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DEVELOPMENT OF A KNOWLEDGE-BASED SYSTEM FOR THE REPAIR AND MAINTENANCE OF CONCRETE STRUCTURES

BY

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Abstract

Information Technology (IT) can exploit strategic opportunities for new ways of facilitating information and data exchange and the exchange of expert and specialist opinions in any field of engineering. Knowledge-Based Systems are sophisticated computer programs which store expert knowledge on specific subject and are applied to a broad range of engineering problems. Integrated Database applications have facilitated the essential capability of storing data to overcome an increasing information malaise. Integrating these areas of Information Technology (IT) can be used to bring a group of experts in any field of engineering closer together by allowing them to communicate and exchange information and opinions.

The central feature of this research study is the integration of these hitherto separate areas of Information Technology (IT). In this thesis an adaptable Graphic User Interface Centred application comprising a Knowledge-Based Expert System (DEMAREC-EXPERT), a Database Management System (REPCON) and Evaluation program (ECON) alongside visualisation technologies is developed to produce an innovative platform which will facilitate and encourage the development of knowledge in concrete repair. Diagnosis, Evaluation, MAintenance and REpair of Concrete structures (DEMAREC) is a flexible application which can be used in four modes of Education, Diagnostic, Evaluation and Evolution. In the educational mode an inexperienced user can develop a better understanding of the repair of concrete technology by navigating through a database of textual and pictorial data.

In the diagnostic mode, pictures and descriptive information taken from the database and performance of the expert system (DEMAREC-EXPERT) are used in a way that makes problem solving and decision making easier. The DEMAREC-EXPERT system is coupled to the REPCON (as an independent database) in order to provide the user with

recommendations related to the best course required for maintenance and in the selection of materials and methods for the repair of concrete.

In the evaluation mode the conditions observed are described in unambiguous terms that can be used by the user to be able to take engineering and management actions for the repair and maintenance of the structure.

In the evolution mode of the application, the nature of distress, repair and maintenance of concrete structures within the extent of the database management system has been assessed. The new methodology of data/user evaluation could have wider implications in many knowledge rich areas of expertise. The benefit of using REPCON lies in the enhanced levels of confidence which can be attributed to the data and to contribution of that data. Effectively, REPCON is designed to model a true evolution of a field of expertise but allows that expertise to move on in faster and more structured manner.

This research has wider implications than within the realm of concrete repair. The methodology described in this thesis is developed to provide technology transfer of information from experts, specialists to other practitioners and vice versa and it provides a common forum for communication and exchange information between them. Indeed, one of the strengths of the system is the way in which it allows the promotion and relegation of knowledge according to the opinion of users of different levels of ability from expert to novice. It creates a flexible environment in which an inexperienced user can develop his knowledge in maintenance and concrete repair structures. It is explained how an expert and a specialist can contribute his experience and knowledge towards improving and evolving the problem solving capability of the application.

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Chapter 1

Introduction

1.1 Introduction

Concrete is one of the most versatile of basic building materials worldwide. It is durable, strong and will take the shape of the form in which it is placed (Cordon, 1974). The durability problem of concrete structures is common worldwide, reducing the lifetime of structures and proving costly in terms of diminishing building value. Over the last decade, there has been considerable interest in the durability and maintenance of concrete structures and a wealth of knowledge has been promulgated at various conferences. The term "durability" has become a popular generic term in the context of concrete structures. ASTM STP 691(1980) states that "Durability is, technically and economically, one of the main considerations in selecting construction materials and how they should be used. In some cases, the word 'durability' refers only to the ability of materials to resist actions such as weathering, corrosion, erosion, abrasion, alkali-silica reaction and freezing-thawing."

Another definition of durability used by RILEM (1994) states that "Durability is the capability of a building, assembly, component, structure or product to maintain minimum performance over at least a specified time under the influence of any of the group of external factors, including weathering, biological, stress, incompatibility and use." Therefore, it can be concluded that durability is the ability of concrete to resist weathering action, chemical attack, physical and mechanical actions and other conditions of service.

Although the two most important requirement of construction works are strength and durability, much construction is still not designed for durability. Because of the many internal and external interacting influences, engineering problems concerned with durability are generally complex. In most developed countries, designing and constructing concrete structures of enhanced durability, thereby reducing maintenance and repair costs, has been a focus in recent decades and more emphasis has been given to the maintenance and repair of existing facilities (ASTM, 1980).

Concrete repair is a complex process, presenting unique challenges very different from those experienced in the field of new concrete construction. Concrete repair must successfully integrate new materials with old materials, forming a composite capable of enduring the exposures of use, the environment, and time. In the last few years, the repair of deteriorated concrete structures has become a significant matter of concern for civil engineers and contractors so that an increasing proportion of the funds being spent on construction, especially concrete bridges, is used for the repair of damaged concrete structures. In addition, a significant number of companies are involved in the development and supply or repair products, in damage appraisal, in product selection, and in the execution of repair and maintenance techniques. Many companies promote themselves as experts in the field of concrete repair. It is not uncommon in view of the above for a client to appoint an inexperienced or incompetent repair contractor, or to become the victim of an inappropriate repair technique (Emmons P.H.; 1993, Evbuomwan et al.; 1994, SERC; 1990).

According to Evbuomwan (1994) and SERC (1990), the current trend in the UK, where concrete repair and maintenance accounts for approximately 40% of construction output and is rising every year, makes it very important to avoid a repair failure. Failure could arise from poor workmanship, improper design and inadequate product selection. A similar situation exists abroad.

In light of the issues discussed above, therefore, there is an urgent need for the optimisation of repair and maintenance costs. These considerations also contributed to the basis for the idea of an intelligent repair and maintenance knowledge-based system and the idea of an advisory management system and a need to marshal all available data in a common format for repair and maintenance of reinforced concrete structures.

1.2 Motivation

The use of Information Technology (IT) in construction is becoming increasingly sophisticated with virtual reality, knowledge-based systems, database management systems, object-oriented approaches and neural networks among the latest technological advances (Betts M, 1999). Integrated engineering computing systems have evolved into sets of algorithmic programs that interact with a central database management system (DBMS) (Howard et al, 1986). Database management systems are important in those engineering computing applications where the volume of data is very large and where the same data must be shared by several users and programs. Engineering computing applications are making increasing use of database management systems to provide these capabilities. Knowledge-based programming techniques or Expert Systems (ES) are applied to a wide range of design, engineering, management and economic problems. The capabilities of expert systems are well suited for work in ill-structured problem domains where conventional algorithmic methods are impractical and where expert problem-solving knowledge is available.

Whilst Information Technology (IT) is used in many different forms such as ES and DBMS, there is little linking and sharing of information between them. Furthermore, most of the prototype expert system applications in engineering could not have been linked to unlimited amount of data and have no facility for sophisticated data management. The combined use of database management systems (DBMS) and knowledge-based expert systems is potentially very valuable for modern engineering computing applications. The large body of knowledge usually required in engineering information systems can be made available to an expert system through an existing commercial database management system. Furthermore, the DBMS itself can be used more intelligently and operated more efficiently if enhanced with expert system features.

Integrating of these two separate areas of Information Technology (IT) can be used to bring a group of experts and specialists in any field of engineering closer together by allowing them to communicate and exchange information and data. Not only will it create a more readily available up-to-date information, it should encourage the more rapid development of knowledge and experience in any field of engineering. It will allow the industry to realise the benefits which can be gained from coupling knowledge-based systems and database management systems in support of the redesigned processes.

