined for each street as a function of the design subgrade modulus and the design traffic for 5-, 10-, and 20- year design ESALs at 50 and 80 percent reliabilities. A value of 0.49 was used for the overall standard deviation of the performance model's prediction. Initial and terminal serviceability levels of 4.2 and 2.5 were used.

b. The effective structural number was estimated from the NDT method and the condition method.

c. The AC overlay thickness requirements for the 5-, 10-, and 20- year design periods, for reliability levels of 50 and 80 percent, were determined using the future structural number and the effective structural numbers from NDT and condition methods. A structural coefficient of 0.44 was used to convert the required structural capacity into a required AC overlay thickness.

Appendix F
Rehabilitation Strategies for Warren County, MS

Recommended Rehabilitation Options Warren County, MS			
Test Section	Expected Design Life		
	5 Years	10 Years	20 years
Jeff Davis Road 0+00 to 160+00	Pulverize existing AC surface, blend with existing base course and recompact, add Double BST [1]	Pulverize existing AC surface, blend with existing base course and recompact, add 2" DGAC[2]	Pulverize existing AC surface, blend with existing base course and recompact, add 3" DGAC
Jeff Davis Road 160+00 to 440+00	Fix all localized distresses and R&R[3] where needed, add seal coat or other suitable surface treatment	Fix all localized distresses and R&R where needed, add minimum 1½" DGAC	Fix all localized distresses and R&R where needed, add 2½" DGAC
Nine Mile Cutoff	Fix all localized distresses and R&R where needed, add seal coat or other suitable surface treatment	Fix all localized distresses and R&R where needed, add 1½" DGAC	Fix all localized distresses and R&R where needed, add 2½" DGAC
Red Bone Road	Fix all localized distresses and R&R where necessary, add minimum 1¼" DGAC or Apply asphalt/rubber chip seal	Fix all localized distresses and R&R where necessary, add 1½" DGAC	Fix all localized distresses and R&R where necessary, add 2½" DGAC or Pulverize existing AC surface, blend with existing base course and recompact, add 3" DGAC

Recommended Rehabilitation Options
Warren County, MS

Test Section	Expected Design Life		
	5 Years	10 Years	20 years
U.S. Highway 80	Localized patching and routine maintenance to restore/maintain ride quality	Repair broken slabs plus diamond grinding or Apply stress relieving layer[4], add 2" DGAC	Crack & seat (or rubblize), add 3" DGAC or Stabilize joints, add 2" asphalt rubber hot mix overlay
Gibson Road	Localized patching and routine maintenance as required or Fix all localized distresses and R&R where needed, add minimum 1¼" DGAC	Fix all localized distresses and R&R where needed, add 1½" DGAC or Pulverize existing AC surface, blend with existing base course and recompact, add Double BST	Fix all localized distresses and R&R where needed, add 2½" DGAC or Pulverize existing AC surface, blend with existing base course and recompact, add 3" DGAC
Mount Alban Road	Repair/reinforce pavement edges, fix all localized distresses and R&R where necessary, add minimum 1¼" DGAC or Apply asphalt/rubber chip seal	Repair/reinforce pavement edges, fix all localized distresses and R&R where necessary, add 1½" DGAC	Repair/reinforce pavement edges, fix all localized distresses and R&R where necessary, add 2½" DGAC or Pulverize existing AC surface, blend with existing base course and recompact, add 3" DGAC

Recommended Rehabilitation Options Warren County, MS			
Test Section	Expected Design Life		
	5 Years	10 Years	20 years
U.S. Highway 61 Northern Section	Mill off upper 2" AC and replace with 2" new DGAC	Remove/mill off entire existing AC surface, apply stress relieving layer, add 4" DGAC	Remove/mill off entire existing AC surface, apply stress relieving layer, add 6" DGAC or Remove/mill off entire existing AC surface, add 3" asphalt rubber hot mix overlay
U.S. Highway 61 Southern Section	Stabilize joints, apply stress relieving layer, add 3" DGAC overlay	Stabilize joints, apply stress relieving layer, add 5" DGAC overlay	Stabilize joints, add 3" asphalt rubber hot mix overlay or Reconstruct outside lanes to 11" total PCC thickness, add 5" bonded PCC overlay on inside lanes or Construct 8" unbonded PCC overlay on all lanes

Notes:

1. Bituminous Surface Treatment
2. Conventional Dense Graded Asphalt Concrete hot mix
3. Removal and replacement of base and surfacing
4. Asphalt impregnated fabric interlayer between PCC slabs and DGAC overlay

