TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
TX-01 4188-1		

4. Title and Subtitle	5. Report Date
Methods to Expedite Construction of PCC Pavements: An Overview	August 2003
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
O. Melchor-Lucero, Y. Wanyan, S. Nazarian and J. Weissmann	Research Report 4188-1
9. Performing Organization Name and Address	10. Work Unit No.
Center for Highway Materials Research The University of Texas at El Paso El Paso, Texas 79968-0516	11. Contract or Grant No. Study No. 0-4188
12. Sponsoring Agency Name and Address	13. Type of Report and Period Covered
Texas Department of Transportation P.O. Box 5051 Austin, Texas 78763	Interim Report Sept. 1, 2000 -Aug 31, 2001
	14. Sponsoring Agency Code

15. Supplementary Notes

Research Performed in Cooperation with TxDOT

16. Abstract

Due to difficulties associated with the maintenance of highways constructed in urban settings, the expedited construction of durable Portland cement concrete (PCC) pavement has become a necessity. To obtain a durable PCC pavement, a number of parameters should be considered. Since most urban roads experience excessive traffic, the desire of highway agencies is to open a newly constructed highway to traffic as soon as possible. Due to heavy traffic, several layers of high-quality or heavily stabilized materials are normally placed during construction. For TxDOT, this consists of one or more layers of stabilized subgrade and base, a layer of ACP to act as a bond breaker, and a PCC slab. The large number of layers may be cost-effective from the standpoint of agency costs; however, the number of steps involved may increase the construction period increasing user costs borne by the motoring public. It may be possible to minimize the number of layers without compromising the performance of the pavement by either thickening or using innovative high-strength materials. This may increase the construction cost, but, considering the user costs, it may in the best interest of TxDOT to follow this option. In this project, a methodology is proposed to mainstream the construction of highways in urban settings.

17. Key Words	18. Distribution Statement
PCC Pavements, Expedited Construction, Nondestructive Testing, Opening to Traffic	No restrictions. This document is available to the public through the National Technical Information Service, 5285 Port Royal Road, Springfield, Virginia 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	142	

Methods to Expedite Construction of PCC Pavements: An Overview

by

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Research Project 0-4188

Development of Methods and Materials to Accelerate Construction and Opening of PCC Pavements

Conducted for
Texas Department of Transportation

The Center for Highway Materials Research
The University of Texas at El Paso
El Paso, TX 79968-0516
Research Report 4188-1
August 2003

NOT INTENDED FOR CONSTRUCTION, BIDDING, OR PERMIT PURPOSES

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Acknowledgements

The authors acknowledge Mr. James Hunt of TxDOT for his ever-present support. Mr. Mark McDaniel provided TxDOT pavement design guidelines. Dr. Moon Won was always available for consultation. Mr. Bob Lopez and Mr. Bill Weseman from the Texas Cement and Concrete Promotion Council (CCPC) provided us with access to their annual meeting, and fitted us in their busy schedule. We also thank the members of the Transportation Research Board Committee A2F01 (PCC Pavement Construction) for helping us by responding to our questionnaire.
Various District Pavement Engineers throughout the State provided us with information on current pavement construction practices.

Executive Summary

Several TxDOT districts throughout the state rely almost solely on Portland Cement Concrete Pavements PCCP (especially Continuously Reinforced Concrete Pavements CRCP) for heavily traveled metropolitan highways and the urban and suburban sections of the interstate. The goal of most urban projects is to provide smooth and maintenance-free roads to the public with a minimal closure time. Timely opening of the roads to traffic is extremely important. Due to difficulties associated with the maintenance of highways constructed in urban settings, the expedited construction of durable Portland cement concrete (PCC) pavement has become a necessity.

Due to heavy traffic, several layers of high-quality or heavily stabilized materials are normally placed during construction. For TxDOT, this consists of one or more layers of stabilized subgrade and base, a layer of asphalt concrete pavement (ACP) to act as a bond breaker, and a PCC slab. The large number of layers may be cost-effective from the standpoint of agency costs; however, the number of steps involved may increase the construction period increasing user costs borne by the motoring public. It may be possible to minimize the number of layers without compromising the performance of the pavement by either thickening or using innovative high-strength materials. This may increase the construction cost, but, considering the user costs, it may in the best interest of TxDOT to follow this option. In this report, the feasibility of this aspect of expediting highways has been explored.

The research unfolded under the umbrella of expert system technology with the intent to capture and preserve any piece of expertise towards expediting highway construction. The search for expertise entailed exhaustive literature searches, and distribution of questionnaires and survey forms among various forums of practitioners. The low level of response and the information provided were not adequate for developing an expert system.

Another survey targeted on the collection of current rigid pavement practices in several TxDOT districts. A sensitivity study of design parameters was performed on a few sections. The rigid pavement design based on AASHTO 1993 is not sensitive to the modulus of subgrade reaction. Therefore, any number of pavement sections with the same slab thickness will provide sufficient capacity to carry the design traffic. Attempts to understand the rational behind the current selection process for the number and nature of supporting layers led to local experience and federal regulatory mandates. No design-related technical patterns could be found in the local choices of layering.

The problem therefore reduces to minimizing construction schedules. A number of simplified construction schedules for traditional design sections were analyzed to identify bottlenecks. Alternate pavement sections were proposed and the critical paths for the hypothetical construction schedules were investigated. The alternate sections show noticeable improvements in time reduction with higher construction costs as tradeoff. However, these sections may not comply with federal regulations.

The user cost reductions for each of the candidate proposed alternate pavement sections will have to be evaluated and checked if the reduction in user costs offsets the additional construction costs associated with these proposed pavement cross sections. Another concern in moving to alternate cross sections was to reduce the variability of construction schedules due to weather conditions. Accordingly, the proposed cross sections were selected to decrease the sensitivity of construction schedules to unexpected bad weather conditions during construction, reducing the variability of construction times.

However, the proposed cross sections need to be tested in real construction situations, through the implementation of pilot constructed sections, to evaluate the parameters related to duration, sensitivity to weather conditions during construction, and overall variability of the duration estimates for the different critical path activities. In addition, the proposed fast-track sections will have to be monitored for adequate performance under cycles of load and climatic conditions.

Implementation Statement

This project is tailored towards developing procedures that are important missing links towards optimizing the duration of construction of PCC roads. Procedures and guidelines for optimizing the duration of the construction of PCC roads were theoretically evaluated from the standpoint of structural feasibility and cost effectiveness. Agency and user costs will be considered later. These procedures lead to a catalog of proposed cross-sections that are feasible for the different TxDOT districts. However, these cross-sections need to be evaluated from the standpoint of pavement performance, constructability and the compression of construction schedules and consequent reduction of user costs through the implementation of pilot test-sections where these parameters would be carefully monitored.

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Chapter 1 Introduction

Several TxDOT districts throughout the state rely almost solely on Portland Cement Concrete Pavements (PCCP), especially Continuously Reinforced Concrete Pavements (CRCP), for heavily traveled metropolitan highways and the urban and suburban sections of the interstate system. The goal of most urban projects is to provide smooth and maintenance-free roads to the public with a minimal closure time. Timely opening of the roads to traffic during construction and lane additions is also extremely important.

Due to heavy forecasted design traffic, several layers of high-quality or heavily stabilized materials are normally placed during construction. For TxDOT, this consists of one or more layers of stabilized subgrade and base, a layer of ACP to act as a bond breaker, and a PCC slab. The large number of layers may be cost-effective from the standpoint of initial costs; however, the number of steps involved may increase the construction period increasing user costs borne by the motoring public, and also in some instances increasing the sensitivity of construction schedules to weather conditions adding to their overall variability. It may be possible to minimize the number of layers without compromising the performance of the pavement by either using innovative high-strength materials. This may increase the construction cost, but, considering the user cost savings, it may in the best interest of an agency such as TxDOT to follow this option.

The process of selecting the most cost-effective and appropriate PCC pavement design for a roadway project in a metropolitan or an urban area, consists of streamlining the construction processes and minimizing traffic disruptions as best possible. This engineering decision-making process strongly relies on budget availability and the expertise of the pavement engineer. In this research project, the feasibility of a computerized methodology was investigated to mainstream the construction of highways in urban settings, as well as in rural areas. We have focused on gathering current rigid pavement construction practices in Texas, as well as expertise from TxDOT personnel and other parties heavily involved in the construction industry.

The advantages of having such expertise stored and organized in a computer program include the portability, readiness, and inexpensive access to specialized knowledge in real-world scenarios, where sound decisions are required.

Unfortunately, as documented in the discussions and recommendations included in Chapter 3, the task of producing a computerized expert system environment to support decisions related to expediting of PCC pavements did not prove to be feasible. An alternative approach is then suggested.

Organization

Chapter 2 contains general background information on rigid pavement design and construction, a brief review of expert system technology and relevant applications to the field.

Chapter 3 describes the process of colleting and analyzing documented and undocumented information, for the integration of an expert system to expedite construction. Surveys were conducted among different forums, including several TxDOT Districts. Preliminary conclusions are discussed.

Chapter 4 discusses the different approaches addressed to streamline the construction process. Design models, construction parameters, and user-cost models were investigated. A sensitivity study was performed on the AASHTO model design parameters. Simplified construction schedules and cost estimates for traditional and alternative pavement sections were prepared to compare and identify critical paths and bottlenecks in each construction process. A catalog of theoretically feasible fast-track cross-sections is proposed and summarized in this chapter.

The research activities and relevant conclusions are summarized in Chapter 5. A series of suggestions are listed as well as recommendations for future research.

Ten appendices contain a literature review summary and references, survey forms, survey response summaries, current rigid pavement design guidelines followed by TxDOT, and construction schedules and costs estimates for traditional and alternative pavement sections.

Chapter 2 Background

The process of selecting the most cost-effective and appropriate PCC pavement design for a roadway project in a metropolitan or an urban area, which will streamline the construction processes and minimize traffic disruptions as best possible, is an engineering decision-making process that strongly relies on budget availability and the expertise of the pavement engineer.

Currently, TxDOT personnel do not typically follow a structured procedure to select an appropriate pavement section for a given project. A recent study by Beg *et al.* (1999) discuss a series of parameters that a pavement engineer should account for when selecting a pavement section. The study summarizes the results from a survey performed in Texas, nationwide and in some Canadian provinces. The factors that affect the selection process range from soil characteristics, pavement types, pavement performance factors, the lowest life cycle cost, as well as a series of subjective factors. Among the subjective factors are historical construction practices, highway classification, traffic volume, material availability, weather, drainage and user costs.

The American Association of State Highway and Transportation Officials (AASHTO) provide guidelines for pavement type selection. AASHTO (1993) suggest the use of engineering procedures and economic analyses as the primary items. They also caution that the structural designs and economic analyses alone are not enough to select a pavement section. More factors should be taken into consideration in the decision-making process. As the process becomes more complex, the engineering experience and judgment of pavement managers and designers become more necessary and crucial in the selection process of optimized pavement cross-sections.

Traditional pavement construction methods are cumbersome and require several layers of different materials to achieve a structurally sound pavement section. Constructing several different layers sequentially increases the time required to open the roadway/intersection to public. Several groups have been working towards streamlining the construction or rehabilitation processes to expedite the opening of road sections and urban intersections to traffic in new construction, expansion and rehabilitation or replacement situations. A number of papers and reports (e.g. Cole and Voight, 1996; and Secmen *et al.*, 1996) have shared their experiences with materials and construction or providing guidelines to facilitate the overall planning and execution to expedite the construction process. For additional related literature refer to Appendix A.

A reduction in the number of underlying layers or a reduction in their thickness, as well as an increase in the concrete slab thickness, regardless of the associated cost, may well be considered as alternatives to streamline the construction process (see Figure 2.1).

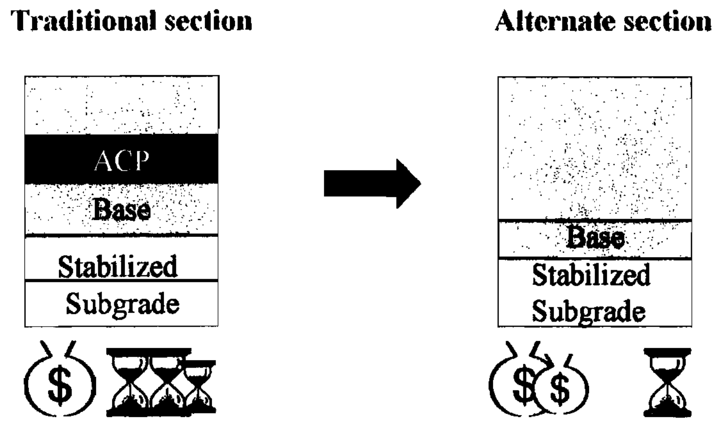

Figure 2.1 – Alternate Approach to Streamline Pavement Construction

The limited or uncertain information associated with the numerous factors to be considered may negatively impact the decisions made on a project, which can lead to an increase in the projected user costs in the form of travel delays, discomfort or accidents.

Each project has its own set of particular conditions and constraints. Therefore, each pavement engineer has to use his/her own judgment and expertise to select the most appropriate type of pavement. Different pavement engineers may disagree to some extent with other decision-makers on the importance that some of the factors may have on the final decision. This difference of opinions is reflected in the lack of consensus for pavement type selection and the lack of rational and objective procedures to perform this task.

Field data and engineering calculations can be stored in databases that can later be summarized and used to support decision making in regards to pavement selection procedures. Nevertheless, the procedure of storing and using expertise is not the same as the one employed in storing and using numerical data such as engineering data. There is no known method that allows storage of the expertise and experience available in the pavement engineering field other than the human brain processes. If the knowledge and expertise are lost, the process of re-acquiring the information could be considerably expensive and time consuming, and there is no guarantee that the same information will be reproduced. Consequently, there would not be consistency in the decision making process among experts to facilitate its reproduced.

The research team's objective is to integrate a methodology to streamline the construction of a rigid pavement into software that will aid in the rational decision-making process and somehow capture the expertise available in the pavement engineering field.

Expert System Technology

Expert systems (ES), a branch of artificial intelligence (AI), have been an alternative approach for the solution of engineering problems that require expertise. Artificial intelligence supports the decision-making process by simulating human reasoning, therefore, becoming very useful and cost effective. Expert systems are computer programs, which can manipulate knowledge as well as data. These systems can be used to represent human expertise (knowledge) in a particular domain (area of expertise) and then use a reasoning mechanism (applying logical deduction and induction processes) to manipulate this knowledge to provide advice in this domain. An expert system either supports or automates decision making in an area in which experts are needed. Expert systems are used to record and distribute scarce expert knowledge, to apply the expert knowledge to remote locations, to ensure the quality of problem solving, and to train experts in a specific field.

Conventional programs and databases can also contain knowledge in addition to quantitative data. Their main function is to retrieve information, conduct statistical analysis, and perform numerical calculations, through algorithms. They do not, however, reason with this knowledge and make inferences as to what actions to take or conclusions to reach. Therefore, what mainly distinguishes 'expert systems' from 'conventional systems' is the capability to reason with knowledge, and explain the reason for its recommendation or conclusion, in a way that an expert would do.

A typical expert system architecture is depicted in Figure 2.2. An expert system is composed of two major components: the development environment and the consultation environment.

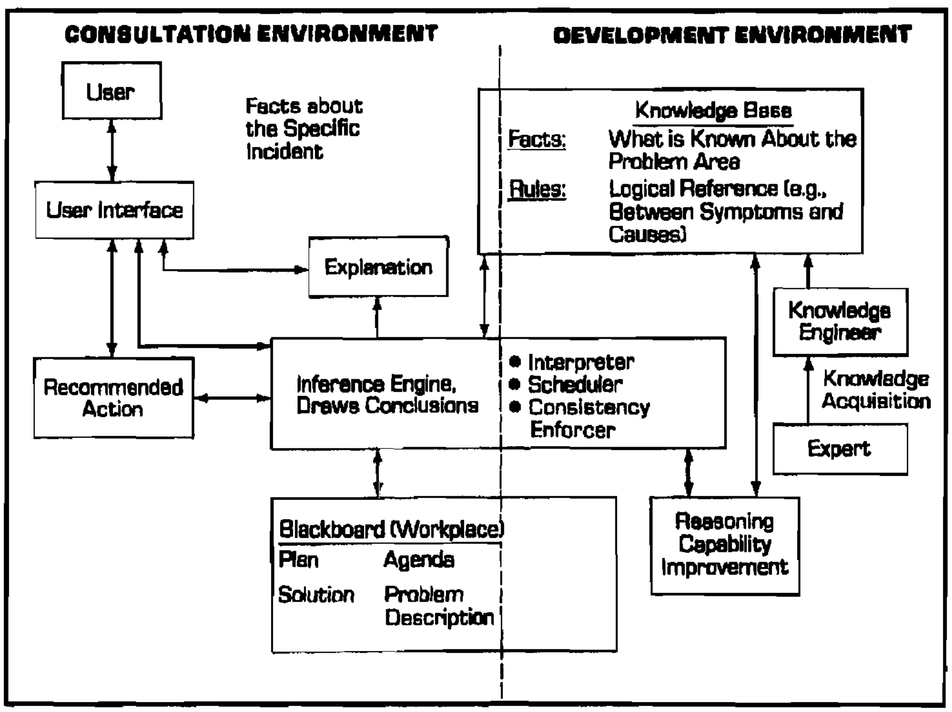

Figure 2.2 – Typical Expert System Architecture (Turban, 1990)

The "development environment" includes the following relevant components:

a. **Knowledge base**: which contains the *facts* and heuristics associated with a specific domain. The facts are represented as declarative knowledge, and the heuristics or "rules of thumb" are commonly represented as *rules*.
b. **Inference engine**: interprets the knowledge base, applies the knowledge (in the knowledge base) to the solution of the actual problems, and controls the direction in which the line of reasoning is performed (backward chaining, forward chaining, etc).

The "consultation environment" contains:

a. **User interface**: which is a highly interactive and user-friendly component that allows access to the expert system, hiding much of the system's complexity. The computer keyboard and monitor screen are two of its sub-components.
b. **Explanation subsystem**: this facility varies from tracing the path of execution to explaining the line of reasoning to the user. Justification for the system's conclusions (how queries), and explanations of required data (why queries) are typical tasks performed with this component.

These components are usually accessed through a knowledge base editor, which helps the programmer locate bugs in the program's performance, maintaining correct rule syntax, and checking consistency on an updated knowledge base, as well as assisting in the addition of new knowledge. Variations of the basic architecture have been developed, such as production system models or blackboard models and more are expected to be developed in the future.

During the development of an expert system, the expert(s) or the knowledge engineer introduces the expert knowledge into the knowledge base. During a consultation, the user obtains expert knowledge and advice, by accessing the knowledge base through the system's user interface via the inference engine.

Expert System Development Process

The development of an expert system entails the following steps (Turban, 1990):

1. Problem Identification and Justification
2. Appropriateness, Requirement Fulfillment and Availability of Knowledge & Experts
3. Conceptual Design, Planning and Feasibility Study
4. Software and Hardware Selection
5. Knowledge Acquisition (System Design and Construction)
6. Knowledge Representation
7. Testing (Case Study Identification, Field Testing)
8. Implementation
9. Maintenance and Update
10. Evaluation

Steps 5 through 7 loop in a cycle called "Prototyping". An important characteristic of the development of an expert system is that they can be quickly prototyped and expanded. All the steps are standard, regardless of the nature of the system built; nevertheless, the content on each step varies accordingly to it.

Knowledge Acquisition (KA)

The process of acquiring knowledge, representing it or codifying it, and explaining why a specific piece of information is needed or how a conclusion is derived, is known as knowledge engineering. The process of extracting, structuring and organizing knowledge from one or more sources of expertise, is also known as knowledge acquisition (KA). During the KA process, the problem and its major characteristics are identified, concepts, goals and relationships are determined, forms of representation are established, and the programming of the knowledge into the knowledge base.

The acquisition of knowledge requires:

a. One or more sources of knowledge domain,
b. One or more experts and/or knowledge engineers, who are knowledgeable in:
    i) Choosing an appropriate representation and inference strategy;
    ii) Guiding the development of the relevant knowledge base; and,
    iii) Implementing the knowledge base in the selected framework.

Table 2.1 summarizes the main categories under which sources of knowledge are grouped into, along with the most common methods of eliciting the knowledge.

Table 2.1 Sources of Knowledge and Methods of Elicitation (Turban, 1990)

Sources of Knowledge		Methods of Elicitation
Documented	Books	Manually Searching through manuals Using AI Retrieve electronically
	Films	
	Computer Files	
	Pictures	
	Stories	
Undocumented	People's minds	Questionnaires Interview Analysis Observation

Occasionally, multiple sources of knowledge or multiple experts are available for elicitation. This situation could be advantageous if the strengths of different approaches of reasoning can be combined or to widen the coverage of proposed solution(s). However, the possibility exists that knowledge may be incomplete in a certain aspect of the problem, or that it may originate from different backgrounds and experiences. These problems can be addressed temporarily by reaching a consensus.

Knowledge Representation

Knowledge can be represented in various forms such as logic, frames, objects, rules, and others. Each has its own advantages and disadvantages. An efficient way to solve problems is to decompose the problem into simpler sub-problems, which are further decomposed into even simpler sub-problems. The production system approach, consists in writing *production rules* of the basic form:

IF X
THEN H with C

Where IF and THEN are the *condition* and *conclusion* clauses, respectively, and (C) is a certainty measure of exactness of the knowledge. This form provides a convenient way of expressing knowledge for the inference process, in which the order of execution of the set of rules depends on the problem solving strategy utilized.

A rule-based system is most appropriate for large domains, where the problems are not well defined and no clear algorithmic solution strategies exist. This often happens when the number of independent paths to find a solution is very large, making it necessary to use "*rules of thumb*" or *heuristics* to prune the search space, so that only a limited number of promising paths are actually investigated. These heuristics represent several; year of problem solving experience and are the results of "short-cut" strategies that the expert has compiled throughout extensive experience.

Implementation strategies

There are two approaches to problem solving used in expert systems: the derivation approach and the formation approach. The derivation approach involves deriving a solution that is most appropriate for the problem at hand from a list of predefined solutions stored in the knowledge base of the expert system. The formation approach involves forming a solution from the eligible solution components stored in the knowledge base. This approach is typically implemented using a lower level; language such as Lisp (Kostem and Maher, 1987). Depending on the complexity of the problem being solved, an expert system may use one or both of these approaches.

The following strategies are appropriate for the implementation of the derivation approach: backward chaining, forward chaining and mixed initiative. These strategies require that the *goal states* represent the potential solutions and the *initial state* represent the input data.

Backward Chaining: Backward chaining is a term used to describe running the rules in a "goal-driven" way. In backward chaining, if a piece of information is needed, the program will automatically check all of the rules to see if there is a rule that could provide the needed information. The program will then "chain" to this new rule before completing the first rule.

This process is recursive, and the new rule may require information that can be found in yet another rule, which will be added to the "chain", and so on. As it receives the required information, the chain "unwinds" back to the original rule.

Example:

Rule 1: Conclude C
IF A can be established
and B can be established
Rule 2: Conclude D
IF C can be established

Begin with the goal to reach (D), use rule 2 to set sub-goal (C), use rule 1 to set sub-goals (A) and (B). Attempt to achieve a desired goal.

Forward Chaining: A "data driven" way to run the rules. In pure forward chaining, rules are simply tested in the order they occur based on available data. If information is needed, other rules are not invoked - instead, the user is asked for the information. Consequently, forward chaining systems are dependent on rule order. This strategy is useful in situations where there are large number of hypotheses and few input data.

Example:

Rule 1: IF A can be established
and B can be established
Then C can be concluded
Rule 2: IF C can be established
Then D can be concluded

Begin with the observed facts A and B, use rule 1 to conclude C, use rule 2 to conclude D. Respond to the current situation.

Mixed Initiative: A combination of forward chaining and backward chaining strategies.

Case Testing

During the prototyping phase of the development of an expert system, the knowledge engineer tests the system by subjecting it to examples, which could be historical cases or sample cases provided by users). The results are shown to the expert(s) and the rules are revised if necessary (e.g. reformulated, redesigned or refined). Periodically, rules may also be deleted or added.

This quality control process measures the expert system with three different tests:

- **Evaluation** : Assess its overall value (e.g. if it's usable, efficient, cost effective).
- **Validation** : Asses if it performs with acceptable level of accuracy (e.g. if it's the "right" system).
- **Verification** : Asses if it correctly implements its specs (e.g. if it's the system is "right").

Expert System Tools

A wide variety of development tools and environments are available in the market. These can be classified in three major groups:

1. **Specific Expert Systems**: These are final products that advise a specific user on a specific issue. These systems are available for sale "off the shelf" in computer stores. Specific expert systems are built with the other two categories of software: shells and tools.
2. **Shells or Skeletal Systems**: Rather than building an expert system from scratch, it is often possible to previously built specific expert system that are stripped from their knowledge component, leaving only, the shell, the explanation and inference components. This provides enough flexibility to develop almost any type of expert system application.
3. **Tools:** These provide skilled programmers with a rapid prototyping environment in which they can build shells. Tools differ from shells in their degree of focus. Tools are more flexible, but less focused, while shells address a narrower application area, but provide a more focused approach.

Most shells are classified as *rule-based*, since the knowledge can be represented explicitly as *rules*. Other systems are classified as *hybrid* since they support different ways of representing and handling inferences, such as frames, object oriented programming and more.

Expert System Development Requirements, Benefits and Limitations

The solution of a problem may be suitable for expert system development if some or all of the following requirements are met (Turban, 1990):

1. the task should not require common-sense knowledge;
2. the task requires only cognitive, not physical, skills;
3. at least one genuine expert, who is willing to cooperate, exists;
4. the experts involved can articulate their methods of problem solving;
5. the experts involved must agree on the knowledge and the solution approach to the problem;
6. the task is not too easy nor too difficult for human experts;
7. the task is well understood, and is defined clearly;
8. the task definition is fairly stable;
9. conventional (algorithmic) computer solution techniques are not satisfactory;
10. the domain must be well bounded and narrow;
11. data and test cases are available;
12. the vocabulary has no more than a couple of hundred concepts;
13. the expertise is needed in many locations;
14. the system can be used for training;
15. the expertise improves performance and/or quality;
16. the ES solution can be derived faster than that which a human can provide;
17. the expert system is more consistent than a human is.

An expert system can provide major benefits to users, such as (Turban, 1990):

- capturing scarce expertise and have it readily available;
- solving complex problems in a narrow domain with better consistency than humans;
- enhancing performance of problem solving and respond much faster than humans;
- learning by adding more rules as knowledge becomes available;
- transferring the knowledge to remote locations and developing countries;
- training novice users.

However, some factors may slow down its development such as (Turban, 1990):

- Knowledge is not always available;
- Experts are not always willing;
- Expertise is hard to extract from humans;
- The vocabulary that experts use for expressing facts and relations is frequently limited and not understood by others;
- Expert systems may not arrive at conclusions;
- Expert systems do make mistakes.

Expert System Applications

Expert systems can be classified using the general problem areas they address (Turban, 1990). These include:

a) *Interpretation systems*: explain observed data by assigning them symbolic meanings describing the situation. This category includes surveillance, image analysis, signal interpretation, and many kinds of intelligence analysis.
b) *Prediction systems*: infer likely consequences of given situations; include weather forecasting, demographic predictions, economic or financial forecasting.
c) *Diagnostic systems*: include medical, electronic, mechanical and software diagnosis. Diagnosis systems typically relate observed irregularities to underlying causes.
d) *Design systems*: configure objects under constraints, such as circuit layout, building design, and plant layout.
e) *Planning systems*: develop plans to achieve goals in areas such as project management, routing, communications, product development, etc.
f) *Monitoring systems*: compare observations to plan vulnerabilities, flagging exceptions. Many computer-aided monitoring systems exist for topics ranging from air traffic to fiscal management tasks.
g) *Debugging systems*: prescribe remedies for malfunctions.
h) *Repair systems*: execute a plan to administer a prescribed remedy.
i) *Instruction systems*: diagnose, debugs and corrects student performance.
j) *Control systems*: they interpret, predict, repair, and monitor system behaviors.

