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Users Guide to the Highway Concrete (HWYCON) Expert System

Lawrence J. Kaetzel, James R. Clifton, Kenneth Snyder
National Institute of Standards and Technology
Gaithersburg, MD

Paul Klieger
Consultant, Northbrook, IL

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Strategic Highway Research Program
National Research Council
2101 Constitution Avenue N.W.
Washington, DC 20418

(202) 334-3774

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Abstract

One of the major goals of the Strategic Highway Research Program (SHRP) was to improve the performance and durability of highway concrete. SHRP Project C-206, Optimization of Highway Concrete Technology, was created to disseminate knowledge of the results of SHRP-sponsored research and recent advancements in concrete materials technology. The products of this project included a synthesis of advances in highway concrete technology, training videos, and the expert system HWYCON (Highway Concrete). HWYCON is designed to assist state highway departments in three areas: 1) diagnosing distresses in highway pavements and structures; 2) selecting materials for construction and reconstruction; and 3) obtaining recommendations on materials and procedures for repair and rehabilitation methods. HWYCON is an operational system and will be distributed to state DOTs through SHRP. This document is intended to provide a reference for users of the system who need information about the knowledge base, installation, and operation of HWYCON.

1. Introduction

The Strategic Highway Research Program (SHRP) C-206 project, Optimization of Highway Concrete Technology, included the development of an expert system for highway concrete activities. This effort resulted in the development of HWYCON (Highway Concrete) which is an operational and computerized knowledge system designed to assist state highway department staff. The knowledge contained in HWYCON addresses three principal areas: 1) diagnostics-distress identification and cause of distress(es); 2) materials selection-the selection of materials for construction and reconstruction; and 3) repair and rehabilitation-recommendations on materials and procedures for concrete pavement repair and rehabilitation. This document is intended to provide a reference for users of the system who need information about the knowledge base, installation, and operation of HWYCON. It also provides information for computer specialists who are involved in making changes (maintaining) to the system. Appendix D is intended to provide the user with information about the operation of HWYCON. In addition, this document provides information on the following:

- Expert systems application and design.
- Purpose of the system and the target audience.
- Knowledge areas covered by the system.
- Use of knowledge.
- Requirements for using the system.
- Approach used in developing HWYCON.
- The system's architecture.
- Installation procedures.
- Guidelines for modifying the system.

Appendix C provides a glossary of expert system terms used in this document.

2. Introduction to Expert Systems

Advances in computer hardware technology and software development make it feasible to develop expert systems that are an effective decision-making tool for highway staff involved in diagnosing distresses, designing concrete structures, and in making decisions related to the selection of repair and rehabilitation procedures and materials. Computerized systems can be developed that integrate different forms of knowledge normally used by highway staff. This knowledge is represented in the form of pictures, drawings, databases, guides, and specifications. With the addition of reasoning from high-level experts, a coherent system has been developed for use by highway staff, including inspectors, engineers, concrete specifiers, and repair and rehabilitation specialists. This system for highway concrete, HWYCON, was developed in Task 3 of the SHRP C-206 project Optimization of Highway Concrete Technology. Examples of applications of expert systems for highway concrete are shown in table 1. HWYCON includes knowledge on all three areas identified in table 1 and is designed to address materials-related issues and problems.

Table 1. Examples of the use of expert systems for highway concrete

Highway Activity	Use of Knowledge
Diagnosing distresses	Distress identification and cause
	Visual display distress characteristics (e.g. pictures, drawings) for better interpretation.
	How-to descriptions and techniques on laboratory and field tests to confirm distress cause(s).
Selection of materials	Recommendations on the design of concrete for alkali-aggregate, freeze-thaw, corrosion, and sulfate durability.
	Examples of concrete mixture proportions to achieve early opening times and desired compressive strength.
	Recommendations on the use of materials with known problems and limitations.
Repair and rehabilitation	Recommendations on the selection of materials that are suitable for specific repair approaches (e.g., full-depth repair, bonded overlays).

Several important factors can contribute to the success of deploying an expert system. The factors considered in the development of HWYCON include the following:

1. Initially limiting the scope of the knowledge domain, then allowing it to grow.
2. Obtaining feedback from users through prototype development and distribution.
3. Selection of a development tool that provides a platform for further enhancements and the addition of new knowledge.
4. Selection of a development tool that allows flexibility for incorporating different knowledge forms and provides a high level of programmer productivity.

When developing expert systems, most developers will attempt to obtain the best-available human knowledge sources to design the knowledge base, critique and review the computerized system, and, based on consideration of the review comments received on the prototype systems, make modifications. This is perhaps the only area in expert system development that has not changed dramatically. There will undoubtedly be disagreement about which knowledge to include, based on its credibility, the preferences and other factors. Accepted guidelines, practices, and test methods sometimes offer solutions to the resolution of a disagreement regarding whether to include a specific piece of knowledge or how to use it if they are up-to-date.

The fundamental components of an expert system have changed little since expert systems were first introduced. The knowledge domain (what is known about the subject area) and the inference engine (the logic portion that operates on the knowledge) represent the two basic components. Figure 1 illustrates these components and the knowledge interfaces that can be included in modern systems.

To help the reader understand the workings of the HWYCON system, the following explanation is given. Although this is not essential for describing the system, it will be

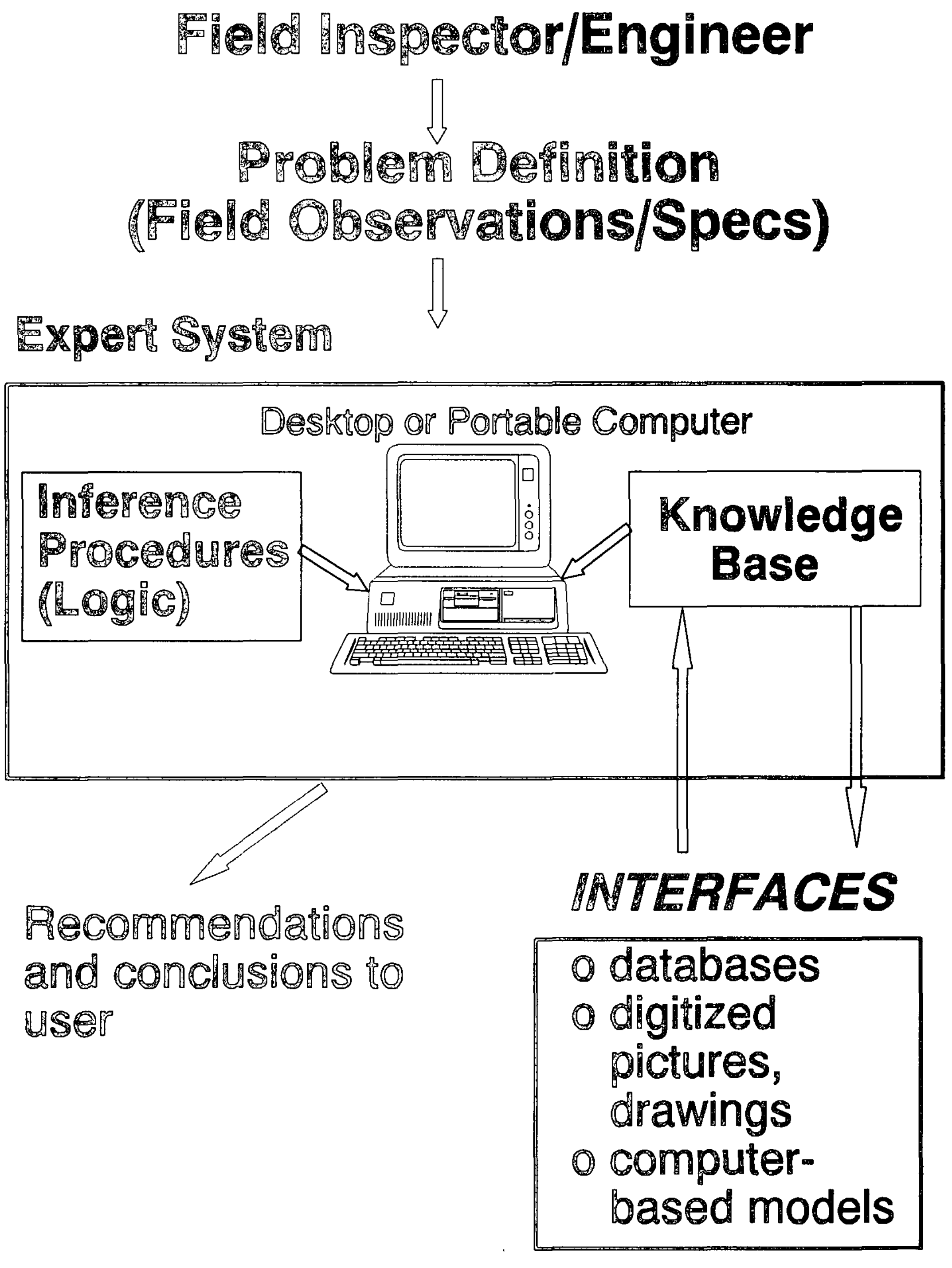


Figure 1. Expert system components and knowledge interfaces that can be included

helpful to develop a prospective of how the system operates. Perhaps the most significant change in expert systems architecture is the representation of the knowledge within the computer and its interrelationships. Most knowledge is represented in the form of rules that tell the inference engine how to use the knowledge. Rules have the basic form of IF **condition**, THEN **action**. For example,

(1) IF a crack develops before the concrete is hardened, and the crack pattern is random, THEN the crack may be a plastic shrinkage crack.

Development tools in use today make use of this form of knowledge representation in combination with other techniques, such as semantic networks. This hybrid system is often called an "object-oriented system." Unlike their predecessors, object-oriented systems use multiple inference procedures. An example is backward chaining, in which the system attempts to reach a goal when given information that leads to that goal, such when giving a recommendation on the amount of concrete cover to use when designing concrete for a corrosive environment. When the forward chaining inference is added, the system can activate other procedures (computer modules, algorithms, or functions) such as performing calculations or displaying information in search of the goal. Other powerful features associated with object-oriented systems allow the knowledge engineer to draw relationships between knowledge components, attach facets, and establish inheritance within the knowledge structure. An example taken from the HWYCON expert system is illustrated in figure 2. The information contained in the ellipses show the path the system would follow to reach the goal of being "caused by poor joint construction or materials in joint." In this figure the object attribute "crack pattern and direction" is defined and its relationships established relative to the conclusion or goal stating that "cracks are caused by corrosion of steel reinforcement." Figure 3 illustrates the object attribute associativity for the object "crack pattern and direction." The question/answer display shown in the figure provides the initial interface to the user when the object crack pattern and direction is processed by the expert systems inference engine. This may be performed in a rule based backward chaining inference procedure or may be activated in a forward chaining inference procedure, such as selecting a button from a previous display. Objects are connected in one of two ways: 1) through a rule contained in the knowledge base; or 2) through associating (connecting) a display with another display or object.

3. Previous Work In the Highway Field

Nearly all expert systems previously developed for the highway field have been developmental prototypes. A survey of expert systems for cement and concrete application, related to the highway field was conducted and reported for the Strategic Highway Research Program (Kaetzel and Clifton 1991). The report identified the three most active areas for highway activities. They are: 1) concrete design use; 2) condition assessment; and 3) repair and rehabilitation. The application of expert systems to the design of concrete mixture proportioning can help to determine compliance with design codes, standards, and guidelines for acceptable practice; and provide information on the selection of materials and use of proper methods for construction. Expert systems can aid the designer in the selection of

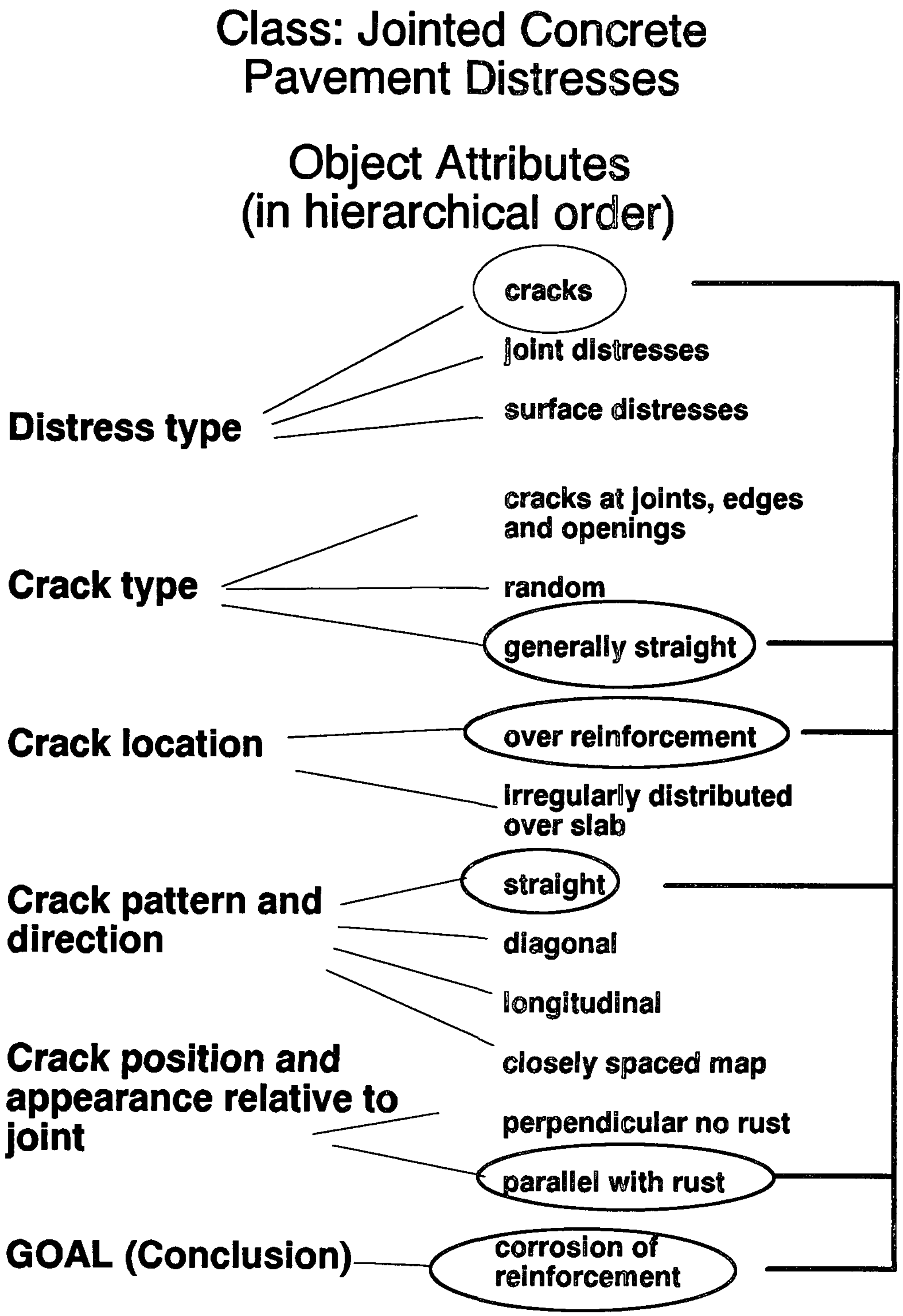


Figure 2. Illustration of an object-oriented knowledge structure

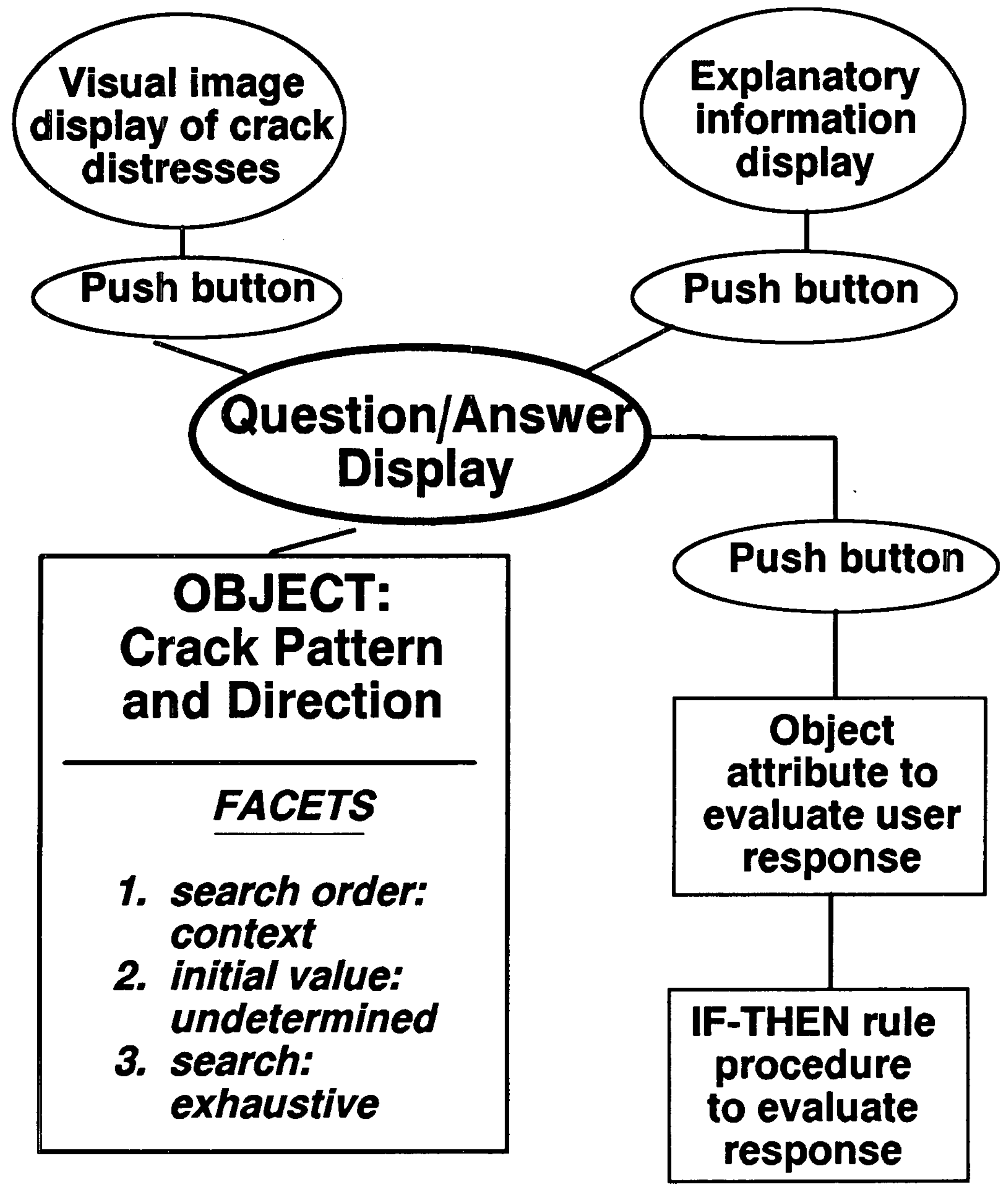


Figure 3. Illustration of connectivity for a HWYCON object

proper constituents for concrete; and assist in design for specific environments; provide information from experts in the concrete mixture proportioning design area; and provide points of reference and checking regarding acceptable design practices. Applications for design and selection of concrete have been developed for concrete mix design (Smith 1987); the selection of ready mix concrete (Seren 1988); and the design of durable concrete (Clifton, Olticar and Johnson 1985). Expert systems applications for concrete design are very limited, compared with other highway engineering activities, such as traffic signaling transportation network design (Ritchie and Harris 1987).

Expert systems for design are more quantitative than systems that deal with planning and diagnostics. The incorporation of knowledge from building design codes and manuals of concrete practice into a knowledge base adds credibility. This information has often been formulated over many years of practice and is supported by standard test methods and revised building practices.

Feedback to the user from design expert systems is normally in the form of recommendations. These recommendations can specify the quantity or type of materials needed for a structure, and for a specific environment. The user specifies the input variables to the expert system that in turn determine the proper constituents. Examples of the information contained in the recommendations for frost-durable concrete include the following:

- Type of cement
- Durability factor
- Percent of entrained air
- Air void spacing
- Compressive strength

The application of expert systems to diagnostics, and repair and rehabilitation activities is perhaps the most beneficial application for highway inspectors, engineers, and decision makers. It can assist the inspector or engineer in: 1) identifying the distresses associated with highway pavements and structures; 2) diagnosing the cause of deterioration; 3) recommending different repair and rehabilitation strategies and projecting their benefits; and 4) providing information for budgeting, planning, and life-cycle-costs. The application of expert systems in this area is growing rapidly because of the reduction in highway budgets, a shift from new highway construction to highway maintenance, the loss of highly-qualified engineers and experts, and advances in data-gathering methods.

A key element in maintaining an expert system for diagnostics, repair and rehabilitation is the need to provide the system with large quantities of input data about the pavement or structure. Quite often, this task is the largest and it represents a frequent data processing problem. Issues such as data quality and subjective observations from the field are important in system development and use. Most systems in use today still utilize visual inspections conducted by field staff and manual record searches to obtain the information the system needs to draw conclusions and make recommendations. Two systems, EXPEAR (Hall et al. 1989) and PAVER (Shahin and Walther 1990), represent the most comprehensive systems, and are the result of 5 and 10 years efforts, respectively. These systems are written in conventional computer programming languages (e.g., FORTRAN, PASCAL) and are considered the only fully operational and supported knowledge based systems for pavements in existence today. However, being written in conventional programming languages, they are difficult to update.

More recently, methods have been developed to assist highway staff in data collection, interpretation, and diagnostics. These include video scanning of highway pavements and structure surfaces (e.g., pavement slabs, bridge decks) using a digital camera. New field test methods also are being developed (Cady et al. 1992). These methods can be effective in detecting distresses such as corrosion in highway structures,and measuring their rate of deterioration. Automated data gathering reduces the time required to capture field information and can eliminate the subjective observations that are characteristic of human observations. By connecting this information to expert system reasoning, decisions can be made more rapidly and with greater reliability.

Of the three areas, condition assessment has received the most attention. Table 2 identifies the characteristics common among most expert systems developed for cement and concrete highway applications during the 1980s. Development of comprehensive systems was prohibited by the lack of knowledge on how to develop such a system and by time requirements. Fortunately, development times have been reduced through advances in development tools and computer technology.

Table 2. Attributes and characteristics of expert systems for concrete developed in the 1980s

Attribute	Characteristic
Expert system architecture and inference method	Rule-based, backward chaining.
Development time	Typically 5-10 years.
Development tool	Expert system shell programs, FORTRAN, PASCAL, and LISP programming languages.
Knowledge format	Represented as rules external program interfaces to include graphics.
Knowledge sources	High-level experts or specialists in the domain, guides, and specifications.
Scope of knowledge	Typically addressed small domain.
Achieved status	Prototype system.