Appendix G
Cincinnati, OH Test Sections

City of Cincinnati
Department of Public Works
Division of Engineering

Streets to be Evaluated

PRIORITY	NAME OF STREET	BEGINNING	END	LENGTH, FT	AVG DAILY TRAFFIC	TRAFFIC CLASS	SURFACE TYPE
1	Kipling Ave	Banning Rd	Colerain Ave	2,500	10,000	Thoroughfare	Asphalt
2	Crawford Ave	Dane Ave	Springlawn Ave	2,300	3,600	Collector	Concrete
3	Highview Dr	Covedale Ave	Beechmeadow	1,550	1,000	Residential	Asphalt with Concrete Base
4	St. Lawrence Ave	Rutledge Ave	Rapid Run Pike	2,200	3,500	Local Service St	Asphalt with Concrete Base
5	Sunset Lane	Sunset Ave	Sunset Ave	2,200	500	Residential	Asphalt
6	Guerley Rd	Sunset Ave	Tuxworth Ln	3,750	9,000	Arterial	Asphalt
7	Eighth St	Linn St	McLean St	2,600	18,000	Principal Arterial	Concrete
8	Kellogg Ave	Waits Ave	Salem Rd	8,800	9,600	Arterial	Asphalt with Concrete Base
9	Dalton St	Linn St	Hopkins St	4,200	6,400	Collector	Concrete
10	Wayside Ave	Sutton Ave	Salem Rd	7,350	3,000	Collector	Asphalt
11	Glenway Ave	Boudinot Ave	Werk Rd	5,400	23,000	Principal Arterial	Asphalt with Concrete Base
12	Gest St	Third St	Freeman Ave	3,600	6,500	Collector	Concrete
13	Lehman Rd	#2600 Lehman Rd	Grand Ave	2,500	3,000	Local Service Street	Asphalt
14	M.L. King Dr	Harvey Ave	Vine St	2,850	25,000	Principal Arterial	Asphalt with Concrete Base
15	Dalton St	Kenner St	Findlay St	2,000	6,800	Collector	Asphalt
16	Eastern Ave	Delta Ave	Bains Pl	16,845	18,340	Principal Arterial	Asphalt
17	Boudinot Ave	Glenway Ave	Westwood N. Blvd	12,694	22,430	Thoroughfare	Asphalt with Concrete Base
18	Wm. Howard Taft Rd	Woodburn Ave	Vine St	9,325	19,160	Arterial	Asphalt with Concrete Base
19	Reading Rd	Dorchester Ave	Paddock Rd	15,939	39,220	Principal Arterial	Asphalt with Concrete Base
20	Pete Rose Wy	Broadway	Central Ave	3,740	16,920	Principal Arterial	Concrete
21	Southside Ave	River Rd	Idaho St	6,620	500	Local Service Street	Asphalt
22	Edwards Rd	Grandin Rd	Observatory Ave	11,859	11,470	Local Service Street	Asphalt

Appendix H
Rehabilitation Strategies for Cincinnati, OH

Recommended Rehabilitation Options Cincinnati, OH			
Test Section	Expected Design Life		
	5 Years	10 Years	20 years
Kipling	Repair edge distresses and R&R[1] where needed, add 1¼" DGAC[2]	Repair edge distresses and R&R where needed, add 2" DGAC	Repair edge distresses and R&R where needed, add 3" DGAC
Crawford Avenue	Continue routine maintenance or R&R portland cement surface where necessary, add 1½" DGAC overlay to restore ride quality	Concrete Restoration or R&R portland cement surface where necessary, apply stress relieving layer, add 2½" DGAC overlay to restore ride quality	Concrete Restoration or R&R portland cement surface where necessary, apply stress relieving layer, add 4" DGAC overlay
Highview Drive	Remove existing asphalt surface, repair severely deteriorated PCC joints and slabs, and replace with 1½" DGAC or Mill existing asphalt concrete, rubblize concrete slabs, add 3½" DGAC	Remove existing asphalt surface, repair all deteriorated PCC joints and slabs, apply stress relieving layer[3], and replace with 2½"DGAC or Mill existing asphalt concrete, rubblize concrete slabs, add 4½" DGAC	Remove existing asphalt surface, repair all deteriorated PCC joints and slabs, apply stress relieving layer, add 4" DGAC overlay or Mill existing asphalt concrete, rubblize concrete slabs, add 5" DGAC

Recommended Rehabilitation Options Cincinnati, OH			
Test Section	Expected Design Life		
	5 Years	10 Years	20 years
St. Lawrence Avenue	Continue routine maintenance	Remove existing asphalt surface, repair severely deteriorated PCC joints and slabs, replace with 2½" DGAC or Mill existing asphalt concrete, rubblize concrete slabs, add 4" DGAC	Remove existing asphalt surface, repair damaged PCC joints and slabs, apply stress relieving layer, add 4" DGAC overlay or Mill existing asphalt concrete, rubblize concrete slabs, add 5" DGAC
Sunset Lane	Localized patching, add 1½" DGAC overlay to restore ride quality	Same as 5 years	Same as 5 years
Guerley Road	Fix all localized distresses, R&R where necessary, add 1½" DGAC overlay	Fix all localized distresses, R&R where necessary, add 2" DGAC overlay or Apply 1¼" asphalt rubber hot mix overlay	Fix all localized distresses, R&R where necessary, add 3" DGAC overlay or Apply 2" asphalt rubber hot mix overlay or Pulverize existing asphalt surfacing, blend with existing base course, recompact, add 3" DGAC

Recommended Rehabilitation Options Cincinnati, OH			
Test Section	Expected Design Life		
	5 Years	10 Years	20 years
Eight Street	Continue routine/repair maintenance	Repair damaged PCC joints and slabs, apply stress relieving layer, add 2" DGAC overlay or Repair damaged PCC joints and slabs, add 1½" asphalt rubber hot mix overlay	Repair damaged PCC joints and slabs, apply stress relieving layer, add 3" DGAC overlay or Repair damaged PCC joints and slabs, add 2" asphalt rubber hot mix overlay
Kellogg Avenue	Continue routine maintenance	Remove existing asphalt surface, repair damaged PCC joints and slabs, apply stress relieving layer, add 2½" DGAC overlay or Remove existing asphalt surface, repair damaged PCC joints and slabs, add 2" asphalt rubber hot mix overlay	Remove existing asphalt surface, repair damaged PCC joints and slabs, apply stress relieving layer, add 4" DGAC overlay or Remove existing asphalt surface, repair damaged PCC joints and slabs, add 3" asphalt rubber hot mix overlay

Recommended Rehabilitation Options
Cincinnati, OH

Test Section	Expected Design Life		
	5 Years	10 Years	20 years
Dalton Street Southern Section	Continue routine maintenance	Repair damaged PCC joints and slabs, apply stress relieving layer, add 2" DGAC overlay or Repair damaged PCC joints and slabs, add 1½" asphalt rubber hot mix overlay	Repair damaged PCC joints and slabs, apply stress relieving layer, add 3" DGAC overlay or Repair damaged PCC joints and slabs, add 2" asphalt rubber hot mix overlay
Wayside Avenue	Continue routine maintenance	1½" DGAC overlay	2½" DGAC overlay
Glenway Avenue	Continue routine maintenance	Apply stress relieving layer, add 2½" DGAC or Apply 2" asphalt rubber hot mix overlay	Remove existing asphalt surface, repair damaged PCC joints and slabs, apply stress relieving layer, add 4" DGAC overlay or Remove existing asphalt surface, repair damaged PCC joints and slabs, add 3" asphalt rubber hot mix overlay