Expert systems are "just right" for tasks where expertise is expensive but available, and facts are known but not precisely. However, they may be too difficult to develop when expertise is not available or nobody knows enough to be an expert, or when innovation is required.

Survey of Expert Systems in Civil Engineering

A comprehensive literature survey was performed to identify the most relevant publications on expert system applications in Civil Engineering in the past fifteen years. Thirty-five papers were identified and classified according to the type of application.

A summary of the most relevant content information is presented in tabular format. Table 2.2 covers more than twenty applications to *pavements*. Table 2.3 addresses a variety of applications in *Civil Engineering* in general. The information in both tables is organized in five columns:

1. authors and year of publication;
2. publication title;
3. topic addressed;
4. expert system shell used (if available), and
5. a free-format column that addressees additional information (if available), such as:
   - sources of expertise,
   - methods of knowledge elicitation,
   - selected format for knowledge representation, number of rules, selected strategy, results, and
   - any other relevant issues (e.g. database or external program links, etc.).

After analyzing the contents of the papers, it can be observed that the most means of extracting knowledge was based on expert interviews and analysis of documented information and case studies. Visual inspections, experiments, and tests were used in some cases. The majority of the projects represented the knowledge in the form of IF-THEN rule statements. A few papers report interfacing with customized applications developed in other developing environments such as Visual Basic, C, Dbase, ArcView and Prolog.

The most popular expert system developing tool is EXSYS, followed by a number of commercial shells such as VP-Expert, CLIPS, Nexpert Object, and Turbo Prolog to name a few.

The papers report expert systems in pavements that range from the advising the selection of pavement management strategies for maintenance and rehabilitation, diagnosis of surface condition, and design of highway pavements. Other topics include diagnosis of damage to structures, design of new construction, such as drilled shafts, or improvement of concrete durability, and selection of earth-moving equipment.

The literature survey did not show any published documents addressing an expert system for the selection of PCC pavement designs for expedited construction. One paper by Hozayen and Haas (1992) provides some useful insight in developing an expert system for expedited construction. This paper addresses the selection of pavement materials for proper mix design, clearly and thoroughly defining the various steps and phases in the development of the expert system.

The following chapter describes the different steps taken towards the development of the proposed expert system, as well as partial results and conclusions derived from the research up to the date of this report.

Table 2.2 Relevant Expert System Applications in Pavements

Author(s) (Year)	Publication Title	Topic Addressed	Expert System Shell	Comments
Abdelrahim & George (2000)	Artificial Neural Network for Enhancing Selection of Pavement Maintenance Strategy	Select an economical treatment for rehabilitation of a deteriorated pavement section.	N/A	
Khedr & Mikhail (1999)	Design of Flexible Pavements and Overlay Using an Expert System	Flexible pavement and overlay design, knowledge included: properties of pavement materials, pavement structures, and tolerable pavement behavior as it related to its structural performance and rutting prediction and fatigue performance programs.	EXSYS	Forward chaining inference. If-then rules used. Traffic loading analysis module addressed.
Flintsch, Zaniewski & Medina (1998)	Development of a knowledge-based formula to prioritize pavement rehabilitation projects	A formula to prioritize pavement rehabilitation projects based on experts' opinion is developed.	N/A	Knowledge acquired first from experiments, then from questionnaires sent to 20 experts from ADOT.
Harter (1998)	An Integrated Geographic Information System Solution for Estimating Transportation Infrastructure Needs: A Florida Example	Transportation Planning and Analysis Software (TPAS) integrates an Arc View GIS application with a knowledge-based expert system.	N/A	ArcView and Visual Basic were selected as the TIS interface.
Darter, Jiang, Owusu Antwi & Von Quintus (1997)	Systems for Design of Highway Pavements: Final Report (NCHRP Project 1-32)	Designer Knowledge-Based Expert System (KBES) for Highway Pavement Design developed for selecting recommended pavement design features.	N/A	
Giannattasio, Crispino, Nicolosi, Ambrosino & Boero (1995)	Expert System as support in maintenance of road pavement surface	Analysis of surface pavement degradation and its causes, selection of the best interventions considering eventual constraints.	(1) Shells of the classes of Nexpert Object; (2) Toolkits of the classes of CLIPS.	Must have a diagnostic section where the pavement inventory data, and surface condition data are analyzed.

Table 2.2 Relevant Expert System Applications in Pavements ...Continued

Author(s) (Year)	Publication Title	Topic Addressed	Expert System Shell	Comments
Prechaverakul & Hadipriono (1995)	Using a Knowledge-Based Expert System and Fuzzy Logic for Minor Rehabilitation Projects in Ohio	A preliminary selection in which a set of alternative treatments is chosen based on pavement distress conditions and other related factors. An ordinal multi-objective decision-making model using fuzzy logic is used to recommend the proper treatment.	Knowledge Pro Gold for Windows (KPWIN) 2.35	Microsoft Visual Basic 3.0 was used for the Input, Multi-objective Decision Making, and Output Modules. KPWIN was used for the Knowledge-base Module.
Sarasua & Jia (1995)	Framework for integrating GIS-T with KBES: a pavement management system example	The integration of a GIS with KBES. The KBES retrieves information from the GIS as needed to produce an outcome and the results can be passed back to the GIS for further analysis and display.	N/A	Use of ARC/INFO software with ARC macro language (AML) and C programming language.
Harriott (1994)	Concrete Research Overview	HWYCON an ES for concrete durability. Developed for making decisions related to the diagnosis, material selection, and repair or rehabilitation of concrete pavements and structures.	N/A	If-then rules used. A rapid test method for screening aggregates that cause D-cracking in concrete is included. Three sub-systems included: Diagnostics, Material Selection, Rehabilitation, and Repair.
Kampe, Khan & Ritchie (1994)	Integrated System to Develop Highway Rehabilitation	An integrated database management expert system to enhance safety in highway rehabilitation projects for PCC Pavement (4RSCOPE), allows gathering of data for a project, assists and documents the process of designing.	EXSYS Professional	Intense interviews conducted. If-then rules used.

Table 2.2 Relevant Expert System Applications in Pavements ...Continued

Author(s) (Year)	Publication Title	Topic Addressed	Expert System Shell	Comments
Wang, Zaniewski, & Delton (1994)	Design of Project Selection Procedure Based on ES and Network Optimization	An assistant for rehabilitation project selection and pavement network optimization, and the results are used in preparing budget proposals.	EXSYS	Data-driven, forward-chaining process. C-language.
Hanna, Hanna & Papagiannakis (1993)	Knowledge-based Advisory System for Flexible Pavement Routine Maintenance	A pavement maintenance advisory system (PMAS) assists in planning effective flexible or asphalt concrete pavement maintenance strategies.	(1) Exsys Professional runs on IBM. (2) Instant Expert Plus runs on Macintosh.	If-then rules used. Three sources of knowledge are used: formal documents, documented case studies, and expert interviews.
Ritchie, Prosser and Lamar (1993)	Combining Symbolic and Algorithmic Methods for Capital Budgeting in Highway Rehabilitation	Pavement Rehabilitation Analysis and Design Mentor (PARADIGM) is a prototype, microcomputer-based, and integrated set of interaction expert systems and algorithmic models. Its results can be used to select the optimal set of rehabilitation and maintenance strategies over a network of segments when next year's construction budget is constrained.	N/A	
Attoh-Okine (1992)	Prototype rule-based system for diagnosis of surface depression in flexible pavement during construction	Diagnosis of surface depression during flexible pavement construction.	VP-Expert	Rule-based. Approaching the knowledge acquisition using problem-task-acquisition mapping. Previous studies collected.

Table 2.2 Relevant Expert System Applications in Pavements ...Continued

Author(s) (Year)	Publication Title	Topic Addressed	Expert System Shell	Comments
Darter, Johnson & Rmeili (1992)	Pavement Evaluation and Development of Maintenance and Rehabilitation Strategies for Illinois Toll way East-West Extension	Field evaluation and development of maintenance and rehabilitation strategies (EXPEAR)	N/A	Developed by Univ. of Illinois. Visual condition survey. Nondestructive deflection testing using FWD, petrography analysis of PCC. Maintenance and rehabilitation strategies for 2-20 year life expectancies.
Denning (1992)	Expert System: Ready to hit the road ?	Pavement Rehabilitation	N/A	If-then rules used
Hozayen & Haas (1992)	Pavement Materials selection and Evaluation Utilizing Knowledge-Based Expert Systems Technology	A new and powerful tool for achieving mix design success. It can integrate various activities and interpret the results, such that the designed mix can meet the production, hauling, placing, and in-service environmental and loading requirements in an optimal way.	INSIGHT2, Version 1.0	DMMD (Diagnosis of Marshall Mix Design) has been tested, calibrated, and verified based on a continuous series of experts' interviews. Contains 401 production rules. User interface contains 10 input and 45 output screens.
Kuprenas, Salazar & Posada (1992)	An ES for the Identification of Causes of Failure of Asphalt Concrete Pavement	PAVE, finds the most common causes of failures on asphalt concrete pavements.	VP Expert by WordTech Systems.	80 If-then rules used
Clifton & Kaetzel (1991)	Expert/Knowledge-based Systems for Cement and Concrete: State-of-the-Art Report	Concrete pavement activities suitable for expert systems Expert System development methods and tools Existing Expert/Knowledge base system applications	Different shells mentioned: ART, KEE, SAVOIR and EXSYS	Several existing expert systems were compared, including: Concrete design applications, Diagnostics, Repair and rehabilitation applications. A brief summary of each expert system was presented. The summary includes: ES name, KB shell used, and methodology.

Table 2.2 Relevant Expert System Applications in Pavements ...Continued

Author(s) (Year)	Publication Title	Topic Addressed	Expert System Shell	Comments
Darter & Hall (1990)	Structural Overlay Strategies for Jointed Concrete Pavements—Volume VI Appendix A—Users Manual for the EXPEAR Computer Program	EXPEAR computerized system to assist in evaluating, rehabilitation alternatives, and cost-effectiveness of alternatives in asphalt pavements.	N/A	If-then rules used. Extensive interviewing of authorities on concrete pavement performance. Performs cost analysis of rehabilitation alternatives.
Williams, Parks & Limarzi (1990)	Expert System for Asphalt-Paving Construction Inspection	Provides advice to inexperienced inspectors concerning how to identify and correct deficiencies in the asphalt construction operation.	Rulemaster 2	8 NYSDOT paving experts provided the information. If-then rules used.
Aougab, Schwartz & Wentworth (1989)	Expert System for Pavement Maintenance Management	PAMEX evaluates pavement performance, identifying pavement problems, and their probable causes, and recommends appropriate corrective measures.	EXSYS Professional	LISP and PROLOG used. An extensive validation program was conducted, involving workshops and follow-up efforts with experts and end users.
Ritchie, Yeh, Mahoney & Jackson (1987)	Surface Condition Expert System for Pavement Rehabilitation Panning	SCEPTRE assists engineers in planning cost-effective flexible pavement rehabilitation strategies at the project level.	EXSYS Professional	If-then rules used.
Ritchie (1986)	Expert Systems In Pavement Management	PAVEADIGM for project-level analysis and design of pavement rehabilitation strategies.	N/A	If-then rules used.

Table 2.3 Relevant Expert System Applications in Civil Engineering

Author(s) (Year)	Publication Title	Topic Addressed	Expert System Shell	Comments
Hanna, Schmitt, & Stetzer (1997)	The use of Tabular Knowledge Base in Construction Decision-Making	Use of a tabular knowledge base format as an efficient tool in the decision-making process.	EXSYS Professional and Instant Expert Plus	If-then rules used. Knowledge sources include personal interviews, lessons-learned files, trade statistics, equipment ratings and specifications, and index surveys.
Brockus & Hunter (1996)	Chip-seal Design using an Expert System	Check chip-seal sign and construction limited life expectancy and to aid engineers in designing these surfaces.	HI-SCREEN XL design system	Four site tests performed. Use of C programming language
Better Roads (a) (1996)	How you can improve concrete durability	A workshop focused on five topics: permeability, freeze-thaw resistance, quality control, non-destructive testing, and expert systems. (HWYCON)	N/A	Knowledge base contains information about materials for concrete bridge decks, sub-structures, and pavements. Information collected by visual inspections and tests.
Liberatore & Stylianou (1995)	Expert Support Systems for New Product Development Decision Making: A Modeling Framework and Applications	A modeling framework that merges knowledge-based expert systems and decision support systems with management science methods for project evaluation.	N/A	Extensive interviews and questionnaires. ES accessed a database file in DBASE III+ format.
Melchor & Ferregut (1995)	Toward an Expert System for damage assessment of structural concrete elements	DASE assists an engineer engaged in the task of assessing post earthquake damage to structural concrete elements.	EXSYS Professional, Version 2.0	Expected behavior of the building and failure mode determination of the element. Retrofit actions for damaged elements. Floor damage classification and restoration 176 If-then rules used. Use of the Analytical Hierarchy Process (AHP)

Table 2.3 Relevant Expert System Applications in Civil Engineering ...Continued

Author(s) (Year)	Publication Title	Topic Addressed	Expert System Shell	Comments
Gemoets & Melchor (1993)	Expert System prototype for property valuation in Mexico	Prototype expert system to assist the civil engineer responsible for property appraisal	VP- Expert 2.0	KA through documented manuals and one interview w/one expert
Abaya, O'Neill & Fisher (1992)	Expert System for drilled shaft construction	Sorts through relevant data and proposes what methods of construction for drilled shafts can best be implemented.	Exsys	If-then rules used. Results include recommendations, details and specific suggestions, as well as preliminary cost estimate for the operation.
Amirkhanian, & Baker (1992)	Expert System for Equipment Selection for earth-moving operations	A rule-based expert system for selecting earth-moving operations.	VP-Expert	If-then rules used
May, Alwani & Tizani (1991)	The development of an intelligent knowledge based system for the diagnosis of causes of cracking in buildings.	Intelligent knowledge based system for the diagnosis of causes of cracking in buildings.	N/A	PROLOG language used.
Yeh, Hsu, & Kuo (1991)	ES for Diagnosing Damage of prestressed Concrete Pile.	An ES—PCPILE for diagnosing the damage of PCP during the construction process.	Turbo Prolog Version 1.5	If-then rules used
Fenves (1986)	What is an Expert System ?	Addressees the clarification of the definition, role and impact of knowledge-based ES in Civil Engineering.	N/A	

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Chapter 3 Collection of Information and Analysis

The chapter describes the steps taken towards the integration of a software program for the optimization and acceleration of typical pavement construction in urban settings, following the steps listed in the previous chapter for the development of an expert system. Several charts and tables illustrate the partial findings of the different phases under the integration. Intermediate conclusions are briefly addressed.

Problem Identification and Development Justification

TxDOT, in a response to the users of the roadway infrastructure, has requested that new pavement sections be developed for expedited construction in urban areas, using methods and materials that require less time between and during phases. A sequencing schedule for the new or improved pavement sections is required as well. The agency's goal is to open to traffic as soon as possible to reduce delays and user costs. This constitutes the *identification of the problem domain.*

The research team believe that *the development of an expert system is justified* since:

1. *Expertise is available*: A few Districts, namely Dallas, Houston and Beaumont, among other locations throughout the State, have experience in accelerating rigid pavement construction, especially at urban intersections;
2. *Expertise is necessary in many locations*: The rapidly growing urban areas throughout the State are also experiencing increasing levels of traffic. Therefore, maintenance and rehabilitation will be required at many intersections. Inter-district experience would grandfather the implementation of techniques to select pavement sections that will optimize and expedite their construction and reduce opening times to traffic;
3. *Expertise could improve quality and/or performance*: Given the complex subgrade conditions in Dallas, Houston and Beaumont districts, the development of an expedited standard design applicable to all conditions, would be an oversimplification;
4. *Expertise can be preserved and used for training*: The integration of current pavement design procedures, user cost estimation, and the expertise of the construction engineers, into a piece of software, could provide the framework under which realistic design and construction processes could be used for determining cross-sections for faster construction in urban areas, and possibly rural areas as well.

Appropriateness, Requirements and Availability of Knowledge Sources

To further narrow down the eligibility of developing an expert system, the research team considered such an expert system *appropriate* since:

1. The selection of an appropriate pavement section involves several factors that are assessed subjectively or are heuristically considered, such as traffic levels, preferred construction practices, and others such as travel delays and user discomfort that can be traduced into user costs. Common knowledge is insufficient to solve the problem;
2. There are only a few pavement engineers, in the State and nationwide, that have experience in the selection and construction of PCC pavements;
3. The knowledge and expertise are very specific and localized (only a few sites along the state have implemented expedited construction techniques). An average pavement engineer may have difficulty to solve the problem; however, the problem is not too difficult to solve;
4. Previous and ongoing projects may serve as case studies to develop and test the software.

The proposed expert system would have *benefited TxDOT* in several aspects, such as:

1. No existing uniform criterion is currently used to arrive at the selection of a pavement section that will be better suited for expedited construction. Currently, a major disadvantage is that the same pavement designs are repeatedly used without differentiating between urban and rural areas;
2. The expert system would allow the integration of opinions from several experts, enriching the quality of the advice;
3. A more rational, faster and consistent manner of selecting a PCC design for expedited construction at a project level, can be obtained by using a computerized approach, possibly reducing a significant amount of effort and costs, during the decision-making process and increasing the quality of the decisions;
4. A reliable source of specific pavement expertise would be available to all TxDOT districts and the expert system can be used for potential low cost training. The expert system may also be used by experts as knowledgeable assistants to enhance the process of selecting an appropriate pavement design;
5. The expert system will be easy to use, flexible and can be expanded at a low cost, as more or new knowledge becomes available;
6. Decisions have to be made under conditions where information could sometimes be uncertain or unavailable.

To *identify possible sources of expertise*, the research team undertook two tasks:

- First, a comprehensive search for *documented* knowledge was conducted, in addition to the preliminary literature survey made during the proposal preparation.
  More than forty papers and technical reports were identified and secured for further analysis. The paper topics range from PCC construction materials and materials selection, to selection, design, construction and performance of concrete overlays, to opening to traffic criteria, to expedited construction/reconstruction scheduling and sequencing. The contents are further discussed in the *knowledge engineering* section.

- Second, the research team engaged in the search for *undocumented knowledge*. A Texas Cement and Concrete Promotion Council (CCPC) Concrete Paving Conference held in

December 2000 was considered an excellent opportunity to determine the availability and extent of expertise. More than one hundred and twenty (120) researchers, DOT pavement engineers, contractors, and material suppliers from various States attended the conference. A preliminary survey was conducted among this forum, and is discussed in the *knowledge engineering* section.

The research team believed that the number of publications found, and the number of attendees to the conference, were sufficient evidence to support the fact that expertise was --possibly-- available. Under this assumption, the conceptual design of the expert system was devised. Such a system would recommend pre-design pavement sections, and provide a ranking based on construction time.

Conceptual Design and Feasibility Study

As previously mentioned, the selection of a pavement section is an engineering decision-making process that strongly relies on budget availability and the expertise of the pavement engineer.

During this process, several factors are accounted for such as: soil characteristics, pavement types, pavement performance factors, and lowest life cycle cost analysis. However, these factors alone are not enough to make a selection. Historical construction practices, highway classification, traffic volume, material availability, weather, user costs, as well as expertise, play a roll in the decision making process. These factors are depicted in Figure 3.1.

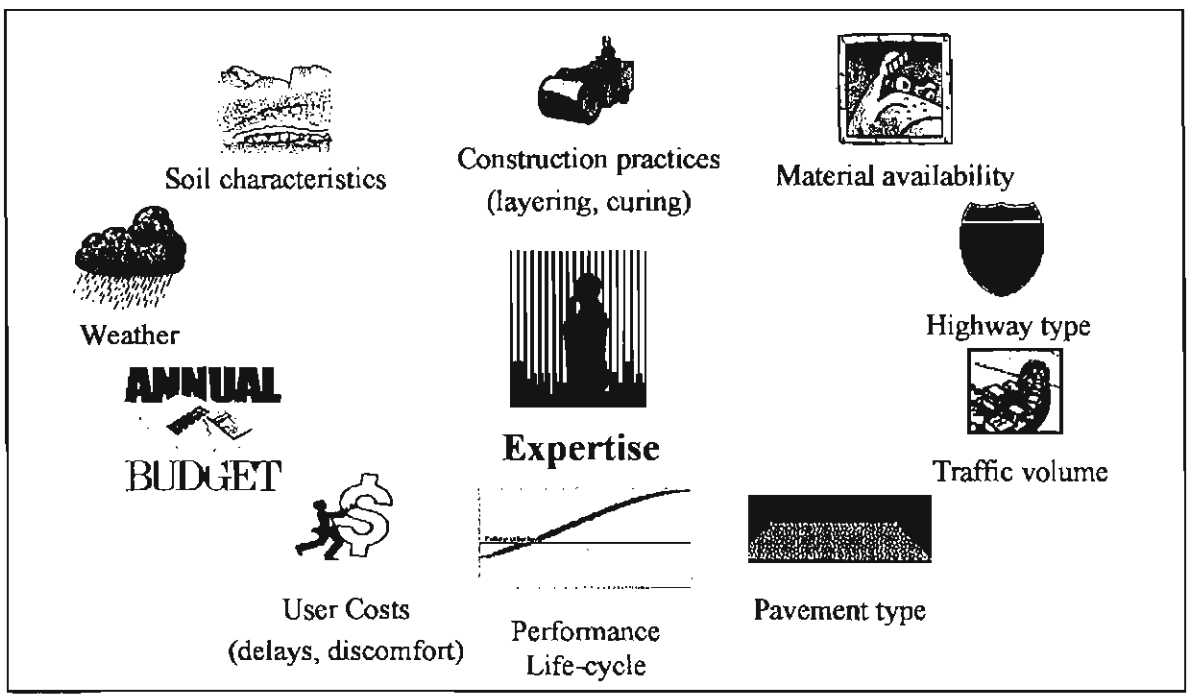


Figure 3.1 – Background Factors Impacting Pavement Section Selection

Figure 3.2 shows a diagram of the anticipated expert system's architecture, to provide a general idea of the flow of execution and its capabilities. The diagram is adapted from a report by Secmen *et al.* (1996).

The general flow of execution is from left to right.

- The *function* illustrated at the center cell, consists of designing a pavement section for expedited construction. The *inputs, constraints, mechanisms* and *outputs* that interface with the *function*, are cells connected through arrows that enter or leave the *function* cell.
- The *inputs* required to perform the *function* are presented on the left-hand side. These will consist of information such as: construction type, concrete mix characteristics, foundation properties, traffic loads, etc.
- The *constraints or controls* that govern the accomplishment of the *function* are depicted in the upper portion of the diagram. The restrictions under which a design will be determined will include: budget limits, appropriate testing equipment available, climate information, time constraints, federal regulations, etc.
- The *mechanisms* (people or tools) that perform the *function* are shown in the lower portion of the sketch. These include: construction equipment, preferred construction methods, soil stabilization practices, or software models that partially perform the design or produce input to complete the design (e.g. empirical-mechanistic or life-cycle cost models).
- The *outputs* (information produced by the function) will consist of two possible designs: a) alternative pavement sections that will expedite the construction, and b) pavement sections for the traditional approach. Each design would be ranked, using a confidence level computed by the expert system, based on degrees of certainty provided by the sources of expertise (e.g. the *experts*). Material and construction specifications, a cost range and a period, would be associated to each design, along with the geometry of the section.

The inputs to the system would be guided by a series of screens that prompt the user to select or enter the required information. The order in which these screens may appear, will depend on the implementation strategy selected for the system (backward chaining, forward chaining or both).

The research team considers that the economic feasibility of developing this expert system has already been supported by TxDOT, with the approval of this proposal. The technical feasibility is discussed in this report.

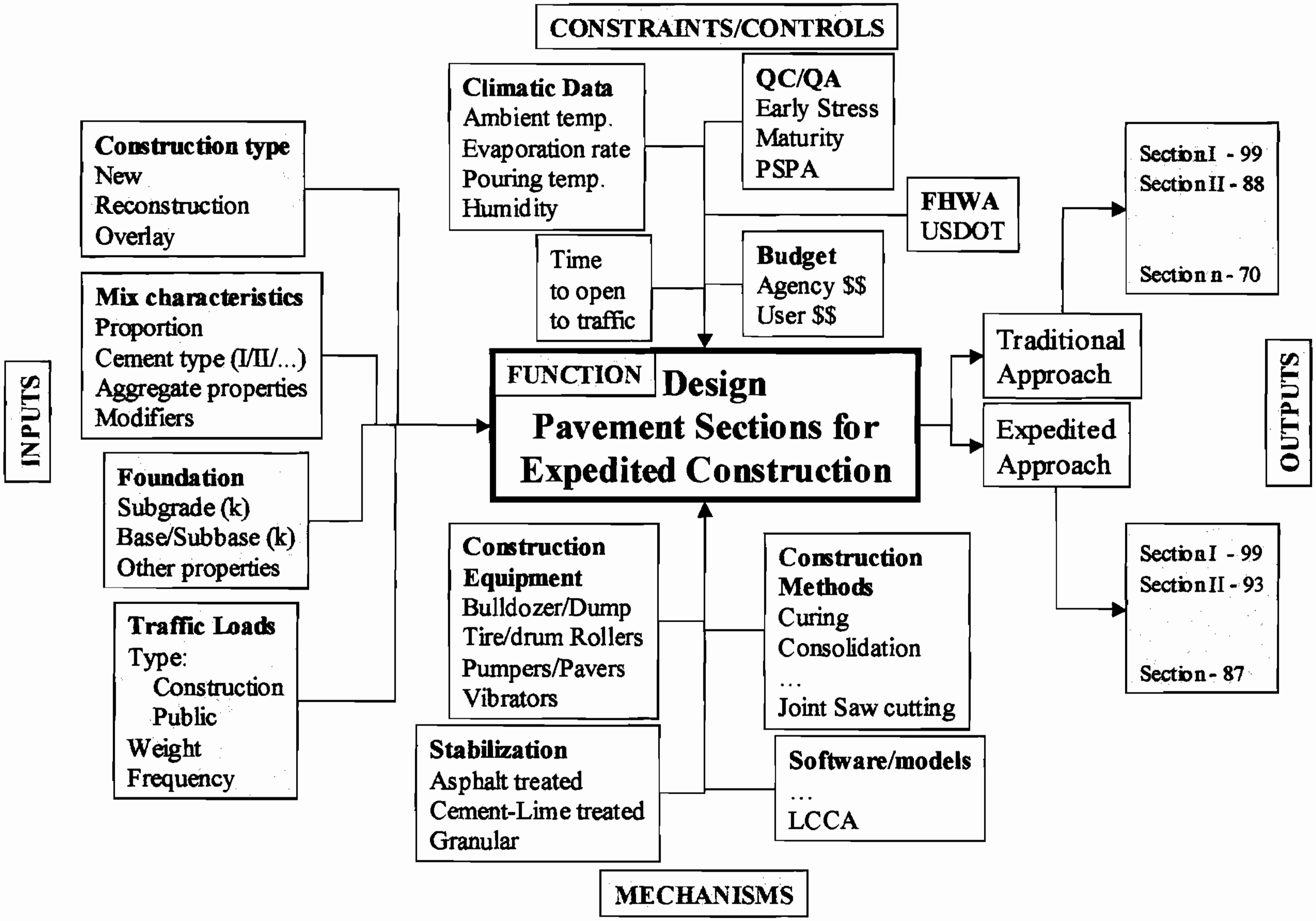


Figure 3.2 – Proposed Expert System Architecture Function-cell Model

Software Tool Selection

To support the construction of the expert system, a survey of expert system development environments was conducted. More than sixty (60) commercially available products were identified through the Internet, and various vendor catalogues. To narrow down the pool of candidates, a number of issues were addressed by the research team, under a selection framework proposed by Stylianou *et al.*, (1994). The issues are summarized in Table 3.1.