4. Purpose and Scope of the HWYCON System

The purpose and scope of HWYCON was defined within the Strategic Highway Research Program (SHRP) C-206 project. HWYCON is designed to assist state highway departments in three areas: 1) diagnosing distresses in highway pavements and structures; 2) selecting materials for construction and reconstruction; and 3) obtaining recommendations on materials and procedures for repair and rehabilitation methods. The SHRP program included many projects that were developing new concrete technology. Recognizing the importance of transferring this new technology to practicing highway engineers, every effort was made to incorporate SHRP-developed technology in the HWYCON system. In some cases this was difficult because the development of the other SHRP products and the expert system were taking place at the same time. Section 7, Knowledge Sources, specifically describes the knowledge that was available. In the absence of SHRP-developed knowledge, knowledge from leading industry organizations and state departments of transportation (DOTs) was used. In each case, the knowledge was tested by the development team and other experts to ensure that it represented the most reliable and applicable information available. During the development, the ETG provided guidance on the knowledge base design and operational requirements for HWYCON. It was decided that the system would primarily address materials-related concrete activities. Prototype systems were developed and reviewed by the user community. The knowledge domain and target audience for HWYCON is illustrated in figure 4.

Examples of distresses that occur in highway structures are those that are induced by poor materials performance are due to exposure to adverse environmental conditions (e.g. sulfate attack, freezing and thawing). For the materials selection subsystem, knowledge regarding the selection of concrete constituents for various environments and selected procedures was included. The final subsystem on repair and rehabilitation includes knowledge that relates to the selection of materials and procedures for various repair and rehabilitation methods.

An important factor in developing any expert system is the need to limit its scope. This is important so that design criteria can be applied effectively (i.e. whether to include a specific piece of knowledge, and in how much detail) and also assists in accomplishing the final goal(s) of the system. Expert systems often fail because the scope of the system is too broad. A more successful approach is to develop a system that accomplishes well-defined goals initially and allows for the addition of new knowledge as it becomes available or as the system matures. HWYCON was developed with these basic principles in mind. The system tends to have more breadth than depth in some areas. The subsystem on materials selection is considered to be comprehensive in its scope. However, other areas may lack depth in the level of knowledge because insufficient availability of more detailed knowledge on a topic. The object oriented architecture of the system and the development tools allow new knowledge to be added, and modifications can be made to the system's operation more easily than with most expert systems that have been developed. In section 13, Future Enhancements to HWYCON, some of the HWYCON areas that could be modified are discussed. This modification would make the system more comprehensive and useful for highway decision making for both the present and the future.

HWYCON is designed to assist various state highway personnel, depending on the subsystem used (see figure 4). For example, it is expected that field inspectors or engineers in the field or central offices would use the Concrete Pavement Diagnostics (CONPAV-D) or Concrete Structures Diagnostics (CONSTRUC-D) to identify distresses and determine their causes. The Concrete Materials (CONMAT) subsystem is useful for staff involved in selecting materials for construction or reconstruction. Examples of its use would be to develop specifications for highway concrete projects. CONMAT knowledge applies to both concrete pavements and structures. The Concrete Pavement Repair and Rehabilitation subsystem (CONPAV-R) would be useful to highway decision makers who need recommendations regarding materials and procedures for concrete pavements needing repair or rehabilitation. As with all expert systems, HWYCON is not intended to replace the high-level expert. It is considered a decision- making tool, and surely there will be solution sets that it can not handle. In other words, there will always be a need for high-level experts, at least for the foreseeable future. HWYCON is considered to be the most comprehensive computerized expert system that has been developed so far that gives recommendations on highway concrete pavements and structures. It will be useful for staff with knowledge levels from beginner to mid level. A consensus opinion developed during the review of the HWYCON prototypes indicated the system would be particularly useful for new inspectors and engineers. Since many high-level staff are retiring from state DOT's, this tool will assist in advancing the level of knowledge and decision making. A description of the types of highway structures, knowledge domain, and the use of knowledge is included in the next section.

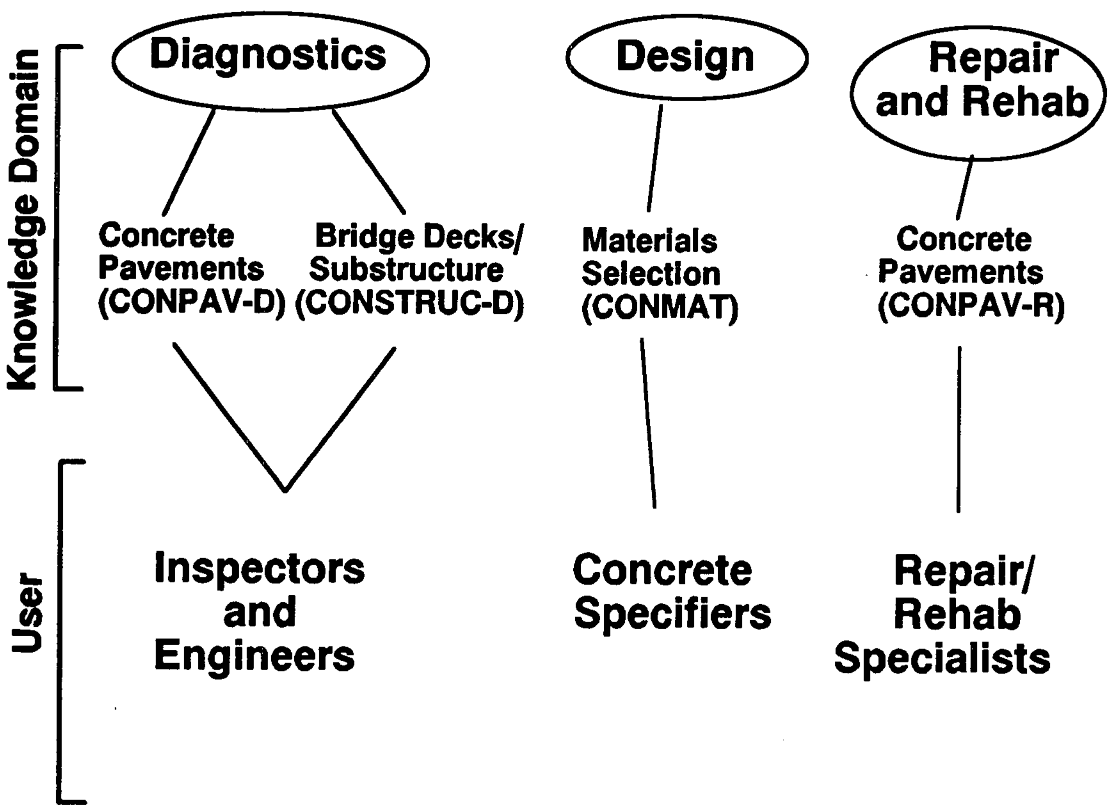


Figure 4. HWYCON knowledge domain and users

5. Knowledge Domain

5.1 Highway Pavements and Structures Covered by HWYCON

The knowledge contained in HWYCON includes information and rules on the three types of highway concrete pavements: 1) jointed reinforced concrete pavements (JRCP); 2) jointed plain concrete pavements (JPCP); and 3) continuously reinforced concrete pavements (CRCP). Knowledge about pavements is represented in all three subsystems, CONPAV-D, CONMAT, and CONPAV-R. Knowledge related to highway concrete structures is also included. Specifically, this includes bridge decks and substructures. Substructures includes concrete elements such as bridge columns, piers, and parapet walls. Information on structures is not as clearly defined as the knowledge on pavements, except in the diagnostics subsystem. Separate modules were developed to address distresses in bridge decks (CONSTRUC-D for bridge decks), and CONSTRUC-D for distresses in structures. Distresses in horizontal and vertical sub-surfaces can be diagnosed in CONSTRUC-D for structures. The CONMAT subsystem can be used to select materials for pavements or structures. For repair and rehabilitation, no knowledge was included on structures, as a separate computer-based decision model developed by SHRP (Purvis et al. 1994). Figures 5 through 9 show the types of pavements and structures, and topics covered by each of the HWYCON subsystems. Tables 3 through 6 show the distress category and type along with the cause or probable causes that are included in HWYCON. It should be noted that the recommendations are based on the most reliable knowledge obtained when the system was developed, and the recommendations are based on the response from the user. Other causes of distresses may be operative in the concrete that would require a recommendation to be modified.

Identifying distresses and determining their cause(s) are important parts of any state DOT concrete program. In order to effectively repair or rehabilitate a structure after a distress has occurred or to assess whether immediate action is needed, it is important to make conclusions based the best observations and information available. Information about the condition of a structure may be obtained from observations conducted within state DOT field offices or with the help of central office staff. Typically, this operation is performed by an inspector or engineer. Information used in making conclusions may be in the form of pictures, drawings, databases, exposure conditions, and the known constituents of the concrete and its surroundings. In some cases, it may not be possible to diagnose the cause due to conflicting or insufficient information about the condition. Tests may needed to confirm the cause. Specimens of the structure's distressed area may need to be examined in a laboratory (e.g., petrographic examination). Also, diagnostic field tests such as the SHRP Alkali-Silica Reaction Test (Stark 1990) for aggregate reactivity may be used to confirm or determine the cause. HWYCON assists in the diagnosis by first identifying the distress, such as "D" cracking, corrosion, and spalling, then it attempts to make a conclusion about the cause of the distress. The system can assist in field observations through the use of a portable computer, or in an office or laboratory environment, through the use of a desk top computer. When the system is used in a laboratory environment, the operator completes a checklist of questions. Examples of these questions and field inspections sheets which may be copied from this document are in appendix A. In some cases, the expert system cannot make a