1.3 Aim and Objectives

The present work is motivated by a need to transfer knowledge and expertise from the research area of repair of concrete structures and make it available to structural and construction engineers so that they may confidently use the repair and maintenance of concrete structures in educational and practical situations. Although the repair of concrete research programmes have produced a large body of expertise, applying that expertise remains difficult for the inexperienced user. There is a need to provide technology transfer of information with practical guidance from experts and specialists to other practitioners and vice versa.

The purpose of this research is to explore the coupling of knowledge-based expert systems with an independent database management system for the repair of concrete structures. Specifically, the research focuses on a radical approach to knowledge engineering in which a database is no longer a static resource under the direction of one organisation. Rather, it evolves according to informed consensus. In this respect, it models the way in which expertise has traditionally evolved. In addition, a flexible interface between a knowledge-based expert system and a database management system has been implemented to demonstrate the strategies developed for dealing with these issues. Each of KBES and DBMS contains knowledge describing its data structures and data access methods.

In this research, the DEMAREC (Diagnosis, Evaluation, MAintenance and REpair of Concrete structures) application is developed as a new software to address the issue of the integration of concrete distresses (cracking, surface and miscellaneous distresses), investigation and diagnosis problems, repair materials and methods and given recommendations relating to durability. DEMAREC is new application and a Visual Basic interface in which a multiple rule based expert system (DEMAREC-EXPERT) is coupled to the REPCON (as an independent database) and an evaluation of concrete program (ECON). The application comprises an Expert System, a Database Management System and a Visual Basic User Interface. The Expert System is implemented in M.4, a commercially available expert system shell. The database is implemented in Microsoft Access and in the Graphic User Interface in Visual Basic running in the Microsoft Windows Environment.

1.4 Definition of Terms

Knowledge-Based Expert System

Knowledge-Based Expert Systems (KBES) or Expert Systems (ES) are computer programs using Artificial Intelligence (AI) techniques which involve human knowledge and experience in solving problems. The Expert System comprises three main components, i.e. the knowledge base, the inference mechanism and the working memory. It can be linked to external application programs such as a Database Management System.

Knowledge Base

A Knowledge Base is the repository of information relating to a particular domain or application derived from a human expert. It comprises documented definitions, facts, rules, procedures and objects.

Inference Mechanism

The Inference Mechanism, also known as Inference Engine, is the processor in an expert system that matches the facts contained in the working memory and the domain knowledge contained in the knowledge base to draw conclusions about the problem.

Working Memory

The Working Memory of the expert system is used as temporary storage for facts discovered during a consultation. Its content alters dynamically and comprises information provided by the user about the specific problem and information derived by the system.

Knowledge Acquisition

Knowledge Acquisition is a way in which knowledge and problem-solving expertise is acquired from some knowledge source and experts for building or extending a knowledge base. Primary sources of knowledge for providing some information on the given problem include technical publications, published codes of practice, standards, domain experts by interview and/or questionnaire, textbooks and case histories.

Knowledge Representation

Knowledge Representation is the method used to encode knowledge in an expert system's knowledge base. Knowledge in expert systems can be represented in many various systems such as rule-based, semantic network, frame and objected-oriented.

Reasoning Techniques

Reasoning or Inferencing is the process in expert systems that controls the selection and use of knowledge and the facts in the knowledge base to draw conclusions about the problem. It achieves by using one of the two main reasoning processes known as forward chaining or backward chaining. These techniques represent the direction of the search through the knowledge base.

Searching Strategies

Searching is the process of problem solving in expert systems in which a particular solution path is preferred over the other. In this process, a set of possible solutions is sought by traversing a state space. The state space is a tree or graph containing nodes and arcs or links used for searching for solution to a given problem. The nodes represent possible problem states and the links possible paths between states. Two different search strategies can be adopted comprising the depth-first search and the breadth-first search.

Expert System Shell

Shell is an expert system development package that has inference mechanism, working memory and perhaps other expert system development facilities without having the knowledge base.

Database Management System (DBMS)

Database Management System (DBMS) is a computer application which manages all interactions with a database. A database is a structured repository collection of information and data sharable between different users. The data of which could be in the any form of text, numbers or pictures.

Data Model

Data Model is a general architecture for data organisation made up of three components: a set of data structure, a set of data operators and a set of inherent integrity rules. The proposed data models include record-based data models such as relational data model and object-based data models such as object-oriented data model.

Expert Database System (EDS)

Expert Database System (EDS) is used in a number of different senses:

- A system formed from the combination of an expert system with a database system.
- An expert system enhanced with database management facilities or a database system enhanced with a deductive component.
- An advanced database system employing new architectures for knowledge representation.
- Any system lying at the interaction of Artificial Intelligence (AI) and database work.

Graphic User Interface (GUI)

The Graphic User Interface (GUI) is a system of screens and dialog boxes through which the user interacts with the internal workings of the program. It enables the user to input the data required by the program and receive the output from the program.

1.5 Organisation

The remainder of this thesis is organised into the following Chapters:

Chapter 2 presents the general problems of the maintenance and repair of concrete structures. In this Chapter it is shown how each of the topics in the repair of concrete can be developed into a database and how those topics contribute to an intelligent repair and maintenance knowledge-based expert system.

Chapter 3 introduces an overview of knowledge-based expert system technology, its principles, development environments and M.4 as a development environment used in this research. In this Chapter expert system technology used in structural design and particularly used in the repair and maintenance of concrete structures is presented.

Chapter 4 discusses the background to database management systems, the evolution of the technology and current development environment. In this Chapter various architectures for interfacing knowledge-based expert systems with database management systems are reviewed.

Chapter 5 presents data survey methods and discusses procedures adopted in developing a questionnaire for the eliciting of knowledge.

Chapter 6 presents the interface of the DEMAREC application and its components for the integrated approach to the diagnosis, evaluation, maintenance and repair of concrete structures. An overview of the interface and its interaction with expert systems, database and evaluation program is discussed.

Chapter 7 describes the REPair of CONcrete (REPCON) database developed as part of the application. It is shown how the REPCON management system is designed to be an effective support tool for experts and specialists whose data can be evaluated to ensure that the evolving database retains its integrity.

Chapter 8 describes the DEMAREC-EXPERT system component of the application. This part of the application is created to disseminate the knowledge of concrete distresses and recent advances in concrete repair problems. In addition, the knowledge acquisition process is also discussed.

Chapter 9 describes the Evaluation of CONcrete (ECON) component of the DEMAREC application. In this Chapter an inspection procedure and rating method for evaluating the physical condition and performance of concrete structures is presented.

Chapter 10 discusses the evaluation of the DEMAREC application and its implementation and presents conclusions and possible future directions in this area of research.

This research has wider implications than within the realm of concrete repair. The research creates a flexible environment in which an inexperienced user can develop his interest in concrete repair technology while an expert can contribute his experience and knowledge towards improving and evolving the problem solving capability of the application. Indeed, one of the strengths of the system is the way in which it allows the promotion and relegation of knowledge according to the opinion of users of different levels of ability from expert to novice. The methodology presented in this research can be applied in any area of expertise which is knowledge based.

Chapter 2

General Problems in the Maintenance and Repair of Concrete Structures

2.1 Introduction

The repair of concrete structures requires much greater attention than may be necessary for new concrete construction (USACE, 1995). These considerations result from the necessity for an accurate assessment of structural conditions and cause(s) of distress, the degree of expertise required for the repair design and specification, the variety of site operations which involve highly specialized construction techniques and the selection of repair materials and methods. The investigation, maintenance and repair of a concrete structure must be considered concurrently.

In the light of the above, there is a need for gathering available information and data in the maintenance and repair of concrete structures in order to arrive at realistic and proper diagnosis of the cause(s) of the distress, to provide expertise advice on material selection and to enable adequate repair techniques. These considerations also contributed to an intelligent repair and maintenance knowledge-based system for reinforced concrete structures. This Chapter aims to discuss the issues that need to be considered in the development of such an intelligent advisory system (discussed in Chapters 3 and 8) in collaboration with a database management system.

