



SEP 20 1994

**NISTIR 5184**

NIST  
PUBLICATIONS

---

---

# Highway Concrete (HWYCON) Expert System User Reference and Enhancement Guide

---

---

Lawrence J. Kaetzel  
James R. Clifton  
Paul Klieger\*  
Kenneth Snyder

Building and Fire Research Laboratory  
Gaithersburg, Maryland 20899

\*Consultant  
Northbrook, Illinois



United States Department of Commerce  
Technology Administration  
National Institute of Standards and Technology

QC  
100  
1456  
no. 5184  
1993



---

---

# Highway Concrete (HWYCON) Expert System User Reference and Enhancement Guide

---

---

Lawrence J. Kaetzel  
James R. Clifton  
Paul Klieger  
Kenneth Snyder

May 1993  
Building and Fire Research Laboratory  
National Institute of Standards and Technology  
Gaithersburg, MD 20899



U.S. Department of Commerce  
Ronald H. Brown, *Secretary*

National Institute of Standards and Technology  
Raymond Kammer, *Acting Director*



## ABSTRACT

One of the major goals of the Strategic Highway Research Program (SHRP) was to improve the performance and durability of highway concrete. The 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 DOT's through SHRP. This document is intended to provide a reference for users of the system who need information that is not covered in the overview and installation document provided with the system.

**Key Words:** Building technology, diagnostics, expert system, highway concrete, HWYCON, materials selection, repair and rehabilitation, SHRP

## CONTENTS

Abstract . . . . .	iii
Acknowledgements . . . . .	vi
List of Tables . . . . .	vii
List of Figures . . . . .	viii
1. INTRODUCTION. . . . .	1
2. INTRODUCTION TO EXPERT SYSTEMS . . . . .	1
3. PREVIOUS WORK IN THE HIGHWAY FIELD . . . . .	6
4. PURPOSE AND SCOPE OF THE HWYCON SYSTEM . . . . .	9
5. KNOWLEDGE DOMAIN . . . . .	12
5.1 Highway Structures covered by HWYCON . . . . .	12
5.2 Use of HWYCON in Highway Practices . . . . .	22
5.2.1 Diagnostics . . . . .	22
5.2.2 Selection of Materials for Construction and Reconstruction . . . . .	25
5.2.3 Repair and Rehabilitation of Concrete Pavements . . . . .	26
6. DEVELOPMENT PROCESS . . . . .	27
7. KNOWLEDGE SOURCES . . . . .	31
8. USER RESPONSIBILITIES . . . . .	32
9. OPERATIONAL REQUIREMENTS . . . . .	32
10. DEVELOPMENT AND IMPLEMENTATION . . . . .	35
10.1 Level5 Object Expert System Shell Development Program . . . . .	35
10.2 Imaging Software . . . . .	37
10.3 HWYCON Architecture . . . . .	38
10.4 Packaging and Distribution . . . . .	42
11. INSTALLATION PROCEDURES . . . . .	48
12. MODIFYING HWYCON . . . . .	51

13. FUTURE ENHANCEMENTS TO HWYCON . . . . .	55
14. REFERENCES . . . . .	57
APPENDIX A. KNOWLEDGE TREES . . . . .	59
APPENDIX B. FIELD INSPECTION SHEETS . . . . .	131
APPENDIX C. BIBLIOGRAPHY OF KNOWLEDGE SOURCES . . . . .	140
APPENDIX D. GLOSSARY OF EXPERT SYSTEM TERMS . . . . .	156

## ACKNOWLEDGEMENTS

The authors wish to acknowledge Dr. David Whiting, Construction Technologies, Inc., Skokie, Illinois. Dr. Whiting served as Principal Investigator for the SHRP C-206 Project on "Optimization of Highway Concrete Technology and provided guidance on the design and development of the expert system. He also conducted reviews of the operation and knowledge base and provided comment which was extremely helpful in the development of the final product. The significant contribution of Mr. Robert Philleo (deceased) to the diagnostic sub-system is also gratefully acknowledged.

Also, the SHRP Expert Task Group is acknowledged for their guidance in the design of the knowledge base, review of the prototype systems and providing useful feedback to the development process. Members of the Expert Task Group included:

Mr. Bernard Brown, Iowa DOT  
Dr. Stephen Forster, FHWA  
Prof. David Gress, Univ. of New Hampshire  
Dr. Inam Jawed, SHRP  
Mr. Crawford Jencks, TRB  
Dr. Terry Mitchell, FHWA  
Dr. Celik Ozyildirim, Virginia Transportation Research Council  
Dr. Robert Perry, New York DOT  
Prof. Charles Scholer, Purdue Univ.  
Mr. Larry Smith (ETG Chairman), Florida DOT



## List of Tables

Table 1.	Example of the use of expert systems for highway concrete . . . . .	2
Table 2.	Attributes and characteristics of expert systems developed for concrete in the 1980's . . . . .	9
Table 3.	Jointed concrete pavement distresses and their associated causes, covered in HWYCON . . . . .	18
Table 4.	Continuously reinforced concrete pavement distresses and their associated causes, covered in HWYCON . . . . .	19
Table 5.	CONSTRUC-D for bridge deck distresses and their associated causes, covered in HWYCON . . . . .	20
Table 6.	CONSTRUC-D for structures and their associated causes, covered in HWYCON . . . . .	21
Table 7.	CONMAT durability and knowledge areas, covered in HWYCON . . . . .	25
Table 8.	CONMAT knowledge for repair and rehabilitation procedures . . . . .	26
Table 9.	Criteria for the development and implementation of HWYCON . . . . .	28
Table 10.	Principal groups involved in the development and implementation of HWYCON . . . . .	29
Table 11.	Image processing parameters for HWYCON digitized images . . . . .	38
Table 12.	CONPAV-D modules and knowledge areas . . . . .	39
Table 13.	CONSTRUC-D modules and knowledge areas . . . . .	40
Table 14.	CONMAT modules and knowledge areas . . . . .	41
Table 15.	CONPAV-R module and knowledge area . . . . .	41
Table 16.	HWYCON user distribution diskette set contents . . . . .	46
Table 17.	HWYCON developers distribution diskette set contents . . . . .	47
Table 18.	Important factors in estimating staff requirements for modifying HWYCON .	52

## List of Figures

Figure 1.	Expert system components and knowledge interfaces that can be included . . .	4
Figure 2.	Illustration of an object oriented knowledge structure . . . . .	5
Figure 3.	Illustration of connectivity for a HWYCON object . . . . .	7
Figure 4.	HWYCON knowledge domain and users . . . . .	11
Figure 5.	Diagram of the CONPAV-D subsystem . . . . .	13
Figure 6.	Diagram of the CONSTRUC-D subsystem for bridge decks . . . . .	14
Figure 7.	Diagram of the CONSTRUC-D subsystem for substructures . . . . .	15
Figure 8.	Diagram of the CONMAT subsystem . . . . .	16
Figure 9.	Diagram of the CONPAV-R subsystem. . . . .	17
Figure 10.	Examples of two crack patterns, ASR and frost attack . . . . .	23
Figure 11.	Drawing of examples of some distresses that could occur in jointed concrete pavements . . . . .	24
Figure 12.	Recommended minimum computer configuration, and the types of user supplied information necessary to use HWYCON . . . . .	39
Figure 13.	CONPAV-D and CONSTRUC-D interrelationships between modules . . . .	43
Figure 14.	CONMAT and CONPAV-R interrelationships between modules. . . . .	44
Figure 15.	HWYCON knowledge components, connectivity, and function . . . . .	45
Figure 16.	Procedures used in the development of HWYCON and the Level5 Object facility used . . . . .	53

Figure 17. Example of the recommended procedure for modifying the HWYCON knowledge base . . . . . 54

Figure 18. Recommended minimum computer configuration for modifying HWYCON . 56



## 1. INTRODUCTION

The Strategic Highway Research Program's (SHRP) C-206 project on "The 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 3 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 that is not covered in the overview and installation document provided with the system. It also provides information for computer specialists who are involved in making changes (maintenance) to the system. In addition, this document provides information on:

- 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 D 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 called (HWYCON) was developed in Task 3 of the SHRP C-206 project "Optimization of Highway Concrete Technology". Examples of how expert systems can be used 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;

- i) initially limiting the scope of the knowledge domain, then allowing it to grow
- ii) obtaining feedback from users through prototype development and distribution
- iii) selection of a development tool that provides a platform for further enhancements and the addition of new knowledge
- iv) 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 from 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 on what knowledge to include, based on its credibility, preferences and other factors. Accepted guidelines, practices, and test methods sometimes may offer solutions to the resolution of a disagreement on whether to include a 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 day 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 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 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. For example, backward chaining, where the system attempts to reach a goal when given information that leads to that goal, such as is the case in 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 Highway Concrete (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 "caused by poor joint construction or materials in joint". In

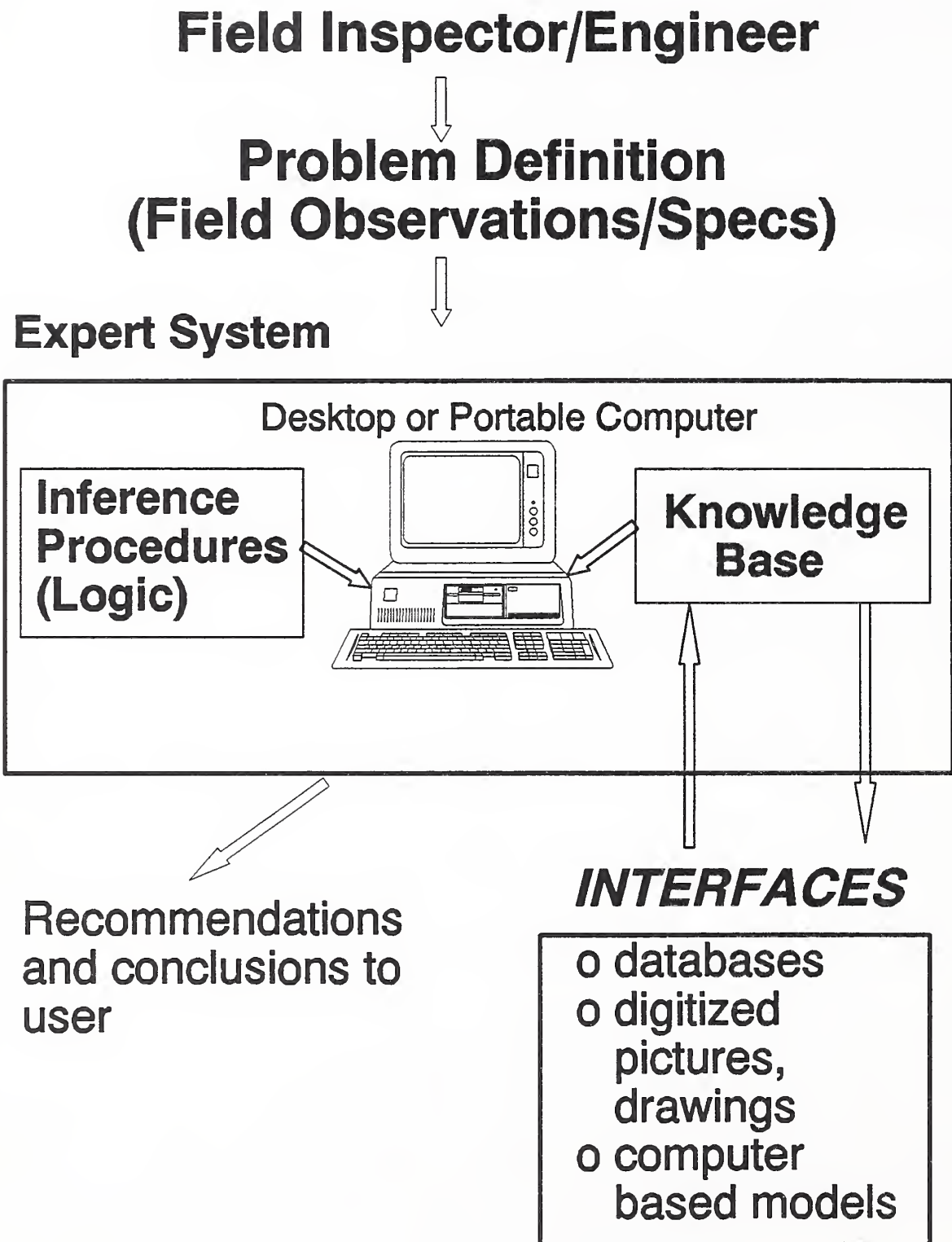


Figure 1. Expert system components and knowledge interfaces that can be included.



# Class: Jointed Concrete Pavement Distresses

## Object Attributes (in hierarchical order)

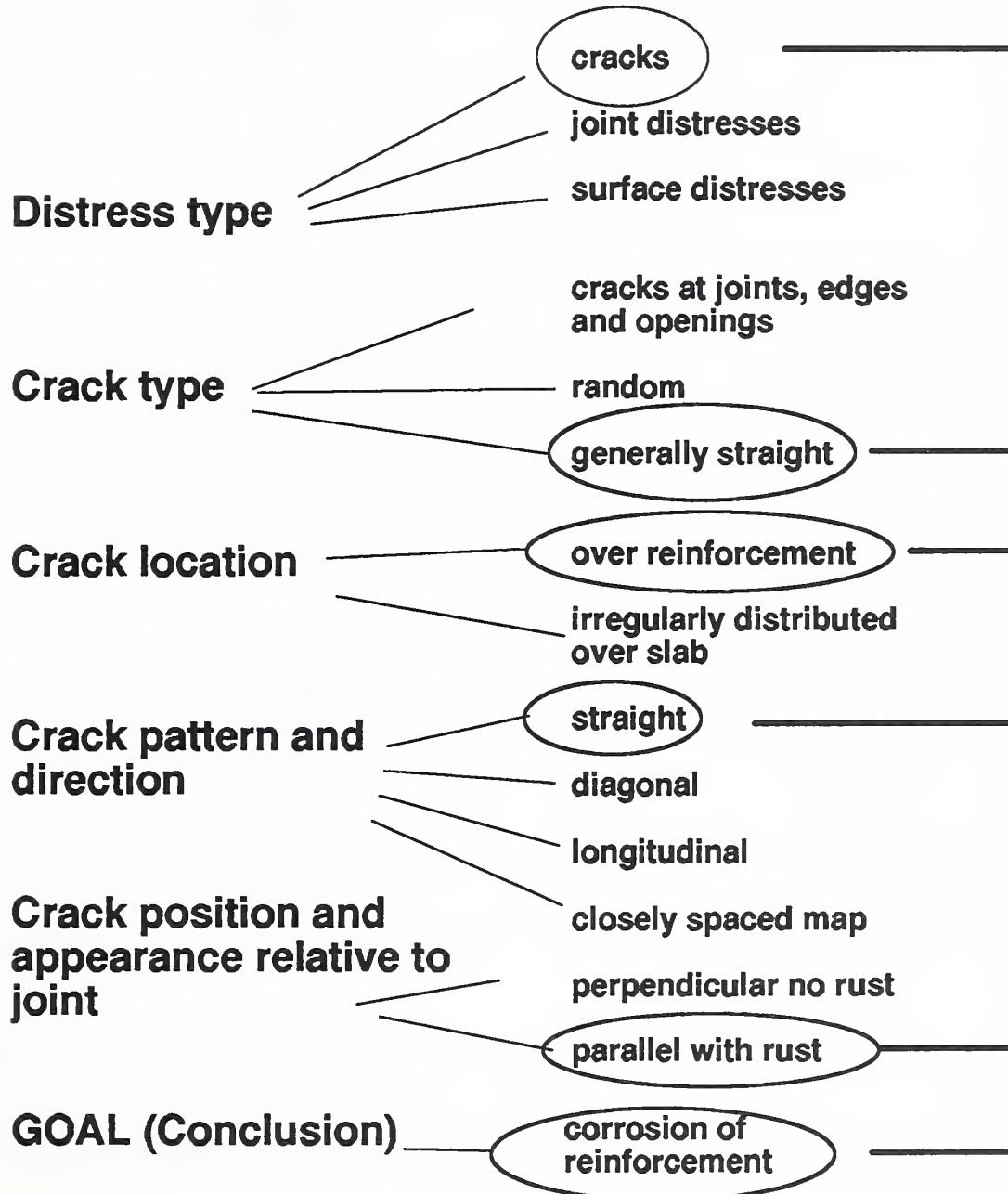


Figure 2. Illustration of an object-oriented knowledge structure.

this figure the object attribute "crack pattern and direction" is defined and its relationships established relative to the conclusion or goal, "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 pushbutton 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 in SHRP Report SHRP-C/UWP-91-527 [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 proper constituents for concrete, design for specific environments, provide information from experts in the concrete mixture proportioning design area, and provide points of reference and checking to 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 1987], and the design of durable concrete [Clifton, et. al. 1985]. Expert systems applications for concrete design are very limited, compared to other highway engineering activities, such as traffic signal, transportation network design [Ritchie 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 which in turn determines the proper constituents. Examples of the information contained in the recommendations for frost durable concrete include:

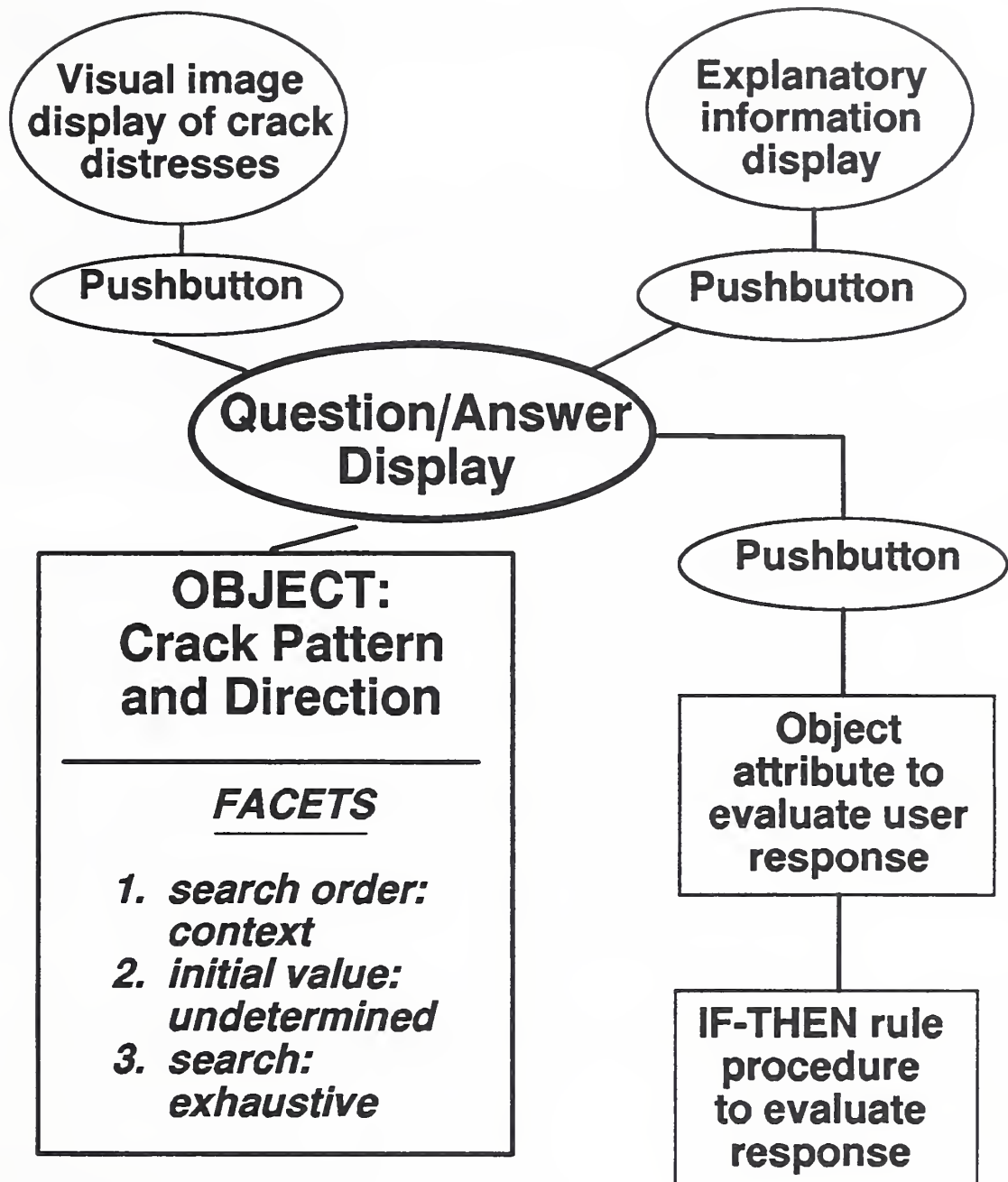


Figure 3. Illustration of connectivity for a HWYCON object.

- type of cement
- durability factor
- percent of entrained air
- air void spacing
- compressive strength

The application of expert systems to diagnostics, 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 for 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 is the largest task 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. 1987] and PAVER [Shahin et. al. 1990], represent the most comprehensive systems, and are the result of five and ten years effort, respectively. These systems are written in conventional computer programming languages (e.g. FORTRAN, PASCAL) and are considered to be 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. Also, new field test methods are being developed [SHRP 1992]. These methods can be effective in detecting distresses and measuring their rate of deterioration, such as corrosion in highway structures. 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 1980's. 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 that exists today.

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

<b>Attribute</b>	<b>Characteristic</b>
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**

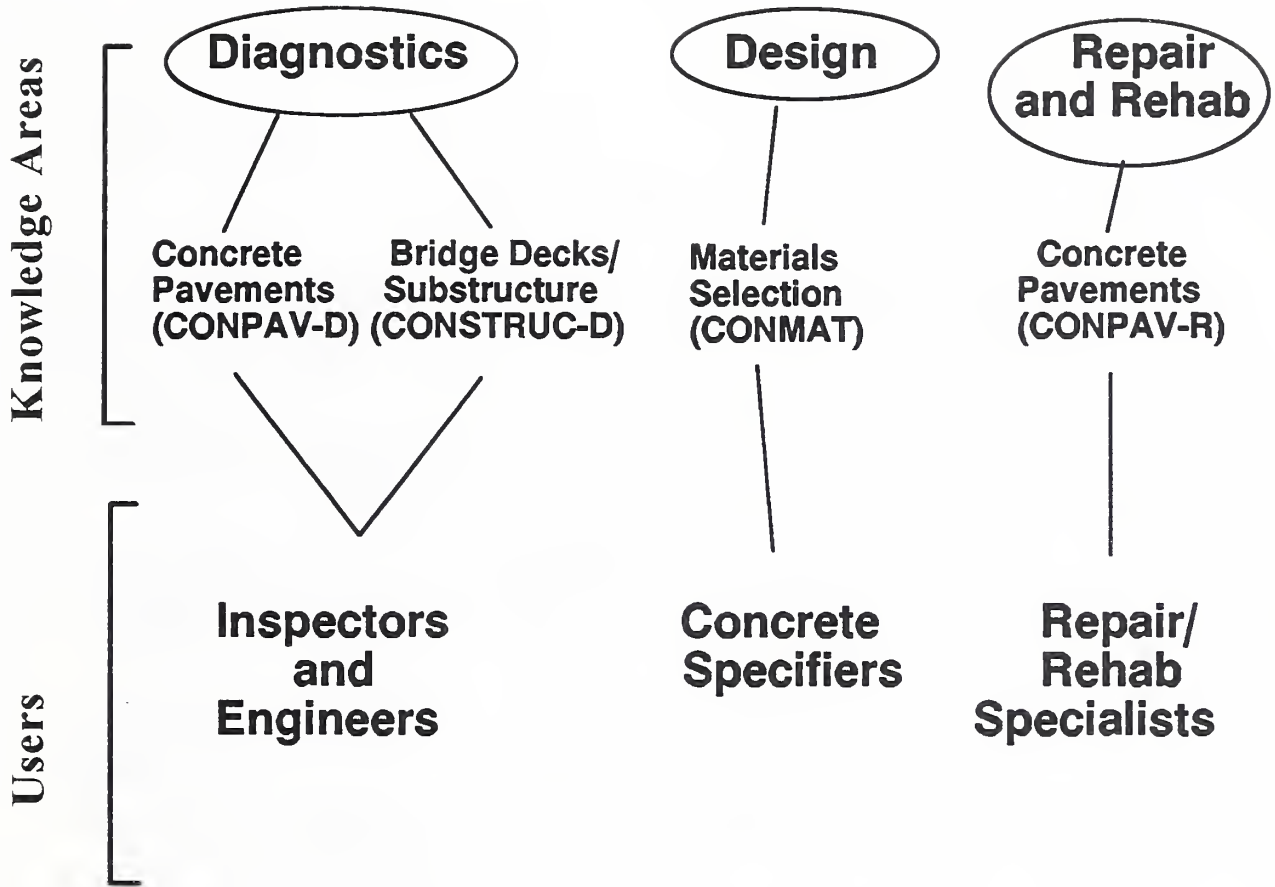
The purpose and scope of HWYCON was defined within the SHRP C-206 project. HWYCON is designed to assist state highway departments in three areas; 1) diagnosing distresses in highway pavements and structures, 2) selecting materials for construction and reconstruction, and 3) obtaining recommendations on materials and procedures for repair and rehabilitation methods. Since SHRP involved many projects related to concrete technology, it is important that this new knowledge reach practicing highway staff, and efforts were made to include as much knowledge as was available from other SHRP projects. In some cases this was difficult due to the parallel time frame of the development of SHRP products and the

expert system. Section 7, "Knowledge Sources" specifically describes the knowledge that was available. In the absence of SHRP knowledge, knowledge from leading industry organizations and state DOT's 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 SHRP Expert Task Group (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 and/or due to exposure to adverse environmental conditions (e.g. sulfate attack, freezing and thawing). For the materials selection subsystem, knowledge on how to select concrete constituents for various environments and selected procedures was included. The final subsystem on repair and rehabilitation includes knowledge which 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 piece of knowledge, or 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 due to insufficient knowledge that is available to provide more detail 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 the section titled "Future Enhancements" some of the HWYCON areas that could be modified are discussed. This 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 on 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.

## **5. KNOWLEDGE DOMAIN**

### **5.1 Highway Pavements and Structures Covered by HWYCON**

The knowledge contained in HWYCON includes information and rules on the 3 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 [SHRP 1989]. Figures 5-9 show the types of pavements and structures, and topics covered by each of the HWYCON subsystems. Tables 3-6 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 may be operative in the concrete which may need a modification of a recommendation.



# CONPAV-D Sub-system

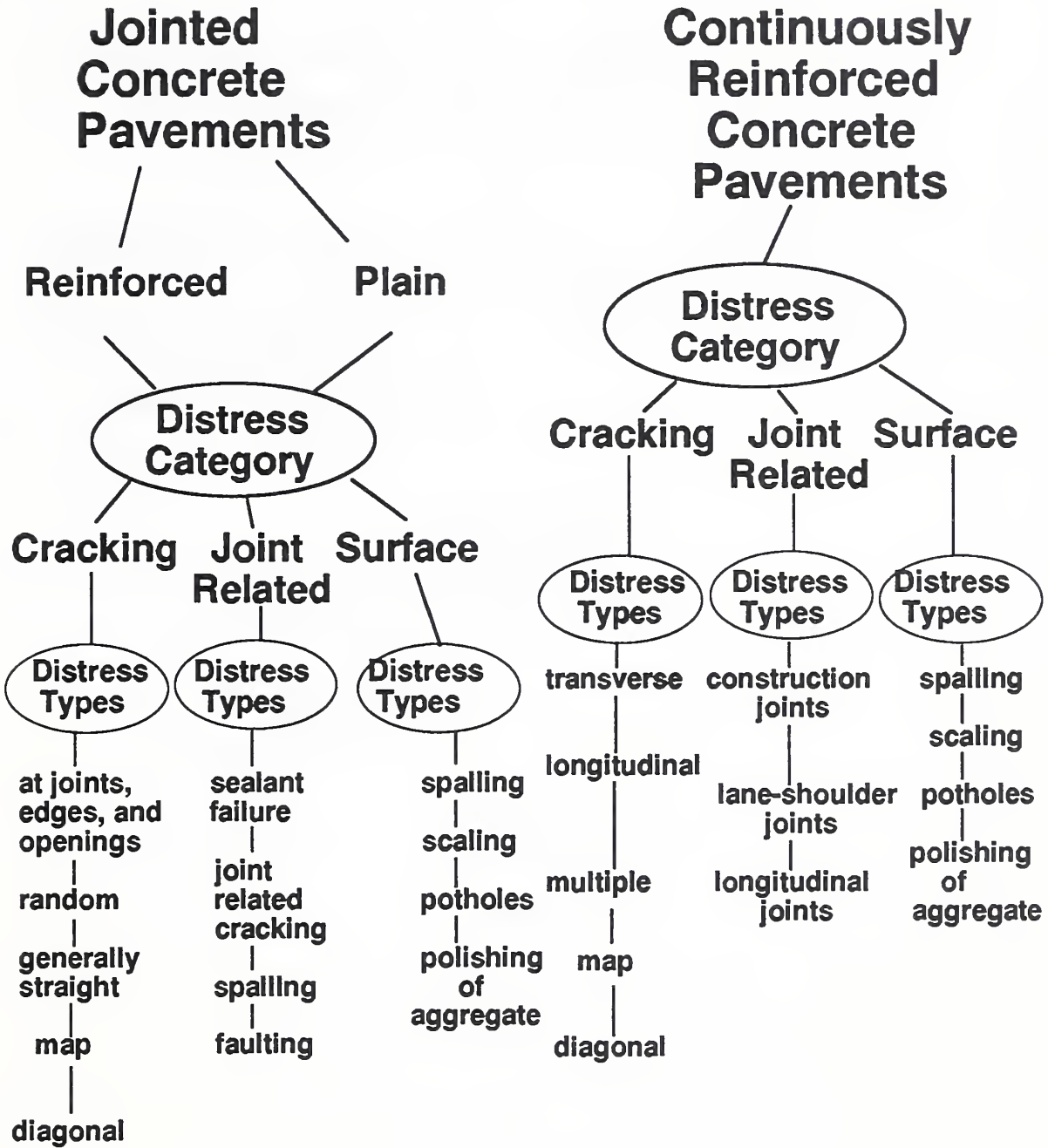


Figure 5. Diagram of the CONPAV-D subsystem.

**CONSTRUC-D Sub-system  
(Bridge Decks)**

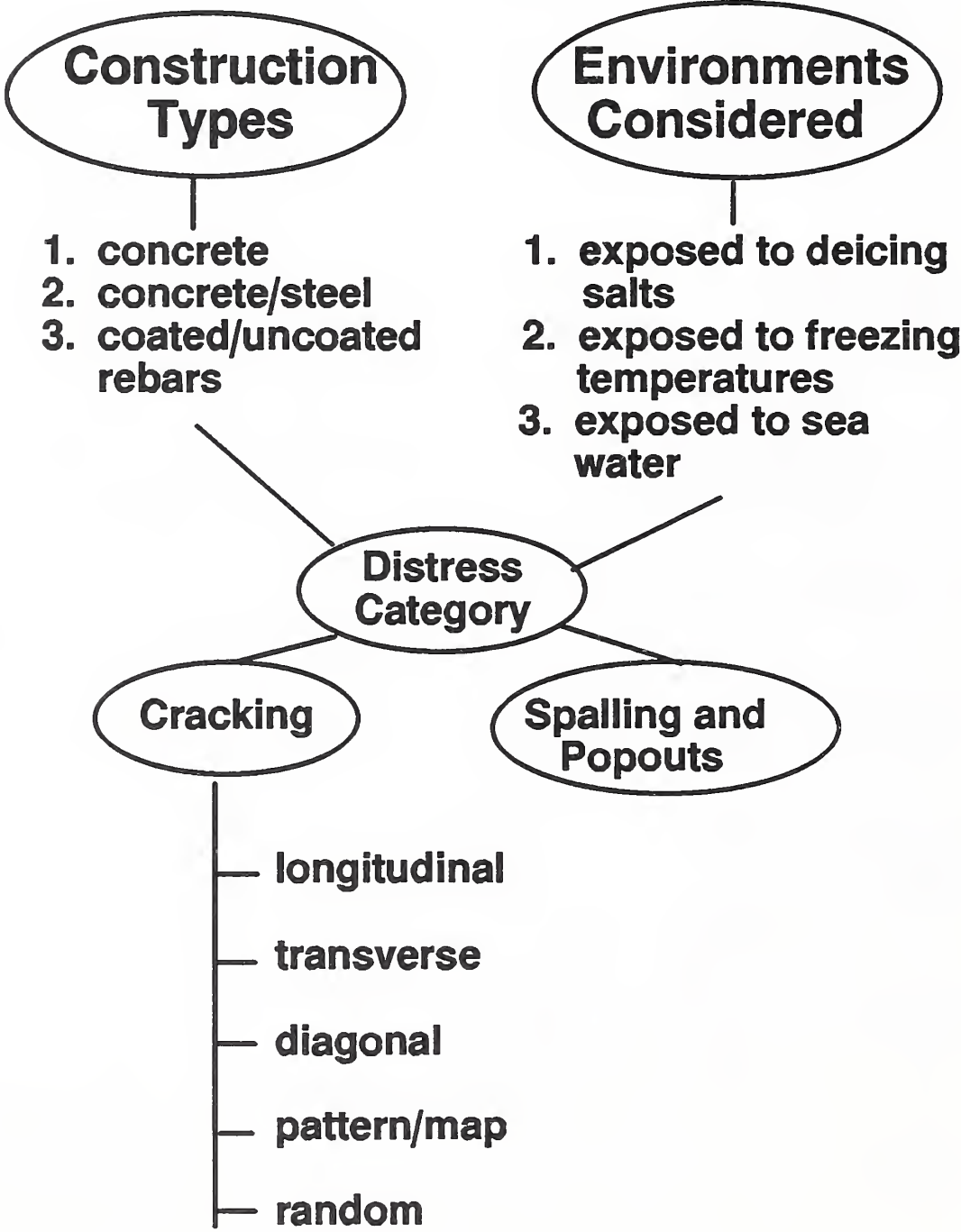


Figure 6. Diagram of the CONSTRUC-D subsystem for bridge decks.

**CONSTRUC-D Sub-system  
(Structures)**

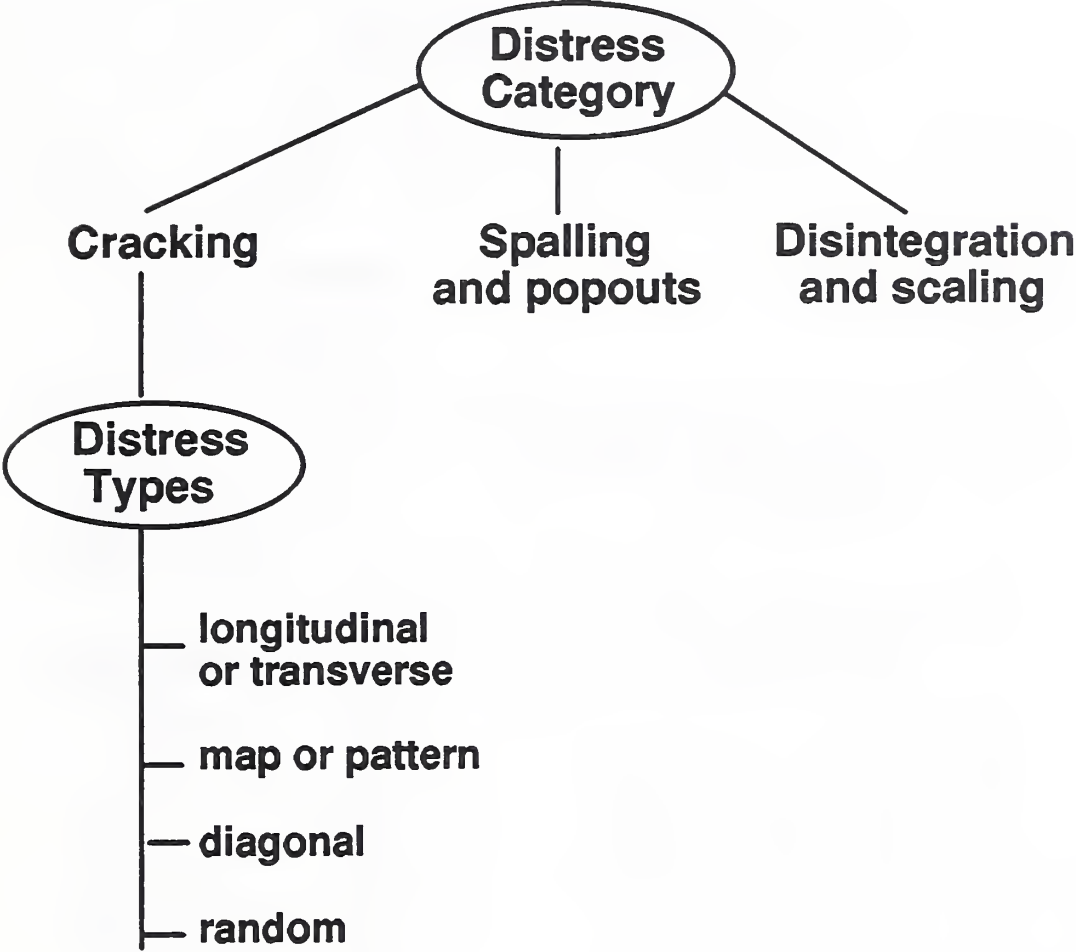


Figure 7. Diagram of the CONSTRUC-D subsystem for substructures.

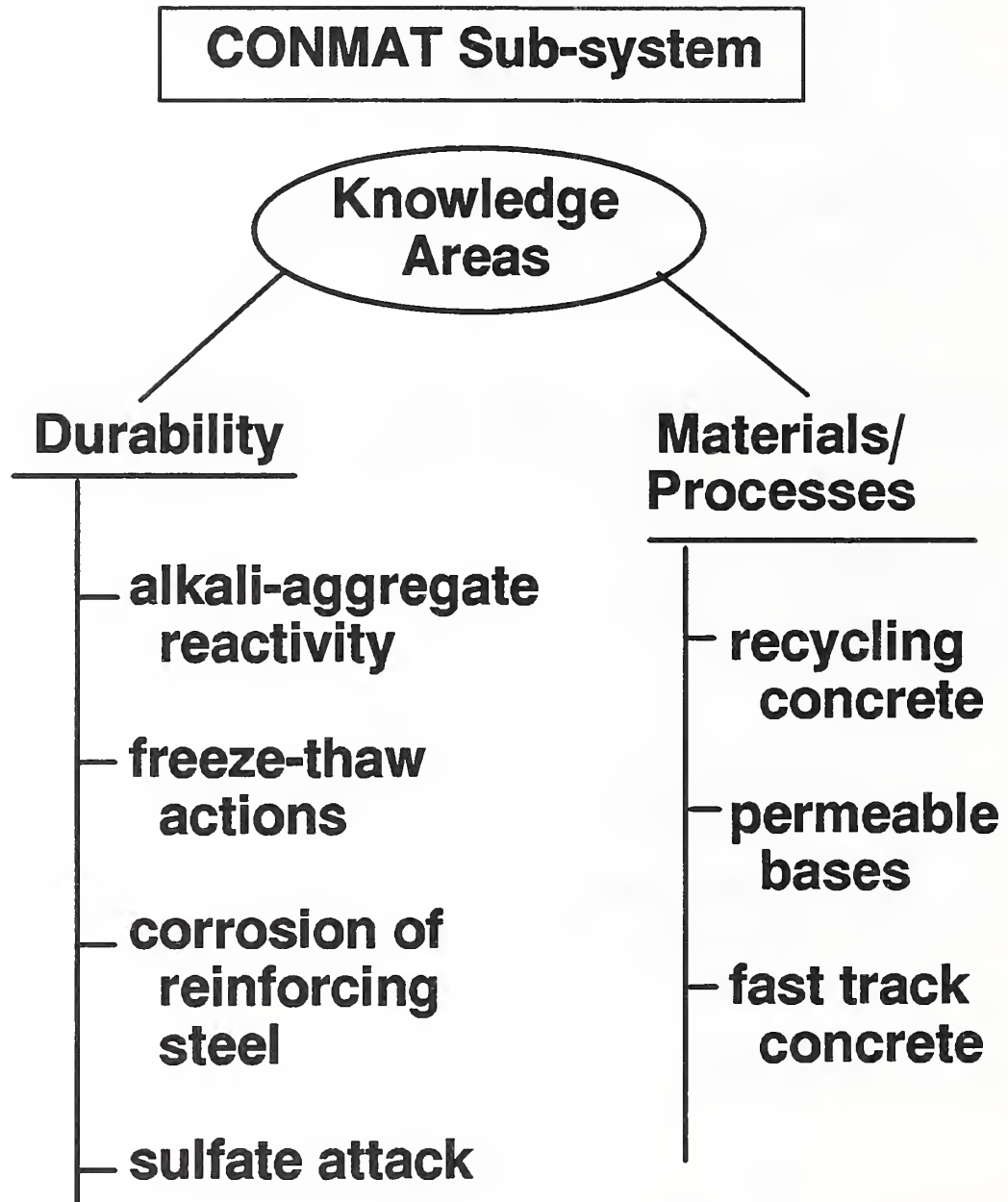


Figure 8. Diagram of the CONMAT subsystem.

# CONPAV-R Sub-system

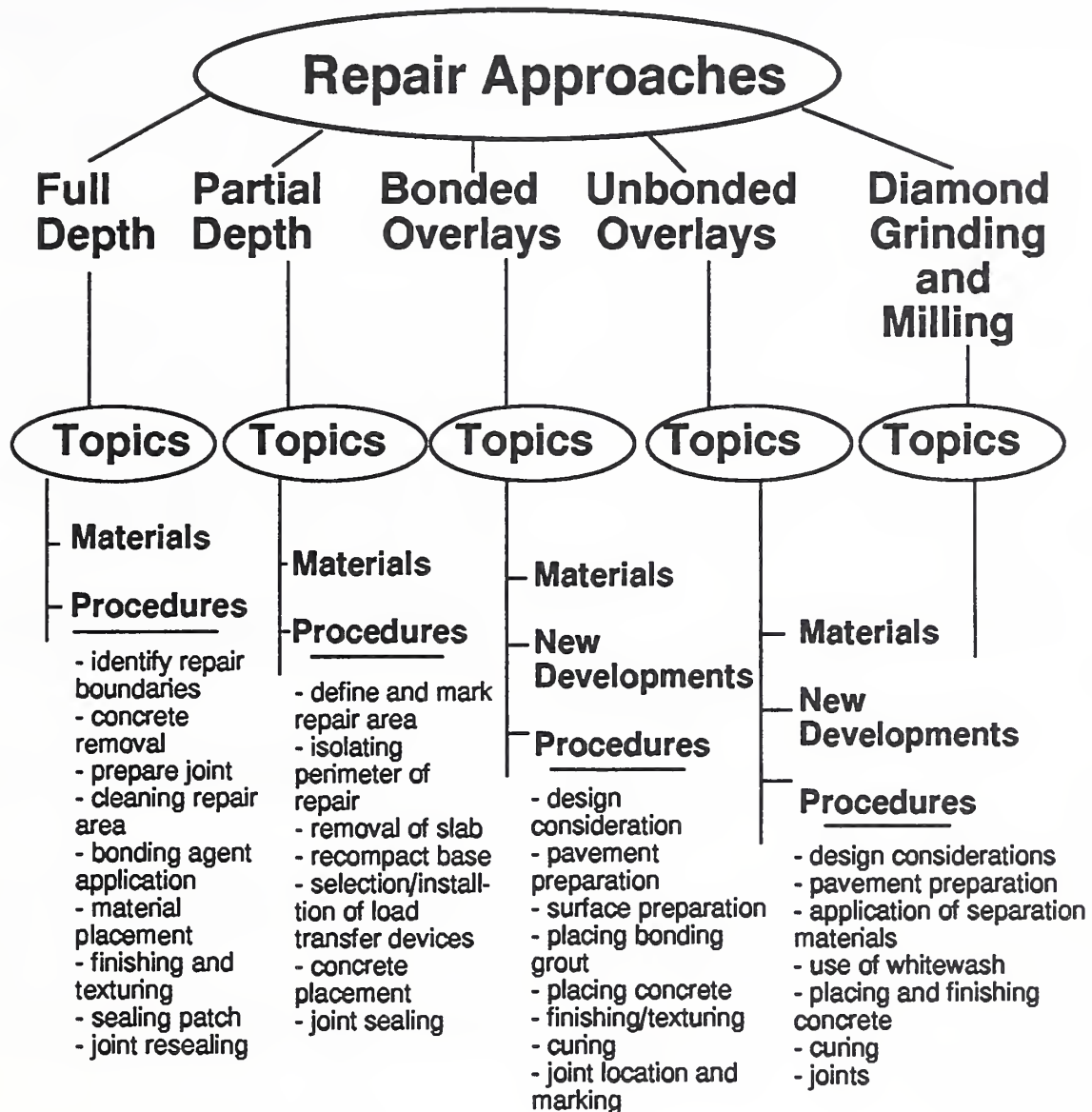


Figure 9. Diagram of the CONPAV-R subsystem.