Table 3.1 Expert System Evaluation Model

BACKGROUND QUESTIONS	ANSWERS
User-Interface	
Who are targeted users of the expert system application?	TxDOT pavement managers
What range of education do of the users have?	Bachelor's in Civil Engineering
What is the computer sophistication of the users?	Basic/Entry level
Are the users expected to be familiar with the subject domain?	Yes, except for novice users
Will the users be predominantly occasional or systematic users?	Occasional
Will the users be expected to maintain their ES application?	No
Developer Interface	
Who are the developers/programmers?	Researcher 5 yr. experience, graduate student
What is the range of ES/AI experience of the developers?	0-3 yrs.
What is the size (estimated number of rules or frames) and complexity of the targeted problem domain?	Unknown, most likely less than 1000 IF-THEN rules
Does the knowledge contain complex mathematical relationships?	Possibly, a few pavement design models will need to be incorporated
System Interface	
What is the hardware platform(s) (development, fielding) for this application?	PC desktop
In what software environment(s) will this application be expected to operate?	Windows 95/98/2000/NT4
What is the required response time frame?	Less than 1 hr.
Interface Engine	
Is the application dealing with uncertain data/knowledge?	Most probably
Are there many different possible solutions?	Yes
Are there many different possible states?	Yes
Knowledge base	
Is this application's knowledge well documented?	Unknown
Does the knowledge have an inherent structure of its own?	Unknown, but highly desired and expected
Is complete knowledge of past decisions made by the expert available?	Unknown
Data Interface	
Will this application be required to interface with other software systems? What kind?	Most likely, LCCA models and pavement design models
Linkage to special purpose software	Most probably
Vendor	
Will this application be developed and supported in-house?	Yes (if necessary)

Four (4) final candidates were selected and further evaluated under various feature and capability criteria proposed by Stylianou *et al.*, (1994). Table 3.2 summarizes the evaluation.

Table 3.2 Commercial Expert System Shells: Selection Criteria

Criteria \ ES Shell	EXSYS Developer 8.0	Rete++ ECLIPSE	Flex + Intelligent Server toolkit	ACQUIRE + SDK
Vendor	EXSYS inc.	The Haley Enterprise	Logic Programming Assoc.	Acquired Intelligence Inc.
Vendor support	✔		✔	✔
Price $$/academic license + maintenance *	$ 3300 + $ 600	$ 2850	$ 900	$1800 + $ 300
User-Interface				
Explanation facility	✔		✔	✔
Documentation: Comprehensive/Readable	✔	✔		✔
Customizable features	Report	C++ , VB, Delphi	Through VB or Delphi	Report
Graphical format				
Developer Interface				
Documentation: Comprehensive/Readable	✔	✔		✔
Interface tracing	✔	✔		✔
Explanation facility	✔			✔
Ability to customize explanations	✔			
Graphical format	✔		✔	✔
Mathematical capabilities	✔	✔	✔	
Customizable features	✔	✔	Through VB or Delphi	✔ Data entry
Rapid prototyping	✔		✔	
Automatic Validation	✔	✔		✔
System Interface				
Application portability		✔		✔
Support for Microcomputers	✔	✔	✔	✔
Embedability		✔	VB, Delphi, Java	✔
Inference Engine				
Forward chaining	✔	Rete algorithm	✔	
Backward chaining	✔	Rete algorithm	✔	
Find all answers				
Certainty factors	✔			
Others	✔			✔

Continued on next page .

Table 3.2 Commercial Expert System Shells: Selection Criteria… Continued

Criteria \ ES Shell	EXSYS Developer 8.0	Rete++ ECLIPSE	Flex + Intelligent Server toolkit	ACQUIRE + SDK
Knowledge base				
Production rules	✔ English syntax	✔ Eclipse syntax	✔ English KSL	✔ Prolog
Partitioned (structured) rules sets	✔			
Data Interface				
Linkage to databases	✔	✔	✔	
Linkage to special purpose software	✔			
Other feature(s)				
What If analysis	✔			
Undo	✔			
Programming required		✔	✔ OOP w/Prolog	✔
General		Component based architecture; automatically generates C++ class taxonomies	Supports calls to DLLs and DDE	Structured approach to acquire knowledge; knowledge representation based on pattern recognition; pragmatic approach to development of KB; supports Active X and DLL function calls; multiple KB access simultaneously
Areas of application	Finance, management, manufacturing, engineering, R&D, troubleshooting, medical, marketing, legal, transportation	Management and automation of business knowledge	Advisory decision support systems; business modeling; diagnostic systems; scheduling and planning systems; legislative help systems.	Administration, operations and customer support

<u>Selected expert system shell : EXSYS Developer 8.0</u>

Knowledge Engineering

After having identified both sources of *documented* as well as *undocumented* knowledge, an exhaustive process of extracting, structuring and organizing the information initiated. The background factors shown in Figure 3.1, in conjunction with the proposed function-cell model depicted in Figure 3.2, provided the framework under which the acquisition was based on.

Documented sources

From the literature review, the most relevant publications for the last fifteen years were summarized in Appendix A. The majority of the papers focus on the material characterization and construction of the PCC layer. The topics range from experimental PCC materials and mixes, QC/QA testing methods (e.g. maturity), opening criteria, rehabilitation or overlay construction. Several publications contain useful information that support the proposed framework model. For example, Beg *et al.* (2000, 1999) address pavement type selection procedures; Anderson *et al.* (1998) thoroughly address various factors involved in the fast-track reconstruction of urban intersections, as well as recommendations to efficiently schedule the activities; Cole and Voigt (1996, 1995, 1995a, 1995b) address general modifications to traditional PCC construction, and Theyse (1999) addresses an alternative base material.

The documented information is "unstructured". Some papers provide "facts" only, while other papers provide measures taken or recommendations, without explaining the reasons or enumerating the prevailing conditions. With this missing link at hand, it is difficult to derive relationships between the facts and the actions taken towards the solution of the problems. Therefore, the development of rules to implement in an expert system seem to be not feasible from *documented* sources.

Undocumented sources

To elicit expertise from experienced professionals practicing PCC pavement design, construction, or research, a short questionnaire with multiple-choice as well as open-ended questions was developed. The questionnaire addressed factors to consider when using expedited construction, criteria used to determine the time to open the pavement to traffic, software used for mechanistic design or life-cycle cost analysis, among others. A sample of the four-page questionnaire is included in Appendix B.

Approximately, one hundred and fifty (150) questionnaires were distributed among various groups of "potential experts". The first set of questionnaires was distributed among the attendants to the Texas CCPC Concrete Paving Conference 2000. The second set was distributed to the TRB A2F01 Pavement Construction Committee, and the third set was forwarded to a group of attendees to a District Pavement Engineers Conference.

A total of twenty-two (22) responses were received. Most of the multiple-choice questions were answered, while very few open-ended questions were partially answered. Appendix C summarizes the responses.

Figure 3.3 shows a plot of number of responses to degree of importance of the listed factors, when considering expediting the construction of PCC pavement sections.

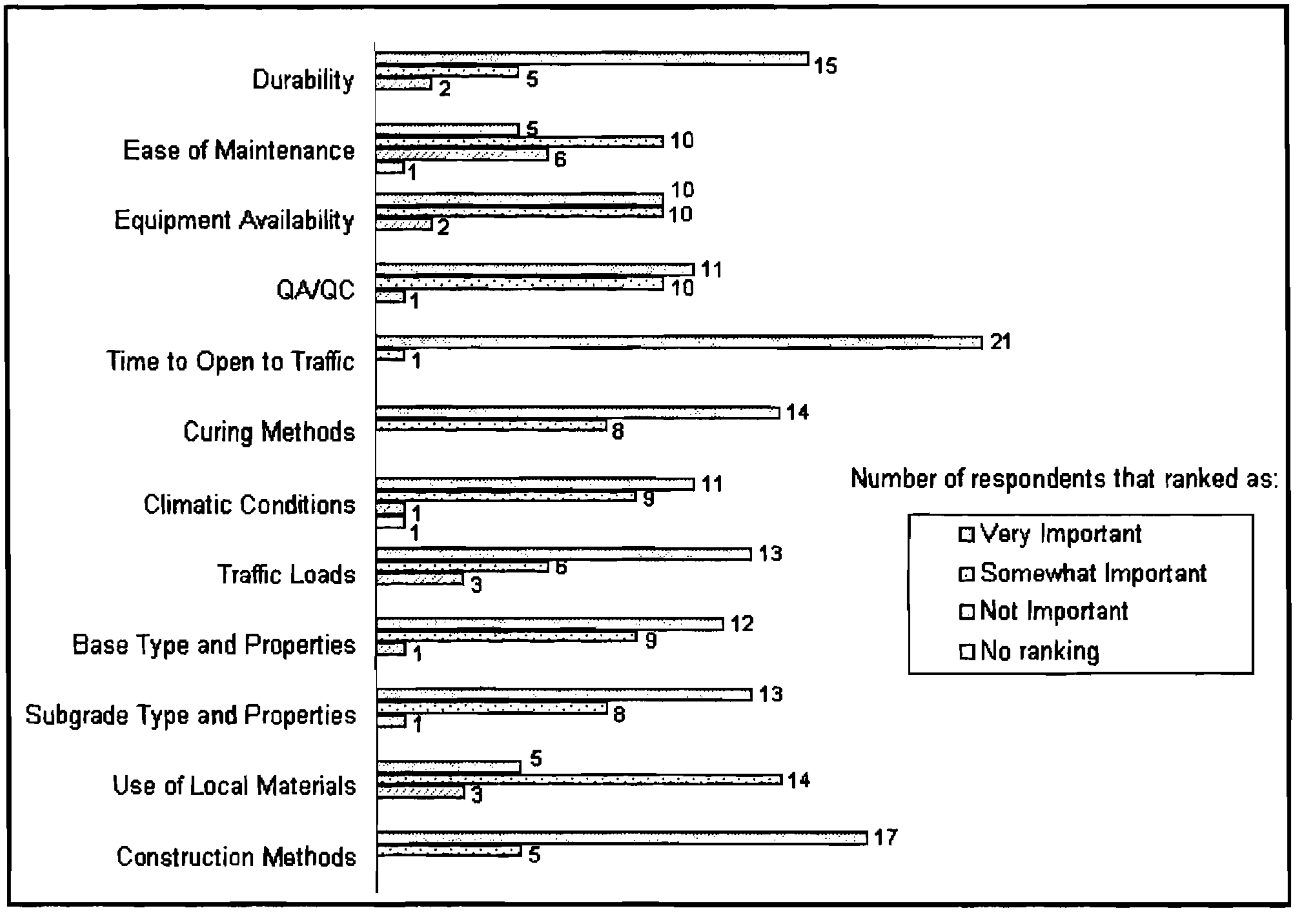


Figure 3.3 – Factors Considered when Expediting PCC Pavement Construction

According to the survey, more than 70% of the respondents agree that the *Time to Open to Traffic, Construction Methods,* and *Durability are* the primary factors to consider when expediting PCC pavement construction, since they are rated as --Very Important --. *Curing Methods, Traffic Loads, Subgrade Type - Base Type and Properties,* follow in degree of importance since more than half of the respondents rated as --Very Important--, and the rest consider them as either -- Somewhat important -- or -- Not Important--.

About 65% of the respondents agreed that *Use of Local Materials* is --Somewhat Important --, while for *Climatic Conditions, Equipment Availability, and QA/QC procedures* about half of the respondents rank them as -- Very Important -- and the rest -- Somewhat Important -- and very few -- Not Important – at all. *Ease of maintenance* is the only factor where the respondents disagree the most in its relative importance to expedite PCC pavement construction.

On Figure 3.4, the number of responses to each factor is plotted. *Flexural strength* seems to be the criteria that rules, while *Compressive Strength* and *Maturity* follow.

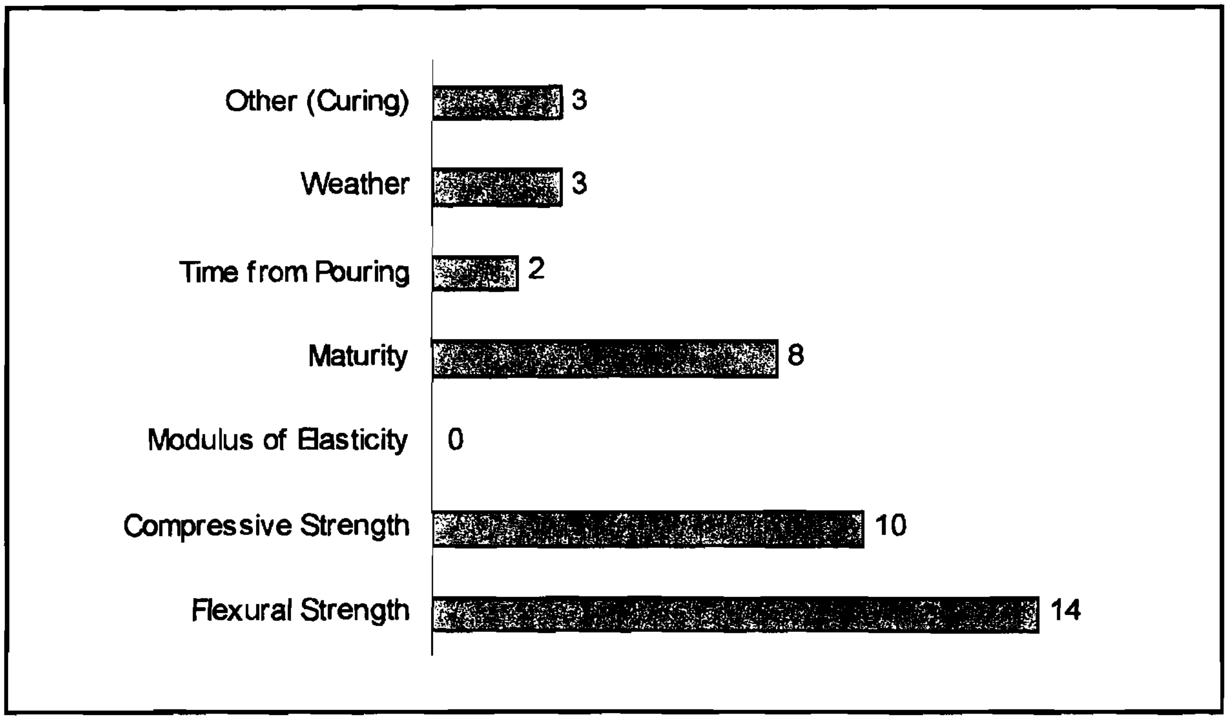


Figure 3.4 – Criteria Considered when Determining Time to Open to Traffic

About half of the respondents, use a wide range of software to design PCC rigid pavements. These software programs are developed by/for different agencies or associations such as, ACI, PCA, and AASHTO to name a few.

Most of the respondents consider an economic analysis when contemplating expediting pavement construction. About a half of them, consider initial costs, user costs, and life-cycle costs. However, only a third of them report using software for economic analysis, such as Darwin, Crystal Ball or customized software developed by research agencies or centers.

Some respondents added a few suggestions towards expediting pavement construction. The suggestions are very general in nature, ranging from stabilizing layers, to improving construction sequencing, to allowing contractor innovation. For additional comments on other survey questions, refer to Appendix D.

The survey answers provide some insight as to the current state of design and construction procedures considered for expediting pavement construction and early opening to traffic. However, the number of responses is surprisingly low. No reasonable conclusions can be drawn from this "small sample of opinions", and in addition, no fact-action relationships can be derived for rule-based representation.

To complement the elicitation of knowledge from *undocumented* sources, a short informal interview was scheduled by the Project Director in Dallas TX, with staff personnel from the Dallas - TxDOT office, local contractors and material suppliers. According to the District personnel, the main bottleneck to open as soon as possible to traffic relies on the efficient management of traffic operations, for both pavement and bridge construction, not in the design optimization or construction of the pavement section itself. In addition, a copy of an official document was provided to the research team, consisting of procedures for determining contract time with a set of tables with daily production rates for standard work items (TxDOTc, 1993).

Based on the low level of "expert" participation, and the futile attempts to acquire useful expertise from *documented* sources, the development of an expert system is practically not feasible, and beyond the reach of this research project. Consequently the project staff concentrated in evaluating the impacts of different proposed fast-track cross sections in terms of structural feasibility and their impacts on construction schedules.

Chapter 4 Sensitivity Analysis to Streamline Construction

Collection of Traditional Pavement Sections

Before performing a sensitivity analysis of design and construction parameters that affect pavement performance and construction time, the collection of "traditional" rigid pavement sections currently built throughout the State, was conducted through a second survey. This survey focused on seventeen (17) Districts that currently build rigid pavements, as depicted in Figure 4.1.

The survey form, included in Appendix D, consists of a few multiple-choice questions requesting basic construction practices within each District, and provides a table with multiple rows and columns to fill out with layer information. Such information may include: layer number (*1-top slab, 2-base, etc., last-subgrade*); layer type (*PCC slab, Base, etc.*); TxDOT design standard if used (*e.g. CRCP (1)-94*); layer thickness; descriptive information; soil classification, if available; and PCC-slab joint and rebar type and spacing.

Thirteen out of seventeen (13/17) Districts replied to this second survey. Abilene and Corpus Christ replied having no rigid pavement construction. Dallas, Forth Worth, Wichita Falls, Lubbock, Tyler, Lufkin, Houston, Yoakum, Atlanta, Beaumont, and El Paso (see Figure 4.2) responded with the different typical sections currently practiced in them. Appendix E shows the different pavement sections. The remaining Districts surveyed are still pending a response.

Most survey forms were filled out properly. Some Districts included a Concrete Pavement Design Standard code, instead of or in addition to filling out the joint and rebar information. The details of these standards can be obtained from the District design engineer or the Construction Division—Pavements Section, or some of them through TxDOT's Roadway Standards web page (TxDOTa, 2001).

Table 4.1 summarizes the rigid pavement practices submitted. Six typical pavement section designs were identified, classified under one, two, three, and four layer structures built above the subgrade. Two and three layer structures are further subdivided in two categories, depending on whether the slab is laid over a treated base or asphalt concrete. The total pavement section depths range between ten and thirty-five (10"-35") inches, including a slab thickness that varies between eight and fourteen (8"-14") inches.

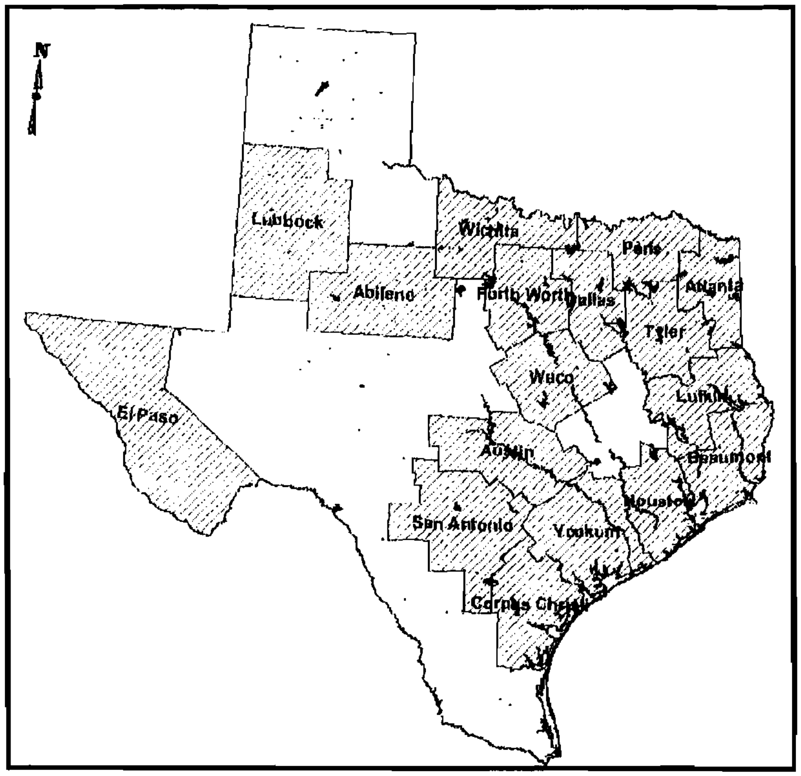


Figure 4.1 – Surveyed Districts with Rigid PCC Pavements

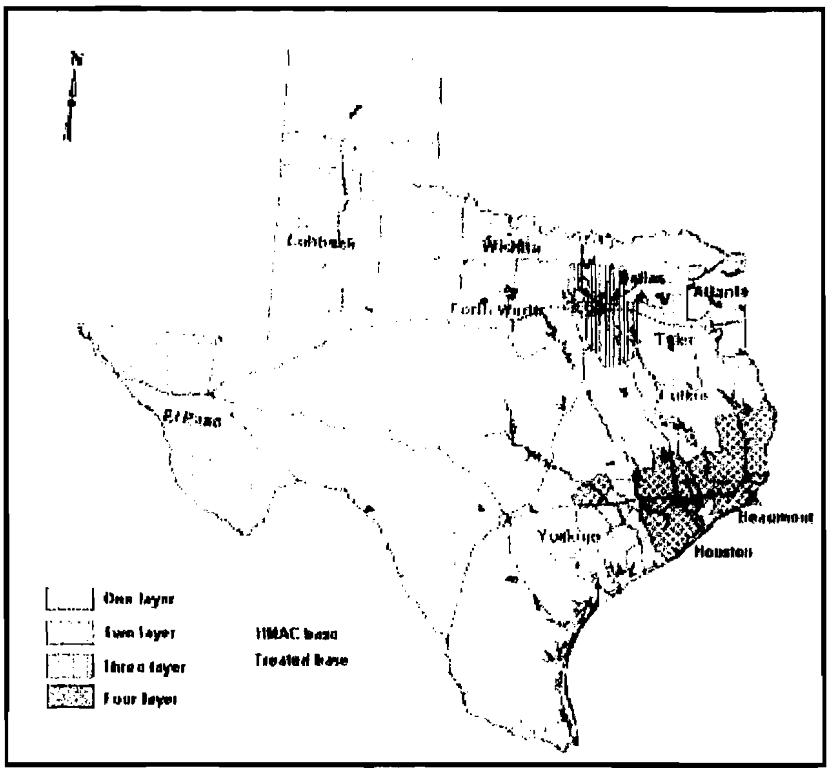


Figure 4.2 – Different Rigid Pavement Sections among Districts

Table 4.1 Summary of Typical Rigid Pavement Section Practices (9 Districts)

Category	Item	4 (Four)	3 (Three)		2 (Two)		1 (One)
Pavement Section Designs	**Num. of layers built above the subgrade inc. PCC slab**	4 (Four)	3 (Three)		2 (Two)		1 (One)
	Top layer **2nd** **3rd** **4th**	PCC Slab Bond breaker Treated base Stabilized SG. SG	PCC Slab 2, 4, 6" AC Stabilized SG. SG	PCC Slab Treated base Stabilized SG. SG	PCC Slab 3-4, 8,10,14" AC SG	PCC Slab Treated Base SG	PCC Slab SG
	Total depth-range (inches)	22 – 26	18, 21 – 35	18 – 25	12,13 – 18, 22-23	16	10, 12
PCC Slab	**Construction Type**	CRCP, JCP	CRCP, JCP	CRCP, JCP	CRCP	JRCP	JCP
	Design Standard (TxDOT)	CPCR 2000, CPCR (B)-89C CPCD	CPCR (2)-94 CPCR (1)-94 CPCD	CPCR-SPL-360-035 CPCD (SPL) CPCR (1)-94	CPCR (1)-94 CPCD	CPCR-SPL	CPCR (1)
	Thickness-range (inches)	10, 12, 13	8-9, 11-14	8 - 13	8, 10 - 14	10	10, 12
Treatment or Stabilization (if applicable)	**Base**	6" Cement 4" Flexible	12" flex base after excavation Asphalt	4" Asphalt 6" Cement • Lime	• Cement • Fly Ash • Asphalt	6" Cement	• Asphalt
	Subgrade	6" Lime • Cement	6, 8 – 19 , 22" Lime (clays) Cement (sands) Lime (4%) sands	6", 8" Lime 6" - 8" .... • Cement	• Fly Ash • Emulsified asphalt	--	• Lime • Cement
Subgrade Soil Classification		*Varies* MC (BM)	CH, CL, SM	--	CL, SM SC	--	
Typical Use	**Highway System**	US/SH/FM, IH, high volume roads	US/SH/FM, IH, high volume roads, streets	US/SH/FM, IH, high volume roads	IH, high volume roads, streets	IH	US/SH/FM
	District(s)	12-Houston 13-Yoakum (Fayette) 20-Beaumont	2- Forth Worth 10-Tyler 18-Dallas	3- Wichita Falls 13-Yoakum (Colorado)** (Warton)** 19-Atlanta	5- Lubbock 18-Dallas 24-El Paso	13-Yoakum (Austin)**	11-Lufkin 18-Dallas
	Project Type(s)	New/Recons/ Repairs	New/Recons/ Repairs	New/Recons/ Repairs	New/Recons/ Repair	--	New/Recons/ Repairs

• Also commonly used - - Not applicable or Not available ** Now overlaid with 3"-4" ACP

Typical slab construction includes: continuously reinforced concrete (CRCP), jointed reinforced concrete (JRCP) and jointed plain concrete (JPCP) slabs. Typical base treatments include six inches (6") with cement or four (4") with asphalt. Occasionally, lime or fly ash is used to treat the base. The subgrade is typically treated with lime, occasionally with cement, and in El Paso with emulsified asphalt. These pavement sections follow federally mandated guidelines set forth by the Federal Highway Administration (FHWA), and are usually used on newly constructed highways, reconstructions, and repairs throughout the Districts, in Interstate and State highways, Farm to Market and high volume roads.

Most Districts have used flexural strength or compressive strength as criteria for opening to traffic. Wichita Falls and Dallas reported using maturity. A few Districts specify 450 psi of flexural strength, or 2800 psi of compressive strength to open to traffic after (4) days, while others specify a combination of 555 psi of flexural strength with maturity. A few Districts only mention following standard specifications. Some Districts open to all traffic after seven (7) or eight (8) days.

Seven districts replied having an interest in using NDT to open the pavements to traffic, two were not interested, and two were not sure whether they would use such technology. Four Districts provided the subgrade soil classification based on the Unified Soil Classification System (USCS), standardized in ASTM D2487.

To complement subgrade condition information, the State Soil Geographic (STATSGO) database for Texas (STATSGO, 2001) was secured. This database is primarily intended for broad planning and management uses covering state and regional areas. The map shown in Figure 4.3 was generated from a polygon file in ArcInfo 7.0 format. The database is mapable into ArcView, which allows queries on bedrock, soil type, and other soil properties.