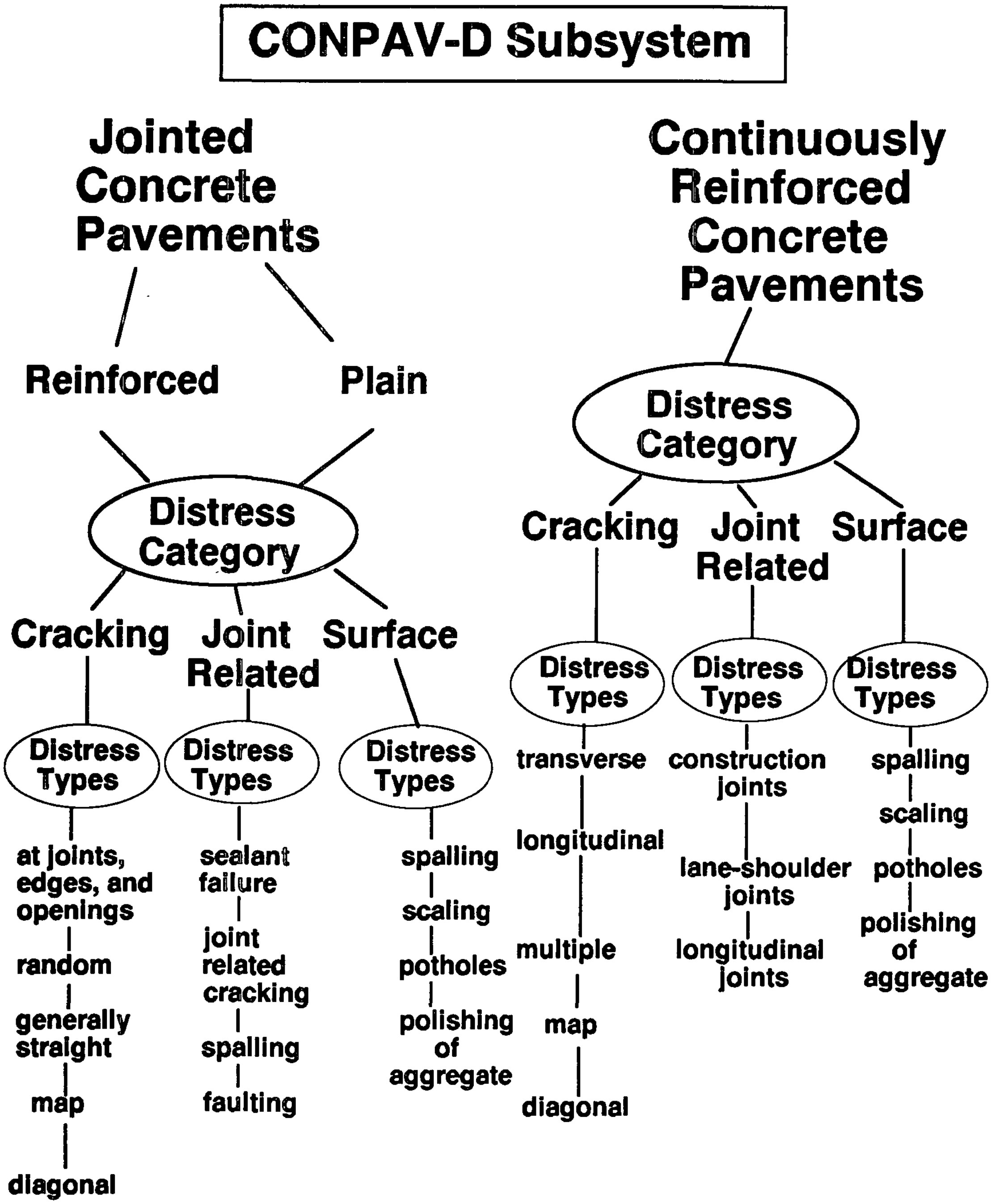


Figure 5. Diagram of the CONPAV-D subsystem

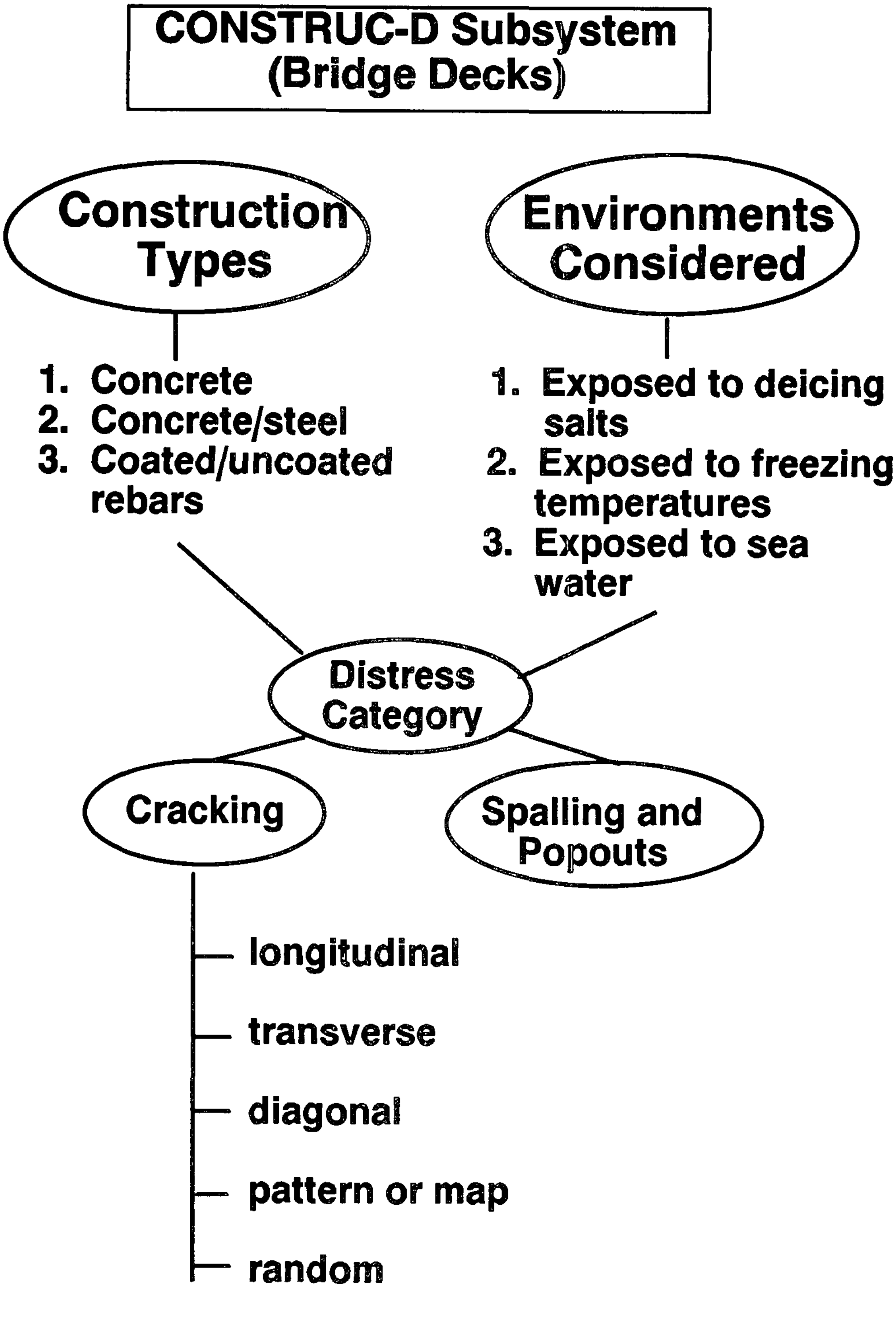


Figure 6. Diagram of the CONSTRUC-D subsystem for bridge decks

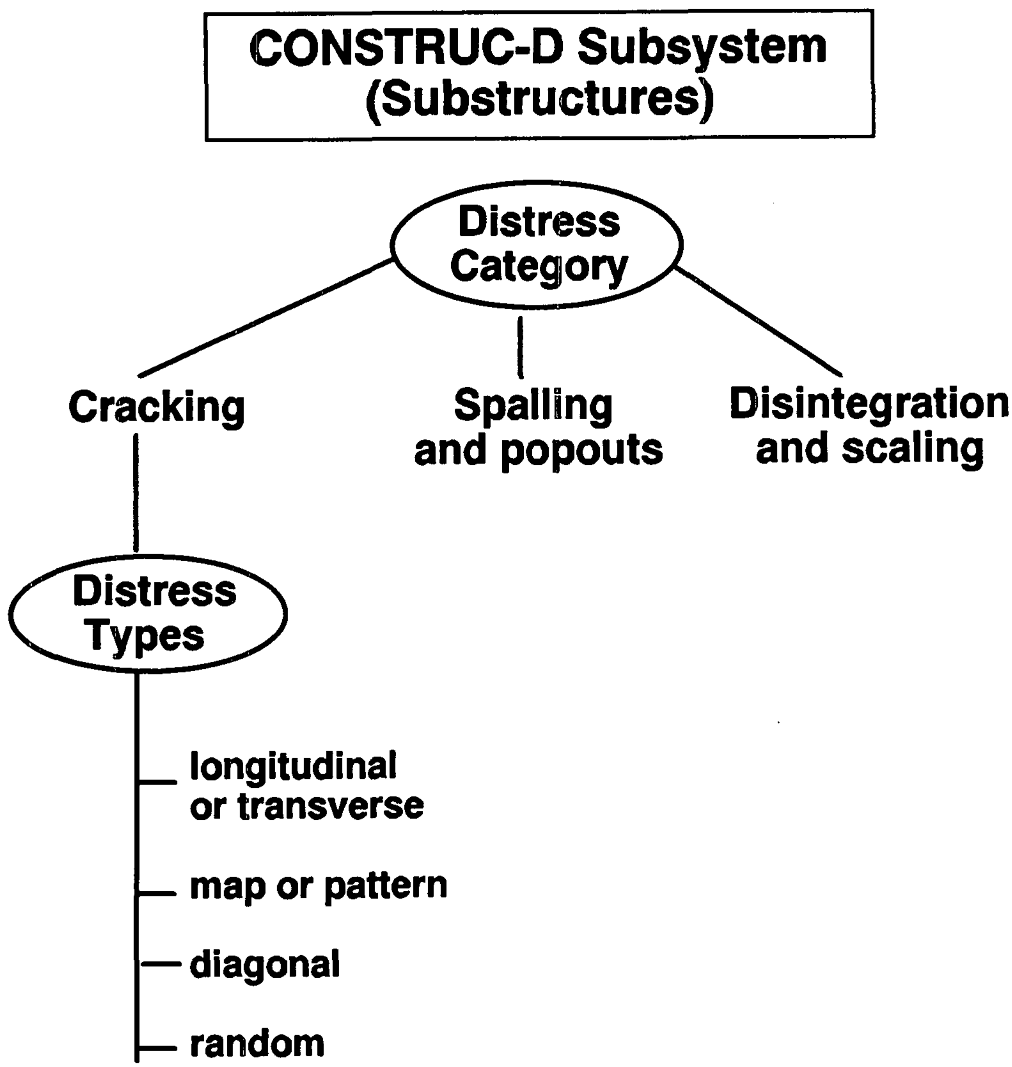


Figure 7. Diagram of the CONSTRUC-D subsystem for substructures

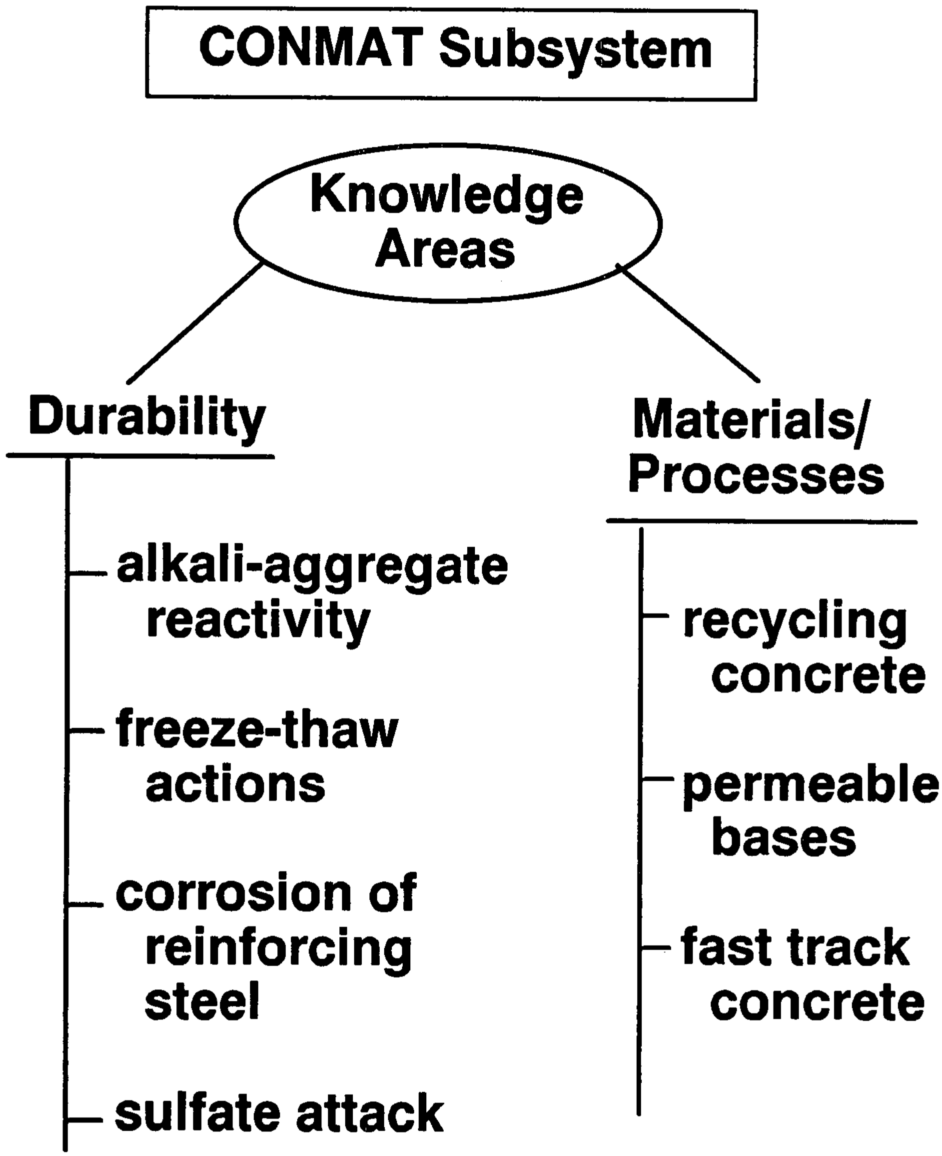


Figure 8. Diagram of the CONMAT subsystem

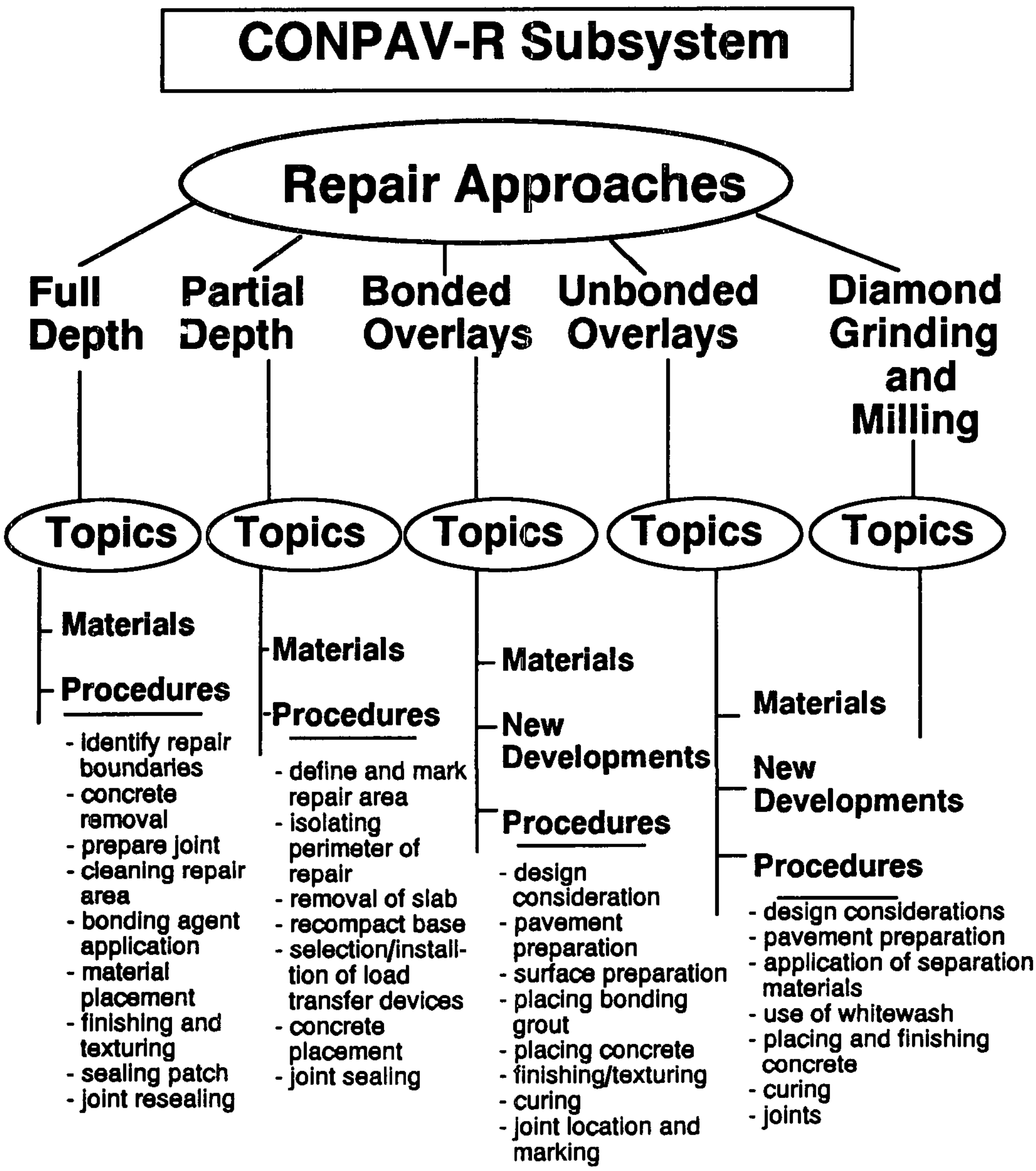


Figure 9. Diagram of the CONPAV-R subsystem

Table 3. Jointed concrete pavement distresses and their associated causes covered in HWYCON

Distress Category and Type	Cause or Probable Cause[1]
Cracks at joints, edges and other openings	Poor joint construction or materials in joint; late sawing; thermal expansion; poor load transfer; frost attack; aggregates freezing; inadequate air-entrained concrete; alkali-aggregate reactivity; sulfate attack.
Random cracking pattern distributed over span	Crazing; plastic shrinkage; drying shrinkage; thermal stress; alkali-silica reaction; sulfate attack; frost attack.
Generally straight cracks in slab	Restrained temperature stress; drying shrinkage; structural defects (dowel bar, late sawing, pavement movement); settlement of subbase or subgrade; inadequate foundation with heavy repeated traffic loads; corrosion; poor consolidation of concrete under reinforcement; alkali-carbonate reaction; alkali-silica reaction; combination (compression failure, poor longitudinal joint construction, drying shrinkage); corrosion.
Sealant failure	Poor bonding ability of sealant; improper preparation of sealant groove; poor application practices; incorrect sealant dimensions; lifetime of sealant reached; premature failure of a poor sealant.
Joint related cracking	Poor construction joint; ingress of incompressible materials into joint; corrosion of dowel; late sawing; thermal expansion; poor load transfer; misalignment of crack inducers.
Joint related spalling	Weak concrete; poor consolidation; infiltration of particles; mechanical damage of joint during construction; incompressibles entering joint; dowel restraint.
Joint faulting	Lack of load transfer system at joint; pumping; settlement of foundation.
Surface spalling and popouts	Corrosion of reinforcing steel; frost attack; contaminated aggregate supply.
Surface scaling	Combination of frost attack and deicing salts; frost attack; poor construction practices.
Potholes	Weak concrete.
Polishing of aggregate	Poor abrasion and polishing resistance

[1]May not be inclusive.

Table 4. Continuously reinforced concrete pavement distresses and their causes covered in HWYCON

Distress Category and Type	Cause or Probable Cause
Transverse cracking	Steel rupture; drying shrinkage; thermal restraint; frictional resistance between the pavement and support base.
Edge punchout	Localized loss of support between two closely-spaced transverse cracks that results in slab deflection under heavy loads.
Longitudinal cracking	Improper construction, corrosion, poor consolidation, loss of foundation support.
Diagonal cracks	Loss of foundation support.
Multiple cracks localized near joint	Frost attack; alkali-aggregate reactivity; sulfate attack.
Multiple cracks irregularly distributed over slab	Alkali-carbonate; alkali-silica reaction; volumetric expansion; sulfate attack; frost attack; change in subgrade; poor quality concrete;poor drainage.
Joint related (construction joints, longitudinal joints, lane-shoulder joints)	Poorly consolidated concrete; improper steel placement; rupture of reinforcing steel; weak concrete; foundation settlement; improper construction.
Surface spalling and popouts	Corrosion of reinforcing steel; frost attack; contaminated aggregate supply; poor quality concrete.
Surface scaling	Frost attack; poor construction; dusting.
Potholes	Weak concrete.
Aggregate polishing	Poor abrasion resistance or polishing resistance.

Table 5. CONSTRUC-D for bridge deck distresses and their associated causes, covered in HWYCON

Distress Category and Type	Cause or Probable Cause[2]
Longitudinal cracking	Corrosion induced by chloride ions; drying shrinkage; alkali-aggregate reaction; plastic shrinkage; plastic settlement.
Transverse cracking	Combination of dead and live loads; weak concrete.
Diagonal cracks	Stresses induced by restraint to load; drying shrinkage; dead and live loads.
Random cracks	Any process that induces cracking.
Pattern or map cracks	Overworking surface during finishing; alkali-aggregate reaction; plastic shrinkage; drying shrinkage; freezing and thawing action; sulfate attack.
Spalling and popouts	Corrosion; freezing water; rebars too close to surface; contamination of cracks at surface; heavy traffic; frost attack; contamination of aggregate supply.
Scaling	Combination of freezing and thawing and application of deicing salts.
Polishing of aggregate	Poor abrasion or polishing resistance.

[2]May not be inclusive.

Table 6. CONSTRUC-D for structures and their associated causes, covered in HWYCON

Distress Category and Type	Cause or Probable Cause[3]
Longitudinal cracking	Corrosion caused by chloride ions; corrosion caused by carbonation; freezing and thawing action; inadequate air-entrainment; alkali-aggregate reaction; plastic settlement; plastic shrinkage; plastic settlement.
Map or pattern cracking	Overworking of concrete surface during finishing; low permeability; sulfate attack; alkali-aggregate reaction; early thermal expansion/contraction; plastic shrinkage; overall expansion.
Diagonal cracking	Shear stresses; tensile stresses.
Random cracking	Various causes that induce cracking.
Scaling and disintegration	Sulfate attack; dusting; frost attack/deicing salts.

determination of the cause of the distress. The program then recommends appropriate tests to determine the cause of the distress.

5.2 Use of HWYCON In Highway Practices

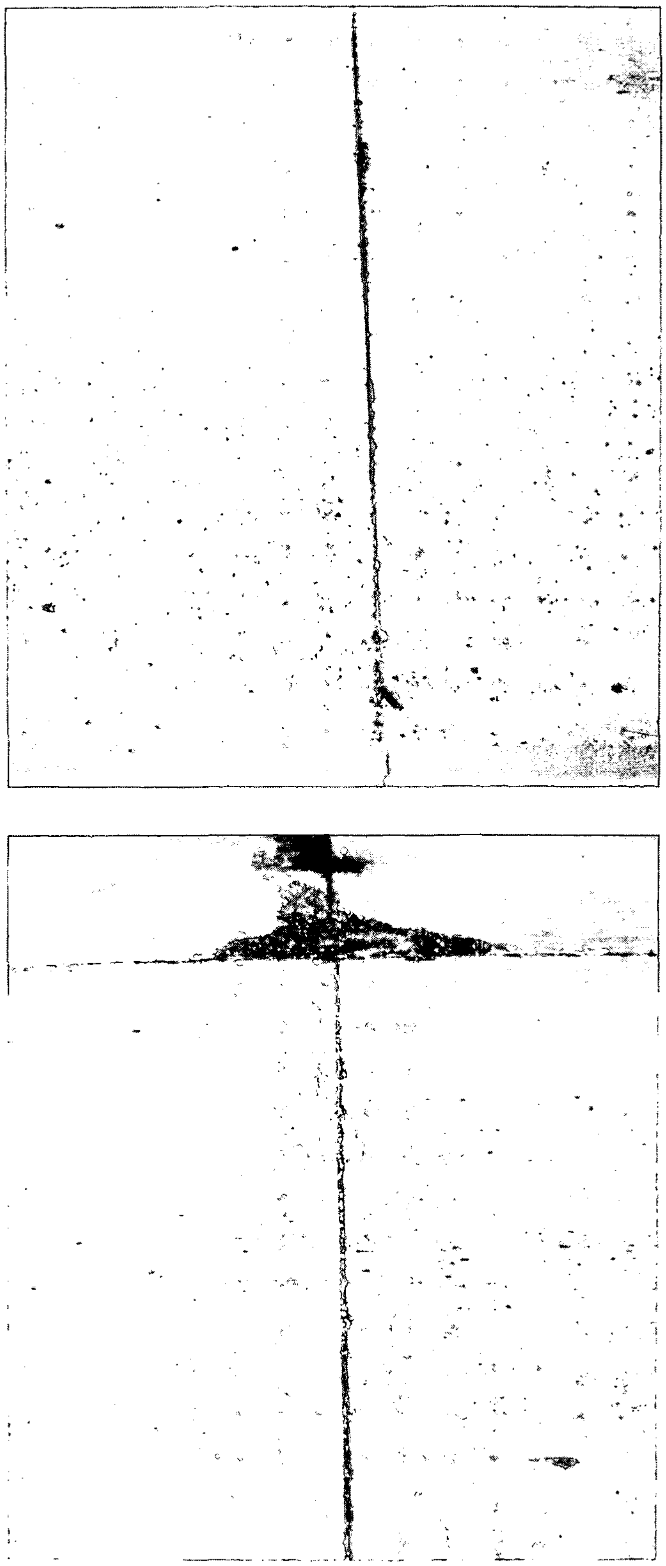
The anticipated users of HWYCON were presented in figure 4. Each subsystem is designed to be used separately. Except in the case of durability and fast-track knowledge in CONMAT, which can be accessed from the repair and rehabilitation subsystem. It is expected that information obtained from one subsystem will be used in another. Identifying distresses and their causes can assist in the design of durable replacement material or the proper rehabilitation method.

5.2.1 Diagnostics

The approach the expert system takes mimics the way an expert would go about diagnosing a distress. It queries the user for information on the type of structure and distress (e.g. cracking in a pavement, spalling of a bridge deck), the location of the distress and exposure conditions. A session may involve questions related to the constituents and composition of the concrete, such as if the concrete is air entrained, what type of aggregate is involved or what the aggregate's history is in relation to known cases of reactivity. Visual presentations of knowledge are used extensively throughout the diagnostics subsystems in the form of digitized photographs and drawings of distresses. Often it is not possible to explain visual features of a distress in text. This capability allows the operator to view examples and see the (sometimes minor) differences in similar distresses, such as the pattern and orientation of cracking. Figure 10 shows an example of two crack patterns that are sometimes confused

[3] May not be inclusive.

Figure 10. Examples of two crack patterns, ASR (top) and frost attack (bottom).



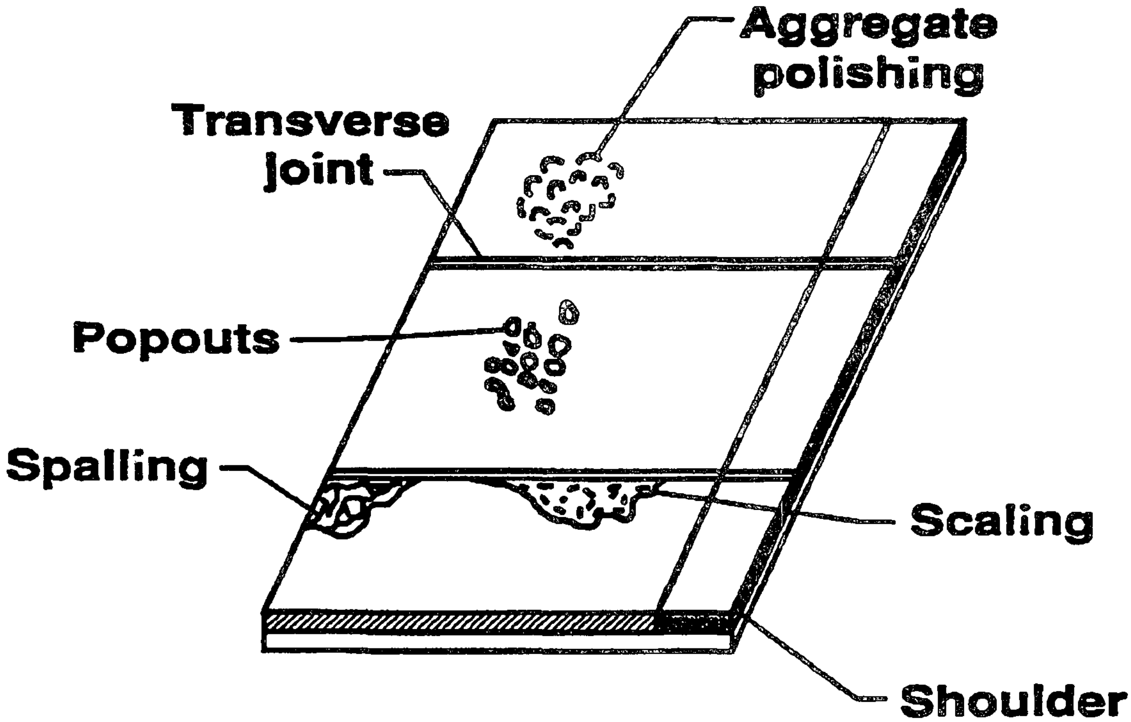


Figure 11. Drawing of examples of some distresses that could occur in jointed concrete pavements.

when making a diagnosis. Figure 11 is a drawing which shows examples of materials-related distresses that could occur in jointed concrete pavements. This approach to diagnostics is considered to be an improvement over conventional methods because it gives the user an approach to problem solving at the expert level, and it provides the operator with a coherent system containing knowledge in different forms. It also formalizes the definitions of distresses; it helps to eliminate ambiguities. Also included in the system is an explanation of the significance of background information on distress types and tests and advises why it is important that certain questions are being asked. An on-line bibliography is also provided to assist the staff in conducting further investigation or analysis of distresses. At this time, HWYCON evaluates distresses individually. At present, there is no provision to make conclusions in situations that involve multiple causes or distresses that occur simultaneously at one location.

5.2.2 Selection of Materials for Construction and Reconstruction

Designing concrete to perform satisfactorily in adverse environments requires knowledge about the anticipated exposure conditions, accepted and proven methods for specifying the amount and performance of constituents, and specifications for the production and placement of the concrete, such as desired opening times. CONMAT gives recommendations on the design of concrete for four areas of durability and includes knowledge on three methods. The durability areas include: 1) corrosion of reinforcing steel; 2) sulfate attack; 3) freezing and thawing actions; and 4) alkali-aggregate reactions. The methods represented in the knowledge base include: 1) recycling concrete; 2) permeable bases; and 3) fast track concrete. Table 7 shows the durability areas and their respective knowledge areas. Table 8 shows the knowledge areas for the materials procedures included in CONMAT.

Materials durability knowledge included in CONMAT closely parallels the *Guide to Durable Concrete* published by the American Concrete Institute, Committee 201. This document served as the basis for developing the knowledge. New knowledge from other SHRP projects on freezing and thawing actions and alkali-aggregate reactivity was also included in the subsystem, along with knowledge from high-level experts in the field of concrete durability. Knowledge related to concrete procedures was developed from states using advanced methods and the SHRP C-205 project on High-Performance Concrete. The use of CONMAT will assist state DOT staff in specifying concrete.

5.2.3 Repair and Rehabilitation of Concrete Pavements

The HWYCON subsystem CONPAV-R gives recommendations on the selection of materials and procedures for the repair and rehabilitation of concrete pavements. The program assumes

Table 7. CONMAT durability and knowledge areas

Durability Area	Knowledge Area
Alkali-aggregate reaction	Determination of reactivity potential, recommendations on use of reactive aggregate.
Corrosion of reinforcing steel	Selection of materials (cementitious materials, aggregate, mix water, reinforcing steel, admixtures). Concrete design (concrete cover, exposure to water, deicing chemicals, soil subbase materials, chlorides).
Freeze and thawing action	Prevention of scaling; severity of freezing and thawing (moderate, severe); conventional highway concrete; high performance concrete; selection of aggregate; selection of admixtures; and cementitious materials.
Sulfate attack	Sulfates in soil and water for mild, moderate, severe, and very severe environments; selection of admixtures; cementitious materials.

Table 8. CONMAT knowledge for repair and rehabilitation procedures

CONMAT Procedure	Knowledge Area
Fast track	Selection of materials for fast track concrete for bridge decks, patches and small sections for early opening times of 4, 12, and 24 hours.
Recycling concrete	Use of aggregate, use of other constituents of concrete if durability problems exist.
Permeable bases	Stabilized and unstabilized bases, separator layers, and edge drainage systems.

that the procedure has already been chosen. The procedures covered in CONPAV-R include bonded and unbonded overlays, full and partial depth repairs, and diamond grinding and milling (see figure 9). CONPAV-R gives recommendations on materials and steps for performing the procedure. The American Concrete Pavement Association has an active program in this area and has published technical bulletins covering this area. Knowledge from these documents and drawings are represented in CONPAV-R. The operation of CONPAV-R involves the user specifying whether information is needed on procedures or materials. The procedures portion of the knowledge includes descriptions of steps for conducting the procedure (e.g. partial-depth repair, bonded overlay). Knowledge about recommendations on materials for procedures is based on the desired opening time. Opening times of 4 to 6 hours, 12 to 24 hours, and greater than 24 hours are available. Bonded and unbonded overlays, and diamond grinding and millings knowledge includes information on new developments in those areas.

6. Development Process

Initial steps in the development of HWYCON involved establishing criteria for determining the scope of the knowledge domain, the sources of knowledge, performance of the computerized system, user review and feedback, and system implementation. Table 9 shows the criteria established for the development and implementation of the expert system. To accomplish this task, numerous groups and individuals were consulted. One of the main objectives of the system was to capture and transfer the knowledge being produced in other SHRP projects. High-level experts at National Institute of Standards and Technology (NIST), SHRP C-206 project team members, and other experts in the field of concrete were chosen to assist in the various activities. State DOTs were asked to provide information related to their area of expertise. Literature searches, guides, specifications and technical notes were

Table 9. Criteria for the development and implementation of HWYCON

Criterion	Goal
Target audience (staff)	*Diagnostics*: inspectors and engineers *Materials Selection*: concrete specifiers *Repair/Rehabilitation*:engineers, decision makers
Target audience (level of existing knowledge)	Mid-level and below
Modifications and enhancements to knowledge base	Selection of a development tool to allow knowledge to be segmented and modified easily.
Interpretation of knowledge	Allowing the use of different forms of knowledge (rules, pictures, drawings, databases, explanatory information).
Implementation computer platform	Use of desktop and portable personal computers.
Feedback and review	Developing prototype systems to allow quick startup and easy user interface.

obtained by the development team for evaluation, review, and incorporation into the knowledge base. The staff of the Federal Highway Administration (FHWA), Transportation Research Board (TRB), and American Association of State Transportation Officials (AASHTO) staff were interviewed. In addition, staff members from associations, institutes, academia, and other groups working in the knowledge domain were interviewed. Table 10 identifies the principal groups involved in the development and implementation of HWYCON, and their area of contribution.