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

<b>Distress Category and Type</b>	<b>Cause or Probable Cause<sup>1</sup></b>
cracks at joints, edges and other openings	poor joint construction or materials in joint, late sawing, thermal expansion, or 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, life time 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

<sup>1</sup>May not be inclusive.

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

<b>Distress Category and Type</b>	<b>Cause or Probable Cause<sup>2</sup></b>
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

<sup>2</sup>May not be inclusive.

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

<b>Distress Category and Type</b>	<b>Cause or Probable Cause<sup>3</sup></b>
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

<sup>3</sup>May not be inclusive.



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

<b>Distress Category and Type</b>	<b>Cause or Probable Cause<sup>4</sup></b>
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

Identifying distresses and determining their cause(s) is an important part of any state DOT concrete program. In order to effectively repair or rehabilitate a structure after a distress has occurred or to assess whether an 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's 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. It may require obtaining specimens of the structure's distressed area requiring further investigation in a laboratory, such as a petrographic examination. Also, field tests such as the SHRP Alkali-silica reaction test [SHRP 91] for aggregate reactivity may be used to confirm or determine the cause. HWYCON assists in the diagnosis by first identifying the distress, such "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

---

<sup>4</sup>May not be inclusive.

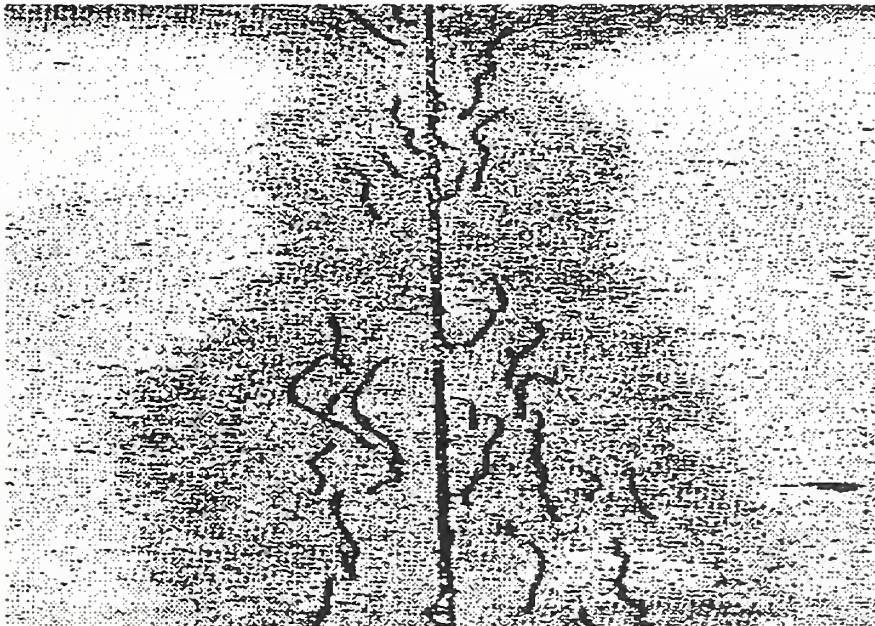
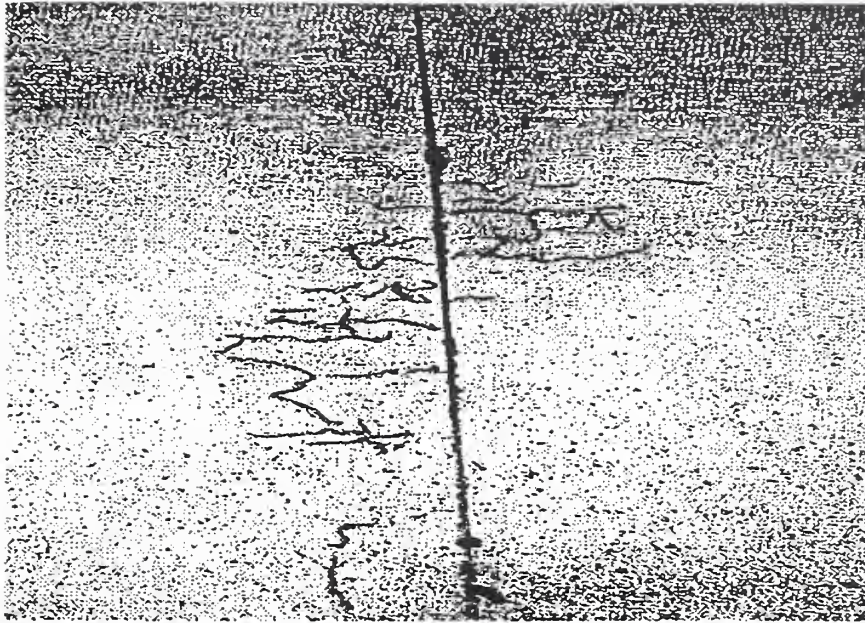
computer. When the system is used in a laboratory environment, completion of a checklist is necessary to answer the questions that are asked of the operator. In some cases, the expert system can not make a determination of the cause of the distress. Recommendations are then given that direct the operator to perform appropriate tests, such as those stated above, 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 would be used in another. Identifying distresses and their causes can assist in the design of durable replacement or the proper rehabilitation method.

### **5.2.1 Diagnostics**

The approach the expert system takes mimics how an expert would go about diagnosing a distress. The expert system 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 whether the concrete is air-entrained and what type of aggregate or the aggregate's history related 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 in text visual features of a distress. 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 which are sometimes confused 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 presents to 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 explanatory information which gives 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.



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

## JOINTED CONCRETE PAVEMENT

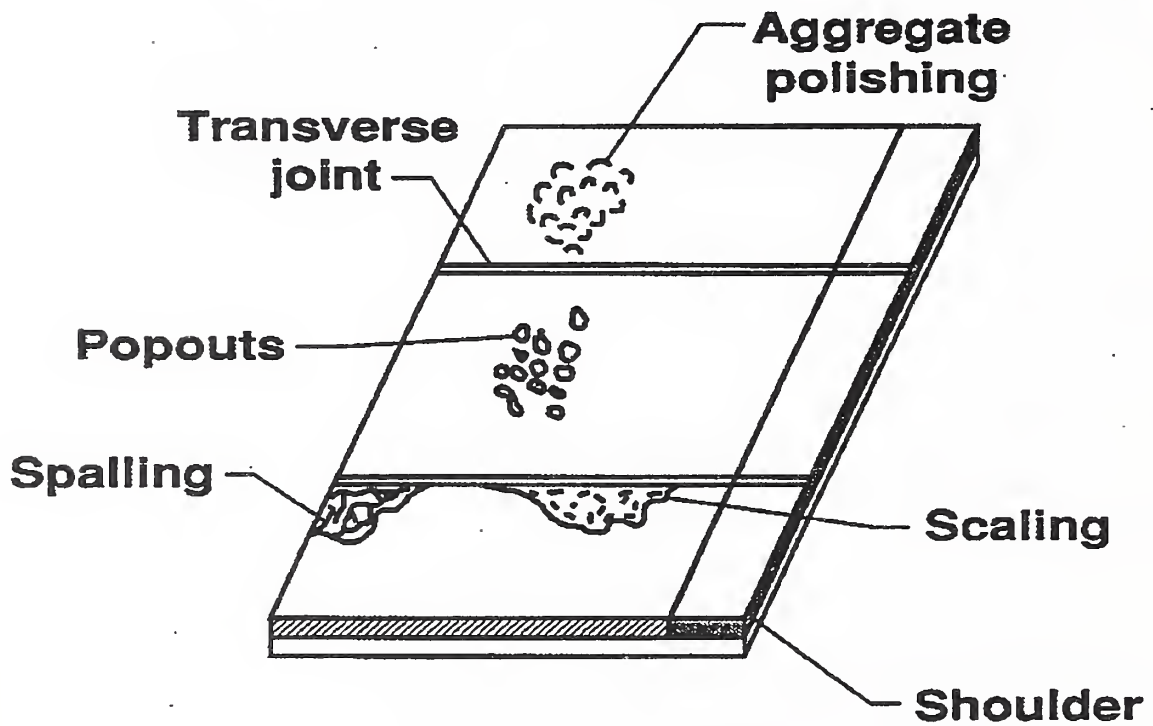


Figure 11. Drawing of examples of some distresses that could occur in jointed concrete pavements.

### 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 3 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.

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	1. selection of materials (cementitious materials, aggregate, mix water, reinforcing steel, admixtures) 2. 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.**

<b>CONMAT Procedure</b>	<b>Knowledge Area</b>
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 unstablized bases, separator layers, and edge drainage systems

Materials durability knowledge included in CONMAT closely parallels the American Concrete Institute, Committee 201 "Guide to Durable Concrete". 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's 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 assumption is made 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 4-6 hours, 12-24 hours, and greater than 24 hours are available. Bonded

and unbonded overlays, and diamond grinding and millings knowledge includes information on new developments in the 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 gives the criteria that was 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 NIST and C-206 team members, and other experts in the field of concrete were chosen to assist in the various activities. State DOT's were asked to provide information related to their area of expertise. Literature searches, guides, specifications and technical notes were obtained by the development team for evaluation, review, and incorporation into the knowledge base. The staff of the Federal Highway Administration (FHWA), The 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.

**Table 9. Criteria for the development and implementation of HWYCON.**

Criterion	Goal
target audience (staff)	<u>Diagnostics</u> : inspectors and engineers <u>Materials Selection</u> : concrete specifiers <u>Repair/Rehabilitation</u> : engineers, decision makers
target audience (level of existing knowledge)	mid level and below
modifications and enhancements to knowledge base	select a development tool to allow knowledge to be segmented and modified easily
interpretation of knowledge	allow the use of different forms of knowledge (rules, pictures, drawings, databases, explanatory information)
implementation computer platform	desktop and portable personal computers
feedback and review	develop prototype systems to allow quick startup and easy user interface

Many steps are involved to produce 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:

**Conceptual Design Phase**

- i) literature review
- ii) develop state-of-the-art report
- iii) evaluate computer hardware and software development tools
- iv) interview domain experts, state DOT's, highway industry

**Knowledge Acquisition and Prototype Development Phase**

- i) develop methods for integrating knowledge
- ii) review and evaluate guides, specs, manuals
- iii) interview domain experts, users
- iv) develop knowledge trees
- v) review knowledge trees by expert team
- vi) acquire and enhance photographs/drawings
- vii) develop computerized prototype



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

Principal Group	Area of Involvement		Review/ Comment	Diagnosics		Knowledge Area	
	System Design	Knowledge Acquisition		Pavements	Structures	Materials Selection	Pavement Repair/Rehab
Academia							
Iowa State Univ			X	X	X	X	
North Carolina State Univ	X	X	X	X	X		X
Purdue Univ	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
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			X	X	X	X	X
CTL Contractor	X	X	X	X	X	X	X
NIST Team	X	X	X	X	X		X
ERES Team	X	X	X	X	X		X
SHRP Staff and ETG	X	X	X	X	X		X
State DOTs	X	X	X	X	X		X
Florida							
Illinois							
Iowa							
Kansas							
Maryland							
New York							
North Dakota							
Virginia							
Washington							
Wyoming							

### **Prototype Review and Revision Phase**

- i) review of prototype system by development team
- ii) modify prototype
- iii) distribute prototype to users for review and demonstrate at transportation shows and conferences
- iv) evaluate review comments and revise prototype as needed

### **Development of Operational System Phase**

- i) develop installation and quick reference manual
- ii) develop user and developer reference document
- iii) 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. Hence, the need for the development of prototype systems to solicit review and comment. This became an important part of the development of the system since it allowed review comments to be evaluated during the course of the project and was instrumental in determining what changes were necessary in the design and operation of future revisions. Comments were received from approximately 60% 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;

- i) Concrete Pavement Diagnostics (CONPAV-R )
- ii) Concrete Structures-Bridge Decks (CONSTRUC-D)
- iii) Concrete Structures-Substructure (CONSTRUC-D)
- iv) Selection of Materials (CONMAT)
- v) 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. Appendix C represents all of the knowledge trees that represent HWYCON's knowledge. The knowledge tree was useful for two purposes; 1) it provided the source document for converting the knowledge to question and answer display, explanatory displays, and 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 the users 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. Due to 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 DOT's
- SHRP Expert Task Group 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:

- ERES Consultants
- Federal Highway Administration (FHWA)
- American Concrete Institute (ACI)
- American Concrete Pavement Association (ACPA)

- U.S. Army Corps of Engineers
- State DOT's.

The strategy in developing 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. These are referenced in explanatory, conclusion, and recommendation displays. Also, push buttons contained in the help facility of each subsystem provide access to a bibliography for the knowledge area. This 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 performance of materials. 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<sup>5</sup> or compatible desk top or portable computer
- DOS<sup>6</sup> software Operating system with Windows 3.0
- 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 that is necessary to use HWYCON involves answering questions that are asked during each session. Each subsystem requires a different type of information, as follows:

#### **Diagnostics (CONPAV-D and CONSTRUC-D)**

- 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)
- exposure conditions (e.g. freezing)
- failure of materials (e.g. adhesion loss of joint sealants)

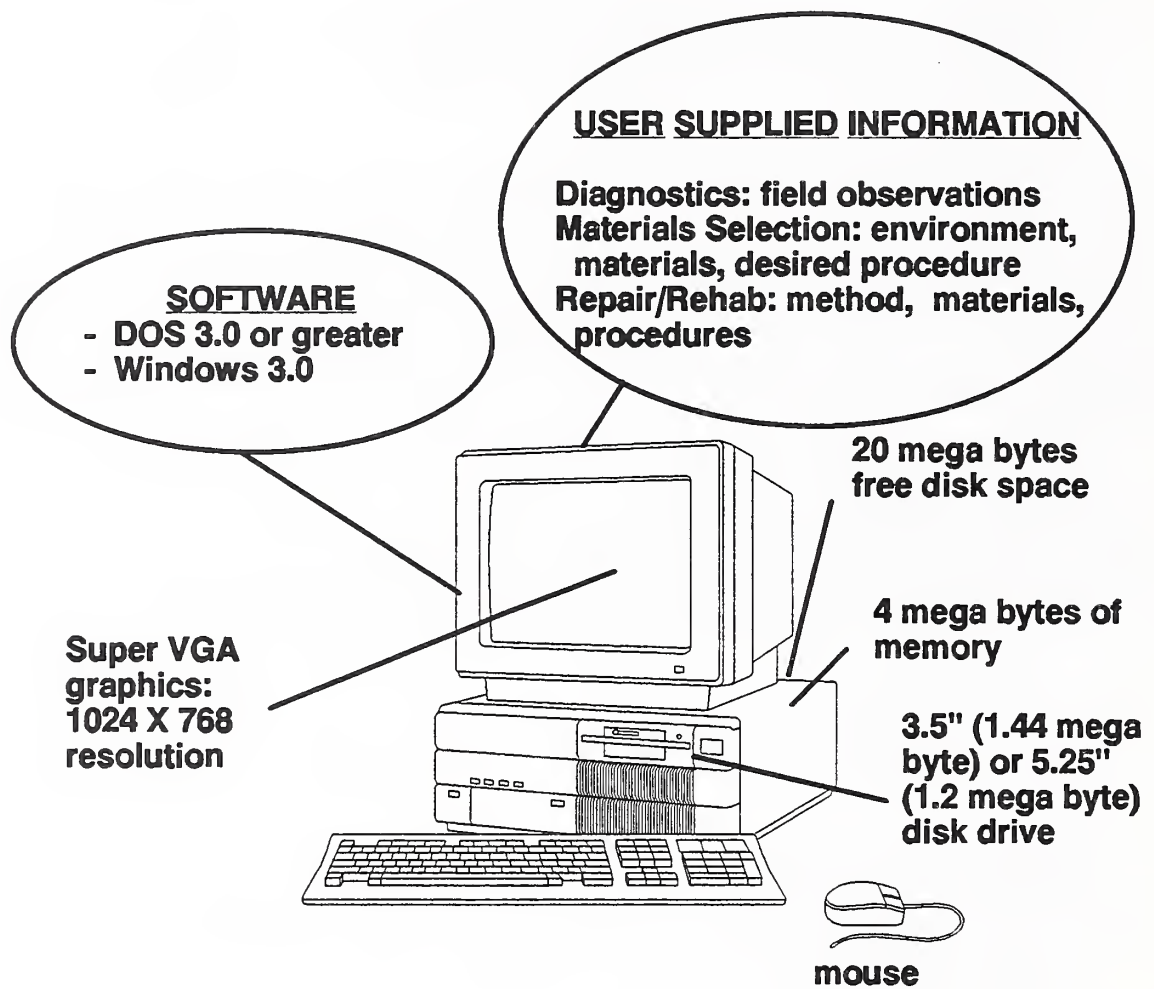
#### **Selection of materials (CONMAT)**

- 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)

---

<sup>5</sup> 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.

<sup>6</sup> 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 3.0 and its supported protocols and programs, HWYCON will also be compatible.



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

### **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 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 to use 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:

- power on and booting procedures
- procedures and commands for loading floppy diskettes
- operation of a mouse pointing device
- basic commands for Windows 3.0 (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 1992a] development tool used to develop HWYCON is an example of commercial software available today. The capabilities included in Level5 are:

- 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 which was obtained from Information Builders. It should be noted that this right is limited to Level5 Object Run-Only, version 2.2. Later revisions require the purchase of individual copies for each system distributed.

One of the major advantages to 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 prespecified 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 (Waterman 86) 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 1992b] and User's Guide [Information Builders 1992c] 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. The contributions that an object oriented structure makes to developing expert systems includes the following:

- 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

In the section describing HWYCON knowledge, reference was made to digitized images that represent photographs and drawings of distresses and procedures (see Figures 10 and 11). This 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 DOT's, the SHRP Long Term Pavement Field Distress Manual [SHRP 1991], 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 91]. This allowed images in the bitmapped 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
half tone	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 15-55 thousand bytes. The size of the original was between 102mm and 203mm in width and 203mm and 254mm 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 3 subsystems, each of which contains modules that contain specific knowledge areas. For example, the CONMAT subsystem is represented in 8 different modules, 1 main module, 4 each for the durability areas, and 3 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 where the knowledge on crack distresses was further divided for operating efficiency. Table 12-15 lists all of the HWYCON subsystem module names and their knowledge areas.

**Table 12. CONPAV-D modules and knowledge areas.**

<b>Module Name</b>	<b>Knowledge Area</b>
CPDMAIN	Main module for selecting pavement type and distresses
CPDCJ	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.**

<b>Module Name</b>	<b>Knowledge Area</b>
CSDMAIN	Main module for selecting bridge deck construction type and exposure conditions
CSDCNYX	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
CSDSXYX	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.**

<b>Module Name</b>	<b>Knowledge Area</b>
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.**

<b>Module Name</b>	<b>Knowledge Area</b>
CONPAVR	Recommendations for concrete pavement repair and rehabilitation materials and procedures

Figures 13 and 14 show the interrelationships between the HWYCON modules. The connecting lines shown between the modules indicate that modules can call other modules. This is performed using a "chaining" capability available in the Level5 Object shell program. Chaining is synonymous with conventional programming subroutine calls where 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.

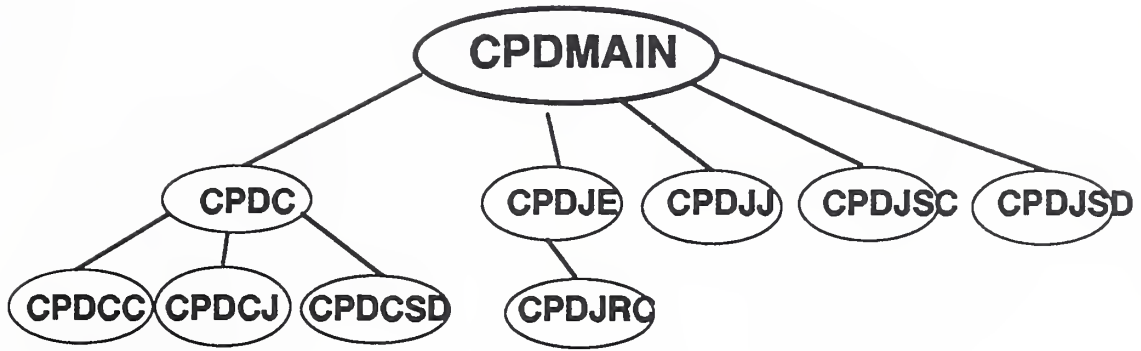
Within each of the HWYCON modules, knowledge is represented in a hierarchical tree structure. This structure logically connects the knowledge components of the system. For example, the CONMAT corrosion of reinforcing steel module (CMATCOR.) includes recommendations on the allowable chloride content and 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 shown in Appendix A (page 115) shows the structure of this knowledge. All knowledge represented in HWYCON is represented in the knowledge tree form and is shown in Appendix A. The knowledge tree was used as a "road map" for reviewing knowledge and making modifications to the computerized system.

In describing the architecture of HWYCON, it can be further stated that the system's knowledge 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 on 3.5" or 5.25" diskettes identified as the "HWYCON User Set" along with a user's guide and this document. The contents of the diskettes are shown in Table 16. Another set of diskettes, identified as the "HWYCON Developers Set", contains the source files for HWYCON and was delivered to SHRP. This set of diskettes is 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 who would make updates and changes and then distribute the system to users. This method is important so that integrity can be maintained in the knowledge base. The knowledge base files contained in the User Diskette Set have been encrypted using a capability available in the Level5 Run-Only program. The application files are identified with a ".app" file name extension and cannot be

# CONPAV-D



# CONSTRUC-D

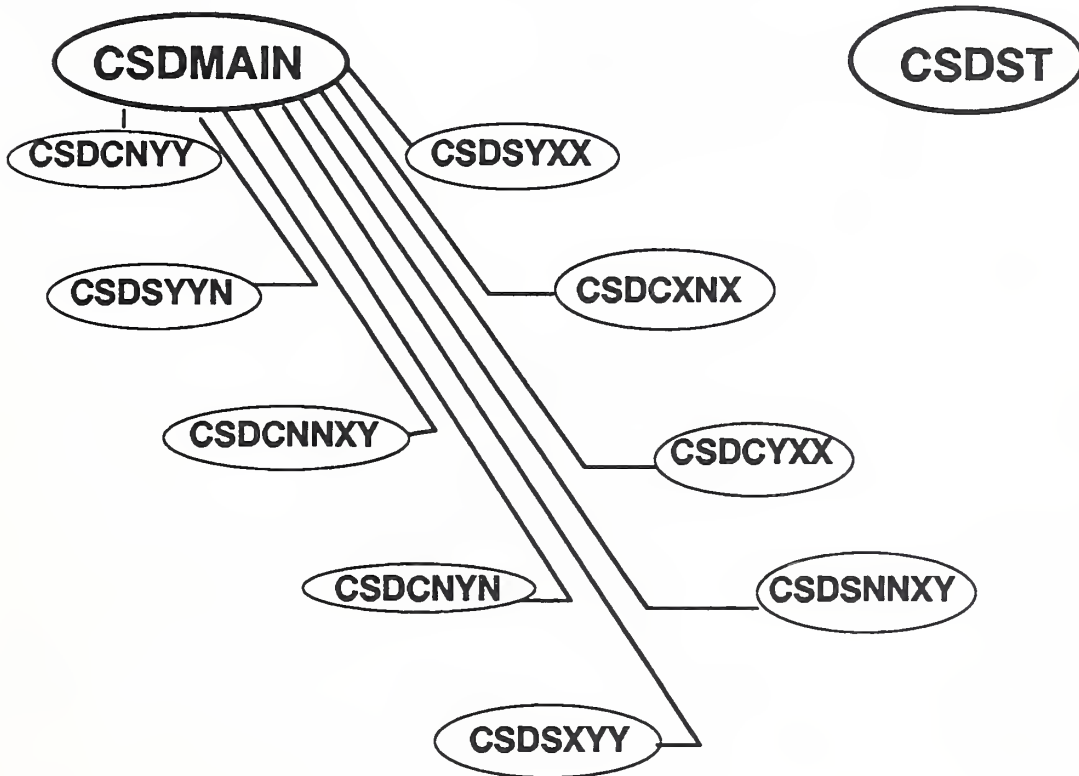


Figure 13. CONPAV-D and CONSTRUC-D interrelationships between modules.

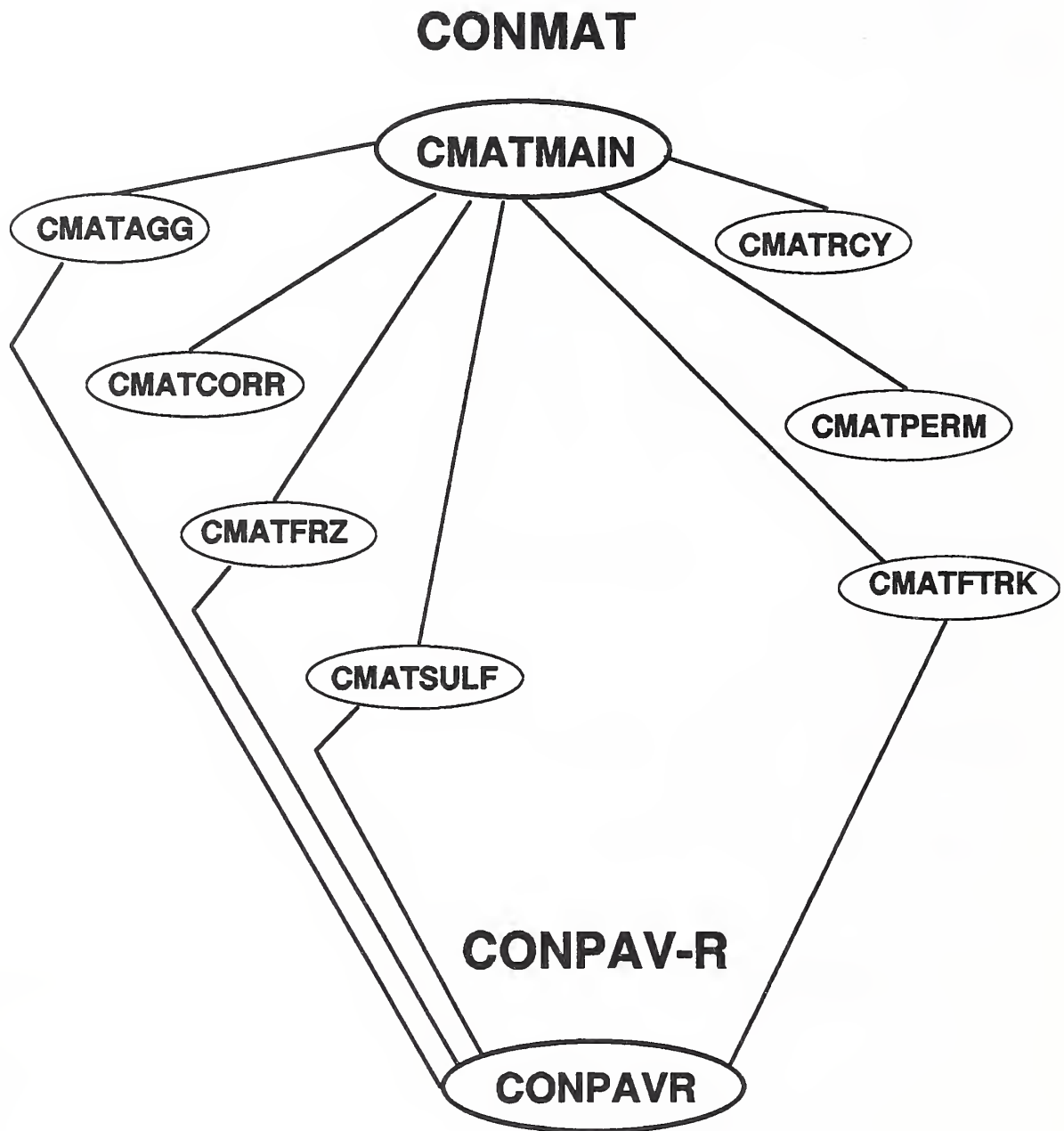


Figure 14. CONMAT and CONPAV-R interrelationships between modules.



# HWYCON COMPONENTS

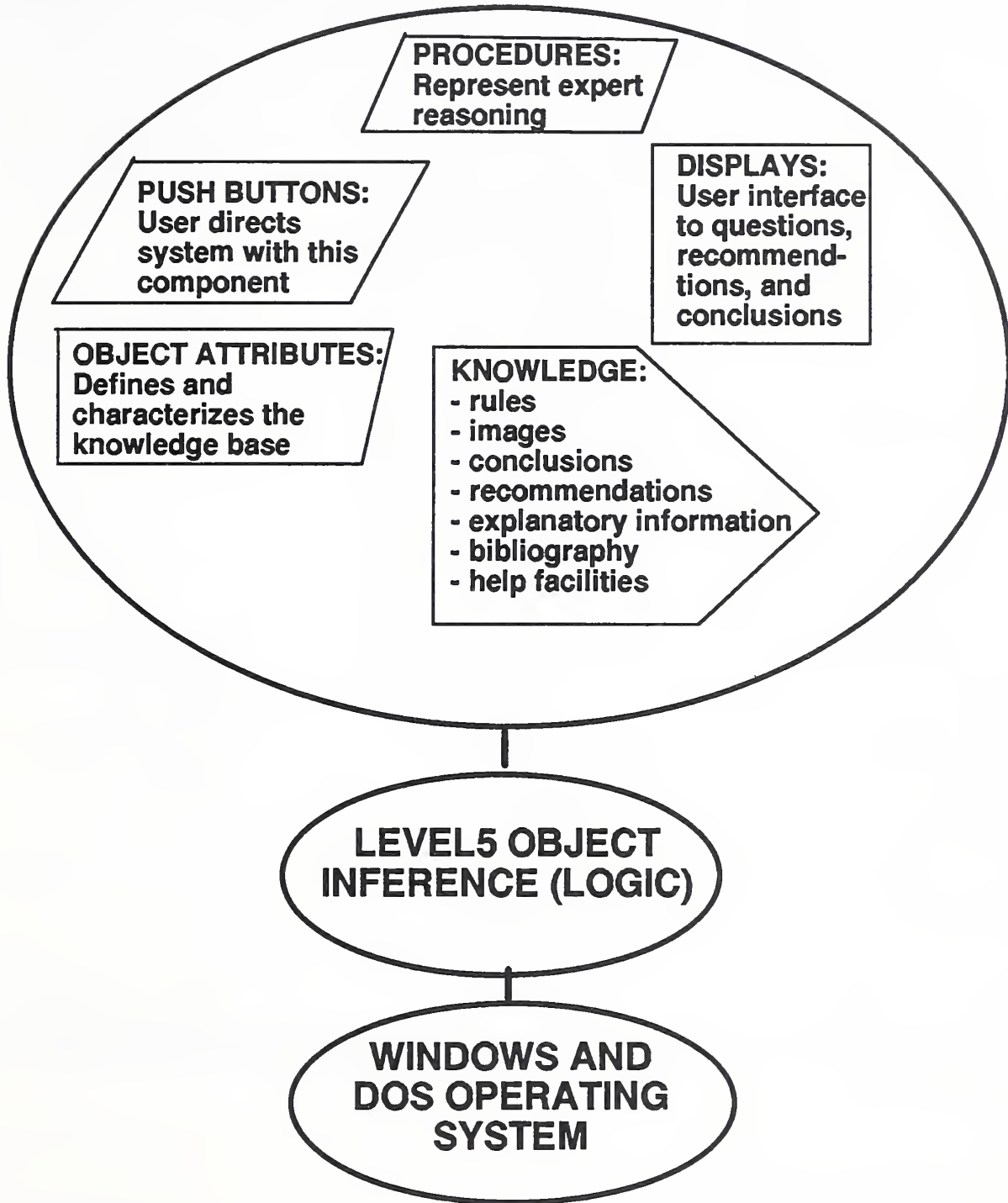


Figure 15. HWYCON knowledge components, connectivity, and function.

**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, CPJDSC.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	CSDST.APP	Concrete Structures Diagnostics (Structures)
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

generate the application files. Table 17 lists the contents of the Developer Distribution 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 1992a]. NIST does not have the license to distribute this program. NIST has the right to distribute the "Run-Only System", version 2.2 distributed with HWYCON, but not later versions.

**Table 17. HWYCON developers distribution diskette set contents.**

Diskette #/Name	File Names	Contents
1. CONPAV-D	CPDC.KNB, CPDCC.KNB CPDCJ.KNB, CPDSD.KNB CPDJE.KNB, CPDJJ.KNB CPDJRC.KNB, CPDJSC.KNB CPDJSD.KNB, CPDMAIN.KNB	Concrete Pavement Diagnostics
2. CONSTRUC-D	CSDC>NNXY.KNB CSDC)NYN.KNB CSDC)NYY.KNB CSDCXNX.KNB CSDCYXX.KNB CSDS>NNXY.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, and CONMAT involves installing the Level5 Run-Only program disk, and the HWYCON knowledge disks. Each diskette requires a separate install procedure. The system will only operate on a hard disk. You may install HWYCON on hard drives or partitions with names other than "C:". However, you must install the HWYCON knowledge disks and the system disk on the same drive or partition. There should be a minimum of 20 million bytes of free disk storage available on the hard disk to install all of the HWYCON subsystems. The instructions below describe the installation commands.

### Installing the Level5 Run-Only Disk

1. Turn on the computer.
2. If Microsoft Windows is running, terminate the program and return to the DOS prompt.
3. Insert the "Disk 1 - Run-Only System Disk" diskette into a 3 1/2" disk drive<sup>7</sup>.
4. At the DOS prompt, change the prompt to the drive containing Disk 1. For example, if you inserted Disk 1 in your A drive, type A: and press enter.
5. Type **install** and depress the ENTER key.

When you depress the ENTER key, the following message appears:

Make sure "Disk 1 - Run-Only System Disk" is in the drive.  
Depress the Enter key and proceed:

6. Depress the ENTER key.

When you depress the ENTER key, the following message appears:

Enter the destination directory for LEVEL5 OBJECT Run-Only files. To select the default c:\L5RO, press <Enter>:

5. To install the default directory, depress the ENTER key. The installation task will create the c:\l5ro directory on your hard disk if it does not already exist.

When you depress the ENTER key the following message may appear:

The specified directory c:\l5ro does not exist. Install will create it and LEVEL5 OBJECT Run-Only files will be installed in c:\l5ro.  
Do you want to proceed (Y/N)?

---

<sup>7</sup> HWYCON is distributed on 3 1/2" diskettes. If 5 1/4" diskettes are needed, please contact NIST to request another set of diskettes.

6. Type **Y** and depress the **ENTER** key.

This message appears:

Extracting Run-Only files to C:\l5ro.

You will see the Disk 1 Run-Only files being installed. When the installation is complete, this message appears:

Installation complete.

You are now ready to install the HWYCON knowledge diskettes.

### **Installing the CONPAV-D, CONSTRUC-D, and CONMAT Knowledge Disks**

1. If necessary, remove the "Disk 1 - Run-Only System Disk" from either drive A: or B:, and insert the "CONPAV-D Knowledge disk".
2. If necessary, at the DOS prompt, type either **a:** or **b:** then **install** followed by the floppy disk drive identification, then the hard disk drive identification.

For example, **b:install b: c:**, then press the "ENTER" key.

3. Using the disk drive identifiers specified in step 2 above, install the CONSTRUC-D knowledge Disks #1, #2, and #3.
4. Using the disk drive identifiers specified in step 2 above, install the CONMAT knowledge disk.

The files on the HWYCON program and knowledge disks will be installed in the hard disk drive specified, the directory names shown below will be created on the drive. Note! The Run-Only System Disk and CONPAV-D Knowledge Disk files must be installed in the default directories, as specified below:

Level5 Run-Only program files = \L5RO\  
CONPAV-D Knowledge files = \hwycon\cpd\  
CONSTRUC-D Knowledge files = \hwycon\csd\  
CONMAT Knowledge files = \hwycon\cmat\

## Creating The HWYCON Window and Icons

The HWYCON subsystems can be activated from a "window" which makes the operation of the various modules more simple. The following procedures can be used to create the HWYCON window and icons for the current and future systems.

### To establish the HWYCON group window:

- start Windows
- click on the Program Manager, Main Window
- click on "File"
- click on "New"
- click on "Program Group"
- click on "ok"
- type: "HWYCON Expert System" (omitting the " (quote) characters)
- click on the "Group File" property box
- type: "HWYCON.GRP" (omitting the " (quote) characters)
- click on "ok"

The empty "HWYCON Expert System" window will appear.

### To establish icons for CONPAV-D, CONSTRUC-D, CONMAT, and CONPAV-R:

- click on "File"
- click on "new"
- click on "ok"
- type: "CONPAV-D" (omitting the " (quote) characters)
- click on the "Command Line" property box
- type: "c:\L5RO\L5RO.exe c:\hwycon\cpd\cpdmain.app"  
(omitting the " (quote) characters...Note that a space appears between "exe" and "c:")
- click on "ok"
- click on "File"
- click on "New"
- click on "ok"
- type: "CONSTRUC-D (Bridge Decks)" (omitting the " (quote) characters)
- click on the "Command Line" property box
- type: "c:\L5RO\L5RO.exe c:\hwycon\csd\csdmain.app"  
(omitting the " (quote) characters...Note that a space appears between "exe" and "c:")
- click on "ok"
- click on "File"
- click on "New"
- click on "ok"
- type: "CONSTRUC-D (Structures)" (omitting the " (quote) characters)
- click on the "Command Line" property box

- type: "c:\L5RO\L5RO.exe c:\hwycon\csd\csdst.app"  
(omitting the " (quote) characters...Note that a space appears between "exe" and "c:")
- click on "ok"
- click on "File:"
- click on "New"
- click on "ok"
- type: "CONMAT" (omitting the " (quote) characters)
- click on the "Command Line" property box
- type: "c:\L5RO\L5RO.EXE c:\hwycon\cmat\cmatmain.app"  
(omitting the " (quote) characters...Note that a space appears between the "exe" and "c:")
- click on "ok"
- click on "File:"
- click on "New"
- click on "ok"
- type: "CONPAV-R" (omitting the " (quote) characters)
- click on the "Command Line" property box
- type: "c:\L5RO\L5RO.EXE c:\hwycon\cpr\conpavr.app"  
(omitting the " (quote) characters...Note that a space appears between the "exe" and "c:")
- click on "ok"

The icons may overlap each other in the Window. If so, click on an overlapping icon and "drag" it to a new location. To record the new location, you must exit Windows with the "Save Changes" option on.

## 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 (described under "Imaging Software" in the HWYCON Development and Implementation Section). 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 and whether present staff are suitable or whether to seek assistance. The important factors in making this determining 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.



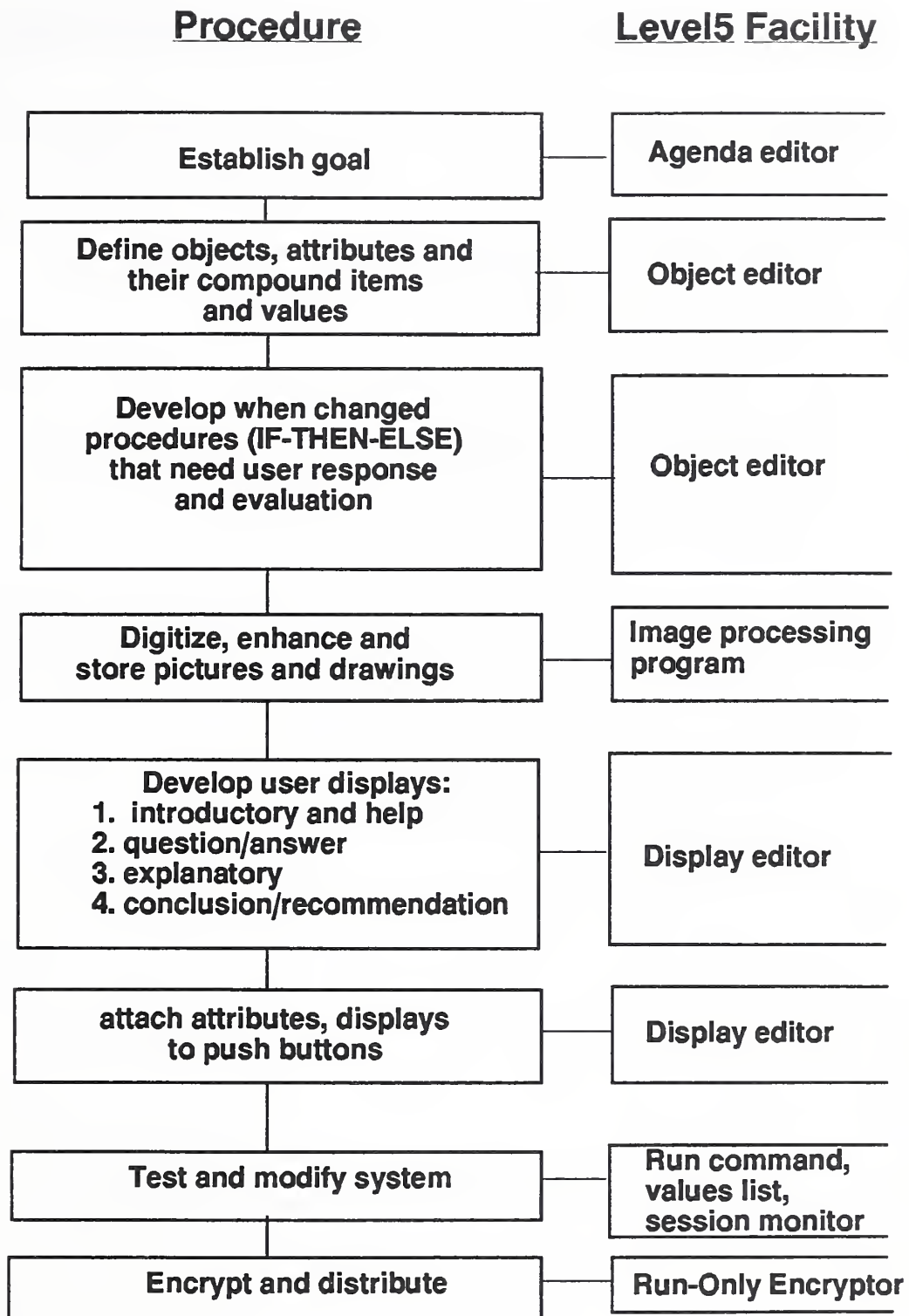


Figure 16. Procedures used in the development of HWYCON and the Level5 Object facility used.

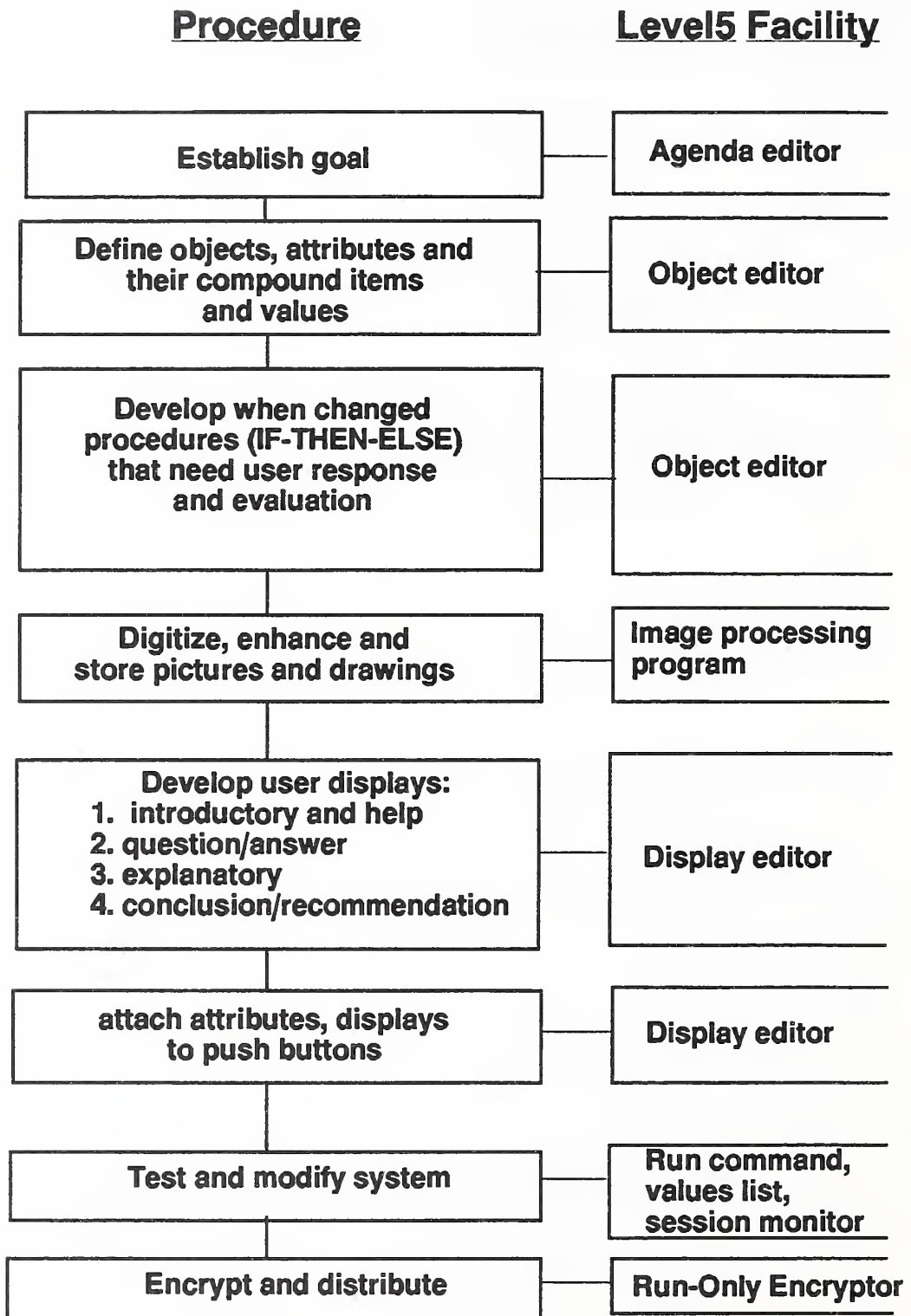


Figure 17. Example of the recommended procedure for modifying the HWYCON knowledge base.