In this Chapter, the general problems of the maintenance and repair of concrete structures are presented. It begins by examining the current needs in the construction industry which would cover the various types of structure and construction and then discusses the possible concrete repair problems currently encountered while considering the various causes, symptoms and manifestations of concrete problem. It also includes information on how to conduct an evaluation of the concrete in a structure. One of the main focuses of this Chapter is to describe the various materials and methods that are available for repair or rehabilitation of concrete structures. Each of the topics in this Chapter has been developed into a database for the repair of concrete structures. This is explained in discussed in Chapters 4 and 7.

2.2 Types of Structure

Integrity and durability problems generally affect any type of concrete structure. Amongst factors such as the history of the structure and its use and location, it is imperative to consider the possible types of concrete structure that might be in need to repair. Such structures include:

Reinforced concrete buildings such as public, industrial or residential, bridges, concrete canals; retaining walls and bulkheads, dams and barriers, car parks, hydraulic and marine structures such as offshore concrete platforms and jetties and so on. Types of structure are listed in Figure 2.1.

2.3 Types of Design and Construction

One of the factors to be considered in the repair and maintenance of concrete structures is the type and nature of the construction of a concrete structure. The final choice of repair strategy will depend on it. General classifications can be used on in-situ, precast, unreinforced concrete and a combination of these systems (Figure 2.2).

2.4 Types of Structural Element

Structural members are subject to an inevitable repair program, depending on the type of structure and level of impairment. Structural elements can be classified into floor and roofing systems (beam, slab and connection), wall, column, deckslab, pedestal, pier, abutment, pile, foundation, joint related and segment. They can be also used in various combinations of geometry, size, design and construction.

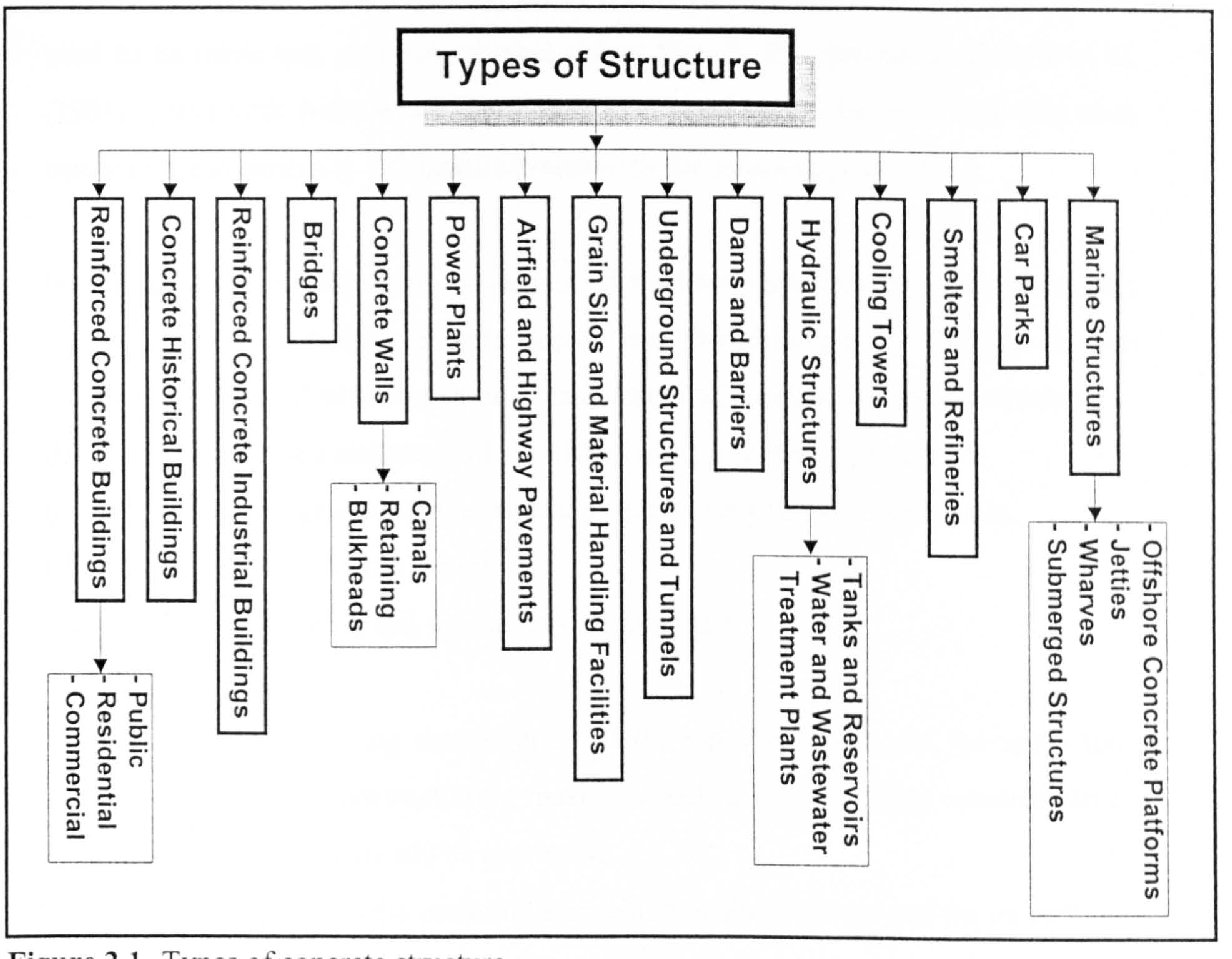


Figure 2.1- Types of concrete structure.