A library containing the most current and state-of-the-art developments in cement and concrete for highway activities was established and is maintained at NIST.

Many steps are involved in the production of an operational expert system . These steps can be divided into four phases: 1) conceptual design; 2) knowledge acquisition and prototype development; 3) review and modification; and 4) product delivery. The specific steps taken for each of the categories were as follows:

Conceptual Design Phase

1. Conduct a literature review.
2. Develop state-of-the-art report.
3. Evaluate computer hardware and software development tools.
4. Interview domain experts, state DOTs, highway industry.

Knowledge Acquisition and Prototype Development Phase

1. Develop methods for integrating knowledge.
2. Review and evaluate guides, specifications, manuals.
3. Interview domain experts, users.
4. Develop knowledge trees.
5. Review knowledge trees by expert team.
6. Acquire and enhance photographs/drawings.
7. Develop computerized prototype.

Prototype Review and Revision Phase

1. Review of prototype system by development team.
2. Modify prototype.
3. Distribute prototype to users for review and demonstrate at transportation shows and conferences.
4. Evaluate review comments and revise prototype as needed.

Development of Operational System Phase

1. Develop installation and quick reference manual.
2. Develop user and developer reference document.
3. Distribute operational system to SHRP.

Since many expert systems never reach an operational status, and a stigma exists concerning expert systems, it was felt that user feedback during the development process was essential. Development of prototype systems was needed in order to solicit review and comment. This became an important part of system development since review comments indicated changes

Table 10. Principal groups involved in the development and implementation of HWYCON

Principal Group	Area of Involvement				Knowledge Area			
	System Design	Knowledge Acquisition	Computerization	Review/ Comment	Diagnostics Pavements	Diagnostics Structures	Materials Selection	Pavement Repair/Rehab
Academia								
Iowa State Univ				X	X	X	X	
North Carolina State Univ	X	X		X			X	
Purdue Univ	X	X		X	X	X	X	X
Univ of New Hampshire	X	X		X	X		X	X
American Association of State Highway Transportation Officials	X	X		X	X	X	X	X
American Concrete Pavement Assoc.	X	X		X				X
American Concrete Institute		X					X	
Federal Highway Administration	X	X		X	X		X	X
SHRP C-206 staff								
CTL Contractor	X	X		X	X	X	X	X
NIST Team	X	X	X		X	X	X	X
ERES Team	X	X		X	X			X
SHRP Staff and ETG	X	X		X	X	X	X	X
State DOTs	X	X		X	X	X	X	X
Florida, Illinois								
Iowa, Kansas								
Maryland, New York								
North Dakota, Virginia								
Washington, Wyoming								

necessary in the design and operation of future revisions. Comments were received from approximately 60 per cent of the systems distributed. This is considered to be an unusually high number of responses, particularly for expert systems.

Each subsystem was initially developed and distributed independently, in the following sequence:

1. Concrete Pavement Diagnostics (CONPAV-R).

2. Concrete Structures-Bridge Decks (CONSTRUC-D).

3. Concrete Structures-Substructure (CONSTRUC-D).

4. Selection of Materials (CONMAT).

5. Concrete Pavement Repair and Rehabilitation (CONPAV-R).

The sequence of acquiring the knowledge and developing the prototype involved determining the scope of the knowledge to be contained in the subsystem; evaluating the literature and interviewing experts; developing the knowledge tree; and finally, developing the computerized version using the expert system development shell program. The knowledge tree served as the vehicle for communication between the experts who interpreted and organized the knowledge in a hierarchical structure and the knowledge engineer who developed the computerized version of the knowledge. A computer text file was used to initially record the knowledge in a question and answer sequence form along with a network diagram. Using this format, the knowledge engineer developed the knowledge tree. The knowledge tree was useful for two purposes: 1) it provided the source document for converting the knowledge to question-and-answer display, and explanatory displays, and for developing the systems rules and procedures (computer-coded algorithms); and 2) it was useful as a synopsis for experts and reviewers to review since it provided a "road map" for the knowledge contained in the system.

Review comments were evaluated by the development team and changes made in operational features and the knowledge base. Most operational changes were made resulting from reviews from the first prototype of the CONPAV-D subsystem. These addressed:

- Repeat session and restart options.
- Increased use of push buttons.
- Multiple choice selections from question and answer screens.
- Improvements in the quality and use of visual information.

Changes were also made to the knowledge base to improve user understanding and to correct errors found in paths, conclusions and recommendations. Again, the knowledge trees were instrumental in identifying the portion of the knowledge base or operational components that required changing. Also, the use of the object-oriented system architecture allowed changes to be made more easily because user displays, rules, and object attributes could be identified quickly.

7. Knowledge Sources

The knowledge base for HWYCON was developed using what was considered to be the best sources available during the development period. Sources were investigated and used based on the analysis and interpretation of the high-level experts. Organizations having expertise and published documents are examples of this knowledge. The decision to include knowledge was made by the expert development team. Because of the vast amount of knowledge and the need to assess its validity, acquiring and validating the knowledge was a major effort in the development stage. The process of knowledge acquisition consisted of the following activities:

- Literature searches.
- Interviews with concrete experts.
- Interviews with state DOTs
- SHRP Expert Task Group (ETG) meetings.
- Review of published guidelines, standards, and practices.
- Interviews with SHRP project investigators.

The major organizations that made significant contributions to the knowledge of HWYCON were the following:

- ERES, Inc.
- Federal Highway Administration (FHWA)
- American Concrete Institute (ACI)
- American Concrete Pavement Association (ACPA)
- U.S. Army Corps of Engineers
- State DOTs

The development strategy for the knowledge base was to first assemble and organize the knowledge using the approach an expert would take to address the problem or activity. Then a narrative description of the knowledge was developed in a question-and-answer format. Goals (conclusions and recommendations) were also developed at this time. A network-like diagram was generated to provide a logical sequence to the knowledge. The network connected the knowledge components to one another and to a specific goal. This format was then reviewed by the expert team, and additions of new knowledge and changes were also made to reflect the most effective approach and best knowledge available. In some cases, reviewers were given this information during the prototype review stage. Bibliographic references are also included in each of the HWYCON subsystems. Appendix B shows a complete bibliography of HWYCON's knowledge sources. These are referenced in explanatory, conclusion, and recommendation displays. Push buttons contained in the help facility of each subsystem provide access to a bibliography for the knowledge area, which will assist users in further investigation and analysis.

8. User Responsibilities

HWYCON's conclusions and recommendations are meant to be used as a decision-making tool. The final responsibility for the decision stills lies with the user. Although the system contains high-level information, it is important to understand that variations can occur in the perception of the structure's performance and condition. The misstatement of the observer or absence of information may make the recommendation invalid. Users are encouraged to conduct the tests and procedures recommended by the system. Also, standard test methods should be used in the prediction and measurement of materials performance. If a result is inconclusive after all tests and procedures have been exhausted, an expert familiar with the problem should be consulted.

9. Operational Requirements

The use of HWYCON requires the following:

- An IBM[4] or compatible desk top or portable computer.
- DOS[5] software Operating system with Windows 3.1.
- Information about the concrete highway structure.

Figure 12 illustrates the recommended computer configuration and software and the types of user-supplied information necessary to use HWYCON. Recommendations on the computer hardware are based on tests that were conducted to measure the optimum performance and resource needs. The software recommendations are based on compatibility requirements for the expert system run-only software and knowledge base files. User-supplied information necessary for the operation of HWYCON involves answering questions that are asked during each session. Each subsystem requires a different type of information, as follows:

<u>Diagnostics (CONPAV-D and CONSTRUC-D)</u>

- Type of pavement or structure.
- Type of construction (e.g., bridge deck).
- Type, location, direction, size or appearance of the distress.
- Information about the constituents of the concrete (e.g., aggregate type).
- Previous history of problems (e.g., sulfate attack).

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[4] The reference to IBM computers does not reflect an endorsement of the manufacturer. Rather, it is meant to give reference to a class of computers that includes many different manufacturers. The performance, price, and compatibility varies greatly among manufacturers and distributors, and this reference implies near compatibility in the central processing unit, the computer bus architecture, and the recording formats for data and programs.

[5] DOS is the "Disk Operating System" that runs the computer hardware. DOS is often referenced by different names, including MS-DOS, PC-DOS, COMPAQ-DOS, IBM-DOS and many others. Often, manufactures change the name of DOS and add extensions or make modifications to the way it performs for certain functions. HWYCON is compatible with all of the above referenced versions of DOS beginning with version 3.0. However, differences may exist in other versions which have not been tested with HWYCON, and users may have configured their computer systems in such a way that HWYCON may not be totally compatible. An example of this could be the video graphics capability. In general, if the computer runs Windows 3.1 and its supported protocols and programs, HWYCON also will be compatible.

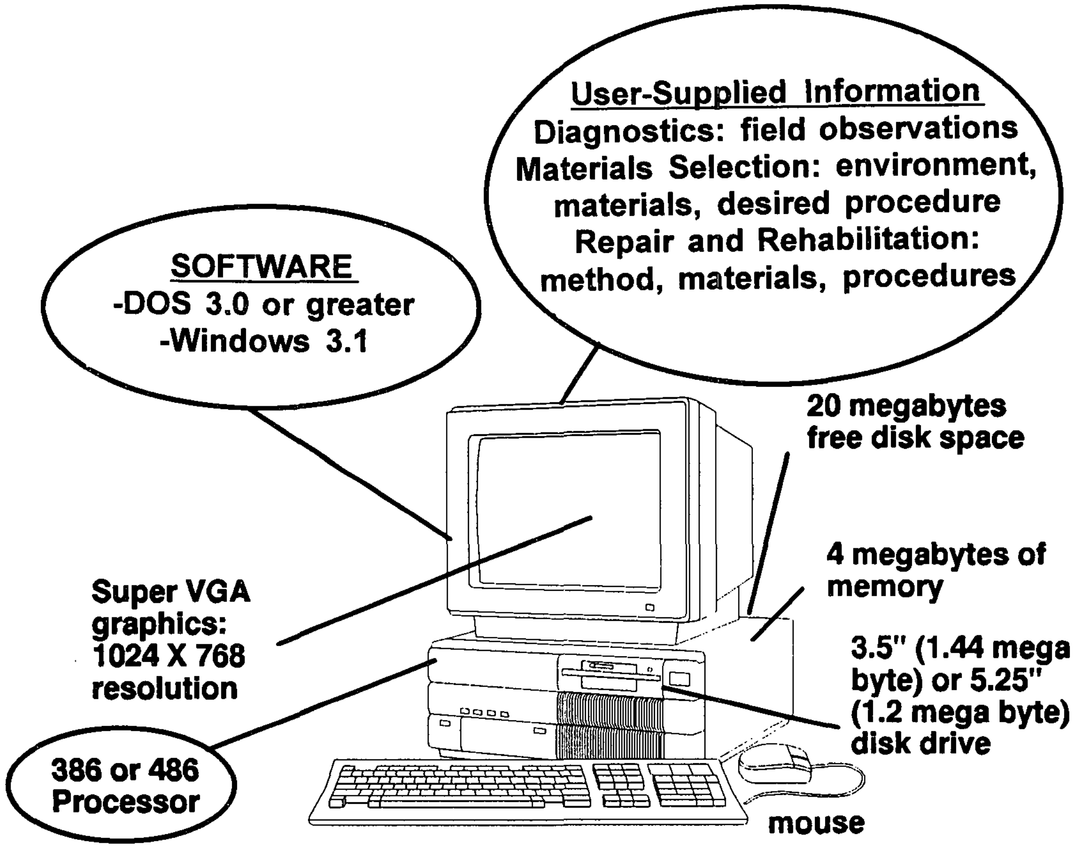

Figure 12. Recommended minimum computer configuration and the types of user-supplied information necessary to use HWYCON

- Exposure conditions (e.g., freezing).
- Failure of materials (e.g., adhesion loss of joint sealants).

Selection of materials (CONMAT)
- Durability area or procedure for designing the concrete.
- Past record or performance of materials based on test methods.
- Type of material to be used in specifying the concrete.
- Exposure conditions.
- Required opening time for project.
- Type of permeable base.
- Type of construction (e.g., reinforced or plain concrete pavement).

Repair and rehabilitation (CONPAV-R)
- Procedure to be used (e.g., full-depth repair, bonded overlay).
- Information type (e.g., recommendations on materials or procedures).
- Required opening time.

Although HWYCON can be instructed through the use of a keyboard, this method is not recommended because it is a very tedious operation. Instead, the use of a pointing device (such as a mouse) is recommended. The pointing device allows the user to select the desired answer(s) to questions and to view the visual and explanatory knowledge contained in the system. Push buttons are used exclusively throughout the system to assist the user in conducting the session. Conclusions and recommendations may suggest tests to be conducted in confirming distress causes, or to predict the performance of materials such as aggregate. HWYCON was designed to be an easy way to use the computer tool that does not require knowledge about how the a computer operates internally. However, the assumption is made that the user is familiar with basic requirements for operating computers and software. These include the following:

- Power on and booting procedures.
- Procedures and commands for loading floppy diskettes.
- Operation of a mouse pointing device.
- Basic commands for Windows 3.1 (e.g., starting, selecting windows, selecting program icons, and exiting Windows).

Help facilities are available at the start of each HWYCON subsystem. The topics covered in the help facilities include: 1) information needed to use the subsystem; 2) use of push buttons; and 3) bibliographic references. These will assist the user in understanding the operational requirements for the system, particularly for new and infrequent users. In addition, an installation and overview document is distributed with the expert system diskettes.

10. HWYCON Development and Implementation

10.1 Level5 Object Expert System Shell Development Program

Expert systems can be developed using a variety of tools and languages. Examples of languages that were developed for expert systems are LISP and PROLOG. It normally takes longer to develop systems using these languages, additional staff may be required and they tend to be highly specialized. Conversely, expert system shell programs tend to take less time for development and they contain development tools to assist the developer. Examples of the tools include display and rule editors, debugging aids, and graphical and imaging capabilities or interfaces. The Level5 Object (Information Builders 1993a) development tool used to develop HWYCON is an example of commercial software available today. The following capabilities are included in Level5 Object:

- Object, display, rule editors.
- Tool for monitoring the session.
- Values editor to determine the status of object and attributes.
- A database interface.
- An agenda editor (for specifying expert system goals).
- Knowledge tree editor and navigator.
- Windows editor.
- Import/export facilities.
- Run facility.

A separate software package available from Information Builders allows developers to produce encrypted knowledge base files for the distribution of production systems. This package, called the Level5 Run-Only Module was used in the distribution of the HWYCON prototype versions through a unlimited right to distribute from Information Builders. Version 3.1 of this software is distributed with HWYCON. A software license for 3,000 copies was obtained from Information Builders, Inc. Copying the Level5 Object Run-Only software diskette is not permitted except to produce a backup copy.

One of the major advantages of using Level5 Object was the ability to use different inference procedures. HWYCON uses both backward chaining and forward chaining inference. An example of how these are used follows:

Backward chaining: Involves the execution of rules in search of a goal. The goal in this case is a conclusion or recommendation. The user supplies information about the structure or procedure and the system attempts to find a suitable goal.

Forward chaining: Involves the use of "when changed" or "when needed" procedures and demons. Procedures and demons are algorithmic statements that direct the computer to process the knowledge in a previously specified manner. When changed procedures are used in HWYCON, demons are not. The use of "when changed" procedures involves a change in the value of an attribute which is triggered by the user selecting a response to a question and then clicking the mouse on the "enter" push button. The push button is attached to an attribute that is linked to a "when changed" procedure that contains a set of IF-THEN-ELSE procedural statements used to evaluate the user's response. Another use of forward chaining involves the attachment of displays to a push button. This in effect "advances" the execution of the expert system in a predetermined logical manner. Although HWYCON is considered to be goal driven, the forward chaining inference is used most frequently in the system.

For a more detailed explanation of expert system inference procedures, Waterman (1986) is a notable reference for understanding the basic fundamentals of how expert systems can operate. To understand how the Level5 Object shell program operates, the *Level5 Reference* (Information Builders 1993b) and *User's Guide* (Information Builders 1993c) is published with the software.

As the name Level5 Object implies, the development tool is based on an object-oriented design. Object oriented programming has become a popular architecture for software engineering today. Object-oriented structure contributes the following features to expert systems:

- Objects can inherit the properties of other objects.
- Object attributes can have attachment that characterize their use and definition (e.g., search method, initial values, displays, queries, "when changed" procedures).
- User displays can be developed that contain objects of many different types and can allow the user to select, modify, or determine their value and status.
- Systems that are object oriented can be easily modified because it is easier to determine where and how knowledge is represented.

- Interfaces to different forms of knowledge are available.

Object-oriented programming is considerably different from conventional programming such as FORTRAN and PASCAL, and the learning curve may be equivalent in time. However, becoming proficient in this method will increase programmer productivity and program readability.

10.2 Imaging Software

The section describing HWYCON knowledge referred to digitized images that represent photographs and drawings of distresses and procedures (see figures 10 and 11). These images became a very important feature of the system. The capture, enhancement, and storage required the use of a scanning device and imaging software. Photographs were obtained from state DOTs, the SHRP *Distress Identification Manual for the Long-Term Pavement Performance Studies* (SHRP 1993), ERES, Inc., and other organizations, such as the American Concrete Pavement Association, and Construction Technology Laboratories. In some cases, the quality of the photographs was unacceptable but the subject matter was desirable. Image processing techniques were used to improve the quality of the photographs. These included sharpening and equalization filters. In nearly all cases, the final image exceeded the quality of the original photograph. For example, crack patterns could be enhanced, making them more pronounced and without changing their characteristics. The software used in acquiring the images was *Publisher's Paintbrush*, version 2.0 (Zsoft 1991). This software allowed images in the bit-mapped format readable by the Level5 Object shell program to be included in the HWYCON displays that are presented to the user.

It was necessary to develop a set of optimum parameters for capturing and processing the images using the imaging software. Critical factors included: 1) disk storage requirements for the image; 2) resolution and quality; 3) compatibility with Windows and Level5 Object; and 4) viewing size. Table 11 lists the adopted parameters that were selected for use with the HWYCON system.

Table 11. Image processing parameters for HWYCON digitized images

Parameter	Value
Resolution	600 dots per inch
Halftone	Bayer
Scale factor	25%
Image format	Bit-mapped
Image type	Gray scale
Brightness and contrast	Automatic as calibrated with scanner
Gray scale levels	256
Sharpening filter	10-30%

The storage requirements for images varied with the size of the original photograph or drawing. The typical storage requirement for each image ranged from 15,000 to 55,000 bytes. The size of the original was between 102 mm and 203 mm in width and 203 mm and 254 mm in height. Considerable emphasis was placed on compressing the size due to the increase in the total size of a Level5 Object module that contains images.

10.3 HWYCON Architecture

The architecture of HWYCON consists of three subsystems, each of which contains modules that with specific knowledge areas. For example, the CONMAT subsystem is represented in eight different modules, one main module, four each for the durability areas, and three each for procedures. This design allowed the system to be modified more effectively and provides the maximum efficiency for operating the system. Generally, once a module is loaded within a HWYCON subsystem, all of the necessary inference procedures and knowledge are resident in the computer's memory. Exceptions to this are in the CONPAV-D and CONSTRUC-D diagnostics subsystems in which the knowledge on crack distresses was further divided for operating efficiency. Table 12 through 15 list all of the HWYCON subsystem module names and their knowledge areas.

Figures 13 and 14 show the interrelationships among the HWYCON modules. The connecting lines shown between the modules indicate that modules can call other modules.

Table 12. CONPAV-D modules and knowledge areas

Module Name	Knowledge Area
CPDMAIN	Main module for selecting pavement type and distresses.
CPDJC	Jointed pavement module for crack distresses.
CPDJE	Jointed pavement module for cracks at joints, edges and other openings.
CPDJRC	Jointed pavement module for random crack distresses.
CPDJSC	Jointed pavement module for straight crack distresses.
CPDJJ	Jointed pavement module for joint-related distresses.
CPDJSD	Jointed pavement module for surface distresses.
CPDC	Continuously reinforced pavement module for selecting of distresses and transverse cracking.
CPDCC	Continuously reinforced pavement module for cracking distresses.
CPDCJ	Continuously reinforced pavement module for joint related distresses.
CPDCSD	Continuously reinforced pavement module for surface distresses.

Table 13. CONSTRUC-D modules and knowledge areas

Module Name	Knowledge Area
CSDMAIN	Main module for selecting bridge deck construction type and exposure conditions.
CSDCNYY	Concrete bridge deck with uncoated rebars; exposed to freezing conditions, and deicing salts.
CSDCNYN	Concrete bridge deck with uncoated rebars; exposed to freezing conditions.
CSDCYXX	Concrete bridge deck with coated rebars.
CSDCXNX	Concrete bridge deck not exposed to freezing conditions.
CSDCNNXY	Concrete bridge deck with uncoated rebars; not exposed to freezing conditions, and exposed to sea water.
CSDSYXX	Concrete and steel bridge deck with coated rebars
CSDSXYN	Concrete and steel bridge deck exposed to freezing conditions, and no deicing salts.
CSDSXYY	Concrete and steel bridge exposed to freezing conditions and deicing salts.
CSDSXNX	Concrete and steel bridge deck not exposed to freezing conditions.
CSDSNNXY	Concrete and steel bridge deck with uncoated rebars; not exposed to freezing conditions and exposed to sea water.
CSDST	Module for diagnostics of the distresses that occur in structures.

Table 14. CONMAT modules and knowledge areas

Module Name	Knowledge Area
CMATMAIN	Main module for selecting the durability area or procedure.
CMATAGG	Recommendations on alkali-aggregate reactivity.
CMATCOR	Recommendations on corrosion of reinforcing steel.
CMATFRZ	Recommendations on freezing and thawing.
CMATSULF	Recommendations on sulfate attack.
CMATRCY	Recommendations on recycling concrete.
CMATPERM	Recommendations on permeable bases.
CMATFTRK	Recommendations on fast track concrete.

Table 15. CONPAV-R module and knowledge area

Module Name	Knowledge Area
CONPAVR	Recommendations for concrete pavement repair and rehabilitation materials and procedures.

