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Expert/Knowledge-Based Systems for Cement and Concrete: State-of-the-Art Report

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CONTENTS

ABSTRACT

This report is the result of a survey of expert/knowledge based systems applications and development methods related to concrete pavements and structures. It is the initial step in the development of expert systems for the SHRP C-206, (Task 3) project. The report addresses three topics: 1) the potential for the application of expert systems for concrete mixture design and diagnostics, repair and rehabilitation, 2) a description of inference procedures that are best suited for representing the concrete pavement and structure knowledge domain, and 3) recent expert/knowledge based systems activities.

1. INTRODUCTION

Expert systems, or knowledge based systems[1], are receiving greater attention from the building industry to aid in the decision making process in areas such as diagnostics, design, and repair and rehabilitation. Although expert systems, a segment of artificial intelligence, has been in existence since the 1970's, the construction industry has been slow to utilize expert systems to solve practical, real-world problems. This was largely due to the lack of expert system tools available to represent the domain knowledge. Also, the level of effort required to develop and maintain the systems was very high, compared to requirements today. Others factors that affected the acceptance of expert systems include the promise of the ability to solve problems and the lack of their performance, and the relative newness of expert systems technology.

In recent years, improvements in the capabilities of commercially available shell programs used in building expert systems, and new architectures for representing and interfacing knowledge have made this technology a viable resource for representing and preserving an expert's knowledge. Systems can now be developed in relatively small time-frames (a few staff years), and can aid significantly in the decision making.

This reports describes the current state-of-the-art of expert systems for cement and concrete used in the construction of rigid highway pavements. It includes; the currently active application areas, development methods, existing applications, and their status. It is the result of a survey of expert system development activities for the period 1985-1990, that addresses this area. Chapter 2 explains the application areas that are considered to be most appropriate for developing expert systems for pavement construction. Chapter 3 presents current state-of-the-art methods and tools for developing expert systems. In chapter 4, a survey of the existing systems, methodology for implementation, and status of the project are presented. Appendix 1 is provided to assist the reader in understanding common terms used in the field of expert system development. Appendix 2 contains a bibliography of expert systems technology that relates to pavement and concrete construction.

2. CONCRETE PAVEMENT ACTIVITIES SUITABLE FOR EXPERT SYSTEMS

This section describes two important areas of concrete construction that can benefit significantly from the application of expert systems. It is meant to provide a brief

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[1] For the purpose of this survey, the terms, expert systems and knowledge based system will be used interchangeably. Both of these terms imply that the systems contain knowledge that is normally associated with that of an expert, and that rules and procedures have been included in the system to operate upon its knowledge.

overview of current developments and their benefits to concrete design, diagnostics, and rehabilitation.

2.1 Design Activities

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 87], the selection of ready mix concrete [Seren 87], and the design of durable concrete [Clifton, Oltikar and Johnson 85]. Expert systems applications for concrete design are very limited, compared to other highway engineering activities, such as traffic signal, transportation network design [Ritchie 87]. Table 1 lists the existing expert systems that have been developed for use in concrete mixture proportioning.

Expert systems for design are less judgmental than other 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.

Section	Expert System	Concrete Design Use	Condition Assessment	Repair	Rehab	Prototype	Operational
4.1.1	BETVAL	X				X	
4.2.1	Bridge Rating Expert System		X			X	
4.1.2	COMIX	X				X	
4.1.3	CONCEX	X				X	
4.1.4	Concrete Mix Designer					X	
4.2.2	CRACK		X			X	
4.2.3	CRACKS		X			X	
4.1.5	DURCON	X				X	
4.1.6	ESCON	X				X	
4.2.4	EXPEAR		X	X	X		X
4.2.5	PAVEMENT EXPERT		X			X	
4.2.6	PAVER		X	X	X		X
4.2.7	REPCON		X			X	

Table 1. Summary of expert systems.

Feedback to the user from design expert systems are 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. A model expert system describing the information needed to design durable concrete for a freeze-thaw environment is described in Figure 1. Recommendations to the user for this case are:

- o type of cement
- o durability factor
- o percent of entrained air
- o air void spacing
- o compressive strength (PSI)

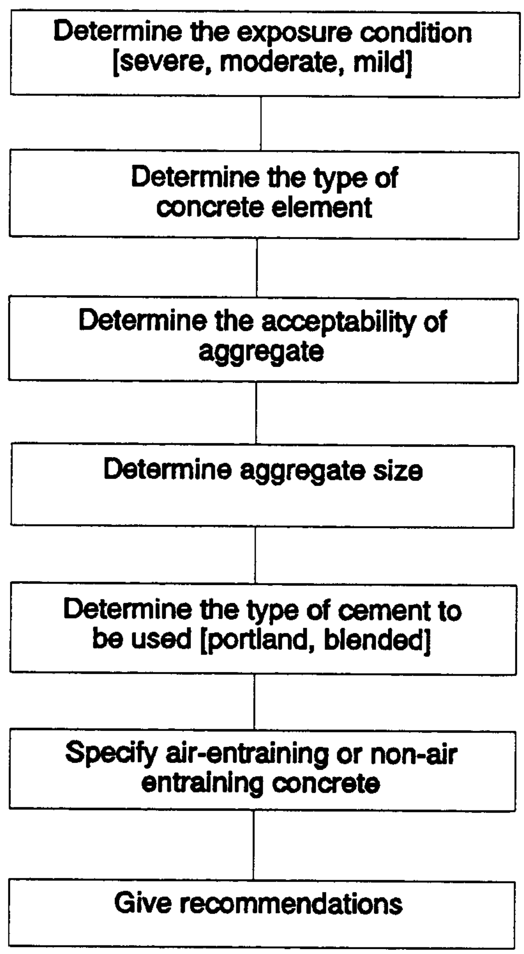

Figure 1. Expert system model for freeze-thaw durability concrete design.