Recommended Rehabilitation Options Cincinnati, OH			
Test Section	Expected Design Life		
	5 Years	10 Years	20 years
Gest Street	Continue routine maintenance	Repair damaged PCC joints and slabs, apply stress relieving layer, add 2" DGAC overlay or Repair damaged PCC joints and slabs, add 1½" asphalt rubber hot mix overlay	Repair damaged PCC joints and slabs, apply stress relieving layer, add 3" DGAC overlay or Repair damaged PCC joints and slabs, add 2" asphalt rubber hot mix overlay or Rubblize PCC and place 4" AC
Lehman Road	Repair all localized distresses, R&R where necessary, add 1½" DGAC overlay	Install edge drains, repair all localized distresses, R&R where necessary, add 2" DGAC overlay	Pulverize existing asphalt surfacing, blend with existing base course, recompact, install underdrains between stations 8+00 and 17+00, add 3" DGAC over entire project

Recommended Rehabilitation Options Cincinnati, OH			
Test Section	Expected Design Life		
	5 Years	10 Years	20 years
Martin Luther King Drive	Continue routine maintenance	Apply stress relieving layer, add 2½" DGAC or Apply 2" asphalt rubber hot mix overlay	Remove existing asphalt surface, repair damaged PCC joints and slabs, apply stress relieving layer, add 4" DGAC overlay or Remove existing asphalt surface, repair damaged PCC joints and slabs, add 3" asphalt rubber hot mix overlay
Dalton street Northern Section	Continue routine maintenance	Remove 2" existing asphalt, repair damaged areas, add 2" DGAC overlay	Remove 3" existing asphalt, repair damaged areas, add 3" DGAC overlay
Eastern Avenue	Continue routine maintenance	Remove 2½" existing asphalt, apply stress relieving layer, add 2½" DGAC or Remove 2" existing asphalt, apply 2" asphalt rubber hot mix overlay	Remove 4" existing asphalt, apply stress relieving layer, add 4" DGAC or Remove 3" existing asphalt, apply 3" asphalt rubber hot mix overlay

Recommended Rehabilitation Options Cincinnati, OH			
Test Section	Expected Design Life		
	5 Years	10 Years	20 years
Boudinot Avenue	Continue routine maintenance	Remove existing asphalt surface, repair damaged PCC joints and slabs, apply stress relieving layer, add 2½" DGAC overlay or Remove existing asphalt surface, repair damaged PCC joints and slabs, add 2" asphalt rubber hot mix overlay	Remove existing asphalt surface, repair damaged PCC joints and slabs, apply stress relieving layer, add 4" DGAC overlay or Remove existing asphalt surface, repair damaged PCC joints and slabs, add 3" asphalt rubber hot mix overlay

Recommended Rehabilitation Options Cincinnati, OH			
Test Section	Expected Design Life		
	5 Years	10 Years	20 years
William Howard Taft Station 0+00 to 39+00	Continue routine maintenance	Remove existing asphalt surface, apply stress relieving layer, add 3" DGAC overlay or Remove existing asphalt surface, add 2" asphalt rubber hot mix overlay	Remove existing asphalt surface, repair damaged PCC joints and slabs, apply stress relieving layer, add 4½" DGAC overlay or Remove existing asphalt surface, repair damaged PCC joints and slabs, add 3" asphalt rubber hot mix overlay or Remove entire existing pavement structure and replace with 9" PCC pavement

Recommended Rehabilitation Options Cincinnati, OH			
Test Section	Expected Design Life		
	5 Years	10 Years	20 years
William Howard Taft Station 39+00 to 93+84	Remove existing asphalt surface, repair damaged PCC joints and slabs, apply stress relieving layer, add 1½" DGAC overlay	Remove existing asphalt surface, repair damaged PCC joints and slabs, apply stress relieving layer, add 2½" DGAC overlay or Remove existing asphalt surface, repair damaged PCC joints and slabs, add 1½" asphalt rubber hot mix overlay	Remove existing asphalt surface, repair damaged PCC joints and slabs, apply stress relieving layer, add 4" DGAC overlay or Remove existing asphalt surface, repair damaged PCC joints and slabs, add 2½" asphalt rubber hot mix overlay
Reading Road	Continue routine maintenance	Remove 2½" of existing asphalt surface, apply stress relieving layer, add 2½" DGAC overlay or Remove 2" of existing asphalt surface, add 2" asphalt rubber hot mix overlay	Remove 4" of existing asphalt surface, apply stress relieving layer, add 4" DGAC overlay or Remove 3" of existing asphalt surface, add 3" asphalt rubber hot mix overlay

Recommended Rehabilitation Options Cincinnati, OH			
Test Section	Expected Design Life		
	5 Years	10 Years	20 years
Pete Rose Way	Continue routine maintenance	Conduct localized concrete pavement restoration as required	Repair damaged PCC joints and slabs, apply stress relieving layer, add 3" DGAC overlay or Repair damaged PCC joints and slabs, add 2" asphalt rubber hot mix overlay
Soutside Avenue	Continue routine maintenance	Maintain/restore surface texture with surface treatment or minimum DGAC overlay	Maintain/restore surface texture with surface treatment or minimum DGAC overlay
Edwards Road	Apply 1½" DGAC overlay to restore ride quality and appearance	Remove 2" of existing asphalt surface, repair distressed areas, add 2½" DGAC overlay or Repair distressed areas, add 2" asphalt rubber hot mix overlay	Pulverize existing asphalt surfacing, blend with existing base course, recompact, add 4" DGAC over entire project