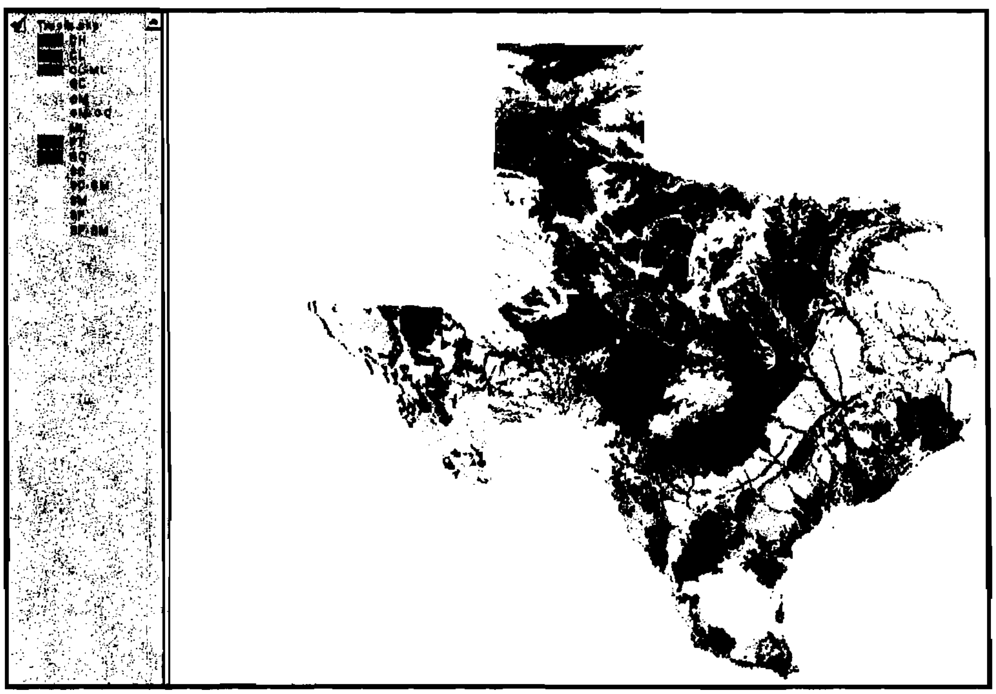


Figure 4.3 – Texas Soil Distribution Map (STATSGO, 2001)

Finally, an online Internet database (ACPA, 2001) containing design, construction and specifications related to concrete pavements, was investigated for information on current rigid pavement practices in Texas. The information was found very limited for the purposes of the research.

Empirical-Mechanistic Design Models

Currently, TxDOT designs new rigid pavements based on the 1986 AASHTO rigid pavement performance model (AASHTO, 1986). The 1986 AASHTO equation is the same in 1993 AASHTO (AASHTO, 1993 -- see section I-1.2) and is as follows:

$$\log W_{18} = Z_R S_o + 7.35\log(D+1) - 0.06 + \left(\frac{\log[\Delta PSI / (4.5-1.5)]}{1 + 1.624 \times 10^7 / (D+1)^{8.46}} \right) + (4.22 - 0.32 p_t) \log\left(\frac{S_c C_d (D^{0.75} - 1.132)}{215.63\, J\, [D^{0.75} - 18.42 / (E_c/k)^{0.25}]} \right) \quad \text{..........(1)}$$

where:

W_{18} : Predicted number of 18-kip ESAL applications that can be carried by the pavement structure after construction;

Z_R : Standard normal deviate corresponding to the selected level of reliability.

S_o : Combined standard deviation of the traffic prediction and performance prediction

D : Slab thickness (inches)

p_t : Design *terminal* serviceability index

ΔPSI : Difference between the *initial* design serviceability index (p_o) and the design *terminal* serviceability index (p_t)

S_c : PCC modulus of rupture used for the specific project, (psi)

C_d : Drainage coefficient

J : Load transfer coefficient used to adjust for load transfer characteristics of a specific design

E_c : PCC modulus of elasticity, (psi)

k : Westergard's Modulus of subgrade reaction, (pci)

AASHTO specifies procedures to modify the modulus of subgrade reaction (**k**) to account for presence of subbase, presence of a rigid foundation at a shallow depth, its variations with the season of the year, and loss of subgrade support. However, AASHTO does not mention how to handle multi-layer pavement sections, such as typical ones in Texas.

TxDOT follows a set of federally mandated guidelines that recommend some design parameters to improve the uniformity of designs prepared statewide. A copy of these guidelines is located in Appendix F. Additional online information is also available in Section 4 of TxDOT's Pavement Design Manual (TxDOTb, 2001).

Sensitivity of Design Parameters

From the design standpoint, a sensitivity study was conducted, to identify pavement layers that may not significantly contribute to the long-term performance of a rigid pavement. In this manner, those layers could be eliminated from the cross-section, either by improving the underlying layers, or thickening, and strengthening the overlaying layers.

A case study was selected from one typical pavement section reported as built in Texas. The three-layer pavement section in Henderson County -- Tyler District, TX. has the following attributes:

Construction type	: JCP
Highway system	: SH-198
TxDOT Design Std.	: CPCD – no tied PCC shoulders reported
Slab thickness	: 9"
Base treatment	: 4" ACP
Subgrade treatment	: 8" lime treated
Note	: Estimate of the projected ADT not provided.

The variables required in Equation 1 are as follows (see Appendix F for recommended values):

D	: 9 "
E_c	: 5,000,000 psi (assumed siliceous river gravel, since Cedar creek is nearby)
p_t	: 2.5
ΔPSI	: 2.0
S_c	: 720 psi
C_d	: 1.01 (based on an annual precipitation of 36" - 40" for geographic region)
J	: 3.2 (based on the CPCD details, no tied PCC shoulders & transverse steel provided)
k	: 350 pci (average of suggested range)
S_o	: 0.39
Z_R	: -1.645 (based on 95% reliability, see Huang, 1993, p. 572. 95% assumed as typical value)

The backcalculated traffic W_{18}, about 10.5 million ESALs. The parameter that represents the pavement structure underneath the slab (number and type of layer material) is the modulus of subgrade reaction (k). All parameters including traffic were fixed, except for the modulus of subgrade reaction (k), which was varied from 100 to 600 pci in increments of 50 pci, (assuming equal likelihood of occurrence at any time) to see the effect on the slab's thickness variation. The variation in the slab thickness with the variation in modulus of subgrade reaction is depicted in Figure 4.4. The maximum difference in thickness is approximately one (1) inch. This corresponds to +0.6 in. when (k) decreases 250 pci and to –0.4 in. when (k) increases 250 pci. This small variation in slab thickness confirms that this parameter is slightly sensitive to (k) the modulus of subgrade reaction.

Similar exercises were performed on other pavement sections from other districts, with similar results. The conclusion is that any number of pavement section designs with the same slab thickness will provide sufficient capacity to carry the design traffic.

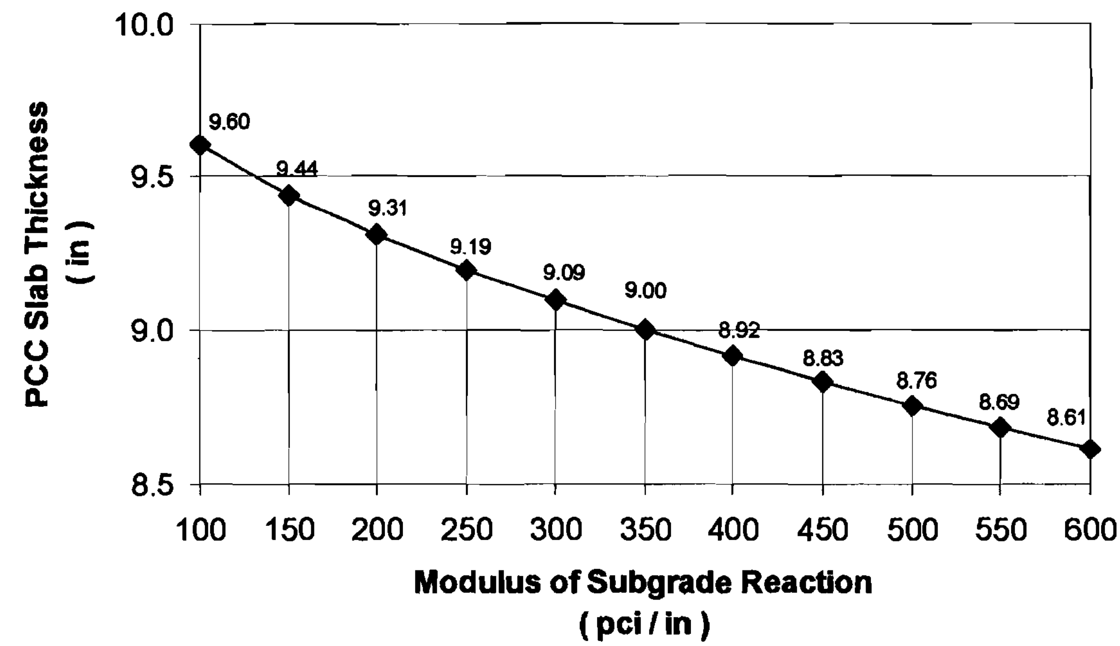


Figure 4.4 – Slab Thickness Variation vs. Modulus of Subgrade Reaction

The lack of sensitivity of the pavement design to the modulus of subgrade reaction is a well-known problem. To understand how different states justify and consider a large number of shift layers in their operations, an electronic inquiry was submitted over the Internet to the subscribers to the PAVENET (a pavement design chat room) and the FWD user's chat room. More than twenty responses were received with no technical information provided. Several states, just as Texas, assume a constant value independent of the number and nature of base and subbase or the condition of subgrade. Many others basically go through the procedure advocated by AASHTO. No group could provide an indirect way of considering the improved remaining life of the pavement because of the added stabilized layers.

Apparently, alternative pavement sections to expedite the construction cannot be obtained from the design standpoint using the AASHTO design procedures. Other mechanistic approaches like Finite Element Analysis (FEM) combined with layered theory analysis should be used to structurally evaluate the proposed fast-track pavement sections. The problem is reduced to a minimization of project schedules, for various pavement sections, where the layer thickness are decreased until eliminated, and simultaneously increasing the thickness of other layers such as the PCC slab.

Construction Parameters

The information collected from the surveys is insufficient to identify the most relevant construction parameters and perform a sensitivity study on them. Another attempt to collect construction parameters consisted of evaluating a few commercially available PCC pavement design programs, some of which were also listed in the survey responses (see Appendix C). The surveyed program demos include: PaveSpec, HiperPav, LEDFAA, HWYCON and PCase, for which a brief description of them follows.

PaveSpec (By ERES Consultants)
PaveSpec is designed and developed to simulate performance-related specifications (PRS) and associated life cycle costs (LCC's) for both as-designed and as-constructed jointed plain concrete pavements (JCPC). The software has specifically been designed to help State highway agencies determine rational performance-related pay factors (and pay adjustments) for JPCP highway pavements.

Pavement performance is expressed in terms of transverse slab cracking, transverse joint faulting, and transverse joint spalling as well as pavement smoothness over time. Each of the distress indicator models is a function of concrete strength, slab thickness, air content, initial smoothness and percent consolidation around dowels.

The software can develop a project-specific PRS, or perform a specification-dependent sensitivity analysis to investigate the effects of acceptance quality characteristics (AQC) changes on pay factors; or develop PR pay factors and pay adjustments based on actual AQC field data.

HiperPav (By TransTec Consultants)
HIPERPAV (HIgh PERformance PAVing) is a concrete paving software product which can be used to assess the influence of PCC pavement design, concrete mix design, construction methods and environmental conditions on the early-age behavior of Portland cement concrete pavements (PCCP). HIPERPAV can be used to:

a. to develop quality control specifications for a particular project based on the available materials and climatic conditions of the region in study;
b. to optimize their pavement designs based on the best selection of the design variables that will produce a better end product and guarantee long-term pavement performance while maximizing economy;
c. to prevent expensive repairs by predicting potential damage due to unexpected conditions and determine the best set of factors that will prevent damage to the pavement;
d. to manage the temperature of the concrete based on mix designs and specific climate and project conditions.

HIPERPAV's integration captures all aspects of a concrete pavement construction project and provides a real systems approach to analyze the first 72 hours after construction, assessing the development of stresses and strength in concrete pavement during these critical first 72 hours to maximize quality, increase long term performance, boost productivity, and optimize pavement options.

LEDFAA (By Federal Aviation Administration)
LEDFAA is a computer program for airport pavement thickness design. It implements layered elastic theory based design procedures developed for new and overlay design of flexible and rigid pavements. The layered elastic procedures are the FAA airport pavement thickness design standards for pavements intended to serve the Boeing B-777 airplane. The core of the program is JULEA, a layer elastic computational program implemented in FORTRAN, with the rest of the application written in Visual Basic. Subgrade vertical strain and horizontal strain at the bottom of the top layer are the design criteria for both pavement types.
The user enters as input different supporting layer characteristics such as Poisson's ratio and subgrade modulus, as well as aircraft names and gross loads, and annual departures and growth for each aircraft. Guidelines for selection of design parameters are provided through a help facility.

HWYCON (By AASHTOWare)
HighWaY CONcrete is an expert system designed to assist highway departments in: 1) diagnosing the cause of distress in highway pavements and structures; 2) determining appropriate repair and rehabilitation strategies; and 3) selecting optimum construction materials. This expert system consists of a series of sub-systems, some of which are briefly addressed in the following.
CONMAT: gives recommendations and guidelines for concrete durability and related procedures, including alkali-aggregate reactivity, corrosion of reinforcing steel, fast track concrete, freeze and thawing, permeable bases, recycling concrete and sulfate attack.
CONPAV-D: designed to identify the various material-related distresses that occur in highway concrete pavements and attempts to diagnose the cause of the distress. This module can be used on JRCP, JPCP, CRCP. Some distresses included cracks, aggregate polishing, potholes, sealant failures, spalling, pop outs, and scaling.
CONPAV-R: assumes that the operator has already chosen the repair/rehabilitation procedure, such as partial-depth repairs, full-depth repairs, bonded concrete overlays, unbonded concrete overlays and diamond grinding and milling. Some information is provided which may help in the selection of the appropriate procedure.

PCase (By Army Corps of Engineers)
Pavement-Transportation Computer Assisted Structural Engineering programs include rigid and flexible airfield design by conventional and layered elastic methodologies, rigid and flexible road design, as well as railroad design and evaluation programs.
The *Road Design (Empirical)* software provides criteria for the design of pavements for roads, streets, walks and open storage areas at U.S. Army and Air Force installations. These criteria include subgrade and base requirements, thickness designs, and compaction requirements, criteria for stabilized layers, concrete pavement joint details, and overlays. The rigid pavement design procedure is based upon critical tensile stresses produced within the slab by the vehicle loading. The accompanying manual provides standard specifications for soil compaction and treatment, a procedure to determine the modulus of subgrade reaction, as well as a procedure for the design of CRCP.

CRCP 8 & 9 (By Center for Transportation Research)
The CRCP programs simulate the early-age behavior of continuously reinforced concrete pavement. They can be used to predict crack spacing, crack width, steel stresses, punch outs

frictional forces, and displacements based on volume changes caused by temperature differentials and drying shrinkage.
CRCP 8 has simplified assumptions of one-dimensional analysis, while CRCP 9 expands the ability of the mechanistic model by incorporating the variations in temperature and moisture changes through the depth of concrete slab and uses two-dimensional finite element model to:

- Develop crack spacing prediction model using the Monte Carlo method.
- Develop failure prediction model using probability theories.

CRCP 9 considers nonlinear variations in temperature and drying shrinkage through the depth of the concrete slab, it considers nonlinear bond-slip relationship between concrete and steel bars, it also considers visco-elastic effect of concrete and curling and warping effects, and it has the ability to change locations of the longitudinal steel bars.
As general input, CRCP9 requires the definition of geometry, concrete and steel material properties, bond-slip relationships between concrete and steel, and between concrete slab and base layer, wheel loads, and environmental loads such as changes in temperature and drying shrinkage. Advanced input may also be defined to further refine the analysis, including creep, curling, and swelling effects, number of primary crack spacings, finite element type, and reliability.

The programs listed above address issues related to fast-track design and construction of the PCC pavement layer. However, very little information is provided or derived for the supporting layers underneath the PCC slab. Only a few standard lift specifications were found. Due to the lack of information, the sensitivity study on the most relevant construction parameters was not feasible.

User Cost Models

Specific user cost models will have to be investigated and should be specifically targeted to lane additions and new construction. The lane addition calculations and modeling of user-costs should address the cases that involve lane closures or lane narrowing or a combination of both. The case of new construction should evaluate network user-cost impacts caused by the unavailability of the new link being constructed.

The lane closure case has been extensively researched in the literature (Memmott and Dudek, 1981.) and several computerized modules are available for evaluating user costs. The lane narrowing case is not widely addressed in the literature and will need additional research by the project staff to address the issue. Once the lane narrowing modeling and calculations are addressed during the second year of this research project, the results will be documented in a future report.
The new construction approach is a more complex issue to be addressed. This will estimate user costs due to the delays in opening to traffic of a specific newly constructed high volume link that would relieve existing congestion on a existing, at capacity, link. Each additional day of delay in the construction of the new link, means additional user costs on the existing congested link. This is a fairly complex problem, that will have to be addressed through estimates of traffic diversions from the existing, at capacity, network link to the new pavement network link under evaluation for expedited construction. A simplified approach to estimate these costs is under investigation by the project staff and will be documented on a future report.

The methodologies and estimates derived for the lane addition and new construction cases will be incorporated in the cost-benefit analysis for the proposed expedited pavement cross-sections for different traffic level scenarios.

Construction Scheduling

Since the design of rigid pavement sections based on AASHTO 1993, is not sensitive to the type and number of layers underneath the slab, different construction schedules were developed for selected pavement sections throughout the State, to identify the obvious bottlenecks in traditional pavement construction.

Simplified sets of construction schedules were developed for the following conditions:

1) ***Roadway section***:
   a) traditional pavement sections for Houston, Forth Worth and El Paso Districts (see Appendix E);
   b) hypothetical project length(s):
      1) 48 ft. x 300 ft. (assuming a four-lane urban intersection, 12 ft. lanes),
      2) 48 ft. x 1.0-mile (assuming a four-lane rural highway section, 12 ft. lanes);
2) ***Construction activities***:
   a) based on some work items listed for new construction or reconstruction used to determine contract time (TxDOTc, 2000), as well as TxDOT's standard specifications for construction of highways (TxDOTd, 1995);
   b) a few activities were eliminated from the schedule scenarios for practical purposes, such as underground utility removal, drainage and manhole installation, bridge or culvert construction, among a few others; joint details and finishing on the concrete slab are also removed from this analysis for simplification reasons;
3) ***Productivity rates***:
   a) based on RSMeans (2001) nationwide compilation;
   b) the schedules assume full-depth construction, beginning with subgrade compaction, and ending with the concrete pouring of the PCC-slab. Any other required wait times before opening to traffic are not included in the analysis;
   c) concrete slab is normal setting and hardening time (no additives or special materials are considered);
   d) concrete reinforcement is not included;
   e) single crew and/or equipment shifts are considered.

The work items addressed in TxDOTc (2000) are generic in nature. No details are provided as to the type of construction equipment considered, or layer thickness assumed for base preparation or wearing courses. Conversely, a range of productivity rates for a variety of detailed work items are listed in RSMeans.

The simplified construction timeframes for the selected pavement sections are included in Appendix G. The schedules are presented in tabular format listing the construction activities considered, the corresponding lift/layer thickness, the selected production rate, units, and the estimated time of completion for each activity, in both *eight-hour-days* and *total-hour* formats. A "serial" sequence of tasks is assumed. No overlaps among construction activities are considered. Each activity has an associated "early start" (ES) time, and corresponding "early finish" time. Both quantities are included in the right-hand side of the tables.

Table 4.2 shows a summary of different production rates per day for four common pavement construction activities, differentiated by lift thickness (according to RSMeans). An estimate of the duration of each item is included for comparison purposes, for a hypothetical roadway section.

Table 4.2 Summaries of Various Production Rates (RSMeans, 2001)
(Four-lane intersection 48' x 300')

Work Item		Rate/Day	Units	Estimated Time	
	Thickness (in.)			Days	Hours
Lime Stabilization	6	1800	S.Y.	0.89	7.11
	8	1700	S.Y.	0.94	7.53
	12	1550	S.Y.	1.03	8.26
Cement Treatment	6	1100	S.Y.	1.45	11.64
	8	1050	S.Y.	1.52	12.19
	12	960	S.Y.	1.67	13.33
Bond Breaker (ACP)	1	9000	S.Y.	0.18	1.42
	1.5	7725	S.Y.	0.21	1.66
	2	6350	S.Y.	0.25	2.02
	3	4900	S.Y.	0.33	2.61
	4	4150	S.Y.	0.39	3.08
Concrete Paving (inc. rebar and curing)	6	3500	S.Y.	0.46	3.66
	7	3350	S.Y.	0.48	3.82
	8	3250	S.Y.	0.49	3.94
	9	3000	S.Y.	0.53	4.27
	10	2600	S.Y.	0.62	4.92
	12	2300	S.Y.	0.70	5.57
	15	2000	S.Y.	0.80	6.40

At this point, no task variability has been considered, which would account for changes in weather (e.g. precipitation) during the construction process.

For each case scenario, the top schedule corresponds to the "**Traditional Design**" pavement section, according to District practices. For example, in Houston District, the construction of four-300 feet long lanes with a four-layer pavement section, can take about twenty-eight (28) consecutive days to build before opening to traffic. While in Forth Worth, a three-layer pavement section in a similar roadway length, can take up to thirty-nine (39) days to open to traffic. Note that the eighteen inches (18") of lime-stabilized subgrade are built in two phases with different production rates that depend on the lift thickness; and for each phase a fourteen (14) day curing period after stabilization is required by specification.

The major bottlenecks in the construction process of the design sections include: "*waiting times after stabilization or treatment*" and "*concrete curing time*".

Two alternative sections were proposed (where applicable) in lieu of the "**Traditional Design**" section, maintaining the total section depth. These alternate sections eliminate or replace layers that require stabilization or treatment with thicker binder or course layers.
These alternate sections include (see Figure 4.5):

1) **ACP Base:** Replace subgrade stabilization with compaction only. Replace lime or cement treated base material with an asphalt concrete binder. Maintain the same concrete slab thickness.
2) **Full-Depth Concrete:** Replace subgrade stabilization with compaction only. Replace lime or cement treated base material and any ACP binder course with full-depth reinforced concrete.

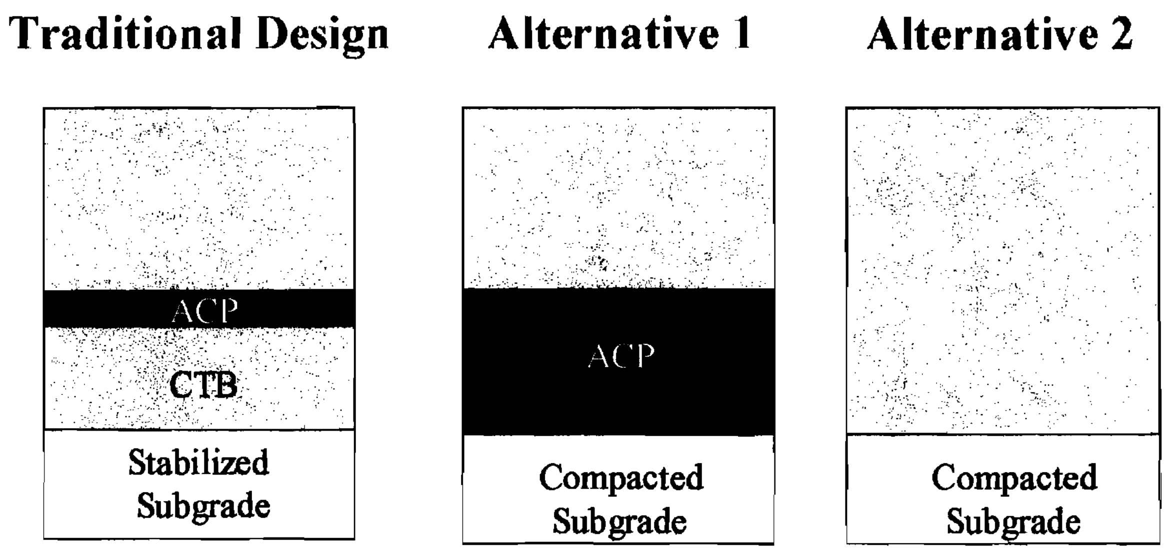
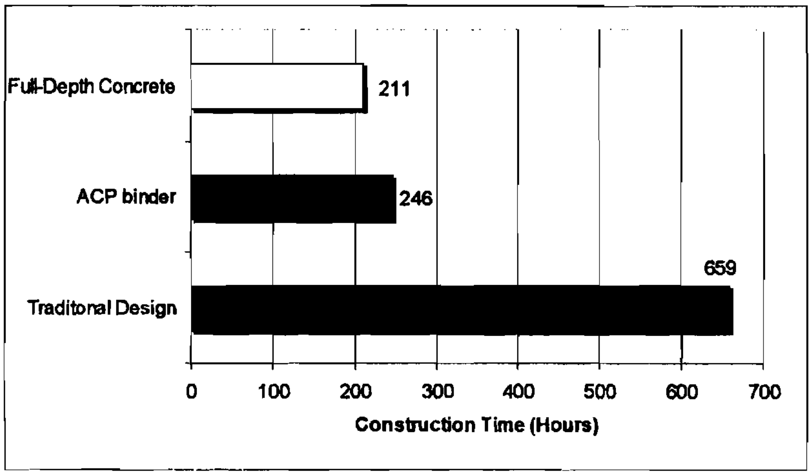


Figure 4.5 – Proposed Alternate Pavement Sections

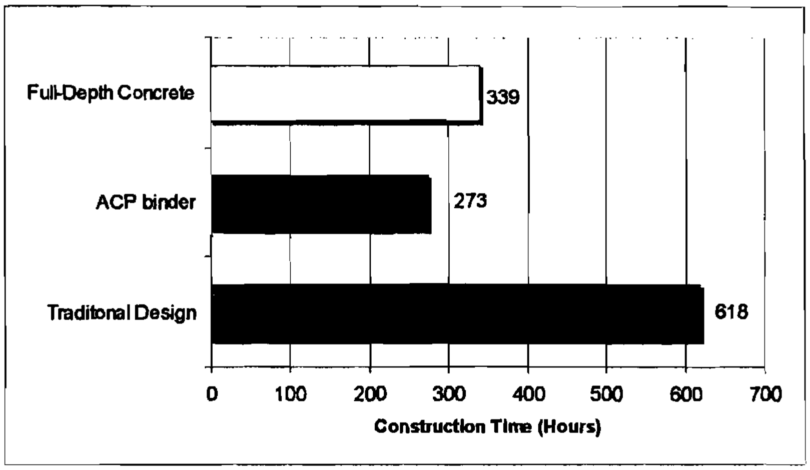
Since no "expert" input was available, the authors proposed these alternatives based on their own judgments. The authors realize that the proposed sections may not comply with federally mandated regulations. Performances of the proposed sections will have to be established through the construction of test sections were parameters will be carefully controlled and productivity rates for construction and the impact on construction schedules will be evaluated.

The alternate construction schedules (Appendix G) show noticeable improvements in construction time reduction for Houston and Forth Worth Districts, for both length scenarios; about 78-84% for the 300 feet scenario, and between 45-70% for the one mile scenario. For El Paso District, the improvements in time reduction are 2% and 6% for the 300 feet and one-mile scenarios, respectively.