Expert systems for concrete design will gain greater acceptance in the construction industry as more systems are developed that interface to building design codes. This feature will improve the communication of information between the various disciplines involved in the design phase (architects, specifiers, construction firms).

2.2 Diagnostics, Repair and Rehabilitation

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 project their benefits; and 4) provide 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, Connor, Darter and Carpenter 87] and PAVER [Shahin and Walther 90], represent the most comprehensive systems, and are the result of five and ten years effort, respectively. These systems are written in conventional computer program languages and are considered to be the only fully operational and supported knowledge based systems for pavements in existence today. Table 1 lists the expert systems related to this area that were found as a result of this survey.

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, such as the activities being conducted by the Strategic Highway Research Program (SHRP), C-100 series projects. 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 accuracy. Two systems found as a result of this survey: 1) the Bridge Rating Expert System described in Section 4.2.1, and 2) the CRACKS expert system described in Section 4.2.3 were the only two existing systems that address distress identification and diagnostics related to highway pavements and structures.

3. EXPERT SYSTEM DEVELOPMENT METHODS AND TOOLS

Expert systems contain two major components: 1) knowledge; and 2) an inference engine. Knowledge is what is known about the domain or subject area. The inference engine is the control part that tells how the knowledge is to be used. As with an expert, these two components must be present in order to solve problems. How knowledge is arranged and represented in the expert system depends on the relationships of each piece of knowledge [Waterman 86], and how each piece of knowledge is to be used with the inference engine. In a hierarchical knowledge structure, the most important component is addressed first (see Figure 2), normally in a top-down design. This design is used when the expert system is designed to achieve a goal and/or sub-goals, based on the resolution of rules that are established. It is typical of diagnostic expert systems.

In an object-oriented designed system, knowledge is organized in a network architecture, where objects contain classes, and instances (see Figure 3). This architecture is similar to frame based systems that have been in existence for a number of years. The most significant difference is the increased inference capabilities that are available (e.g. backward chaining, forward chaining, demons, rules, objects). A combination of these inferences can be used with the knowledge within a single expert system. In an objects-oriented system, objects can inherit properties of other objects. Objects are supported by attributes (rules, demons, and procedures), that operate on the knowledge. This type of expert system design provides greater flexibility in using the knowledge, and a better interface to external procedures (e.g. computer models, statistical programs, visual information, etc.).

This section describes the various methods that are appropriate for knowledge engineering, and expert system tools that allow the implementation of these methods. For the purpose of this report, only those architectures that are considered relevant to pavement applications, and those that were used in systems surveyed in this report, will be discussed.