Notes:

1. Removal and replacement of base and surfacing
2. Conventional Dense Graded Asphalt Concrete hot mix
3. Asphalt impregnated fabric interlayer between PCC slabs and DGAC overlay

Appendix I
Berkeley, CA Test Sections

City of Berkeley
Department of Public Works
Engineering Division

Streets to be Evaluated

PRIORITY	NAME OF STREET	BEGINNING	END	LENGTH, FT	AVERAGE DAILY TRAFFIC	TRAFFIC CLASS	SURFACE TYPE
1	Haste St	Fulton St	Bowditch St	0.51	10,000	Arterial	Overlay
2	M.L. King	Ashby Ave	Adeline St	0.19	19,000	Arterial	Asphalt
3	Shasta Rd	Cragmont Ave	Keeler Ave	0.13	4,000	Collector	Overlay
4	Cedar St	Oxford St	Spruce St	0.06	11,000	Collector	Overlay
5	Rose St	Milvia St	Shattuck Ave	0.13	7,000	Collector	Overlay
6	Wildcat Canyon Rd	Sunset Ln	The Spiral	0.45	5,000	Collector	Overlay
7	Mathews St	Dwight Wy	Parker St	0.12	1,000	Residential	Overlay
8	Francisco St	Chestnut St	Acton St	0.21	1,000	Residential	Overlay
9	Stuart St	Sacramento St	M.L. King	0.46	2,000	Residential	Overlay
10	Rugby Ave	N. City Limit	Vermont Ave	0.04	1,000	Residential	Overlay
11	Stuart St	M.L. King	Milvia St	0.13	2,500	Residential	Overlay
12	Bancroft Wy	Piedmont Ave	Panoramic Wy	0.03	2,000	Residential	Overlay
13	Ward St	Acton St	Sacramento St	0.14	2,500	Residential	Overlay
14	Visalia Ave	West City Limit	Vincente Ave	0.23	2,000	Residential	Overlay
15	Ward St	Sacramento St	M.L. King	0.46	2,500	Residential	Overlay
16	Channing Wy	College Ave	Piedmont Ave	0.12	8,000	Residential	Overlay
17	4th St	Addison St	Dwight Wy	0.49	3,500	Collector	Overlay
18	Solano Ave	The Alameda	Contra Costa Ave	0.10	12,000	Collector	Asphalt
19	6th St	Cedar St	Virginia St	0.13	12,000	Collector	Overlay
20	Hearst Ave	6th St	San Pablo Ave	0.31	3,500	Collector	Overlay
21	Cedar St	Sacramento St	M.L. King	0.49	9,500	Collector	Overlay

PRIORITY	NAME OF STREET	BEGINNING	END	LENGTH, FT	AVERAGE DAILY TRAFFIC	TRAFFIC CLASS	SURFACE TYPE
22	Cedar St	6th St	San Pablo Ave	0.31	11,000	Collector	Overlay
23	Woolsey St	Tremont St	Telegraph Ave	0.43	4,000	Residential	Overlay
24	West St	Bancroft Wy	Dwight Wy	0.25	1,000	Residential	Overlay
25	62nd St	M.L. King	City Limit	0.10	1,000	Residential	Overlay
26	8th St	Columbus School	Dwight Wy	0.32	1,500	Residential	Overlay
28	Jones St	4th St	6th St	0.13	1,500	Residential	Overlay
29	Euclid Ave (NB)	Beg of Divided Rd	End of Divided Rd	0.16	3,000	Residential	Concrete
31	Grant St	Rose St	Cedar St	0.25	1,500	Residential	Overlay
32	Regal Rd	Marin Ave	Euclid Ave	0.10	1,500	Residential	Overlay
33	Parker St	4th St	San Pablo Ave	0.44	2,500	Residential	Overlay
34	Vine St	Milvia St	Shattuck Ave	0.13	5,000	Residential	Overlay
35	Bonita Ave	Rose St	Vine St	0.13	2,000	Residential	Overlay
36	Vine St	M.L. King	Miliva St	0.13	3,500	Residential	Overlay
37	Neilson St	North City Limit	Bartd	0.17	2,000	Residential	Overlay
38	Euclid Ave	End of Divided Rd	Eunice St	0.17	6,000	Residential	Overlay
39	Henry St	Rose St	Vine St	0.13	4,000	Residential	Overlay
40	Curtis St	North City Limit	Hopkins St	0.45	2,500	Residential	Overlay
41	Vine St	Edith St	Grant St	0.06	2,000	Residential	Overlay
42	Bonita Ave	Cedar St	Virginia St	0.13	2,000	Residential	Overlay
43	Channing Way	10th St	San Pablo Ave	0.05	3,500	Residential	Overlay
45	Mendocino Ave	Arlington Ave	Los Angeles Ave	0.31	1,000	Residential	Overlay
46	Napa Ave	The Alameda	Hopkins St	0.18	800	Residential	Overlay
47	Adeline St	Derby St	Stuart St	0.14	17,000	Arterial	Concrete
48	Adeline St	Alcatraz Ave	South City Limit	0.20	36,000	Arterial	Asphalt
49	M.L. King	Adeline St	South City Limit	0.06	38,000	Arterial	Asphalt