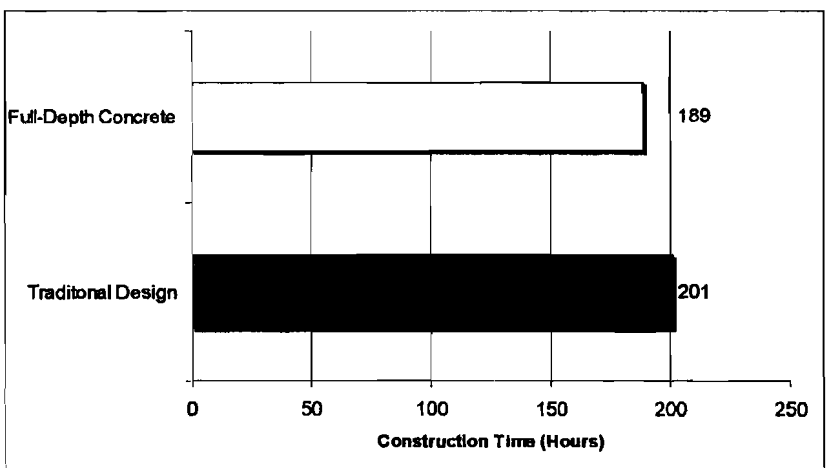
Figure 4.6 shows the total construction time comparison between the traditional design pavement sections, and the proposed alternatives for the one mile case scenario in all three Districts.



a) Houston District (4 lane, 1.0 mile long)



b) Forth Worth District (4 lane, 1.0 mile long)



c) El Paso District (4 lane, 1.0 mile long)

Figure 4.6 – Construction Time Comparison among Alternative Section Designs

Furthermore, an approximate construction cost was determined for each alternative section, including the traditional design approach. RSMeans (2001) cost data was used to estimate the construction cost for each region (see Appendix H). The total activity cost includes cost of bare material, bare labor, bare equipment, overhead, and profit. The crew identification number is provided as well. The components of each crew are included at the end of Appendix H.

Considering that the cost analysis performed is very limited, the overall cost tendency of the alternate pavement sections is higher than for the "**traditional design**". A full-depth concrete section is more expensive than an ACP binder course, which was expected, considering that the total section depth is kept fixed. This cost can reasonably be lowered for thinner concrete slabs.

Nonetheless, a more detailed cost analysis on a project basis would give more accurate results.

Opening to traffic

Time to open to traffic has an impact on the process as well. Yuan *et al.* (2001), a companion report to this report, describe the tools that are available for that purpose. Basically, either maturity, seismic or a combination of the two methods can be used to estimate the state of concrete and to predict the time to opening. With these methods, the quality of material and construction will have a direct impact on how long the road has to be closed to traffic. Currently, in most projects, the time to opening to traffic is arbitrarily set somewhere between three to seven days. For more information the reader is referred to Yuan *et al.* (2001).

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Chapter 5 Summary and Conclusions

Summary

This report summarizes the efforts to develop a methodology based on expert system technology to collect and preserve expertise in streamlining the construction process of highways for early opening to traffic.

Chapter 2 provides some background information on rigid pavement design and construction, as well as a brief introduction to expert systems and their applications to pavements. More than three dozen papers were identified (see Appendix A) and the most relevant issues were summarized in a table.

Chapter 3 provides a detailed description of all steps taken towards the integration of the expert system software, from the conceptual design, to the selection of the software development tool, to the acquisition of documented and undocumented information on rigid pavement construction. The most relevant publications of the last fifteen years provide vast amounts of facts related to fast-track. However, the relationships among these are very difficult to derive for the development of rules to incorporate into an expert system.
A number of questionnaires were forwarded to various forums to elicit any expertise from practicing professionals. Less than 15% of the surveyed professional replied to the survey with very limited responses. The Project Management Committee always provided strategic support to elicit as much participation as possible from various "potential" sources. However, due to the low level of "expert" participation, and to the futile attempts to collect pieces of useful expertise from *documented* sources, knowledge representation is practically "not feasible".

In Chapter 4, the compilation of the results of the survey of several TxDOT districts for current rigid pavement section practices is included. A sensitivity study on design parameters based on AASHTO 1993 was performed on a few sections. The results showed that the PCC slab design is not very sensitive to the type and number of layers underneath. Consequently, alternative pavement sections that can expedite the construction of highways cannot be determined from the design standpoint. A nationwide attempt to obtain quantitative information yielded no additional information. Therefore, two non-federally compliant alternative pavement structures were proposed, determining simplified construction schedules and cost estimates. Some potential directions for evaluating user-costs were documented in this chapter.

The alternate sections show noticeable improvements in time reduction with higher construction costs as tradeoff. The proposed sections were evaluated using standard construction estimation tools such as RSMeans construction indices. Potential directions for evaluating user-costs were documented in this chapter. In addition, the proposed cross-sections need to be evaluated for pavement performance, constructability and impacts on construction schedules and associated user costs through the construction of test-sections.

Future work

In view of this year's research outcome, the research team proposes for fiscal year 2001-2002 the following:

1. Quest and propose structurally sound alternate pavement cross-sections and construction processes to expedite their constructions that are compatible with traditional methods. These alternate pavement sections could be a function of geographic location, weather and soil characteristics, level of traffic, highway type, and construction type (new construction, reconstruction or lane addition) among others. The alternate pavement sections should at least reach the same performance level as the conventional sections.
2. Perform the structural evaluation of the alternate pavement sections using mechanistic approaches such as in KenSlab or JSlab, for three different levels of subgrade condition: weak, average and strong. The determination of strains and stresses will allow the prediction of their pavement performance.
3. Determine the theoretical construction time and cost, assuming simplified schedules of construction activities for new construction and lane additions, hypothetical roadway lengths, and base productivity rates and unit costs on RSMeans databases.
4. Determine a theoretical Cost-Benefit ratio for each type of section analyzed based on construction costs and user's cost.
5. Complete the information in the matrix of feasible expedited cross-sections regarding the user-cost impacts for the lane additions and new construction cases as discussed in Chapter 4 of this report.

The feasibility of these cross-sections needs to be evaluated from the standpoint of pavement performance, constructability and the compression of construction schedules and consequent reduction of user costs, through the implementation of pilot test-sections where these parameters would be carefully monitored.

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Appendix A Expedited Construction Literature Summary

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The following paragraphs address a brief summary of the most relevant publications collected for expedited pavement design and construction.

- To evaluate alternative pavement types for roadway projects, agency costs, user delay costs, and performance levels are important factors for comparing alternative strategies (Beg *et al.* 2000 and 1999). Different types of pavement and materials are mentioned and a procedure where the above factors are evaluated are included. Economic evaluations are based on the life cycle cost analysis. Cost effectiveness analysis is also included in the procedure and it uses area under the performance curve as a measure of pavement strategy's effectiveness. There are some limitations in the economic evaluations, since the final selection is often affected by considerations that are not explicitly evaluated in economic analyses. There are also some miscellaneous factors such as initial budget constraints, historical practice, and traffic volume; local materials also often have an impact on pavement type selection. A computer program TxPTS was developed to automate the procedure. The final strategy selection is based on the economic alternative considering traffic, local materials, and recycleability, along with economic outputs. The decision should be made based on engineering judgment, honest consideration of project constraints, and impacts of local factors. Two questionnaire surveys were conducted to collect information, one at a state level and the other at a national level.

- Recently, Hurd (2000) researched the possibility of using rapid-hardening-cement concrete (RHCC) on fast track construction. This kind of concrete is expected to have a long service life—as much as twice that of ordinary Portland cement concrete. The rapid-hardening cement is hydraulic—that is, it sets and hardens by reacting chemically with water, and can even harden underwater if necessary. Mix proportions for RHCC are very similar to those for PCC. RHCC can be used anywhere Portland-cement concrete can be used. When doing the curing procedures, precautions must be taken to protect RCHH from high temperatures and dry winds.

- A paper by Packard (2000) presents a reconstruction project on Interstate 10 in California. A 2.8 lane-km of concrete pavement was replaced in 55 hours over one weekend. The rehabilitation project used fast-track concrete with 4-hr curing time and two different construction windows: one 55-hr weekend lane closure and a series of repeated nighttime closures of 7 and 10 hours. The weekend closures were 55% more productive than nighttime closures. The overall progress of the project was found not to be controlled by the demolition activities. Concrete delivery to the site was found to be the constraining factor.

- A paper by Delatte and Laird (1999) presents performance of bonded concrete overlays (BCO). BCO is a concrete pavement rehabilitation method used to extend the life of an existing concrete pavement. The BCO should bond fully with the existing concrete, leading to a thicker composite pavement section, a much stiffer pavement, and a considerable decrease in pavement stresses. For one project, cost estimates for a BCO were half as much as for full-depth replacement of a pavement. In some cases, BCOs have debonded shortly after construction. If this occurs, the design assumptions are violated and the increase in pavement life may not be achieved. This paper discusses some of the causes of early age debonding in BCOs. The early age behavior of newly constructed BCOs is examined. The factors affecting the long-term performance of the BCO include the quality of the surface preparation, the materials used in the BCO, and the curing of the BCO. Weather monitoring during BCO construction is recommended to identify periods when weather conditions threaten bond development, and construction should by halted. Some methods of detecting and mapping debonding are discussed. The recommendations are used to analyze case studies of BCO. The lessons learned are useful not only for investigating BCO performance but also for understanding and preparing BCO construction specifications.

- Theyse (1999) discusses the use of emulsion-treated gravel; water bound macadam, composite macadam, and Premamix material in the base layers of several experimental sections constructed labor-intensively for assessing their quality and performance constructed this way. Accelerated Pavement Testing (APT) of these sections using a Heavy Vehicle Simulator (HVS) largely contributed to the rapid assessment of these experimental sections. HVS test results from a very rapid test program made it possible to do a relative rating of the bearing capacity and benefit-cost ratios of these test sections. Preliminary application guidelines are suggested for the base layer materials used on the experimental sections. The HVS test results are currently being supplemented by static and dynamic laboratory test results with the aim of establishing a link between laboratory and APT testing.

- A paper by McCullough *et al.* (1999) presents recommendations for High Performance Concrete Paving (HPCP) practice. The ideas and recommendations presented in the paper reflect 20 years of study in Houston--Texas on improving concrete pavements placed in hot weather, especially those pavements using thermally expansive coarse aggregates. Early-age thermal cracking and poor vertical strength profiles (resulting in spalling) are a significant problem in Texas and other states that must place PCC pavements when midday temperatures may exceed 90°F. This paper gives useful recommendations on improving pavement performance, especially for PCC pavement and gives guidelines for selecting coarse aggregate. The paper provides concrete placement guidelines and some conclusions relative to general PCC pavement developments, such as the evaporation of surface moisture and operational techniques.

- Morian *et al.* (1999) present several criteria to select materials and to control construction quality. The I-15 reconstruction project in Salt Lake City was issued as a design-build contract with both maintenance and warranty requirements, to build a pavement which would perform in an excellent manner for forty years or more. Innovations in concrete mix design, and materials management were made to aid the progress of the project, and to assure that construction schedules and quality objectives are maintained. The design criteria were essentially the same as that one used by the Utah DOT, (a): the performance criterion were based on durability, friction level, structural capacity, etc.; (b) the construction quality measured by strength, air-entrainment, W/C ratio, slump, etc. The paper also encourages the optimization of <u>life cycle costs</u> during the pavement design process.

- Ramseyer *et al.* (1999) wrote an article on very-early-strength (VES) Portland cement concrete suitable for patching rigid pavements. The problem addressed is about the time required for a concrete mixture to achieve a minimum compressive strength since it influences the timing of opening a repaired road to service. The study consisted of three groups of experiments. In group 1 the admixtures were held constant but the cement content and the water to cement (w/c) ratio were varied. In group 2, the amounts of accelerator and high-range-water-reducers (HRWR) were varied independently, while the cement content and the w/c ratio were held constant. Finally, in group 3, an air entraining agent was added to the mix design. The research lead to the following conclusions:

- A VES concrete with minimal cement content is possible.
- A VES concrete with cement content of 357 kg/m^3 and a w/c ratio of 0.35 can be made with good workability and improved strength gain.
- The VES described above demonstrated improved shrinkage characteristics as compared to other mixtures such as the one used in I-40 Cross-Town Bridge in Oklahoma City.
- Decreasing the cement content decreased the shrinkage significantly in concrete mixtures suitable for patching.

- Two papers by Sprinkel (1999 and 1988) describe the condition of the first high-early strength latex-modified concrete (LMC-HE) overlay to be constructed for the Virginia DOT. The overlay was prepared with Type III cement and with more cement and less water than is used in the conventional LMC overlay. It was anticipated that the LMC-HE overlays can be used in situations in which it is desirable to expedite construction; to reduce inconvenience to motorist; to allow for installation during off-peak traffic periods such as weekends; to provide a more rapid cure in cold weather; to provide low permeability (compared to concrete without latex); and to provide high strength, particularly, high early strength.

- A paper by Anderson *et al* (1998) covers general issues in fast track reconstruction. To expedite reconstruction of urban intersections within 72 hours is complex because many different factors must be analyzed, such as traffic volumes, site access, pavement materials, cost of construction, construction sequencing and scheduling, location of business entrances, utility requirements and risks involved. Components of intersection reconstruction process model was given and conclusions with four main components for expedited urban intersection reconstruction were drawn as follow:

  (1) Planning: screens the intersection to determine if it is a candidate for expedited reconstruction within 72 hrs.
  (2) Design: confirms that the intersection can be completed within 72 hours or less, and develops design documents that contain sufficient information for contractors to effectively bid a 72-hour intersection reconstruction project.
  (3) Contractor interaction: is critical for planning the details of construction to ensure that the most efficient and cost effective construction effort is accomplished and completed within the contract time allowed.
  (4) Construction operations: monitored to ensure that the intersection is completed and opened as planned.

- A paper by Benz *et al.* (1998) describes that TxDOT faced rehabilitating of Interstate Highway 45 due to an aging structure that had exceeded its design life. Several measures were used to reduce the duration of the project. These measures included using a reconstruction process using computer modeling, cost + time bidding, bonus/penalties for early/later completion, a fast track construction sequence using precast structural member, and a public relations campaign to help inform motorists and minimize the impact of construction. The paper has some useful information on time plus cost bidding and on how to provide a questionnaire to get public information in a project survey.

- A paper by Dobrowolski and Bressette (1998) discusses Caltrans QC/QA specifications for Asphalt Concrete (AC), the QC Manual, the implementation process, some of the issues identified in the early projects, the resulting changes to the specifications and outline Caltrans plans for QC/QA development. QC/QA has changed the historical owner-contractor relationship. When projects with QC/QA specifications are compared to projects that did not use QC/QA specifications the QC/QA projects are being bid about 2.6% higher per tonne. This is lower than the 5% to 6% increase for QC cost. The final pay factors for completed projects ranged from 0.98 to 1.045 with an average of approximately 1.03.

- An article by Pasko (1998) discusses the past, present, and future of concrete pavements in the United States. The author proposed a design concept called "Pick A Slab Thickness—Protect It Forever", which shifted the emphasis from slab thickness to concentrating on seeing that all design assumptions were met, that the pavement was built as the designer intended with long-lasting materials, and that the pavement was protected and maintained to fulfill the design assumptions. The research needs for the future are addressed, primarily from the materials and construction point of view. The paper suggested that if Portland cement concrete pavement construction is to stay competitive, ways must be found to place concrete more economically, with less delay to the traffic, and in a way that the pavements provide more assurance of a maintenance-free design life. The use of high-strength concrete, if it is to be economical, will probably require new slab configurations that are untested.

- A paper by Ansari *et al.* (1997) describes a full-depth repair of jointed concrete slabs before bituminous overlay, developed by the New Jersey DOT. The agency requirements for the concrete included: a compressive strength of about 2500 psi and a modulus of rupture of about 350 psi in 6 to 7 hours after placement operations; use of accelerators limited to nonchloride-based admixtures; and workability for placement and finishing operations. Essential to the successful production of very high early-strength concrete include the mix proportions, concrete temperature, admixture dosage rates, curing and early age thermal insulation of the pavement joint. In this project, Type I cement was used but there were variations among different brands. Comprehensive studies in terms of cement brands and durability issues for these mixes were developed afterwards.

- A paper by Godiwalla (1997) discusses the total demolition and reconstruction of a heavy-duty intersection at Hobby Airport. Since only one runway can carry commercial airline traffic during reconstruction, the intersection was constructed on a fast track basis and was reopened to aircraft traffic within sixteen days. This required the use of high performance concrete, specified to 750 psi of flexural strength in 24 hours, and 850 psi in 28 days. The type of cement specified was Pyrament, CTS or Type III high-early-strength cement.

- A paper by Jeppson *et al.* (1997) addressed three methods for paving intersections with concrete: a) full depth repair, where the existing pavement is removed and replaced with concrete; b) white topping, where a depth of 4 to 5 in. of asphalt is removed and replaced with concrete; and c) ultra-thin white topping techniques may be only 2.5 in. thick. Initial costs can be competitive with asphalt. The ultra thin techniques require further research and development. An intersection rehabilitated at night during weekends with fast track techniques can be back in service for the Monday morning rush hour.

- A paper written by Walker (1997) discusses the wide range of initiatives and innovations that will ensure that the concrete paving industry is well placed to meet the challenge of future road transport requirements or policies. The modification and improvement on "whisper" concrete and overlays are discussed. Whisper concrete is the answer to the tire/noise problem and the overlays is a technique that adds on layers that can be thin bonded or partially bonded layers onto asphalt or old concrete roads. Details from the British fast track concrete paving (FTCP) proving trial show how an adequate concrete strength can be achieved in a concrete road slab at a very early age using Portland cement.

- Fast-track paving has centered on the use of construction materials and methods to improve the rate of placement and curing to reduce the traffic delay time. The state of Iowa has been able to make large improvements in the fast track process to meet target traffic delay constraints through material selection and construction methods. At the same time, the methods for monitoring concrete strength gain and quality have not changed. A paper by Cable (1996) illustrated advances being made by the Iowa DOT and Iowa State University in the use of maturity measurements and other electronic methods to reduce traffic delay and construction project duration. The paper suggests that nondestructive testing employing maturity concepts can be used on any type of concrete paving or patching project regardless of the thickness being placed. Because of these projects, the Iowa DOT instituted an Instructional Memorandum for use on several state highway projects in 1996 to utilize the use of maturity measurements in the control of traffic sensitive areas.

- Three papers by Cole and Voigt (1996, 1995a, 1995b) address modifications to traditional fast-track PCC pavement construction. Fast track often uses conventional concrete paving materials and procedures, but key changes can significantly expedite construction, such as material modifications, equipment specifications, changes in worker responsibilities, construction staging, pavement joint construction, blanket curing, nondestructive testing and opening-to-traffic criteria.

- Another paper by Delatte *et.al.* (1996) presents criteria for opening expedited bonded concrete overlays (BCO) to traffic. For rehabilitation of concrete pavements, resurfacing with a bonded concrete overlay may provide significantly longer life and reduced maintenance costs. Two important issues considered in rehabilitation are bonding and rapid reopening of resurfaced sections. The purpose of expedited concrete paving is to limit both the duration of lane closure and the inconvenience to the public. Expedited BCOs offer an economical method for substantially extending rigid pavement life. Research for expedited BCOs in El Paso and For Worth, Texas, has been carried out for the Texas DOT. Results of previous expedited BCO construction are reviewed. Laboratory testing for this project included a high-early-strength mix design, bond development of that mix design, and early-age fatigue strength of half-scale BCO models. A 122-m-long test strip was cast with eight different expedited BCO designs, and accelerated traffic loading was imposed at 12 hr. Current recommendations made to TxDOT by Center for Transportation Research (CTR) suggest that the BCO be at least 12 hr old and attain a splitting tensile strength of at least 3450 KPa (500 psi).

- Grove and Jones (1996) discuss various aspects of fast track concrete paving and offer some examples of opening times based on various combinations of Portland cement type, cement content, ambient concrete and curing temperatures. These elements control concrete mixture properties and greatly influence when a pavement can be opened to traffic. According to cement types, conventional Type I and II cements used in most paving, can also be used in a fast track mixture. Fast track offers the opportunity to open pavement sections when needed.

- A paper from Hall (1996) illustrates the evolution of fast track paving procedures on four projects in Wisconsin. Two of them consist of hand-placed and slip-formed pilot projects, which employed mixes with a water reducer, and 420 and 385 kg/m^3 of Type III cement respectively, a curing compound and insulating blankets. Another project was a hand-placed intersection where Type III cement was used with heated water, and calcium chloride to attain 21 MPa (3 ksi) compressive strength in about 8 hours. A curing compound and insulating blankets were also used. In the fourth project, a slip-formed runway project used 392 kg/m^3 of Type III cement with a water-reducer to achieve 24 MPa (3.6 ksi) of compressive strength in 12 hours. Only a curing compound was used. Some key lessons can be learned from these projects: (1) Cooperation between the contractor and the agency throughout all stages of planning and construction of a fast-track project are absolutely essential; (2) Good results can be obtained using relatively "low tech" materials and construction methods; (3) Careful consideration of slab temperature is required to prevent cracking; (4) Maturity meters can provide an effective means to minimize the amount of strength testing required on larger projects; (5) End-result specifications five the contractor the flexibility to customize fast track procedures to fit each job best.

- Risser and Johnston (1996) provide some tips for reconstructing concrete intersections. Intersections represent a special challenge in concrete pavement construction. Having to accommodate traffic flow while striving to meet project specifications for drainage, smoothness, and other structural requirements tests a contractor's construction and organizational skills. By carefully considering phase options, employing fast-track paving techniques such as the use of high-early-strength concrete, and using proper approaches to drainage and jointing, contractors can construct a concrete intersection that will serve for decades.

- A paper by Cole and Okamoto (1995) presents rational criteria for opening concrete roadways to traffic, based on flexural strength to apply to new construction, reconstruction and concrete overlays, except bonded concrete overlays. The criteria to open pavements to traffic are generally based on in-place concrete strength, not on time. The rate of concrete strength gain is affected by a number of factors other than time, such as water-to-cement ratio and properties of cement (composition and fineness). The flexural strength required for opening depends on a number of pavement-specific factors such as pavement application (new construction, unbonded overlay, concrete overlay of existing asphalt); type, weight, and frequency of anticipated loadings; distance and distribution of loads from edge of pavement and others. The concrete pavement's in-place flexural strength can be determined by nondestructive testing (NDT) measurements of the pavement, particularly maturity and pulse velocity testing, which offer several advantages over cylinder or beam testing. Although it is impossible to account for all combinations of factors affecting opening flexural strength, reasonable values or range of values of these factors can be selected.

- There are findings by Hauer *et al.* (1994) indicating that in some fast track projects, safety initially declined. However, in resurfacing and reconditioning and preservation projects, safety improved. Two methodological innovations may be of interest: First, because the safety effect of resurfacing changes as the pavement ages, it was necessary to find a way to examine changes in safety as a function of time. Second, the accuracy of studies of this kind is often limited by the sporadic of accident data.

- A paper by Hossain *et al.* (1994) describes a section of fast track concrete pavement built in an urban setting in Manhattan, Kansas. The section had its mixture design developed using a special Type-III cement and three different types of locally available aggregates. Strength gain of this mix in the field was satisfactory except on a few occasions when the daily low temperature dropped below 0°C (32°F). Two mixes with different water-cement ratios performed equally in terms of strength gain. The maturity data collected in the slabs and field beams indicate that the maturity of companion field beams lagged that of the slab bottom or top. However, the maturity number was well correlated with the 24-hr flexural strength of the beams when the beam strengths were corrected for temperature of testing. The field beams appeared to mature earlier than the laboratory beams and thus showed higher strengths at the same age. Multiple surveys of this fast track pavement during the past few years did not reveal any major distress.

- Nagi *et al.* (1994) researched on minimum strength levels of concrete used for rapid repair of pavements. The article reports on the scope of the investigation, field test techniques, and the findings at field sites. The following field tests are used: water content using microwave oven drying; temperature matched curing, maturity monitoring and ultrasonic pulse velocity. Based on the results of the study, the authors draw five conclusions: 1) microwave oven drying is a rapid means to determine water content of fresh concrete, 2) early strength gain can be monitored via maturity and pulse velocity during the curing period in pavement repair slabs, 3) the maturity approach offers a more exact prediction of strengths close to time opening, 4) nondestructive test readings must be calibrated to strength prior to construction, and 5) curing test cylinders in a well-insulated curing box may offer a simple means of prediction in-place strength of rapid repair mixes.

- An investigation of the strength and durability of field concretes used for rapid highway repairs was described by Nagi and Whiting (1994). This Strategic Highway Research Program study involved sites in Georgia and Ohio. Three categories of opening times were chosen: 2 to 4 hours, 4 to 6 hours, and 12 to 24 hours. Compressive strength and splitting tensile strength were tested as well as freeze-thaw resistance testing. Results of the study indicate that relatively high long term compressive strengths can be achieved using a variety of rapid pavement repair materials typically obtained by using a high cement content, low water-to-cementitious materials ratio and accelerating admixtures.

- Okamoto and Whiting (1994) addressed rapid strength-gain concrete repair mixtures that cure within 4 to 12 hours and were used to carry out full-depth slab repairs on a section of Interstate highway I-20 west of Augusta, Georgia. The mixtures included a calcium chloride accelerated mix, a very-early-strength mix developed under the Strategic Highway Research Program, and a "fast track" mix previously used for early opening of concrete intersection. Pulse velocity and maturity functions were used to predict in-situ strength gain of concrete in instrumented test repair sections. Temperatures were monitored through the depths of the test slabs during the initial 8 hour of curing. Temperatures at mid-depth ranged from 60°C to 70°C for these mixes. After 4 hour of curing, the very early strength mix exceeded 14 MPa (2 ksi) compressive strength, as determined by in-situ methods. The other two mixes gained strength at a slower rate.

- Technology for fast cure concrete was used in a highway pavement according to Nam and Tatum (1992). During July 1986, a 4 in. concrete overlay was applied to 7 miles of U.S. Highway 71, north of Storm Lake, Iowa. The project team developed a new type of concrete mix that cures fast to allow traffic onto the road in only 24 hours. This innovation provides an example of cooperative government-industry effort and successful procurement policies implemented by a government agency. Initiated as a response to competition from other materials, the development of fast track concrete illustrates the process and involvement of many organizations in product innovation. This paper describes the development of paving technologies in Iowa, the formation of an industry association, and the innovation process to bring about technical improvements and cost competitiveness. The last section describes elements of government policy to foster an increased rate of innovation in U.S. public construction, including supporting increased technical capability, using demonstration projects, encouraging competing technologies.

- White and Pumphrey (1992) discussed overlay design procedures for PCC pavements for the Indiana DOT. Initial analysis of tests and performance observations based on a statistical experiment design resulted in unsatisfactory performance functions. Because great care had been applied in identifying the significant factors and their levels in arriving at the experimental design, the overall concept of the experiment was reviewed. As a result, it was realized that the experimental design grouped all combinations of PCC and composite pavements. The database used included several pavement combinations.

- Drinkard (1991) reported a repair work made to a runway of an Air Force Base that reopened to traffic within several hours. A number of logistical problems were solved and a functional scheme using new cement materials was proposed after continuous designer and contractor input. This paper details the pavement design, the characteristics of the new cement technology, and the construction methods utilized in successfully completing the 67 day replacement of a complete runway intersection while maintaining daytime aircraft operations. The relative economical benefits are compared to those of facility shutdown. The advantage of designer/contractor interaction during the design of a fast track project is also emphasized. The experience of using new material technology combined with intensive designer/contractor interaction during design as well as construction, resulted in a successful project that should give outstanding performance for many years.