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 space of free space should be available. Memory requirements for running the Level5 Object shell program is 4 mega bytes. Figure 18 shows the recommended configuration for a development computer suitable for making changes to HWYCON.

### **13. FUTURE ENHANCEMENTS TO HWYCON**

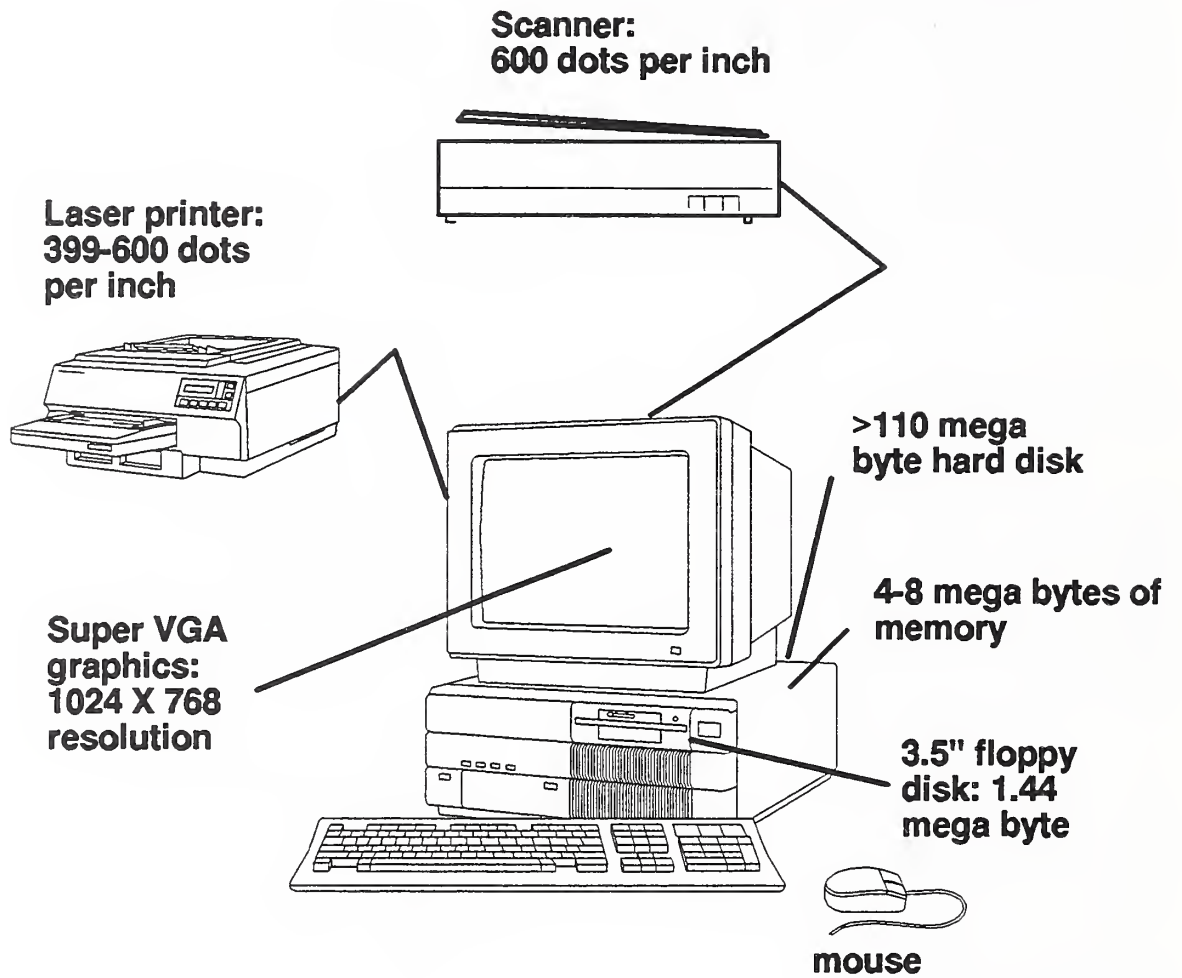
In order for expert systems not to become obsolete, they must be nurtured and kept current. This involves a mechanism for making modifications as knowledge and needs change, and to include new knowledge. Under the SHRP C-206 project, guidelines were established for the scope of knowledge and the criterion 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 DOT's. 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 will be completed concurrently with the C-206 project, and it would be important to include this newly developed knowledge in HWYCON. An example of this new knowledge is being developed in the SHRP C-104 project which addresses mainly corrosion of reinforcing steel associated with 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 new knowledge on new repair/maintenance materials, SHRP C-104 project knowledge on repair and rehabilitation of bridge decks.

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



**Figure 18. Recommended minimum computer configuration for modifying HWYCON.**

## 14. REFERENCES

- Clifton, J.R., Oltikar, B.C., Johnson, S.K. (1985) Development of DURCON, An Expert System for Durable Concrete: Part I, National Bureau of Standards, Gaithersburg, MD, NBSIR 85-3186.
- Hall, K.T., Connor, J.M., Darter, M.I., Carpenter, S.H. (1989) Rehabilitation of Concrete Pavements, Volume III: Concrete Pavement Evaluation and Rehabilitation System, Federal Highway Administration, McLean, VA, Publication No. FHWA-RD-88-073.
- Information Builders (1992a) Level5 Object: Object-Oriented Expert System for Microsoft Windows, Version 2.2, Information Builders, Inc., New York, NY.
- Information Builders (1992b) Level5 Object: Object-Oriented Expert System for Microsoft Windows, User's Guide, Information Builders, Inc., New York, NY.
- Information Builders (1992c) Level5 Object: Object-Oriented Expert System for Microsoft Windows, Reference Guide, Information Builders, Inc., New York, NY.
- Kaetzel, L.J. and Clifton, J.R. (1991) Expert/Knowledge Based Systems for Cement and Concrete: State-of-the-Art Report, SHRP, Washington, DC, SHRP-C/UWP-91-527.
- Ritchie, S.G. and Harris, R.A., Expert Systems in Transportation Engineering, Expert Systems for Civil Engineers: Technology and Application, Chapter 8, ASCE, New York, NY, 1987.
- Seren, K. (1988) An Expert system for Choosing the type of Ready Mix Concrete, The Nordic Concrete Federation, Finland, Publication No. 7.
- Shahin, M.Y., Walther, J.A. (1990) Pavement Maintenance Management for Roads and Streets Using the PAVER System, U.S. Army Corps of Engineers (USA CERL), Champaign, IL, Technical Report M-90/05.
- SHRP (1989) Methodology for the Protection and Rehabilitation of Existing Reinforced Concrete Bridges, Project C-104, SHRP, Washington, DC.
- SHRP-LTPP/FR-90-001 (1990) Distress Identification Manual for the Long-Term Pavement Performance Studies, SHRP, Washington, DC.

SHRP-S/FR-92-103/110 (1992) Condition Evaluation of Concrete Bridges Relative to Reinforcement Corrosion, SHRP, Washington, DC.





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

Zsoft Corp. (1991) Publisher's Paintbrush, Version 2.0, Zsoft Corp., Marietta, GA.

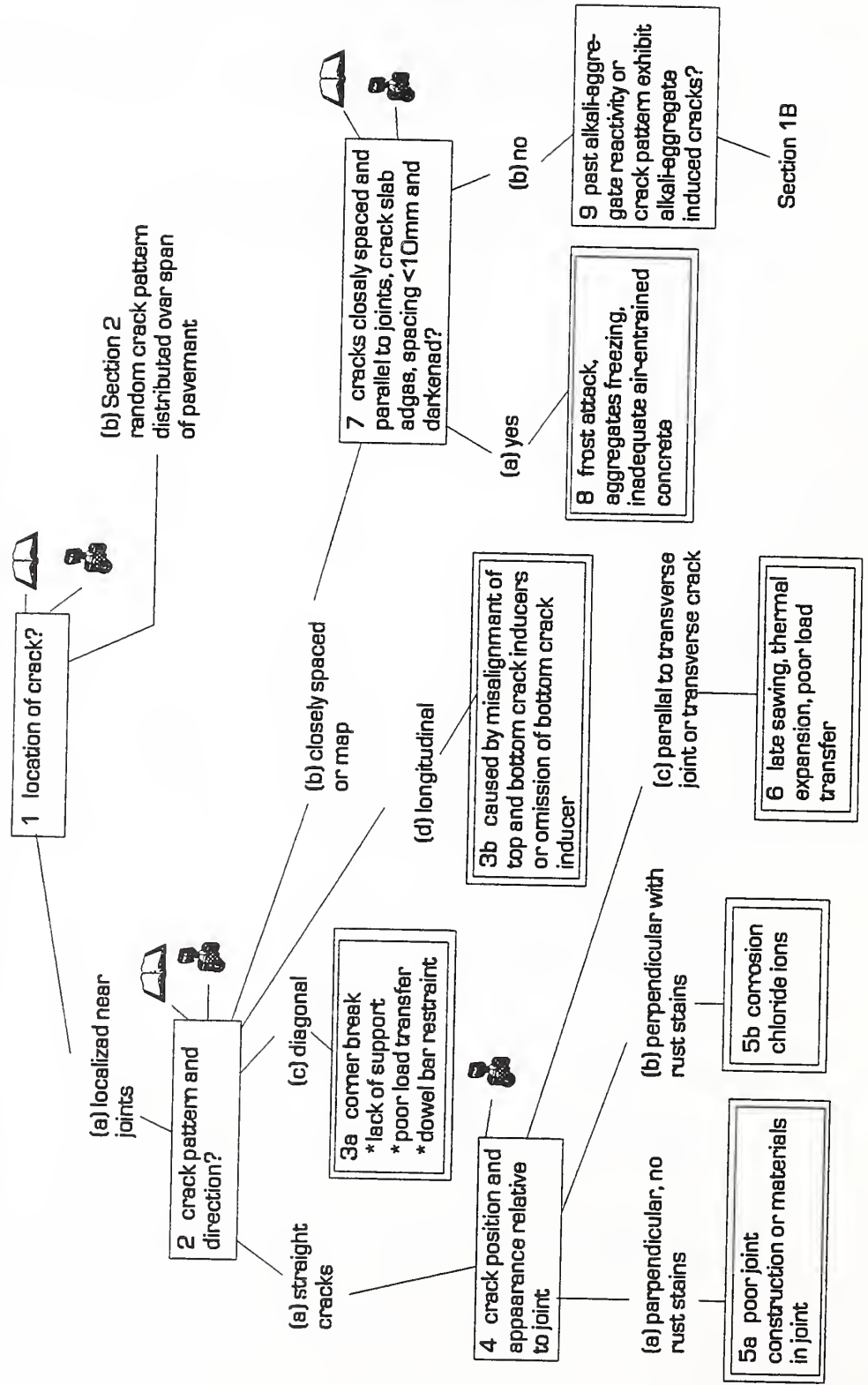
# APPENDIX A: KNOWLEDGE TREES

## CONPAV-D

### Legend:

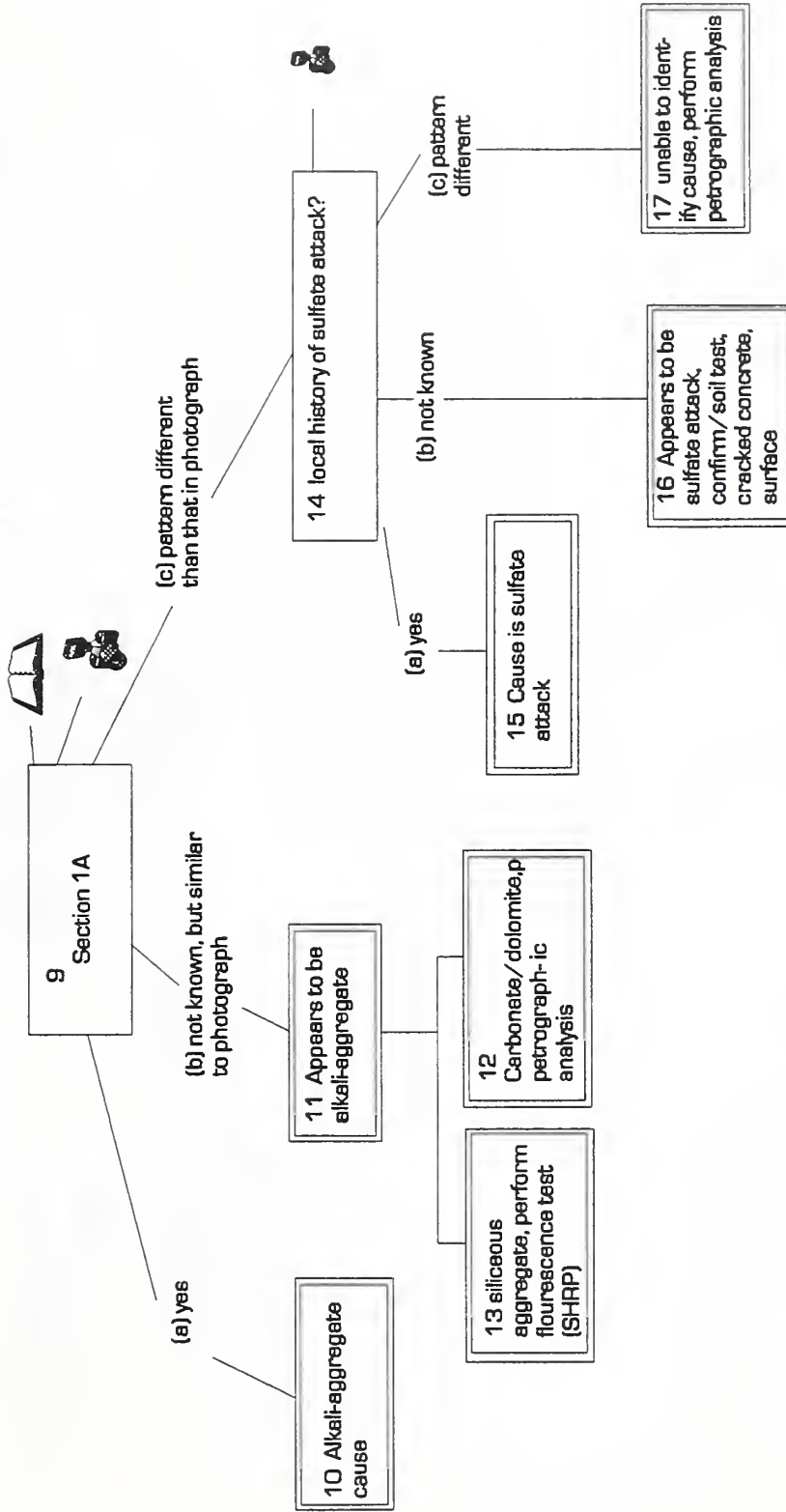
Picture or Drawing	=	
alpha/numeric references (e.g. 2A)	=	reference to narrative text
explanatory information	=	
operator response(s)	=	(a) _____
question box	=	
conclusion or recommendation box	=	

Cracks at Joints, Edges and Other Openings

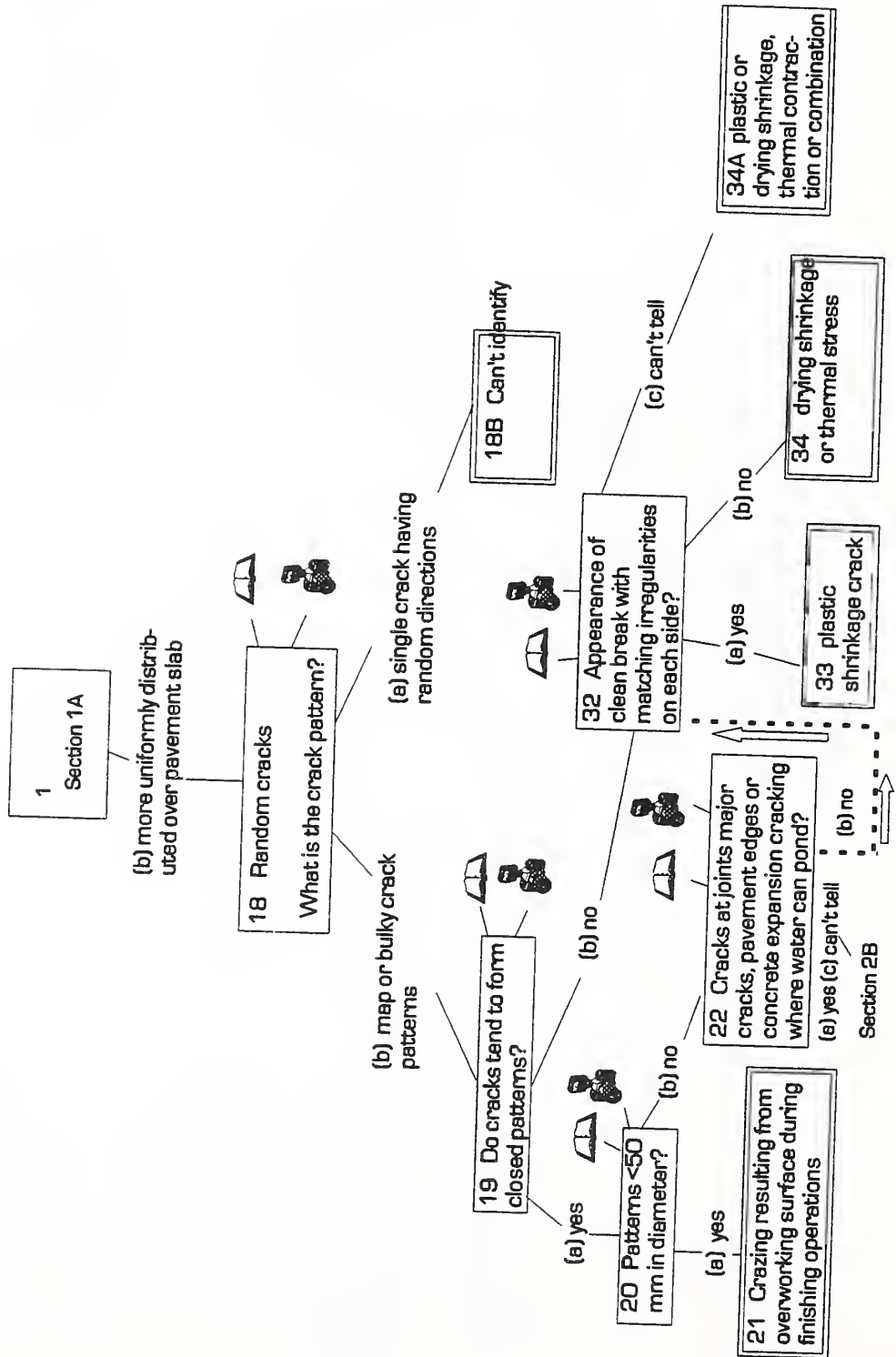




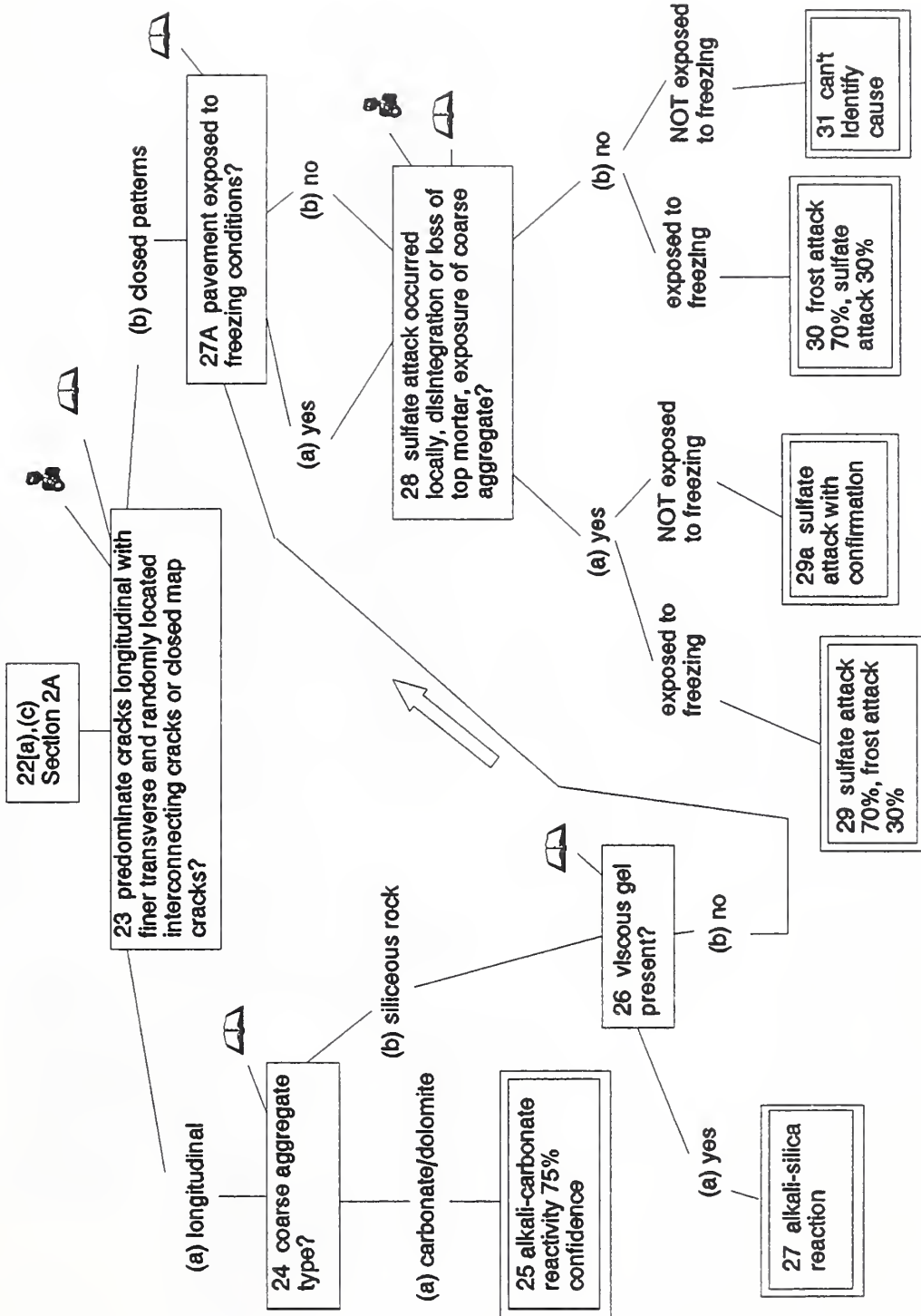
Cracks at Joints, Edges, and Other Openings



Random Crack Pattern Distributed Over Slab

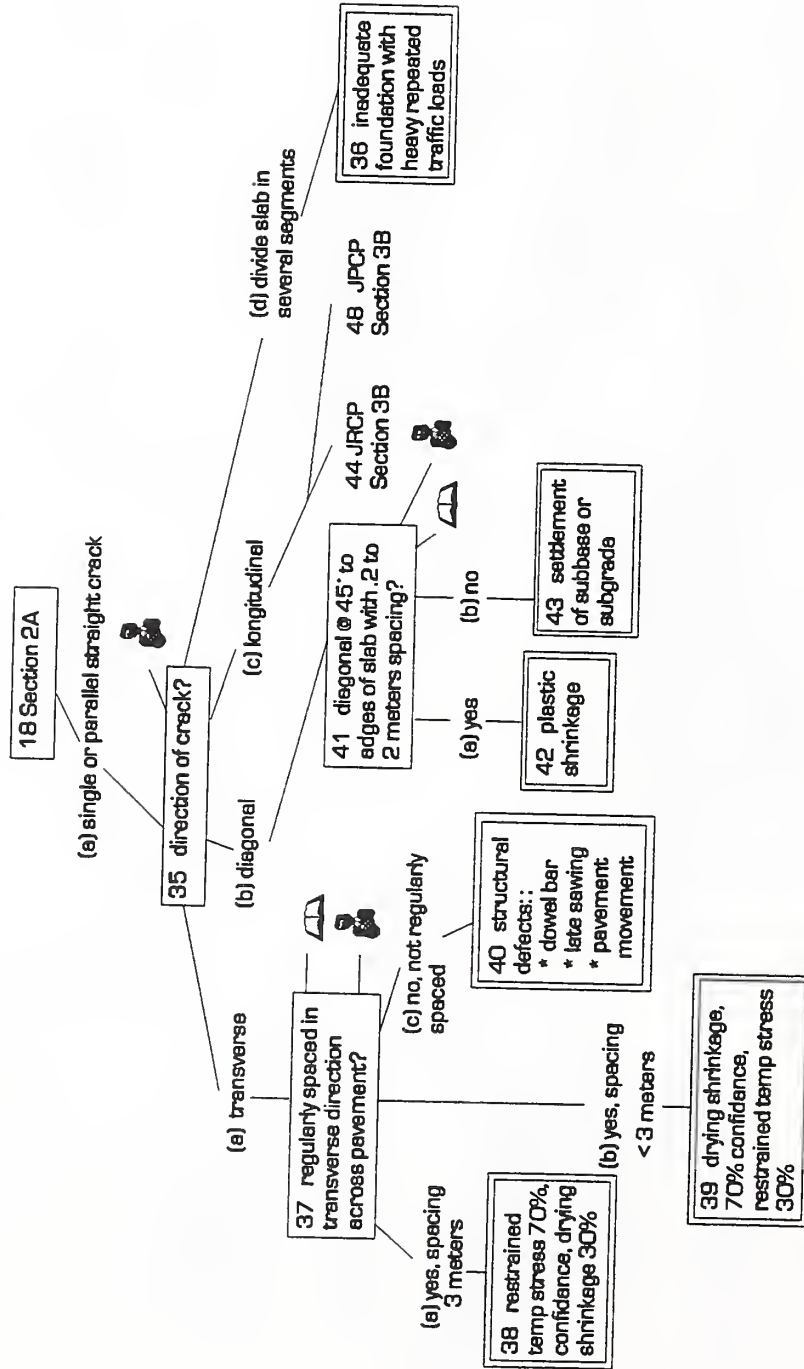


CONPAVD Knowledge 3.0 - JCP Cracks - Section 2B - 3/30/93  
 Randon Cracks Distributed Over Slab

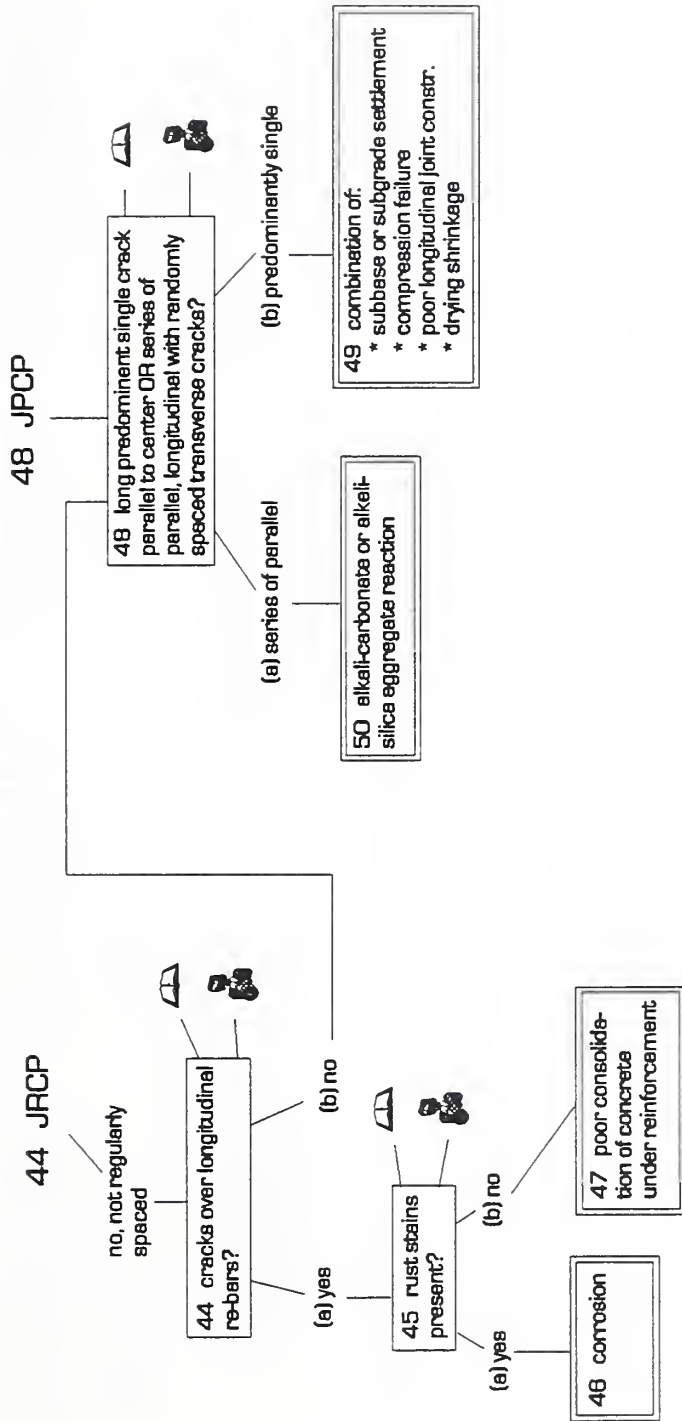


CONPAVD Knowledge 3.0 - JCP Cracks - Section 3A - 3/30/93

Generally Straight Cracks in Slab

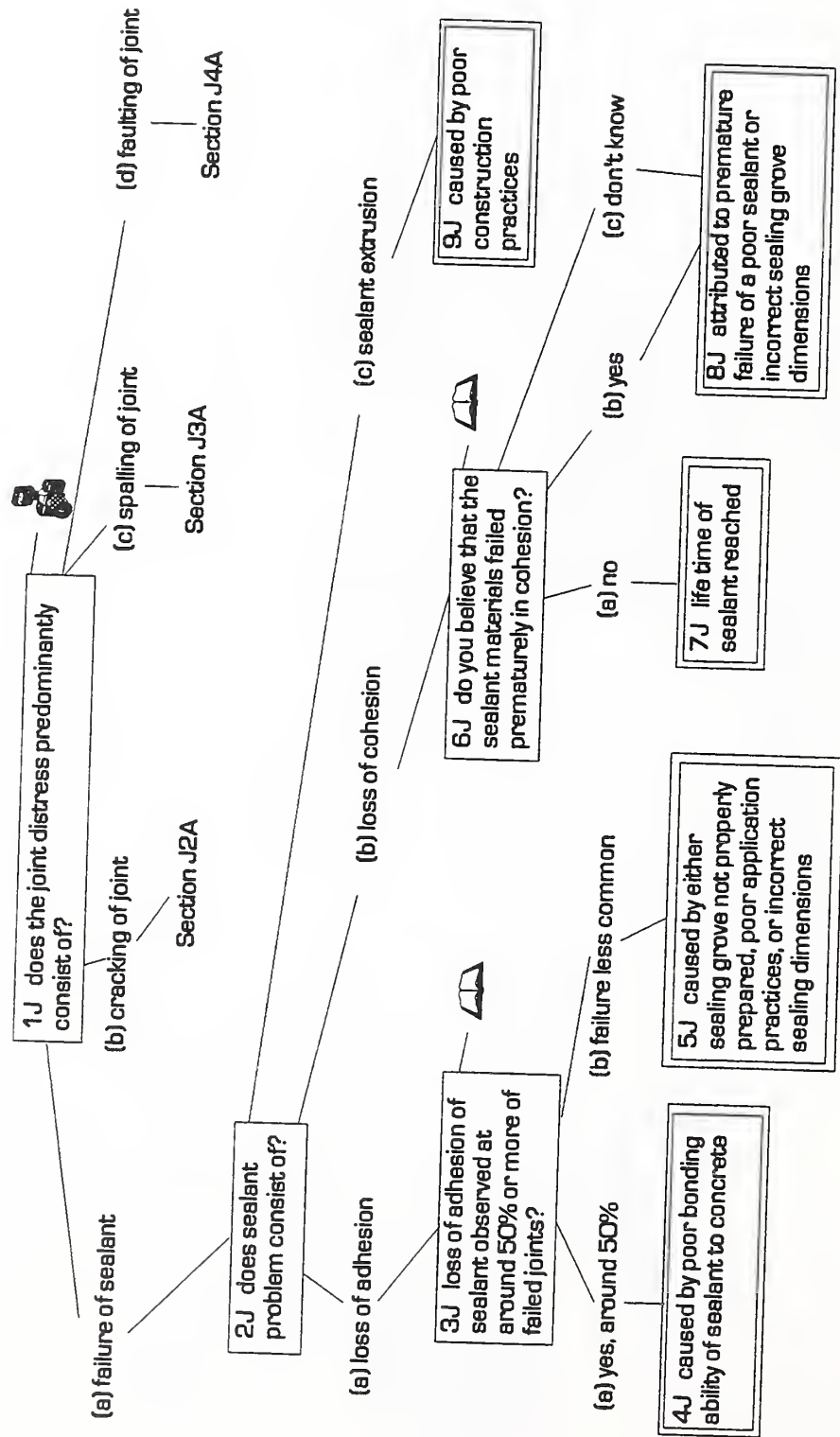


Generally Straight Cracks in Slab

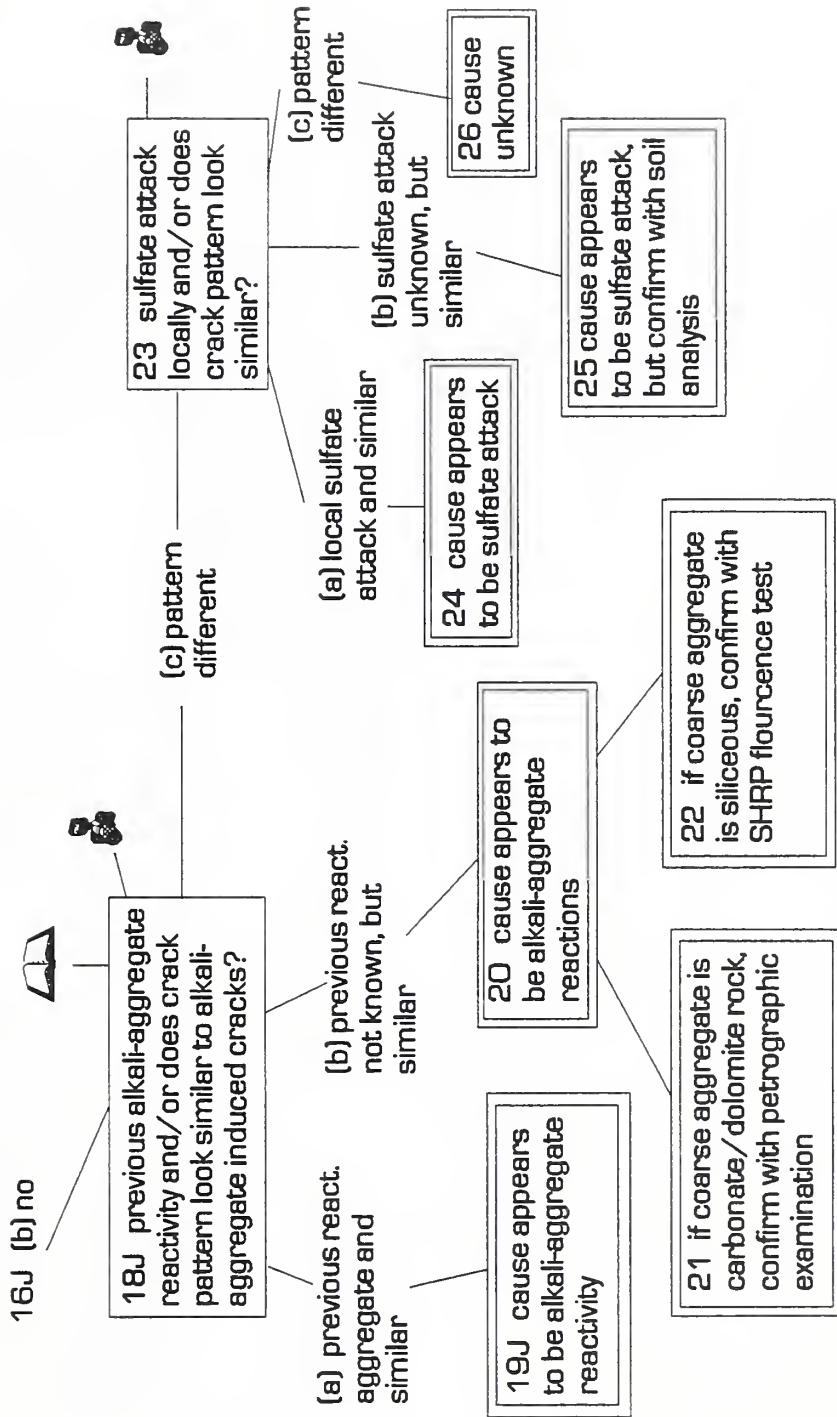


CONPAVD Knowledge 3.0 - JCP Joint Distresses - Section J1A - 3/30/93

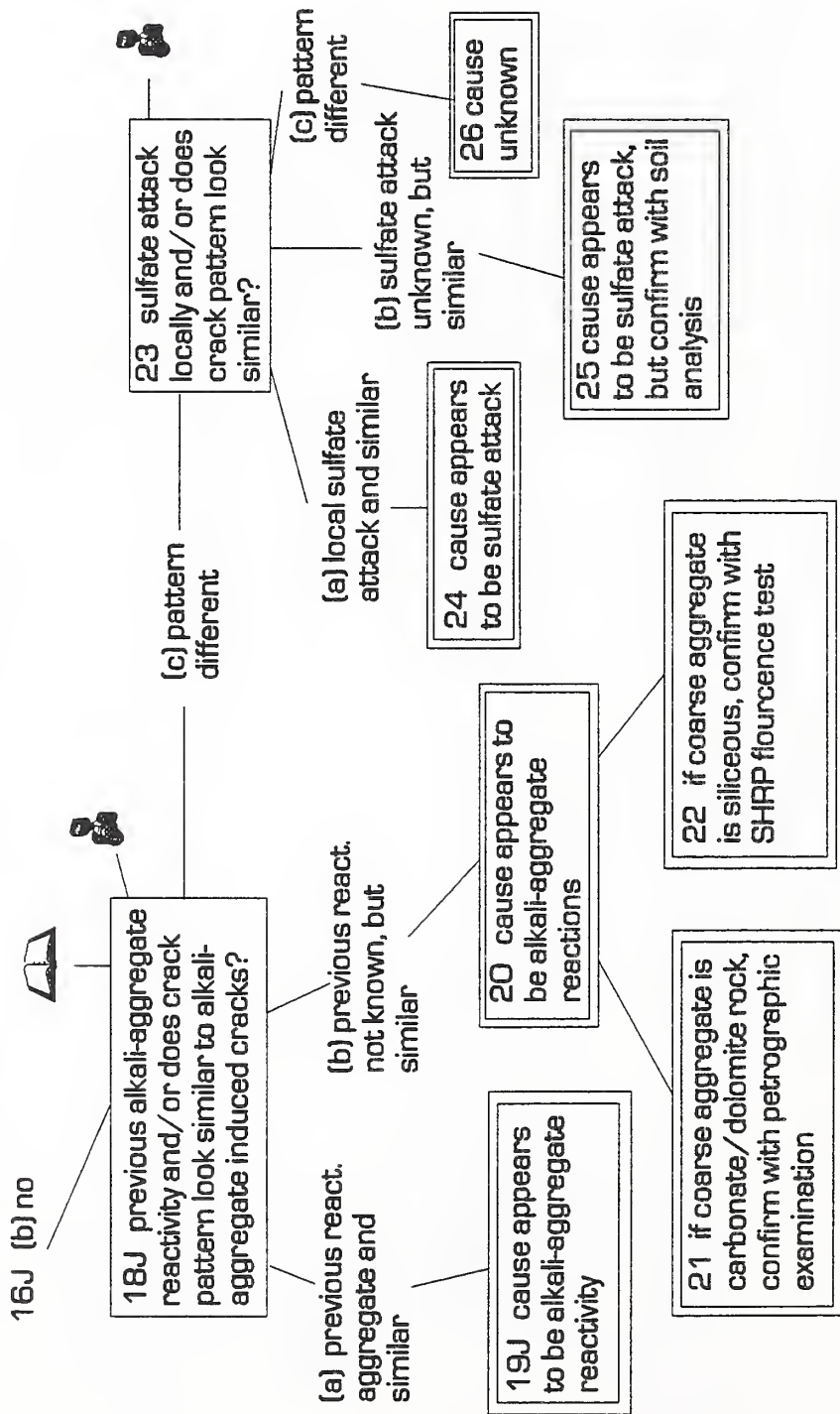
Sealant Failure



Cracking - continued



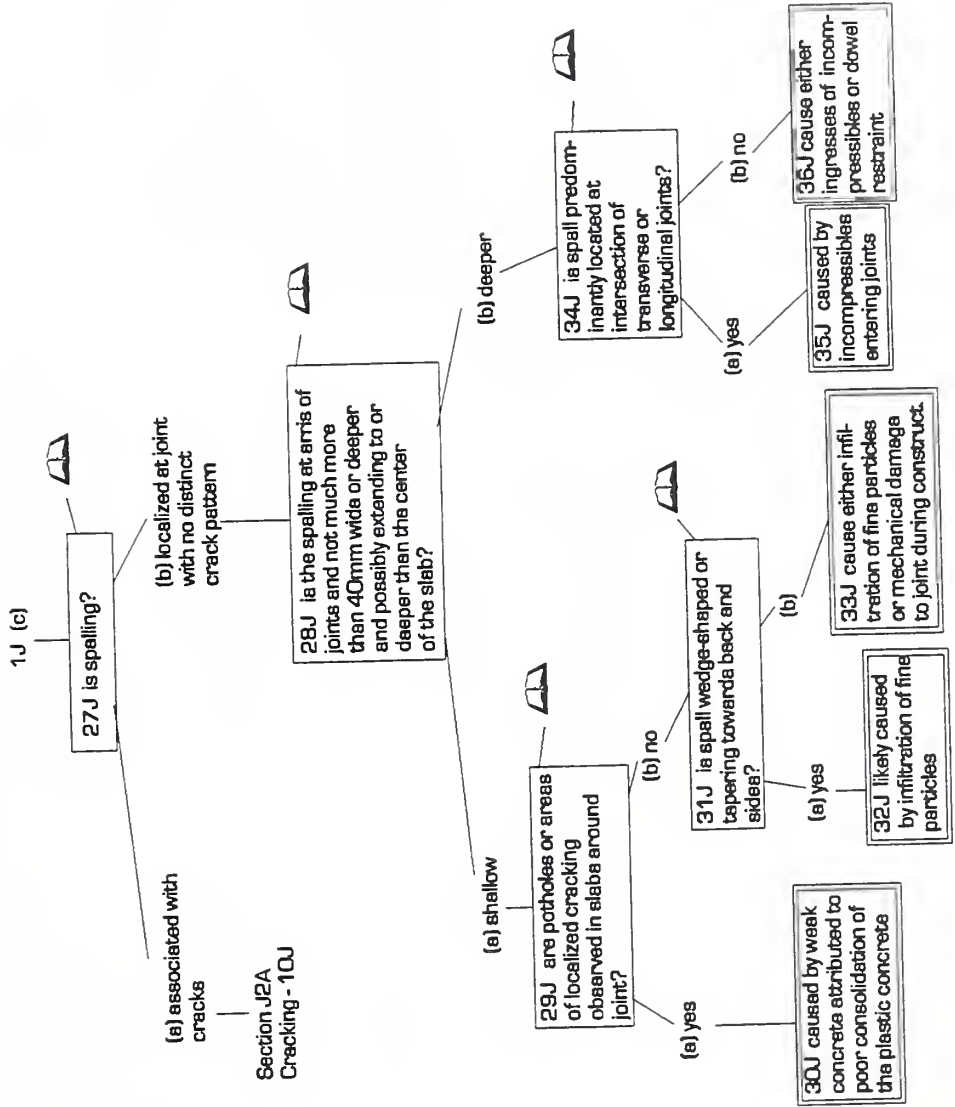
Cracking - continued





CONPAVD 3.0 JCP Joint Distresses - Section 3A - 3/30/93

Spalling



### Faulting



1d (d)

37J is faulting occurring at?