PRIORITY	NAME OF STREET	BEGINNING	END	LENGTH, FT	AVERAGE DAILY TRAFFIC	TRAFFIC CLASS	SURFACE TYPE
50	Hearst Ave	Oxford St	Spruce St	0.05	25,000	Arterial	Overlay
51	Sacramento St	Oregon St	Ashby Ave	0.19	24,000	Arterial	Asphalt
53	Hearst Ave	McGee Ave	M.L. King	0.26	6,500	Collector	Overlay
54	Seawall Dr	University Ave	South End	0.16	3,500	Residential	Asphalt
55	Arcade Ave	Grizzly Peak Blvd	Fairlawn Dr	0.06	1,000	Residential	Overlay
56	California St	Oregon St	Ashby Ave	0.18	3,000	Residential	Overlay
57	Seawall Dr	North End	University Ave	0.26	3,500	Residential	Overlay
58	Prince St	Sacramento St	M.L. King	0.42	2,000	Residential	Overlay
59	Russell St	Milvia St	Adeline St	0.02	1,500	Residential	Overlay
60	Ward St	Shattuck St	Fulton St	0.15	1,500	Residential	Overlay
63	Oxford St	University Ave	Bancroft Wy	0.32	30,000	Arterial	Overlay
64	Hearst Ave	M.L. King	Milvia St	0.13	7,500	Arterial	Overlay
65	Oxford St	Berkeley Way	University Ave	0.06	28,000	Arterial	Overlay
66	Oxford St	Hearst Ave	Berkeley Wy	0.05	28,000	Arterial	Overlay
67	Indian Rock Ave	The Circle	Santa Barbara Rd	0.41	2,000	Residential	Overlay
68	Russell St	Claremont Blvd	East City Limit	0.03	8,000	Residential	Overlay
69	Russell St	College Ave	Claremont Blvd	0.48	2,000	Residential	Overlay
71	Parker St	Fulton St	Dana St	0.25	2,500	Residential	Overlay
72	Alvarado Rd	Bridge Rd	North City Limit	0.36	3,000	Residential	Overlay
73	Hearst Ave	San Pablo Ave	Acton St	0.45	3,500	Residential	Overlay
74	Webster St	College Ave	Claremont Ave	0.33	1,500	Residential	Overlay
76	Walnut St	Berkeley Wy	University Ave	0.06	1,500	Residential	Overlay
77	Gilman St	State P/L	6th St	0.28	21,000	Arterial	Overlay
80	Yolo Ave	Milvia Ave	Sutter St	0.07	1,000	Residential	Overlay
81	Addison St	Sacramento St	M.L. King	0.50	2,500	Residential	Overlay

PRIORITY	NAME OF STREET	BEGINNING	END	LENGTH, FT	AVERAGE DAILY TRAFFIC	TRAFFIC CLASS	SURFACE TYPE
82	Berkeley Way	Grant St	M.L. King	0.13	1,500	Residential	Overlay
83	Talbot Ave	North City Limit	Santa Fe Ave	0.26	1,000	Residential	Overlay
84	California St	Hearst Ave	University Ave	0.11	2,500	Residential	Overlay
86	Addison St	Milvia St	Oxford St	0.26	3,000	Residential	Overlay
87	Evelyn Ave	North City Limit	Santa Fe Ave	0.19	1,500	Residential	Overlay
88	Yolo Ave	The Alameda	Milvia St	0.11	1,000	Residential	Overlay
89	Grant St	Hearst Ave	University Ave	0.11	1,500	Residential	Overlay
90	Grant St	Virginia St	Ohlone Park	0.16	800	Residential	Overlay
91	8th St	Camelia St	Page St	0.08	1,800	Residential	Overlay
92	Grant St	University Ave	Dwight Way	0.57	1,500	Residential	Overlay
93	Mc Gee Ave	Hearst Ave	University Ave	0.11	1,500	Residential	Overlay
94	University Ave	San Pablo Ave	Sacramento St	0.56	40,000	Arterial	Overlay
95	Derby St	Warring St	Belrose Ave	0.23	23,000	Arterial	Overlay
96	Hopkins St	Sacramento St	Hopkins Ct	0.04	15,000	Arterial	Overlay
97	California St	Ada St	Cedar St	0.27	800	Residential	Overlay
98	Catherine Dr	Keoncrest Dr	Keoncrest Dr	0.08	800	Residential	Overlay
99	Acton St	Hopkins St	Rose St	0.12	1,000	Residential	Overlay
100	4th St	Harrison St	Camelia St	0.26	2,500	Residential	Overlay
101	Ada St	Sacramento St	Mc Gee St	0.16	1,500	Residential	Overlay
102	Ordway St	North City Limit	Hopkins St	0.26	800	Residential	Overlay
103	Acton St	Rose St	Cedar St	0.12	2,000	Residential	Overlay
104	Tohlee Dr	Juanita Wy	Acton St	0.06	500	Residential	Asphalt
105	Tangelwood Rd	Belrose Ave	East City Limit	0.16	500	Residential	Overlay
106	Keoncrest Dr	Rose St	Acton St	0.18	800	Residential	Overlay
108	Albina Ave	North City Limit	Hopkins St	0.14	800	Residential	Overlay

PRIORITY	NAME OF STREET	BEGINNING	END	LENGTH, FT	AVERAGE DAILY TRAFFIC	TRAFFIC CLASS	SURFACE TYPE
109	Hopkins St	Gilman St	Sacramento St	0.10	17,000	Residential	Overlay
110	Hopkins St	Peralta Ave	Gilman St	0.27	4,000	Residential	Overlay
111	College Ave	Derby St	Ashby Ave	0.35	18,000	Arterial	Overlay
112	College Ave	Dwight Wy	Derby St	0.52	16,000	Arterial	Overlay
123	Dwight Wy	Sacramento St	M.L. King	0.50	14,000	Arterial	Overlay
124	Dwight Wy	Milvia Wy	Shattuck Ave	0.13	15,000	Arterial	Overlay
129	Haskell St	San Pablo Ave	Acton St	0.29	1,000	Residential	Overlay
138	Piedmont Crescent	Dwight Wy	Warring St	0.05	22,000	Collector	Overlay
140	Prospect St	US Campus (Stadium)	Dwight Wy	0.24	2,500	Residential	Overlay
144	The Uplands	Hillcrest Rd	Tunnel Rd	0.30	2,500	Residential	Overlay
145	Telegraph Ave	Dwight Wy	Ward St	0.33	21,000	Arterial	Overlay
146	Telegraph Ave	Ward St	Ashby Ave	0.30	28,000	Arterial	Overlay
159	Cedar St	Shattuck Ave	Oxford St	0.12	9,000	Collector	Overlay
166	University Ave	6th St	San Pablo Ave	0.31	45,000	Arterial	Overlay
167	7th St	Dwight Wy	Grayson St	0.35	19,000	Collector	Overlay
168	7th St	Grayson St	Heinz Ave	0.13	19,000	Collector	Overlay
169	East Frontage Rd	Gilman St	University Ave	0.81	6,000	Collector	Overlay