- A paper by Parker and Shoemaker (1991) presents laboratory and field studies conducted to evaluate three rapid-setting PCC pavement patch materials and several construction techniques. Laboratory mix design studies reveal that PCC with and without steel fibers can be produced with early strengths adequate for one-day patch construction. Four-hour compressive strengths for these materials are lower than proprietary patch material, but after 5 to 6 hours, their strengths are higher. Anchor optimization studies indicate that ultimate loads resisted by simulated patches are linearly proportional to the amount of anchor steel and that smaller anchor sizes perform best. During a field study, the effects of pavement location and condition, construction temperature, anchors, and sawing to outline patch areas are evaluated. Patches constructed of fibrous PCC perform best. The inclusion of anchors does not improve patch performance. Patches constructed during warm weather perform better than those constructed during cool weather. Patch performance is influenced by overall pavement condition with better patch performance on pavements with better condition. Sawing to outline patch area improves patch performance and aids patch construction.

- Abdulshafi *et al.* (1990) describe the use of fast track concrete paving on the mainline portion of a major four-lane arterial street in Cedar Rapids, Iowa, which permitted achievement of the opening strength of 440 psi in less than 12 hr. Because of the traffic volume and the detour problem, closure of the intersections, even for one day was not feasible. Fast Track II (mix with a higher cement content compared to Fast Track mix), used for the intersection, achieved the opening strength of 350 psi in 6 to 7 hr. Flexural and compression specimens of two sections each in the Fast Track (Class F) and Fast Track II sections were subjected to pulse velocity tests. Maturity curves were developed after monitoring the temperatures. Correlations were performed between the pulse velocity and flexural strength and between the maturity and flexural strength. The project established the feasibility of using Fast Track II to construct Portland cement concrete pavement at night and opening the roadway to traffic the next day.

- A paper by Knutson (1990) presented a cost-effective, long-term solution to improve the structural capacity and rideablility of existing concrete pavements. One option is a thin-bonded concrete overlay. By increasing slab thickness, a bonded overlay substantially increases pavement structural capacity resulting in less pavement damage per applied load. Increasing the monolithic slab thickness beyond eleven (11) inches practically eliminates fatigue cracking except under extremely heavy traffic conditions. Compared with asphalt overlays, bonded concrete overlays provide significantly more structural improvement per inch of thickness.

- In the past, fast track concrete has proven to be successful in obtaining high early strengths. This benefit does not come without cost. Special Type III cement and insulating blankets to accelerate the cure, add to its expense when compared to conventional paving. Grove (1989) addressed a research program attempting to determine the benefit derived from the use of insulating blankets to accelerate strength gain in three concrete mixes using Type I cement. The goal was to determine mixes and curing procedures that would result in a range of opening times. This determination would allow the most economical design for a particular project by tailoring it to a specific time restraint. Three mix designs with various cement content were tested in the field. The results showed a significant improvement in early strength gain with the use of insulating blankets.

- Iowa used quick setting, fast track concrete that allowed traffic back on the pavement within 24 hours. A paper by Knutson and Riley (1988) addressed details of the installation and construction of these pavements. The pavements are constructed to last 30 years. The quick setting concrete was mixed with conventional equipment. With refinement, new equipment may be developed that mixes concrete immediately in front of the paver, a process that would allow even quicker setting concretes. To maximize curing, a heavy coat of curing compound was applied and an insulating blanket was used to cover the concrete. Although fast track construction added $1 to $2 per sq yd to the cost, the increase is offset by reductions in traffic rerouting and liability.

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Appendix B Survey Form #1

Expedited Pavement Construction Survey
The University of Texas at El Paso
The University of Texas San Antonio

A. General Information

Name: ____________________________ Title: __________________________
Tel No: (   )___________ Fax No: (   )___________ E-mail:_______________
Address: ____
City: _________________________ Zip:_________

Do you consider yourself (Mark as many as applicable)
☐ Contractor ☐ Designer ☐ Researcher
☐ Construction Engineer/ Inspector ☐ Material Supplier
☐ Other ______________________

B. Pavement Cross-Section Selection

1. Check the appropriate box representing the importance given to the following factors when considering using expedited construction? We have provided space on pages 3 and 4 for you to comment on each of the 12 items below:

Factor	Very Important	Somewhat Important	Not Important
1. Construction Methods	☐	☐	☐
2. Use of Local Materials	☐	☐	☐
3. Subgrade Type and Properties	☐	☐	☐
4. Base Type and Properties	☐	☐	☐
5. Traffic Loads	☐	☐	☐
6. Climatic Conditions	☐	☐	☐
7. Curing Methods	☐	☐	☐
8. Time to Open to Traffic	☐	☐	☐
9. QC/QA	☐	☐	☐
10. Equipment availability	☐	☐	☐
11. Ease of Maintenance	☐	☐	☐
12. Durability	☐	☐	☐

13. Please name other important factors that are missing:

2. Do you use software to design pavements for expedited projects? ☐ Yes ☐ No
If yes, which software programs?

____

3. What criteria do you consider to determine the time to open the pavement to traffic? (Mark as many as applicable)

☐ Flexural Strength ☐ Compressive Strength ☐ Modulus of Elasticity
☐ Maturity ☐ Time from Pouring ☐ Weather
☐ Other Criteria: ____________________

Please explain how you use the criteria:

____
____
____
____
____

4. Do you consider economic analysis when considering expedited pavement projects?
☐ Yes ☐ No

If yes, what parameters do you consider? (Mark as many as applicable)
☐ Initial costs ☐ User Costs ☐ Life-cycle Costs
☐ Other Costs ____________________

Do you use software for economic analysis? ☐ Yes ☐ No
If yes, name the software ____________________

5. Please provide any suggestions you may have on expediting pavement construction? (For example: new materials, construction methods, modifiers, reduced pavement sections such as removing a specific layer, etc.):

____
____
____
____

6. Do you know of any experimental or innovative projects throughout the nation that we should consider as a case study in this project?

____
____
____
____

7. Do you mind if we contact you for some clarification and information? ☐ Yes ☐ No
If no, what is the best means? ☐ Phone ☐ e-mail

8. The 13 items included in the table on page 1 are again included below. Please feel free to comment on any or all of the items.

(1) Construction Methods:

(2) Use of Local Materials:

(3) Subgrade Type and Properties:

(4) Base Type and Properties:

(5) Traffic Loads:

(6) Climatic Conditions:

(7) Curing Methods:

(8) Time to open to Traffic:

(9) QC/QA:

(10) Equipment Availability:

(11) Ease of Maintenance:

(12) Durability:

(13) Others:

Appendix C Survey Form #1: Summary of Replies

1. **Check the appropriate box representing the importance given to the following factors when considering using expedited construction.**

Factor	Very Important	Somewhat Important	Not Important
1. Construction Methods	16	6	0
2. Use of Local Materials	5	14	3
3. Subgrade Type and Properties	13	8	1
4. Base Type and Properties	12	9	1
5. Traffic Loads	13	7	3
6. Climatic Conditions*	10	10	1
7. Curing Methods	13	9	0
8. Time to Open to Traffic	21	1	0
9. QC/QA	10	11	1
10. Equipment availability *	10	9	2
11. Ease of Maintenance*	4	12	5
12. Durability	16	5	1
13. Please name other important factors that are missing: • Clear Right of way, utilities moved, contractor having unobstructed access to work area. • Traffic management options (detours, lane closures, etc), type of pavement (plain, doweled, continuously reinforced). • Ease of construction and risk of failure factor, strength of contract term enforcement. • Joint Design • Time of initialization • Cost incentives for early completion / disincentives for late opening			

* One respondent left these blank.

Notes from some respondents:

- Traffic volumes are **Somewhat Important**, and the traffic loads are **Not Important**.
- Only cover the first question and leave others blank.

2. **Do you use software to design pavements for expedited projects?**
   (11) Yes (9) No (2) Blank

   If Yes, which software programs?

- ACPA
- ACI
- FAA
- Darwin from AASHTOware to determine the time to open the pavement to traffic.
- LEDFAA
- PCA
- AASHTO
- ISLAB 86 – Automated AASHTO Method

- ISLAB 2000, a program developed for White topping to determine the pavement thickness
- AASHTO'93 - WINPAS BY ACPA
- TxDOT standard software
- TSLAB is used to determine concrete thickness
- FPS 19

3. What criteria do you consider to determine the time to open the pavement to traffic? (Mark as many as applicable)

(15) Flexural Strength (10) Compressive Strength (None) Modulus of Elasticity
(9) Maturity (2) Time from Pouring (2) Weather
(2) Other Criteria: Curing, Temperature-curing time

Please explain how you use the criteria:

- We recommend strength, not time, for determining when to open to traffic.
- Owner's specifications
- Usually, we just wait the required time from pouring to open section, with the specific required testing of the cylinders.
- Maturity meter based upon prior performances data of mix design. Testing cylinders/beams to confirm strength generated.
- Time to open is always strength to perform, balanced against need to use. Strength can be measured in any suitable way. We currently use compressive for PCCP, due to ease of measurement. Maturity can be more accurate and site specific and may allow earlier opening, not due to more definitive test method. Flexural, time, modulus of elasticity, etc. are all ways of measuring strength and suitability for loading.
- If we use compressive strength for opening to traffic, we make a number of informational cylinders and cure them next to the slab. The road may be open to traffic if the informational cylinders break above 2500 psi. When we go fast track, maturity vs. compressive strength curve is made at a field tests slab near the project to find the degree-hours needed to reach 2500 psi. We monitor the degree-hours on the project and open after the specified degree-hours are obtained.
- MDOT (Michigan) specimens require beam breaks at jobsite to verify flexural strength before opening.
- As outlined in the specific book.
- The Atlanta district has done one intersection under accelerated conditions.

4. Do you consider economic analysis when considering expedited pavement projects?
(19) Yes (3) No

If yes, what parameters do you consider? (Mark as many as applicable)
(10) Initial costs (12) User Costs (12) Life-cycle Costs
(3) Other Costs: Construction Costs, Airline delays, Maintenance costs, traffic control costs,

preliminary and construction engineering costs, along with rehabilitation costs.

Do you use software for economic analysis? (6) Yes (11) No

If yes, name the software:

- TTI does work for us
- ACI/ACPA/FAA
- Spreadsheets
- Crystal Ball
- Darwin has a module for life cycle cost
- MDOT has its own procedures
- QUEUES program for user delay.

5. **Please provide any suggestions you may have on expediting pavement construction? (For example: new materials, construction methods, modifiers, reduced pavement sections such as removing a specific layer, etc.):**

- Pavement expedition is always enhanced by: a clear plan of action, clear understanding of operations, clear understanding of consequences, a clear field of operations (as uncomplicated a working area as possible), and use of materials/designs suitable to provide the service needed. New materials, methods, modifiers, reduced sections, etc. are worthless if they shorten designed life, increase maintenance, or otherwise affect economic performance.
- Improve sequencing and make available the most area to pave.
- In airfields-remove concrete down to CTB and come back up
- Inlay replacement
- Permeable base course
- PCC Bonded overlays
- More streamlined process for introducing new products and construction techniques, more emphasis on concrete pavement subbase structure, and longer life-cycle pavements, more disseminating of knowledge to contractors regarding pavement distress for warranty work.
- Don't limit contractor innovation. Decide what factors are important.
- Preparation, preparation and preparation
- We have used calcium chloride and super plasticizers to speed the process.
- MDOT (Michigan) and the industry are finding that complete closures often have the best cost/benefit to the motoring public as well as offering safer constructor for drivers and workers. Public seems to agree: close it and get it done vs. lane closures.
- Bonus/Penalty incentives
- Full depth concrete intersections.
- This depends on the scope of work. For rehabilitation projects, recommend in place stabilization of existing material, then base or HMA overlay.

6. **Do you know of any experimental or innovative projects throughout the nation that we should consider as a case study in this project?**

- RALE pavement design (research not completed but shows promise for long life pavement and use of alternate concrete products).
- 33-day reconstruction of RW9R at Atlanta Herfsfield international airport-1999.
- 9-month reconstruction of RW 18 R in Memphis-2002
- Atlanta, Georgia Airport—Runway Reconstruct in 33 days and Lane reconstruction in 55 hours.
- Any pre-cast panel replacement projects
- Refer to NCHRP project 10-50A which is in the process of being finalized. The title of the study is "Guidelines For Selecting Strategies For Rehabilitation of Rigid Pavements Subjected to high Traffic Volumes." The PI is Stuart Anderson.
- Michigan has a number of "A+B" projects on reconstructs and concrete overlays using a variety of methods. I-75 in Detroit, US 23 overlays, I-69 overlay, and I-275 reconstruction.

7. **Do you mind if we contact you for some clarification and information**?
   (3) Yes (18) No

   If no, what is the best means? (4) Phone (8) e-mail (7) either

Appendix D Survey Form #2

PCC Pavement Construction Survey in Texas

Survey Conducted by

The University of Texas at El Paso and The University of Texas at San Antonio

A. GENERAL INFORMATION

Name: ____________________

Title/Position: ____________________

E-mail: ____________________

TxDOT District Office: ____________________

Address: ____________________

City: ____________________ Zip: __________

B. PROJECT INFORMATION

Please answer the following questions and provide any additional information

1. Do you have PCC surfaced rigid pavement construction in your District?
   ☐Yes ☐ No (If no, please stop and just fax this page back to us)

2. On which **type of projects** is PCC commonly used in your District? (Mark as many as applicable)
   ☐ New ☐ Reconstruction ☐ Repairs/Rehabilitations ☐Other
   Specify: ____________________

3. Which **opening to traffic criteria** does your District follow?
   ☐ None ☐ Flexural strength ☐ Compressive strength ☐ Maturity
   ☐ Other
   Specify time: ____________________
   Specify required psi: ____________________

3a. Would you like to use NDT to open the pavement to traffic? ☐Yes ☐ No

4. What are the most common **base treatment** methods used (if any) in your District? (Mark as many as applicable)
   ☐ Lime ☐ Cement ☐ Asphalt ☐ Fly-ash ☐ Other __________

5. What are the most common **subgrade treatment** methods used (if any) in your District? (Mark as many as applicable)
   ☐ Lime ☐ Cement ☐ Asphalt ☐ Fly-ash ☐ Other __________

6. Comments
   ____
   ____
   ____

7. TYPICAL RIGID PAVEMENT SECTIONS in your District

Select construction type, highway system and fill out table with applicable information. NOTE: Copy this page as necessary to document additional pavement sections.

☐ JRCP ☐ JCP ✔ CRCP

✔ Interstate **X** High Volume/Urban ☐ US/SH/FM ☐ Other

Layer system	Type	TxDOT Design Standard (if used)	Thick (in.) Laid or treated	Construction Joint Spacing @ (ft) (if applicable)		Rebar Size @ Spacing (in) (if applicable)				
				Transv. (Width)	Long. (travel lane)	No of rebar layers	Single or bottom		Top	
							Transv.	Long.	Transv.	Long.
No. 1 (top)	slab	CPCR(2)-94	13	81	9	2	6@24	6@5.5	6@24	6@5.5
No.	Asphalt concrete		4							
No.	Base		12	Cement stabilized						
No.	Subgrade		10	Lime treated						
No.										
Soil	Subgrade			Silty sand with High PI clay lenses						
	✔ ASTM (USCS) ☐ AASHTO			Classification (if known): SM						

✔ JRCP ☐ JCP ☐ CRCP

☐ Interstate ✔ High Volume/Urban ☐ US/SH/FM ☐ Other

Layer system	Type	TxDOT Design Standard (if used)	Thick (in.) Laid or treated	Construction Joint Spacing @ (ft) (if applicable)		Rebar Size @ Spacing (in) (if applicable)				
				Transv. (Width)	Long. (travel lane)	No of rebar layers	Single or bottom		Top	
							Transv.	Long.	Transv.	Long.
No. 1 (top)	slab	CPCR(1)-94	10	70	8.5	1	6@36	6@8.5		
No.	Base		24	Granular						
No.										
No.										
No.										
Soil	Subgrade		12	Silty soil						
	☐ ASTM (USCS) ✔ AASHTO			Classification (if known): A-4						

Appendix E Survey Form #2: Summary of Replies

D02 - FORT WORTH (1)

☐ JRCP ☐ JCP **X** CRCP

☐ Interstate ☐ High Volume/Urban **X** US/SH/FM **X** Other

Layer system	**Type**	**TxDOT Design Standard** (if used)	**Thick (in.)** Laid or treated	**Construction Joint Spacing @ (ft)** (if applicable)		**Rebar Size @ Spacing (in)** (if applicable)				
				Transv. (Width)	**Long.** (travel lane)	**No of rebar layers**	**Single or bottom**		**Top**	
							Transv.	**Long.**	**Transv.**	**Long.**
No. 1 (top)	Slab	CPCR(2)-94	8"	See standard	See standard	One	See standard	See standard		
No. 2	Asphalt Concrete		4"							
No. 3	Lime Stab. SG (clays) or Cement Stab. SG (sands)		8"-18"							
Soil	Subgrade									
	✔ ASTM (USCS) ☐ AASHTO			Classification (if known):CH, CL, SM						

D02 - FORT WORTH (2)

☐ JRCP ☐ JCP **X** CRCP

X Interstate **X** High Volume/Urban **X** US/SH/FM ☐ Other

Layer system	**Type**	**TxDOT Design Standard** (if used)	**Thick (in.)** Laid or treated	**Construction Joint Spacing @ (ft)** (if applicable)		**Rebar Size @ Spacing (in)** (if applicable)				
				Transv. (Width)	**Long.** (travel lane)	**No of rebar layers**	**Single or bottom**		**Top**	
							Transv.	**Long.**	**Transv.**	**Long.**
No. 1 (top)	Slab	CPCR(2)-94	12"-13"	See Standard	See Standard	One	See standard	See standard		
No. 2	Asphalt Concrete		4"							
No. 3	Lime Stab. SG (clays) Or Cement Stab. SG (sands)		8"-18"							
Soil	Subgrade									
	✔ ASTM (USCS) ☐ AASHTO			Classification (if known):CH,CL, SM						

D03 - WICHITA FALLS

☐ JRCP ☐ JCP **X** CRCP

☐ Interstate ☐ High Volume/Urban **X** US/SH/FM ☐ Other

Layer system	**Type**	**TxDOT Design Standard** (if used)	**Thick (in.)** Laid or treated	**Construction Joint Spacing @ (ft)** (if applicable)		**Rebar Size @ Spacing (in)** (if applicable)				
				Transv. (Width)	**Long.** (travel lane)	**No of rebar layers**	**Single or bottom**		**Top**	
							Transv.	**Long.**	**Transv.**	**Long.**
No. 1 (top)	CRCP	CPCR(1)-94	10							
No. 2	Black (Asphalt) Base		4	Asphalt Treated Base						
No. 3	Lime Subgrade		8	Lime Treated Subgrade						
Soil	Subgrade									
	☐ ASTM (USCS) ☐ AASHTO			Classification (if known):						

D05 - LUBBOCK (1)

☐ JRCP ☐ JCP **X** CRCP

X Interstate ☐ High Volume/Urban ☐ US/SH/FM ☐ Other

Layer system	**Type**	**TxDOT Design Standard** (if used)	**Thick (in.)** Laid or treated	**Construction Joint Spacing @ (ft)** (if applicable)		**Rebar Size @ Spacing (in)** (if applicable)				
				Transv. (Width)	**Long.** (travel lane)	**No of rebar layers**	**Single or bottom**		**Top**	
							Transv.	**Long.**	**Transv.**	**Long.**
No. 1 (top)	Slab	CPCR(1)-94	10	105	12	1	6@24	6@8.5		
No. 2	Asphalt Concrete		4							
Soil	Subgrade									
	✓ ASTM (USCS) ☐ AASHTO			Classification (if known): CL and SM						

D05 - LUBBOCK (2)

☐ JRCP ☐ JCP **X** CRCP

☐ Interstate **X** High Volume/Urban ☐ US/SH/FM ☐ Other

Layer system	Type	TxDOT Design Standard (if used)	Thick (in.) Laid or treated	Construction Joint Spacing @ (ft) (if applicable)		Rebar Size @ Spacing (in) (if applicable)				
				Transv. (Width)	Long. (travel lane)	No of rebar layers	Single or bottom		Top	
							Transv.	Long.	Transv.	Long.
No. 1 (top)	Slab	CPCR(1)-94	10	70	12	1	6@36	6@8.5		
No. 2	Asphalt Concrete									
Soil	Subgrade									
	✓ASTM (USCS) ☐ AASHTO			Classification (if known): CL and SM						

D10 – TYLER (1) Cherokee Co. 0198-04-027 US 175 Jacksonville

☐ JRCP ☐ JCP **X** CRCP

☐ Interstate ☐ High Volume/Urban **X** US/SH/FM ☐ Other

Layer system	Type	TxDOT Design Standard (if used)	Thick (in.) Laid or treated	Construction Joint Spacing @ (ft) (if applicable)		Rebar Size @ Spacing (in) (if applicable)				
				Transv. (Width)	Long. (travel lane)	No of rebar layers	Single or bottom		Top	
							Transv.	Long.	Transv.	Long.
No. 1 (top)	Paveme nt "C"	CRCP (1)-94	11		CL, 20' R, 20'L	1	6@24	6@7		
No. 2	ACP Base		2							
No. 3	Subgrade		8	Lime Treated						
Soil	Subgrade									
	☐ ASTM (USCS) ☐ AASHTO			Classification (if known):						

D10 – TYLER (2) I-20 Sabine River/ESTES Parkway

☐ JRCP ☐ JCP **X** CRCP

X Interstate ☐ High Volume/Urban ☐ US/SH/FM ☐ Other

Layer system	**Type**	**TxDOT Design Standard** (if used)	**Thick (in.)** Laid or treated	**Construction Joint Spacing @ (ft)** (if applicable)		**Rebar Size @ Spacing (in)** (if applicable)				
				Transv. (Width)	**Long.** (travel lane)	**No of rebar layers**	**Single or bottom**		**Top**	
							Transv.	**Long.**	**Transv.**	**Long.**
No. 1 (top)	Paveme nt *	CRCP (1)-94	13		CL, 12' R, 12'L	1	6@36	6@5.5		
No. 2	HMAC Base		4							
No. 3			6	Soil Cement Base						
Soil	Subgrade									
	☐ ASTM (USCS) ☐ AASHTO			Classification (if known):						

* Section where information is taken from is STA. 748+75.51

D10 – TYLER (3) Van Zandt Co. 0108-02-030- SH-19 Canton

☐ JRCP **X** JCP ☐ CRCP

☐ Interstate ☐ High Volume/Urban **X** US/SH/FM ☐ Other

Layer system	**Type**	**TxDOT Design Standard** (if used)	**Thick (in.)** Laid or treated	**Construction Joint Spacing @ (ft)** (if applicable)		**Rebar Size @ Spacing (in)** (if applicable)				
				Transv. (Width)	**Long.** (travel lane)	**No of rebar layers**	**Single or bottom**		**Top**	
							Transv.	**Long.**	**Transv.**	**Long.**
No. 1 (top)	Paveme nt "B"	CPCD	9		* 7'	N/A				
No. 2	ACP Base		4							
No. 3	Flex Base		12	Subbase excavation / replace w/ flex base & Rap						
Soil	Subgrade									
	☐ ASTM (USCS) ☐ AASHTO			Classification (if known):						

* Contractor's choice of joint placement 7' R or L of CL

D10 – TYLER (4) SH-334

☐ JRCP **X** JCP ☐ CRCP

☐ Interstate ☐ High Volume/Urban **X** US/SH/FM ☐ Other

Layer system	**Type**	**TxDOT Design Standard** (if used)	**Thick (in.)** Laid or treated	**Construction Joint Spacing @ (ft)** (if applicable)		**Rebar Size @ Spacing (in)** (if applicable)				
				Transv. (Width)	**Long.** (travel lane)	**No of rebar layers**	**Single or bottom**		**Top**	
							Transv.	**Long.**	**Transv.**	**Long.**
No. 1 (top)		CPCD	9		* 5.5 or 16.5					
No. 2	ACP Base		4							
No. 3	Subgrade		8	Lime treated						
Soil	Subgrade									
	☐ ASTM (USCS) ☐ AASHTO			Classification (if known):						

* Contractor's choice of joint placement 5.5 R or L of CL or 16.5' R or L of CL

D10 – TYLER (5) Henderson & Kaufman Cos. 0697-02-027- SH-198 Canton

☐ JRCP **X** JCP ☐ CRCP

☐ Interstate ☐ High Volume/Urban **X** US/SH/FM ☐ Other

Layer system	**Type**	**TxDOT Design Standard** (if used)	**Thick (in.)** Laid or treated	**Construction Joint Spacing @ (ft)** (if applicable)		**Rebar Size @ Spacing (in)** (if applicable)				
				Transv. (Width)	**Long.** (travel lane)	**No of rebar layers**	**Single or bottom**		**Top**	
							Transv.	**Long.**	**Transv.**	**Long.**
No. 1 (top)		CPCD	9		7' R or L of CL	N/A				
No. 2	ACP Base		4							
No. 3	Subgrade		8	Lime treated						
Soil	Subgrade									
	☐ ASTM (USCS) ☐ AASHTO			Classification (if known):						

* Contractor's choice of joint placement 7' R or L of CL

D11 – LUFKIN

☐ JRCP | **X** JCP | ☐ CRCP

☐ Interstate | ☐ High Volume/Urban | **X** US/SH/FM | ☐ Other

Layer system	Type	TxDOT Design Standard (if used)	Thick (in.) Laid or treated	Construction Joint Spacing @ (ft) (if applicable)		Rebar Size @ Spacing (in) (if applicable)				
				Transv. (Width)	Long. (travel lane)	No of rebar layers	Single or bottom		Top	
							Transv.	Long.	Transv.	Long.
No. 1 (top)	CRCP	CPCR (1)	12	12	15					
Soil	Subgrade									
	☐ ASTM (USCS) ☐ AASHTO			Classification (if known):						

D12 - HOUSTON (1)

☐ JRCP | ☐ JCP | **X** CRCP

☐ Interstate | ☐ High Volume/Urban | ☐ US/SH/FM | ☐ Other

Layer system	Type	TxDOT Design Standard (if used)	Thick (in.) Laid or treated	Construction Joint Spacing @ (ft) (if applicable)		Rebar Size @ Spacing (in) (if applicable) GR.60				
				Transv. (Width)	Long. (travel lane)	No of rebar layers	Single or bottom		Top	
							Transv.	Long.	Transv.	Long.
No. 1 (top)	Slab	CRCP 2000	10			1	6@36	6@9.0		
No. 2	Bond Breaker		1	Black Base						
No. 3	PCTB		6	Cement Stabilized						
No. 4	Subgrade		6	Lime Treated						
Soil	Subgrade			Varies						
	☐ ASTM (USCS) ☐ AASHTO			Classification (if known):						

D12 - HOUSTON (2)

□ JRCP　□ JCP　X CRCP

□ Interstate　□ High Volume/Urban　□ US/SH/FM　□ Other

Layer system	Type	TxDOT Design Standard (if used)	Thick (in.) Laid or treated	Construction Joint Spacing @ (ft) (if applicable)		Rebar Size @ Spacing (in) (if applicable) GR.70/75				
				Transv. (Width)	Long. (travel lane)	No of rebar layers	Single or bottom		Top	
							Transv.	Long.	Transv.	Long.
No. 1 (top)	Slab	CRCP 2000	10			1	5@36	5@7.5		
No. 2	Bond Breaker		1	Black Base						
No. 3	PCTB		6	Cement Stabilized						
No. 4	Subgrade		6	Lime Treated						
Soil	Subgrade			Varies						
	□ ASTM (USCS)	□ AASHTO		Classification (if known):						

D12 - HOUSTON (3)