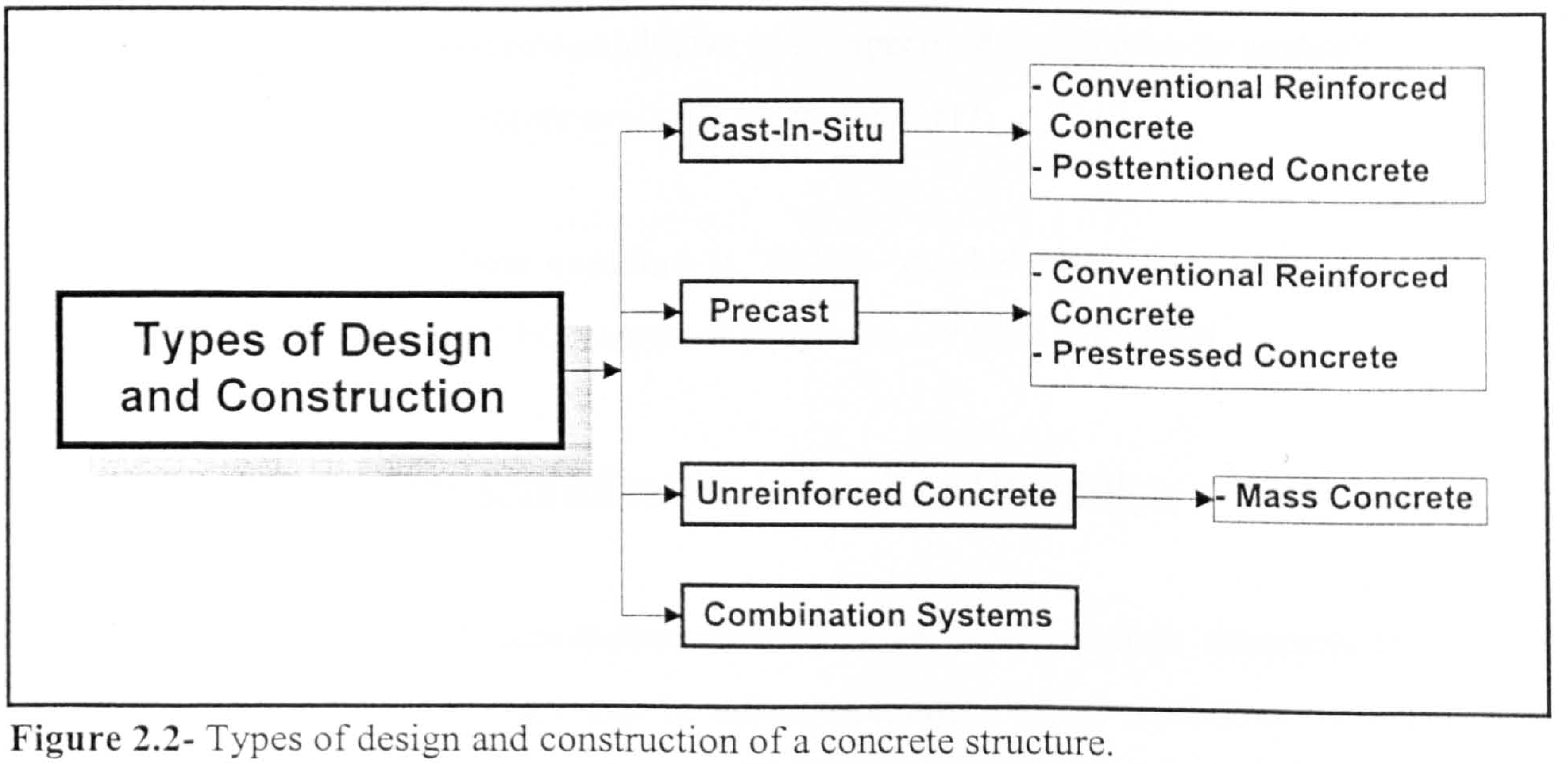


Figure 2.2- Types of design and construction of a concrete structure.

2.5 Constraints to Concrete Repair and Maintenance

Restoration projects are usually subject to numerous and complex constraints which need to be taken into account amongst others factors. By comparing Tracy's et al. (1989) works with Evbuomwan and Anumba (1994), it can be concluded that such constraints can generally be classified relative to the following conditions:

(a) Site access - in relation to movement of workers, materials, and equipment into and out of the facility. Simple access into the structure of buildings is also markedly affected in the repair and maintenance of reinforced concrete structures.
(b) Current operations and usage of structure during restoration project.
(c) Scheduling - programming the most appropriate time to carry out repairs.
(d) Availability of skills and expertise.
(e) Availability of testing and investigation equipment.

Therefore, before finilizing the selection of the repair material and the application method, the system's constructibility must be checked. To determine constructibility, the following questions should be addressed:

- Can it be built within the constraints specified by the engineer and the owner?
- Will the specified installation technique allow the repairs to go into service within the time specified?
- Is the working environment conducive to the specified installation technique?
- Are experienced contractors available for the project?

If the answer to any of these questions is "no" or "maybe", then the choice of repair material and method should be reassessed (Emmons, 1993; ICRI, 1992).

2.6 The Conditions Contributing to Lack of Durability

Inappropriate design and construction methods often cause concrete structures to be affected by lack of durability, integrity and serviceability. These conditions can occur at any time in a structure's service life. Definitions and terms are defined by The

Concrete Society (2000), Emmons (1993), FIP (1991), ASTM (1980), RILEM (1994), Tracy (1989), Allen (1993), and Campbell (1991). They emphasise and represent conditions of damage, defect, deterioration and degradation of concrete structures under various factors. Overall, it can be concluded that these conditions can be classified broadly into *defect, damage* and *deterioration.*

- *Defects* are usually impairments of a structure as a result of structural errors, materials and faults or error of design. Defects often occur early in a structure's life and these impairments are revealed at the first investigation.

- *Damage* is impairment of a structure caused by external mechanical factors while a structure is in service.

- *Deterioration* in a concrete structure can emerge in the event of structural weakness and usually influences concrete members after the structure has been completed and it is in service. It demonstrates the commonest of concrete problems, but generally emerges in a slower process than defects or damage.

2.7 The Causes of Defect, Damage and Deterioration

According to Emmons P. H. (1993) and RILEM (1994), Tracy et al (1989) and Waddell (1980), concrete can be defective for several reasons including inadequate design and analysis, error in construction owing to general poor workmanship and unsuitable materials selection and construction method. Causes of concrete defect are shown in Figure 2.3.

Concrete can also deteriorate or be damaged in use. Damage can be caused by fire (Figure 2.4), natural calamities such as earthquake and flood; impact; abrasion of floor slabs or marine structures and explosion (Figure 2.5). The nature and extent of the damage depends on the severity of the causative agent (Allen, 1993; Evboumwan et al., 1994; Mallett, 1994; Tracy et al., 1989).

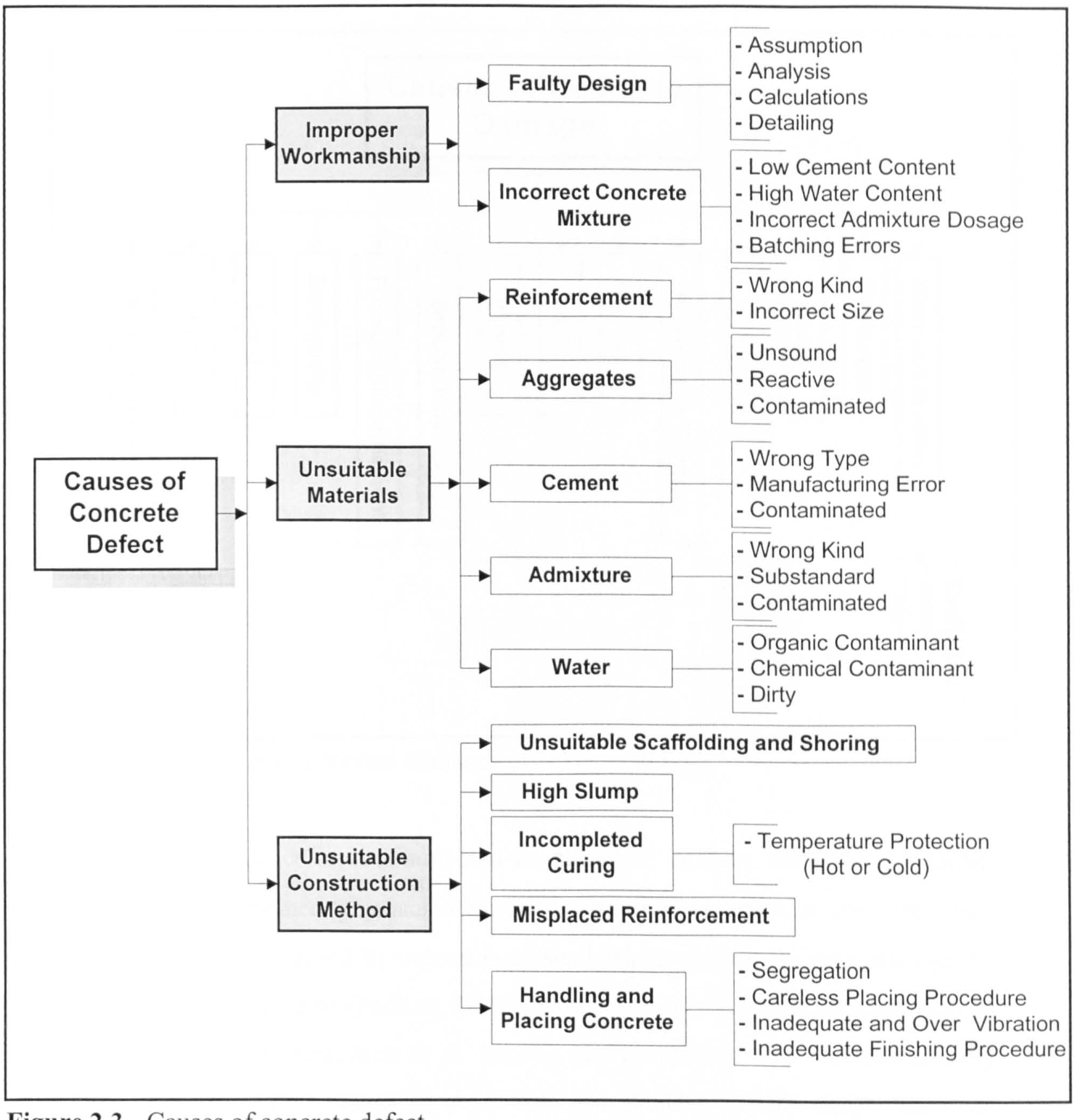


Figure 2.3 - Causes of concrete defect.