Appendix J
Rehabilitation Strategies for Berkeley, CA

Recommended Rehabilitation Options
Berkeley, CA

Priority No.	Street Name	Traffic Class	Area Sq. Ft.	Year	PCI	% Alligator	Existing AC (in)	AC Overlay (in)	Routine Maintenance Pre-Overlay Treatment	Comments
1	Haste St.	A	107200	1963	72	2	5.00	2.00	ML 1", FDP	
2	Martin Luther King	A	29550	1971	55	1	16.00	2.00	ML 2", FDP	
3	Shasta Rd.	C	27200	1969	57	5	1.50	3.50	FDP, SC	
4	Cedar St.	C	12060	1957	47	3	5.00	2.00	ML 2", FDP	
5	Rose St.	C	24300	1950	72	1	3.50	2.00	ML 1", FDP	
6	Wildcat Canyon Rd.	C	57600	1969	45	6	4.00	3.00	FDP, SC	
7	Mathews St.	R	23220	1969	43	8	2.00	2.00	ML 1", FDP	
8	Francisco St.	R	33900	1950	44	9	1.50	4.00	ML 4", Recompact Base	See Note 1
9	Stuart St.	R	86580	1948	41	10	2.00	4.00	ML 4", Recompact Base	See Note 1
10	Rugby Ave.	R	5880	1963	52	5			This section was not tested, follow the M&R for Priority No. 14	
11	Stuart St.	R	23760	1947	42	23	2.00	4.00	ML 4", Recompact Base	See Note 1
12	Bancraft Way	R	4860	1963	41	11	2.50	2.50	ML 2.5", Recompact Base	See Note 1
13	Ward St.	R	26172	1952	67	2	2.00	2.00	FDP, SC	
14	Visalia Ave.	R	29160	1960	51	1	3.50	2.00	FDP. SC	
15	Ward St.	R	87732	1976	44	8	1.00	4.00	ML 4", Recompact Base	See Note 1
16	Channing Way	R	22680	1964	50	1	4.50	2.0	FDP, SC	
17	Fourth St.	C	93960	1969	46	12	1.50	5.50	ML 5.5", Recompact Base	See Note 1
18	Solano Ave.	C	22440	1960	61	1	5.00	2.00	FDP, SC	
19	Sixth St.	C	32400	1969	55	10	7.00	5.50	ML 7", Recompact Base	See Note 1

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Recommended Rehabilitation Options
Berkeley, CA

Priority No.	Street Name	Traffic Class	Area Sq. Ft.	Year	PCI	% Alligator	Existing AC (in)	AC Overlay (in)	Routine Maintenance Pre-Overlay Treatment	Comments
20	Hearst Ave.	C	59400	1950	59	1	4.50	2.00	FDP, SC	
21	Cedar St.	C	93600	1964	73	2	4.50	2.00	ML 1", FDP	
22	Cedar St.	C	64350	1958	47	8	6.50	0.00	FDP, SC	
23	Woolsey St.	R	82620	1952	46	1	2.75	2.00	ML 1.5", FDP	
24	West St.	R	47700	1974	70	2	3.00	2.00	ML 1.5", FDP	
25	Sixty-Second St.	R	18900	1967	45	8	5.00	2.00	ML 2", FDP	
26.1	Eighth St.	R	61380	1950	68	9	1.50	4.50	ML 4.5" Recompact Base	See Notes 1 & 2
26.2	Eighth St.	R		1950	68	9	4.50	0.00	Apply M&R Policy	See Note 2
28	Jones St.	R	24660	1952	42	2	3.00	2.00	ML 0.5", FDP	
29	Euclid Ave. (NB)	R	15300	1965	43	0	1.00	2.00	ML 1", Saw Joints in Overlay	
31	Grant St.	R	47700	1965	61	2	4.00	0.00	FDP, ST	
32	Regal Rd.	R	12100	1950	48	7	4.00	0.00	FDP, SC, ST	
33	Parker St.	R	83700	1963	50	8	3.00	2.00	FDP	
34	Vine St.	R	24120	1966	50	5	7.00	0.00	FDP, ST	
35	Bonita Ave.	R	23760	1952	61	2	3.50	2.00	ML 1", FDP	
36	Vine St.	R	23940	1966	54	4	3.00	2.00	FDP	
37	Nellson St.	R	23140	1950	64	4	3.00	2.00	FDP	
38	Euclid Ave.	R	36900	1965	46	0	3.50	2.00	ML 2"	
39	Henry St.	R	23760	1965	50	2	4.00	3.00	ML 1", FDP	
40	Curtis St.	R	72000	1950	66	3	4.00	3.00	FDP	

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Recommended Rehabilitation Options
Berkeley, CA