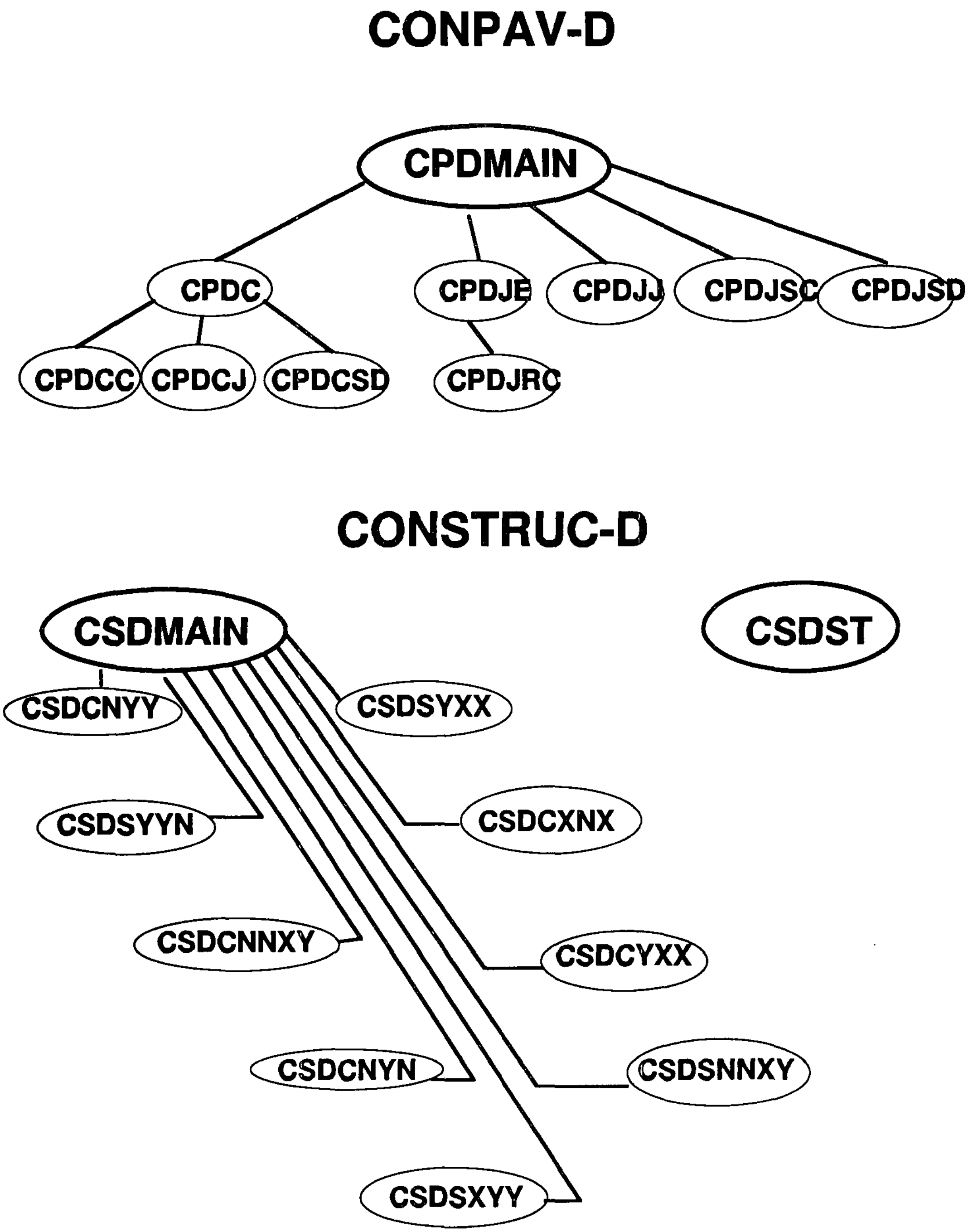

Figure 13. CONPAV-D and CONSTRUC-D interrelationships among modules

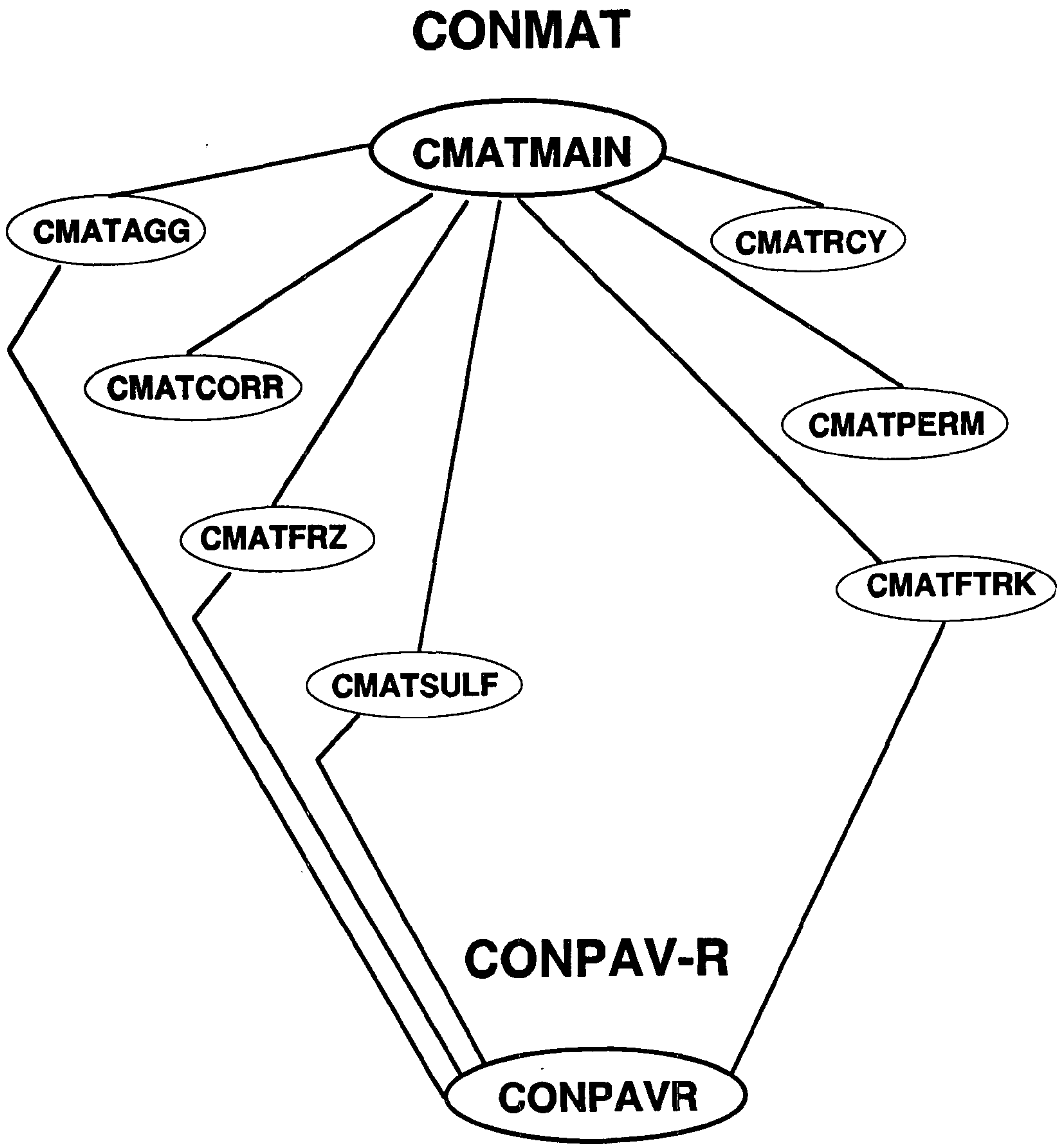

Figure 14. CONMAT and CONPAV-R interrelationships among modules

This function is performed using a "chaining" capability available in the Level5 Object shell program. Chaining is synonymous with conventional programming subroutine calls in which programs can call other programs. This action is initiated by the user selecting options shown in the question and answer displays. At the top of each subsystem diagram the main module (e.g., CPDMAIN) is shown. This module serves as the starting point for each subsystem and is activated by the user clicking on the icon shown in the HWYCON expert system window.

Within each of the HWYCON modules, knowledge is represented in a hierarchical tree structure. This structure logically connects the knowledge components of the system. For example, the CONMAT corrosion of reinforcing steel module (CMATCOR.) includes recommendations on the allowable chloride content and cement type. The knowledge contained in the recommendations is connected to question-and-answer displays that request the user to specify the topic desired, namely, recommendations on chloride content or selection of cementitious materials. The knowledge tree was used as a road map for reviewing knowledge and making modifications to the computerized system.

HWYCON's is divided into components. In this context, components include objects, procedures, and displays that are necessary to represent the knowledge. Figure 15 shows the components of HWYCON, how they are connected, and their definition or function. Another major component of the system is the processing capability, or logic, for the system that is provided by the Level5 Object inference engine. The inference engine uses rules, procedures, push buttons and object attribute values and their status to process the knowledge. Processing of the knowledge implies that a sequence of occurrences (question-and-answer display) is presented to the user in search of a conclusion or recommendation (a goal).

10.4 Packaging and Distribution

HWYCON is distributed to users with this document and seven 3.5-in. diskettes. The diskettes' contents are shown in table 16. The developers diskette set, which contains the source files for HWYCON, were delivered to SHRP and were not intended for distribution to users. The philosophy behind the development of HWYCON was to maintain a pristine copy that would be modified by a central organization. The organization would make updates and changes and then distribute the system to users, which would maintain integrity in the knowledge base. The knowledge base files contained in the user diskette set were encrypted using a capability available in the Level5 Run-Only program. The application files are identified with an ".app" file name extension and cannot be modified. The knowledge base files in the developers diskette set are identified with the ".knb" file name extension. These files were used to generate the application files. Table 17 lists the contents of the developers diskette set. In order to modify any of the HWYCON knowledge base files, the developer would have to purchase a copy of the Level5 Object Expert System Shell Program (Information Builders 1993a).

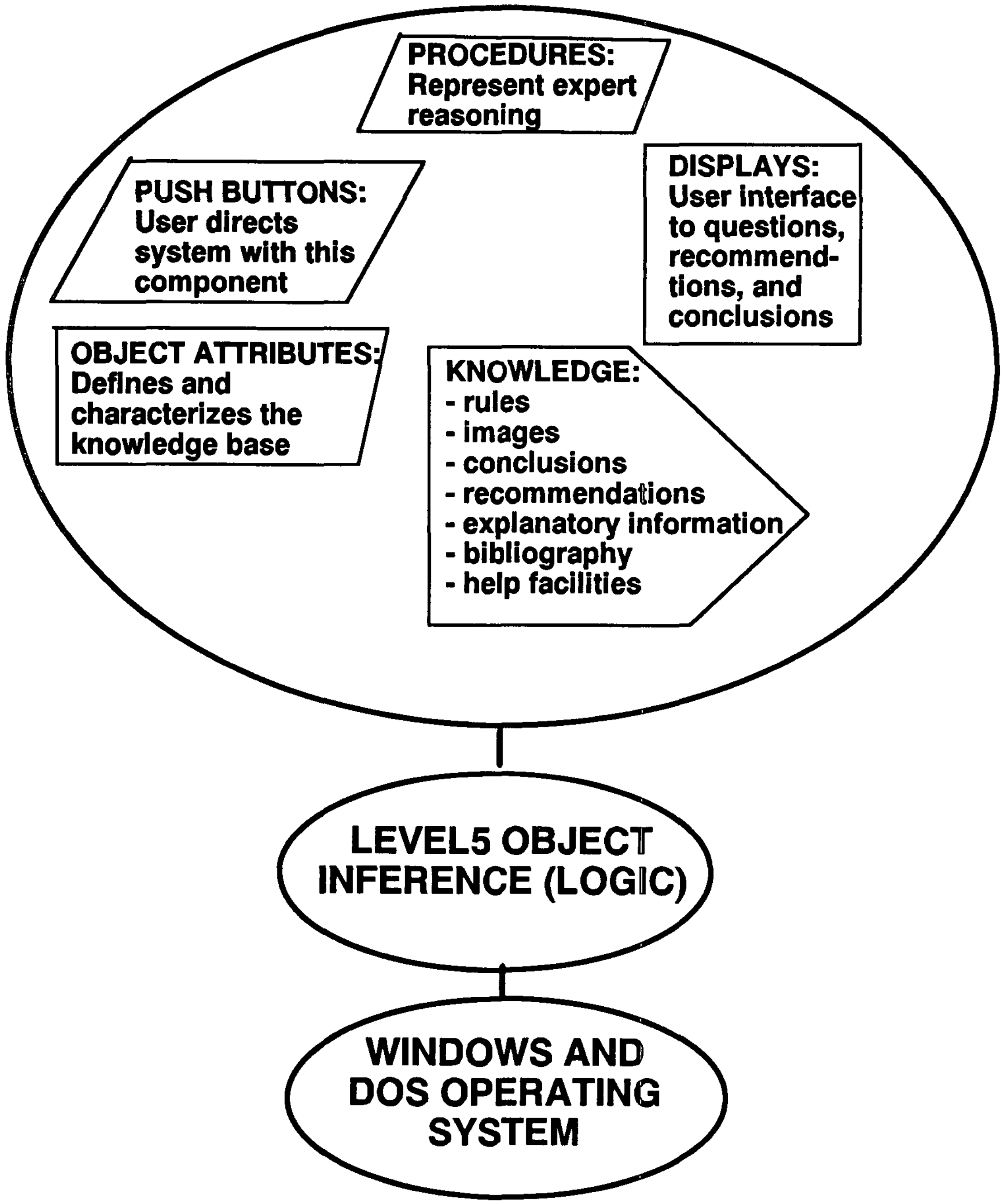

Figure 15. HWYCON knowledge components, connectivity, and function

Table 16. HWYCON user distribution diskette set contents

Diskette #/Name	File Names	Contents
1. Run-Only System Disk		Level5 Object Run-Only program
2. CONPAV-D	CPDCC.APP CPDC.APP CPDCJ.APP CPDCSD.APP CPDJE.APP CPDJJ.APP CPDJRC.APP CPDJDSC.APP CPDJSD.APP CPDMAIN.APP	Concrete Pavements Diagnostics
3. CONSTRUC-D	CSDMAIN.APP CSDCNNXY.APP CSDCNYN.APP CSDCNYY.APP CSDCXNX.APP CSDCYXX.APP CSDSNNXY.APP CSDSXNX.APP CSDSXYN.APP CSDSXYY.APP CSDSYXX.APP	Concrete Structures Diagnostics (Bridge Decks)
4. CONSTRUC-D	CSDSXNX.APP CSCSXYN.APP CSDSXYY.APP CSDSYXX.APP	Concrete Structures Diagnostics (Bridge Decks)
5. CONMAT	CMATAGG.APP CMATCOR.APP CMATFRZ.APP CMATSULF.APP CMATPERM.APP CMATRCY.APP CMATFTRK.APP	Concrete Materials Selection
6. CONPAV-R	CONPAVR.APP	Concrete Pavement Repair/Rehabilitation

Table 17. HWYCON developers distribution diskette set contents

Diskette #/Name	File Names	Contents
1. CONPAV-D	CPDC.KNB, CPDCC.KNB, CPDCJ.KNB,CPDCSD.KNB, CPDJE.KNB, CPDJJ.KNB, CPDJRC.KNB, CPDJSC.KNB, CPDJSD.KNB, CPDMAIN.KNB	Concrete Pavement Diagnostics
2. CONSTRUC-D	CSDCNNXY.KNB CSDCNYN.KNB CSDCNYY.KNB CSDCXNX.KNB CSDCYXX.KNB CSDSNNXY.KNB CSDSXNX.KNB CSDSXYN.KNB CSDSXYY.KNB CSDSYXX.KNB CSDMAIN.KNB	Concrete Structures Diagnostics (Bridge Decks)
3. CONSTRUC-D	CSDST.KNB	Concrete Structures Diagnostics (Structures)
4. CONMAT	CMATAGG.KNB CMATCOR.KNB CMATFRZ.KNB CMATSULF.KNB CMATPERM.KNB CMATRCY.KNB CMATFTRK.KNB CMATMAIN.KNB	Concrete Materials Selection
5. CONPAV-R	CONPAVR.KNB	Concrete Pavement Repair/Rehabilitation
6. CONPAV-D, CONSTRUC-D, CONPAV-R	*.BMP	HWYCON digitized images

11. Installation Procedures

The installation of HWYCON subsystems, CONPAV-D, CONSTRUC-D, CONMAT, and CONPAV-R involves installing the Level5 Run-Only Program Diskette, the six HWYCON knowledge diskettes, and creating a HWYCON window and program icons. The Run-Only program diskette and six knowledge diskettes each require a separate installation procedure. The installation procedures also include the steps necessary to create a HWYCON window and program icons. You may install HWYCON on hard drives or partitions with drive designations other than C:. However, you must install the HWYCON knowledge diskettes and the Run-Only Program Diskette in the same drive and subdirectory. There should be a minimum of 15 million bytes of free disk storage available on the hard disk to install all of the HWYCON subsystems. The instructions below describe the installation procedures.

11.1 Install the Run-Only Program

1. Start Windows
2. Insert the HWYCON Run-Only System Disk into floppy drive a: or b:
3. Select the Windows Program Manager window, click on **File**, then on **Run**
4. Type **a:setup.exe** or **b:setup.exe**, depending on the floppy drive being used
5. Click on **OK**
6. Follow the instructions given by the Level5 Object Run Only setup process.

Use the default options for the installation, with the following exception: Specifiy HWYCON as the subdirectory for storage of the Run-Only Program. See procedure b below.

Following is an example of the question and response sequence:

a. click **OK** to install the Run-Only Program Files

b. enter the subdirectory name, type **c:\hwycon**

If you are using a different hard drive designation other than c:, substitute that letter for the c: portion of the File command.

c. click **OK** to modify the autoexec.bat file

d. click **OK** to examine the autoexec.bat file

e. click **OK** to exit setup

11.2 Installing the HWYCON Knowledge Diskettes

1. Insert the HWYCON Knowledge Disk 1 in drive a: or b:
2. Select the Windows Program Manager window, click on **File**, then on **Run**
3. Type **a:install.exe** or **b:install.exe**, depending on the floppy drive being used
4. Click on **OK**
5. Follow the instructions displayed. Use the defaults when acceptable. The following default values will be displayed:

- install floppy drive = a:
- hard disk drive = c:
- subdirectory = \hwycon

Insert the remaining five diskettes when requested, and return to Windows when prompted to do so.

11.3 Creating the HWYCON Version 4 Program Group and Icons

Establish the program group

1. Select the Windows Program Manager window
2. Click on **File**, then **New**
3. Click on Program Group, then click on **OK**
4. Type: **HWYCON Version 4.0** in the Description field
5. Type: **hwycon4.grp** in the Group File field
6. Click on **OK**

Establish the CONPAV-D icon

1. Select the Windows Program Manger window
2. Click on **File**, then **New**
3. Click on **OK**
4. Type: **CONPAV-D** in the Description field
5. Type: **l5ro.exe cpdmain.app** in the Command Line field
6. Type: **c:\hwycon** in the Working Directory field
7. Click on **OK**

Establish the CONSTRUC-D [Bridge Decks] icon

1. Select the Windows Program Manger window
2. Click on **File**, then **New**
3. Click on **OK**
4. Type: **CONSTRUC-D [Bridge Decks]** in the Description field
5. Type: **l5ro.exe csdmain.app** in the Command Line field
6. Type: **c:\hwycon** in the Working Directory field
7. Click on **OK**

Establish the CONSTRUC-D [Structures] icon

1. Select the Windows Program Manger window
2. Click on **File**, then **New**

3. Click on **OK**
4. Type: **CONSTRUC-D [Structures]** in the Description field
5. Type: **l5ro.exe csdt.app** in the Command Line field
6. Type: **c:\hwycon** in the Working Directory field
7. Click on **OK**

Establish the CONMAT icon

1. Select the Windows Program Manger window
2. Click on **File**, then **New**
3. Click on **OK**
4. Type: **CONMAT** in the Description field
5. Type: **l5ro.exe cmatmain.app** in the Command Line field
6. Type: **c:\hwycon** in the Working Directory field
7. Click on **OK**

Establish the CONPAV-R icon

1. Select the Windows Program Manger window
2. Click on **File**, then **New**
3. Click on **OK**
4. Type: **CONPAV-R** in the Description field
5. Type: **l5ro.exe conpavr.app** in the Command Line field
6. Type: **c:\hwycon** in the Working Directory field
7. Click on **OK**

Installation of HWYCON is now complete. Select a program icon to run a HWYCON module.

12. Modifying HWYCON

Modifying the operation, logic, and knowledge base for HWYCON requires the Level5 Object expert system shell program. To include new images or to change existing images, an image processing program is also required (see section 10.2). In order to use the Level5

Object program, one must be familiar with the various editors, inference procedures, and object attribute types available in the development program. It would be difficult to predict how long it would take for someone to learn to use the tool. This would depend on their knowledge of computing algorithms, object-oriented programming, and the magnitude of the changes to be made. Some guidance can be offered, however, that will help in estimating the level of effort required and whether present staff are suitable or whether to seek assistance. The important factors in making this determination are presented in table 18 along with their associated weight. By analyzing the factors and developing a total score, one can develop a rough estimate of staff suitability. If the score is below 2.0, then it is suggested that assistance be obtained from more knowledgeable resources. In any case, if no prior experience exists with the Level5 Object program, one can assume that a minimum of 12 staff months would be required to learn the program and make major changes to the system. There are learning tools available for the Level5 program through courses and an applications study guide. However, experience indicates that these are only marginally helpful. They tend to focus on aspects of the tool that are not necessarily helpful in the development of HWYCON.

Table 18. Important factors in estimating staff requirements for modifying HWYCON

Factor	Assigned Weight
Familiar with Level5 Object shell program.	1
Past experience with rule-based shell programs.	.5
Past experience with algorithmic programming languages (e.g., FORTRAN, PASCAL).	.5
Past experience with artificial intelligence programming languages (e.g. LISP, PROLOG).	.5
Familiar with imaging software.	.5
Work or experience in highway concrete activities.	1
Familiar with DOS and Windows.	.5

A number of strategies can be developed for modifying HWYCON. A particular strategy would depend on the nature of the change and the person performing the changes. As one gets more familiar with the knowledge and how it is to be represented and processed in its computerized form, it is reasonable to expect that development strategies will change. This was the case in the development of HWYCON. At first, the backward chaining rule-based inference procedure was used exclusively, then it was determined through feedback from users and desired operational efficiency that the forward-chaining procedures with push buttons was preferred. Figure 16 shows the strategy used in developing a HWYCON module and the Level5 Object facility needed. Figure 17 offers a scenario on how to reflect a change in the CONMAT, corrosion of reinforcing steel module (CMATCOR). The change in figure 17 suggests that a new explanatory display is required to present the user with more information about the selection of concrete variables and materials pertinent to their effect on corrosion of reinforced concrete.