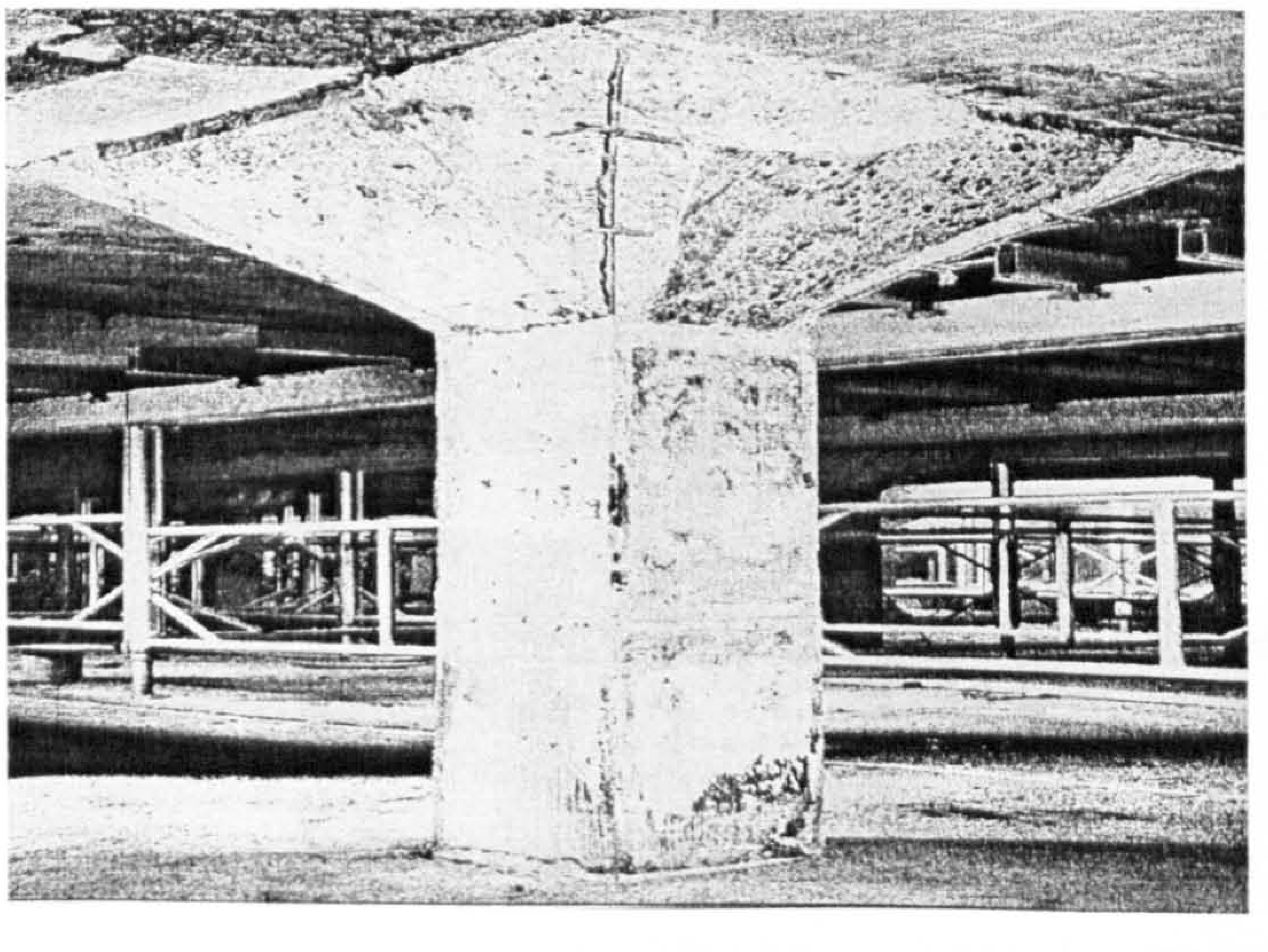


Figure 2.4 - Reinforced concrete structure damaged by fire.