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41	Vine St.	R	12060	1968	52	4	3.50	0.00	FDP, ST	
42	Bonita Ave.	R	24120	1958	62	1	2.00	2.00	FDP	
43	Channing Way	R	6000	1966	52	7	4.00	2.00	ML 1", FDP	
45	Mendocino Ave.	R	52800	1960	41	16	3.00	3.00	ML 3", Recompact Base	See Note 1
46	Napa Ave.	R	1536	1966	40	6	3.00	2.00	ML 1", FDP	
47	Adeline St.	A	60000	1969	57	0	15.00	0.00	SC	
48	Adeline St.	A	79420	1977	59	0	12.00	0.00	SC	
49	Martin Luther King	A	25460	1971	57	0	16.00	0.00	SC, ST	
50	Hearst Ave.	A	14500	1984	51	4	6.00	2.50	FDP	
51	Sacramento St.	A	57176	1980	61	2	6.50	2.00	ML 1.5", FDP	
53	Hearst Ave.	C	48780	1959	44	19	3.00	4.50	ML 4.5", Recompact Base	See Note 1
54	Seawall Dr.	R	23800	1962	48	3	3.00	3.00	ML 0.5", FDP	
55	Arcade Ave.	R	7750	1950	46	5	3.50	2.00	ML 1.5", FDP	
56	California St.	R	39900	1946	44	19	1.50	2.00	ML 2", Recompact Base	See Note 1
57	Seawall Dr.	R	37800	1962	74	7	2.00	2.00	FDP	
58.1	Prince St.	R	79920	1967	71	2	3.00	2.00	ML 1.5", FDP	See Note 2
58.2	Prince St.	R		1967	71	2	3.75	0.00	Apply M&R Policy	See Note 2
59	Russell St.	R	4140	1966	50	3	13.00	0.00	FDP, SC	
60	Ward St.	R	28080	1966	48	8	2.00	2.00	FDP, SC	
63	Oxford St.	A	135200	1964	58	10	6.00	5.50	ML 6", Recompact Base	See Note 1

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Recommended Rehabilitation Options
Berkeley, CA

Priority No.	Street Name	Traffic Class	Area Sq. Ft.	Year	PCI	% Alligator	Existing AC (in)	AC Overlay (in)	Routine Maintenance Pre-Overlay Treatment	Comments
64	Hearst Ave.	A	26800	1959	46	15	3.50	4.50	ML 4.5", Recompact Base	See Note 1
65	Oxford St.	A	20160	1964	51	0	8.00	2.00	ML 2"	
66	Oxford St.	A	8700	1984	56	0	5.00	3.00	SC	
67	Indian Rock Ave.	R	77904	1968	46	6	4.00	2.00	ML 1.5", FDP	
68	Russell St.	R	4860	1955	46	3	4.00	2.00	ML 1", FDP	
69	Russell St.	R	90540	1957	41	7	5.50	0.00	FDP, SC	
71	Parker St.	R	47880	1965	45	5	2.50	2.00	FDP, SC	
72	Alvarado Rd.	R	45360	1956	70	10	3.00	4.00	ML 4", Recompact Base	See Note 1
73	Hearst Ave.	R	84600	1965	49	15	3.00	4.00	ML 4", Recompact Base	See Note 1
74	Webster St.	R	63360	1958	44	16	4.50	3.00	ML 4.5", Recompact Base	See Note 1
76	Walnut St.	R	11340	1948	46	17	2.50	2.50	ML 2.5", Recompact Base	See Note 1
77	Gilman St.	A	71280	1984	68	4	7.00	2.50	FDP, SC	
80	Yolo Ave.	R	13500	1968	42	7	3.00	2.00	ML 1", FDP	
81	Addison St.	R	94320	1952	63	4	5.00	0.00	FDP, SC	
82	Berkeley Way	R	23450	1984	46	17	3.75	3.00	ML 3.75", Recompact Base	See Note 1
83	Talbot Ave.	R	40500	1952	52	4	2.00	2.00	ML 0.5", FDP	
84	California St.	R	25200	1952	40	29	2.00	2.00	ML 2", Recompact Base	See Note 1
86.1	Addison St.	R	56375	1952	49	7	7.00	0.00	Apply M&R Policy	See Note 2
86.2	Addison St.	R		1952	49	7	5.00	0.00	Apply M&R Policy	See Note 2
87	Evelyn Ave.	R	29400	1947	65	3	2.00	2.00	ML 1", FDP	

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Recommended Rehabilitation Options
Berkeley, CA

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88	Yolo Ave.	R	20520	1963	41	2	3.00	2.00	ML 1", FDP	
89	Grant St.	R	21600	1964	67	2	4.00	0.00	FDP, SC	
90	Grant St.	R	30348	1964	42	22	2.00	2.00	ML 2", Recompact Base	See Note 1
91	Eighth St.	R	15840	1966	55	1	5.00	0.00	FDP, SC, ST	
92	Grant St.	R	126210	1952	40	20	5.00	3.00	ML 5", Recompact Base	See Note 1
93	McGee Ave.	R	21600	1948	50	4	3.00	0.00	FDP, SC	
94	University Ave.	A	188160	1986	74	4	7.00	2.00	ML 1", FDP	
95	Derby St.	A	43380	1984	69	0	5.00	2.00	ML 1.5"	
96	Hopkins St.	A	7200	1984	47	8	7.00	2.00	ML 1", FDP	
97	California St.	R	50580	1942	47	13	1.50	3.00	ML 3", Recompact Base	See Note 1
98	Catherine Dr.	R	10660	1954	47	12	4.00	3.00	ML 4", Recompact Base	See Note 1
99	Acton St.	R	19200	1964	41	15	3.50	3.00	ML 3.5", Recompact Base	See Note 1
100	Fourth St.	R	49500	1963	48	0	5.50	3.00	ML 0.5"	
101	Ada St.	R	30960	1950	47	7	2.50	2.00	FDP	
102	Ordway St.	R	50040	1950	49	4	2.00	2.00	FDP, SC	
103	Acton St.	R	22860	1950	46	17	2.00	3.00	ML 3", Recompact Base	See Note 1
104	Tomlee Dr.	R	8580	1946	72	1	2.50	0.00	FDP, SC	
105	Tanglewood Rd.	R	30600	1951	52	0	6.00	2.00	ML 2"	
106	Keoncrest Dr.	R	24700	1938	51	6	2.00	0.00	FDP, ST	
108	Albina Ave.	R	23360	1966	62	5	5.00	0.00	FDP	