(a) transverse joint

(b) longitudinal joint

38J does pavement have drainage system

41J usually caused by settlement of foundation

(a) yes

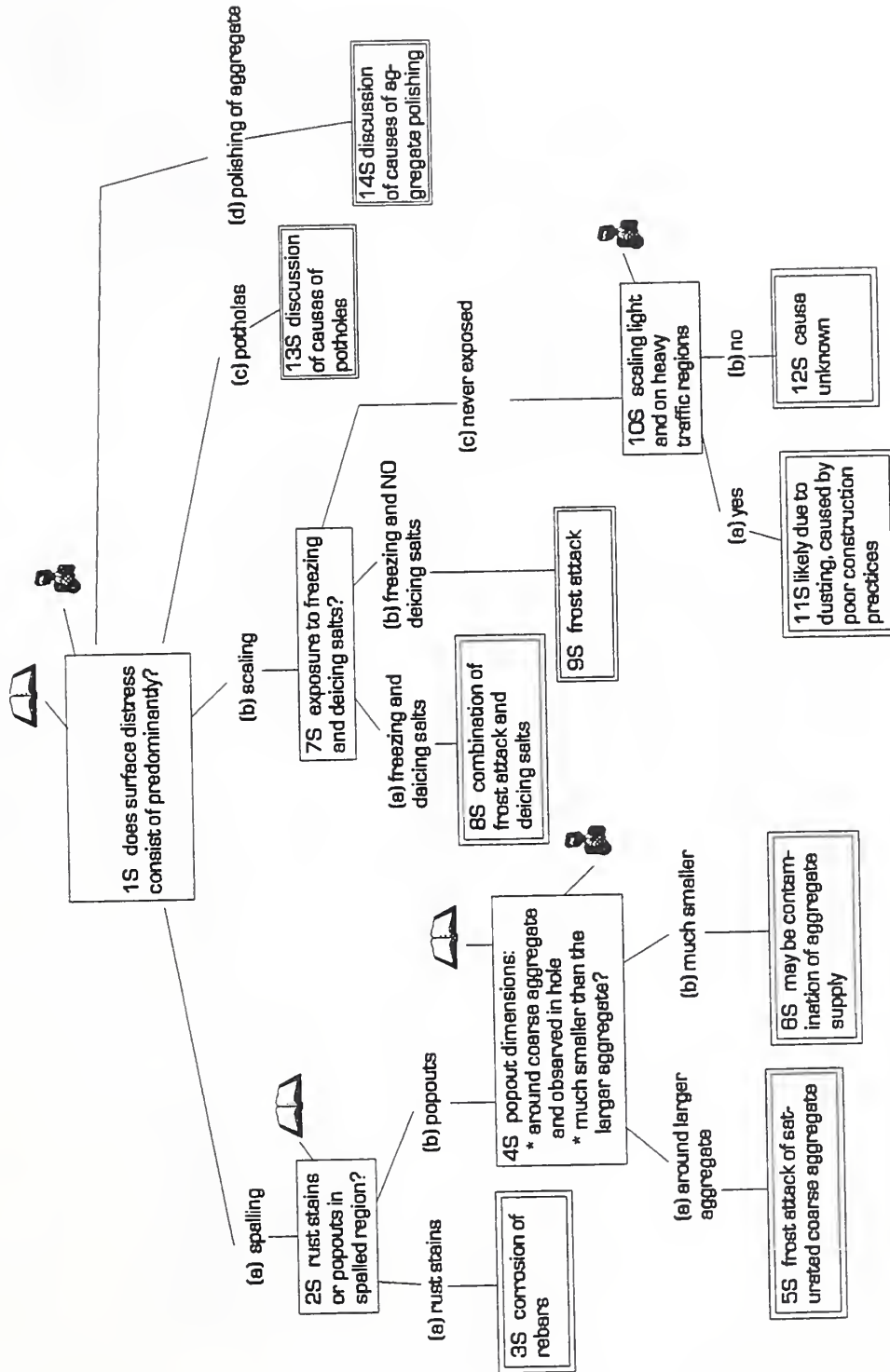
(c) no, not needed

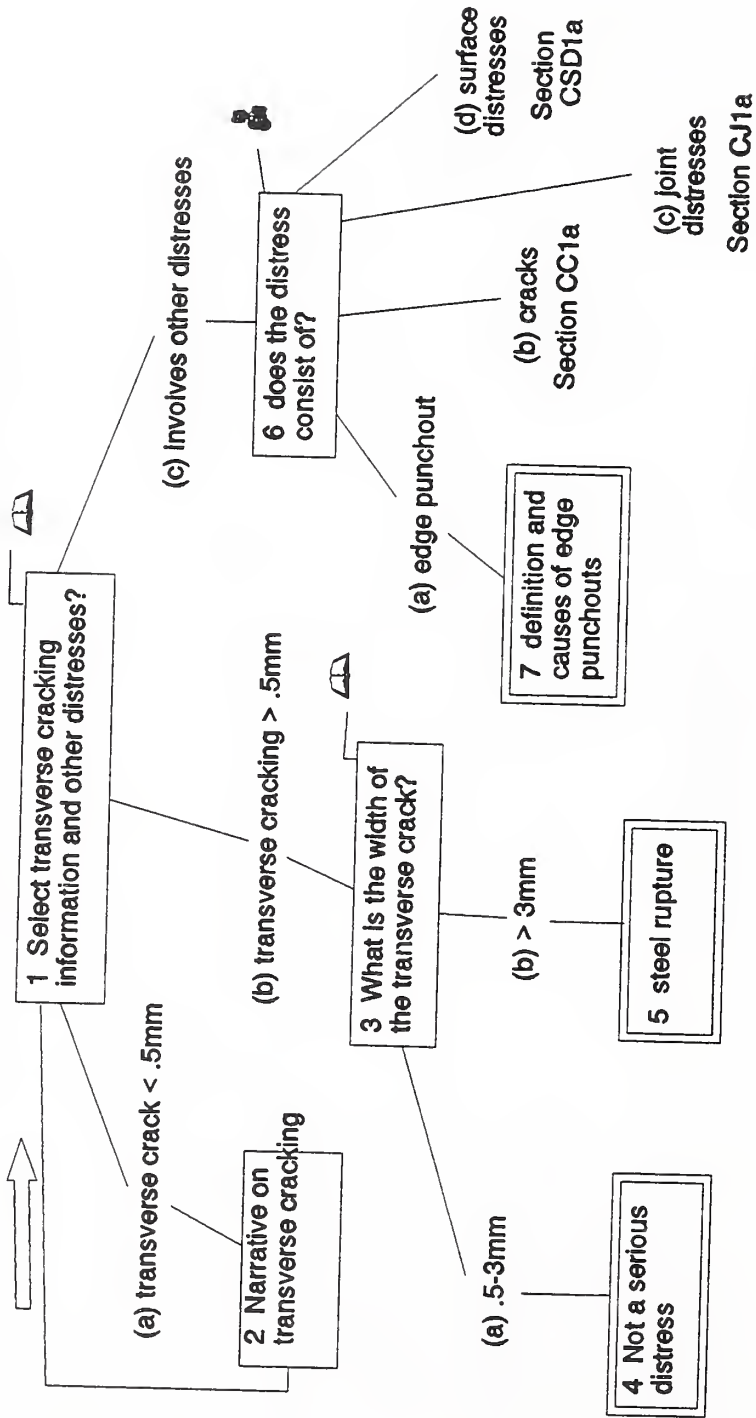
(b) no, and exposed to precipitation

39J cause due to lack of effective load transfer systems at joint

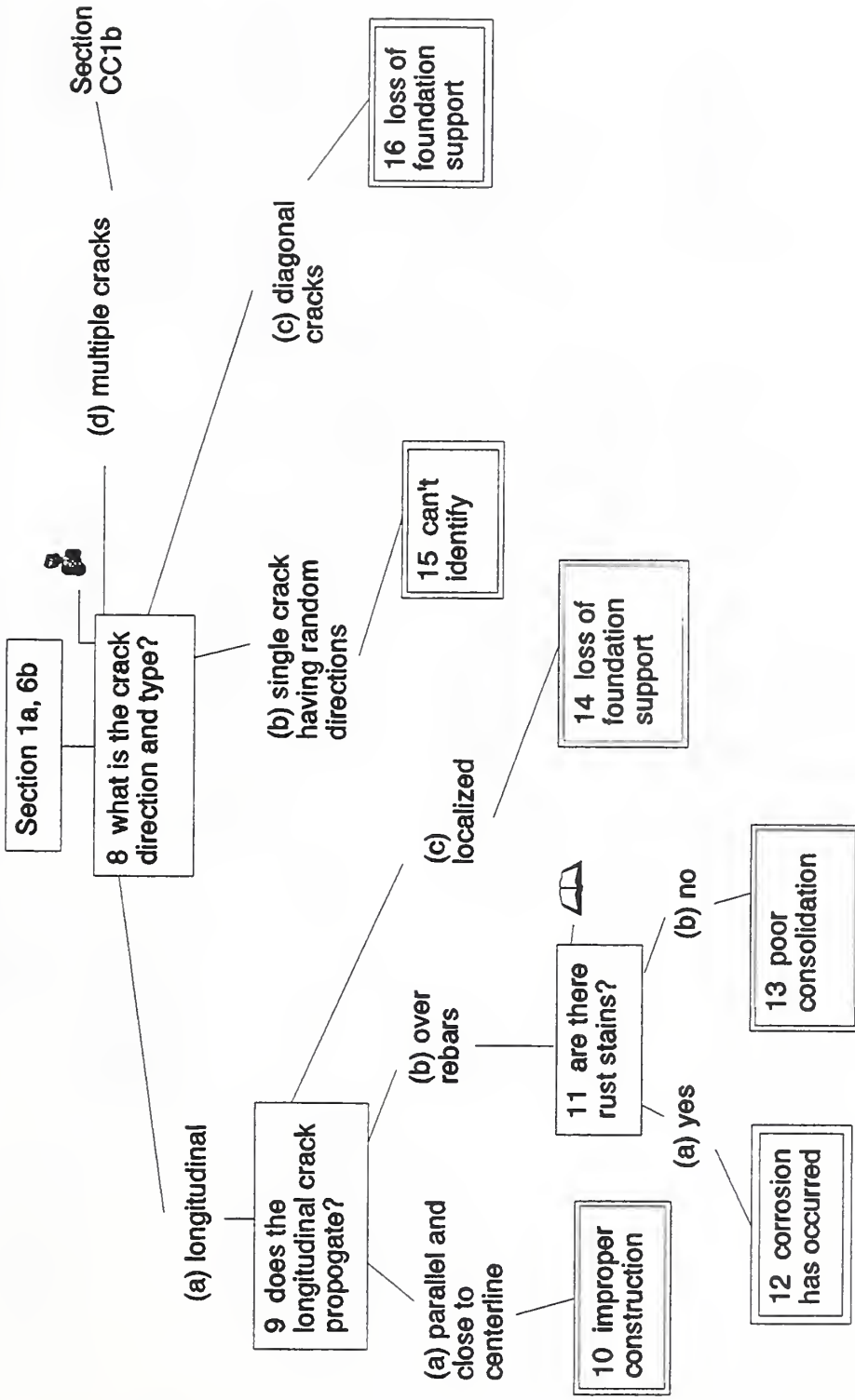
40J lack of edge drainage system causing pumping at joint

CONPAVD Knowledge 3.0 - JCP Surface Distresses - Section S1A - 3/30/93

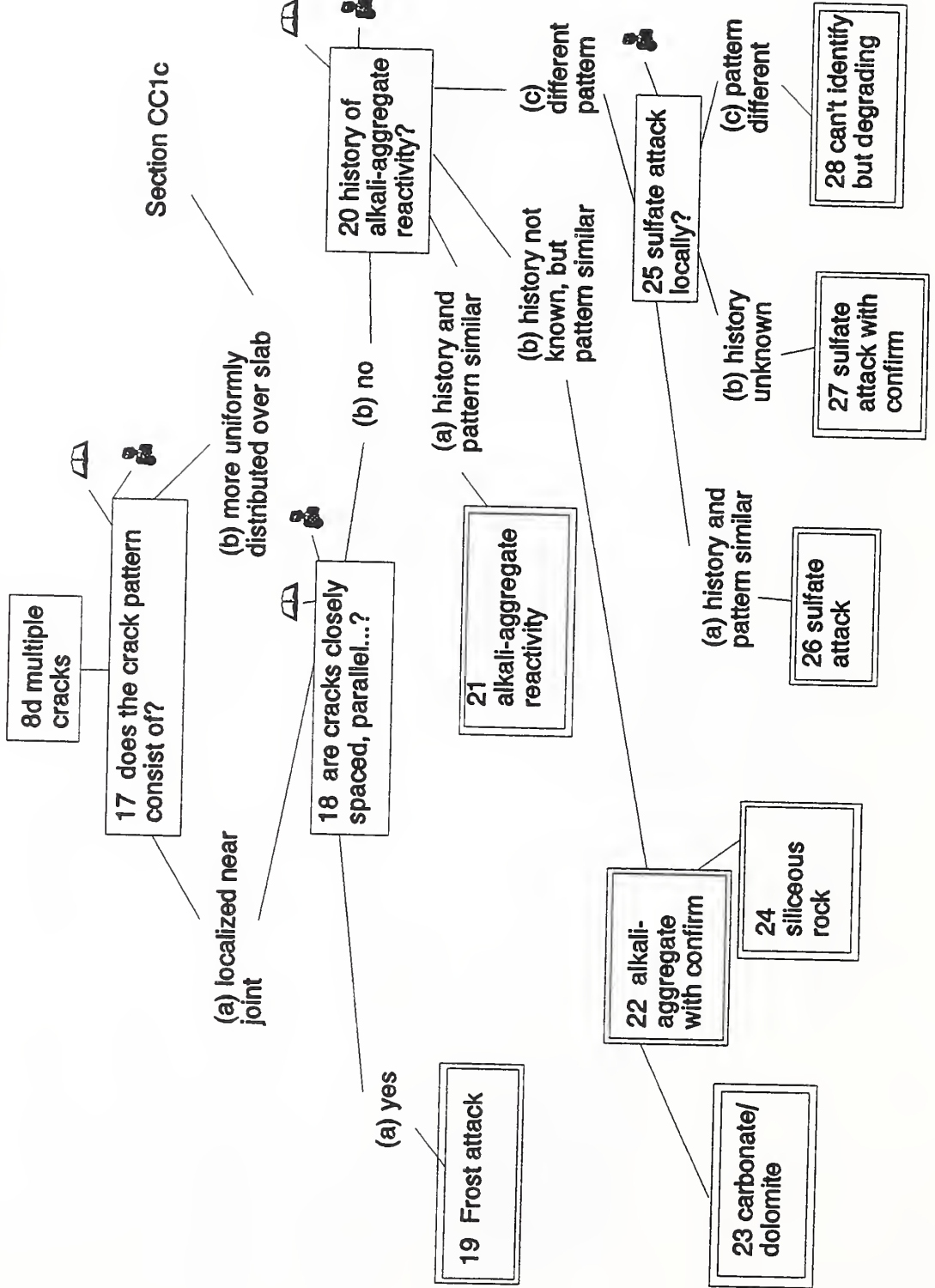


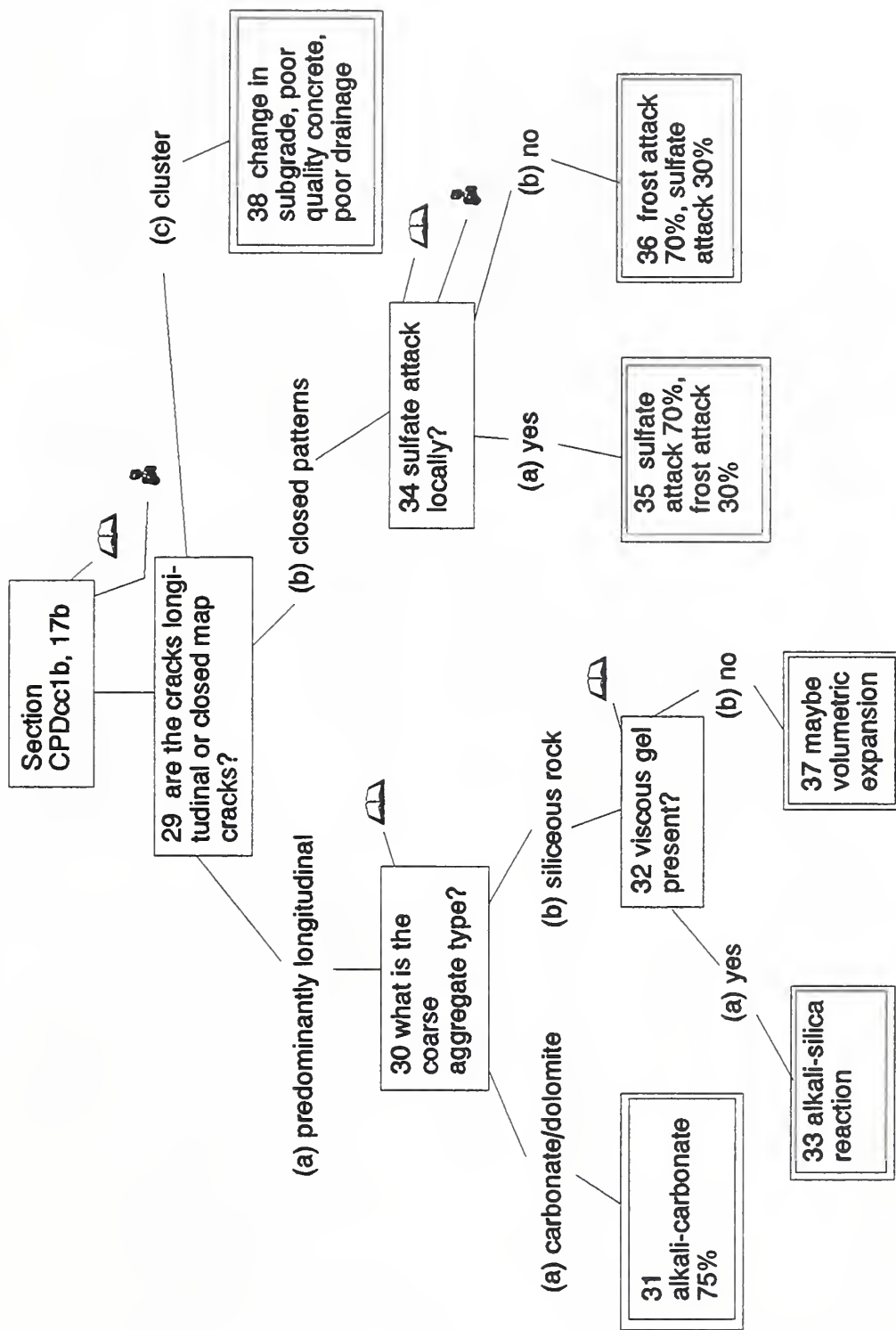


CONPAVD Knowledge 3.0 - CRCP Cracks - Section CC1A - 3/30/93

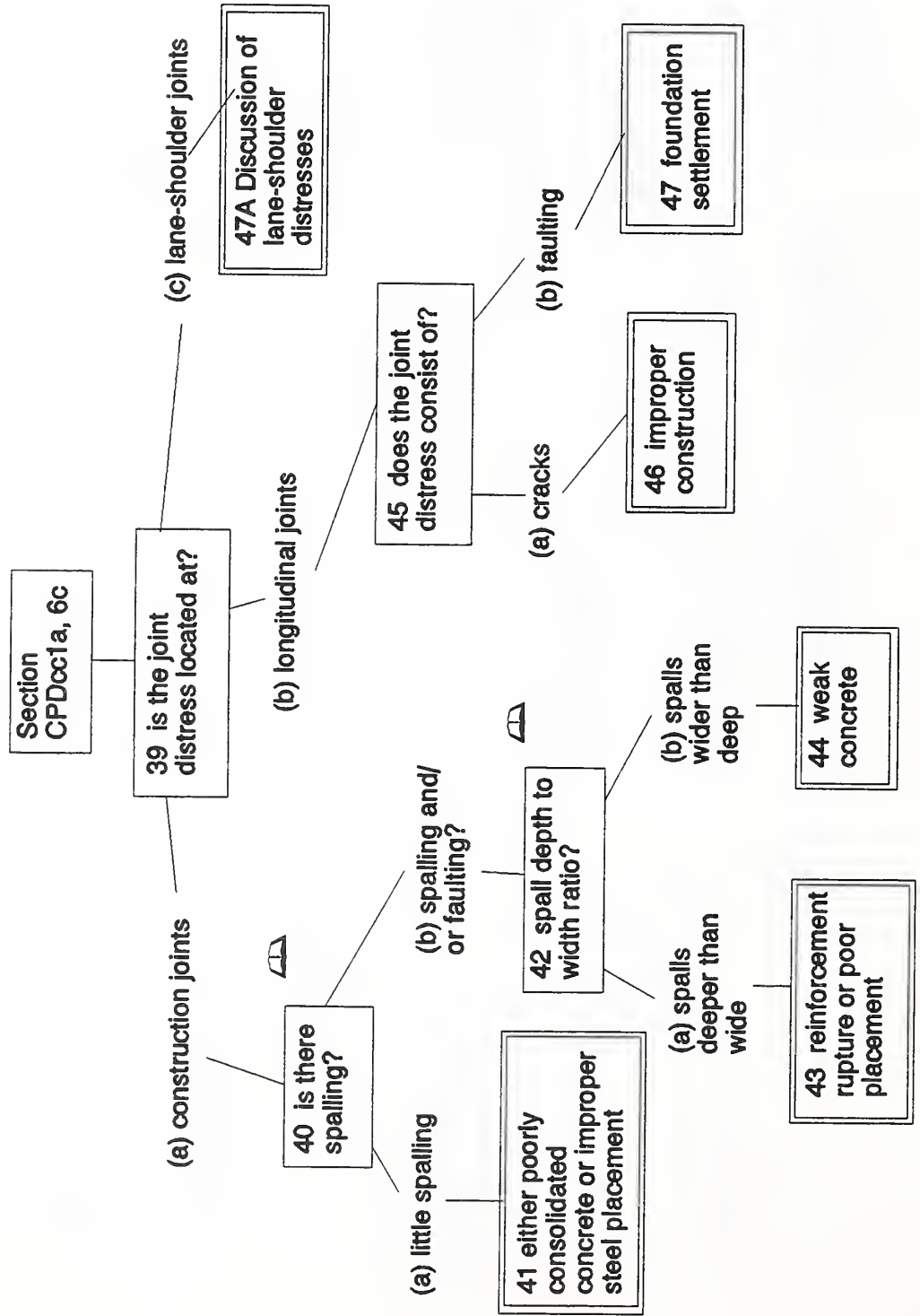


CONPAVD Knowledge 3.0 - CRCP Cracks - Section CC1B - 3/30/93

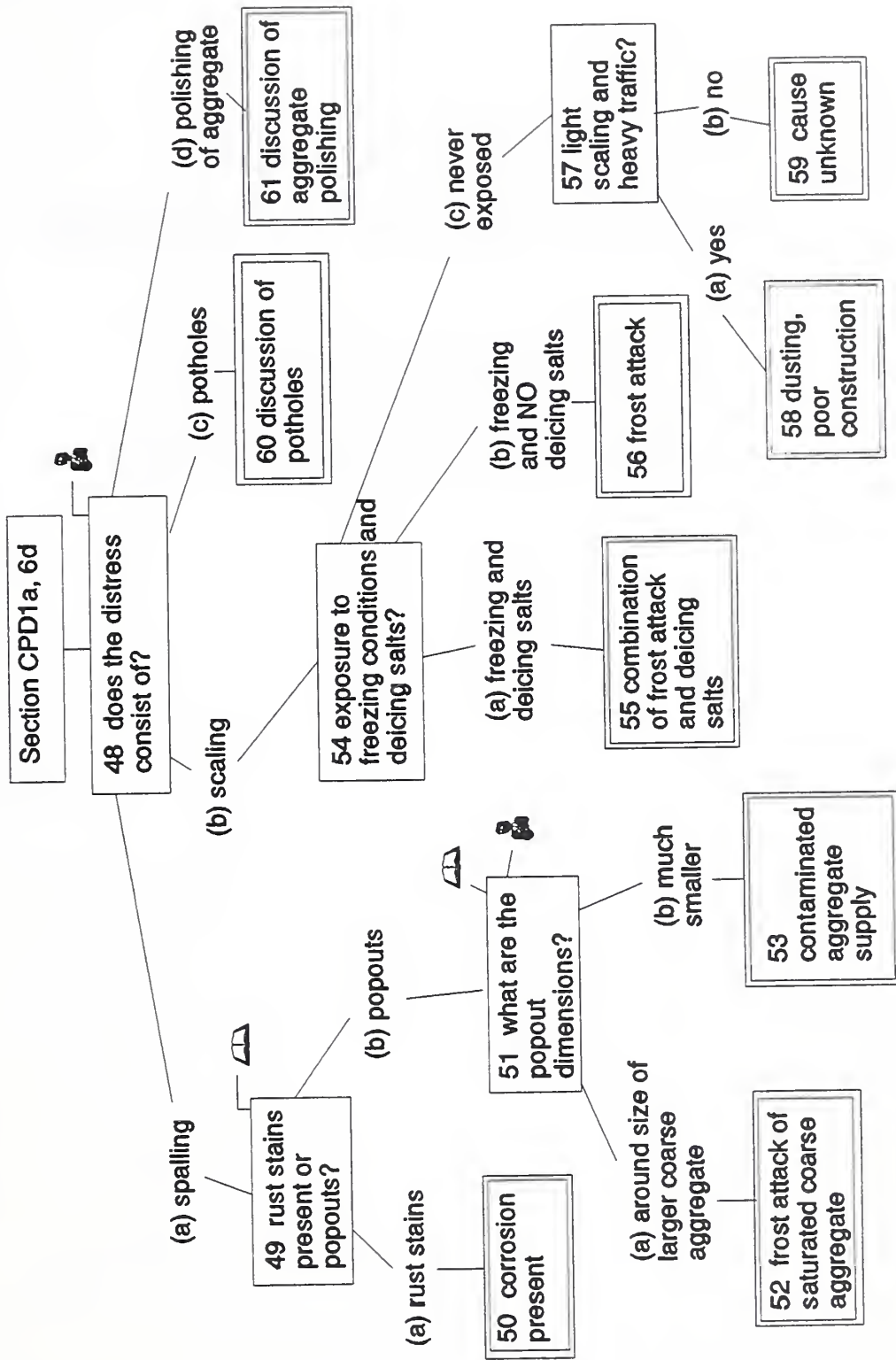




CONPAVD Knowledge 3.0 - CRCP Joint Distresses - Section CJ1A - 3/30/93





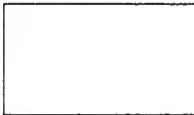
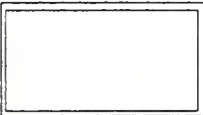




# APPENDIX A: KNOWLEDGE TREES

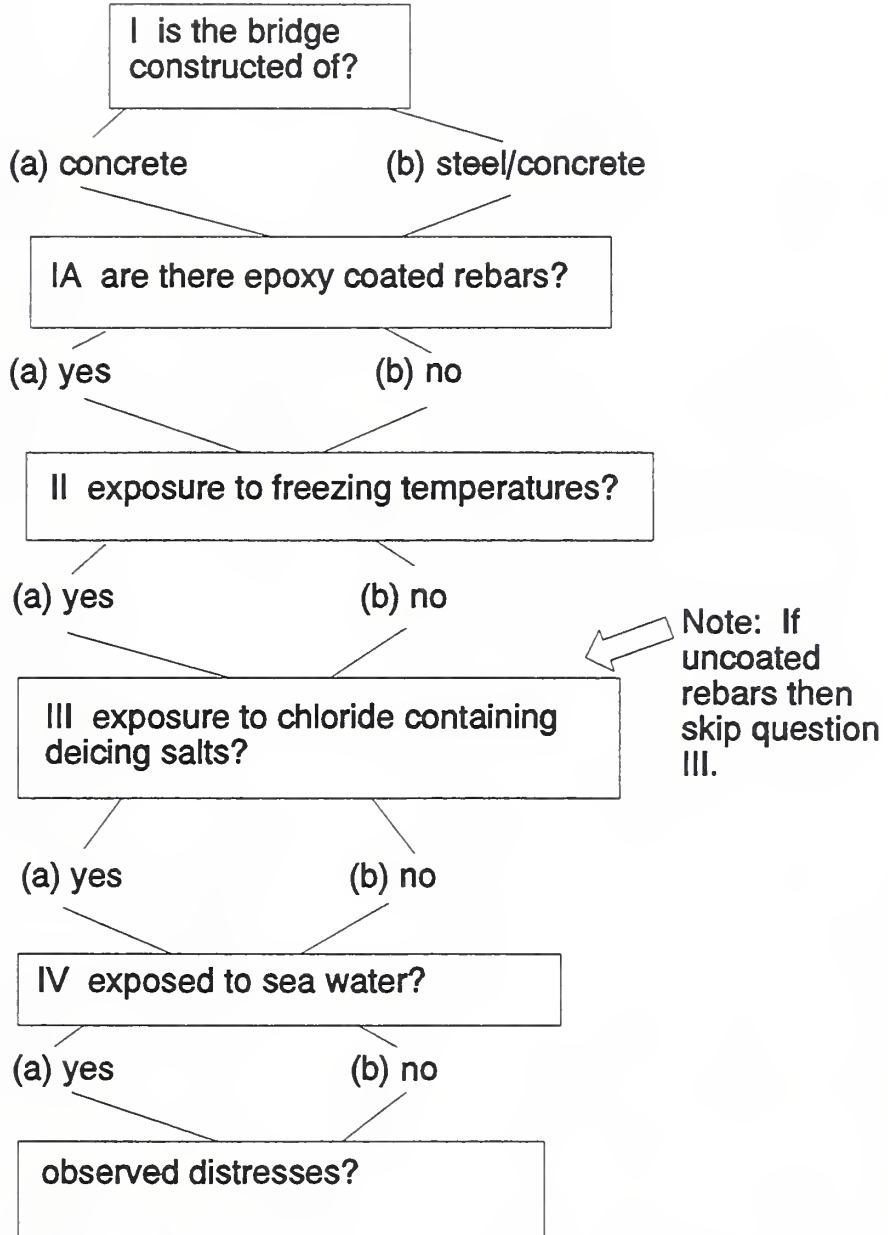
## CONSTRUC-D (BRIDGE DECKS)

### Legend:

Picture or Drawing	=	PIC
alpha/numeric references (e.g. 2A)	=	reference to narrative text
explanatory information	=	EXP
operator response(s)	=	(a) _____
question box	=	
conclusion or recommendation box	=	

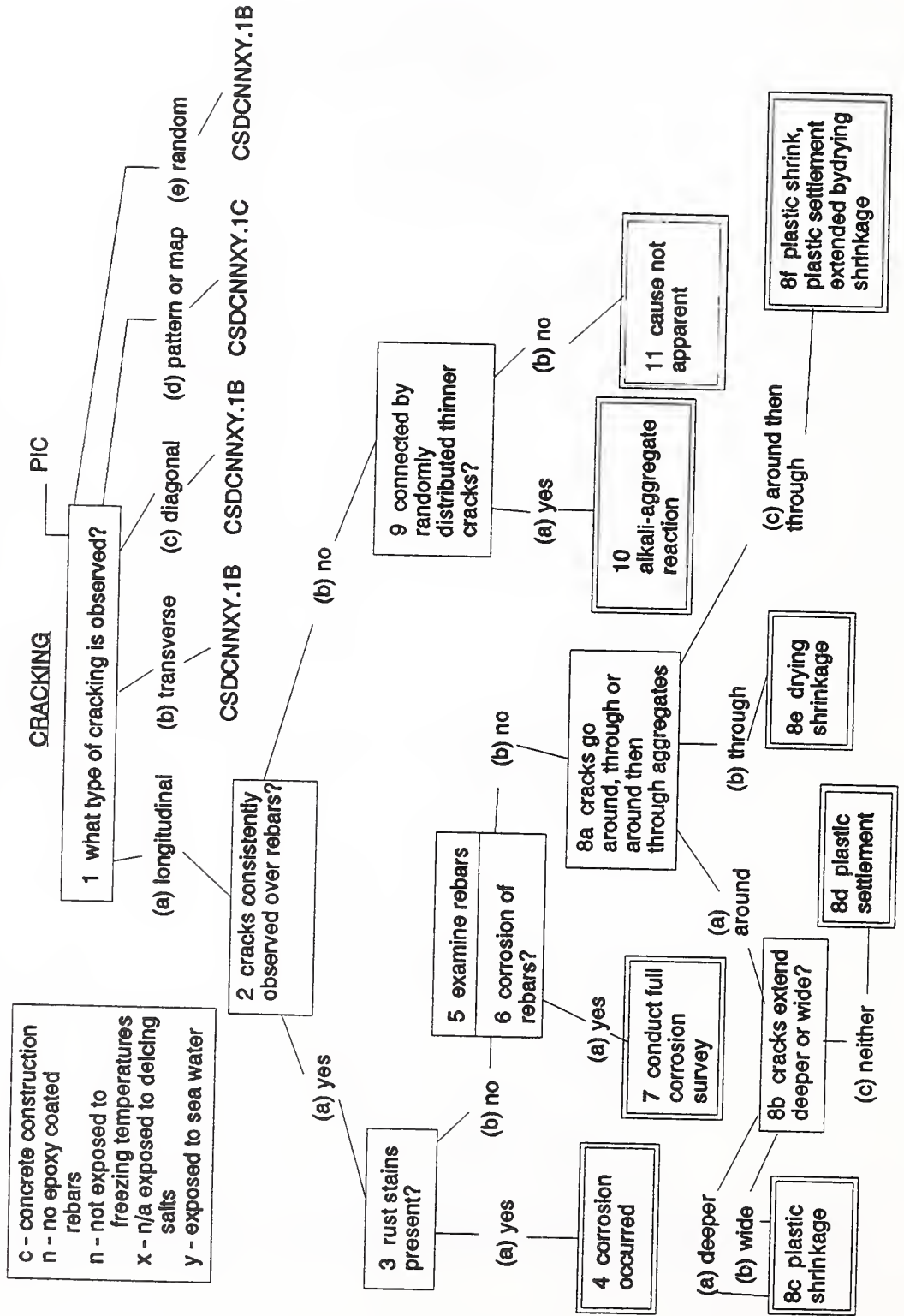


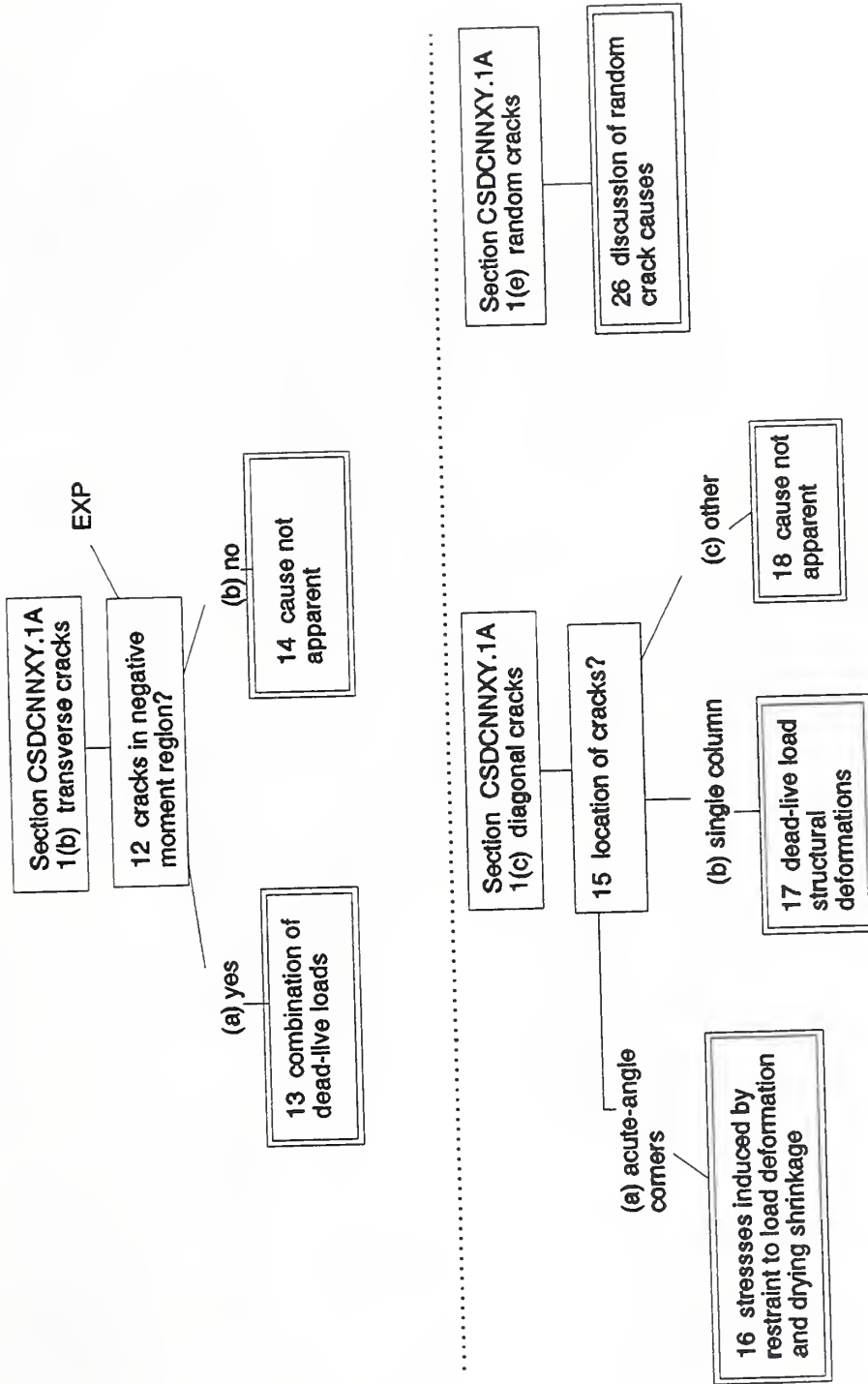
CONSTRUC-D  
Distresses in Bridge Decks  
Ver. 3.0 - 3/30/93



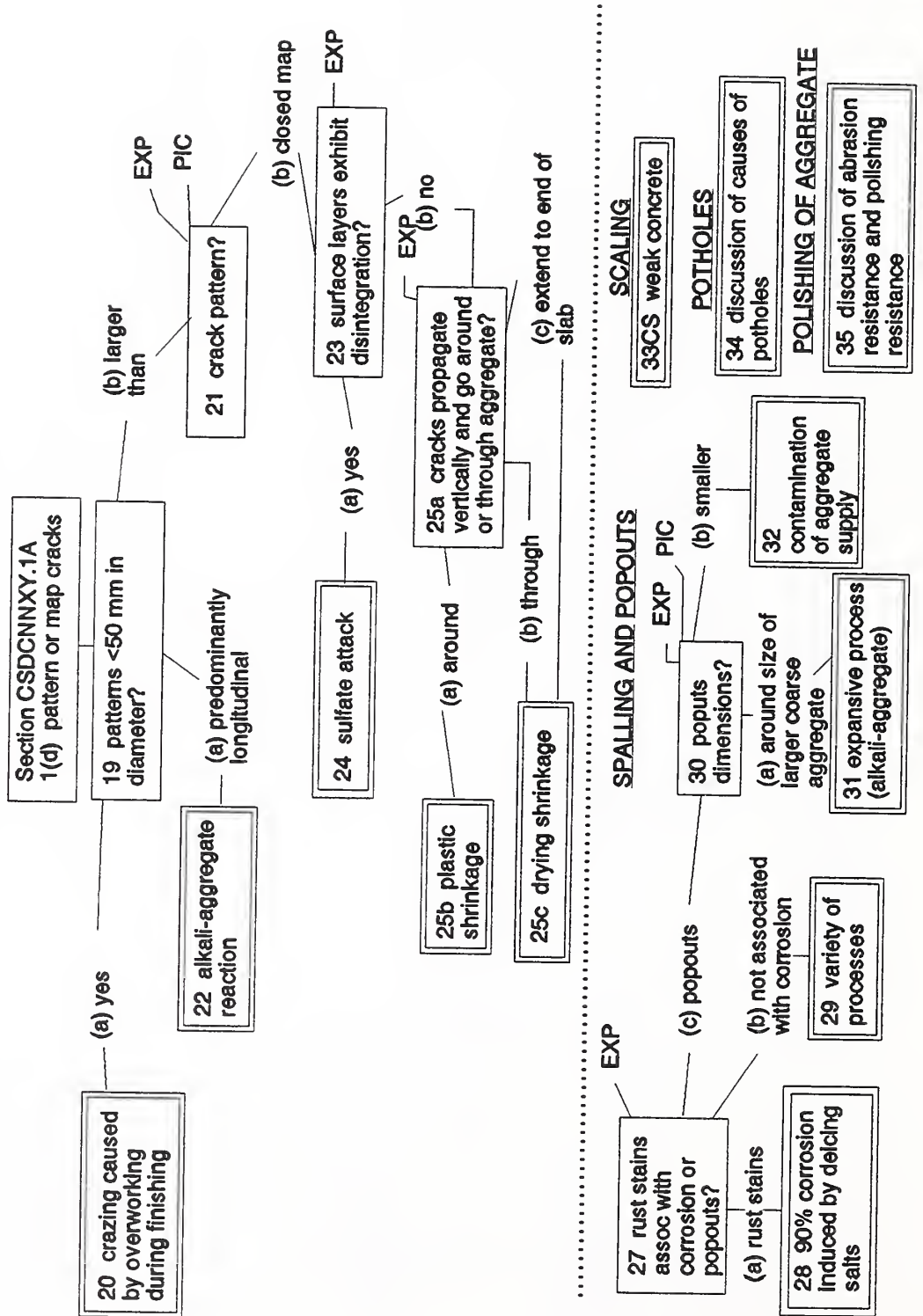
(a) cracking (b) scaling (c) spalling/popouts (d) potholes (e) polishing of aggregate