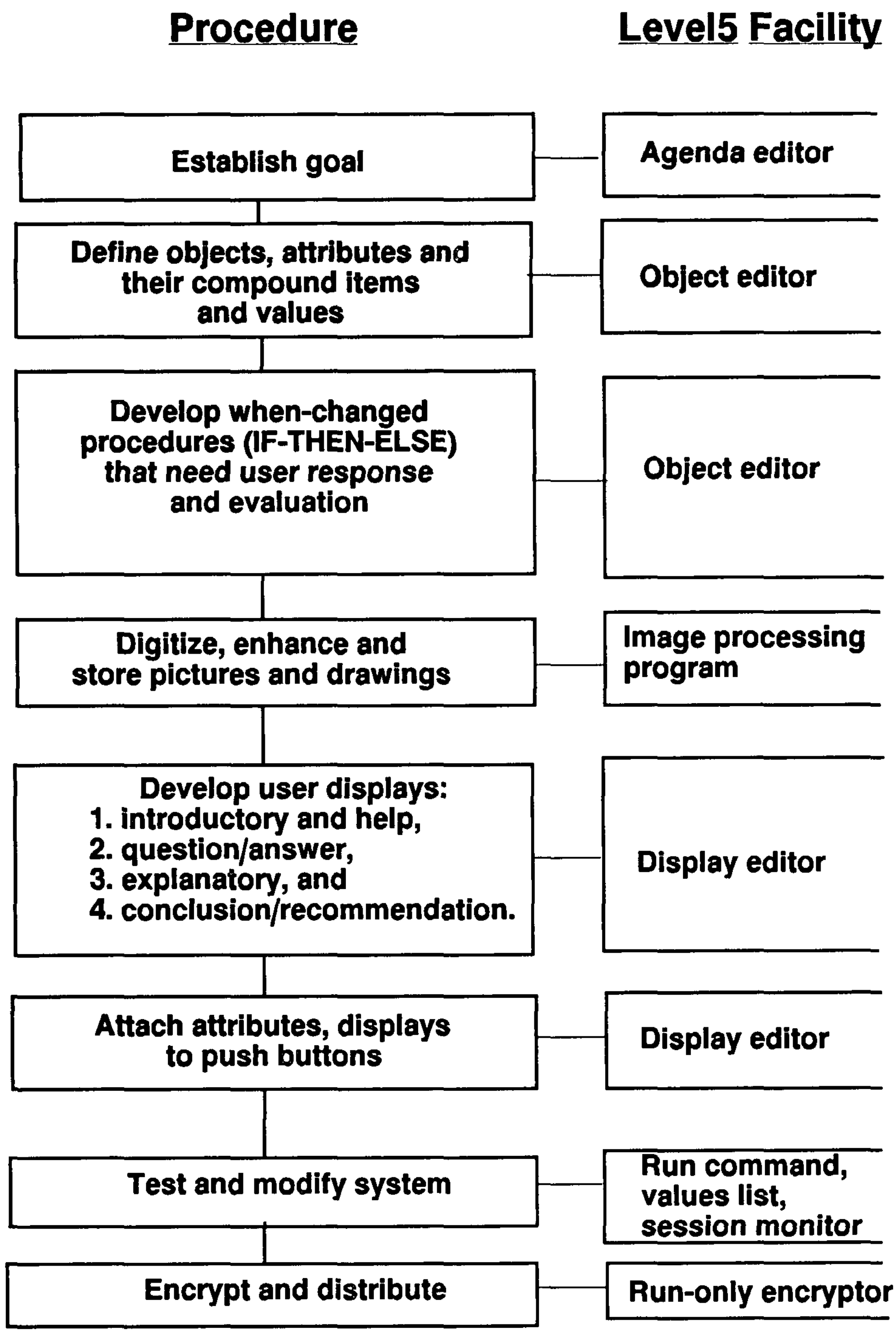

Figure 16. Procedures used in the development of HWYCON and the Level5 Object facility used

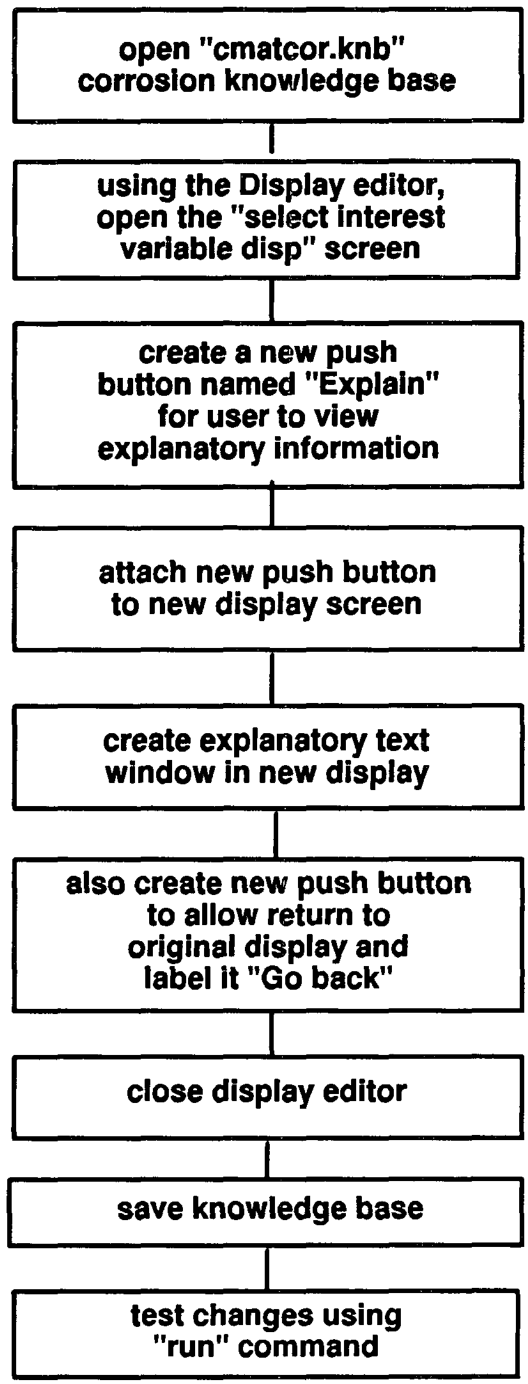

Figure 17. Example of the recommended procedure for modifying the HWYCON knowledge base

The computer hardware and software requirements for making changes to HWYCON are similar to those needed to operate the system. One exception is the scanning device for acquiring images and the disk space necessary to store them. If no changes are necessary for the visual information in HWYCON, then there is no need to have them available. In order to store the entire knowledge base, both in .knb and .app formats, a hard disk with at least 80 megabytes of free space should be available. Memory requirements for running the Level5 Object shell program are 4 megabytes. Figure 18 shows the recommended configuration for a development computer suitable for making changes to HWYCON.

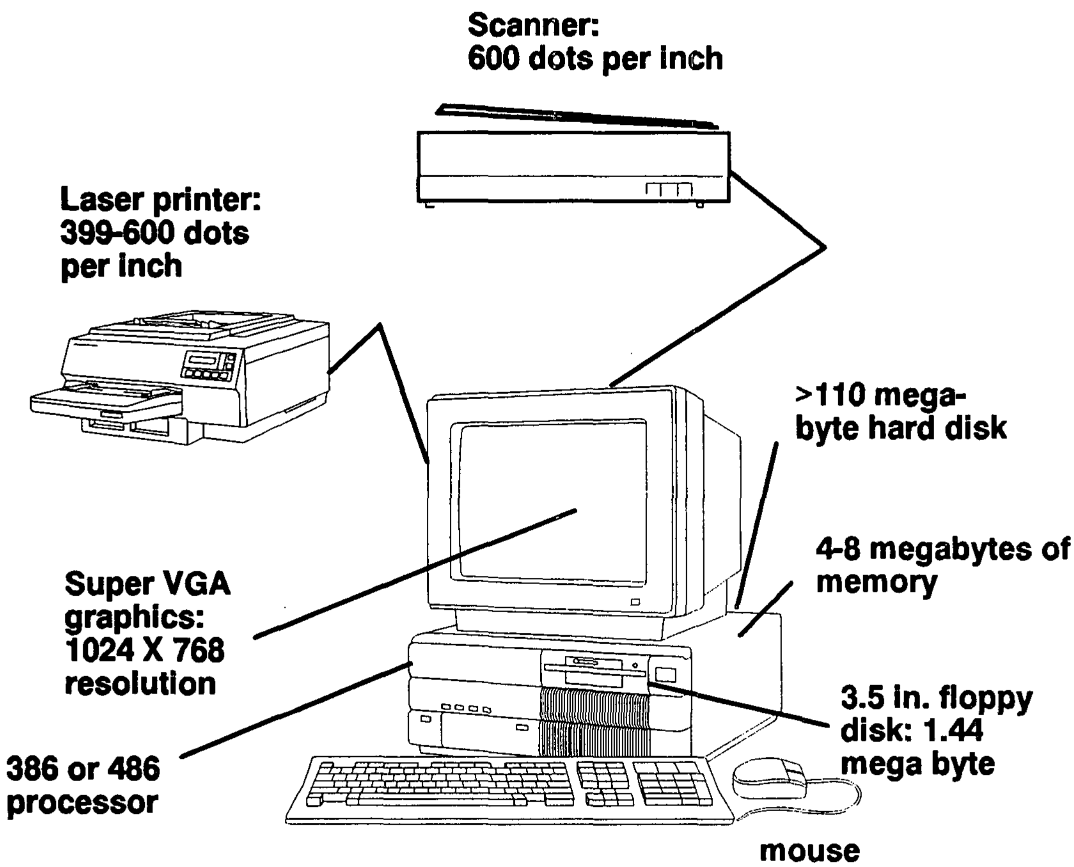

Figure 18. Recommended minimum computer configuration for modifying HWYCON

13. Future Enhancements to HWYCON

In order for expert systems not to become obsolete, they must be nurtured and kept current or they will become obsolete. This requires a mechanism for making modifications as knowledge and needs change, and to include new knowledge. Under the SHRP C-206 Project, guidelines were established for the scope of knowledge and the criterion for implementing the system. HWYCON can be made to address other problems and the scope can be enlarged. This would make the system more comprehensive and useful to state DOTs. In the three areas that HWYCON addresses, specific items have been identified.

For example, causes of distresses often involve non-materials-related factors. Other distress types could be added to include those dealing with interactions between concrete and the soil, and structurally induced cracks in concrete pavements. Also, other SHRP projects were completed concurrently with the C-206 project. It may be important to include this newly developed knowledge in HWYCON. One example is the new knowledge developed in the SHRP C-104 Project, which addressed the corrosion of reinforcing steel in bridge decks.

Other knowledge being developed in the SHRP C-205 project on High Performance Concrete could be included in the CONMAT selection of materials module. Also, intrinsic materials-related problems could be added to CONMAT. These would include areas such as plastic shrinkage and thermal cracking. As stated earlier, the concrete repair and rehabilitation subsystem (CONPAV-R) assumes that the user has already selected the procedure. This subsystem could be enhanced to give recommendations on the selection of the repair method based on the cause and the density of the distress. This would be a very powerful feature. Other enhancements to CONPAV-R could include information on new repair/maintenance materials, such as that gathered for the SHRP C-104 project on the repair and rehabilitation of bridge decks (Purvis et al. 1994)

New operational features could also be included that were identified in the review and feedback process from the prototype systems but were not included because of resource limitations.

Appendix A. Field Checklists for CONPAV-D and CONSTRUC-D

FIELD INSPECTION CHECKLIST
HWYCON-CONPAV-D (Jointed Concrete Pavements)

Place a mark in the appropriate box to indicate conditions observed in the pavement. This information will be needed when operating CONPAV-D.

PAVEMENT TYPE: ☐ Jointed Reinforced Concrete Pavement (JRCP)
☐ Jointed Plain Concrete Pavement (JPCP)

DISTRESS TYPE:

☐ CRACKING

☐ At joints, edges and other openings

☐ localized near joints
☐ random crack pattern

Pattern:

☐ single crack having random directions
☐ map or bulky

Form closed Patterns:

☐ yes
Diameter: ☐ < 50 mm ☐ = > 50 mm
☐ no

Appearance of clean break with matching irregularities:

☐ yes ☐ no ☐ can't tell

Direction:

☐ straight

Direction and Appearance:

☐ perpendicular and no rust
☐ perpendicular with rust

☐ diagonal
☐ longitudinal
☐ **closely spaced or map**

Spacing:
☐ < 10 mm and darkened
☐ = > 10 mm

☐ viscous gel present

☐ Generally straight crack

Direction:

☐ transverse ☐ longitudinal
☐ diagonal ☐ divides slab in segments

☐ diagonal @ 45 degrees to slab edges (0.2 to 2 meter spacing)
☐ transverse cracking regularly spaced 3 meters
☐ transverse cracking not regularly spaced
☐ longitudinal cracking over rebars in JRCP
☐ rust stains present in JRCP
☐ long predominantly straight cracks parallel to center in JRCP
☐ series of parallel, longitudinal cracks with randomly spaced transverse cracks in JPCP

CONTINUED ON BACK

CONPAV-D FIELD INSPECTION CHECKLIST (CONTINUED)

DISTRESS TYPE:

- ☐ **JOINT RELATED DISTRESSES**
  - ☐ **Sealant failure**
    - ☐ **loss of adhesion**
      - ☐ at 50% or more of joints
      - ☐ at < 50% of joints
    - ☐ loss of cohesion
    - ☐ sealant extrusion
  - ☐ **Cracking**
    - ***Pattern:***
    - ☐ **predominantly straight**
      - ☐ short, 1-2 meters, no rust
      - ☐ perpendicular to joint, with rust
      - ☐ parallel to transverse joints
    - ☐ **closely spaced or map**
      - ☐ < 10 mm, parallel to joints
    - ☐ longitudinal crack
  - ☐ **Spalling**
    - ☐ associated with cracks
    - ☐ localized near joint
      - ***Depth:***
      - ☐ **shallow**
        - ☐ wedge shaped or tapering toward back and sides
      - ☐ extending to or deeper than slab center
  - ☐ **Faulting**
    - ☐ at transverse joint
    - ☐ at longitudinal joint
    - ☐ drainage system present

- ☐ **SURFACE DISTRESSES**
  - ☐ **Spalling**
    - ☐ rust stains present
    - ☐ **popouts**
      - ☐ larger than coarse aggregate
      - ☐ much smaller
  - ☐ **Scaling**
    - ☐ light
    - ☐ heavy and on traffic regions
  - ☐ **Potholes**
  - ☐ **Polishing of Aggregate**

FIELD INSPECTION CHECKLIST
HWYCON-CONPAV-D (Continuously Reinforced Concrete Pavements)

Place a mark in the appropriate box to indicate conditions observed in the pavement. This information will be needed when operating CONPAV-D.

DISTRESS TYPE:

- ☐ **CRACKING**
  - ☐ transverse < 0.5 mm
  - ☐ transverse > 0.5 mm
  - ☐ longitudinal, parallel and close to centerline
  - ☐ longitudinal, and over rebars
    - ☐ rust stains present
  - ☐ longitudinal, localized
  - ☐ single crack having random directions
  - ☐ diagonal cracks
  - ☐ multiple cracks
    - ☐ localized near joints
      - ☐ closely spaced
    - ☐ more uniformly distributed over slab
      - ☐ predominantly longitudinal
        - ☐ viscous gel present
      - ☐ closed patterns
      - ☐ cluster cracks

- ☐ **JOINT RELATED DISTRESSES**
  - ☐ **Construction joints**
    - ☐ spalling present
      - ☐ little
      - ☐ spalling and/or faulting
        - ☐ spalls deeper than wide
        - ☐ spalls wider than deep
  - ☐ **Longitudinal joints**
    - ☐ consists of cracks
    - ☐ consists of faulting
  - ☐ **Lane-shoulder joint**

CONTINUED ON BACK

CONPAV-D FIELD INSPECTION CHECKLIST (CONTINUED)

☐ **SPALLING**
- ☐ rust stains present
- ☐ popouts
  - ☐ around the size of larger coarse aggregate
  - ☐ much smaller than the larger coarse aggregate size

☐ **SCALING**
- ☐ exposed to freezing and deicing salts
- ☐ never exposed to freezing and deicing salts
  - ☐ light scaling
  - ☐ heavy traffic

☐ **POTHOLES**

☐ **POLISHING OF AGGREGATE**

☐ **EDGE-PUNCHOUT**

FIELD INSPECTION CHECKLIST
HWYCON-CONSTRUC-D (Bridge Decks)

Place a mark in the appropriate box to indicate conditions observed in the pavement. This information will be needed when operating CONSTRUC-D.

Construction Type:

- ☐ concrete
- ☐ concrete and steel

Distress Type:

- ☐ **CRACKING**
  - ☐ longitudinal
    - ☐ over rebars
    - ☐ rust stains present in crack area
    - ☐ corrosion of rebars
    - ☐ cracks extend deeper than rebars, through slab
  - ☐ transverse
    - ☐ pass through aggregate
    - ☐ around aggregate
    - ☐ around then pass through aggregate
  - ☐ diagonal
    - ☐ at acute-angle corner
    - ☐ at a single column pier
  - ☐ random
  - ☐ pattern or map
    - ☐ patterns generally $<$ 50 mm in diameter
    - ☐ larger than 50 mm in diameter
      - ☐ predominantly longitudinal
      - ☐ closed map
        - ☐ exhibit disintegration

- ☐ **SPALLING AND POPOUTS**
  - ☐ rust stains or rusted rebars present
  - ☐ general spalling
  - ☐ popouts
    - ☐ around the size of larger coarse aggregate
    - ☐ much smaller

- ☐ **SCALING**

- ☐ **POLISHING OF AGGREGATE**

FIELD INSPECTION CHECKLIST
HWYCON-CONSTRUC-D (Structure Submembers)

Place a mark in the appropriate box to indicate conditions observed in the pavement. This information will be needed when operating CONSTRUC-D.

SUBMEMBER:

- ☐ pier
- ☐ column
- ☐ parapet wall
- ☐ other

ORIENTATION:

- ☐ horizontal
- ☐ vertical

DISTRESS TYPE:

☐ CRACKING

- ☐ longitudinal or transverse
    - ☐ over reinforcing steel
    - ☐ propagate horizontally
        - ☐ separation of column from beam or similar element
    - ☐ propagate vertically
        - ☐ crack spacing at least 3 meters
    - ☐ horizontal crack connected somewhat by parallel cracks
- ☐ cracks at joints or edges
    - ☐ closely spaced < 10 mm and darkened
    - ☐ propagate in random direction from joint
- ☐ series of random (map or pattern)
    - ☐ form closed patterns
    - ☐ crack horizontal 3 - 5 mm wide
    - ☐ crack vertical < 1 mm wide
    - ☐ exposed to soil or sea water
    - ☐ evidence of overall expansion
    - ☐ disintegration of the top surface with map cracking below
    - ☐ scaling and "D" cracking present
- ☐ diagonal cracks
    - ☐ propagate from opening in wall
    - ☐ propagate from rigid inclusion to slab
- ☐ random cracks

☐ SPALLING AND POPOUTS

- ☐ rust stain or rusted rebars present
- ☐ popouts
    - ☐ around the size of the larger coarse aggregate
    - ☐ much smaller than larger coarse aggregate

CONTINUED ON BACK

CONSTRUC-D (STRUCTURE SUBMEMBERS) FIELD INSPECTION CHECKLIST (CONTINUED)

□ **DISINTEGRATION AND SCALING**

- □ distress observed where concrete is exposed to soil or in splash zone
- □ disintegration of top surface with map cracking below
- □ light scaling

Appendix B.Bibliography of Knowledge Sources for Diagnostics of Concrete Pavements and Structures

ACI. 1990. *Abrasion Resistance*. American Concrete Institute Committee 201 Guide to Durable Concrete, American Concrete Institute Manual of Concrete Practice, Part 1. American Concrete Institute, Detroit, MI.

ACI. 1990. *Hot Weathering Concrete*. American Concrete Institute 305, Manual of Concrete Practice, Part 2, American Concrete Institute, Detroit, MI.

ACI. 1990. *Guide to Durable Concrete*, American Concrete Institute Committee 201. American Concrete Institute Manual of Concrete Practice, Part I. American Concrete Institute, Detroit, MI.

ASTM. 1993. *Half-Cell Potentials of Uncoated Reinforcing Steel in Concrete*. Standard C 676-93. American Society for Testing and Materials, Philadelphia, PA.

Cady, P., et al. 1992. *Condition Evaluation of Concrete Bridges Relative to Reinforcement Corrosion, Volumes 1 through 8*. Report no. SHRP-C-331. Strategic Highway Research Program, National Research Council, Washington, DC.

Clifton, J. R., et al. 1991. *Chloride Ion Diffusion in Low Water-to-Solid Cement Pastes*. Report no. NISTIR 4549. National Institute of Standards and Technology, U.S. Department of Commerce, Washington, DC.

Darter, M. I, K. D. Smith, and D. G. Peshkin. 1991. *Field-Calibrated Mechanistic-Empirical Models for Jointed Concrete Pavements*. Paper no. 92-0757. 70th Annual Meeting of the Transportation Research Board, National Research Council, Washington DC.

Dean, R. C., J. H. Havens, A. S. Rahal and W. V. Azevedo. 1980. "Cracking in Concrete Pavements", *Transportation Engineering Journal of the American Society of Civil Engineers*, Vol 106, No. TE2, pp. 155-69.

FHWA. 1991. *Bridge Inspector's training Manual 90*. Turner-Fairbank Highway Research Center, Federal Highway Administration, U.S. Department of Transportation, McLean, VA.

FHWA. 1990. *Paved Shoulders*. Technical Advisory T 5040.29. Federal Highway Administration, U.S. Department of Transportation, Washington, DC.

FHWA. 1975. "Rapid Measurement of Concrete Cover on Bridge Decks," *Public Roads*, Vol. 39, No. 2.

McCullough, B. L. 1988. Chapter 8, "Criteria for Design and Construction of Continuously Reinforced Concrete Pavements", pp 279-318, in *Concrete Pavements*, A. F. Stock, ed., Elsevier Applied Science, New York NY.

Mildenhall, H. S., and G.D.S. Northcott. 1989. *A Manual for the Maintenance and Repair of Concrete Roads*. Department of Transportation of the Cement and Concrete Association, England.