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Recommended Rehabilitation Options
Berkeley, CA

Priority No.	Street Name	Traffic Class	Area Sq. Ft.	Year	PCI	% Alligator	Existing AC (in)	AC Overlay (in)	Routine Maintenance Pre-Overlay Treatment	Comments
109	Hopkins St.	R	1954	1954	613	3	6.00	2.50	FDP	
110	Hopkins St.	R	51912	1954	52	0	11.00	3.50	ML 1"	
111	College Ave.	A	66600	1952	58	1	7.00	3.00	ML 1"	
112	College Ave.	A	99720	1952	54	2	8.00	0.00	FDP, SC	
123	Dwight Way	A	104600	1968	72	4	6.00	2.00	FDP	
124	Dwight Way	A	26980	1984	51	10	6.00	6.00	ML 6", Recompact Base	See Note 1
129	Haskell St.	R	54180	1960	43	6	2.00	2.00	FDP	
138	Piedmont Crescent	C	15960	1953	66	1	4.00	0.00	FDP, SC	
140	Prospect St.	R	45360	1969	41	2	6.50	2.00	ML 2"	
144	The Uplands	R	52875	1993	42	25	2.50	2.50	ML 2.5", Recompact Base	See Note 1
145	Telegraph Ave.	A	117300	1968	66	5	4.00	2.00	FDP, SC	
146	Telegraph Ave.	A	107440	1968	66	3	12.00	0.00	FDP, SC	
159	Cedar St.	C	24765	1960	80	1	7.00	0.00	Apply M&R Policy	
166	University Ave.	A	98280	1986	68	5	4.00	5.50	FDP	
167	Seventh St.	C	79292	1958	53	5	12.00	0.00	FDP, SC	
168	Seventh St.	C	31740	1961	55	0	4.00	2.00	ML 1"	
169.1	East Frontage Rd.	C	137600	1965	51	10	10.00	7.50	ML 10", Recompact Base	See Notes 1 & 2
169.2	East Frontage Rd.	C		1965	51	10	16.00	7.00	ML 16", Recompact Base	See Notes 1 & 2
169.4	East Frontage Rd.	C		1965	51	10	6.00	7.50	ML 6", Recompact Base	See Notes 1 & 2

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Appendix K
Recommended Specifications Template for a Request for Bid

1. GENERAL.

The contractor shall provide all supplies, labor and equipment to conduct nondestructive tests (NDT) on roads in (city/county). A report listing rehabilitation strategies based on the average daily traffic (ADT) for 5,10,and 20 years for each road evaluated shall be provided.

Note: These ADT's are not mandatory, but are suggested so multiple maintenance techniques will be available for selection, and one can be selected based on available funds.

2. GOVERNMENT RESPONSIBILITIES.

a. The city/county shall furnish a tabulation of streets to be tested. The table shall include the following: name of street, length, location (beginning and ending points), number of lanes, traffic classification, surface classification, and ADT's. The ADT's shall include the percentage of trucks traffic for each road.

b. The city/county shall furnish a map that displays the location of each roadway to be tested, Attachment A.

c. Since the collection of pavement layer thickness data can be a significant portion of the contract time and cost, the amount of available layer thickness data shall be made known at the time of Request for Proposal, Attachment B.

d. Liability associated with pavement rehabilitation shall be accepted by the city/county and/or the contractor performing the rehabilitation construction.

3. CONTRACTOR RESPONSIBILITIES.

a. Field work. Test measurements shall be obtained with a falling-weight type impulse load device that is in accordance with ASTM D 4694, Standard Test Method for Deflections with a Falling-Weight-Type Impulse Load Device. The testing effort shall conform to Type ____ level as described in ASTM D 4695, Standard Guide for General Pavement Deflection Measurements.

   Note: Three levels of testing are described. As described in the Standard, Type II is a routine analysis of pavement for purposes such as overlay design projects.

b. Pavement thickness. Pavement layer thicknesses shall be determined by reviewing construction records. Subsurface investigation of the roadway structure may be necessary to determine and/or verify layer thicknesses when such data is questionable or unavailable. Acceptable methods of obtaining pavement layer thicknesses include coring, boring, test pits, ground penetrating radar, and /or the use of a dynamic cone penetrometer. When subsurface excavation is required, the contractor shall be responsible for obtaining the proper permits and/or notifying the utility companies.

c. Material properties. When required material property data is not available, the contractor shall collect samples and conduct laboratory tests to determine these properties (ie. flexural strength of concrete).

d. Traffic control. The contractor shall be responsible for traffic control during the data acquisition process. Traffic control shall be in accordance with the Manual of Uniform Traffic Control Devices.

e. Any liability due to accidents associated with the field testing shall be covered by the contractor.

f. Report. The final report shall consist of a summary of test results, analysis of results, and recommendations for maintenance and rehabilitation required to support the estimated future traffic.

Note: There are many analysis and design methods that can be used, some are empirical while others are mechanistic/empirical. The methods should conform to the American Association of State Highway and Transportation Officials (AASHTO) or US Army Corps of Engineers procedures.

4. AREAS TO BE TESTED.

A prioritized list of roads to be tested, their locations, and descriptions are provided as attached.

5. PREMEETING.

Prior to initiating the work, representatives from the city/county and contractor shall meet at the work site to coordinate the testing and evaluation of the pavements. The following items shall be addressed.

a. The city/county shall furnish the contractor a copy of any pavement design, maintenance, and rehabilitation records for the roads selected for evaluation.

b. The city/county shall provide the contractor traffic estimates for the next 5,10, and 20 years for the selected roadways. Percentages of trucks should be included.

c. Previous distress survey data for the selected roads shall be provided to the contractor.

d. Any design constraints such as curb height restrictions, no surface treatments allowed, etc. shall be discussed.

e. If life cycle costs are to be included as part of the requirements of the contract, past construction cost data such as unit costs for resurfacing, patching, etc. should be provided.

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