CONSTRUCD 3.0 Program: CSDC>NNXY - Section CSDC>NNXY.1A - 3/30/93



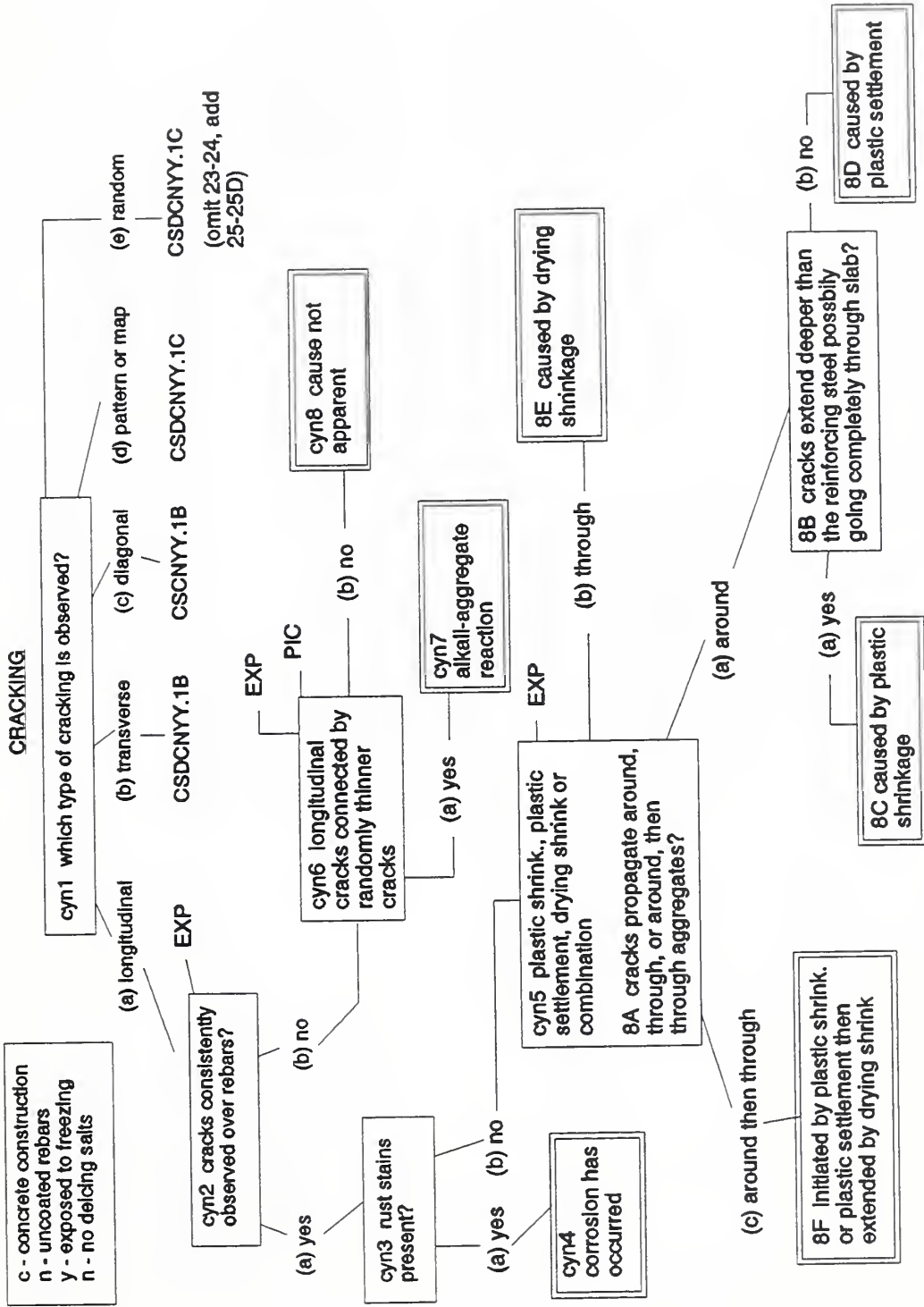


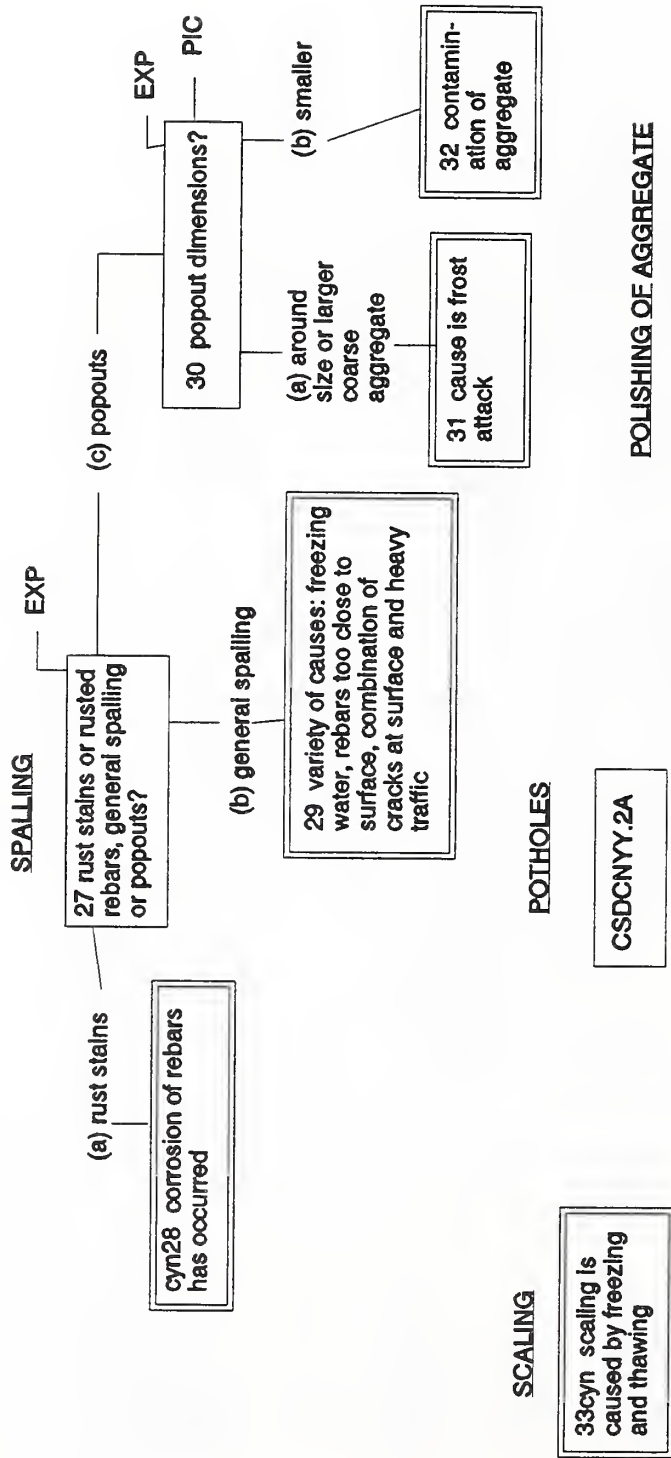
CONSTRUCD 3.0 - Program: CSDCANNXY - Section CSDCANNXY.1C - 3/30/93

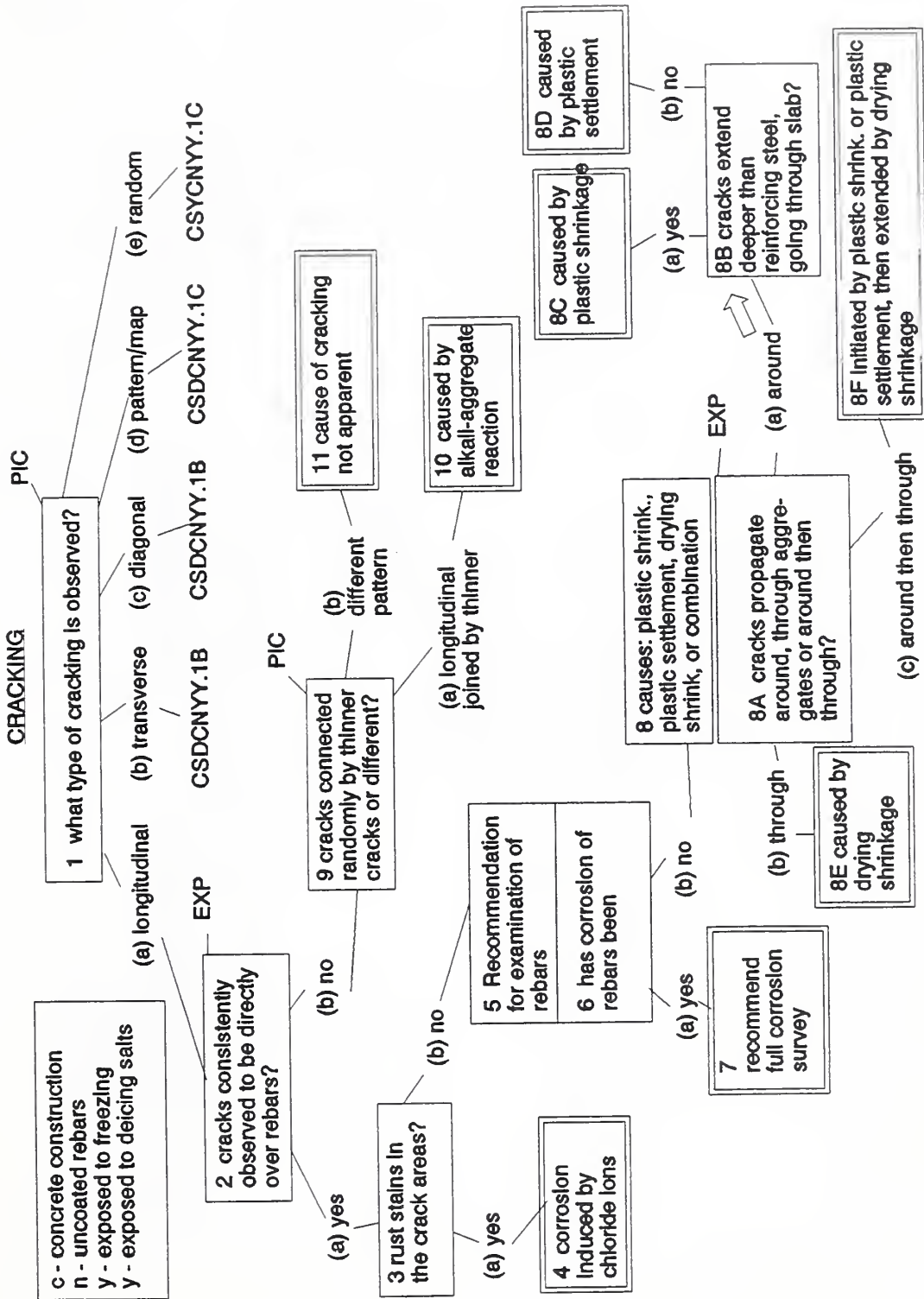




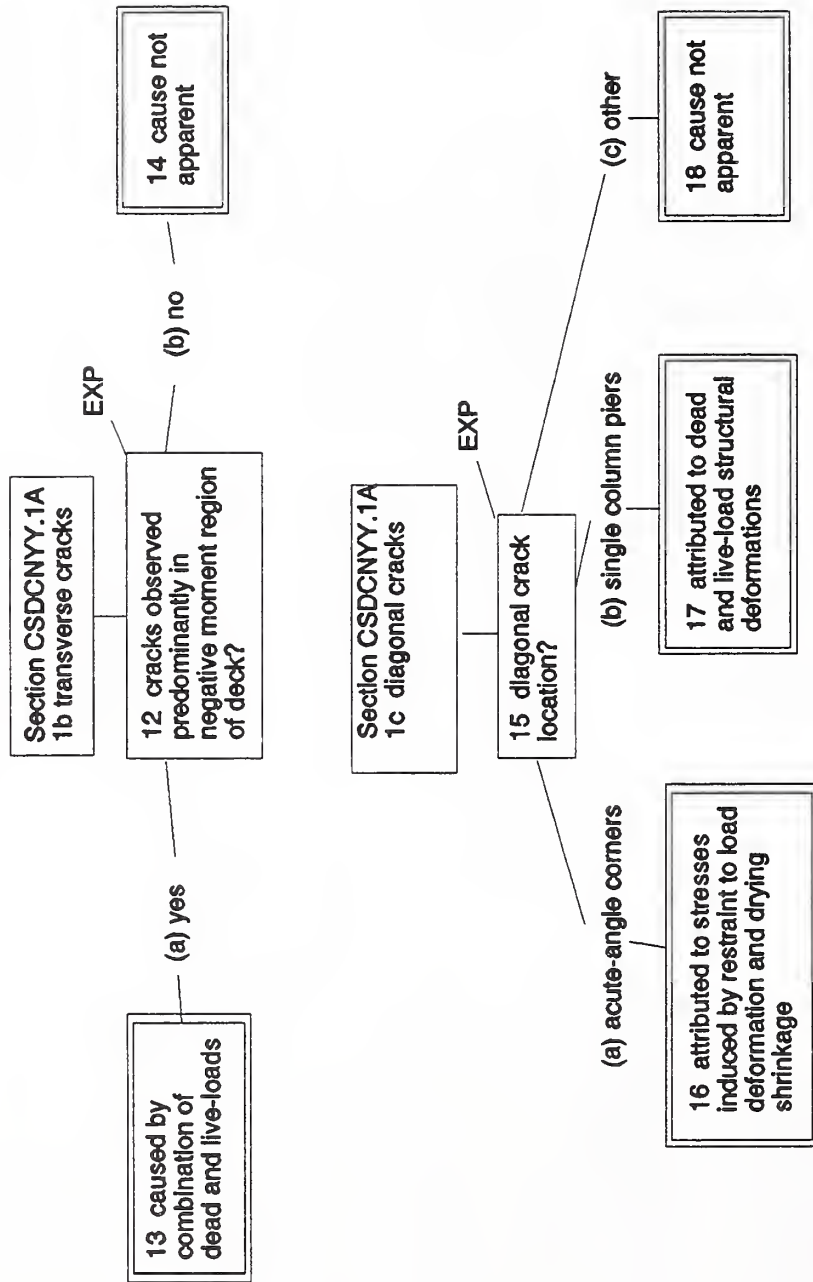
CONSTRUUCD 3.0 - Program: CSDCNYN - Section CSDCNYN.1A - 3/30/93



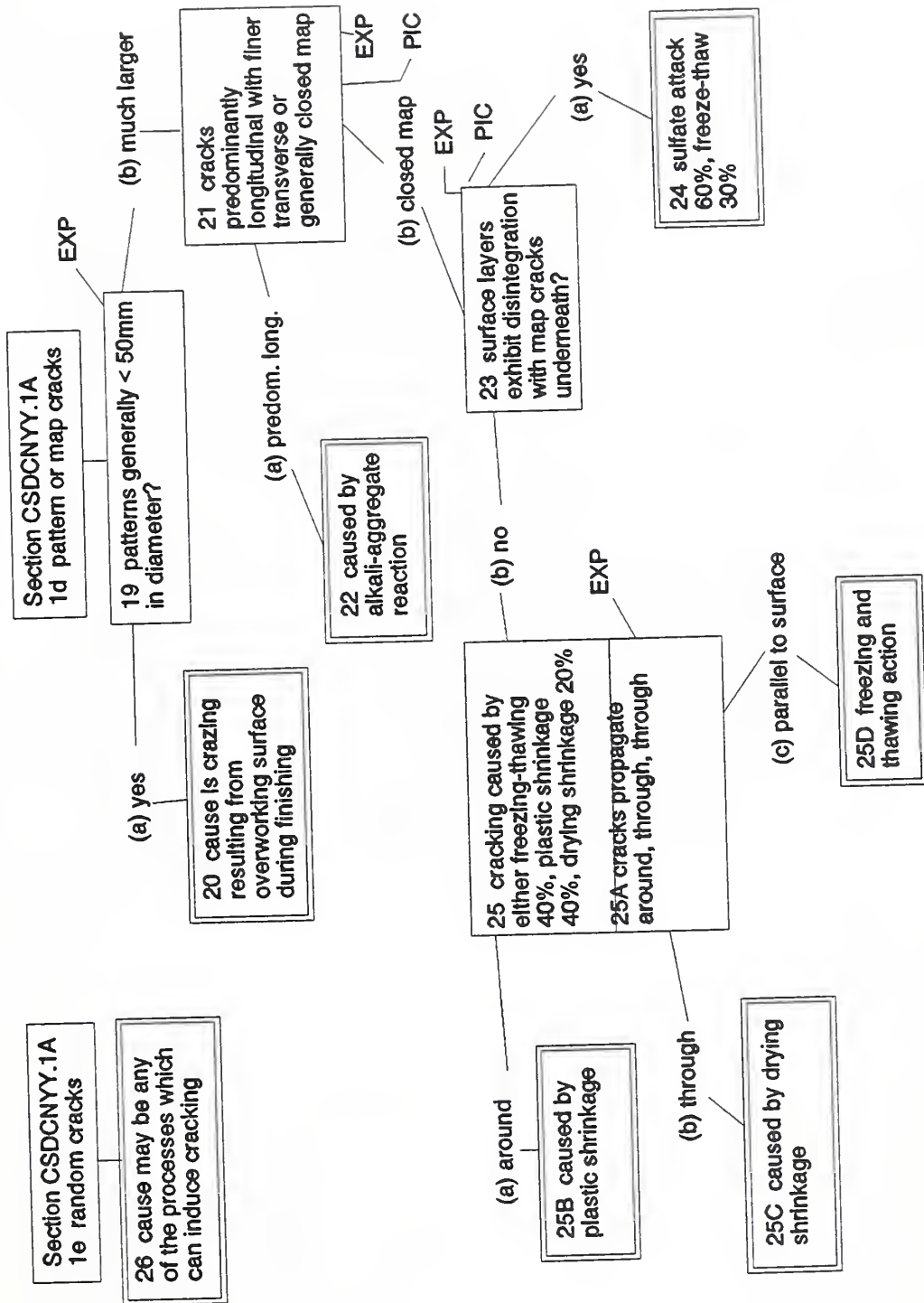


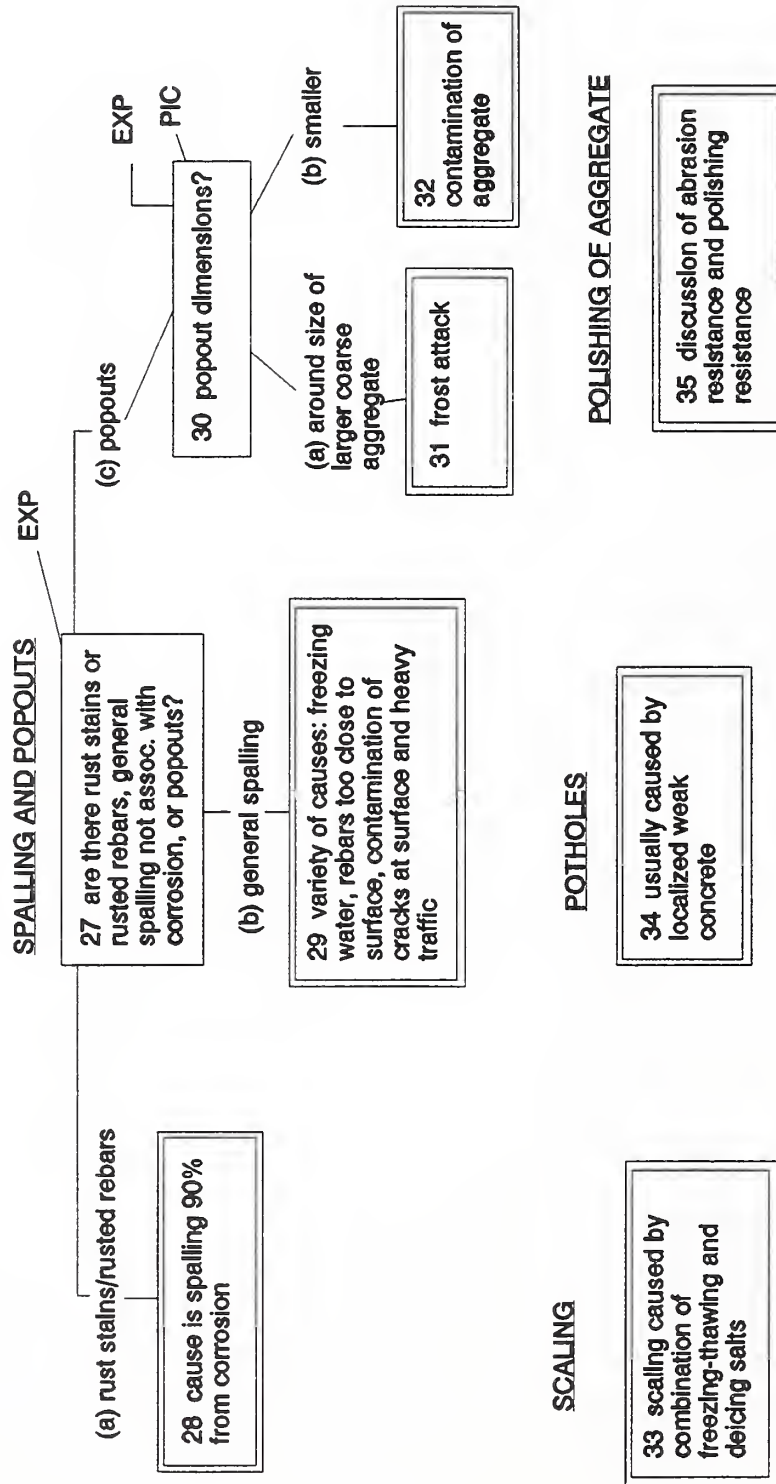


CONSTRUCD 3.0 Program: CSDCNYY - Section CSDCNYY.1B - 3/30/93

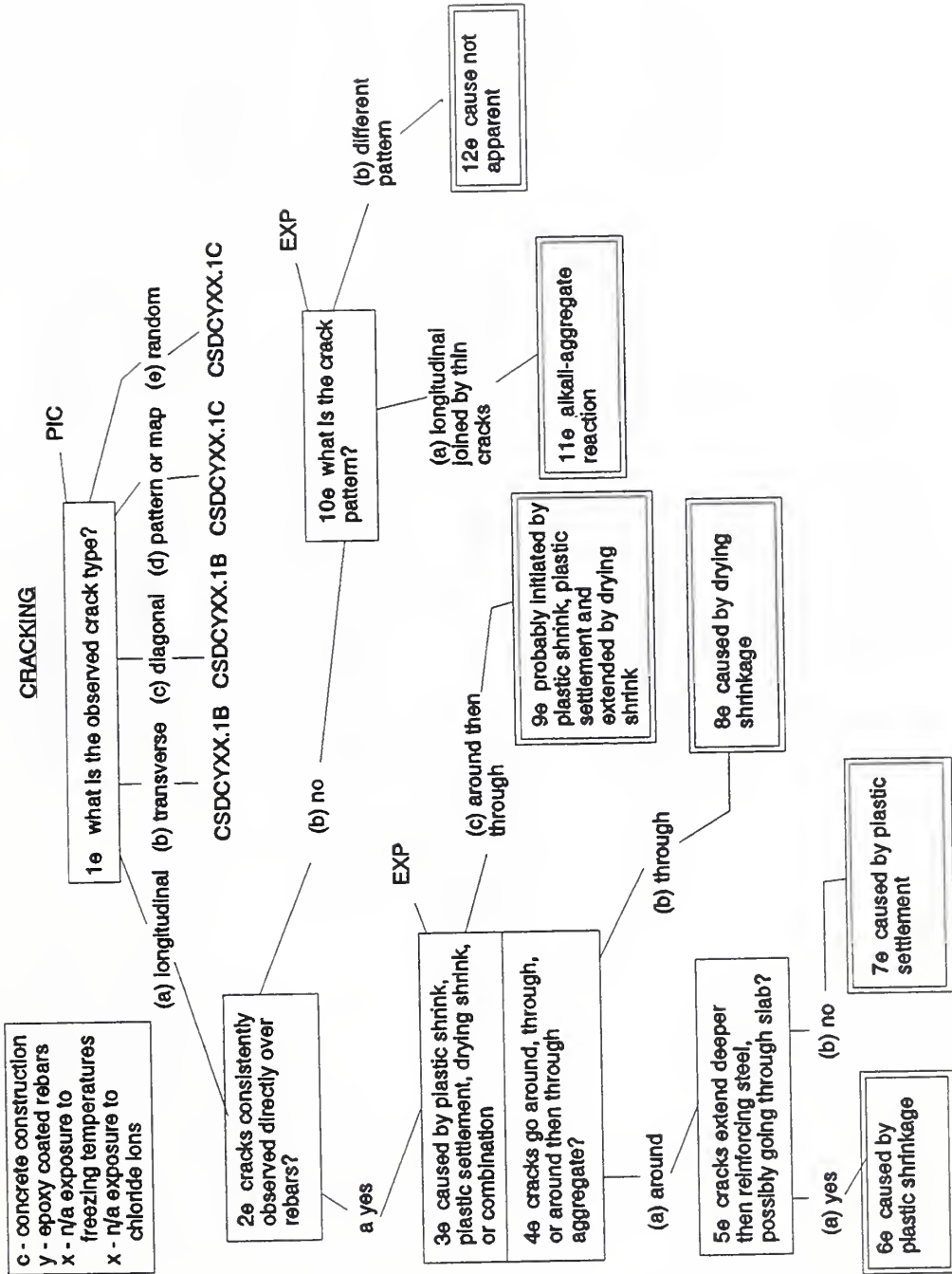


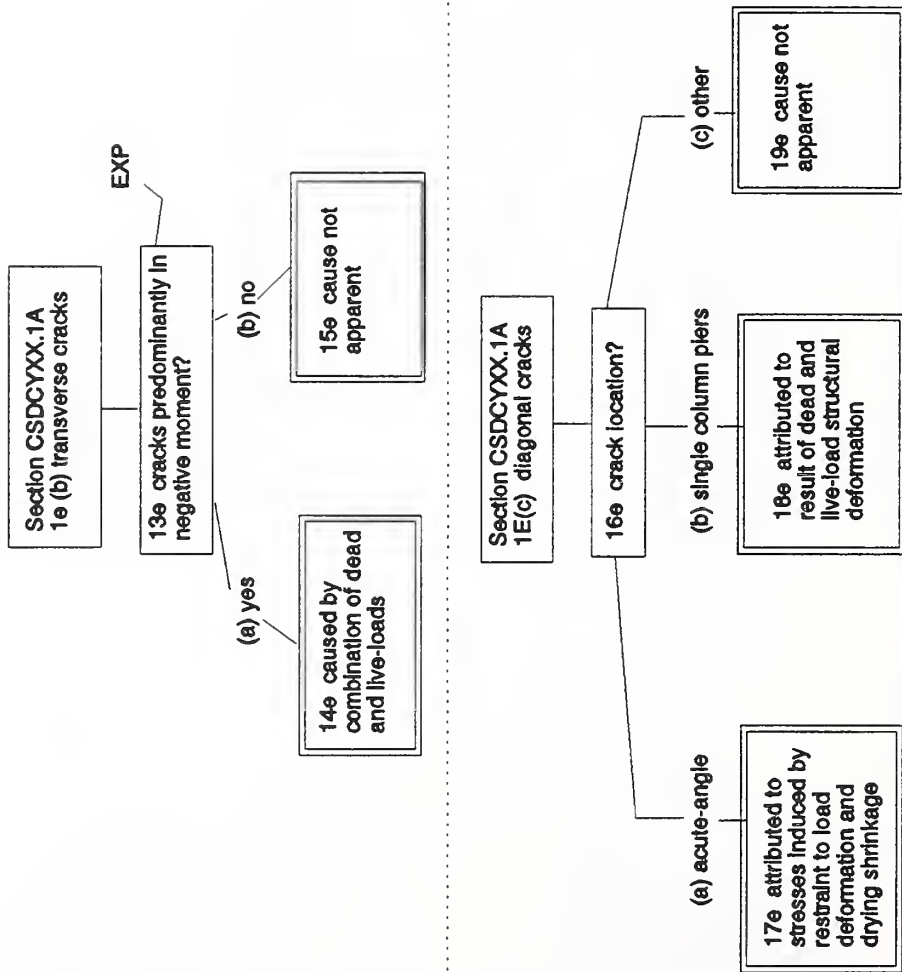
CONSTRUCD 3.0 Program: CSDCNY - Section CSDCNY.1C - 3/30/93





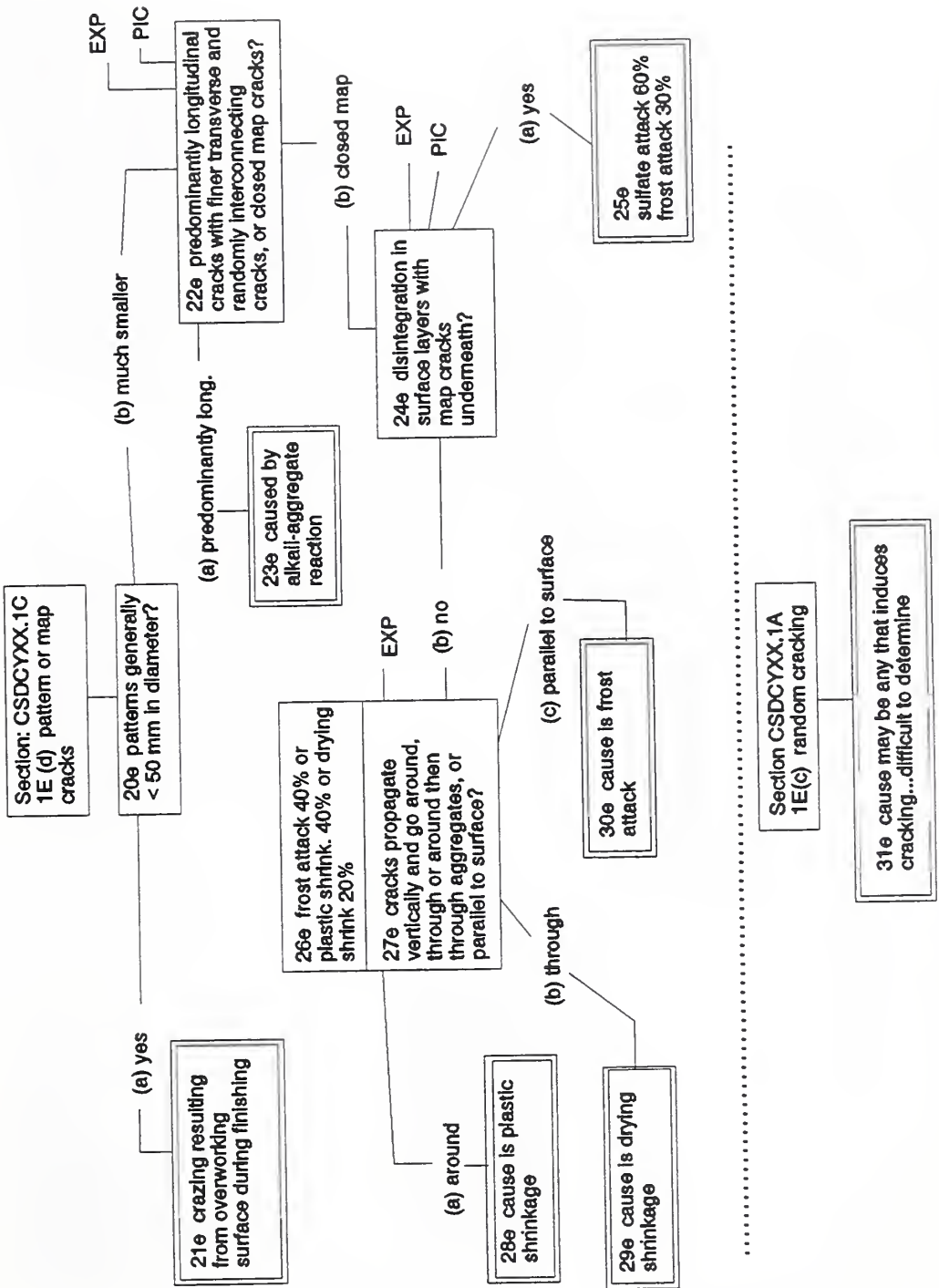
CONSTRUCD 3.0 Program: CSDCYXX - Section CSDCYXX.1A - 3/30/93



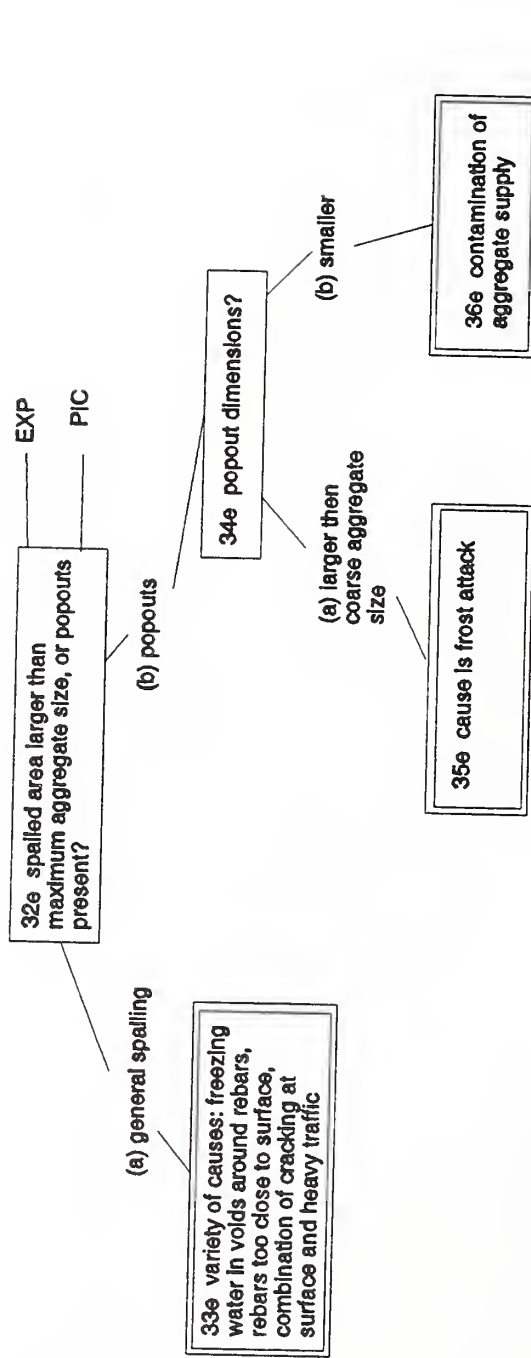




CONSTRUCD 3.0 Program: CSDCYXX - Section CSDCYXX.1C - 3/30/93



**SPALLING AND POPOUTS**



**SCALING**

37e caused by combination of frost attack and delcing salts

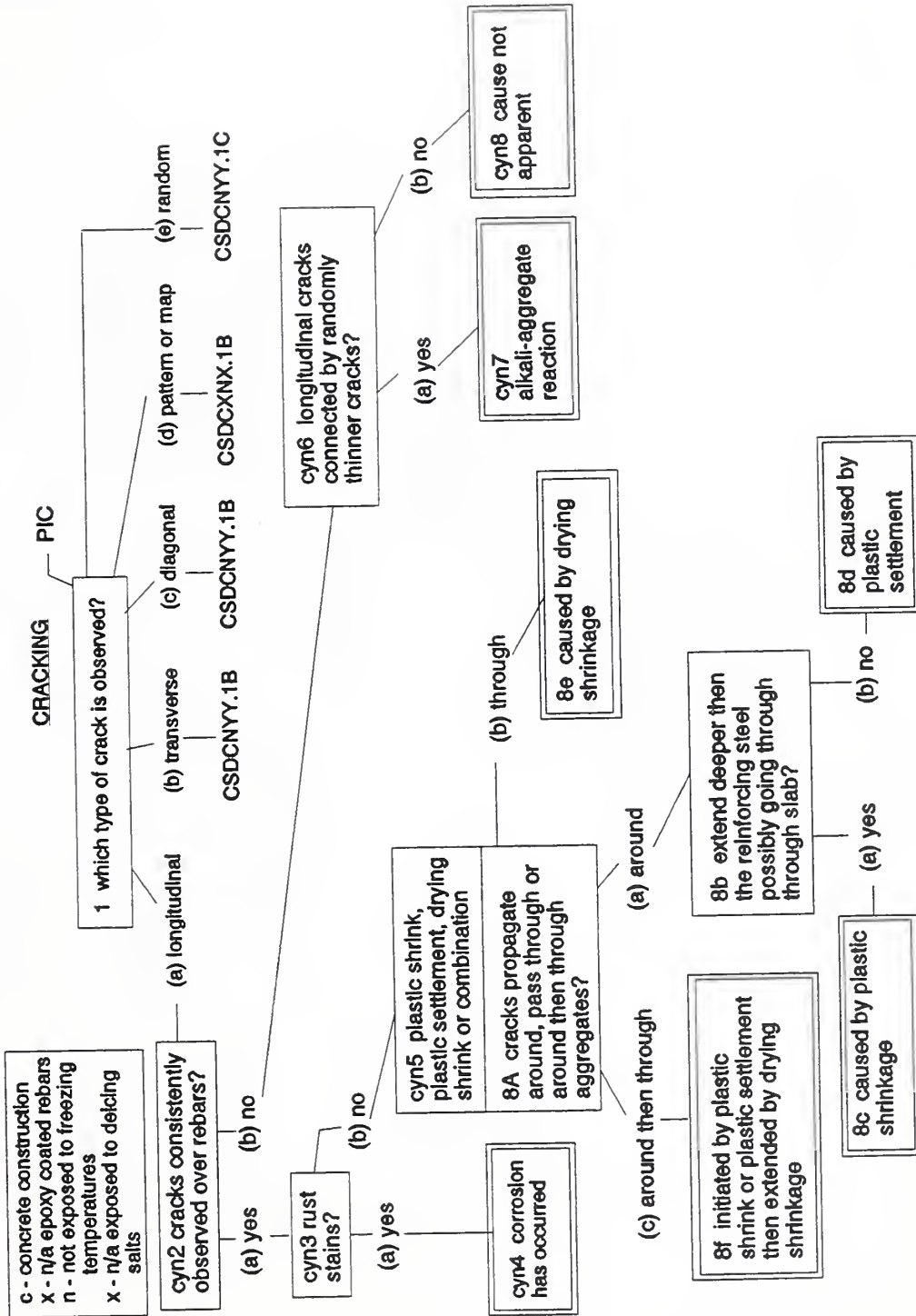
**POTHOLES**

39e discussion of causes of potholes

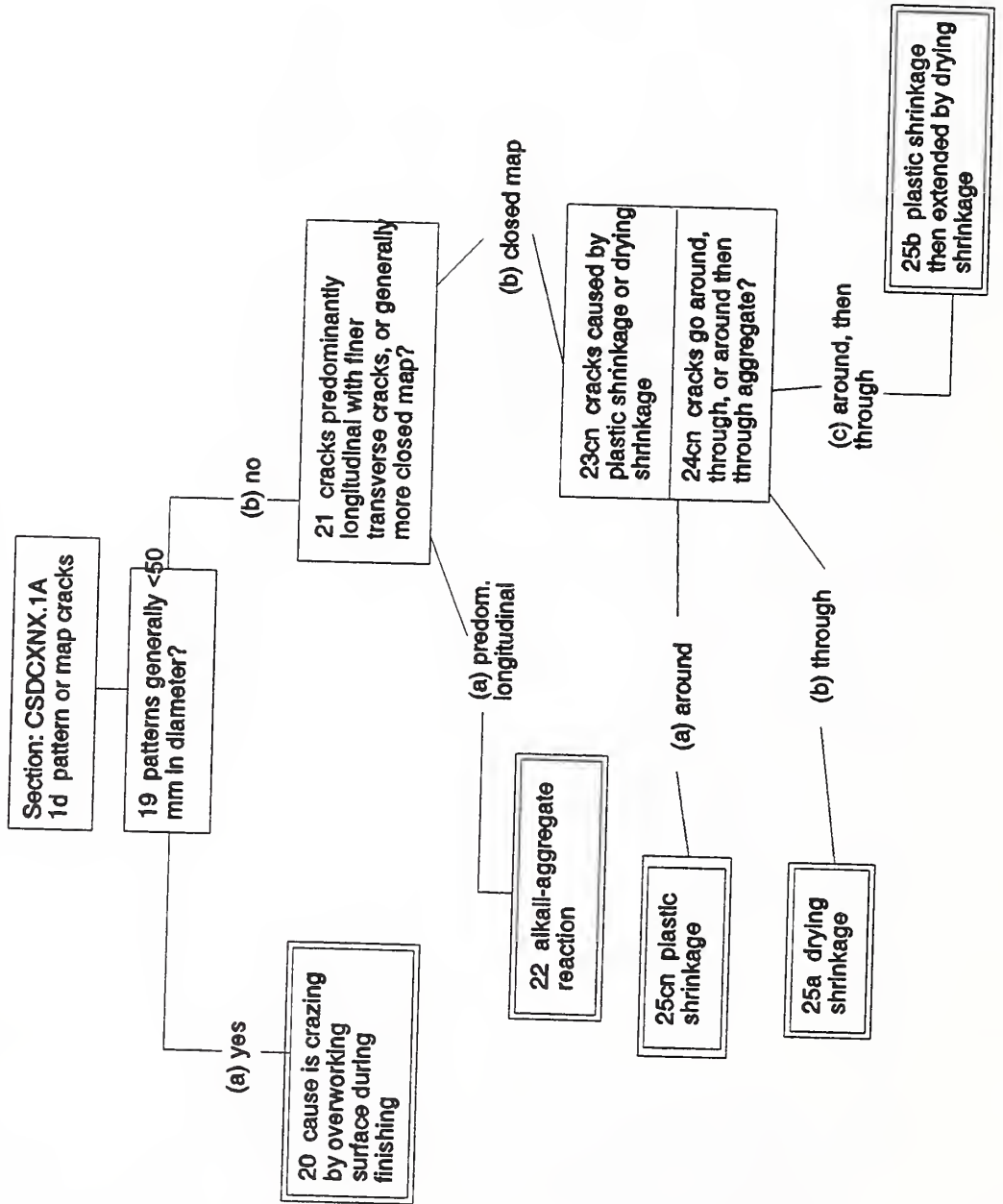
**POLISHING OF AGGREGATES**

39e discussion of abrasion resistance and polishing resistance

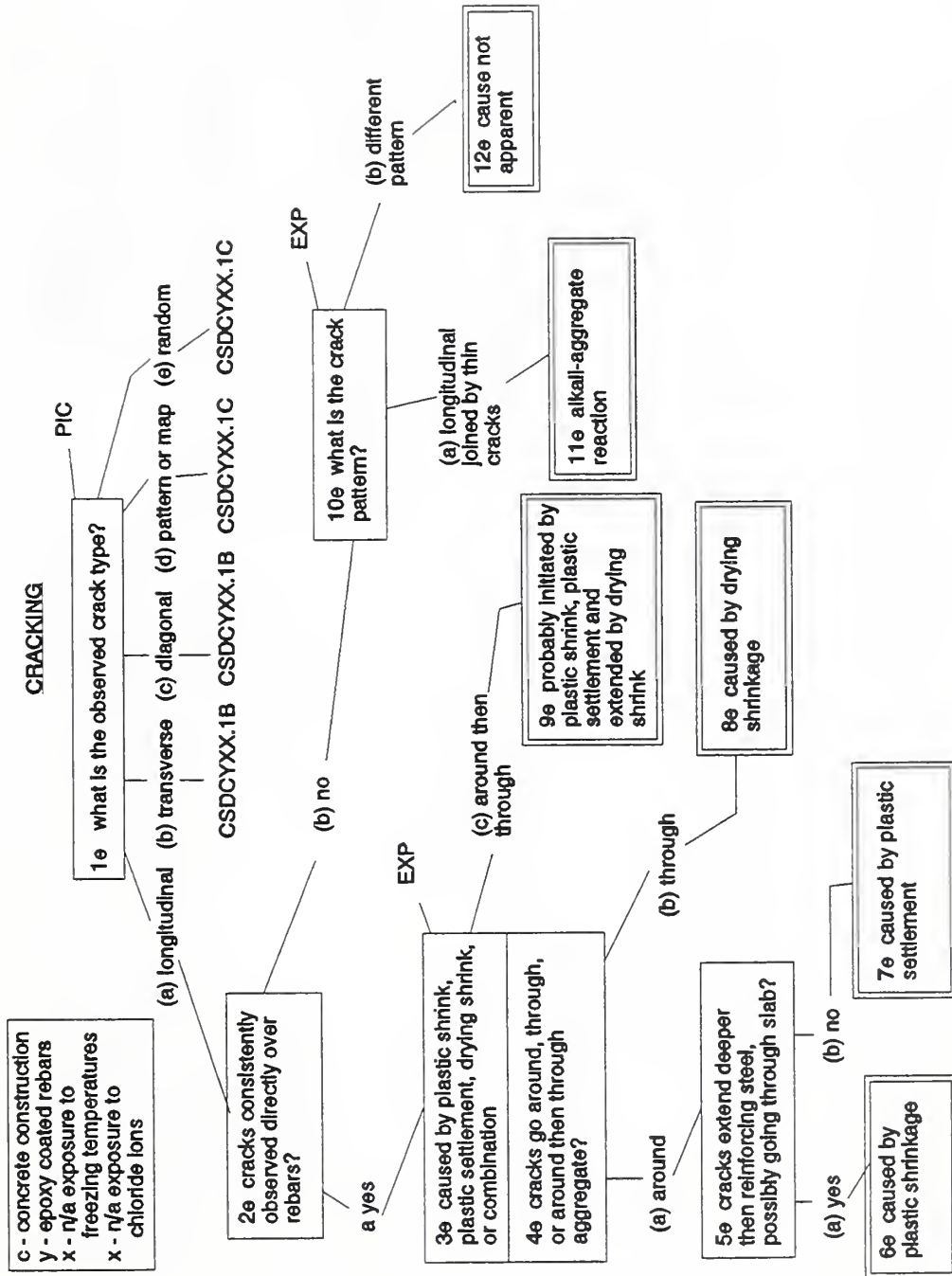
CONSTRUCD 3.0 Program: CSDCXNX - Section CSDCXNX.1A - 3/30/93



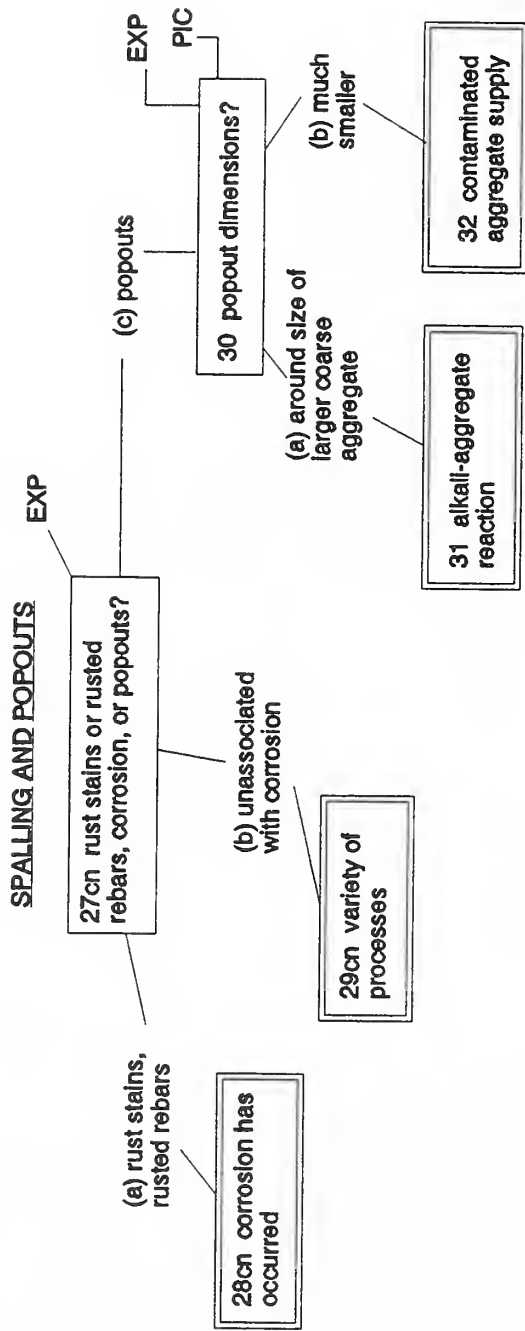
CONSTRUCD 3.0 Program: CSDCXNX - Section CSDCXNX.1B - 3/30/93



CONSTRUCD 3.0 Program: CSDCYXX - Section CSDCYXX.1A - 3/30/93



CONSTRUCD 3.0 Program: CSDCXNX - Section CSDCXNX.1C - 3/30/93



.....