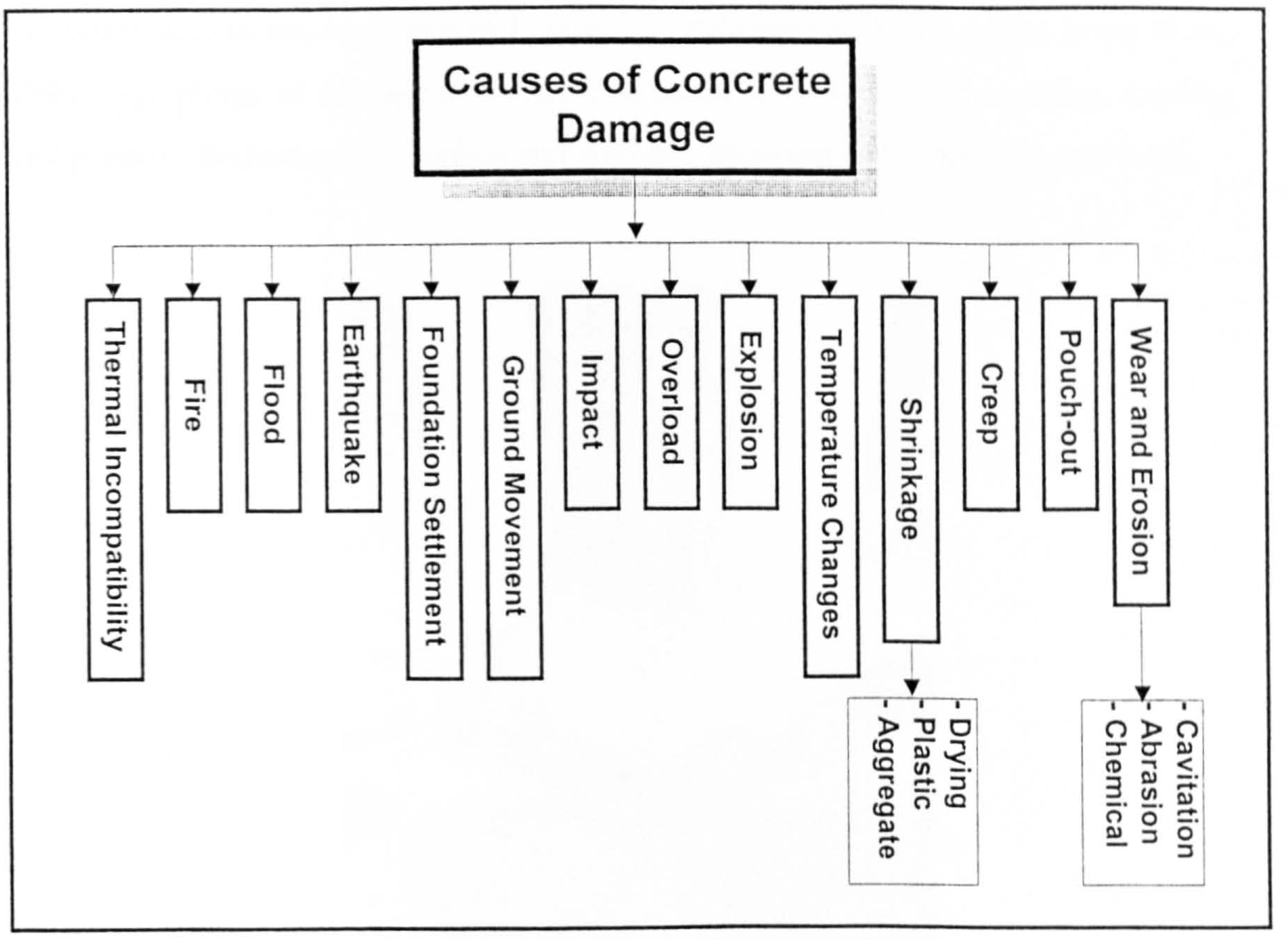


Figure 2.5 - Causes of concrete damage.

Deterioration of concrete structures can be classified in three categories: physical, chemical and combined physical-chemical causes. For example, a concrete crack owing to expansion caused by corrosion of steel reinforcement can take place at the last category (Figure 2.6) (Perkins, 1997). So many researchers and authors such as Campbell (1994), Evboumwan et al. (1994), Mallett (1994), The Concrete Society (2000), RILEM (1994), Tracy et al. (1989) and Waddell (1980) assert numerous causes of concrete deterioration. Some of these causes include factors such as freezing-thawing, sulphate and chloride attack, corrosion of reinforcement, carbonation, leaching, inadequate cover of reinforcement and alkali-silica reactions (ASR) of aggregate (Figure 2.7). Causes of concrete deterioration are shown in Figure 2.8.

2.8 Manifestations of Defect, Damage and Deterioration

Defects generally manifest themselves in the form of honeycombing, discolouration, cracking, segregation, bleeding channel, scaling and disintegration, abnormal deflection and so on, as shown in Figure 2.9 (Evboumwan et al., 1994; Tracy et al., 1989). Symptoms of damage of concrete structure include surface cracking, spalling and popouts, deflection and curling and warping, scouring and pitting (Figure 2.10).

Figure 2.6 - Cracking owing to severe corrosion of reinforcement in concrete column.

Figure 2.7 - Map cracking typical of Alkali-Silica Reaction (ASR).

The various symptoms and manifestations of deterioration of concrete structure include physical, chemical or combined physical-chemical causes. A list of some common symptoms owing to concrete deterioration include the following: internal expansion and cracking, pitting, dusting, corrosion of reinforcing bar, scaling and disintegration, spalling and popouts (Figure 2.11) (Emmons, 1994; Evboumwan et al., 1994). These symptoms are shown in Figure 2.12.

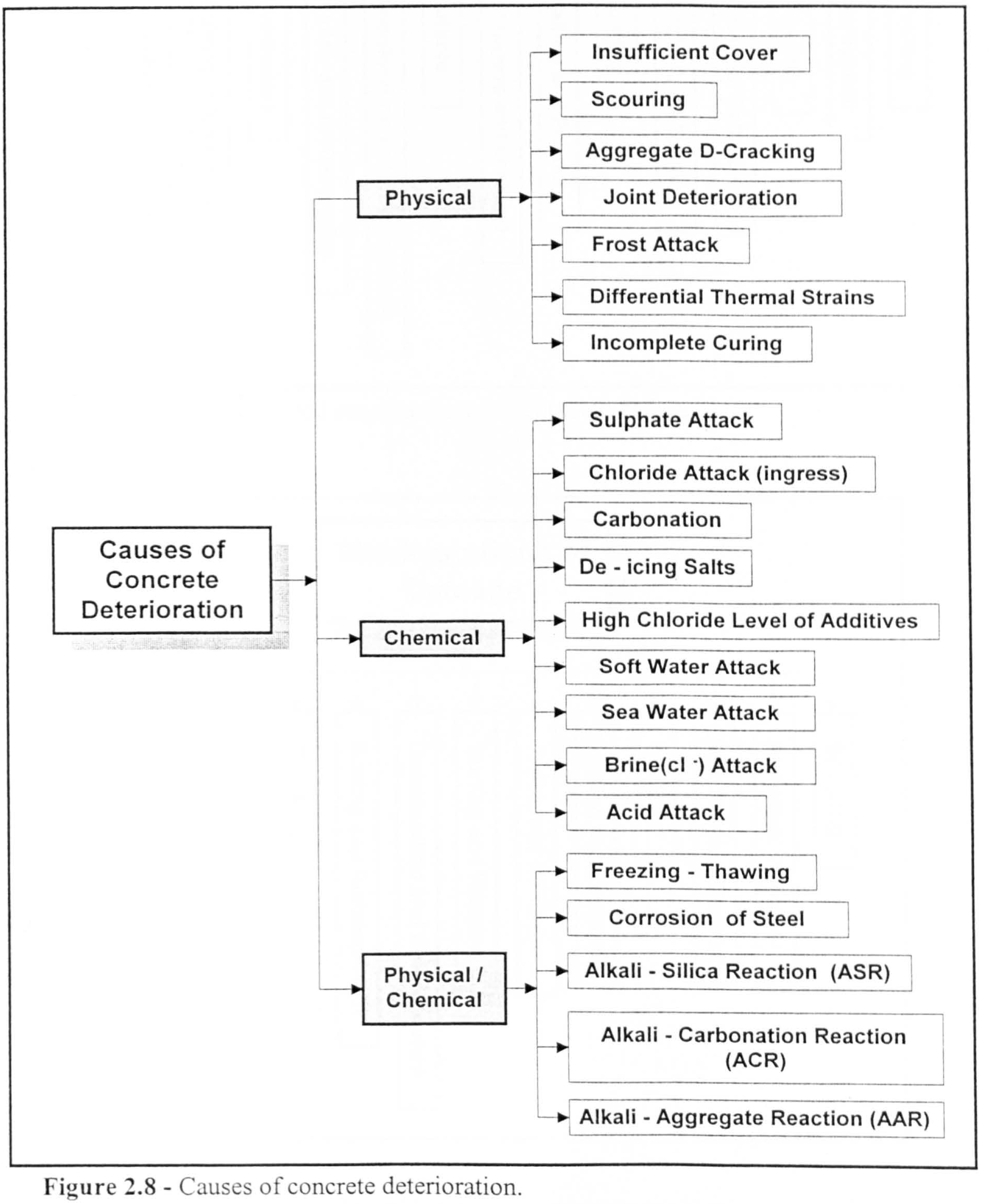


Figure 2.8 - Causes of concrete deterioration.