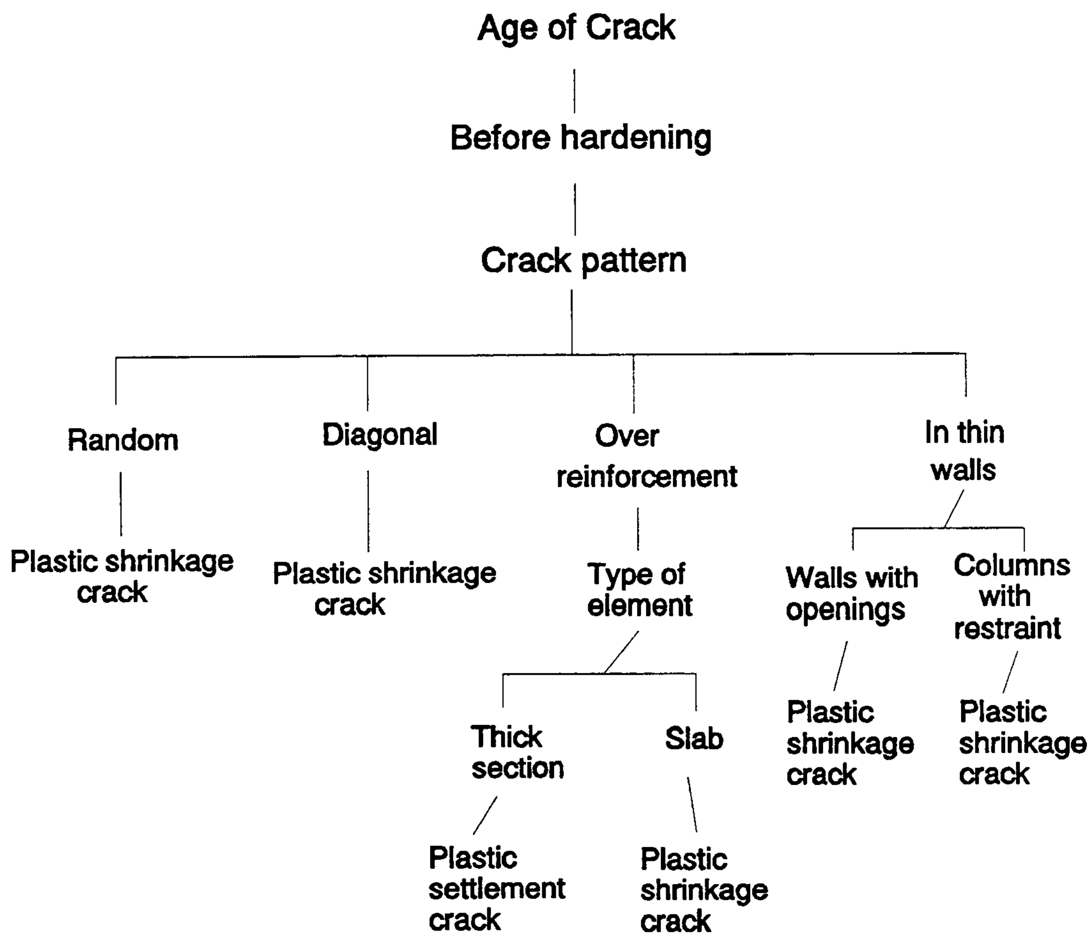

Figure 2. Example of a rule based hierarchical knowledge structure.

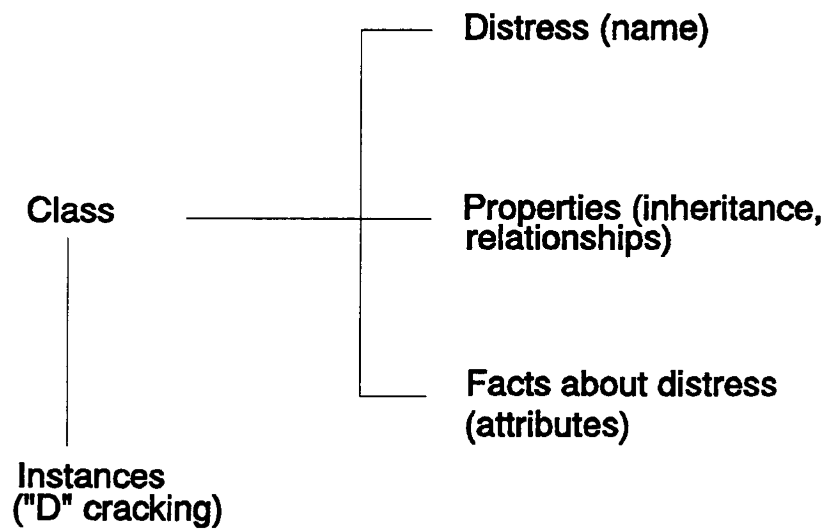

Figure 3. Example of an object-oriented knowledge structure.

3.1 Knowledge Engineering

3.1.1 Rule Based Systems

The majority of expert systems developed today that use shell programs, use the rule based method of representing knowledge. Rules are developed that tell the inference engine how to use the knowledge. Rules represent IF **condition** THEN **action** statements. For example,

[1] If the age of the concrete is before hardening, and the crack pattern is random, then the crack may be a plastic shrinkage crack.

The inference engine will employ a backward chaining, or forward chaining procedure to test for true/false conditions of a related sub-set of rules. This procedure is continued until an established goal and/or sub-goal is achieved. The goal may represent recommendations, conclusions, or a hypothesis.

The use of backward chaining inference implies that there is a single path (sub-set) of rules in attempting to find the goal. End-user input (answers to questions) are used to find the correct solution-set of rules. This is most common in diagnostic systems. In backward chaining inference, the system goals are stored in the knowledge base and it searches for the rules that can achieve it.

In the forward chaining inference procedure, there may be several solution-sets of rules possible in reaching the goal(s). The consequence of one rule being true may infer that another rule is true. Rules are chained in a forward direction, as the system attempts to search for new information in achieving the goal(s).

A powerful feature that exists in rule based expert system inference mechanisms allows the expert system designer to alter the true/false condition of rules. This procedure deals with uncertainty of whether the rule is 100% true or false. For example, an operator response to a question may allow a range of certainty to be specified, (e.g. 70% sure of its accuracy). This capability is discussed in Section 3.1.3.

3.1.2 Object Oriented (Frame) Systems

In an object-oriented system, knowledge is grouped in a way that an expert normally thinks of the knowledge domain. The advantage of an object-oriented expert systems is its ability to:

[1] use multiple inference methods for a single knowledge base
[2] allow objects to be defined and relationships drawn to other objects
[3] integrate different forms of knowledge
[4] increase the knowledge engineer's productivity

The two major components of an object are: class and instance. The class component defines the objects properties and attributes. The instance contains the knowledge values. For example, a class called "distress" may be established, this class may be further divided into subclasses for materials related distresses and in-service related distresses. The members of these subclasses share the characteristics and behavior of the class "distress".

The attributes of a class involve facets, methods, rules, and demons. These affect the behavior and control of the class.

Object-oriented programming has become a popular method for developing computer software and is becoming more popular in representing knowledge. Meyer in his text, "Object-Oriented Software Construction" [Meyer 88], suggests that object-oriented programming is neither trivial or a fad. This is obvious as shown by the number of software tools available commercially toady. One example of the current expert system development tools available is the Level5 Object program from Information Builders [Information Builders 90].