**SCALING**

33cn weak concrete

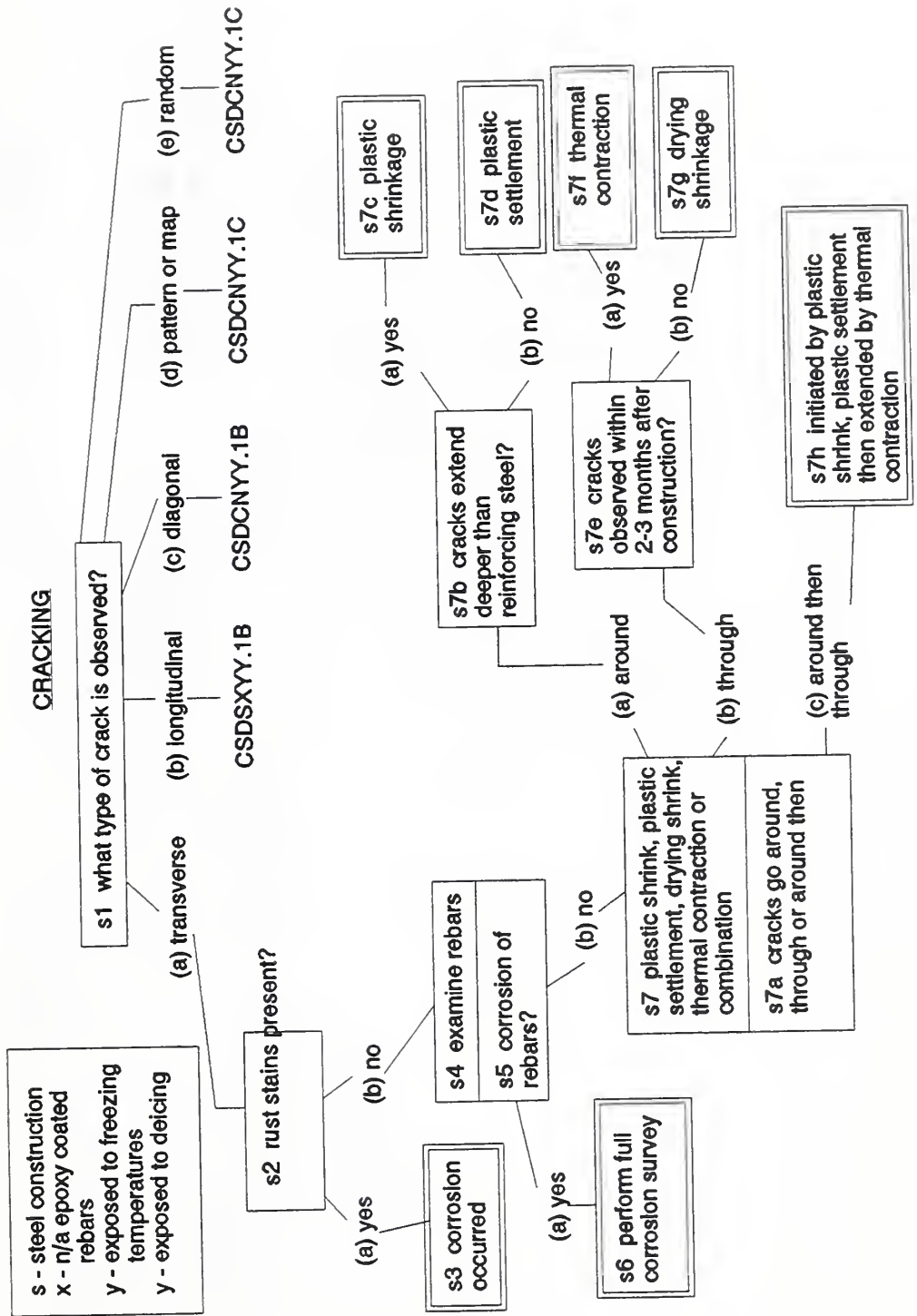
**POTHOLES**

34 discussion of potholes

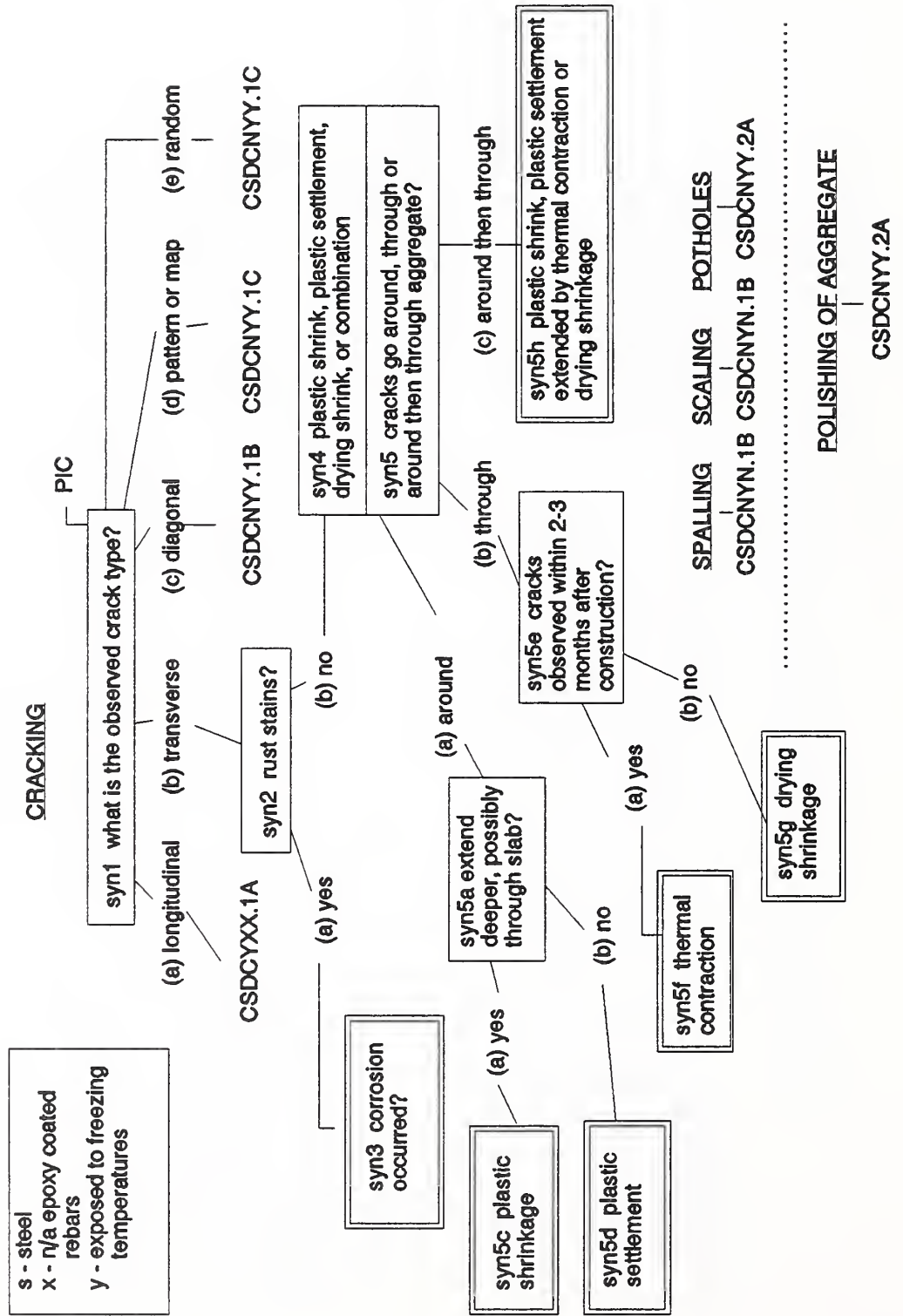
**POLISHING OF AGGREGATE**

35 discussion of abrasion resistance and polishing resistance

CONSTRUCD 3.0 Program: CSDSXY - Section CSDSXY.1A - 3/30/93

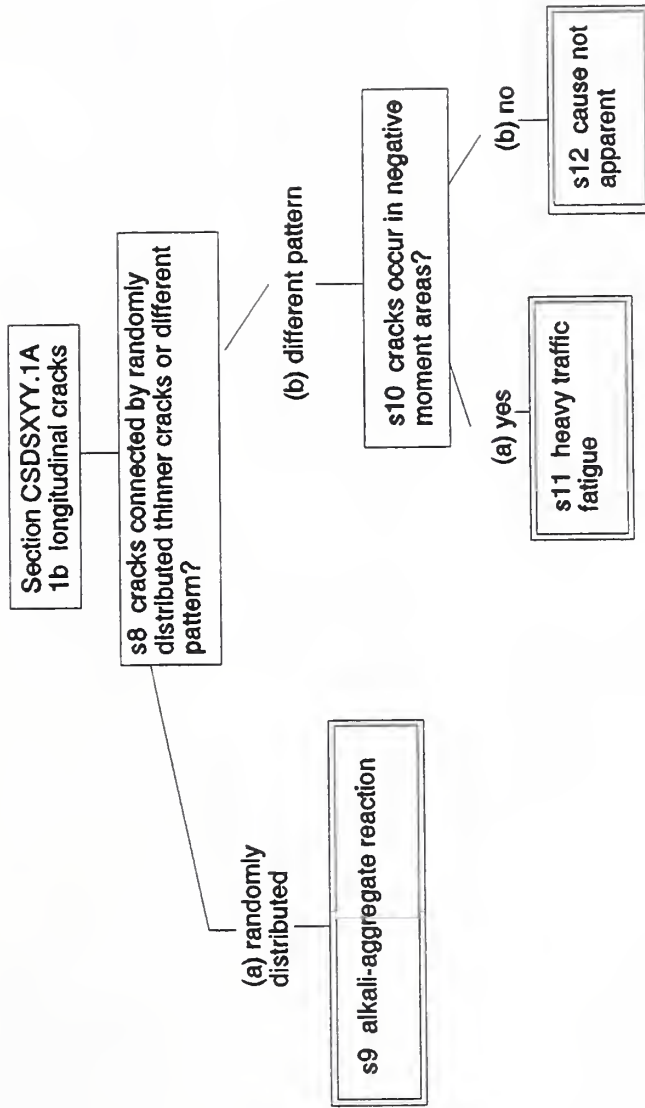


CONSTRUCD 3.0 Program: CSDSXYN - Section CSDSXYN.1A - 3/30/93





CONSTRUCD 3.0 Program: CSDSXYY - Section CSDSXYY.1B - 3/30/93



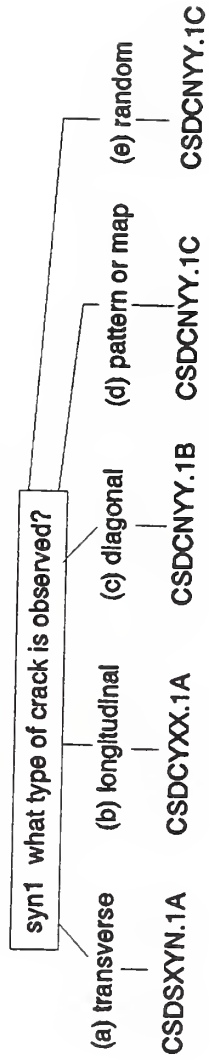
.....

SPALLING AND POPOUTS	SCALING	POTHOLES	POLISHING OF AGGREGATE
CSDCNYY.2A	CSDCNYY.2A	CSDCNYY.2A	CSDCNYY.2A

CONSTRUCD 3.0 Program: CSDSXNX - Section CSDSXNX.1A - 3/30/93

s - steel construction  
 x - n/a epoxy coated  
   rebars  
 n - not exposed to freezing  
   temperatures  
 x - n/a exposed to deicing  
   salts

CRACKING



SPALLING OR POPOUTS

CSDCXNX.1C

SCALING

CSDCXNX.1C

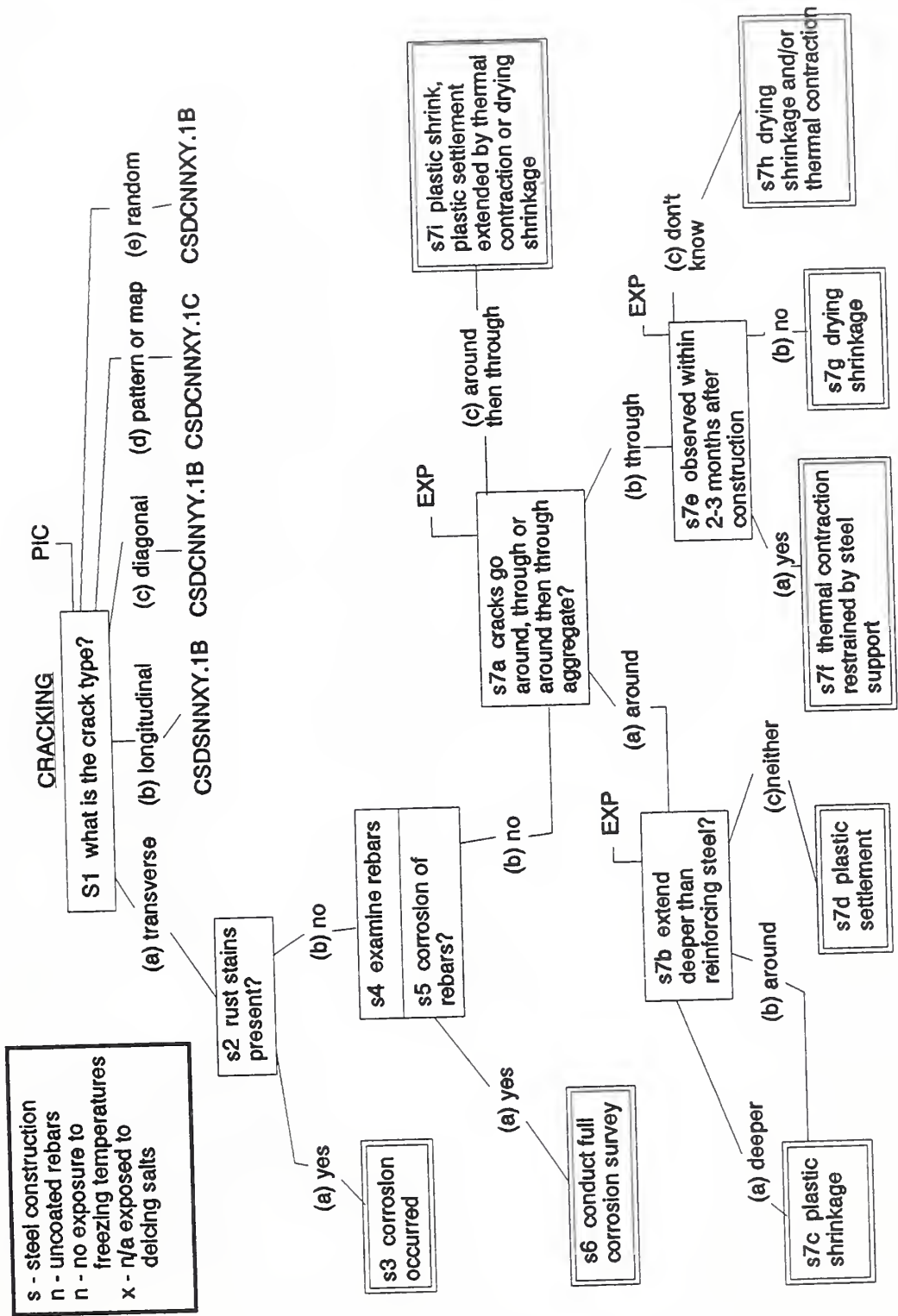
POTHOLES

CSDCXNX.1C

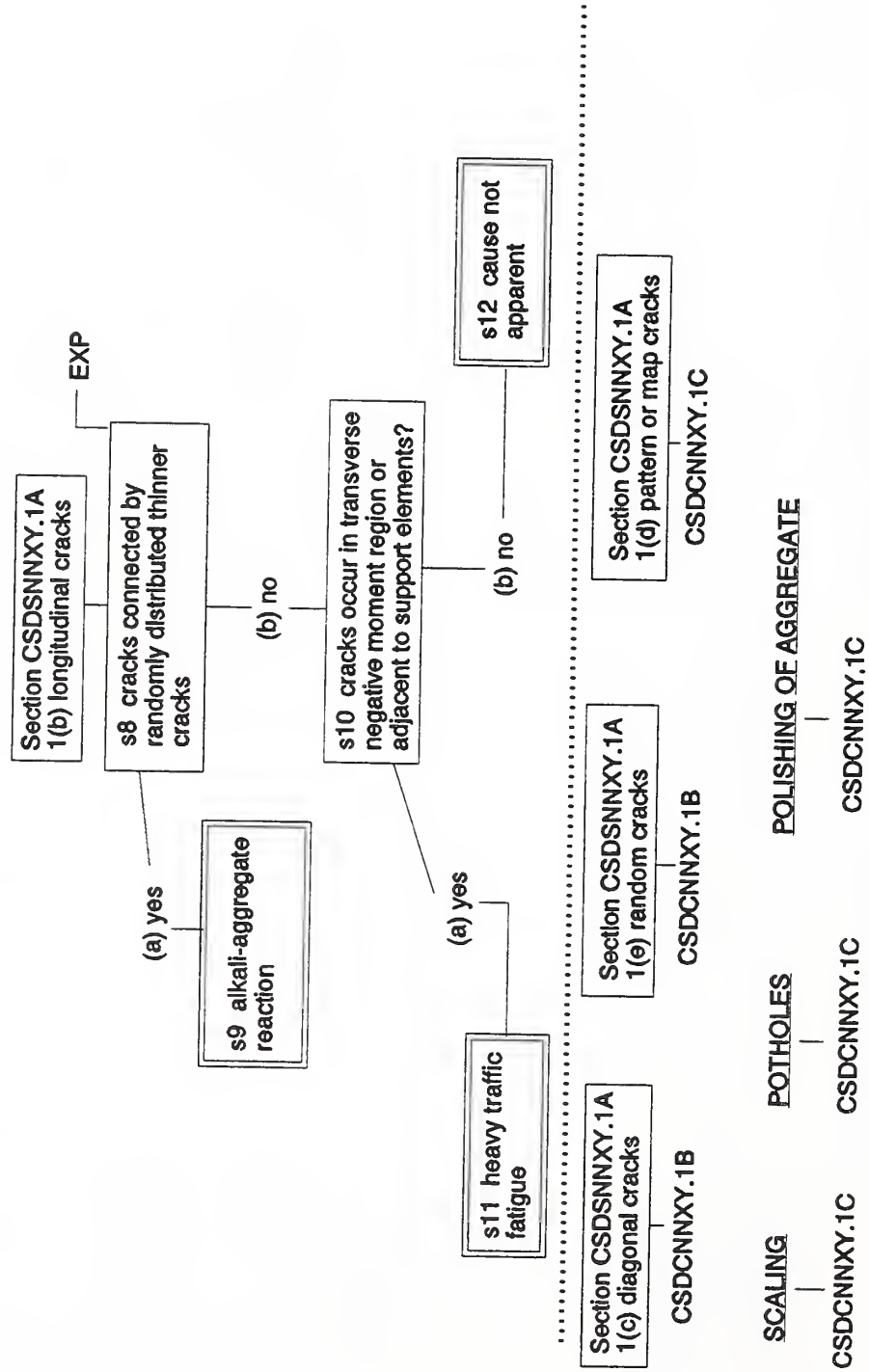
POLISHING OF AGGREGATES

CSDCXNX.1C

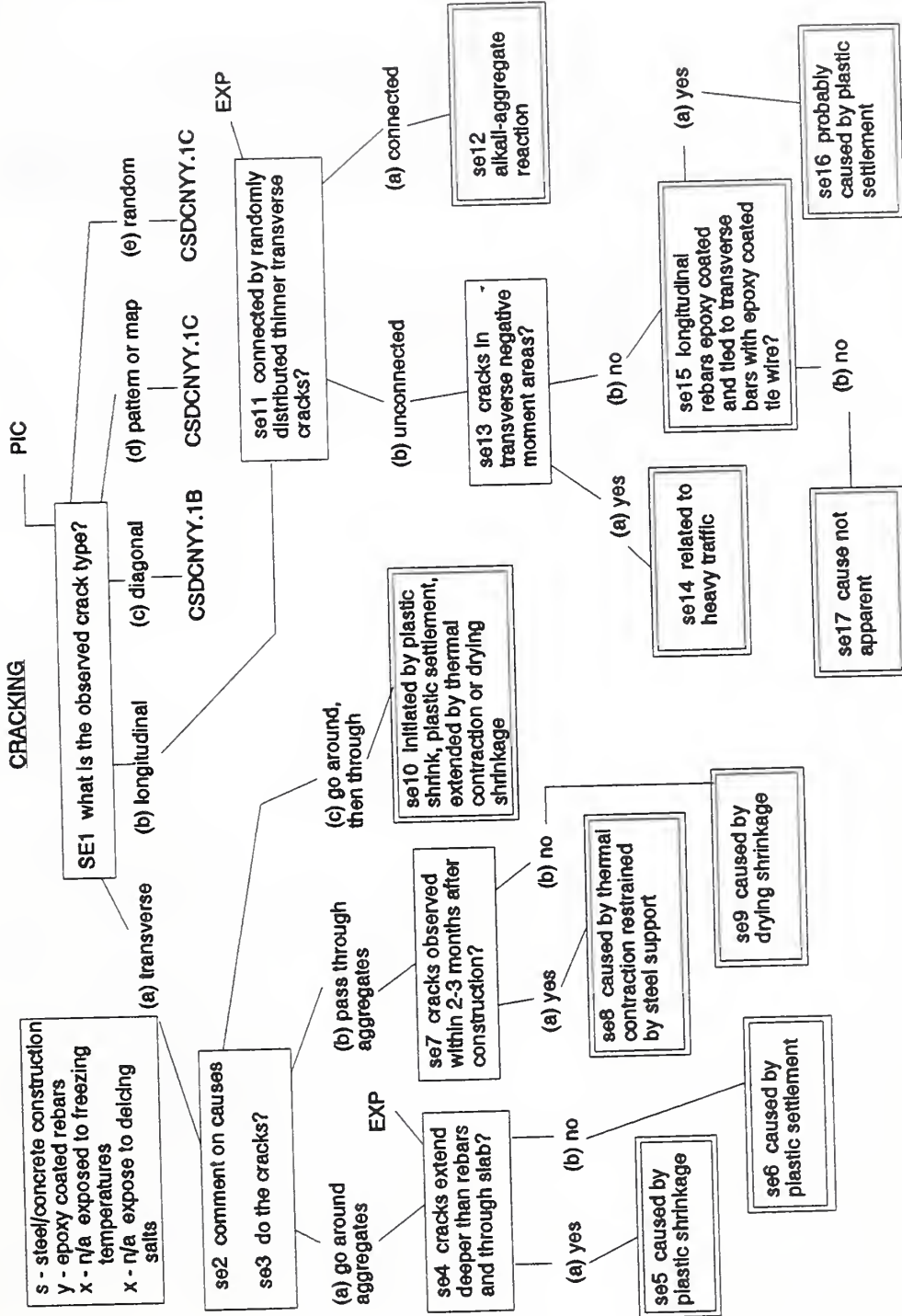
CONSTRUCD 3.0 Program: CSDNXY - Section CSDSNNXY.1A - 3/30/93



CONSTRUCD 3.0 Program: CSDSNXXY - Section CSDSNXXY.1B - 3/30/93



CONSTRUCD 3.0 Program: CSDSYXX - Section CSDSYXX.1A - 3/30/93



**CONSTRUCD 3.0 Program: CSDSYXX - Section CSDSYXX - 3/30/93**

**SPALLING AND POPOUTS**

Section: CSDCNY.2A  
(27)

**SCALING**

CSDCNY.2A (33)

**POTHLES**

CSDCNY.2A (34)



**POLISHING OF AGGREGATE**

CSDCNY.2A (35)

# APPENDIX A: KNOWLEDGE TREES

## CONSTRUC-D (STRUCTURES)

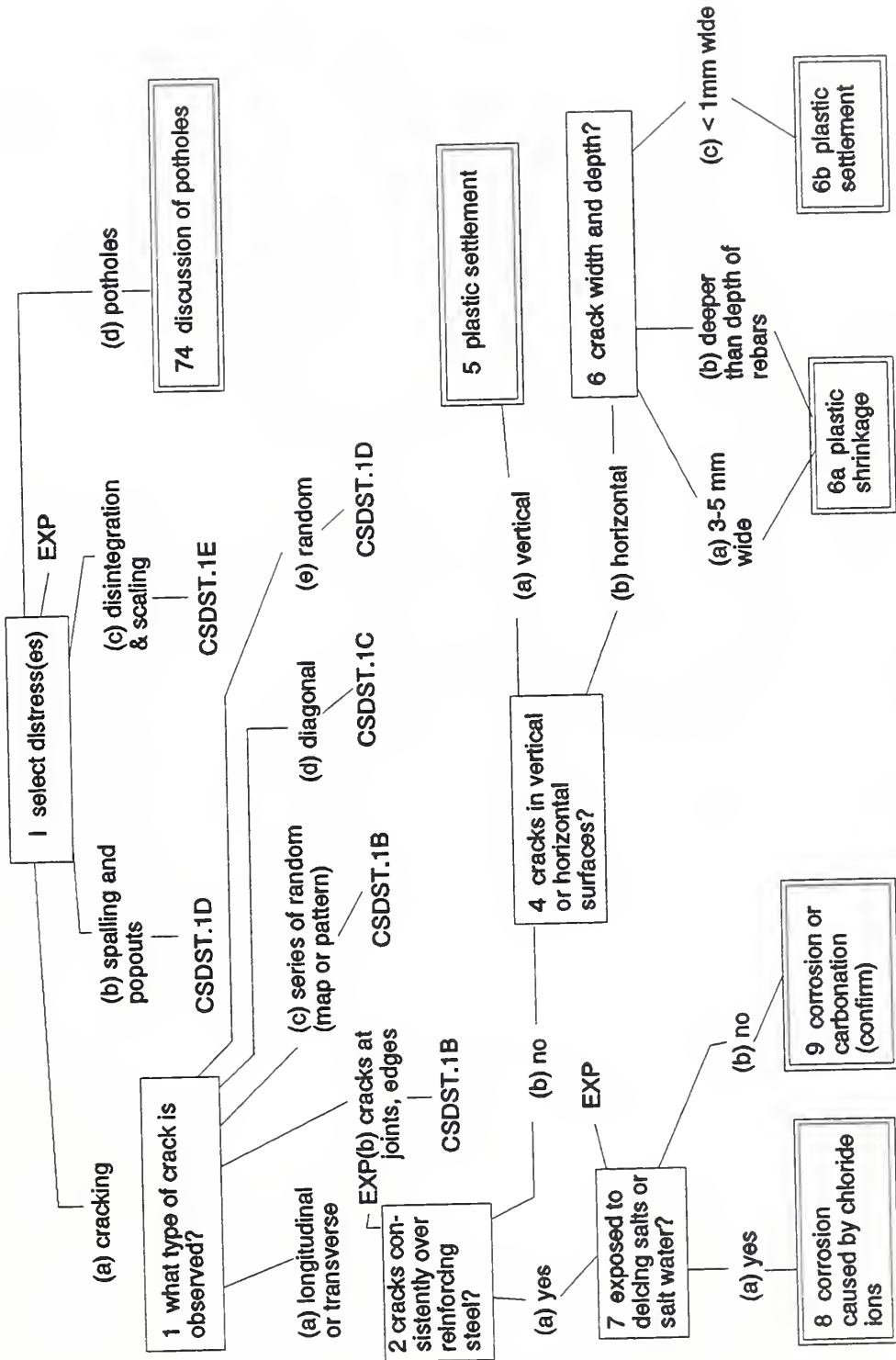
### Legend:

Picture or Drawing	=	PIC
alpha/numeric references (e.g. 2A)	=	reference to narrative text
explanatory information	=	EXP
operator response(s)	=	(a) _____
question box	=	
conclusion or recommendation box	=	



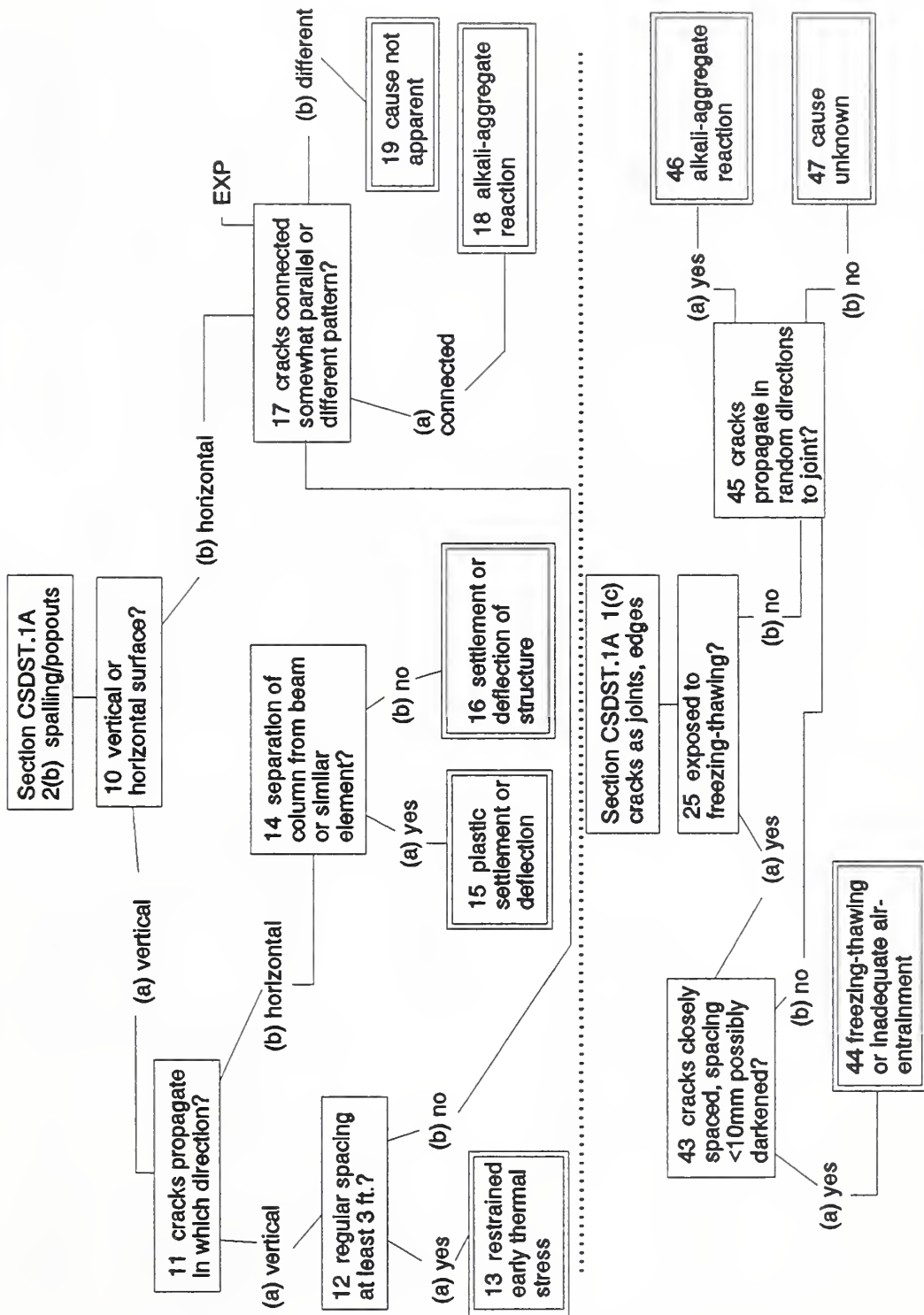


CONSTRUCD 3.0 Program: CSDST - Section CSDST.1A - 3/30/93

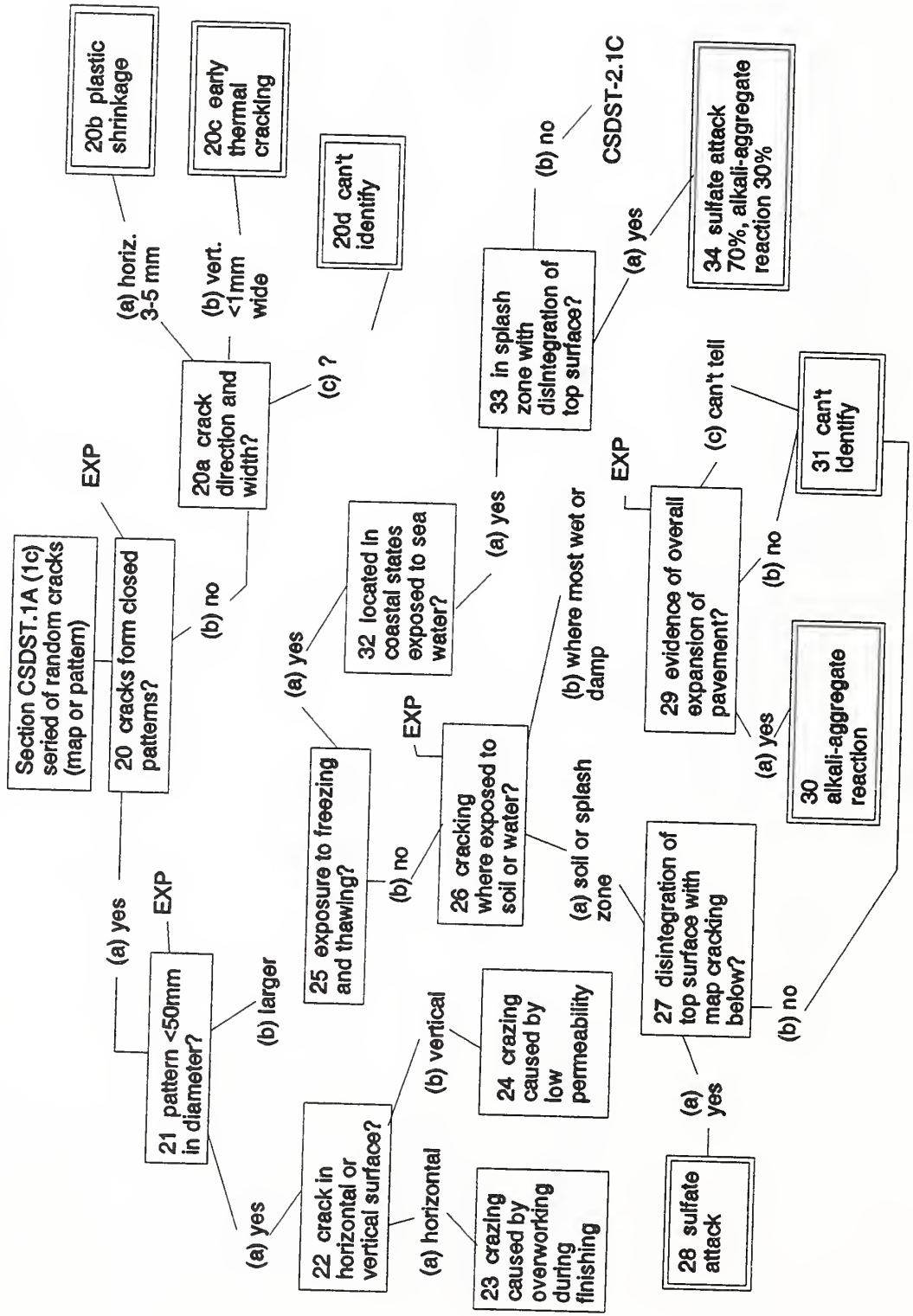




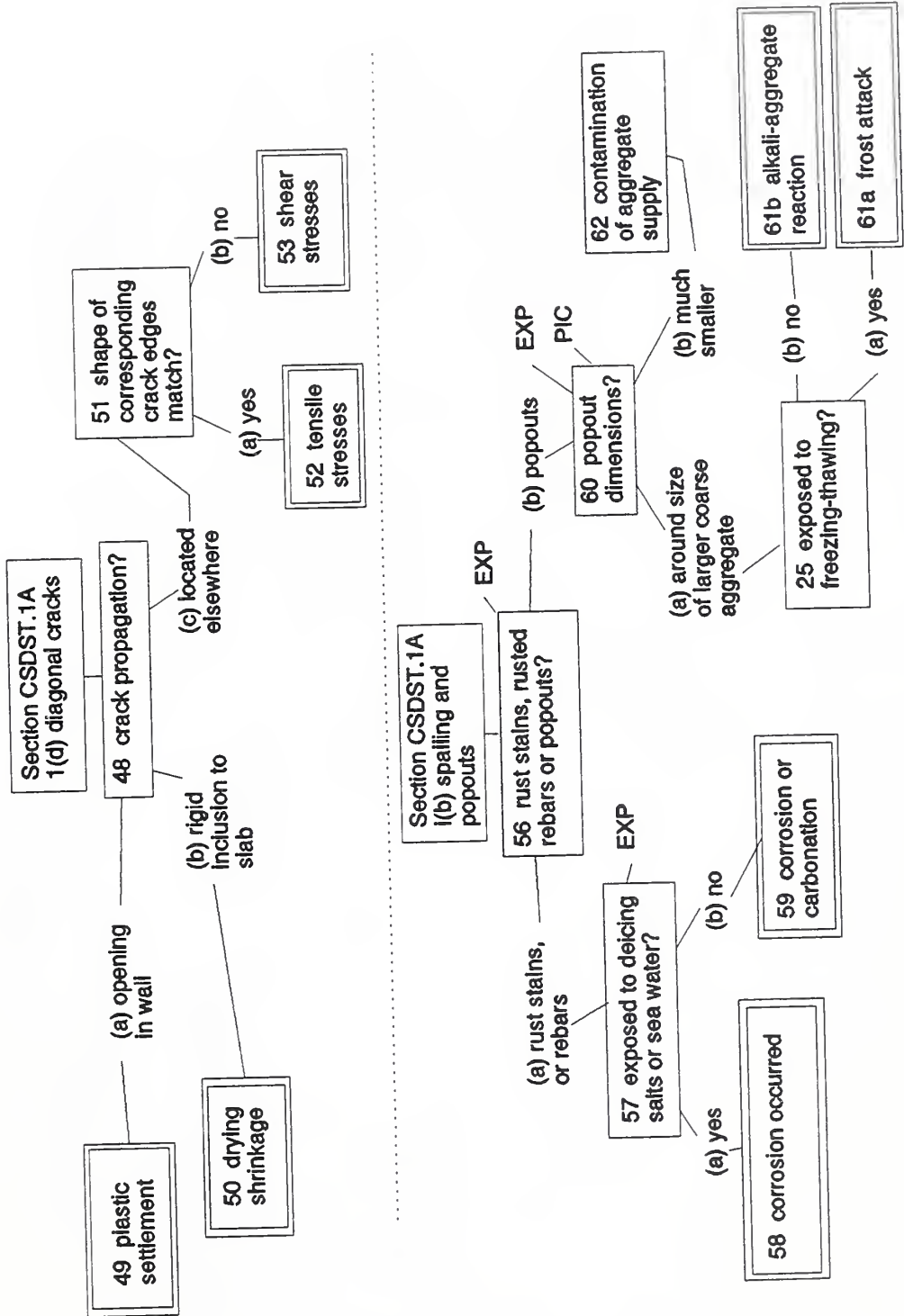
CONSTRUCD 3.0 Program: CSDST - Section CSDST.1B - 3/30/93



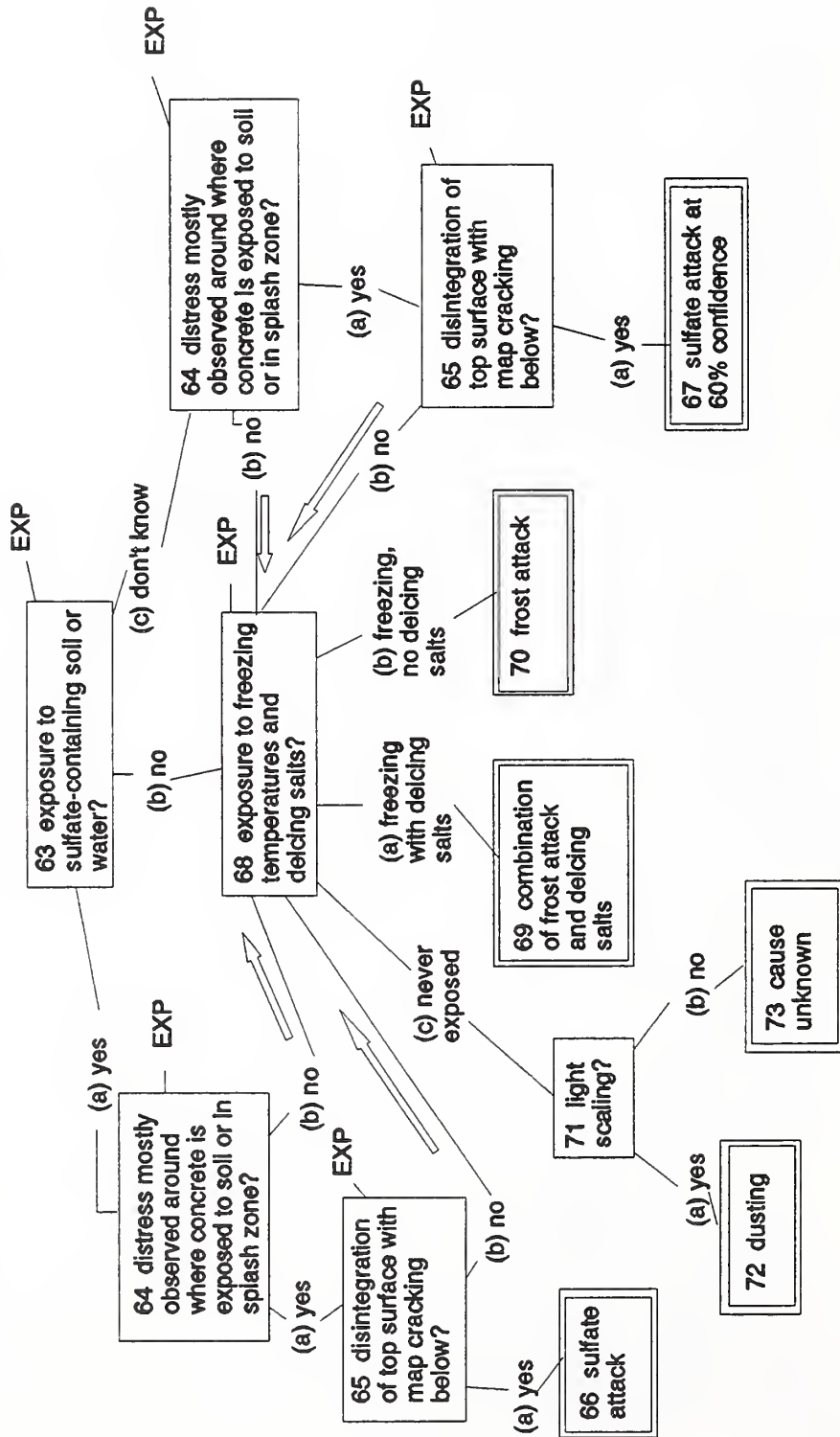
CONSTRUCD 3.0 Program: CSDST - Section CSDST.1C - 3/30/93