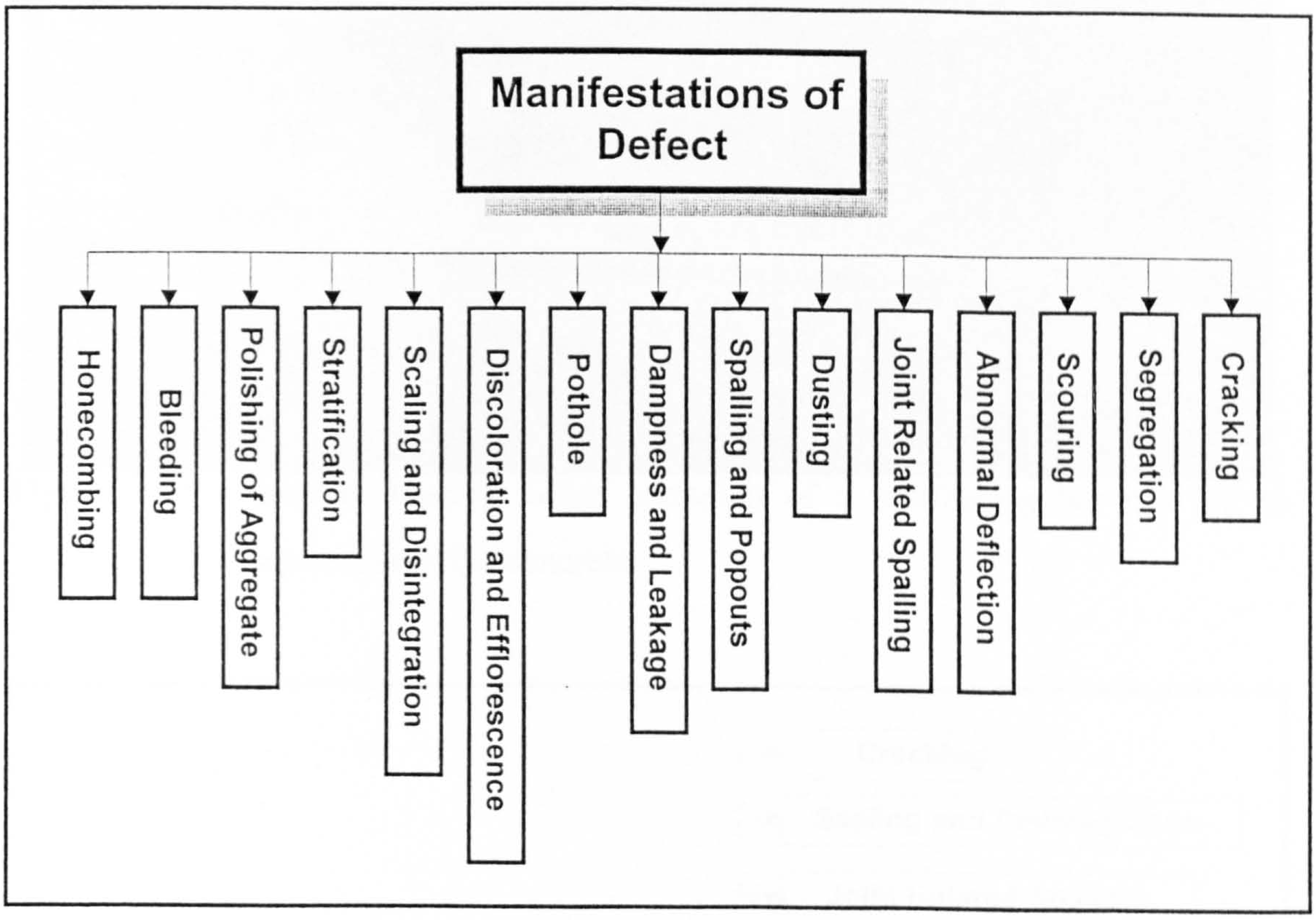


Figure 2.9 - Symptoms and manifestations of concrete defect.

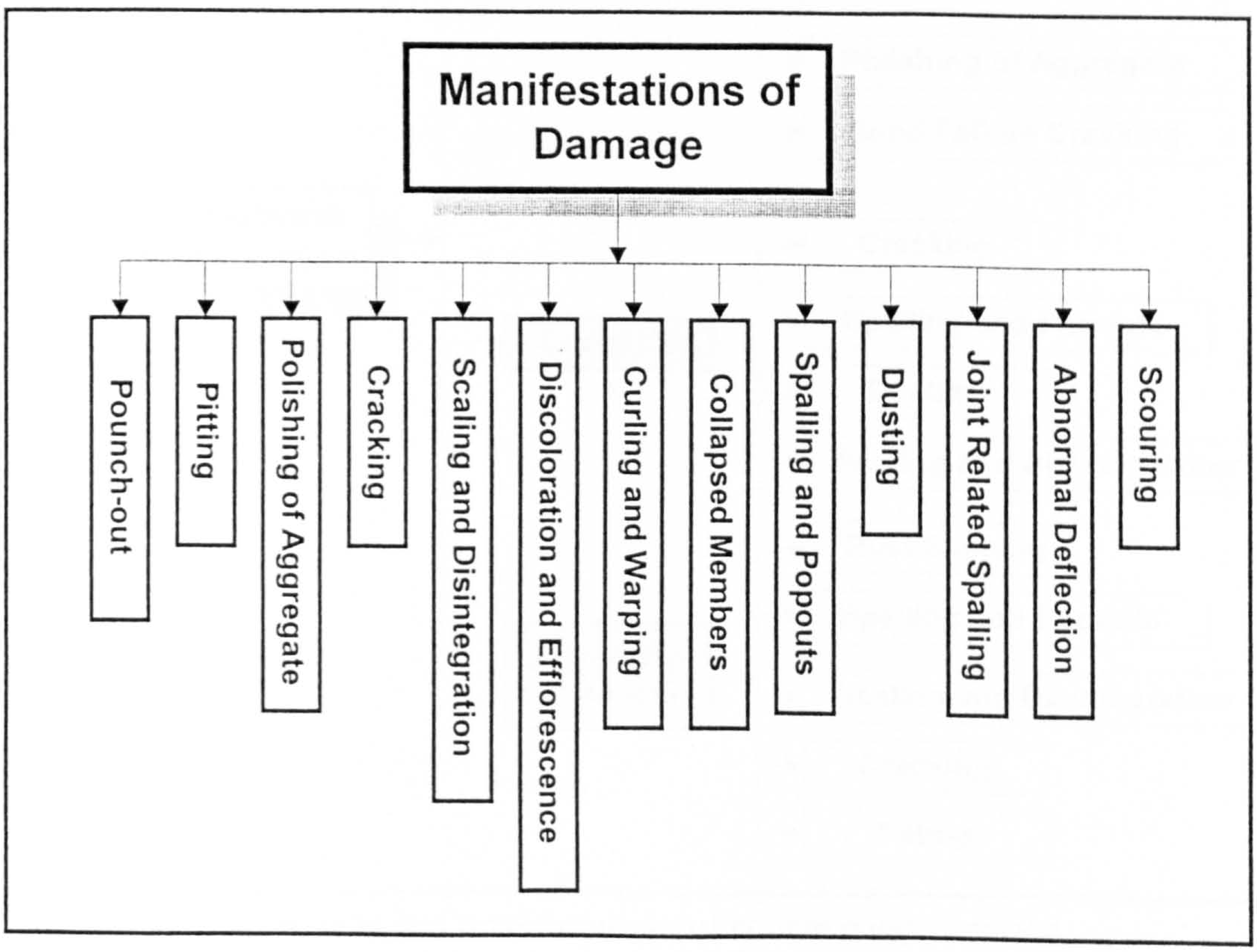


Figure 2.10 - Symptoms and manifestations of concrete damage.