NCHRP. 1985. *Portland Cement Concrete Pavement Evaluation System COPES*, Report no. 277. National Cooperative Research Program, National Research Council, Washington, DC.

NCHRP. 1979. *Failure and Repair of Continuously Reinforced Concrete Pavement*, Report no. 60. National Cooperative Research Program, National Research Council, Washington, DC.

NYSDOT. 1982. *Bridge Inspection Manual-82*. New York State Department of Transportation, Albany, NY.

Ontario Ministry of Transportation and Communications. 1983. *Bridge Deck Rehabilitation Manual Part One: Condition Survey*. Research and Development Branch, Ontario Ministry of Transportation and Communications, Ontario, Canada.

Panek, J. R. and J. P. Cook. 1984. *Construction Sealants and Adhesives*. 2d edition. John Wiley and Sons, New York, NY.

PCA. 1970. *Durability of Concrete Bridge Decks: Final Report of a Cooperative Study*. Portland Cement Association, Skokie, IL.

PCA. 1967. *Durability of Concrete bridge Decks: Cooperative Study*. Report 3. Portland Cement Association, Skokie, IL.

Pitt, J. M., M. C. Schluter, D. Lee, and W. Dubberke. 1987. "Sulfate Impurities from Deicing Salts and Durability of Portland Cement Mortar," *Transportation Research Record 110*, pp. 16-23. Transportation Research Board, National Research Council, Washington, DC.

Popovics, S. 1979. *Concrete-Making Materials*. Hemisphere Publishing Co.

Stark, D. 1991. *Handbook for the Identification of Alkali-Silica Reactivity in Highway Structures*. Report no. SHRP-C-315. Strategic Highway Research Program, National Research Council, Washington, DC.

Stock, A. F., ed. 1988. *Concrete Pavements*. Elsevier Applied Science, New York NY.

The Concrete Society. 1982. *Non-Structural Cracks in Concrete*. Report no. 23. The Concrete Society, London, England.

TRB. 1991. *Field Calibrated Mechanistic-Empirical Models for Joints in Concrete Pavements*. Paper no. 91-0757. 70th Annual Meeting of the Transportation Research Board. Transportation Research Board, National Research Council, Washington, DC.

U.S. Army. 1986. *U.S. Army Corps of Engineers Manual Evaluation and Repair of Concrete Structures*. Report no. EM 1110-2-2002. U.S. Army Corps of Engineers, Washington, DC.

Bibliography of knowledge sources for selection of materials

ACI. 1992. "Organic-Based Corrosion-Inhibiting Admixture for Reinforced Concrete," *Concrete International*, Vol. 14, no. 4, pp. 45-51.

ASTM. 1992. "Reinforced Concrete Durability and American Society for Testing and Materials," *American Society for Testing and Materials Standardization News*, pp. 46-51.

ACI. 1991. "American Concrete Institute 201, 'Guide to Durable Concrete'," *American Concrete Institute Materials Journal*. Vol. 88, No. 5, pp. 544-82. American Concrete Institute, Detroit, MI.

ACI. 1991. "American Society for Testing and Materials C 989-89, Specification for Ground Granulated Blast Furnace Slag Cement Concrete," *Durability of Concrete*. American Concrete Institute SP-126. American Concrete Institute, Detroit, MI.

ACI. 1991. "Proposed Revision of: Guide to Durable Concrete" *American Concrete Institute Materials Journal*, Vol. 88, No. 5, pp. 544-82. American Concrete Institute, Detroit, MI.

ACI. 1990. "American Concrete Institute Code 318," *Manual of Concrete Practice*. American Concrete Institute, Detroit, MI.

ACI. 1990. "American Concrete Institute Guide 213R-87, Guide for Structural Lightweight Aggregate Concrete," *Manual of Concrete Practice*. American Concrete Institute, Detroit, MI.

ACI. 1990. "Chemical Admixtures", *Manual of Concrete Practice*, Guide 212. American Concrete Institute, Detroit, MI.

ACI. 1990. *Corrosion of Metals in Concrete.* American Concrete Institute Committee 222. American Concrete Institute, Detroit, MI.

Baumgardner, R. H. 1992. *Notes on Permeable Bases.* Pavement Division, Federal Highway Administration, U.S. Department of Transportation, Washington, DC.

Berke, N. S. 1991. "Corrosion Inhibitors in Concrete," *Concrete International*, pp. 24-27.

Berke, N. S., and L. R. Roberts. 1989. *Use of Concrete Admixtures to Provide Long-Term Durability from Steel Corrosion.* American concrete Institute SP-119, Superplasticizers and Other Chemical Admixtures in Concrete, pp. 383-403. American Concrete Institute, Detroit, MI.

Berke, N. S., D. E. Pfeifer, and T. G. Weil. 1988. "Protection Against Chloride-Induced Corrosion," *Concrete International: Design and Construction*, Vol. 10, No. 12, pp. 45-56.

Berner, E. K., and R. A. Berner. 1987. *The Global Water Cycle.* Prentice-Hall, Inc., Englewood Cliffs, NJ.

Bisque, R. E., and J. Lemish. 1960. "Silicification of Carbonate Aggregates in Concrete," *Transportation Research Bulletin 239*, pp. 41-55. Transportation Research Board, National Research Council, Washington, DC.

Browne, R. D. "Mechanisms of Corrosion of Steel in Concrete," American Concrete Institute SP-65, *Concrete in Relation to Design, Inspection and Repair of Offshore and Coastal Structures.* American Concrete Institute, Detroit, MI.

Buck, A. 1987. "Use of Cementitious Materials Other than Portland Cement", *Concrete Durability: Katherine and Bryant Mather International Conference.* Report no. SP-100, pp. 1863-81. American Concrete Institute, Detroit, MI.

Carrasquillo, R. L., and J. Farbiarz. 1989. *Alkali-Aggregate Reaction in Concrete Containing Fly Ash: Final Report.* Research report 450-3F. Center for Transportation Research, University of Texas at Austin.

Clifton, J. R., H. F. Beeghly, and R. G. Mathey. 1974. *Nonmetallic Coatings in Concrete Reinforcing Bars.* Report no. Federal Highway Administration-RD-74-18. Federal Highway Administration, U.S. Department of Transportation, Washington, DC.

Clifton, J. R., and B. C. Olkikar. 1987. *Expert System for Selecting Concrete Constituents: Computer Applications in Concrete Technology.* American Concrete Institute SP-198. American Concrete Institute, Detroit, MI.

Cohen, M. D. and A. Benture. 1988. "Durability of Portland Cement–Silica Fume Pasts in Magnesium Sulphate and Sodium Sulphate Solutions," *Journal of the American Concrete Institute*, Vol. 85, No. 3, pp. 148-57. American Concrete Institute, Detroit, MI.

Dikeou, J. T. 1976. *Fly Ash Increases Resistance of Concrete to Sulfate Attack*. Research Report No. 23-A Water Resource Publication, U.S. Bureau of Reclamation, Denver, CO.

Duncan, M.A.G., E. G. Swenson, J. E. Gillott, and M. R. Foran. 1973. "Alkali-Aggregate Reactions in Nova Scotia: I. Summary of a Five-Year Study," *Cement and Concrete Research, Volume 3*, pp. 55-69.

Dunstan, E. R. 1980. "A Spec Odyssey—Sulfate-Resistant Concrete for the 80s," *George Verbeck Symposium on Sulfate Resistance of Concrete*. American Concrete Institute SP-77, pp. 41-62. American Concrete Institute, Detroit, MI.

Foy, C., M. Pigeon and N. Banthia. 1991. "Freeze-Thaw Durability and Deicer Salt Scaling of a 0.25 Water-Cement Ratio Concrete," *Cement and Concrete Research*, Vol. 21, American Concrete Institute, Detroit, MI.

Gaynor, R. D. 1985. "Understanding Chloride Percentage," *Concrete International: Design and Construction*, Vol. 7, No. 9, pp. 26-27. American Concrete Institute, Detroit, MI.

Gillott, J. E. "Cell Test Method for Study of Alkali-Carbonate Rock Reactivity," *Proceedings, American Society for Testing and Materials*, Vol. 63, pp. 1195-1206. American Society for Testing and Materials, Philadelphia, PA.

Heiman, J. L. 1986. *The Durability of Cast-In-Situ Reinforced Concrete*. Technical Record 511, pp. 33. National Building Technologie Centre, Australia.

Kalousek, G. L., L. C. Porter, and E. J. Benton. 1972. "Concrete for Long-Time Service in Sulfate Environment," *Cement and Concrete Research*. Vol. 2, pp. 79-89. American Concrete Institute, Detroit, MI.

Kessler, R. J. and R. G. Powers. 1987. *Corrosion Evaluation of Substrate Long Key Bridge*. Interim report no. 87-9A. Florida Department of Transportation.

Khayat, K. H., and P. C. Aitcin. 1991. "Silica Fume in Concrete-An Overview," in *CANMET International Workshop on Silica Fume in Concrete*, pp. 1-46. Washington, DC.

Klieger, P. 1956. "Curing Requirements of Scale Resistance of Concrete," *Highway Research Board Bulletin 150*, pp. 18-31. Highway Research Board, National Research Council, Washington, DC; and *PCA Research Department Bulletin 82*, Portland Cement Association, Skokie, IL.

Klieger, P., D. Stark, and W. Teske. 1978. *The Influence of Environment and Materials on "D"-Cracking, Final Report*. Construction Technology Laboratories, Skokie, IL.

Mehta, P. K. 1986. "Effect of Fly Ash Composition on Sulfate Resistance of Concrete," *Journal of the American Concrete Institute*, Vol. 83, No. 6, pp. 994-1000. American Concrete Institute, Detroit, MI.

Neeley, B. D., W. E. McDonald, and M. K. Lloyd. 1992. *Investigation of Proprietary Air-Entraining Admixtures to Produce Frost-Resistant Concrete with Low Air Content*. Technical report no. SL-92-6. U.S. Army Corps of Engineers Structures Laboratory, Vicksburg, MS.

Oberholster, R. E., and G. S. Davies. 1986. "An Accelerated Test Method for Testing the Potential Alkali Reactivity of Siliceous Aggregates", *Cement and Concrete Research, Vol. 16*, pp. 181-9.

Osborne, G. J. 1991. "The Sulphate Resistance of Portland and Blast-Furnace Flag Cement Concrete," *Durability of Concrete*. American Concrete Institute SP-126. American Concrete Institute, Detroit, MI.

Patzias, T. 1987. "Evaluation of Sulfate Resistance of Hydraulic-Cement Mortars by the American Society for Testing and Materials C 1012 Test Method", *Katherine and Bryant Mather International Symposium on Concrete Durability*. American Concrete Institute SP-100, pp. 2103-20. American Concrete Institute, Detroit, MI.

Philleo, R. E. 1986. *Freezing and Thawing Resistance of High-Strength Concrete*. NCHRP Synthesis no. 129. National Cooperative Highway Research Program, Transportation Research Board, National Research Council, Washington, DC.

Pigeon. M., et al. 1991. "Freezing and Thawing Tests of High-Strength Concretes," *Cement and Concrete Research*, Vol. 21, pp. 844-52. American Concrete Institute, Detroit, MI.

Raja, A. 1991. *Factors Affecting Deterioration of Transverse Cracks in Jointed Reinforced Concrete Pavements (JRCP)*. Department of Civil and Environmental Engineering, Michigan State University, East Lansing, MI.

Reed, J. A. 1989. *FBECR-The Need for Correct Specification and Quality Control*. FBECR Symposium at Sheffield University, England.

Rogers, C., and G. Woda. 1977. *The Chloride Ion Content of Concrete Aggregate from Southern Ontario*. Report no. EM-17. Ontario Ministry of Transportation and Communication, Ontario, Canada.

Rogers, C. A. 1989. *General Information on Standard Alkali Reactive Aggregates from Ontario, Canada*. Engineering Materials Office, Ministry of Transportation, Ontario, Canada.

Rogers, C. A. 1986. "Evaluation of the Potential for Expansion and Cracking of Concrete Caused by the Alkali-Aggregate Reaction", *Cement Concrete and Aggregate, Volume 8*, pp 13-24.

Smith, P. 1964. "Learning to Live with a Reactive Carbonate Rock," *Highway Research Record no. 46*, pp. 126-133. Transportation Research Board, National Research Council, Washington, DC.

Stark, D. 1989. *Durability of Concrete in Sulfate-Rich Soils*. Research and Development Bulletin RD 097.01T. Portland Cement Association, Skokie, IL.

Tikalsky, P. J., and R. L. Carrasquillo. 1989. *The Effect of Fly Ash on the Sulfate Resistance of Concrete*. Research report 481-5. Center for Transportation Research, University of Texas at Austin.

USACE. 1986. Appendix C, *Engineering and Design Standard Practice for Concrete*. Report no. EM 1110-2-2000. U.S. Army Corps of Engineers, Washington, DC.

Van Dodson. 1990. Table 6-3, *Concrete Admixtures*, pp. 136-7. Van Nostrand, New York NY.

Verbeck, G. J. 1966. *Field and Laboratory Studies of the Sulphate Resistance of Concrete*. PCA Research Department Bulletin 227. Portland Cement Association, Skokie, IL.

Verbeck, G. J., and R. Landgren. 1960. "Influence of Physical Characteristics of Aggregate on the Frost Resistance of Concrete," *Proceedings, American Society for Testing and Materials*, Vol. 30, pp. 1063-79. American Society for Testing and Materials, Philadelphia, PA.

Virmani, V. P. 1991. *Time-to-Corrosion of Reinforcing Steel in Concrete Slabs Vol. VI: Calcium Nitrite Admixture*. Report no. Federal Highway Administration-RD-88-165. Federal Highway Administration, U.S. Department of Transportation, McLean, VA.

Virmani, Y. P. 1982. "Epoxy-Coated Rebars as a Protective System for New Construction," *Research and Technology Transporter*, p. 5. Federal Highway Administration, U.S. Department of Transportation, Washington, DC.

Walker, H. N. 1978. *Chemical Reactions of Carbonate Aggregates in Cement Paste*. STP-169B, Significance of Tests and Properties of Concrete and Concrete-Making Materials, pp. 722-743. American Society for Testing and Materials, Philadelphia, PA.

Whiting, D., A. Todres, M. Nagi, T. Yu, D. Peshkin, M. Darter, J. Holm, M. Andersen, M. Geiker. 1993. *Synthesis of Current and Projected Concrete Highway Technology*. Report no. SHRP-C-345. Strategic Highway Research Program, National Research Council, Washington, DC.

Yrjanson, W. W. 1989. *Recycling of Portland Cement Concrete Pavements*. Synthesis of Highway Practice 154. National Cooperative Highway Research Program, Transportation Research Board, National Research Council, Washington, DC.

Zia, P., M. L. Leming, and S. H. Ahmad. 1991. *High Performance Concrete—A State-of-the-Art Report*. Report no. SHRP-C-315. Strategic Highway Research Program, National Research Council, Washington, DC.

Bibliography of knowledge sources for repair and rehabilitation of concrete pavements

AASHTO. 1990. *Guide Specification for Concrete Overlays of Pavements and Bridge Decks*. American Association of State Highway and Transportation Officials, Washington, DC.

AASHTO. 1986. "Iowa Fast Track Paving," *American Association of State Highway and Transportation Officials Quarterly*, Vol. 6, American Association of State Highway and Transportation Officials, Washington, DC.

ACPA. 1990. *Guidelines for Bonded Concrete Overlays*. Technical Bulletin TB-007.0.C. American Concrete Pavement Association, Arlington Heights, IL.

ACPA. 1989. *Guidelines for Full-Depth Repair*. Report no. TB-002.0 CPR. American Concrete Pavement Association, Arlington Heights, IL.

ACPA. 1989. *Guidelines for Partial Depth Repair*. Technical Bulletin TB-003.0.CPR. American Concrete Pavement Association, Arlington Heights, IL.

Bugate, M, et al. 1985. *An Experimental Thin-Bonded Concrete Overlay Pavement*. Research report no. 357-2F. Center for Transportation Research, University of Texas at Austin.

Darter, M, E. Barenberg, and W. Yrjanson. 1985. *Joint Repair Method for Portland Cement Concrete Pavements*. Report no. 281. National Cooperative Highway Research Program, Transportation Research Board, Washington, DC.

ERES. 1987. *Techniques for Pavement Rehabilitation*. 3d revision, participants notebook. Prepared by ERES, Inc., for the National Highway Institute, Federal Highway Administration, U.S. Department of Transportation, McLean, VA.

FHWA. 1989. *Rehabilitation of Concrete Pavements, Volume I: Repair Rehabilitation Techniques*. Report Federal Highway Administration/RD-88-071, Federal Highway Administration, U.S. Department of Transportation, Washington, DC.

FHWA. 1988. *Rigid Pavement Analysis and Design*. Federal Highway Administration/RD-88-068, Federal Highway Administration, U.S. Department of Transportation, Washington, DC.

FHWA. 1987. *Field Inspection Guide for Restoration of Jointed Concrete Pavements*. Demonstration Projects Division, Federal Highway Administration, U.S. Department of Transportation, Washington, DC.

Koesno, K., and F. McCullough. 1988. "Evaluation of the Performance of Bonded Concrete Overlay on Interstate Highway 610 North, Houston, Texas," *Transportation Research Record 1196*, pp. 201-11.

McGhee, K. H., and C. Ozyildirim. 1992. *Construction of Thin-Bonded Portland Cement Concrete Overlay Using Accelerated Paving Techniques*. Virginia Department of Transportation, Charlottesville, VA. Also, paper no. 920436. 72d Annual Meeting of the Transportation Research Board, National Research Council, Washington, DC.

Smith, K. D., D. G. Peshkin, E. H. Rmeili, T. Van Dam, K. D. Johnson, M. I. Darter. 1991. *Innovative Materials and Equipment for Pavement Surface Repairs, Volume I: Summary of Material Performance and Experimental Plans*. Report no. SHRP-M/UFR-91-504. Strategic Highway Research Program, National Research Council, Washington, DC.

Temple, W. H., et al. 1992. *Design and Construction of a Bonded Fiber Concrete Overlay of CRCP (Louisiana Interstate Route 10, August 1990)*. Paper no. 920881. 72d Annual Meeting of the Transportation Research Board, National Research Council, Washington, DC.

TRB. 1985. "Fibrous Portland Cement Concrete Overlay Research in Greene County, Iowa," *Transportation Research Record 1040*, pp 1-7.

Voight, G., M. Darter, and S. Carpenter. 1987. *Rehabilitation of Concrete Pavements, Volume II: Overlay Rehabilitation Techniques*. Report Federal Highway Administration/RD-88-072, Federal Highway Administration, U.S. Department of Transportation, Washington, DC.

Voight, G., and M. I. Darter. 1982. *Resurfacing with Portland Cement Concrete*. Synthesis of Highway Practice 99, National Cooperative Highway Research Program, Transportation Research Board, National Research Council, Washington, DC.

Whiting, D., A. Todres, M. Nagi, T. Yu, D. Peshkin, M. Darter, J. Holm, M. Andersen, M. Geiker. 1993. *Synthesis of Current and Projected Concrete Highway Technology*. Report no. SHRP-C-345. Strategic Highway Research Program, National Research Council, Washington, DC.

Appendix C. Glossary of Expert System Terms

backward chaining An inference method where the expert system starts with what it wants to prove and tries to establish the facts it needs to prove it.

certainty factor A degree of certainty with a fact or rule is believed to be true.

demon A forward-chaining IF-THEN rule.

domain knowledge An area of expertise or knowledge that deals with a specific application.

expert system A computer program that contains knowledge about a specific domain, and inference procedures that tell how to use the knowledge.

facets Provides control over how the inference engine processes and uses class attributes.

forward chaining An inference strategy that starts with known facts or data about a situation and infers new facts about the situation based on information contained in the knowledge base.

frame A knowledge representation method that incorporates nodes and objects and are defined in terms of slots.

fuzzy set Information which is known about a situation within a problem that can be expressed as a true/false state. What is known is expressed in some degree of fuzziness. For example, some number between 0 and 1.

goal An intermediate or final objective which is established in the expert system (e.g., conclusion, recommendation).

inference engine That part of the expert system that operates upon the knowledge and contains the problem-solving capabilities.

knowledge base That part of the expert system that contains what is known about a subject (e.g., an expert's knowledge).

knowledge engineer The expert system designer and builder who interacts with the experts.

methods Procedures that are established by the developer to support class attributes.

rule A method of representing a recommendation, directive, or strategy, in an IF condition THEN action form.

shell An expert system building tool that provides programming, knowledge representation, and inference capabilities.

slots An attribute of a frame. It may represent an object, concept or event.

Appendix D. Operating the HWYCON Subsystems

Operating the Highway Concrete (HWYCON) subsystems requires the following steps:

1. Starting the computer.
2. Starting Windows.
3. Selecting the "HWYCON Expert System" window.
4. Selecting (clicking) an icon to activate the desired subsystem.
5. Conducting a session.
6. Terminating HWYCON and returning to the Windows program manager.

When a HWYCON icon is selected, a command is processed to load the selected HWYCON computer program and knowledge base. Each program begins by displaying identifying information, start options, and help facilities. The user must select the "start session" push button to begin a session. When sufficient information has been obtained from the user (through a series of question-and-answer screens), a screen containing a conclusion or recommendation is displayed. At this point, the user may chose to view additional explanatory information, restart the session, repeat the same session (with different questions), or quit HWYCON and return to the Windows program manager.

HWYCON will ask questions involving conditions observed in the structure, its environment, and its history. To assist the user in this procedure, checklists for concrete pavements, bridge decks, and bridge substructures field inspection are provided in appendix A. These will be useful when a desktop computer is used. They will not be necessary when portable computers are used in the field. To help the user become familiar with the types of information needed by HWYCON, a list of the knowledge topics is provided in the following sections.

D.1 Field Information Needed to Conduct a CONPAV-D Session

In order to answer the questions posed by Concrete Pavement-Diagnostics (CONPAV-D), you should have the following applicable information available about the pavement (examples are shown).

- the type of concrete pavement
  - jointed reinforced concrete pavement (JRCP)
  - jointed plain concrete pavement (JPCP)
  - continuous reinforced concrete pavement (CRCP)

- the location of the distress
  - within the slab
  - at joints
  - at the surface

- for symptoms that involve cracking, the crack pattern, direction, and width

- transverse cracking
- longitudinal
- cracks at edges, openings
- straight crack(s)
- map or cluster cracks

- for certain distresses, it will be helpful to know any history of aggregate reactivity, or sulfate attack that has occurred locally and the type of aggregate used, such as carbonate/dolomite or siliceous rock

- other symptoms related to the pavement's visual appearance such as rust staining, will also be helpful.