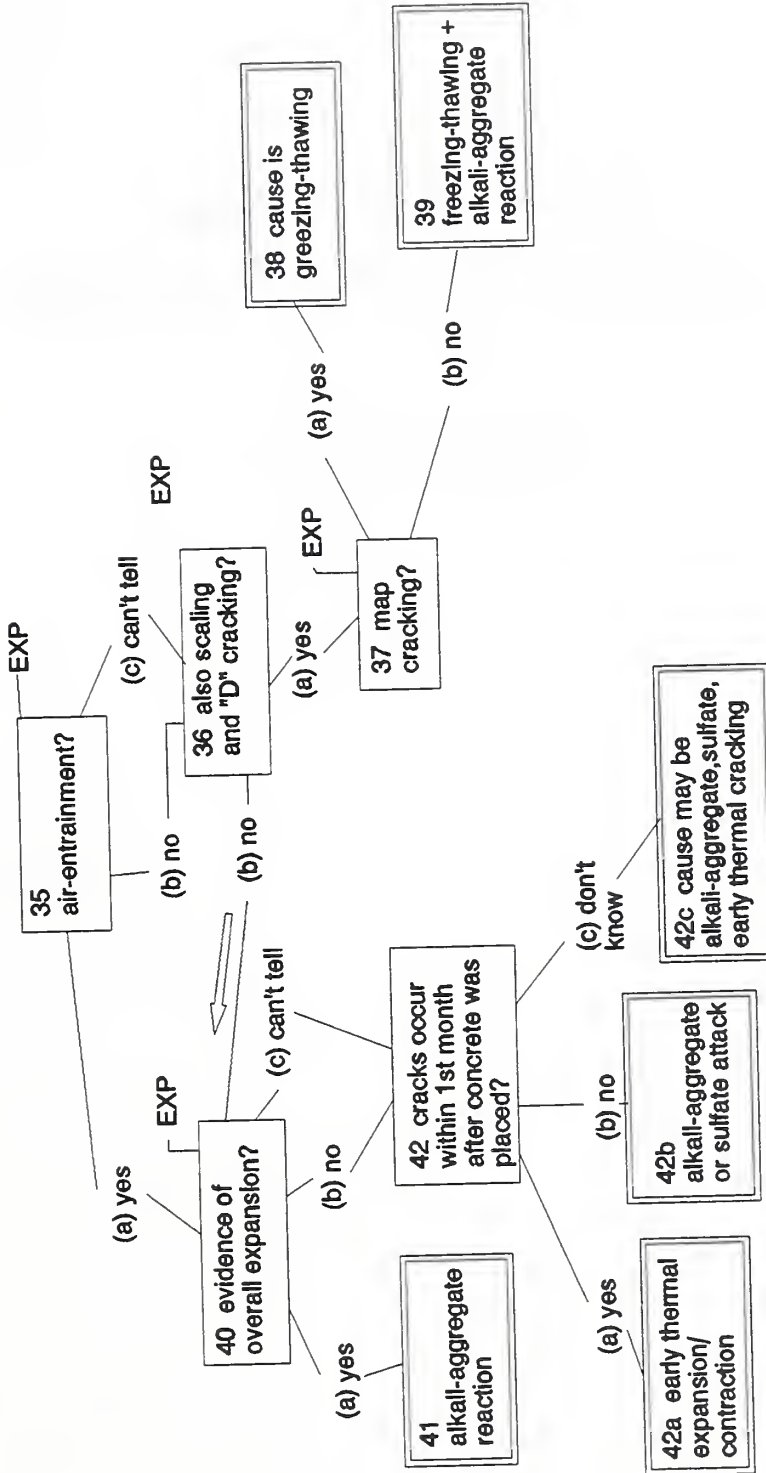
CONSTRUCD 3.0 Program: CSDST - Section CSDST.1D - 3/30/93



CONSTRUCD 3.0 Program: CSDST - Section CSDST.1E - 3/30/93



CONSTRUCD 3.0 Program: CSDST - Section CSDST-2.1C - 3/30/93



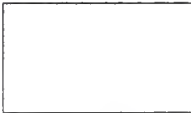





# APPENDIX A: KNOWLEDGE TREES

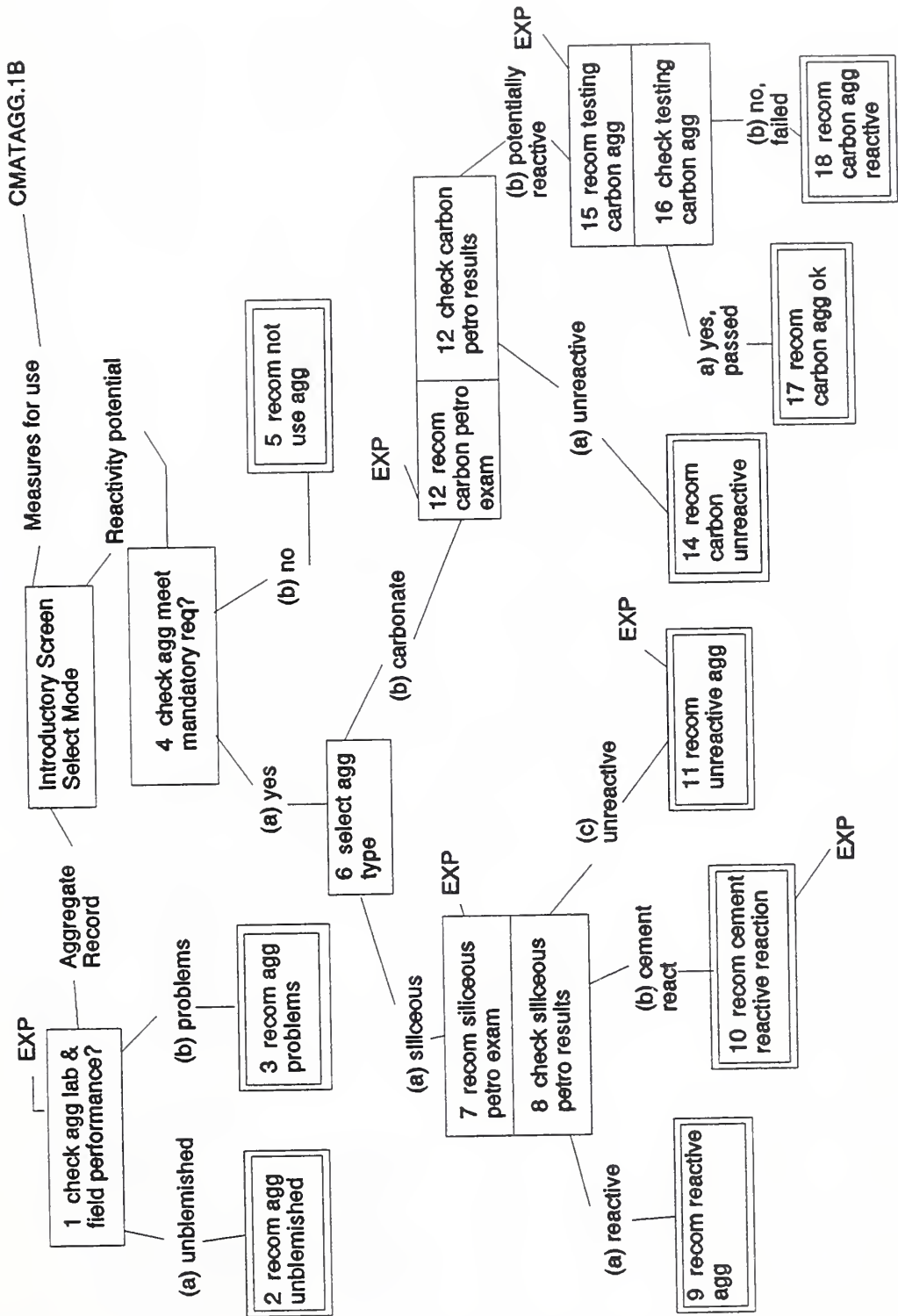
## CONMAT

### Legend:

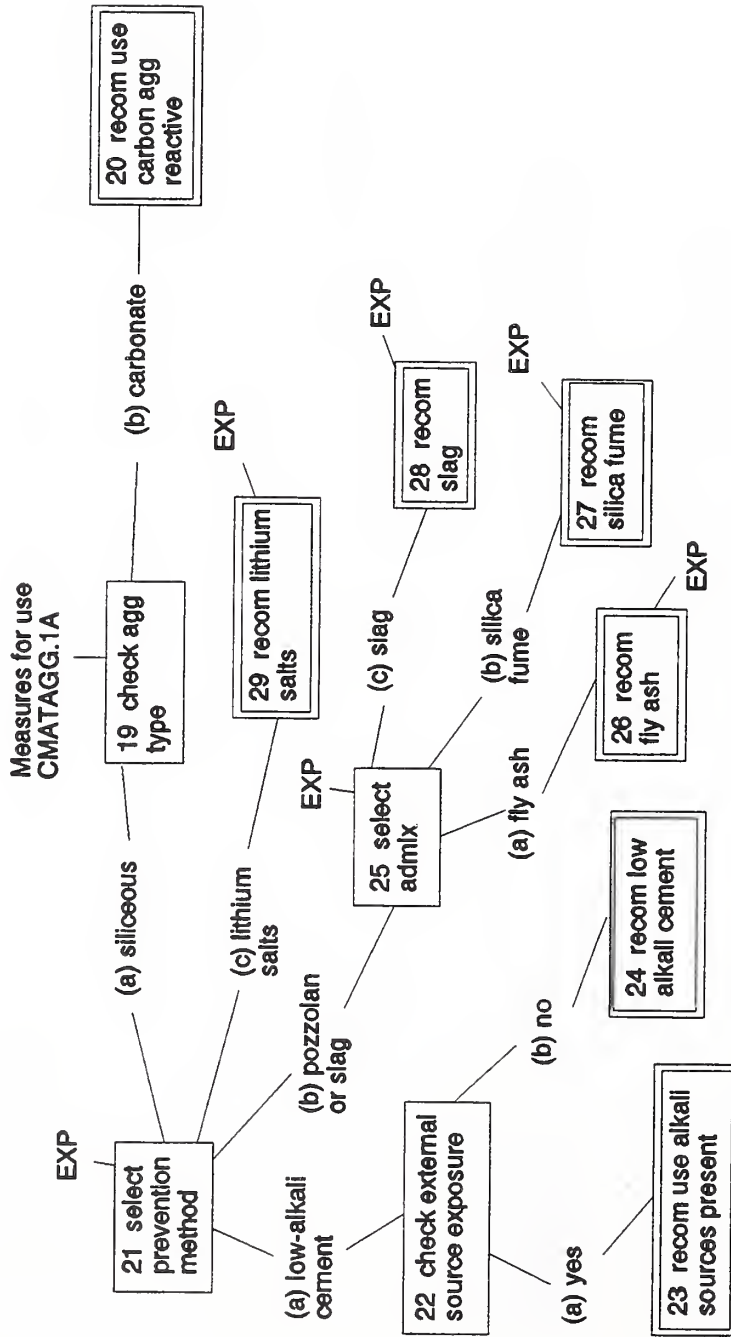
Picture or Drawing	=	PIC
alpha/numeric references (e.g. 2A)	=	reference to narrative text
explanatory information	=	EXP
operator response(s)	=	(a) _____
question box	=	
conclusion or recommendation box	=	



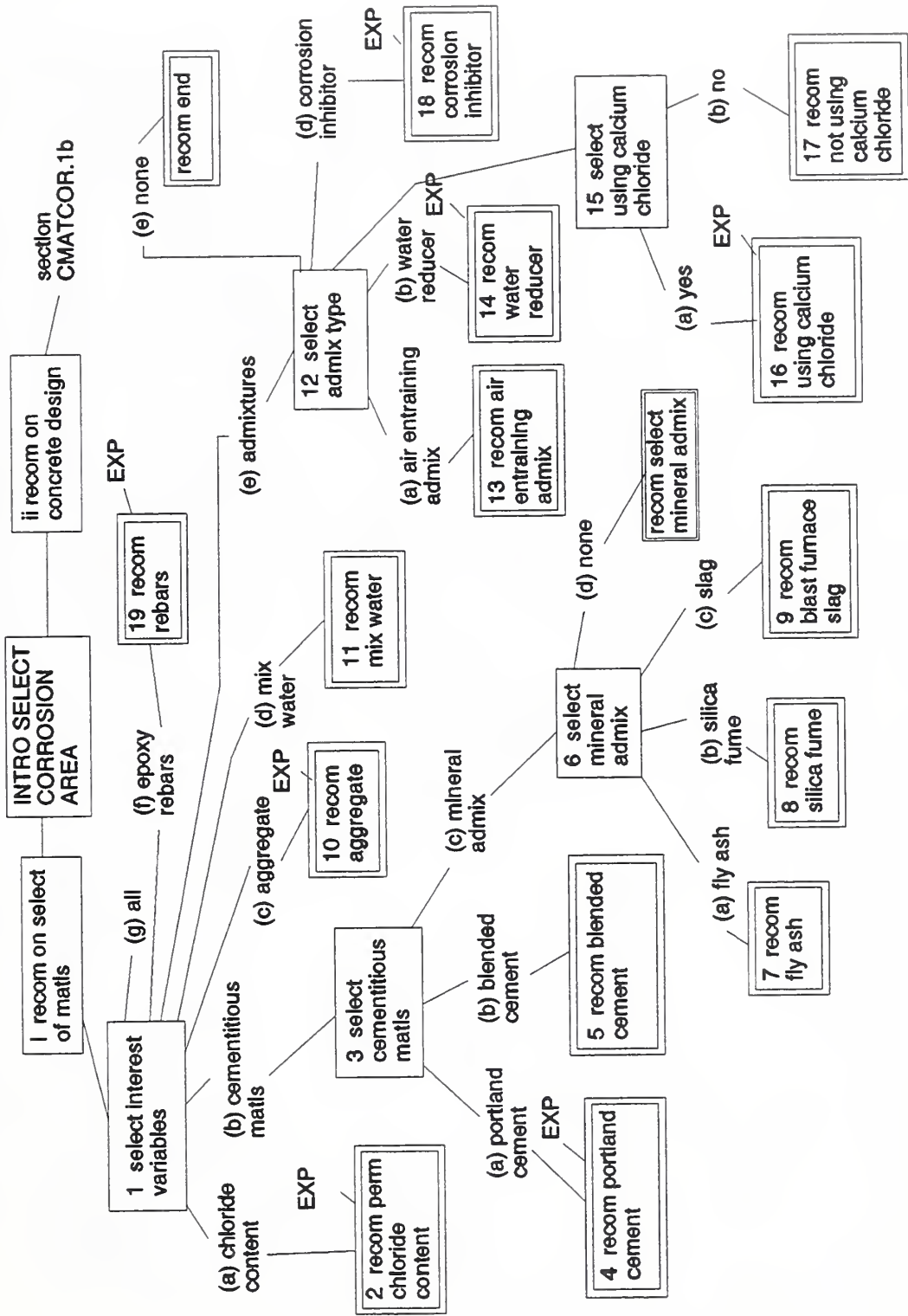
CONMAT 3.0 Program: CMATAGG - Alkali-Aggregate Reactivity - Section CMATAGG.1A - 3/30/93



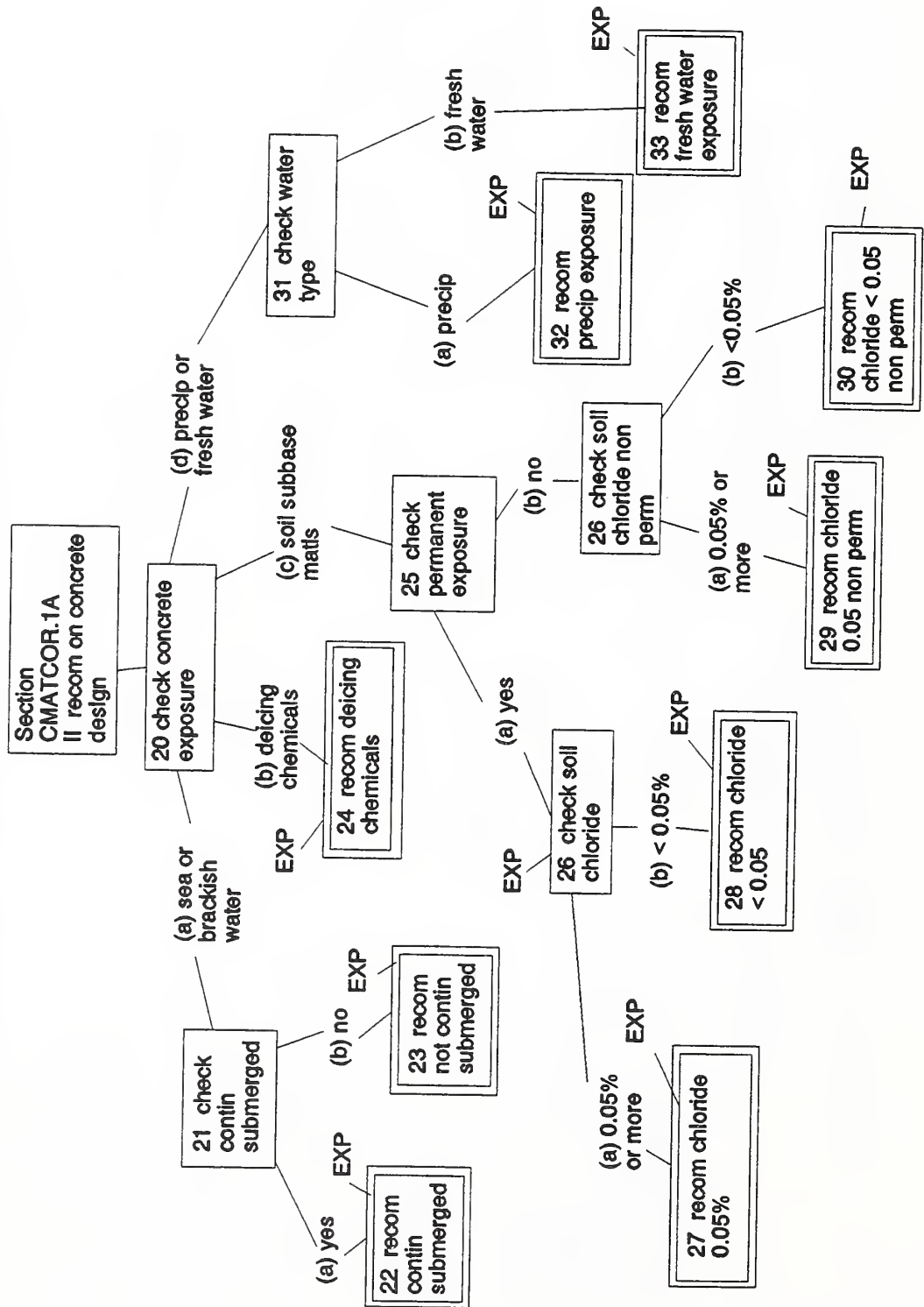
CONMAT 3.0 Program: CMATAGG - Alkali-Aggregate Reactivity - Section CMATAGG.1B - 3/30/93



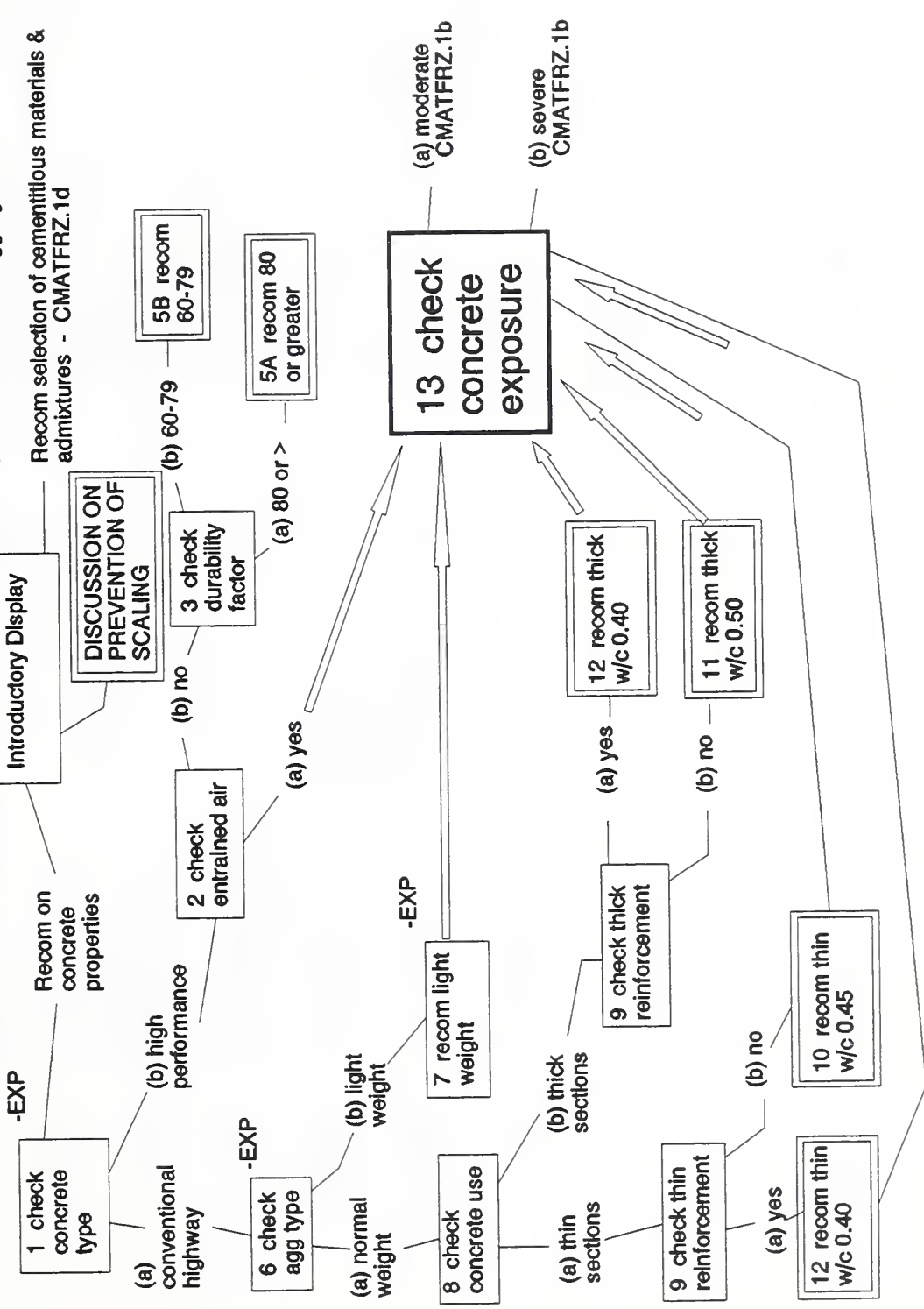
CONMAT 3.0 Program: CMATCOR - Corrosion - Section CMATCOR.1A - 3/30/93



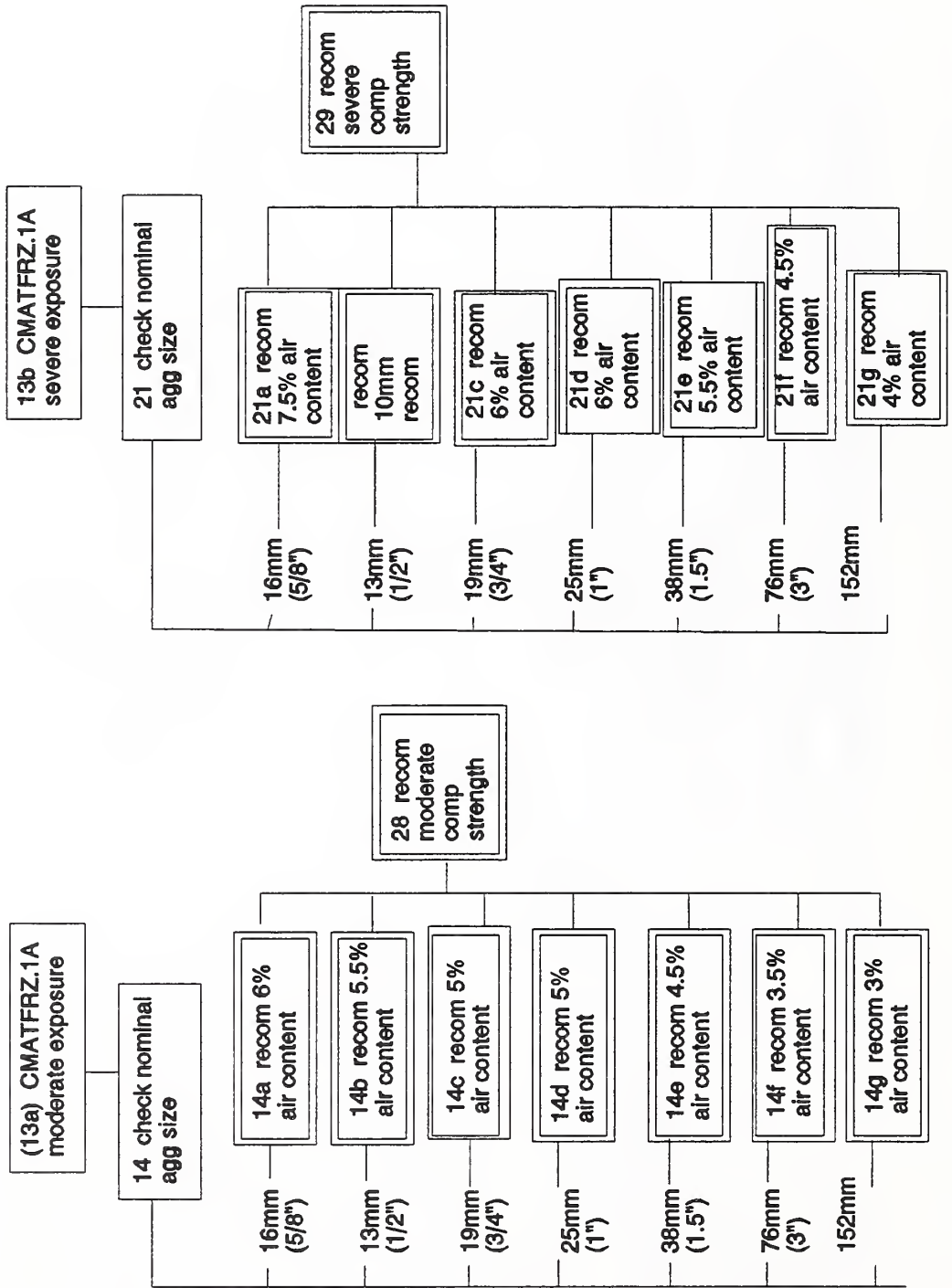
CONMAT 3.0 Program: CMATCOR - Corrosion - Section CMATCOR.1B - 3/30/93



**CONMAT 3.0 Program: CMATFRZ - Freezing and Thawing - Section CMATFRZ.1A - 3/30/93**  
 Recom selection of aggregate - CMATFRZ.1c  
 Recom selection of cementitious materials & admixtures - CMATFRZ.1d



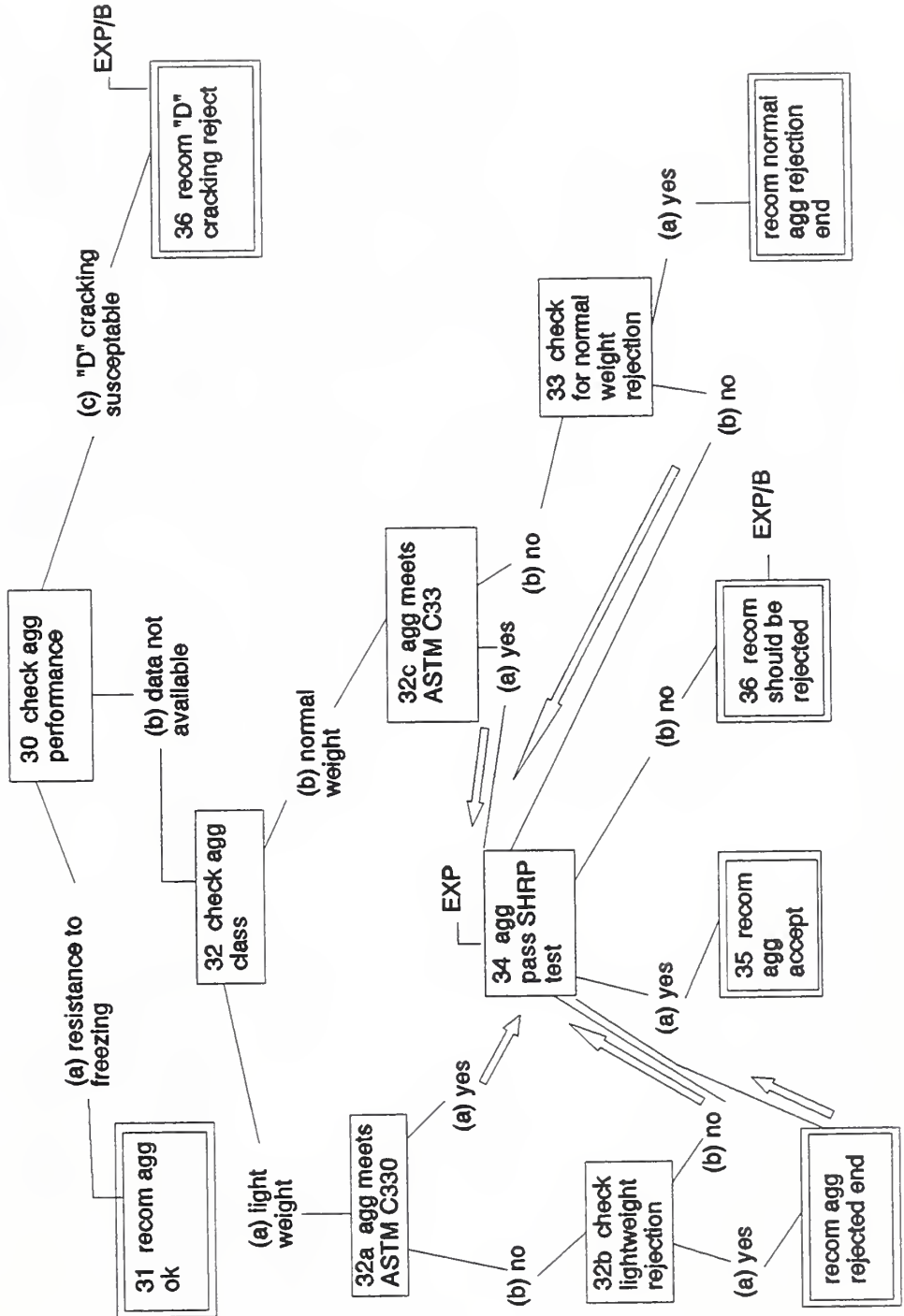
CONMAT 3.0 Program: CMATFRZ - Freezing and Thawing - Section CMATFRZ.1B - 3/30/93





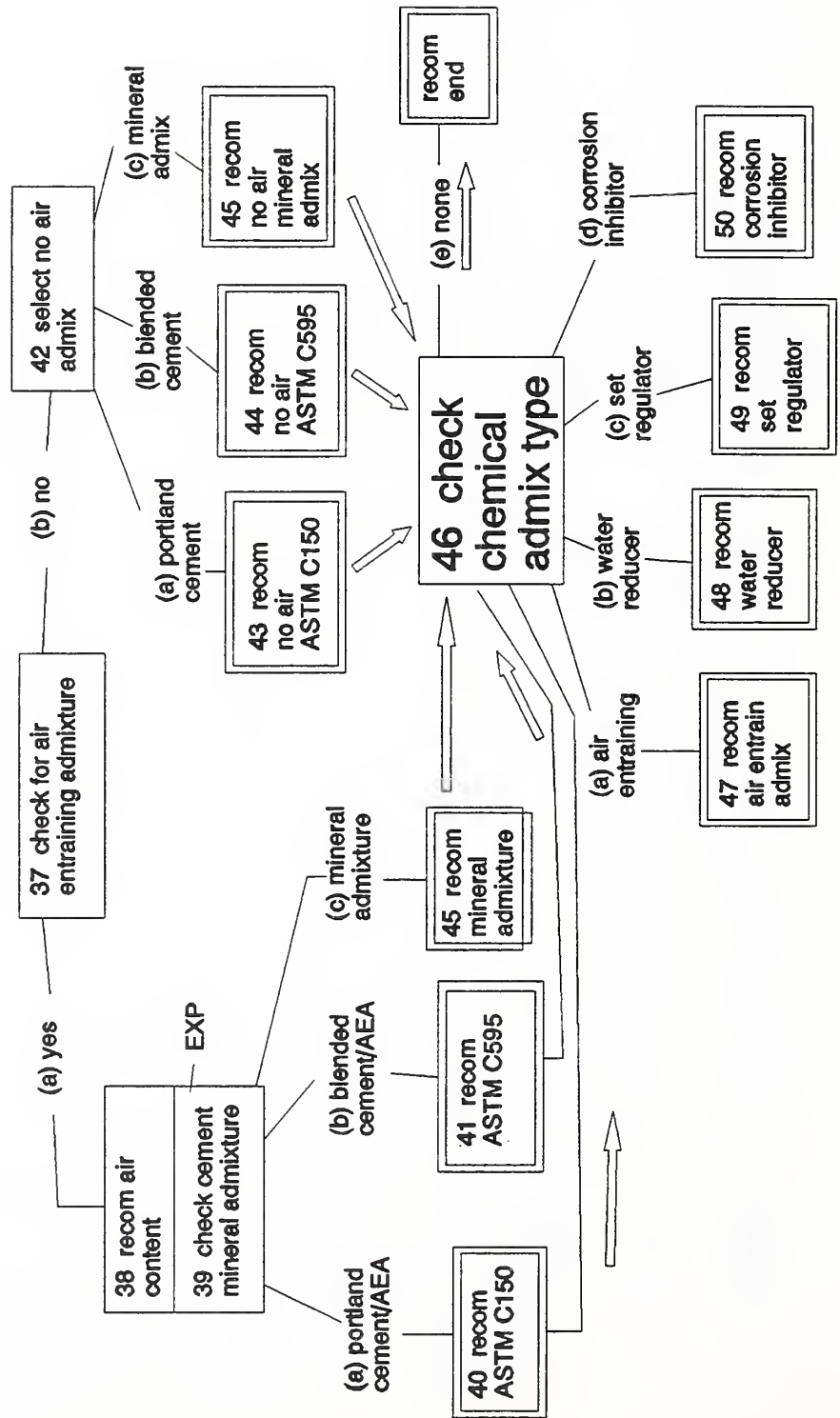
CONMAT 3.0 Program: CMATFRZ - Freezing and Thawing - Section CMATFRZ.1C - 3/30/93

SELECTION OF AGGREGATE

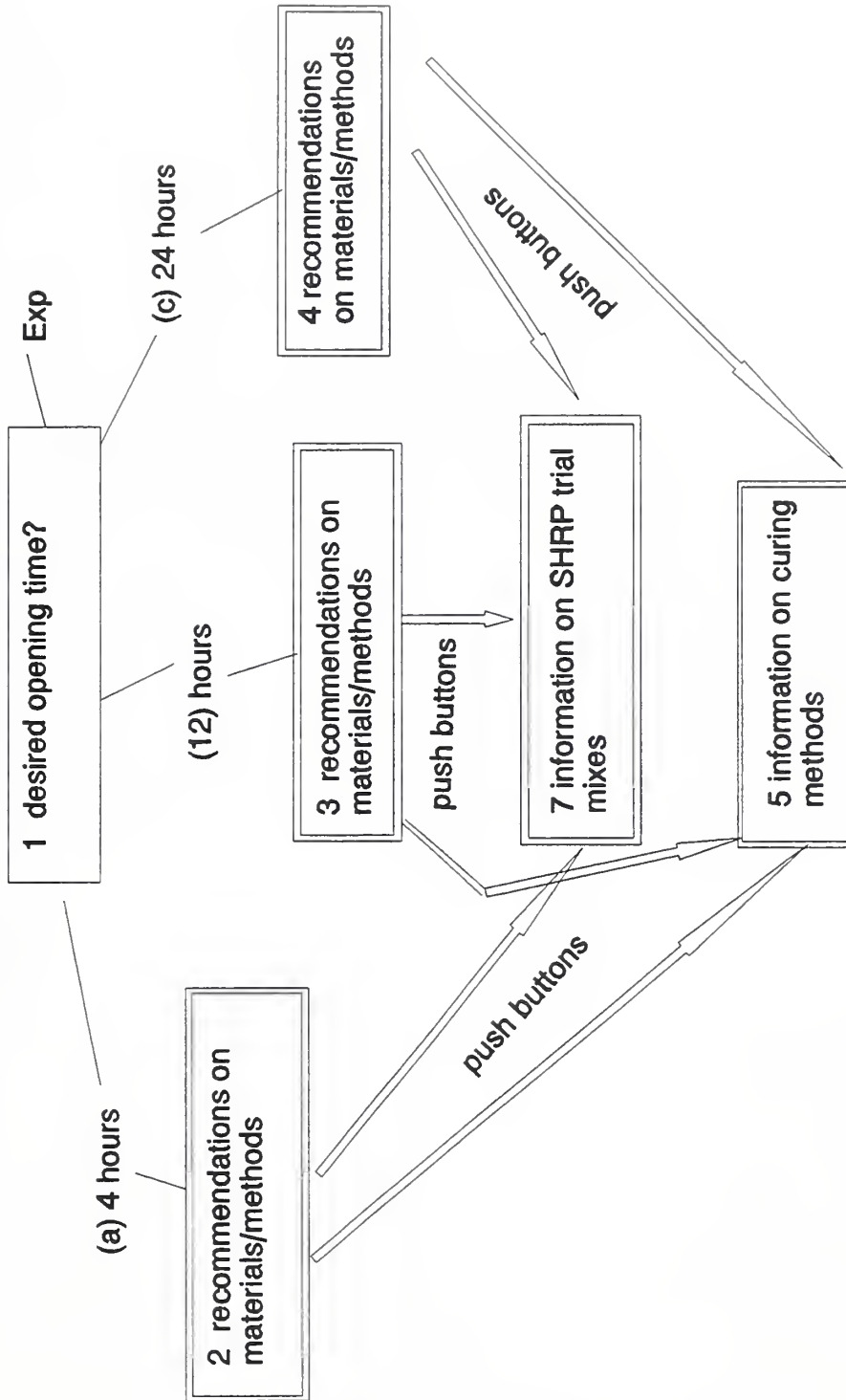


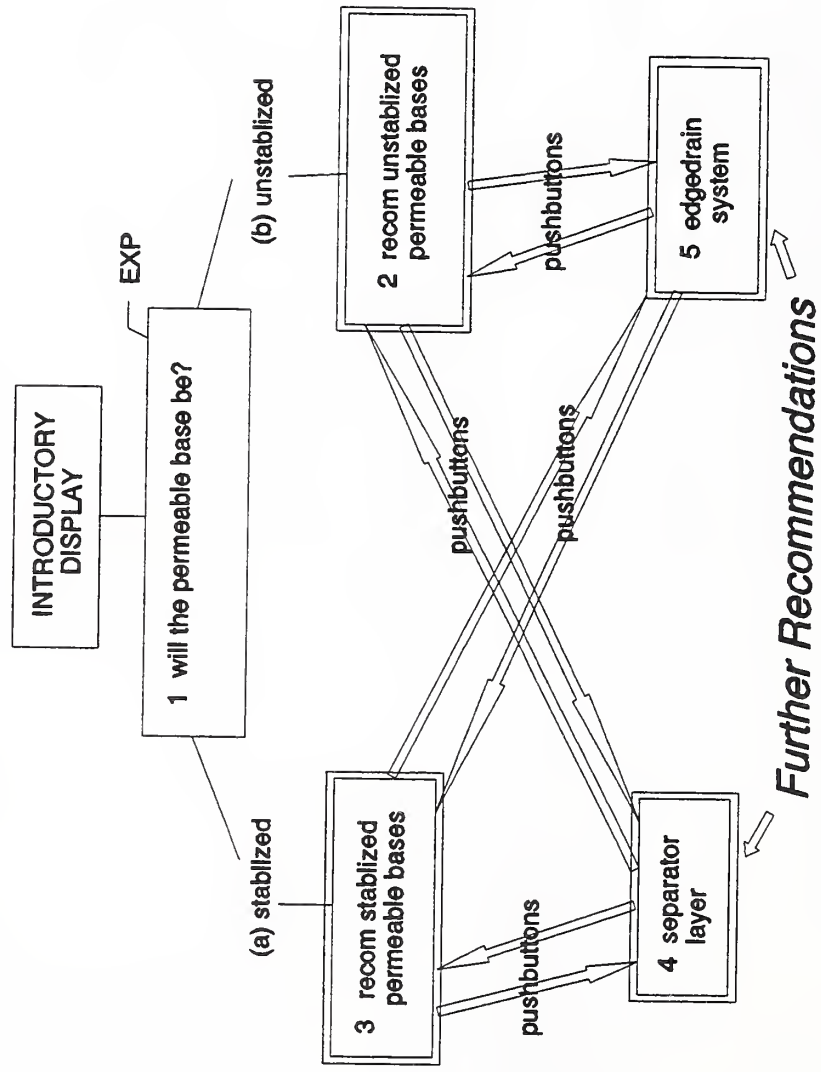
CONMAT 3.0 Program CMATFRZ - Freezing and Thawing - Section CMATFRZ.1D - 3/30/93

SELECTION OF CEMENTITIOUS MATERIALS & ADMIXTURES

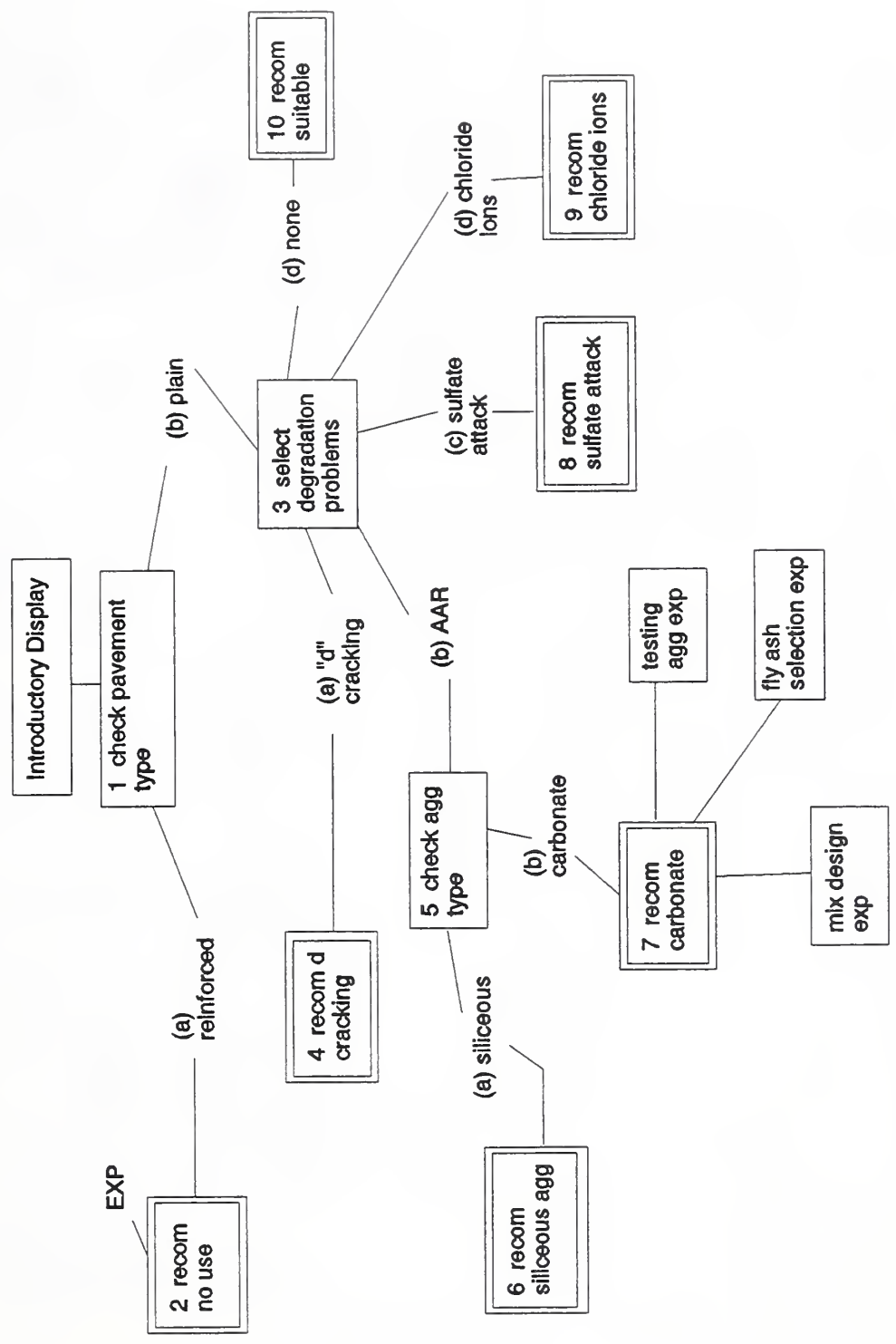


CONMAT 3.0 Program CMATFTRK Section CMATFTRK.1A - 3/30/93

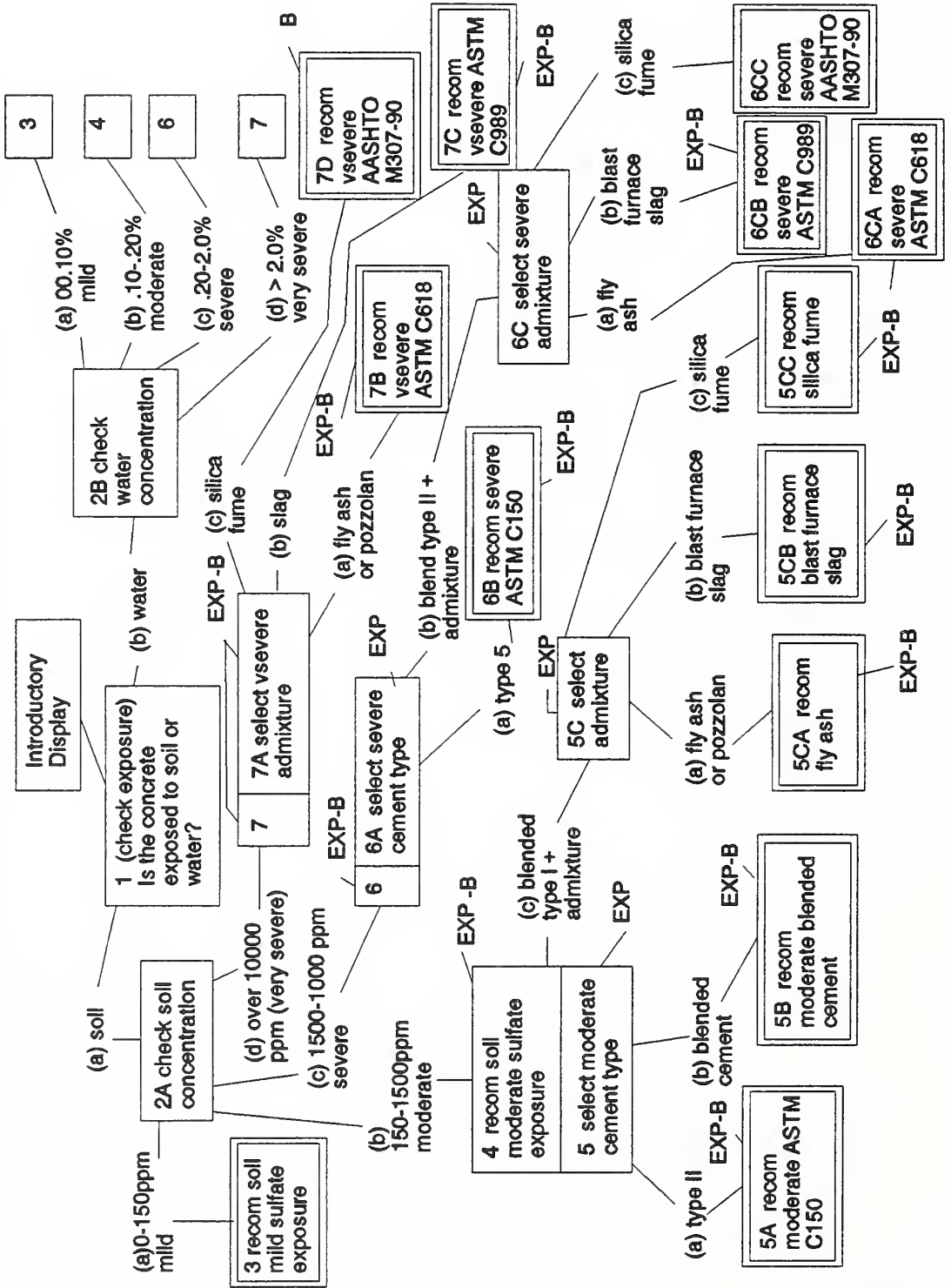




CONMAT 3.0 Program: CMATRCY - Recycling Concrete - Section CMATRCY.1A - 3/30/93




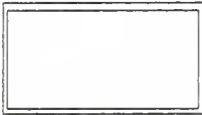
CONMAT 3.0 Program: CMATSULF - Sulfate Attack - Section CMATSULF.1A - 3/30/93