3.1.3 Certainty Factors and Fuzzy Sets

Facts and rules of an expert system may not always be true or false. This affects the accuracy and validity of the information. Expert system tools can provide a mechanism to account for this uncertainty. Certainty factors or fuzzy set theory [Negoita 85] programmed in the inference procedure provides this capability. One expert system surveyed in this report uses certainty factors to incorporate subjective observations in assessing the condition of concrete structures in the field [Mijamoto 89]. Although this may seem a powerful and obvious feature to design into an expert system, it may present a difficult problem in acquiring knowledge (establishing thresholds for example) and for the execution of rules. Another possible use of utilizing certainty factors would be to report probabilities of a failure diagnosis. For example, based on what is known about the situation, there might be a 60% probability that a failure of a concrete structure is early drying shrinkage or a 40% probability that the failure is thermal stress.

3.2 Development Tools

3.2.1 Knowledge Engineering Languages

Early developers of expert systems were left with few development tools for implementation. Computer programming languages that were designed to represent knowledge in a symbolic way were the only choice, other than conventional languages, such as FORTRAN and PASCAL. The symbolic languages LISP and PROLOG were predominately used. However, the use of these languages required many man years to complete the expert system programming effort (10-20 years in some cases). Also, they required a long learning curve, and the systems were difficult to maintain, due to the lack of qualified programmers. This was a major factor in the slow acceptance of expert systems in practice. These languages did, however, accomplish the objective of separating domain knowledge from the inference engine, unlike conventional languages.

The trend today is away from the use of knowledge engineering programming languages. This is largely due to the flexibility of expert system shell programs (their relatively low level of development effort), and the introduction of small computer based tools. This is not to say that programming languages are not used in the development of expert systems. Comprehensive expert systems are commonly hybrid systems that use expert system shell programs to support the main body of knowledge and inference engine, and extensions written in either conventional or knowledge engineering languages, to interface specific procedures (e.g. models, computation, graphics, etc.).

3.2.2 Expert System Shells

One of the first shell programs to be developed was OPS5. A mid-sized computer was used to develop the program at Carnegie Mellon University [Brownston, Farrell, Kant and Martin 85]. Since then, it has been adapted to smaller computer systems such as personal computer workstations. The microcomputer shell program dominates the market today. Scientific and engineering workstations have also been used successfully in the development of expert system shells such as ART and KEE.

Probably the greatest impact on the availability of shell programs was the introduction of the desktop and portable personal computer. In 1986, for example, there were more than 30 shell programs available for the IBM and compatible personal computer. A constraint of these systems, however, was that they were developed to address a particular type of knowledge domain, and the inference procedures were inflexible. Also, poor software quality, and slow performance characterized these tools. These tools were typically used to develop small prototypes and to learn expert system development techniques. Several shell programs have emerged as productive tools for developing expert systems today. This survey revealed the most popular programs used for cement and concrete activities include: SAVOIR [ISI Ltd.]; Personal Consultant Plus [Texas Instruments, Inc.]; Level5 PC and Level5 Object [Information Builders], and EXSYS [Exsys, Inc.]. These systems were predominantly used in the expert systems surveyed in this report. It is expected that advances in the development of expert system shell programs will be made, and they will continue to dominate the development of expert systems in the future.

3.2.3 Computer Platforms

As stated earlier, expert systems can be developed for all sizes of computer systems. Clearly, the most economical development alternatives exist in utilizing the personal computer. This is reflected in the number of systems surveyed in this report. One consideration for this type of system, however, is the lack of support for development tools, compared to mainframe and mid-sized computers. Also, small computer based tools tend to be less versatile, the developer must consider the possibility of developing custom computer programs to accomplish the final objective of the system. Shells based on larger computers may have greater flexibility in interfacing databases and graphics, and manufacturers maintain a large support staff.

Given that these constraints exist, personal computers still represent the ideal computer platform for pavement expert systems. These systems are routinely found in highway departments. Therefore, inspectors and engineers already know how to use the equipment. They provide an economical platform for placing expert system technology in practice. Advances in the performance capabilities of PC's, and in user interfaces permit fast microprocessor systems to be installed for approximately $5000.

Another significant feature that can be provided on a desktop computer is a graphical user interface to the expert system. Some expert system tools already use this method of providing the user with visual information in the form of graphics, pictures, and icons [Information Builders and Neuron Data]. These assist the user in better understanding the knowledge or to report the information that is necessary to support the decision making process. For example, since knowledge often can be represented more appropriately in the form of displayed photographs and drawings of distress conditions, a significant increase in user acceptance and understanding can be achieved.

4. EXISTING EXPERT/KNOWLEDGE BASE SYSTEM APPLICATIONS

4.1 Concrete Design Applications

4.1.1 **BETVAL.** BETVAL is a rule based expert system that provides advice on the selection of ready mix concrete for the job site. The purpose of the system is to assist construction site personnel in choosing the type of fresh concrete ordered from the ready mix concrete plant.

Methodology. Recommendations provided by the system are based on three areas of knowledge: 1) the compressive strength class and appropriate concreting techniques (e.g. curing, heating and heat treatment; 2) concrete consistency value based on the type of structure and the production equipment, and 3) recommendations on choosing the maximum size aggregate.

Current State of Project. BETVAL is one of several knowledge based systems developed at the Technical Research Center of Finland (VTT). The system was developed using Insight2+ and uses an IBM PC/XT or AT computer. It is a demonstration prototype system that is being used primarily as a learning tool. Increasing the knowledge base for BETVAL would be required before it could be used as a production system.

Reference. [Seren 88]

4.1.2 **COMIX.** COMIX is a rule and frame based knowledge based system that gives recommendations on the design of concrete mixes. The system is designed to be used by concrete technologists, design engineers, and consultants.