□ JRCP　□ JCP　X CRCP

□ Interstate　□ High Volume/Urban　□ US/SH/FM　□ Other

Layer system	Type	TxDOT Design Standard (if used)	Thick (in.) Laid or treated	Construction Joint Spacing @ (ft) (if applicable)		Rebar Size @ Spacing (in) (if applicable) GR 70				
				Transv. (Width)	Long. (travel lane)	No of rebar layers	Single or bottom		Top	
							Transv.	Long.	Transv.	Long.
No. 1 (top)	Slab	CRCP 2000	13			1	#7@36	#8@8.0		
No. 2	Bond Breaker		1	Black Base						
No. 3	PCTB		6	Cement Stabilized						
No. 4	Subgrade		6	Lime Treated						
Soil	Subgrade			Varies						
	□ ASTM (USCS)	□ AASHTO		Classification (if known):						

D13 - YOAKUM (1) Colorado Co. I-10-6 (38) 683, Now overlaid with 3”-4” ACP

☐ JRCP ☐ JCP **X** CRCP

X Interstate ☐ High Volume/Urban ☐ US/SH/FM ☐ Other

Layer system	**Type**	**TxDOT Design Standard** (if used)	**Thick (in.)** Laid or treated	**Construction Joint Spacing @ (ft)** (if applicable)		**Rebar Size @ Spacing (in)** (if applicable)				
				Transv. (Width)	**Long.** (travel lane)	**No of rebar layers**	**Single or bottom**		**Top**	
							Transv.	**Long.**	**Transv.**	**Long.**
No. 1 (top)	Slab	CPCR-SPL	8	24		1	#4@30	#5@7.5		
No. 2	Cement Treated Select Material		6							
No. 3	Lime Treated SG		6							
Soil	Subgrade									
	☐ASTM (USCS)	☐ AASHTO		Classification (if known):						

D13 - YOAKUM (2) Warton Co. US-59 P518 (22), Now overlaid with 3” ACP

☐ JRCP ☐ JCP **X** CRCP

☐ Interstate ☐ High Volume/Urban **X** US/SH/FM ☐ Other

Layer system	**Type**	**TxDOT Design Standard** (if used)	**Thick (in.)** Laid or treated	**Construction Joint Spacing @ (ft)** (if applicable)		**Rebar Size @ Spacing (in)** (if applicable)				
				Transv. (Width)	**Long.** (travel lane)	**No of rebar layers**	**Single or bottom**		**Top**	
							Transv.	**Long.**	**Transv.**	**Long.**
No. 1 (top)	Slab	CPCR-SPEC.	8	24		1	#4@30	#5@7.5		
No. 2	Cement Treated Select Material		6							
No. 3	Lime Treated SG		6							
Soil	Subgrade									
	☐ASTM (USCS)	☐ AASHTO		Classification (if known):						

D13 - YOAKUM (3) Austin Co. I-10-7(122)730, Now overlaid with 3"-4" ACP

X JRCP ☐ JCP ☐ CRCP

X Interstate ☐ High Volume/Urban ☐ US/SH/FM ☐ Other

Layer system	**Type**	**TxDOT Design Standard** (if used)	**Thick (in.)** Laid or treated	**Construction Joint Spacing** @ (ft) (if applicable)		**Rebar Size @ Spacing (in)** (if applicable)				
				Transv. (Width)	**Long.** (travel lane)	**No of rebar layers**	**Single or bottom**		**Top**	
							Transv.	**Long.**	**Transv.**	**Long.**
No. 1 (top)	Slab	CPCR-SPL	10	24	60'-6"	1	6"*6" wire mesh, #1 wire			
No. 2	Cement Treated Base		6							
Soil	Subgrade									
	☐ASTM (USCS) ☐ AASHTO			Classification (if known):						

D13 - YOAKUM (4) Fayette Co. SH71, still uncovered F417 (29)

☐ JRCP ☐ JCP **X** CRCP

☐ Interstate ☐ High Volume/Urban **X** US/SH/FM ☐ Other

Layer system	**Type**	**TxDOT Design Standard** (if used)	**Thick (in.)** Laid or treated	**Construction Joint Spacing** @ (ft) (if applicable)		**Rebar Size @ Spacing (in)** (if applicable)				
				Transv. (Width)	**Long.** (travel lane)	**No of rebar layers**	**Single or bottom**		**Top**	
							Transv.	**Long.**	**Transv.**	**Long.**
No. 1 (top)	Slab	CPCR (B)-89C	10	24		1	#4@29	#6@8.5		
No. 2	ACP		2							
No. 3	Flexible Base		4							
No. 4	Lime Treated Subgrade		6							
Soil	Subgrade									
	☐ASTM (USCS) ☐ AASHTO			Classification (if known):						

D18 – DALLAS(1) US 75 Mainline

☐ JRCP ☐ JCP **X** CRCP

☐ Interstate ☐ High Volume/Urban **X** US/SH/FM ☐ Other

Layer system	**Type**	**TxDOT Design Standard** (if used)	**Thick (in.)** Laid or treated	**Construction Joint Spacing @ (ft)** (if applicable)		**Rebar Size @ Spacing (in)** (if applicable)				
				Transv. (Width)	**Long.** (travel lane)	**No of rebar layers**	**Single or bottom**		**Top**	
							Transv.	**Long.**	**Transv.**	**Long.**
No. 1 (top)	Slab	CPCR	13							
No. 2	AC (Type A)		3							
No. 3	AC (Type D)		3							
No. 4	Lime Treated (4%) SG		10	(Density Control)						
Soil	Fill Material (PI<=20		18							
	☐ ASTM (USCS) ☐ AASHTO			Classification (if known): Sand						

D18 – DALLAS(2) US 75 Mainline

☐ JRCP ☐ JCP **X** CRCP

☐ Interstate ☐ High Volume/Urban **X** US/SH/FM ☐ Other

Layer system	**Type**	**TxDOT Design Standard** (if used)	**Thick (in.)** Laid or treated	**Construction Joint Spacing @ (ft)** (if applicable)		**Rebar Size @ Spacing (in)** (if applicable)				
				Transv. (Width)	**Long.** (travel lane)	**No of rebar layers**	**Single or bottom**		**Top**	
							Transv.	**Long.**	**Transv.**	**Long.**
No. 1 (top)	Slab	CPCR	13							
No. 2	AC (Type A)		3							
No. 3	AC (Type D)		3							
No. 4	Lime Treated (4%)		10	(Density Control)						
Soil	Fill Material (PI<=20)		21							
	☐ ASTM (USCS) ☐ AASHTO			Classification (if known): Clay						

D18 – DALLAS(3) I.H.35E NB Mainlanes; I.H.35E / 190 T Turnpike Interchange; I.H.35E (SB Entrance / NB Exit)

☐ JRCP ☐ JCP **X** CRCP

X Interstate ☐ High Volume/Urban ☐ US/SH/FM ☐ Other

Layer system	**Type**	**TxDOT Design Standard** (if used)	**Thick (in.)** Laid or treated	**Construction Joint Spacing @ (ft)** (if applicable)		**Rebar Size @ Spacing (in)** (if applicable)				
				Transv. (Width)	**Long.** (travel lane)	**No of rebar layers**	**Single or bottom**		**Top**	
							Transv.	**Long.**	**Transv.**	**Long.**
No. 1 (top)	Slab	CRCP	13, 14							
No. 2	AC (Type B)		6, 4							
No. 3	Lime Treated (6%) SG		18, 19	(2Lifts-10"Bottom, 8"Top)						
Soil										
	☐ ASTM (USCS) ☐ AASHTO			Classification (if known):						

D18 – DALLAS(4) I.H.35E NB & SB Frontage Roads

☐ JRCP ☐ JCP **X** CRCP

X Interstate ☐ High Volume/Urban ☐ US/SH/FM ☐ Other

Layer system	**Type**	**TxDOT Design Standard** (if used)	**Thick (in.)** Laid or treated	**Construction Joint Spacing @ (ft)** (if applicable)		**Rebar Size @ Spacing (in)** (if applicable)				
				Transv. (Width)	**Long.** (travel lane)	**No of rebar layers**	**Single or bottom**		**Top**	
							Transv.	**Long.**	**Transv.**	**Long.**
No. 1 (top)	Slab	CPCD	8							
No. 2	AC (Type B)		6							
No. 3	Lime Treated (6%)		8							
Soil										
	☐ ASTM (USCS) ☐ AASHTO			Classification (if known):						

D18 – DALLAS(5) SH 66

☐ JRCP ☐ JCP **X** CRCP

☐ Interstate ☐ High Volume/Urban **X** US/SH/FM ☐ Other

Layer system	**Type**	**TxDOT Design Standard** (if used)	**Thick (in.)** Laid or treated	**Construction Joint Spacing @ (ft)** (if applicable)		**Rebar Size @ Spacing (in)** (if applicable)				
				Transv. (Width)	**Long.** (travel lane)	**No of rebar layers**	**Single or bottom**		**Top**	
							Transv.	**Long.**	**Transv.**	**Long.**
No. 1 (top)	Slab	CPCD	8							
No. 2	HMAC		4							
No. 3	Lime Treated (7%) SG		22							
No. 4	0.25GAL/SY Subgrade Treatment									
Soil										
	☐ ASTM (USCS) ☐ AASHTO			Classification (if known):						

D18 – DALLAS (6) SH 66 Embankment; (Washington Street; Rusk Street)

☐ JRCP ☐ JCP **X** CRCP

☐ Interstate ☐ High Volume/Urban **X** US/SH/FM **X** Other

Layer system	**Type**	**TxDOT Design Standard** (if used)	**Thick (in.)** Laid or treated	**Construction Joint Spacing @ (ft)** (if applicable)		**Rebar Size @ Spacing (in)** (if applicable)				
				Transv. (Width)	**Long.** (travel lane)	**No of rebar layers**	**Single or bottom**		**Top**	
							Transv.	**Long.**	**Transv.**	**Long.**
No. 1 (top)	Slab	CPCD	8							
No. 2	HMAC		4							
No. 3	Lime Treated (7%) SG		6							
No. 4	0.25GAL/SY Subgrade Treatment									
Soil										
	☐ ASTM (USCS) ☐ AASHTO			Classification (if known):						

D18 – DALLAS(7) IH 30 Mainlane Widening

☐ JRCP ☐ JCP **X** CRCP

X Interstate ☐ High Volume/Urban ☐ US/SH/FM ☐ Other

Layer system	**Type**	**TxDOT Design Standard** (if used)	**Thick (in.)** Laid or treated	**Construction Joint Spacing @ (ft)** (if applicable)		**Rebar Size @ Spacing (in)** (if applicable)				
				Transv. (Width)	**Long.** (travel lane)	**No of rebar layers**	**Single or bottom**		**Top**	
							Transv.	**Long.**	**Transv.**	**Long.**
No. 1 (top)	Slab	CPCR	15							
No. 2	AC 600#/SY									
No. 3	Embank (TY C) (w/6" 4% Lime)		18							
Soil										
	☐ ASTM (USCS) ☐ AASHTO			Classification (if known):						

D18 – DALLAS(8) Lakeshore Dr.; Scenic Dr.; Heritage; Harborside

☐ JRCP ☐ JCP **X** CRCP

☐ Interstate ☐ High Volume/Urban ☐ US/SH/FM **X** Other

Layer system	**Type**	**TxDOT Design Standard** (if used)	**Thick (in.)** Laid or treated	**Construction Joint Spacing @ (ft)** (if applicable)		**Rebar Size @ Spacing (in)** (if applicable)				
				Transv. (Width)	**Long.** (travel lane)	**No of rebar layers**	**Single or bottom**		**Top**	
							Transv.	**Long.**	**Transv.**	**Long.**
No. 1 (top)	Slab	CPCD (CL K)	8							
No. 2	HMAC		8, 14							
Soil										
	☐ ASTM (USCS) ☐ AASHTO			Classification (if known):						

D18 – DALLAS(9) US 75 SB.Mainline

☐ JRCP ☐ JCP **X** CRCP

☐ Interstate ☐ High Volume/Urban **X** US/SH/FM ☐ Other

Layer system	**Type**	**TxDOT Design Standard** (if used)	**Thick (in.)** Laid or treated	**Construction Joint Spacing @ (ft)** (if applicable)		**Rebar Size @ Spacing (in)** (if applicable)				
				Transv. (Width)	**Long.** (travel lane)	**No of rebar layers**	**Single or bottom**		**Top**	
							Transv.	**Long.**	**Transv.**	**Long.**
No. 1 (top)	Slab	CPCR	13							
No. 2	AC (Type A)		3							
No. 3	AC (Type D)		3							
No. 4	AC (Type D)		4							
Soil										
	☐ ASTM (USCS) ☐ AASHTO			Classification (if known): Rock						

D18 – DALLAS(10) 2nd Street

☐ JRCP ☐ JCP **X** CRCP

☐ Interstate ☐ High Volume/Urban ☐ US/SH/FM **X** Other

Layer system	**Type**	**TxDOT Design Standard** (if used)	**Thick (in.)** Laid or treated	**Construction Joint Spacing @ (ft)** (if applicable)		**Rebar Size @ Spacing (in)** (if applicable)				
				Transv. (Width)	**Long.** (travel lane)	**No of rebar layers**	**Single or bottom**		**Top**	
							Transv.	**Long.**	**Transv.**	**Long.**
No. 1 (top)	Slab	CPCD	8							
No. 2	HMAC		4							
Soil										
	☐ ASTM (USCS) ☐ AASHTO			Classification (if known):						

D18 – DALLAS(11) Bobtown Road

☐ JRCP ☐ JCP **X** CRCP

☐ Interstate ☐ High Volume/Urban ☐ US/SH/FM **X** Other

Layer system	**Type**	**TxDOT Design Standard** (if used)	**Thick (in.)** Laid or treated	**Construction Joint Spacing @ (ft)** (if applicable)		**Rebar Size @ Spacing (in)** (if applicable)				
				Transv. (Width)	**Long.** (travel lane)	**No of rebar layers**	**Single or bottom**		**Top**	
							Transv.	**Long.**	**Transv.**	**Long.**
No. 1 (top)	Slab	CPCD	10							
No. 2	AC (Approx. 880#/SY)		8							
Soil										
	☐ ASTM (USCS) ☐ AASHTO			Classification (if known):						

D18 – DALLAS(12) IH 30 Frontage Road

☐ JRCP ☐ JCP **X** CRCP

X Interstate ☐ High Volume/Urban ☐ US/SH/FM ☐ Other

Layer system	**Type**	**TxDOT Design Standard** (if used)	**Thick (in.)** Laid or treated	**Construction Joint Spacing @ (ft)** (if applicable)		**Rebar Size @ Spacing (in)** (if applicable)				
				Transv. (Width)	**Long.** (travel lane)	**No of rebar layers**	**Single or bottom**		**Top**	
							Transv.	**Long.**	**Transv.**	**Long.**
No. 1 (top)	Slab	CPCD	10							
No. 2	AC 800#/SY									
Soil										
	☐ ASTM (USCS) ☐ AASHTO			Classification (if known):						

D19 - ATLANTA (1)

□ JRCP X JCP □ CRCP

□ Interstate X High Volume/Urban X US/SH/FM X Other

Layer system	Type	TxDOT Design Standard (if used)	Thick (in.) Laid or treated	Construction Joint Spacing @ (ft) (if applicable)		Rebar Size @ Spacing (in) (if applicable)				
				Transv. (Width)	Long. (travel lane)	No of rebar layers	Single or bottom		Top	
							Transv.	Long.	Transv.	Long.
No. 1 (top)	Slab	CPCD (SPL)	10-13	15	12					
No. 2	ACP		4							
No. 3	Subgrade		6-8							
Soil										
	□ ASTM (USCS)	□ AASHTO		Classification (if known):						

D19 - ATLANTA (2)

□ JRCP □ JCP X CRCP

□ Interstate X High Volume/Urban X US/SH/FM X Other

Layer system	Type	TxDOT Design Standard (if used)	Thick (in.) Laid or treated	Construction Joint Spacing @ (ft) (if applicable)		Rebar Size @ Spacing (in) (if applicable)				
				Transv. (Width)	Long. (travel lane)	No of rebar layers	Single or bottom		Top	
							Transv.	Long.	Transv.	Long.
No. 1 (top)	Slab	CPCR (1)-94	8-13			1	Varies	Varies		
No. 2	ACP		4				#5-#6	#5-#6		
No. 3	Subgrade		6-8				@24" to 36"	@5.5" to 9"		
Soil										
	□ ASTM (USCS)	□ AASHTO		Classification (if known):						

D20 – BEAUMONT

□ JRCP **X** JCP □ CRCP

X Interstate **X** High Volume/Urban **X** US/SH/FM □ Other

Layer system	**Type**	**TxDOT Design Standard** (if used)	**Thick (in.)** Laid or treated	**Construction Joint Spacing @ (ft)** (if applicable)		**Rebar Size @ Spacing (in)** (if applicable)				
				Transv. (Width)	**Long.** (travel lane)	**No of rebar layers**	**Single or bottom**		**Top**	
							Transv.	**Long.**	**Transv.**	**Long.**
No. 1 (top)	Slab	CPCD	12	NA	16					
No. 2	Bond Breaker		1	ACP						
No. 3	Base		6	Cement Stabilized						
No. 4	Subgrade		6	Lime Treated						
Soil	Subgrade			Silty Clay						
	! ASTM (USCS) □ AASHTO			Classification (if known): BM						

D24 - EL PASO

□ JRCP □ JCP **X** CRCP

X Interstate □ High Volume/Urban □ US/SH/FM □ Other

Layer system	**Type**	**TxDOT Design Standard** (if used)	**Thick (in.)** Laid or treated	**Construction Joint Spacing @ (ft)** (if applicable)		**Rebar Size @ Spacing (in)** (if applicable)				
				Transv. (Width)	**Long.** (travel lane)	**No of rebar layers**	**Single or bottom**		**Top**	
							Transv.	**Long.**	**Transv.**	**Long.**
No. 1 (top)	Slab	CPCR (1)-94	10-14		12	1-2	6@24"	6@6"	6@24"	6@6"
No. 2	HMAC		3-4							
Soil	Subgrade			Clayey Sand						
	! ASTM (USCS) □ AASHTO			Classification (if known):						

Appendix F Rigid Pavement Design Guidelines

STATE DEPARTMENT OF HIGHWAYS AND PUBLIC TRANSPORTATION

DEWITT C. GREER STATE HIGHWAY BLDG.
11TH & BRAZOS
AUSTIN, TEXAS 78701-2483

July 20, 1987

IN REPLY REFER TO
D-8PD

SUBJECT: Rigid Pavement Design

TO: DISTRICT ENGINEERS
ATTN: District Pavement Managers

The attached preliminary guidelines for Rigid Pavement Design have been prepared to assist in the design and documentation of rigid pavements. These guidelines are based on The 1986 AASHTO Guide For Design of Pavement Structures. The new material provided here should significantly improve our pavement design capabilities. These guidelines should also help to improve the uniformity of designs prepared statewide, prior to their submission to the FHWA.

This draft document only covers the preparation of designs for new construction (the rehabilitation portion is currently being prepared).

We are asking Districts to begin implementing this material in the preparation of their rigid pavement design documentation. Please contact the Pavement Design Section of the Highway Design Division with any questions or comments you might have regarding these guidelines.

Sincerely,

Frank D. Holzmann
Chief Engineer, Highway Design

Attachment
cc: Engineer-Director
Deputy Directors
Internal Review
General Counsel
D-18

RIGID PAVEMENT DESIGN

(Draft 1/27/1987)
(Revised 5/18/1987)

The following guidelines have been adapted from the 1986 AASHTO Guide For Design of Pavement Structures. If desired, additional information can be obtained on the various topics by referring to the articles of The AASHTO Guide indicated in parenthesis.

MEAN CONCRETE MODULUS OF RUPTURE (720 psi)
(Article 2.3.4, Page II-17)

Texas SDHPT currently specifies an average modulus of rupture of 650 psi 7 day center point loading. The new design procedure requires an average modulus of rupture at 28 days using third point loading. Utilizing the appropriate correction factors our specification can be equated with a value of 720 psi at 28 days for third point loading.

Please note that this value has NO safety factor applied to it as was done in the past. The design procedure requires that the value input be the average modulus of rupture at 28 days using third point loading. Safety factors (reliability in design) are accommodated elsewhere in the design.

CONCRETE ELASTIC MODULUS (4 or 5 million psi)
(Article 2.3.3, Page II-14)

For the concrete elastic modulus, two values will be recommended based on the coarse aggregate anticipated for the project under consideration. These values are identical to those recommended in the past:

4,000,000 psi for crushed limestone
5,000,000 psi for siliceous river gravels

The actual modulus values may vary. The aggregate type that is used on the job may even be something other than that anticipated. It should be noted however that these eventualities will not significantly alter the design and should therefore not cause alarm.

The values recommended above are provided strictly to maintain some level of consistency in design.

PRELIMINARY
SUBJECT TO REVISION

EFFECTIVE MODULUS OF SUBGRADE REACTION (100-400 pci)
(Article 2.3.1, Page II-13)
(Article 2.3.2, Page II-14)
(Article 2.4.3, Page II-28)
(Article 3.2.1, Page II-37)

The new design procedure allows the designer to more accurately predict the support provided to a given pavement structure over its life span. This is accomplished through several modifications that have been made:

1.) Subgrade strength values are now approximated by incorporating the modulus values and layer thicknesses of all the significant layers located beneath the concrete slab.

2.) Loss of support due to erosion, or deterioration can be incorporated into the design as well.

It should be noted that these modifications are fairly similar to the material that has been provided in the Department's design manual. This material has not been fully utilized in the past however partially due to the lack of emphasis placed on subgrade support in the design equations.

In reviewing this material it has been determined that the additional credit due with the use of less-erosive stabilized subbases will produce reductions in slab thickness worth noting. Therefore, rather than using the values of 100-200 pci exclusively as in the past values of 300-400 pci will now be used when stabilized subbase are to be provided.

SERVICEABILITY LOSS (2.0)
(Article 2.2.1, Page II-12)

Rather than establishing the appropriate values for initial and terminal serviceability it has been determined that the difference between the two is the only value of real significance. Therefore rather than attempting to predict what initial ride quality will be provided or at what point the pavement will be considered failed, it is requested that a value of two (2.0) be used as the difference between these two points in time.

PRELIMINARY
SUBJECT TO REVISION

LOAD TRANSFER COEFFICIENT (2.9 - 4.2)
(Article 2.4.2, Page II-27)

The load transfer coefficient has been reincorporated in the design equation primarily to allow designers to account for the used of tied concrete shoulders. The load transfer coefficient also takes into account provisions made for load transfer across transverse joints and or cracks.

The following values are provided for the various conditions:

With Tied PCC shoulders, Curb and Gutter, or greater than 2 lanes of traffic in one direction;

Steel provided at transverse joints and cracks

Yes J=2.9

No J=3.7

No Tied PCC shoulders;

Steel provided at transverse joints and cracks

Yes J=3.2

No J=4.2

These values should be used consistently in the design of all concrete pavement types (CRCP,JRCP,CPCD). This is intended to avoid the design of different thicknesses based on pavement type. No findings have yet been produced to warrant such a differential.

DRAINAGE COEFFICIENT (0.91 - 1.16)
(Article 2.4.1, Page II-22)

A drainage coefficient has been incorporated in the design equation to account for the significant impact water has on the performance of PCC pavements. The coefficient likewise has a very significant impact on the pavement design.

It is suggested that the values used here should be based on anticipated exposure to moisture as well as the quality of the drainage provided. As a whole, the state has not been typically providing significant drainage systems for its concrete pavements. This is primarily based on the belief that such efforts are not warranted at this time. The non-erosive stabilized subbases currently used around the state are performing satisfactorily in most cases. It is believed that these stabilized subbases provide a "fair" level of drainage. With this in mind the drainage coefficient will be selected based solely on the anticipated exposure to water, anticipating that a non-erosive stabilized subbase will be provided.

PRELIMINARY
SUBJECT TO REVISION

For our purposes we will use annual rainfall data to represent the anticipated exposure to water, as shown on the aiiebtnx sheet from the Texas Almanac. Drainage coefficients will be assigned as follows:

Annual Rainfall (inches)	Drainage Coefficients
58-50	0.91-0.95
48-40	0.96-1.00
38-30	1.01-1.05
28-20	1.06-1.10
18-8	1.11-1.16

If something other than a non-erosive stabilized subbase is to be provided and/or the drainage is anticipated to be something other than fair, the drainage coefficient should be appropriately altered in cooperation with D-8PD.

OVERALL STANDARD DEVIATION (0.39)
(Article 4.3, Page I-62)
(Article 2.2.3, Page II-9)

The overall standard deviation has been added to represent the variability of the input values used. For rigid pavements a range of 0.30 to 0.40 is indicated with 0.35 being the overall standard deviation at the AASHO Road Test. It is our belief that the inputs we will be utilizing in design will be considerably less accurate than those of the Road Test. For this reason a conservative value of 0.39 has been selected until a better value can be developed.

RELIABILITY (85,95,99,99.9)
(Article 4.4, Page I-62)
(Article 2.1.3, Page II-9)

One reliability factor is now provided to accommodate the designers desire to economically assure adequate performance. This "factor of safety" was applied primarily to the concrete strength in the past. This reliability is now provided as a separate input to encourage designers to establish their desired reliability independent of the other design inputs used.

PRELIMINARY
SUBJECT TO REVISION

In an effort to provide more consistency in the use of these reliability factors it is being proposed that these values be assigned based on the ADT projected for the end of the design life as provided by D-10. The tentative breakdown will be as follows:

Projected ADT/Lane		
Contolled Access Freeway	Other Highways	Recommended Reliability (%)
N/A	<15,000	85
<15,000	15,000 - 20,000	95
15,000 - 20,000	21,000 - 25,000	99
>20,000	>25,000	99.9

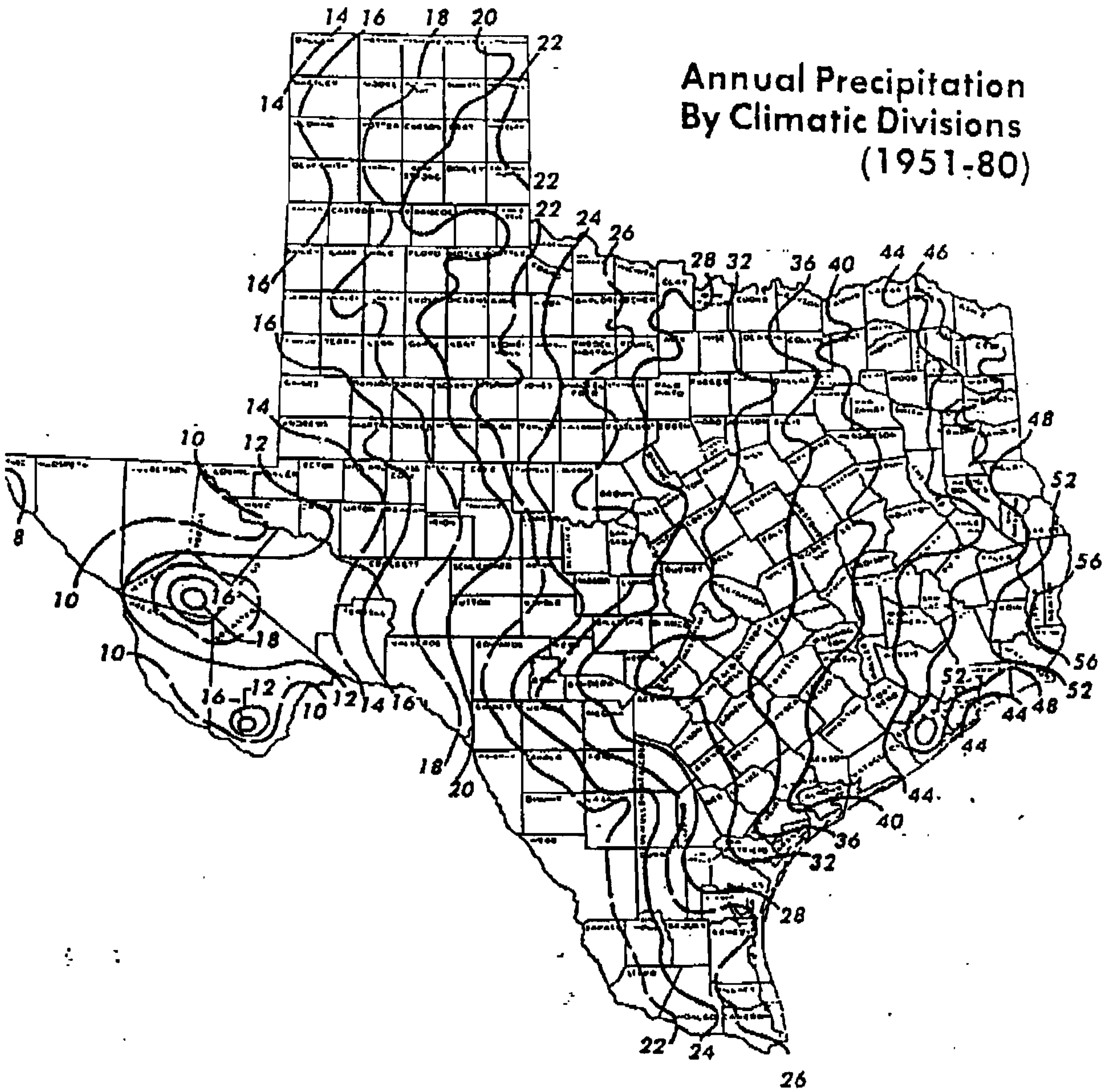
DESIGN TRAFFIC
(Article 2.1.2, Page II-7)

Traffic data will be requested from D-10 as in the past. The 18 kip equivalent single axle loads (KESAL) will also still be corrected for the number of lanes to be provided. We will continue to use the following lanal distribution factors (based on the total number of lanes in both directions):

1.0 - 4 lanes and less
0.7 - 6 lanes
0.6 - 8 lanes or more

The only real change in the design traffic used will be in the design life. For rigid pavements a design life of thirty (30) years will now be used.