D.2 Field Information Needed to Conduct a CONSTRUC-D Session

Bridge Decks:

The following information may be needed to operate the Concrete Structures-Diagnostics (CONSTRUC-D/bridge deck) subsystem. Some items depend on the type of distress selected.

- Type of bridge construction (concrete or steel and concrete)
- Existence of epoxy coated reinforcing bars
- The exposure of the bridge deck to: freezing temperatures, chloride ions, or sea water
- The distress type
- Crack direction, pattern, location, depth, and width
- Popout dimensions
- Age of crack

Structures:

The following information may be needed to operate the Concrete Structures (CONSTRUC-D/Structures) subsystem.

- Structural element (e.g. slab, pier).
- Distress type (e.g. cracking, spalling).
- Distress location (e.g. vertical, horizontal surface).
- Crack pattern, width, depth, direction.
- Exposure conditions (e.g. freezing temperatures, soil or sea water).
- Evidence of overall expansion.
- Whether the concrete is air entrained.
- Age of cracks.

- Popout dimensions.

D.3 Information Needed to Conduct a Concrete Materials (CONMAT) Session

- Durability area or procedure for designing the concrete.
- Past record or performance of materials based on test methods.
- Type of material to be used in specifying the concrete.
- Exposure conditions.
- Required opening time for project.
- Type of permeable base.
- Type of construction (e.g. reinforced or plain concrete pavement).

D.4 Information Needed to Conduct a Concrete Pavement Repair and Rehabilitation (CONPAV-R) Session

- Procedure to be used (e.g. full-depth repair, bonded overlay).
- Information type (e.g. recommendations on materials or procedures).
- Required opening time.

Only information that is relevant to the structure being evaluated will be asked during a user session.

D.5 Operating Commands

Responding to Questions The format of a HWYCON session consists of a question-and-answer dialog between the computerized system and the operator. Operating HWYCON involves pointing to an area (e.g. push button, response to a question) of the screen and clicking the left-hand mouse button. No typed commands are required to operate the system. There will be more than one possible response to a question, and the user should select the single choice (in some cases, multiple choices may be selected) that answers the question best. Many question-and-answer screens contain **PICTURE**, **DRAWING**, and **EXPLAIN** push buttons. When selected, these push buttons display digitized photographs of distresses, drawings of distresses and procedures, and explanatory information, respectively. To return to the previous question and answer screen from a **PICTURE**, **DRAWING**, or **EXPLAIN** screen, the **GO BACK** push button is provided. The user must select the **ENTER** push button to record the choice(s) selected from the question-and-answer screen. An example of the HWYCON question-and-answer screen is illustrated in figure 19. An example of an explanatory screen is illustrated in figure 20.

Help facilities are available at the start of each HWYCON subsystem. The topics covered in the help facilities include: (1) information needed to use the subsystem; (2) use of push buttons; and (3) bibliographic references.

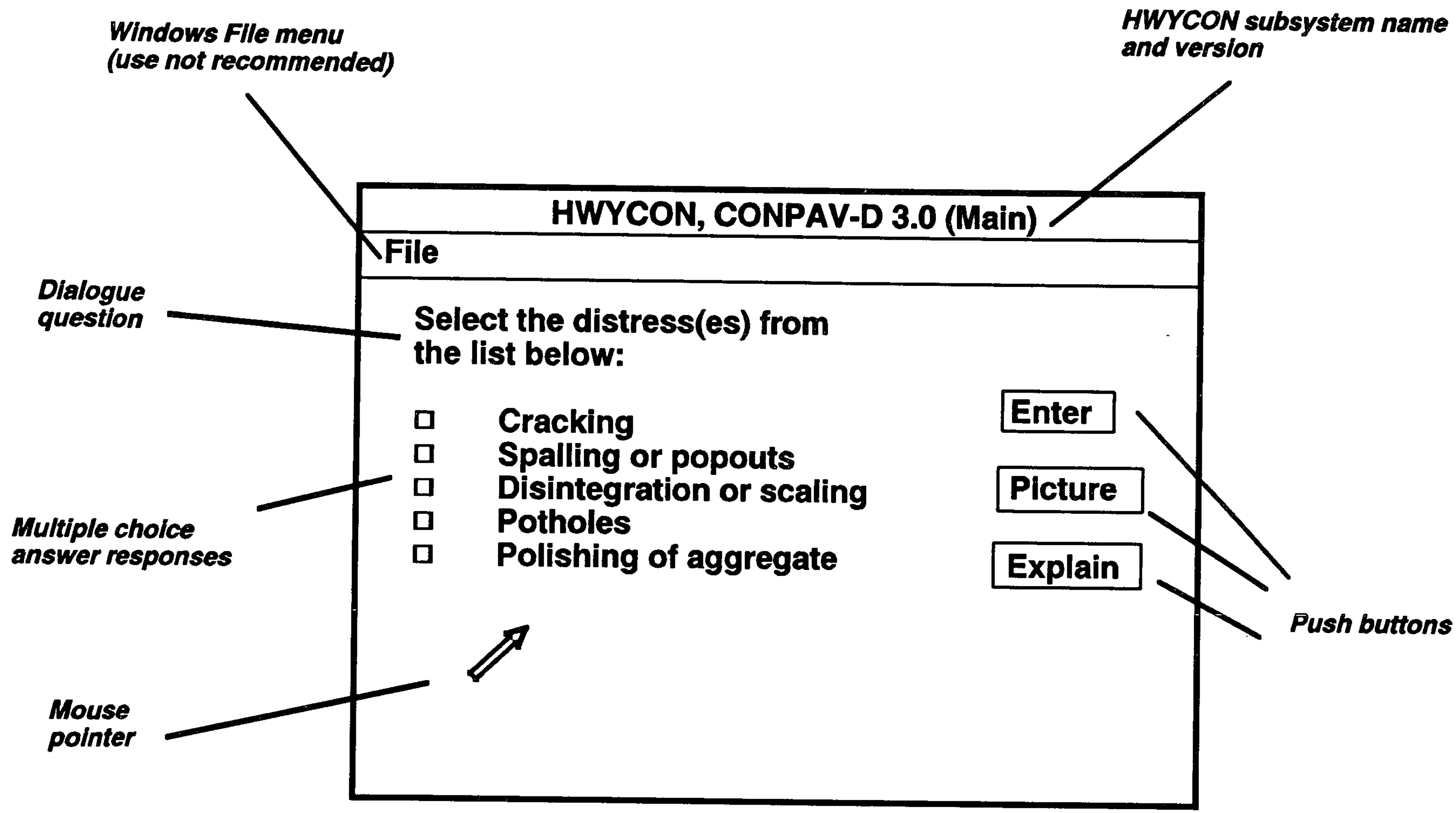

Figure 19. HWYCON question-and-answer screen

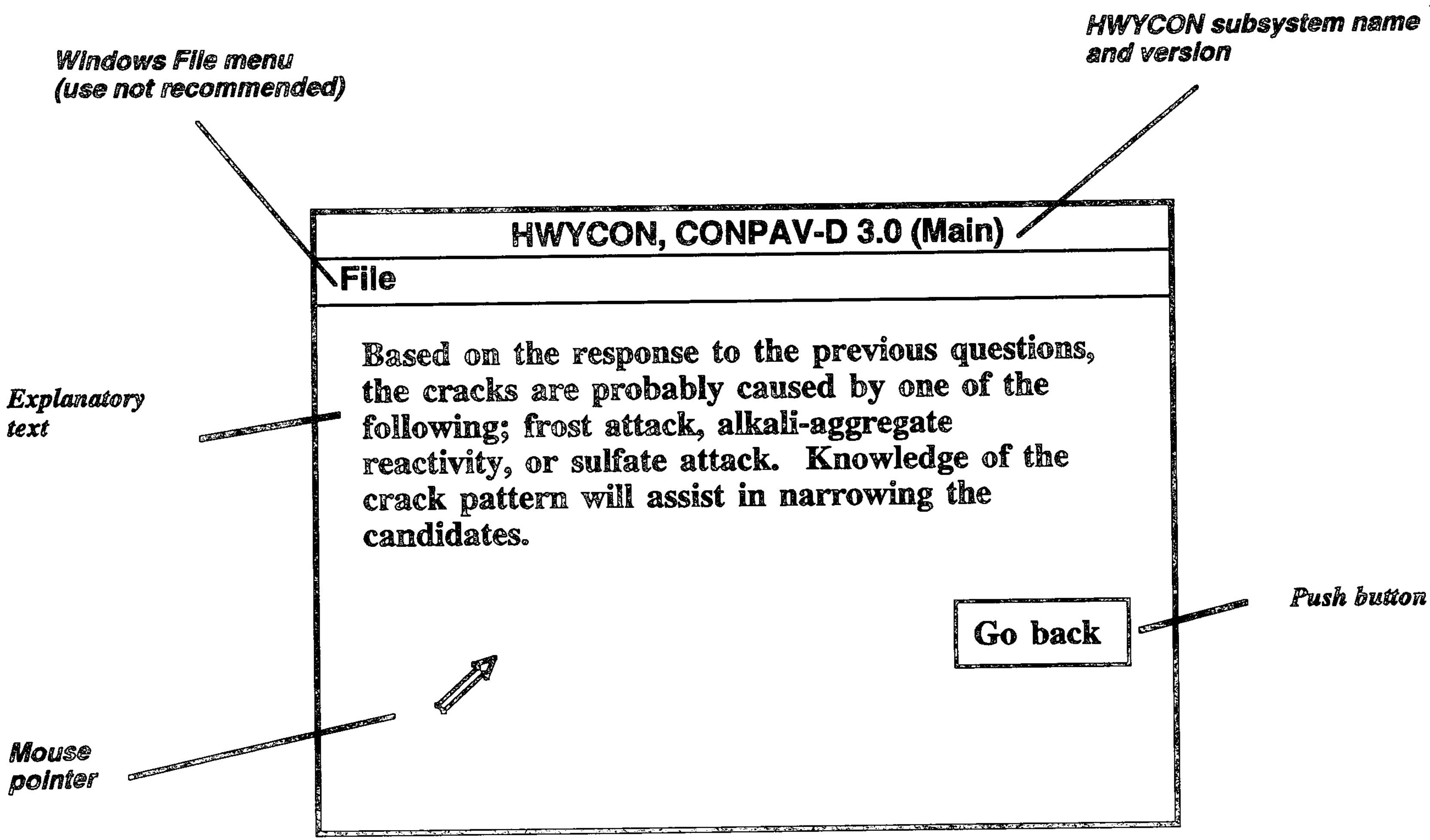

Figure 20. Example of a HWYCON explanatory screen

HWYCON Conclusions and Recommendations When the user has input enough information, a conclusion or recommendation screen will be displayed. Additional information in the form of explanations, table, or references may also be available and can be selected using one of the push buttons provided in the screen. These push buttons contain information that describes tests to confirm the systems diagnosis, bibliographic references, or explanatory information, or provide the user with the ability to select another HWYCON subsystem. In many cases, the information contained in the HWYCON screens extends beyond the screen's vertical limits. The user may scroll through the text by placing the mouse pointer over the up-and-down cursor in the scroll bar to continue reading the remaining text or review previously displayed text. Figure 21 provides an example of a CONPAV-D conclusion screen.

Completing a Session When the user has reviewed the conclusion screen several push button options are available. These include:

1. restart the subsystem
2. repeat the same session with different user input
3. continue processing (if multiple responses were selected in previous screens)
4. view bibliographic references
5. view explanatory information
6. activate another HWYCON knowledge topic
7. quit the session.

Not all conclusion and recommendation screens contain every option listed above. Only those that are relevant to the knowledge being described are displayed.

D.6 Distribution Package and Requirements for Using HWYCON

The HWYCON distribution package consists of the following items:

- The report *Users Guide to the Highway Concrete (HWYCON) Expert System*

- HWYCON User Distribution Diskette Set containing the following diskettes:
  - Run-only system diskette
  - Concrete Pavement–Diagnostics (CONPAV-D) knowledge diskette
  - Concrete Structures–Diagnostics (CONSTRUC-D) knowledge diskettes
  - Concrete Materials (CONMAT) knowledge diskette
  - Concrete Pavement–Repair and Rehabilitation (CONPAV-R) knowledge diskette

The contents of the knowledge disks are listed in section 5.1, Highway Pavements and Structures Covered by HWYCON.

To use HWYCON you must install a computer system that is compatible with the hardware and software described below.

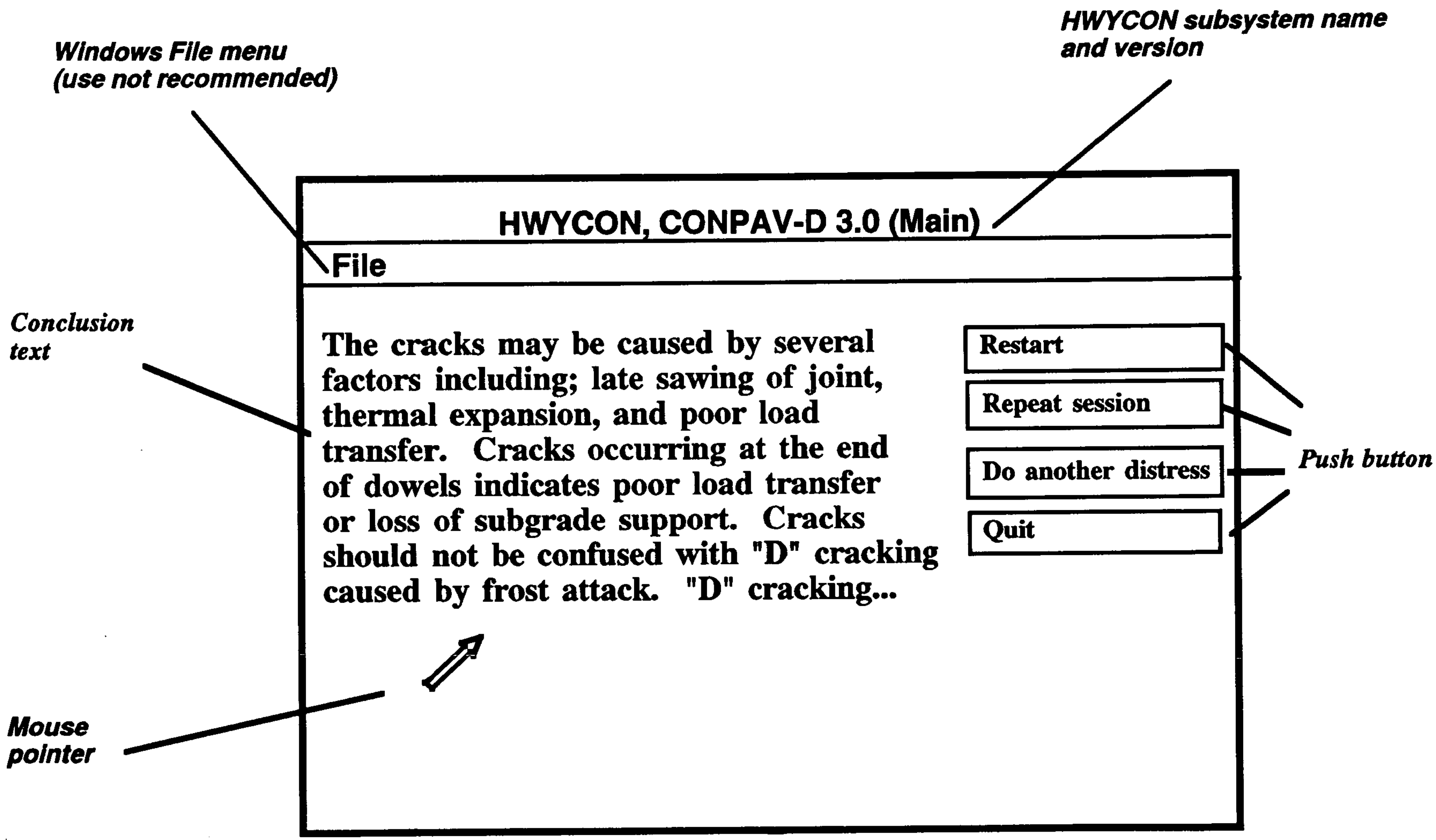

Figure 21. Example of a HWYCON conclusion screen

Computer Hardware

- IBM or compatible desktop or portable computer 386 or 486
  - at least 2 megabytes of memory
  - a hard disk drive with at least 15 megabytes of available disk space
  - a 3.5-in. floppy disk drive
  - EGA, VGA or Super VGA graphics adapter and monitor
  - Microsoft-compatible mouse device

Computer Software

- DOS operating system, version 3.0 or later (Compaq 1987)
- Microsoft Windows, version 3.1

To install and use the HWYCON system, you should have a working knowledge of the Microsoft Windows Program Manager. Information on this topic is covered in the *Windows User's Guide* (Microsoft 1992).

Although HWYCON can be operated using a keyboard, this method is not recommended because it is a very tedious operation. Instead, the use of a pointing device (such as a mouse) is recommended.

To use HWYCON, it is assumed that the user has a basic knowledge of the operation of the recommended computer system and its operating commands, these include the following:

- Power on and booting procedures.
- Procedures and commands for using floppy diskettes, and hard disk drives.
- Operation of a mouse pointing device.
- Basic commands for Windows 3.1 (e.g. starting, selecting windows, selecting program icons, and exiting Windows).

Detailed instructions for these operating procedures are described in the documentation that was supplied with your computer hardware and software.

D.7 Deinstalling Previous Versions of HWYCON

The following commands may be omitted:

1. Start Windows and select the HWYCON Window
2. Click once on the **HWYCON** program icon (i.e., **CONPAV-D**)
3. Click on **File**
4. Click on **Delete**
5. Click on **Yes** to delete the program icon.
6. Repeat steps 2 through 5 for each HWYCON program icon
7. Exit to DOS, click on the **DOS** icon from the main window

The following commands are required:

- Delete all files from \hwycon\cpd\.
- Remove the directory \hwycon\cpd\.
- Delete all files from \hwycon\csd\.
- Remove the directory \hwycon\csd\.
- Delete all files from \hwycon\cmat\.
- Remove the directory \hwycon\cmat\.
- Delete all files from \hwycon\cpr\.
- Remove the directory \hwycon\cpr\.
- Return to Windows.

D.8 Problems and Incompatibilities

Problems While Operating HWYCON

HWYCON was rigorously tested during its development. Many different computer brands and configurations were tested by both the developers and users. Few incompatibilities resulted that were not related to the Microsoft Windows problem described above. Efforts were made to identify potential compatibility problems that could occur through the use of HWYCON. However, it was not possible to anticipate every variation in computer configurations. Those problems that did occur were associated with computer hardware or software malfunctions or improper configuration of DOS or Windows software. It can be stated through experience, and with a high degree of confidence, that if a problem does exist with the installation or operation of HWYCON, it most likely relates to incompatibility in the software versions, or a machine malfunction. Users should first check to ensure that the proper computer configuration and software versions are correctly installed, as described in section 11, Installation Procedures. Generally, if Windows executes without problems, then HWYCON will also.

References

Cady, P., et al. 1992. *Condition Evaluation of Concrete Bridges Relative to Reinforcement Corrosion*. Report no. SHRP-S-331. Strategic Highway Research Program, National Research Council, Washington, DC.

Clifton, J. R., B. C. Oltikar, and S. K. Johnson. 1985. *Development of DURCON, An Expert System for Durable Concrete: Part I*. Report no. NBSIR 85-3186. National Bureau of Standards, Gaithersburg, MD.

Compaq Computer Corporation. 1987. *MS-DOS Version 3.3 Reference Guide*. Houston, TX.

Hall, K. T., J. M. Connor, M. I. Darter, S. H. Carpenter. 1989. *Rehabilitation of Concrete Pavements, Volume III: Concrete Pavement Evaluation and Rehabilitation System*. Report no. FHWA-RD-88-073. Turner-Fairbank Highway Research Center, Federal Highway Administration, U.S. Department of Transportation, McLean, VA.

Information Builders. 1993a. *Level5 Object: Object-Oriented Expert System for Microsoft Windows, Version 2.2*. New York, NY.

Information Builders. 1993b. *Level5 Object: Object-Oriented Expert System for Microsoft Windows, User's Guide*. New York, NY.

Information Builders. 1993c. *Level5 Object: Object-Oriented Expert System for Microsoft Windows, Reference Guide*. New York, NY.

Kaetzel, L. J., and J. R. Clifton. 1991. *Expert/Knowledge Based Systems for Cement and Concrete: State-of-the-Art Report*. Report no. SHRP-C/UWP-91-527. Strategic Highway Research Program, National Research Council, Washington, DC.

Kaetzel, L. J., Clifton, J. R., Snyder, K. A., Klieger, P. 1993. *Highway Concrete (HWYCON) User Reference and Enhancement Guide*. Report no. NISTIR 5184. National Institute of Standards and Technology, Gaithersburg, MD.

Microsoft Corporation. 1992. *Microsoft Windows User's Guide, Version 3.1 for the MS-DOS Operating System*. Redmond, WA.

Purvis, R. L., K. Babaei, K. C. Clear, and M. J. Markow. 1994. *Live-Cycle cost Analysis for Protection and Rehabilitation of Concrete Bridges Relative to Reinforcement Corrosion*.

Report no. SHRP-S-377. Strategic Highway Research Program, National Research Council, Washington, DC.

Ritchie, S. G., and R. A. Harris. 1987. Chapter 8, *Expert Systems in Transportation Engineering, Expert Systems for Civil Engineers: Technology and Application*. American Society of Civil Engineers, New York, NY.

Seren, K. 1988. *An Expert system for Choosing the Type of Ready Mix Concrete,* Publication No. 7, The Nordic Concrete Federation, Finland.

Shahin, M. Y. and J. A. Walther. 1990. *Pavement Maintenance Management for Roads and Streets Using the PAVER System*, Technical Report no. M-90/05. U.S. Army Corps of Engineers, Champaign, IL.

SHRP. 1993. *Distress Identification Manual for the Long-Term Pavement Performance Studies*. Report no. SHRP-P-338. Strategic Highway Research Program, National Research Council, Washington, DC.

Smith, L. M. 1987, *Interim Report on COMIX: An Expert System for Concrete Mix Design*. Report no. M4.87/1. Central Laboratories, New Zealand.

Stark, D. 1991. *Handbook for the Identification of Alkali-Silica Reactivity in Highway Structures*. Report no. SHRP-C-315. Strategic Highway Research Program, National Research Council, Washington, DC.

Waterman, Donald A. 1986. *A Guide to Expert Systems*. Addison Wesley, Reading, MA.

Zsoft. 1991. *Publishers Paintbrush Version 2.0*. Zsoft Corporation, Marietta, GA.

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Terry Mitchell
Federal Highway Administration

Celik Ozyildirim
Virginia Transportation Research Council

Robert J. Perry
New York State Department of Transportation

Charles F. Scholer
Purdue University