Methodology. COMIX first computes the amounts of cement, course aggregate and sand for $1m^3$ of concrete. The mix design is based on the New Zealand code Specification for Concrete Construction. The system relates the type of structure to the consistency, and placement method. The system also recommends a water/cement ratio from a specified strength and calculates the amount of cement. The volume of coarse aggregate and sand if finally calculated and the masses of the components of the concrete mix are calculated and displayed.

Current State of Project. The system was developed at Central Laboratories in New Zealand. The knowledge contained in the system represents expert information from a resident authority. Changes are being made to the system to extend the knowledge base to include revision of cement types and their strength factors.

Reference. [Smith 87]

4.1.3 **CONCEX.** CONCEX is a knowledge based expert system designed to assist in the quality assurance of concrete at the construction site. The system seeks to provide an understanding of factors effecting the concrete quality, tests at various ages to predict quality, and to provide an easily accessible method of consultation and explanatory reasoning process to the user.

Methodology. The knowledge base for CONCEX represents information obtained from books, journals, manuals and experts in the field. The system consists of five modules:

[1] calculate concrete strength
[2] mix design and properties
[3] diagnosis of slump or air content
[4] compressive strength prediction
[5] compressive strength prediction as various ages

CONCEX was developed at Rutgers University, using the RuleMaster expert system development tool. The knowledge is represented in IF-THEN production rules. Programs written in C and FORTRAN are embedded in CONCEX. These programs perform numerical calculations needed for the expert system. The expert system is operational on an IBM PC microcomputer system.

Current State of Project. CONCEX is currently in a development stage.

Reference. [Williams, Khajuria and Balaguru 91]

4.1.4 **Concrete Mix Designer.** Concrete Mix Designer is a rule based expert system designed to provide information on trial mix proportions of concrete. The expert system knowledge is represented as IF-THEN rules that are grouped together as "frames". Each frame represents a component of the concrete, such as amount of coarse aggregate, dry sand, and includes an expert system goal. The system is designed to serve as a tool for engineering students and practicing engineers.

Methodology. Concrete Mix Designer uses the absolute-volume method to determine the proper proportions of ingredients. The knowledge contained in the system was obtained from The American Concrete Institute, Publication SP-1 and a Portland Cement Association publication. The system determines the following properties of the cement:

o appropriate slump
o water/cement ratio
o amount of air content
o amount of coarse aggregate
o amount of dry sand

The user specifies the strength of the concrete, type of structure, and exposure condition. The system then attempts to derive conclusions based on its knowledge. Conclusions in the form of text are presented to the user. Graphics and tutorial information may be selected to substantiate the knowledge and provide explanatory information.

Current State of Project. Concrete Mix Designer is a prototype expert system that executes on a personal computer. The system was developed at the University of Miami in the Dept. of Civil and Architectural Engineering. The system was developed using the Personal Consultant Plus expert system shell. Also, computer programs were written in BASIC to provide question and answer capability. These programs interface to the expert system knowledge base and provide modularity.

Reference. [Malasri and Maldonado 88]

4.1.5 **DURCON.** DURCON is an expert system that gives recommendations on the selection of concrete constituents for the following durability areas: corrosion, freeze-thaw, sulfate attack, alkali-aggregate reaction. The system also recommends the water/cement ratio and amount of cover for different environments. It was developed to provide expert knowledge for specifiers of concrete.

Methodology. The embodied knowledge of DURCON represents the American Concrete Institute, Guide to Durability of Concrete, ACI 201.2R-77, and expert knowledge from ACI Committee 201 members. The approach taken in the development of DURCON was to divide the knowledge into four sub-systems, each representing an area of durability. The user of the system first selects the durability area, then answers questions related to the types of exposure, and concrete constituents such as aggregate size, and admixture.

DURCON was developed originally in the conventional programming languages of FORTRAN and PASCAL. It was later converted to the Insight expert system shell, and in 1988 upgraded to the Level5 PC shell. The shell environment provided an improved method for knowledge enhancement by separating the knowledge from the inference (logic) procedures. DURCON is designed to run on an IBM PC/XT/AT using the DOS operating system.

Current State of Project. The system has been distributed to ACI constituents for critique. An ACI 201 task group is currently revising the system to include new knowledge from the revised ACI 201 guide.

Reference. [Clifton, Oltikar and Johnson 85]

4.1.6 **ESCON.** ESCON is a rule based expert system designed to model the production of conventional concrete. The objective of the system is to improve the quality of concrete by minimizing mistakes in batch and mixing procedures. The system is designed to provide an understanding of concrete batching and mixing methods for new and inexperienced personnel.

Methodology. The structure of ESCON can be divided into two major parts: 1) batching and 2) mixing of concrete. Recommendations related to batching include: on-site and off-site; volume batching and weight batching; concrete quality; user selected equipment; and production rates. Recommendations related to mixing include: mixing method; quality control of the mix (e.g. cement balls, head packs, overmixing).

State of Project. ESCON is currently in a development state. It is being expanded to include additional knowledge related to concrete operations, namely transportation, finishing and curing.

ESCON was developed using the SAVOIR expert system shell. The system represents a joint effort between Eastern Mediterranean University, Famagusta, Cyprus, and Loughborough University of Technology, in England.