PRELIMINARY
SUBJECT TO REVISION


Annual Precipitation
By Climatic Divisions
(1951-80)

Appendix G Traditional and Alternative Pavement Sections: Construction Times

(Four-lane roadway section 48 ft. x 300 ft.)

HOUSTON	**Width (ft)**	**Length (ft)**	**Area**		**Volume**	
(4 lanes 12' wide ea.; 300' long)	48	300	14400 ft - ft		266.6666667	C.Y.
			1600 S.Y.			

SECTION: TRADITIONAL DESIGN

	Thickness	**Rate/Day**	**Unit**	**Days**	**Hours(8hr/d)**	**ES**	**EF**
Lime mix and curing Time				4	32	0.0	32.0
Lime Stabilization SG	6	1800	S.Y.	0.89	7.1	32.0	39.1
Wait Time after Stabilization				14	112.0	39.1	151.1
Cement treated base	6	1100	S.Y.	1.45	11.6	151.1	162.7
Wait Time after Treatment				3	24.0	162.7	186.7
HMA base	1	7725	S.Y.	0.21	1.7	186.7	188.4
Concrete paving (Inc. curing)	10	2100	S.Y.	0.76	6.1	188.4	**194.5**
curing time + open to normal traffic				3	24.0	194.5	**218.5**
	23.00			28.00			

ALTERNATIVE A: ACP BINDER BASE

	Thickness	**Rate/Day**	**Unit**	**Days**	**Hours(8hr/d)**	**ES**	**EF**
Soil Compaction (riding, vibrating roller,12"lift,4 passes)	6	2600	C.Y.	0.10	0.8	0.0	0.8
Asphalt Base I	4	4150	S.Y.	0.39	3.1	0.8	3.9
Asphalt Base II	3	4900	S.Y.	0.33	2.6	3.9	6.5
Concrete paving (Inc. curing)	10	2100	S.Y.	0.76	6.1	6.5	**12.6**
curing time + open to normal traffic				3	24.0	12.6	**36.6**
	23.00			5.00			

ALTERNATIVE B: FULL-DEPTH CONCRETE

	Thickness	**Rate/Day**	**Unit**	**Days**	**Hours(8hr/d)**	**ES**	**EF**
Soil Compaction (riding, vibrating roller,12"lift,4 passes)	6	2600	C.Y.	0.10	0.8	0.0	0.8
Concrete paving I (Inc. curing)	9	2500	S.Y.	0.64	5.1	0.8	5.9
Concrete paving II (Inc. curing)	8	2750	S.Y.	0.58	4.7	5.9	**10.6**
curing time + open to normal traffic				3	24.0	10.6	**34.6**
	23.00			4.00			

(Four-lane roadway section 48 ft. x 300 ft.)

FORTH WORTH	Width (ft)	Length (ft)	Area		Volume		
(4 lanes 12' wide ea.; 300' long)	48	300	14400 ft - ft		266.6666667	C.Y.	
			1600 S.Y.				

SECTION: TRADITIONAL DESIGN	Thickness	Rate/Day	Unit	Days	Hours(8hr/d)	ES	EF
Lime mix and curing Time				4	32	0.0	32.0
Lime Stabilization SG	12	1550	S.Y.	1.03	8.3	32.0	40.3
Wait Time after Stabilization				14	112.0	40.3	152.3
Lime Stabilization SG	6	1800	S.Y.	0.89	7.1	152.3	159.4
Wait Time after Stabilization				14	112.0	159.4	271.4
HMA base	4	4150	S.Y.	0.39	3.1	159.4	162.5
Concrete paving (Inc. curing)	12	1800	S.Y.	0.89	7.1	162.5	**169.6**
curing time + open to normal traffic				3	24.0	169.6	**193.6**
	34.00			39.00			

ALTERNATIVE A: ACP BINDER BASE	Thickness	Rate/Day	Unit	Days	Hours(8hr/d)	ES	EF
Soil Compaction (riding, vibrating roller,12"lift,4 passes)	6	2600	C.Y.	0.10	0.8	0.0	0.8
Asphalt Base I	4	4150	S.Y.	0.39	3.1	0.8	3.9
Asphalt Base II	4	4150	S.Y.	0.39	3.1	3.9	7.0
Asphalt Base III	4	4150	S.Y.	0.39	3.1	7.0	10.1
Asphalt Base IV	4	4150	S.Y.	0.39	3.1	10.1	13.2
Concrete paving (Inc. curing)	12	1800	S.Y.	0.89	7.1	7.0	**14.1**
curing time + open to normal traffic				3	24.0	14.1	**38.1**
	34.00			6.00			

ALTERNATIVE B: FULL-DEPTH CONCRETE	Thickness	Rate/Day	Unit	Days	Hours(8hr/d)	ES	EF
Soil Compaction (riding, vibrating roller,12"lift,4 passes)	6	2600	C.Y.	0.10	0.8	0.0	0.8
Concrete paving I (Inc. curing)	14	1500	S.Y.	1.07	8.5	0.8	9.4
Concrete paving II (Inc. curing)	14	1500	S.Y.	1.07	8.5	9.4	**17.9**
curing time + open to normal traffic				3	24.0	17.9	**41.9**
	34.00			5.00			

(Four-lane roadway section 48 ft. x 300 ft.)

EL PASO	Width (ft)	Length (ft)	Area		Volume		
(4 lanes 12' wide ea.; 300' long)	48	300	14400 ft - ft		266.6666667	C.Y.	
			1600 S.Y.				

SECTION: TRADITIONAL DESIGN							
	Thickness	**Rate/Day**	**Unit**	**Days**	**Hours(8hr/d)**	**ES**	**EF**
Soil Compaction (riding, vibrating roller,12"lift,4 passes)	6	2600	C.Y.	0.10	0.8	0.0	0.8
HMA base	4	4150	S.Y.	0.39	3.1	0.8	3.9
Concrete paving (Inc. curing)	10	2100	S.Y.	0.76	6.1	3.9	**10.0**
curing time + open to normal traffic				3	24.0	10.0	**34.0**
	20.00			4.00			

ALTERNATIVE A: FULL-DEPTH CONCRETE							
	Thickness	**Rate/Day**	**Unit**	**Days**	**Hours(8hr/d)**	**ES**	**EF**
Soil Compaction (riding, vibrating roller,12"lift,4 passes)	6	2600	C.Y.	0.10	0.8	0.0	0.8
Concrete paving (Inc. curing)	14	1500	S.Y.	1.07	8.5	0.8	**9.4**
curing time + open to normal traffic				3	24.0	9.4	**33.4**
	20.00			5.00			

(Four-lane roadway section 48 ft. x 1.0 mile)

HOUSTON	Width (ft)	Length (ft)	Area		Volume	
(4 lanes 12' wide ea.; 1 mile long)	48	5280	253440 ft - ft		4693.333333	C.Y.
			28160 S.Y.			

SECTION: TRADITIONAL DESIGN	Thickness	Rate/Day	Unit	Days	Hours(8hr/d)	ES	EF
Lime mix and curing Time				4	32	0.0	32.0
Lime Stabilization SG	6	1800	S.Y.	15.64	125.2	32.0	157.2
Wait Time after Stabilization				14	112.0	157.2	269.2
Cement treated base	6	1100	S.Y.	25.60	204.8	269.2	474.0
Wait Time after Treatment				3	24.0	474.0	498.0
HMA base	1	7725	S.Y.	3.65	29.2	498.0	527.1
Concrete paving (Inc. curing)	10	2100	S.Y.	13.41	107.3	527.1	**634.4**
curing time + open to normal traffic				3	24.0	634.4	**658.4**
	23.00			83.00			

ALTERNATIVE A: ACP BINDER BASE	Thickness	Rate/Day	Unit	Days	Hours(8hr/d)	ES	EF
Soil Compaction (riding, vibrating roller,12"lift,4 passes)	6	2600	C.Y.	1.81	14.4	0.0	14.4
Asphalt Base I	4	4150	S.Y.	6.79	54.3	14.4	68.7
Asphalt Base II	3	4900	S.Y.	5.75	46.0	68.7	114.7
Concrete paving (Inc. curing)	10	2100	S.Y.	13.41	107.3	114.7	**222.0**
curing time + open to normal traffic				3	24.0	222.0	**246.0**
	23.00			31.00			

ALTERNATIVE B: FULL-DEPTH CONCRETE	Thickness	Rate/Day	Unit	Days	Hours(8hr/d)	ES	EF
Soil Compaction (riding, vibrating roller,12"lift,4 passes)	6	2600	C.Y.	1.81	14.4	0.0	14.4
Concrete paving I (Inc. curing)	9	2500	S.Y.	11.26	90.1	14.4	104.6
Concrete paving II (Inc. curing)	8	2750	S.Y.	10.24	81.9	104.6	**186.5**
curing time + open to normal traffic				3	24.0	186.5	**210.5**
	23.00			26.00			

(Four-lane roadway section 48 ft. x 1.0 mile)

FORTH WORTH	Width (ft)	Length (ft)	Area		Volume	
(4 lanes 12' wide ea.; 1 mile long)	48	5280	253440 ft - ft		4693.333333	C.Y.
			28160 S.Y.			

SECTION: TRADITIONAL DESIGN	Thickness	Rate/Day	Unit	Days	Hours(8hr/d)	ES	EF
Lime mix and curing Time				4	32	0.0	32.0
Lime Stabilization SG	12	1550	S.Y.	18.17	145.3	32.0	177.3
Wait Time after Stabilization				14	112.0	177.3	289.3
Lime Stabilization SG	6	1800	S.Y.	15.64	125.2	289.3	414.5
Wait Time after Stabilization				14	112.0	414.5	526.5
HMA base	4	4150	S.Y.	6.79	54.3	414.5	468.8
Concrete paving (Inc. curing)	12	1800	S.Y.	15.64	125.2	468.8	**593.9**
curing time + open to normal traffic				3	24.0	593.9	**617.9**
	34.00			92.00			

ALTERNATIVE A: ACP BINDER BASE	Thickness	Rate/Day	Unit	Days	Hours(8hr/d)	ES	EF
Soil Compaction (riding, vibrating roller,12"lift,4 passes)	6	2600	C.Y.	1.81	14.4	0.0	14.4
Asphalt Base I	4	4150	S.Y.	6.79	54.3	14.4	68.7
Asphalt Base II	4	4150	S.Y.	6.79	54.3	68.7	123.0
Asphalt Base III	4	4150	S.Y.	6.79	54.3	123.0	177.3
Asphalt Base IV	4	4150	S.Y.	6.79	54.3	177.3	231.6
Concrete paving (Inc. curing)	12	1800	S.Y.	15.64	125.2	123.0	**248.2**
curing time + open to normal traffic				3	24.0	248.2	**272.2**
	34.00			48.00			

ALTERNATIVE B: FULL-DEPTH CONCRETE	Thickness	Rate/Day	Unit	Days	Hours(8hr/d)	ES	EF
Soil Compaction (riding, vibrating roller,12"lift,4 passes)	6	2600	C.Y.	1.81	14.4	0.0	14.4
Concrete paving I (Inc. curing)	14	1500	S.Y.	18.77	150.2	14.4	164.6
Concrete paving II (Inc. curing)	14	1500	S.Y.	18.77	150.2	164.6	**314.8**
curing time + open to normal traffic				3	24.0	314.8	**338.8**
	34.00			42.00			

(Four-lane roadway section 48 ft. x 1.0 mile)

EL PASO	Width (ft)	Length (ft)	Area		Volume			
(4 lanes 12' wide ea.; 1 mile long)	48	5280	253440 ft - ft		4693.333333	C.Y.		
			28160 S.Y.					

SECTION: TRADITIONAL DESIGN	**Thickness**	**Rate/Day**	**Unit**	**Days**	**Hours(8hr/d)**	**ES**	**EF**
Soil Compaction (riding, vibrating roller,12"lift,4 passes)	6	2600	C.Y.	1.81	14.4	0.0	14.4
HMA base	4	4150	S.Y.	6.79	54.3	14.4	68.7
Concrete paving (Inc. curing)	10	2100	S.Y.	13.41	107.3	68.7	**176.0**
curing time + open to normal traffic				3	24.0	176.0	**200.0**
	20.00			25.00			

ALTERNATIVE A: FULL-DEPTH CONCRETE	**Thickness**	**Rate/Day**	**Unit**	**Days**	**Hours(8hr/d)**	**ES**	**EF**
Soil Compaction (riding, vibrating roller,12"lift,4 passes)	6	2600	C.Y.	1.81	14.4	0.0	14.4
Concrete paving (Inc. curing)	14	1500	S.Y.	18.77	150.2	14.4	**164.6**
curing time + open to normal traffic				3	24.0	164.6	**188.6**
	20.00			24.00			

Appendix H Traditional and Alternative Pavement Sections: Construction Costs

(Four-lane roadway section 48 ft. x 300 ft.)

HOUSTON
(48 ft x 300 ft)

TRADITIONAL DESIGN

Qty	Unit	CSI Number	Description	Crew	Total Incl. O&P	ZC Prefix
1,600.000	S.Y.	023405002200	Soil stabilization, hydrated lime, for base, 6% mix, 6" deep	B74	$ 14,880.00	770
1,600.000	S.Y.	023405001100	Soil stabilization, cement, 4% mix, 6% mix, 6" deep	B74	$ 12,480.00	770
1,600.000	S.Y.	027403000080	Asphaltic conc pvmt, and lg paved areas, binder course, 1-1/2" thick	B25	$ 4,352.00	770
1,600.000	S.Y.	027501000300	Conc pavement, w/jt,fnsh&curing,fx form,12' pass,unreinforced,10"T	B26	$ 52,000.00	770
			Total		**$ 83,712.00**	

ALTERNATIVE A: ACP BINDER BASE

Qty	Unit	CSI Number	Description	Crew	Total Incl. O&P	ZC Prefix
266.670	C.Y.	023153005100	Compaction, riding, vibrating roller, 12" lifts, 4 passes	B10Y	$ 85.33	770
1,600.000	S.Y.	027403000200	Asphaltic conc pavement, and lg paved areas, binder course, 4" thick	B25	$ 10,720.00	770
1,600.000	S.Y.	027403000160	Asphaltic conc pavement, and lg paved areas, binder course, 3" thick	B25	$ 8,240.00	770
1,600.000	S.Y.	027501000300	Conc pavement, w/jt,fnsh&curing,fx form,12' pass,unreinforced,10"T	B26	$ 52,000.00	770
			Total		**$ 71,045.33**	

ALTERNATIVE B: FULL-DEPTH CONCRETE

Qty	Unit	CSI Number	Description	Crew	Total Incl. O&P	ZC Prefix
266.670	C.Y.	023153005100	Compaction, riding, vibrating roller, 12" lifts, 4 passes	B10Y	$ 85.33	770
1,600.000	S.Y.	027501000200	Concrete pavement, fix form, 12' pass, unreinforced, 9" thick	B26	$ 48,000.00	770
1,600.000	S.Y.	027501000100	Conc pavement, w/jt,fnsh&curing, fx form,12' pass,unreinforced,8"T	B26	$ 41,600.00	770
			Total		**$ 89,685.33**	

(Four-lane roadway section 48 ft. x 300 ft.)

FORTH WORTH
(48 ft x 300 ft)

TRADITIONAL DESIGN

Qty	Unit	CSI Number	Description	Crew		Total Incl. O&P	ZC Prefix
1,600.000	S.Y.	023405002160	Soil stabilization, hydrated lime, for base, 4% mix, 12" deep	B74	$	13,840.00	760
1,600.000	S.Y.	023405002100	Soil stabilization, hydrated lime, for base, 4% mix, 6" deep	B74	$	8,880.00	760
1,600.000	S.Y.	027403000200	Asphaltic conc pavement, and lg paved areas, binder course, 4" thick	B25	$	11,040.00	760
1,600.000	S.Y.	027501000400	Conc pavement, w/jt,fnsh&curing,fx form,12' pass,unreinforced,12"T	B26	$	56,800.00	760
			Total		**$**	**90,560.00**	

ALTERNATIVE A: ACP BINDER BASE

Qty	Unit	CSI Number	Description	Crew		Total Incl. O&P	ZC Prefix
266.667	C.Y.	023153005100	Compaction, riding, vibrating roller, 12" lifts, 4 passes	B10Y	$	80.00	760
6,400.000	S.Y.	027403000200	Asphaltic conc pavement, and lg paved areas, binder course, 4" thick	B25	$	44,160.00	760
1,600.000	S.Y.	027501000400	Conc pavement, w/jt,fnsh&curing,fx form,12' pass,unreinforced,12"T	B26	$	56,800.00	760
			Total		**$**	**101,040.00**	

ALTERNATIVE B: FULL-DEPTH CONCRETE

Qty	Unit	CSI Number	Description	Crew		Total Incl. O&P	ZC Prefix
266.667	C.Y.	023153005100	Compaction, riding, vibrating roller, 12" lifts, 4 passes	B10Y	$	80.00	760
3,200.000	S.Y.	027501000500	Conc pavement, w/jt,fnsh&curing,fx form,12' pass,unreinforced,15"T	B26	$	129,600.00	760
			Total		**$**	**129,680.00**	

(Four-lane roadway section 48 ft. x 300 ft.)

EL PASO
(48 ft x 300 ft)

TRADITIONAL DESIGN

Qty	Unit	CSI Number	Description	Crew		Total Incl. O&P	ZC Prefix
266.667	C.Y.	023153005100	Compaction, riding, vibrating roller, 12" lifts, 4 passes	B10Y	$	80.00	798
1,600.000	S.Y.	027403000200	Asphaltic conc pavement, and lg paved areas, binder course, 4" thick	B25	$	11,280.00	798
1,600.000	S.Y.	027501000300	Conc pavement, w/jt,fnsh&curing,fx form,12' pass,unreinforced,10"T	B26	$	53,600.00	798
			Total		**$**	**64,960.00**	

ALTERNATIVE A: FULL-DEPTH CONCRETE

Qty	Unit	CSI Number	Description	Crew		Total Incl. O&P	ZC Prefix
266.670	C.Y.	023153005100	Compaction, riding, vibrating roller, 12" lifts, 4 passes	B10Y	$	80.00	798
1,600.000	S.Y.	027501000500	Conc pavement, w/jt,fnsh&curing,fx form,12' pass,unreinforced,15"T	B26	$	65,600.00	798
			Total		**$**	**65,680.00**	

(Four-lane roadway section 48 ft. x 1.0 mile)

HOUSTON
(48 ft x 1.0 mi)

TRADITIONAL DESIGN

Qty	Unit	CSI Number	Description	Crew	Total Incl. O&P	ZC Prefix
28,160.000	S.Y.	023405002200	Soil stabilization, hydrated lime, for base, 6% mix, 6" deep	B74	$ 261,888.00	770
28,160.000	S.Y.	023405001100	Soil stabilization, cement, 4% mix, 6% mix, 6" deep	B74	$ 219,648.00	770
28,160.000	S.Y.	027403000080	Asphaltic conc pvmt, and lg paved areas, binder course, 1-1/2" thick	B25	$ 76,595.20	770
28,160.000	S.Y.	027501000300	Conc pavement, w/jt,fnsh&curing,fx form,12' pass,unreinforced,10"T	B26	$ 915,200.00	770
				Total	**$ 1,473,331.20**	

ALTERNATIVE A: ACP BINDER BASE

Qty	Unit	CSI Number	Description	Crew	Total Incl. O&P	ZC Prefix
4,693.333	C.Y.	023153005100	Compaction, riding, vibrating roller, 12" lifts, 4 passes	B10Y	$ 1,501.87	770
28,160.000	S.Y.	027403000200	Asphaltic conc pavement, and lg paved areas, binder course, 4" thick	B25	$ 188,672.00	770
28,160.000	S.Y.	027403000160	Asphaltic conc pavement, and lg paved areas, binder course, 3" thick	B25	$ 145,024.00	770
28,160.000	S.Y.	027501000300	Conc pavement, w/jt,fnsh&curing,fx form,12' pass,unreinforced,10"T	B26	$ 915,200.00	770
				Total	**$ 1,250,397.87**	

ALTERNATIVE B: FULL-DEPTH CONCRETE

Qty	Unit	CSI Number	Description	Crew	Total Incl. O&P	ZC Prefix
4,693.333	C.Y.	023153005100	Compaction, riding, vibrating roller, 12" lifts, 4 passes	B10Y	$ 1,501.87	770
28,160.000	S.Y.	027501000200	Concrete pavement, fix form, 12' pass, unreinforced, 9" thick	B26	$ 844,800.00	770
28,160.000	S.Y.	027501000100	Conc pavement, w/jt,fnsh&curing, fx form,12' pass,unreinforced,8"T	B26	$ 732,160.00	770
				Total	**$ 1,578,461.87**	

(Four-lane roadway section 48 ft. x 1.0 mile)

FORTH WORTH
(48 ft x 1.0 mi)

TRADITIONAL DESIGN

Qty	Unit	CSI Number	Description	Crew	Total Incl. O&P	ZC Prefix
28,160.000	S.Y.	023405002160	Soil stabilization, hydrated lime, for base, 4% mix, 12" deep	B74	$ 243,584.00	760
28,160.000	S.Y.	023405002100	Soil stabilization, hydrated lime, for base, 4% mix, 6" deep	B74	$ 156,288.00	760
28,160.000	S.Y.	027403000200	Asphaltic conc pavement, and lg paved areas, binder course, 4" thick	B25	$ 194,304.00	760
28,160.000	S.Y.	027501000400	Conc pavement, w/jt,fnsh&curing,fx form,12' pass,unreinforced,12"T	B26	$ 999,680.00	760
			Total		**$ 1,593,856.00**	

ALTERNATIVE A: ACP BINDER BASE

Qty	Unit	CSI Number	Description	Crew	Total Incl. O&P	ZC Prefix
4,693.333	C.Y.	023153005100	Compaction, riding, vibrating roller, 12" lifts, 4 passes	B10Y	$ 1,408.00	760
112,640.000	S.Y.	027403000200	Asphaltic conc pavement, and lg paved areas, binder course, 4" thick	B25	$ 777,216.00	760
28,160.000	S.Y.	027501000400	Conc pavement, w/jt,fnsh&curing,fx form,12' pass,unreinforced,12"T	B26	$ 999,680.00	760
			Total		**$ 1,778,304.00**	

ALTERNATIVE B: FULL-DEPTH CONCRETE

Qty	Unit	CSI Number	Description	Crew	Total Incl. O&P	ZC Prefix
4,693.333	C.Y.	023153005100	Compaction, riding, vibrating roller, 12" lifts, 4 passes	B10Y	$ 1,408.00	760
56,320.000	S.Y.	027501000500	Conc pavement, w/jt,fnsh&curing,fx form,12' pass,unreinforced,15"T	B26	$ 2,280,960.00	760
			Total		**$ 2,282,368.00**	

(Four-lane roadway section 48 ft. x 1.0 mile)

EL PASO
(48 ft x 1.0 mi)

TRADITIONAL DESIGN

Qty	Unit	CSI Number	Description	Crew	Total Incl. O&P		ZC Prefix
4,693.333	C.Y.	023153005100	Compaction, riding, vibrating roller, 12" lifts, 4 passes	B10Y	$	1,408.00	798
28,160.000	S.Y.	027403000200	Asphaltic conc pavement, and lg paved areas, binder course, 4" thick	B25	$	198,528.00	798
28,160.000	S.Y.	027501000300	Conc pavement, w/jt,fnsh&curing,fx form,12' pass,unreinforced,10"T	B26	$	943,360.00	798
			Total		**$**	**1,143,296.00**	

ALTERNATIVE A: FULL-DEPTH CONCRETE

Qty	Unit	CSI Number	Description	Crew	Total Incl. O&P		ZC Prefix
4,693.333	C.Y.	023153005100	Compaction, riding, vibrating roller, 12" lifts, 4 passes	B10Y	$	1,408.00	798
28,160.000	S.Y.	027501000500	Conc pavement, w/jt,fnsh&curing,fx form,12' pass,unreinforced,15"T	B26	$	1,154,560.00	798
			Total		**$**	**1,155,968.00**	

(Construction Crew Composition)

Crew B25 (Union)	
1	Labor Foreman
7	Laborers
3	Equip. Oper. (med.)
1	Asphalt Paver, 130 H.P
1	Tandem Roller, 10 Ton
1	Roller, Pneumatic Wheel
88 L.H., Daily Totals	

Crew B26 (Union)	
1	Labor Foreman (outside)
6	Laborers
2	Equip. Oper. (med.)
1	Rodman (reinf.)
1	Cement Finisher
1	Grader, 30,000 Lbs.
1	Paving Mach. & Equip.
88 L.H., Daily Totals	

Crew B74 (Union)	
1	Labor Foreman (outside)
1	Laborer
4	Equip. Oper. (med.)
2	Truck Drivers (heavy)
1	Motor Grader, 30,000 Lb.
1	Grader Attach., Ripper
2	Stabilizers, 310 H.P.
1	Flatbed Truck, 3 Ton
1	Chem. Spreader, Towed
1	Vibr. Roller, 29,000 Lb.
1	Water Tank 5000 Gal.
1	Truck, 30 Ton
64 L.H., Daily Totals	

Crew B10Y (Union)	
1	Equip. Oper. (med.)
.50	Laborer
1	Vibratory Drum Roller
8 L.H., Daily Totals	