# APPENDIX A: KNOWLEDGE TREES

## CONPAV-R

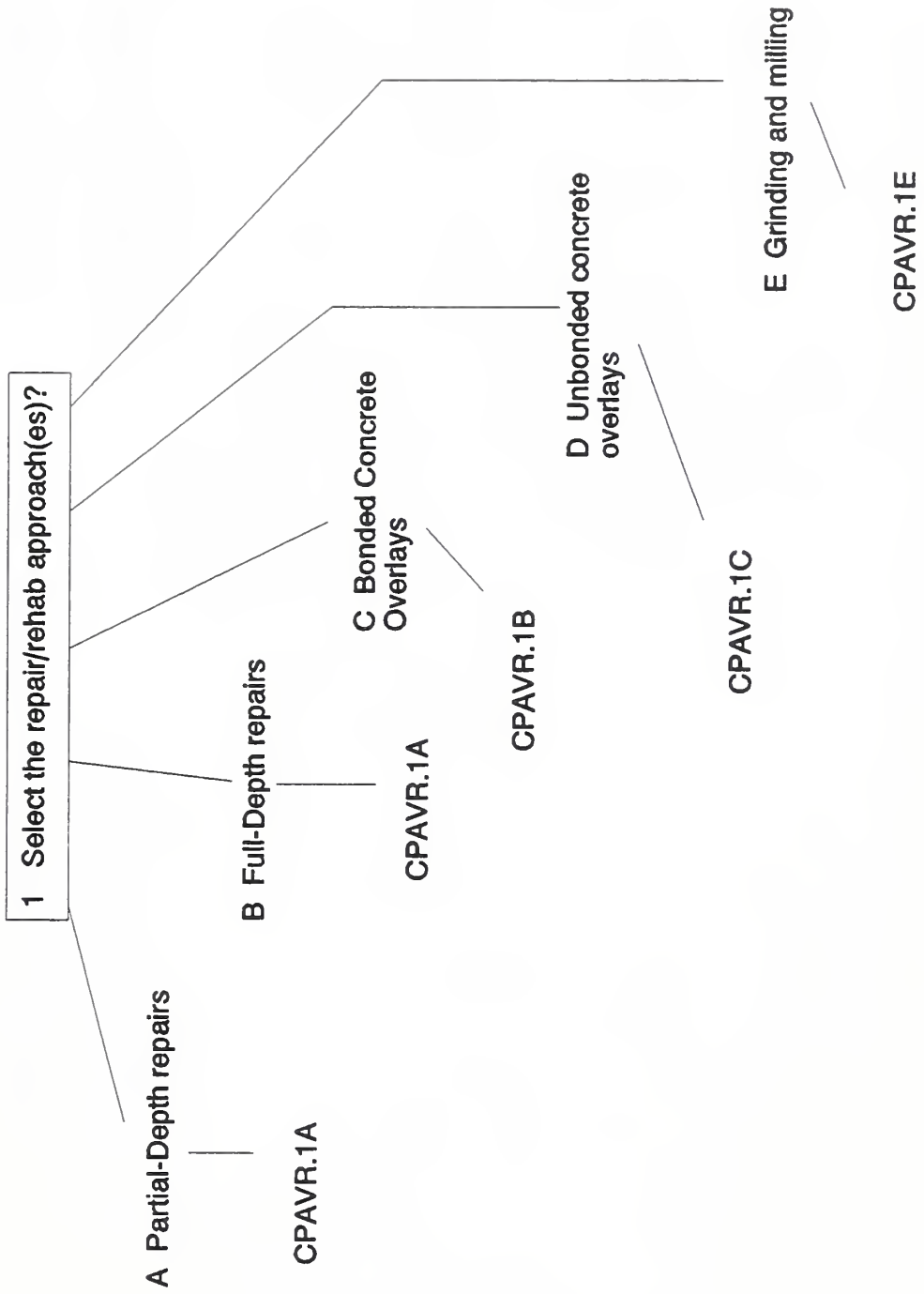
### Legend:

Picture or Drawing	=	PIC
alpha/numeric references (e.g. 2A)	=	reference to narrative text
explanatory information	=	EXP
operator response(s)	=	(a) _____
question box	=	
conclusion or recommendation box	=	



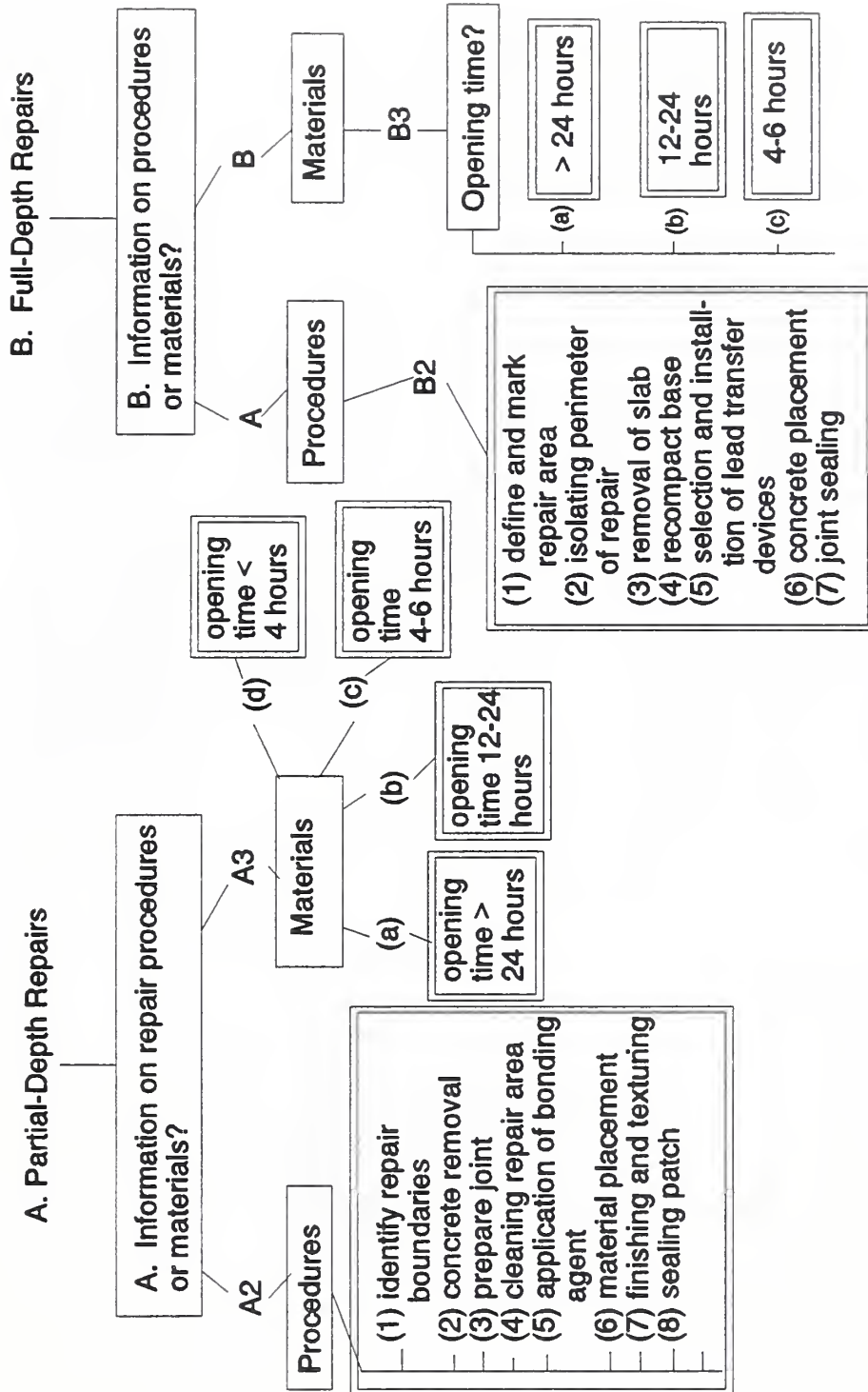


CONPAVR 3.0 Program CONPAVR - Main Section CPAVR.1D - 3/30/93

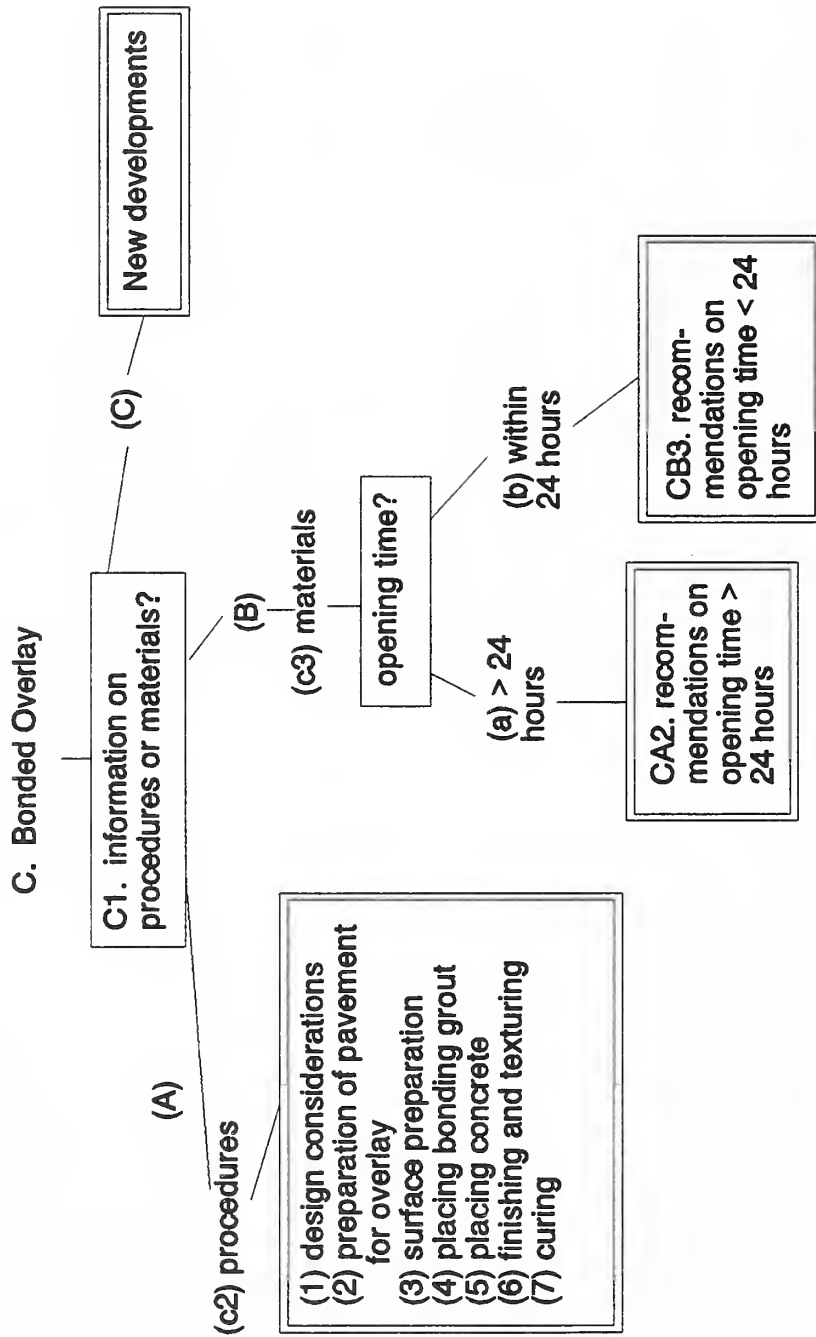




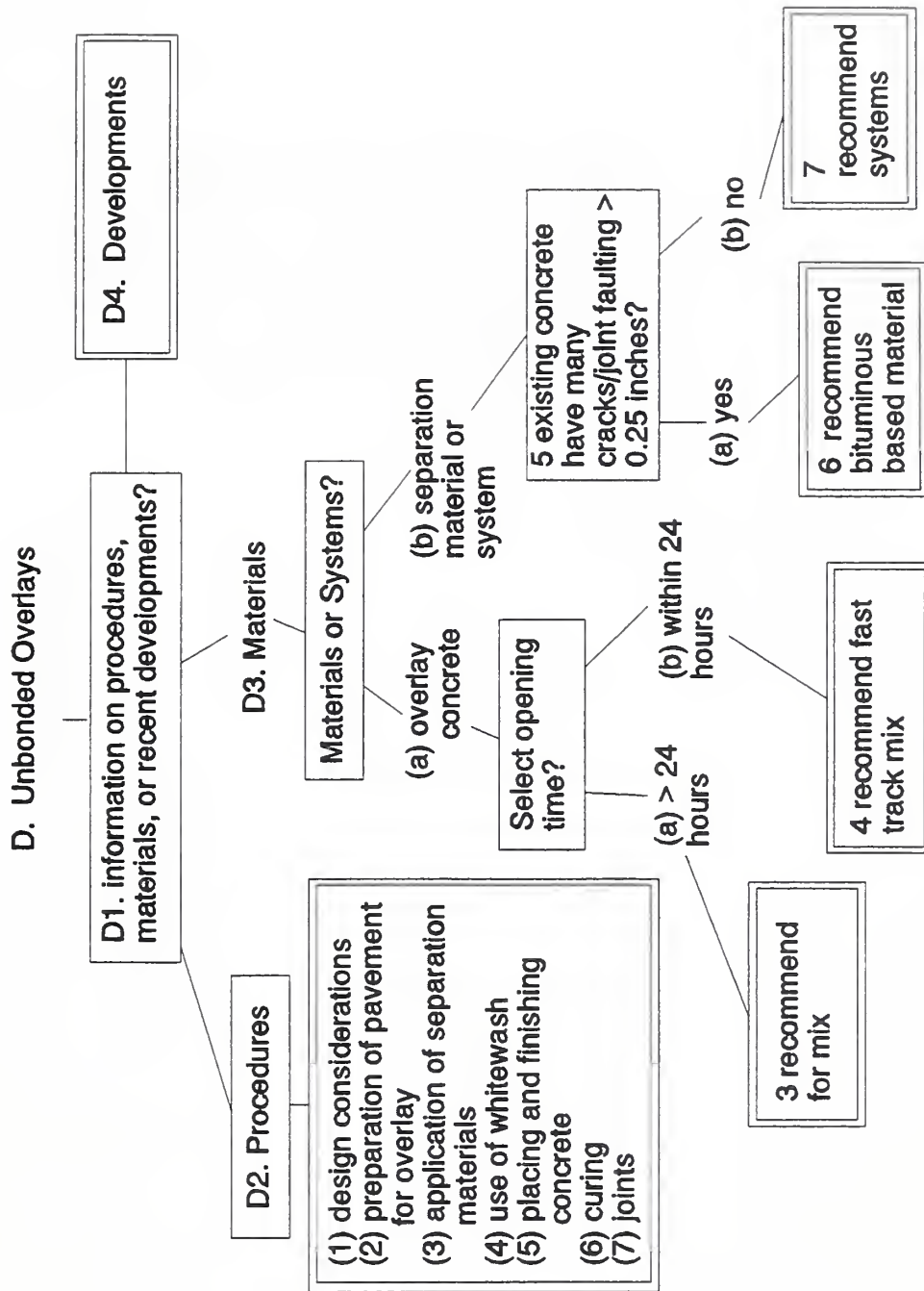
CONPAVR 3.0 Program: CONPAVR - Section CPAVR.1A - 3/30/93



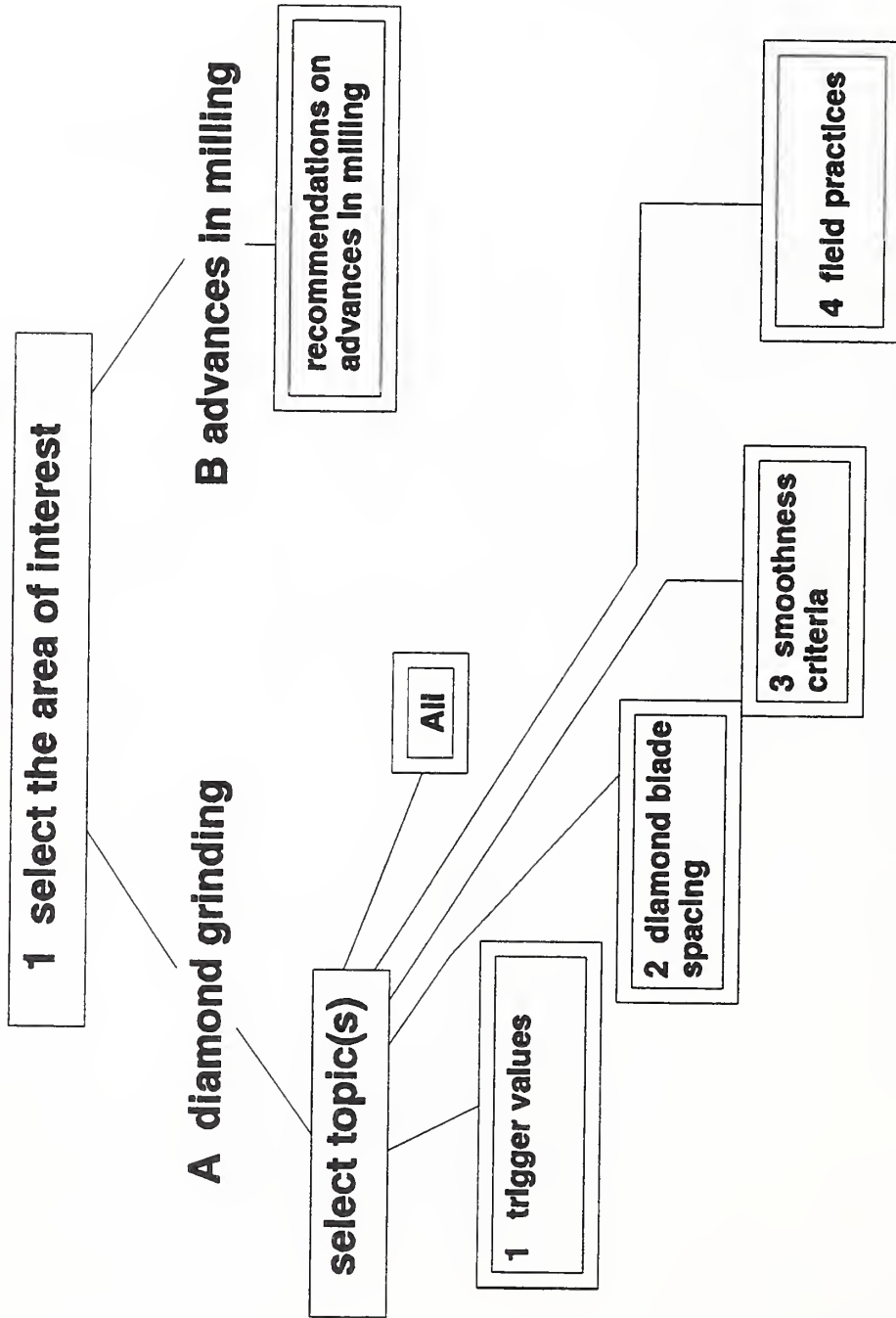
CONPAVR 3.0 Program: CONPAVR - Section CPAVR.1B - 3/30/93



CONPAVR 3.0 Program: CONPAVR - Section CPAVR.1C - 3/30/93



Diamond Grinding and Milling



# **APPENDIX B: FIELD INSPECTION SHEETS**





**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(.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 < .5mm
- transverse > .5mm
- 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 < 50mm in diameter
  - larger than 50mm 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

THE UNIVERSITY OF CHICAGO  
DEPARTMENT OF CHEMISTRY  
EXPERIMENTAL PHYSICS

REPORT OF THE UNIVERSITY OF CHICAGO  
DEPARTMENT OF CHEMISTRY  
EXPERIMENTAL PHYSICS

THE UNIVERSITY OF CHICAGO  
DEPARTMENT OF CHEMISTRY  
EXPERIMENTAL PHYSICS

THE UNIVERSITY OF CHICAGO  
DEPARTMENT OF CHEMISTRY  
EXPERIMENTAL PHYSICS

THE UNIVERSITY OF CHICAGO  
DEPARTMENT OF CHEMISTRY  
EXPERIMENTAL PHYSICS

**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 < 10mm and darkened
  - propagate in random direction from joint
- series of random (map or pattern)
  - form closed patterns
  - crack horizontal 3-5mm wide
  - crack vertical <1mm 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 C: BIBLIOGRAPHY OF KNOWLEDGE SOURCES**



## **APPENDIX C-1. Bibliography of knowledge sources for diagnostics of concrete pavements and structures.**

"Concrete Pavements", A.F. Stock, ed., Elsevier Applied Science (New York, 1988).

"Portland Cement Concrete Pavement Evaluation System COPES," National Cooperative Highway Research Report No. 277 (1985).

"Failure and Repair of Continuously Reinforced Concrete Pavement", National Cooperative Highway Research Program: Synthesis of Highway Practice No. 60 (1979).]"

NCHRP No. 60 ('Failure and Repair of Continuously Reinforced Concrete Pavement.

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

"Non-Structural Cracks in Concrete," Concrete Society Technical Report No. 23, The Concrete Society (England, 1982).

U.S. Army Corps of Engineers' manual 'Evaluation and Repair of Concrete Structures', EM 1110-2-2002, July 1986 (obtain from U.S. Army Corps of Engineers, Washington, DC 20314-1000)

"Handbook for the identification of Alkali-Silica Reactivity in Highway Structures" (SHRP-C/FR-91-101).

"Paved Shoulders", Federal Highway Administration, FHWA Technical Advisory, T 5040.29, (1990). "

"Guide to the Durability of Concrete", ACI Manual of Concrete Practice, Part 1 (1990)

"Concrete Making Materials," by S. Popovics (Hemisphere Publishing Corp. 1979)

R.C. Dean, J.H. Havens, A.S. Rahal, and W.V. Azevedo,  
"Cracking in Concrete Pavement," *Transportation Engineering Journal of ASCE*, Vol 106, No. TE2, pp. 155-169 (1980).

A Manual for the Maintenance and Repair of Concrete Roads,' prepared by H.S. Mildenhall and G.D.S. Northcott and published by the Dept. of Transportation of the Cement and Concrete Association (England) in 1989.

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

M.I. Darter, K.D. Smith, and D.G. Peskin, "Field-Calibrated Mechanistic-Empirical Models for Jointed Concrete Pavements," Paper No. 91-0757, Transportation Research Board 70th Annual Meeting, Washington, DC (January 1991)

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

"D" Cracking -"Cracking in Concrete Pavements", Dean, R.C., Havens, J.H., Rahal, A.S., Azevedo, W.V., *Transportation Engineering Journal of ASCE*, Vol 106, No. TE2, pp 155-169 (1980).

"Non-Structural Cracks in Concrete", Concrete Society Technical Report No. 23, The Concrete Society, England (1982).

"Hot Weathering Concrete", American Concrete Institute 305, Manual of Concrete Practice, Part 2, American Concrete Institute, Detroit, MI (1990).

"A Manual for the Maintenance and Repair of Concrete Roads", Mildenhall, H.S., Northcott, G.D.S., Dept of Transportation of the Cement and Concrete Association, England (1989).

"Field Calibrated Mechanistic-Empirical Models for Joints Concrete Pavements", Paper No. 91-0757, 70th Annual Meeting Transportation Research Board, Transportation Research Board, Washington, DC (1991).

"Construction Sealants and Adhesives", Panek, J.R., Cook, J.P., 2nd Edition, John Wiley and Sons, New York, NY (1984).

"Paved Shoulders", Federal Highway Administration, FHWA Technical Advisory, T 5040.29 (1990).

"Criteria for Design and Construction of Continuously Reinforced Concrete Pavements", McCullough, B.L., Concrete Pavements, Chapter 8, pp 279-318, Elsevier Applied Science, New York, NY (1988).[]

"Bridge Inspection Manual-82", New York State Dept. of Transportation, Albany, NY (1982).

"Bridge Inspector's Training Manual 90", U.S. Dept. of Transportation, Federal Highway Admin., McLean, VA (January 1991).

"Durability of Concrete Bridge Decks: Final Report of a Cooperative Study," Portland Cement Association, Skokie, IL (1970).

"Rapid Measurement of Concrete Cover on Bridge Decks," Public Roads, Vol. 39, No. 2, Federal Highway Administration, Washington, DC (1975).

"Chloride Ion Diffusion in Low Water-To-Solid Cement Pastes", NISTIR 4549, J.R. Clifton, et. al., National Institute of Standards and Technology (April 1991).

"Half-Cell Potentials of Uncoated Reinforcing Steel in Concrete," ASTM C-676, ASTM, Philadelphia, PA.

"Rolling Pachometer", Federal Highway Administration. Washington, DC.

"Bridge Deck Rehabilitation Manual, Part One: Condition Survey," Research and Development Branch, Ontario Ministry of Transportation and Communications (November 1983).

SHRP C-104 project, "Methodology for the Protection of Existing Reinforced Concrete Bridges".

"Durability of Concrete Bridge Decks: Cooperative Study," Report 3, Portland Cement Association, Skokie, IL (1967).

"Durability of Concrete Bridge Decks: Final Report of a Cooperative Study," Portland Cement Association, Skokie, IL (1970).

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

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

Chloride Ion Diffusion in Low Water-To-Solid Cement Pastes, NISTIR 4549, J.R. Clifton, et. al., National Institute of Standards and Technology (April 1991).

J.M. Pitt, M.C. Schluter, D. Lee, and W. Dubberke, "Sulfate Impurities from Deicing Salts and Durability of Portland Cement Mortar," Transportation Research Board Record 1110, pp. 16-23 (1987)



## **APPENDIX C-2. Bibliography of knowledge sources for selection of materials.**

R.E. Oberholster and G.S. Davies, "An Accelerated Test Method for Testing The Potential Alkali Reactivity of Siliceous Aggregates", *Cement and Concrete Research*, Vol. 16, pp. 181-189 (1986).

C.A. Rogers, "General Information on Standard Alkali-Reactive Aggregates from Ontario, Canada", Engineering Materials Office, Ministry of Transportation, Ontario, Canada (June 1989).

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

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

H.N. Walker, "Chemical Reactions of Carbonate Aggregates in Cement Paste", ASTM STP-169B, *Significance of Tests and Properties of Concrete and Concrete-Making Materials*, pp. 722-743 (1978).

J. Croteau, J. Quinn, and K. Shelat, "A Laboratory Evaluation of the Alkali-Carbonate Reaction.

R.E. Bisque and J. Lemish, "Silicification of Carbonate Aggregates in Concrete", *Bulletin No. 239*, Transportation Research Board, pp. 41-55 (1960).

J.E. Gillott, "Cell Test Method for Study of Alkali-Carbonate Rock Reactivity", *Proceedings, ASTM*, Vol. 63, pp. 1195-1206 (1963).

P. Smith, "Learning to Live with a Reactive Carbonate Rock", *Highway Research Record*, No. 46, Transportation Research Board, pp. 126-133 (1964).

"Engineering and Design Standard Practice for Concrete", Appendix C, EM 1110-2-2000, U.S. Army Corps of Engineers, Washington DC (September 1986).

A. Buck, "Use of Cementitious Materials Other Than Portland Cement", Concrete Durability: Katherine and Bryant Mather Intl. Conference, ACI SP-100, pp. 1863-1881 (1987).

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

"Guide to Durable Concrete", ACI 201 Committee, American Concrete Institute, Detroit, MI.

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

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

R.D. Gaynor, "Understanding Chloride Percentage", Concrete International: Design & Construction, Vol. 7, No. 9, pp. 26-27 (1985).

C. Rodgers, and G. Woda, "The Chloride Ion Content of Concrete Aggregate from Southern Ontario", Report No. EM-17, Ontario Ministry of Transportation and Communication (1977).

"Organic-Based Corrosion-Inhibiting Admixture for Reinforced Concrete", Concrete International, Vol. 14, No. 4, pp. 45-51 (April 1992).

Y.P. Virmani, "Time-To-Corrosion of Reinforcing Steel in Concrete Slabs, Vol. VI: Calcium Nitrite Admixture", Report No. FHWA-RD-88-165, Federal Highway Administration (September 1991).

N.S. Berke, and L.R. Roberts, "Use of Concrete Admixtures to Provide Long-term Durability from Steel Corrosion", ACI SP-119, Superplasticizers and Other Chemical Admixtures in Concrete, pp. 383-403 (1989).

"Reinforced Concrete Durability and ASTM", ASTM Standardization News, pp. 46-51 (January 1992).

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

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

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

J.L. Heiman, "The Durability of Cast-in-situ Reinforced Concrete", Technical Record 511, pp. 33, National Building Technologie Centre, Australia (1986).

J.R. Clifton, H.F. Beeghly, and R.G. Mathey, "Nonmetallic Coatings in Concrete Reinforcing Bars", Report No. FHWA-RD-74-18, Federal Highway Administration (January 1974) (NTIS # PB No. 236424).

R.J. Kessler, and R.G. Powers, "Corrosion Evaluation of Substrate Long Key Bridge", Interim Report 87-9A, Florida Department of Transportation (September 1987).

J.A. Reed, "FBECR-The Need for Correct Specification and Quality Control", FBECR Symposium at Sheffield Univ. (May 17, 1989).

Y.P. Virmani, "Epoxy-Coated Rebars as a Protective System for New Construction", Research and Technology Transporter, p. 5, FHWA (January 1992).

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

R.E. Philleo, "Freezing and Thawing Resistance of High-Strength Concrete", NCHRP Synthesis No. 129, Transportation Research Board (1986).

K.H. Khayat and P.C. Aitcin, "Silica Fume in Concrete-An Overview", pp. 1-46, in CANMET International Workshop on Silica Fume in Concrete, Washington, DC (April 7-9, 1991).

M. Pigeon, et. al., "Freezing and Thawing Tests of High-Strength Concretes", Cement and Concrete Research, Vol. 21, pp. 844-852 (1991).

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

G.J. Verbeck, and R. Landgren, "Influence of Physical Characteristics of Aggregate on the Frost Resistance of Concrete", Proceedings ASTM, V. 30, pp. 1063-1079 (1960).

P. Klieger, D. Stark, and W. Teske, "The Influence of Environment and Materials on "D"-cracking, Final Report", Construction Technology Laboratory (October 1978).

P. Zia, M.L. Leming, and S.H. Ahmad, "High Performance Concrete - A-State-of-the-Art Report", SHRP Report C/FR-91-103 (1991).

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

ACI 318, Manual of Concrete Practice, American Concrete Institute, Detroit, MI.

ACI 201, "Guide to Durable Concrete", ACI Materials Journal, Vol. 88, No. 5, pp. 544-582 (September-October 1991).

P. Klieger, "Curing Requirements of Scale Resistance of Concrete", Highway Research Board Bulletin 150, pp. 18-31 (1956), and PCA Research Department Bulletin 82.

B.D. Neeley, W.E. McDonald, and M.K. Lloyd, "Investigation of Proprietary Air-Entraining Admixtures to Produce Frost-Resistant Concrete with Low Air Content", US Army Corps of Engineers Technical Report SL-92-6, US Army Corps of Engineers Structures Laboratory, Vicksburg, MS (March 1992).

"Concrete Admixtures", by Van Dodson, Table 6-3, pp. 136-137, Van Nostrand, New York, NY (1990)

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

R.H. Baumgardner, "Notes on Permeable Bases", FHWA Pavement Division (February 1992).

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

"Synthesis of Current and Projected Concrete Highway Technology", SHRP C-206, Strategic Highway Research Program, National Research Council, Washington, DC (1992).

A. Raja, "Factors Affecting Deterioration of Transverse Cracks in Jointed Reinforced Concrete Pavements (JRCP)", Dept. of Civil and Environmental Engineering, Michigan State University (1991).

P. Klieger, and D. Stark, "The Influence of Environment and Materials on "D"-cracking, Final Report", Construction Technology Laboratory, Skokie, IL (October 1978).

"Engineering and Design Standard Practice for Concrete", Appendix C, EM 1110-2-2000, U.S. Army Corps of Engineers, Washington, DC (September 1986).

Carrasquillo, and Farbiarz, "Alkali-Aggregate Reaction in Concrete Containing Fly Ash: Final Report", Research Report 450-3F, Center for Transportation Research, University of Texas at Austin (October 1989).

T. Patzias, "Evaluation of Sulfate Resistance of Hydraulic-Cement Mortars by the ASTM C1012 Test Method", Katherine and Bryant Mather International Symposium on Concrete Durability, ACI SP-100, pp. 2103-2120 (1987).

D. Stark, "Durability of Concrete in Sulfate-Rich Soils", Research and Development Bulletin RD097.01T, Portland Cement Association, Skokie, IL (1989).

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

P.K. Mehta, "Effect of Fly Ash Composition on Sulfate Resistance of Cement", Journal of American Concrete Institute, Vol. 83, No. 6, pp. 994-1000 (1986).

ASTM C989-89, "Specification for Ground Granulated Blast-Furnace Slag Cement Concrete", Durability of Concrete, ACI SP-126 (1991).

G.J. Osborne, "The Sulphate Resistance of Portland and Blast-Furnace Slag Cement Concrete", Durability of Concrete, ACI SP-126 (1991).

M.D. Cohen, and A. Bentur, "Durability of Portland Cement-Silica Fume Pastes in Magnesium Sulphate and Sodium Sulphate Solutions", Journal of the American Concrete Institute, Vol. 85, No. 3, pp. 148-157 (1988).

"Proposed revision of: Guide to Durable Concrete", ACI Materials Journal, Vol. 88, No. 5, pp. 544-582 (1991).

J.R. Clifton, and B.C. Olkikar, "Expert System for Selecting Concrete Constituents", Computer Applications in Concrete Technology, ACI SP-98, pp. 1-24 (1987).

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

E.R. Dunstan, "A Spec Odyssey - Sulfate Resistant Concrete for the 80's", George Verbeck Symposium on Sulfate Resistance of Concrete, ACI SP-77, pp. 41-62 (1980).

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

### **APPENDIX C-3. Bibliography of knowledge sources for repair and rehabilitation of concrete pavements.**

Figure 6 of FHWA publication No. FHWA-RD-88-071  
("Rehabilitation of Concrete Pavements, Volume I: Repair  
Rehabilitation Techniques", July 1989)

G. Voight, M. Darter, S. Carpenter, "Rehabilitation of Concrete  
Pavements, Volume II - Overlay Rehabilitation Techniques", Federal  
Highway Administration Report FHWA/RD-88-072 (1987)]

Field Inspection Guide for Restoration of Jointed Concrete Pavements",  
Demonstration Projects Division, Federal Highway Administration  
(December 1987).

"Guidelines for Partial-Depth Repair", Report TB-003.0 CPR,  
American Concrete Pavement Association (1989).

"Techniques for Pavement Rehabilitation", Participants Notebook,  
Prepared by ERES, Inc., National Highway Institute/Federal Highway  
Administration, Third Revision (1987).

"Rehabilitation of Concrete Pavements, Volume I: Repair Rehabilitation  
Techniques", FHWA Publication No. FHWA-RD-88-071 (July 1989)."

FHWA Pavement Rehabilitation Manual (FHWA-ED-88-025),

NCHRP Report No. 281

M. Darter, E. Barenberg, and W. Yrjanson, "Joint Repair  
Method for Portland Cement Concrete Pavements", NCHRP  
Report No. 281, p. 13 (1985).

Innovative Materials and Equipment for Pavement Surface Repairs, Volume I: Summary of  
Material Performance and Experimental Plans", SHRP H105, p.  
5-33, (1991).

Field Inspection Guide for Restoration of Jointed Concrete  
Pavements", Demonstration Projects Division, Federal  
Highway Administration (December 1987).

"Guidelines for Full-Depth Repair", Report TB-002.0 CPR,  
American Concrete Pavement Association (1989).

"Techniques for Pavement Rehabilitation", Participants Notebook, Prepared by ERES, Inc., National Highway Institute/Federal Highway Administration, Third Revision (1987).

"Rehabilitation of Concrete Pavements, Volume I: Repair Rehabilitation Techniques", FHWA Publication No. FHWA-RD-88-071 (July 1989)."

G. Voight, M. Darter, S. Carpenter, "Rehabilitation of Concrete Pavements, Volume II - Overlay Rehabilitation Techniques", Federal Highway Administration Report FHWA/RD-88-072 (1987).

"Guidelines for Bonded Concrete Overlays", ACPA Technical Bulletin TB-007.0.C (1990).

"Resurfacing with Portland Cement Concrete", NCHRP Synthesis of Highway Practice 99, Transportation Research Board (1982)."

Resurfacing with Portland Cement Concrete", NCHRP Synthesis of Highway Practice 99, Transportation Research Record (1982), G. Voight, M. Darter,

"Guidelines for Bonded Concrete Overlays", ACPA Technical Bulletin TB-007.0.C (1990))

K. McGhee and C. Ozyildirm, "Construction of a Thin-Bonded Portland Cement Concrete Overlay Using Accelerated Paving Techniques", Virginia Dept. of Transportation (1992)).

"Guidelines for Bonded Concrete Overlays", American Concrete Pavement Association Technical Bulletin TB-007.0.C (1990).

"Guide Specification for Concrete Overlays of Pavements and Bridge Decks", American Association of State Highway and Transportation Officials (1990)).



W.H. Temple, et. al., "Design and Construction of a Bonded Fiber Concrete Overlay of CRCP (Louisiana, Interstate Route 10, August 1990", Paper No. 920881, 72nd Annual Meeting of Transportation Research Board, January 1992)

K. Koesno and F. McCullough, "Evaluation of the Performance of Bonded Concrete Overlay on Interstate Highway 610 North, Houston, Texas", Transportation Research Record 1196, pp. 201-211, 1988)

M. Bugate, et. al., "An Experimental Thin-Bonded Concrete Overlay Pavement", Research Report 357-2F, Center for Transportation Research, Univ. of Texas at Austin (1985) (NTIS No. PB88-118906))

D. Whiting, et. al., "Synthesis of Current and Projected Concrete Highway Technology", SHRP C-206

"Guidelines for Unbonded Concrete Overlays", Technical Bulletin TB-005.0.D, American Concrete Pavement Association (1990))

"Rigid Pavement Analysis and Design", FHWA/RD-88-068, Federal Highway Administration (1988)).

"Field Inspection Guide for Restoration of Jointed Concrete Pavements", Demonstration Projects Division, Federal Highway Administration (December 1987).

"Guidelines for Full-Depth Repair", Report TB-002.0 CPR, American Concrete Pavement Association (1989).

"Techniques for Pavement Rehabilitation", Participants Notebook, Prepared by ERES, Inc., National Highway Institute/Federal Highway Administration, 3rd Revision (1987).

"Rehabilitation of Concrete Pavements, Volume I: Repair Rehabilitation Techniques", FHWA Publication No. FHWA-RD-88-071 (July 1989).

"Joint Repair Method for Portland Cement Concrete Pavements", NCHRP Report No. 281, p. 13 (1985).

"Fibrous Portland Cement Concrete Overlay Research in Green County, Iowa", Transportation Research Record 1040, pp. 1-7 (1985).

"Guide Specification for Concrete Overlays of Pavements and Bridge Decks", American Association of State and Highway and Transportation Officials (1990).

"Design and Construction of a Bonded Fiber Concrete Overlay of CRCP (Louisiana, Interstate Route 10 (August 1990))", 72nd Annual Meeting of Transportation Research Board, Paper No. 920881 (January 1992).

"An Experimental Thin-Bonded Concrete Overlay Pavement", Research Report 357-2F, Center for Transportation Research, Univ. of Texas at Austin, NTIS No. PD88-118906 (1985).

"Iowa Fast Track Paving", American Association of State Highway Transportation Officials Quarterly, Vol. 6, pp. 10-12 (October 1986).

"Construction of Thin-Bonded Portland Cement Concrete Overlay Using Accelerated Paving Techniques", K.H. McGhee, C. Ozyildirim, 72nd Annual Meeting of Transportation Research Board, Paper No. 920436, January 1992).

"Resurfacing with Portland Cement Concrete", NCHRP Synthesis of Highway Practice 99, Transportation Research Board (1982).

"Rehabilitation of Concrete Pavements, Volume II: Overlay Rehabilitation Techniques", Federal Highway Administration Report FHWA/RD-88-072 (1987).

"Rigid Pavement Analysis and Design", FHWA/RD-88-068, Federal Highway Administration (1988).

Pavement Texturing by Milling",  
Final Report for Iowa Highway Research Board: Project HR-283, January 1987)).

Diamond Grinding and Concrete Pavement Restoration 2000", American Concrete Pavement Assoc., Technical Bulletin, TEP-008.0 (1990))

Field Inspection Guide for Restoration of Jointed Concrete",  
Federal Highway Administration, Demonstration  
Projects Program (December 1987).

ACPA Technical Bulletin TB-006.0-C "Constructing Smooth Concrete Pavements".

"A Level Road Rides Better, Lasts Longer", International  
Grooving and Grinding Association (1989).

"Concrete Pavement Restoration Performance Review",  
Pavements Division and Demo Project.



**APPENDIX D:  
GLOSSARY OF  
EXPERT SYSTEM TERMS**



## APPENDIX D. 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.