Reference. [Celik, Thorpe and McCafter 89]

4.2 Diagnostics, Repair and Rehabilitation Applications

4.2.1 **BRIDGE RATING EXPERT SYSTEM**. The BRIDGE RATING EXPERT SYSTEM is designed to provide a serviceability rating for bridge structures in Japan. The system was developed to assist engineers in assessing the condition of various bridge elements. The system addresses serviceability, durability, and load capacity. The system incorporates knowledge from experts, probability theory (for subjective observations), and a relational database component.

Methodology. There are two basic components to the expert system: 1) The Bridge Rating Expert System, and 2) a Fuzzy Relational Database. These two components contain inference rules for the system, and knowledge about the structure, respectively. The expert system addresses reinforced slab and girder components of bridges. The knowledge domain includes information on the following conditions:

- o cracks
- o corrosion of steel
- o deflection of girders
- o dynamic properties of slabs

The goal of the system is to rate the condition of the bridge, in one of five categories, from safe to dangerous. The system uses the Dempster and Shafer's theory of basic probability to determine the appropriate category. The fuzzy set relational database was developed from information contained in questionnaires received from highway staff. This information represented opinions based on observations made by practicing engineers. The system uses both forward and backward chaining inference. The system performed well during tests of three bridge sites.

The expert system was developed using the computer languages of PROLOG and C. dBASE II was used to manage the database. The system executes on a NEC personal computer system.

State of Project. The Bridge Rating Expert System is currently in the development stage. The system is being expanded to include data from new structures.

Reference. [Miyamoto, Kimura and Nishimura 89]

4.2.2 **CRACK.** CRACK is a rule based expert system designed to diagnose the causes of cracking of cast-in-place concrete structures, namely, tunnels, tanks, and foundation walls. The system also recommends methods for controlling and repairing cracking. The system contains Chinese design codes and specifications for constructing concrete structures.

Methodology. CRACK knowledge and inference is represented in four modules and two external computer programs. Their functions are to check for design and construction deficiencies, diagnose cracking, and evaluate the risk and recommend repair methods.

The CRACK design checking capabilities are based on the Chinese design codes and specifications. The minimum requirements on grades of concrete, steel reinforcement, and limitations on stress concentration for the construction codes are represented in the expert system rules. An external computer program is used to input information about a structure's characteristics, environment, and operation. These data are later used by the diagnostic module to calculate stress, temperature, and crack dimensions.

The CRACK construction fault-checking module checks against Chinese construction codes, specifications, and standards. This module addresses the effect of construction on concrete constituents, mix, operation, vibration, curing and formwork.

The diagnosis module of CRACK attempts to determine the stress condition. This module uses information from the user obtained in the acquisition module. It describes the crack age, pattern, location, direction, depth, length, and width.

The repair and rehabilitation module of CRACK evaluates the consequences of the cracking and recommends a repair method. The recommendations are based on the cause and characteristic of the cracking, load factors, and crack history.

As stated previously, the CRACK knowledge base was developed from Chinese design and construction code, and includes concrete diagnostic expert knowledge, from the field. The system was developed using an expert system shell and the programming language FORTRAN for external calculations.

State of Project. CRACK is a developmental prototype system and is undergoing field testing.

Reference. [Wang, Qin and Li 89]

4.2.3 **CRACKS.** CRACKS is a rule based expert system designed to provide inspectors and facility managers with conclusions about the probable cause of cracks in concrete. The system deals with primarily non-structural cracks in concrete elements, such as slabs, columns, thick sections, and thin walls. The CRACKS knowledge base is represented in three forms: 1) facts, and rules of thumb; 2) database information; and 3) digitized images.

Methodology. CRACKS attempts to identify the probable cause of the crack by first requesting the age of the observed crack in the element. Drawings and photographs of actual failures are used to provide the user with a visual display for identification and confirmation. The system currently deals with cracks in early ages, after hardening and when the age of the crack is unknown. The system relies on the inspector's visual inspection and uses knowledge from experts in the field of concrete crack diagnostics to derive its conclusions. When a goal has been reached, the system displays the probable cause (e.g. plastic shrinkage, "D" cracking, etc.). Also, examples are displayed of typical crack patterns associated with the specific cause. The images help the user in confirming the conclusion reached by the expert system.

CRACKS was developed using the Level5 PC expert system shell. An IBM PC/XT/AT/386 personal computer or compatible is recommended for its use. Custom computer programs were written in the programming language C. These programs provide explanatory facilities, image display, and utility functions.

Current State of Project. CRACKS is a developmental prototype system developed at the National Institute of Standards and Technology. The system is currently available for review and comment. Additional knowledge covering other types of distress (e.g. spalling, disintegration, etc.), and recommendations on tests to confirm system hypotheses would be needed to make CRACKS an operational system.

Reference. [Kaetzel, Clifton and Bentz 89]

4.2.4 **EXPEAR.** EXPEAR is a knowledge based system designed to assist highway engineers in evaluating and rehabilitating concrete pavements. EXPEAR is designed to simulate a consultation between a highway engineer and a pavement expert. The system has the following capabilities: pavement evaluation; identifying type and some general causes of deterioration; selecting rehabilitation techniques and strategies; and predicting performance of rehabilitation alternatives. Three pavement types are considered by the system: 1) jointed reinforced concrete pavement (JRCP); 2) jointed plain concrete pavement (JPCP); and 3) continuously reinforced concrete pavement (CRCP).

Methodology. EXPEAR maintains the most comprehensive knowledge base on concrete pavement evaluation and rehabilitation available. EXPEAR is a highly data driven system that uses data and knowledge from pavement studies dating back to 1985, and from experts in concrete pavements. The system deals primarily with pavement performance, and uses predictive models to show future pavement performance. EXPEAR uses the following procedures to obtain its recommendations:

- o project data collection (present condition)
- o prediction of future condition without rehabilitation
- o physical testing
- o selection of main rehabilitation approach
- o development of rehabilitation strategy and performance prediction
- o cost analysis of alternatives
- o selection of preferred rehabilitation strategy

EXPEAR integrates both diagnostic (evaluation) and design (rehabilitation) activities for pavement management. The system is intended to be used on Interstate-type divided highways with two lanes in each direction and either asphalt or concrete shoulders. The major problem areas covered by EXPEAR include:

- o structural capacity
- o drainage
- o foundation stability
- o roughness
- o concrete durability
- o skid resistance
- o transverse joint condition
- o longitudinal and transverse joint construction
- o load transfer
- o slab support
- o joint sealant reservoir design
- o shoulder condition

Concerning durability, EXPEAR addresses only D-cracking and alkali-aggregate reactivity. It does not provide recommendations on the selection of materials.

EXPEAR is written in PASCAL and executes on an IBM or compatible personal computer. Adapting EXPEAR to execute in an expert shell environment would enhance the maintenance and future enhancements to the system.

State of Project. The current version of EXPEAR is 1.3. The system was developed initially for the Federal Highway Administration. Support has continued for system development through the Illinois Department of Transportation. EXPEAR is an operational system.

Reference. [Hall, Connor, Darter and Carpenter 89]

4.2.5 **PAVEMENT EXPERT.** PAVEMENT EXPERT is a rule based expert system designed to assist inspectors and engineers in condition assessment and making field observations on concrete pavements. The system automates the process of making observations, and produces a pavement rating to support decision making.

Methodology. The system is based on the manual Pavement Condition Rating (PCR) index for pavements. It considers incidence, severity, and the extent of range of distress for each road section. Twelve distresses are analyzed by the system. These distresses are included in the following categories: surface deterioration, patching, pumping joint spalling, and cracking.

PAVEMENT EXPERT involves several procedures:

- o initial inspection and data logging
- o review observations
- o detailed inspection
- o review PCR indexes

During the initial inspection and data logging phase, a mobile unit and portable computer are used to make visual observations of the pavement condition. From this phase, a preliminary evaluation is provided to the user. A graphical display aids the user in reviewing and identifying the observed distresses. A detailed inspection is then performed to enable the PCR index to be determined. During this time, the user maintains a dialogue with the system. The system directs the user to the sections in distress. A help facility can be used to obtain information summarizing the distresses, give details, describe the current stage of the evaluation and start and stop the inspection. The final step in the system is to review the results and make adjustments in pavement section boundaries. The results are summarized and the PCR, and Structural Design indexes are computed.

The SAVOIR expert system shell was used to develop the expert system. Computer programs written in PASCAL were linked to the expert system. The programs were used to represent procedural logic. The system executes on an IBM or compatible personal computer.

Current State of Project. PAVEMENT EXPERT is an operational prototype system. The system is being used by highway staff in the U.K.

Reference. [Al-Shawi, Cabrera and Watson 89]

4.2.6 **PAVER.** PAVER and Micro PAVER are knowledge based or decision support systems for pavement management. PAVER is the mainframe version, and Micro PAVER executes on a microcomputer. PAVER has been developed to optimize the use of funds allocated for pavement maintenance and rehabilitation. Micro PAVER can be used to manage roads, streets, parking lots, and airfield pavements. The PAVER systems were developed to provide engineers with a systematic approach for determining maintenance and rehabilitation needs and priorities for pavement management. The PAVER system address distresses in asphalt and concrete roads, parking areas and airfields.

Methodology. The PAVER system is based on the Pavement Condition Index condition survey and rating procedure developed at the U.S. Army Construction Engineering Research Laboratory. Although PAVER was developed for use at military installations, its use is applicable to municipalities, airports, universities, and consultants. Requirements for using PAVER are to develop a Network Inventory. This involves the establishment of a database to identify and describe the pavement, condition survey results, construction and repair information, and surface type. Once the network has been established, the user can use the system to perform a "network analysis" or project analysis. Network analysis can be used for projecting long-term maintenance and rehabilitation needs. Project analysis is for current year or near-term needs.

The Network Analysis results in a projected condition, budget scenario, and work plan. This can subsequently be used to produce an actual budget and priority list for projects. Project analysis provides the user with detailed condition survey information, feasible alternatives for maintenance and rehabilitation.

Data collection for PAVER has been implemented using condition distress sheets to standardize and facilitate the process. Reporting capabilities of the system include: inventory, inspection scheduling, Pavement Condition Index frequency, budget condition forecasting, and network maintenance.

The pavement condition survey is a key component of the PAVER system. During this operation, the distress, severity, and condition index is determined. This is performed through a visual inspection of random units of the pavement inventory (sections). Once the condition survey has been recorded in the database, the various network analysis and project analysis reports can be generated.

PAVER has been developed for a mainframe timesharing computer. It can be accessed via telephone lines using a computer terminal and modem, or personal computer. Micro PAVER can be purchased to execute on an IBM Personal Computer. The programming languages of FORTRAN and C were used to develop computer program for PAVER and Micro PAVER. Data file structures are compatible with the RBASE database management system.

Current State of Project. The systems are revised frequently to incorporate new techniques for pavement management. They are considered operational systems. Version 2.12 is the current version. Version 3.0 of Micro PAVER will be available in the Spring of 1991. It will include increased capabilities for family analysis curves (graphical representations of related pavement sections), reporting, and file export.

Reference. [Shahin and Walther 90]

4.2.7 **REPCON.** REPCON is a rule based expert system designed to help engineers to judge the condition of damaged concrete structures and to recommend repair proposals. The system is based on the German Association for Concrete and Reinforced Concrete regulations.

Methodology. The user of REPCON first describes the structure, structural parts of the building, and information concerning the damage. The knowledge base considers damages to structure due to carbonation, chlorides, chemical causes. REPCON then attempts to analyze the damage and produces a repair proposal. Data files are interfaced to the expert system. These files contain information about the structure (its name, size, and type), a description of the damage and different repair strategies. The data files are used by the data management program to recommend the appropriate set of repair strategies. The expert system also utilizes pictures of typical damages to support the decision making process. Certainty factors are used in the system to deal with "don't know" or "uncertain" responses from the user.

REPCON was developed using the Personal Consultant Plus expert system shell. The system operates on an IBM Personal Computer or compatible.

State of Project. REPCON is a developmental prototype system.

Reference: [Reinhart and Sohni 89]

4.2.8 **SEVADER.** SEVADER is the expert system component of a highway network management system designed to assist highway technicians and decision makers. The information management portion of the highway management system is called ORAGE. ORAGE is an optimized management model for storing and prioritizing highway structure information. The systems are designed to be used in French cities by staff involved in designing and maintaining streets, sidewalks, gutters and sidewalks.

Methodology. ORAGE and SEVADER may be used separately or together. However, the use of both systems provides the end user with the advantage of using a comprehensive management system, especially since ORAGE provides a relational database tool for storing the structure's history. Data is gathered and stored in ORAGE and allows the user to set up priorities based on:

- o pavement surface deterioration
- o bearing capacity of pavement structures
- o loading
- o conditions of gutters and curbs
- o condition of sidewalks.

Data contained in the ORAGE relational database relates to street functionality, type of use, presence of underground networks and history. Users may obtain reports containing a dictionary of streets, segmentation of road network, evaluation of road and classification segments, various statistics relating to conditions and use requirements, and topical maps. This information can then be used by practicing engineers to interact with SEVADER, which contains the reasoning (rules and logic). The knowledge of SEVADER includes choices of surface for overlaying and grinding, feasibility of geometrical factors, durability and costs. Users may establish priorities for six different aspects of pavement management decision making:

[1] durability
[2] environment
[3] comfort
[4] maintenance
[5] economy
[6] safety.

The knowledge domain of SEVADER is organized into three specific areas:

[1] Diagnostics - for assessing the condition of examined roads facilities
[2] Recommendations - for searching to obtain appropriate repair strategies
[3] Pavements - to aid in the best choice of products.

The recommendations given by SEVADER are based on the objectives and priorities established by the user (as related to the six different areas), and the repair strategy that is feasible based on technical and geometric constraints. The system also determines the minimum durability requirements. SEVADER gives recommendations on both bituminous and hydraulic concrete pavement and structure types. An optional analysis report and reasoning used by the system is also available. In addition, the system makes recommendations that indicate no work or minimum work (e.g. patching) is needed. One of the most important features of the system is that it provides the user with an effective on-line aid of 65 prioritized road segment indicators.

SEVADER was developed using the ESCOP expert system shell program which is written in LISP. The system currently contains approximately 15,000 lines of computer code and 600 rules. The ORAGE component was develop using the ORACLE relational database management system. Both components of the system were developed by the Association of Engineers of French Cities (AIVF). They are designed to operate on either a 286 or 386 based microcomputer, depending on the number of highway segments to be managed, and whether the systems are to be used separately or combined.

State of Project. SEVADER and ORAGE is an operational system currently in use in France. ORAGE is being used in 30 different cities, SEVADER in 7. Future plans for enhancement include computer networking to tie together data collection systems, management models, and expert systems for geographically dispersed highway facilities.

Reference. [Christory and Laye 91].

5. FUTURE TRENDS

Since there are many pavement management systems being used by highway departments today, and there is a need to automate the process of diagnosing and repairing pavements, one could expect that the use of more automated ways of accomplishing these goals will be implemented. Vast amounts of information are being collected and stored in databases and are being used to aid decision makers. What has not been accomplished, on a large scale, is the connectivity to decision making rules and procedures, construction codes, and guidelines. This knowledge integration will enhance the decision making process by providing more accurate and timely information for rehabilitation, planning, and budgeting of pavement projects. The improved development tools that are now available for expert systems make them easier to develop, and in less time. This is expected to result in more comprehensive and intelligent systems that possess automated methods of distress detection and analysis, connectivity to databases, and improved decision making capabilities.

6. CONCLUSIONS

The result of this survey has revealed several key factors relating the development and use of expert systems for concrete pavement applications:

1. Existing applications tend to have a very shallow knowledge domain (except for EXPEAR and PAVER).
2. Most systems are hybrid (they use more that one development tool, such as a shell and conventional programming language).
3. Many of the systems are prototypes and are not fully operational.
4. The existing systems have been developed for specific and very narrowly defined applications.
5. There are few expert systems in existence that address the concrete pavement knowledge domain, and virtually no operational systems using expert system development tools.

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Appendix 1. Glossary of expert system terms

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

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

demon A forward-chaining IF-THEN rule.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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