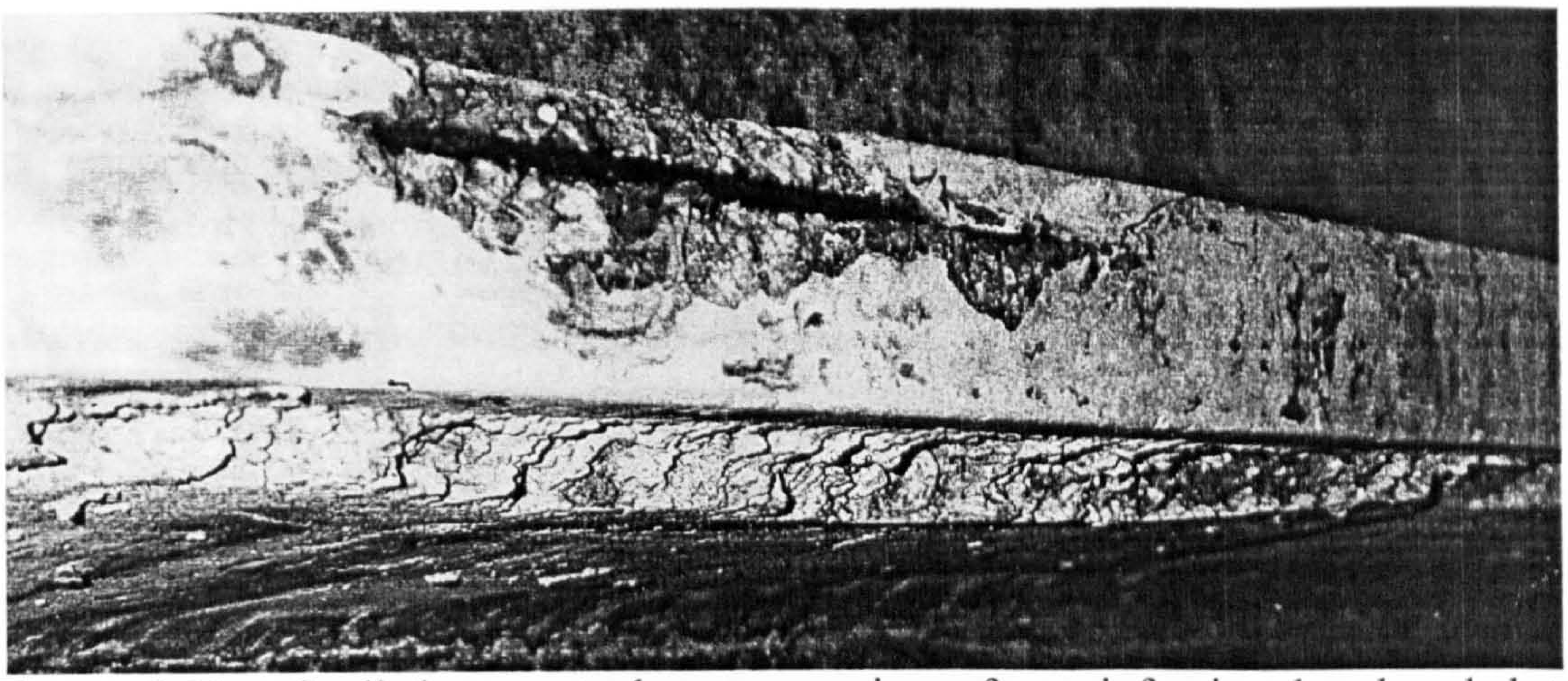


Figure 2.11 - Spalled concrete beam corrosion of a reinforcing bar has led to separation of the concrete.

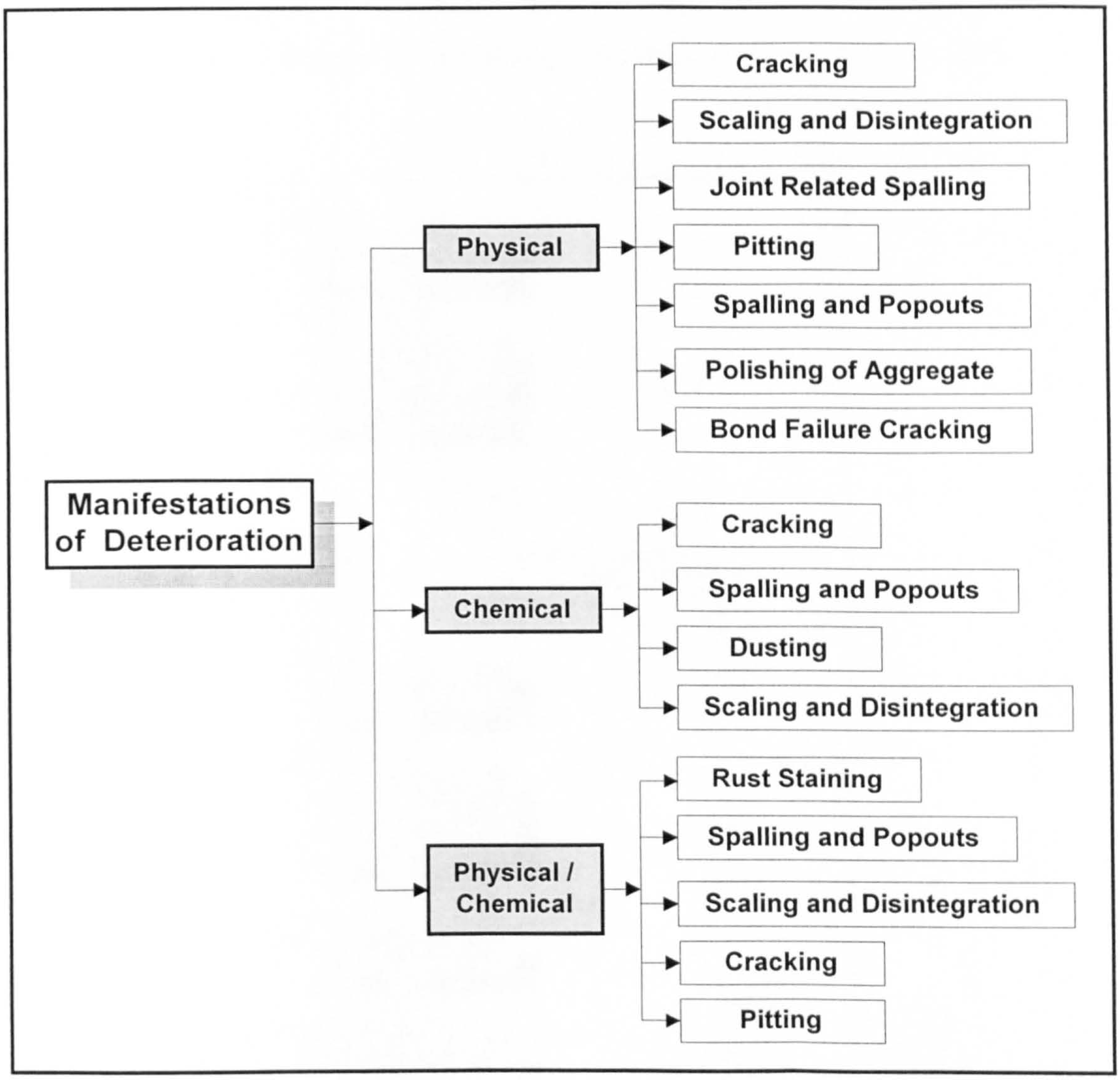


Figure 2.12 - Symptoms and manifestations of concrete deterioration.

2.9 Investigation and Diagnosis of Defect, Damage and Deterioration

Before deciding on any repair work, the cause of impairment must be diagnosed as clearly as possible. Sometimes the cause is obvious, but as a rule careful investigation is required. Only then should the method of repair be chosen (Allen, 1993). A thorough and logical investigation of the current condition of the structure is the first step of any repair or rehabilitation project. According to Emmons P. H. (1993) and Waddell (1980), the process leading to an effective and durable repair is diagnosis, prognosis or evaluation of the impairment, progressing through selection of materials and method, preparation of the damaged area and application of the repair. A successful repair program on the foregoing basic steps is shown in Figure 2.13.

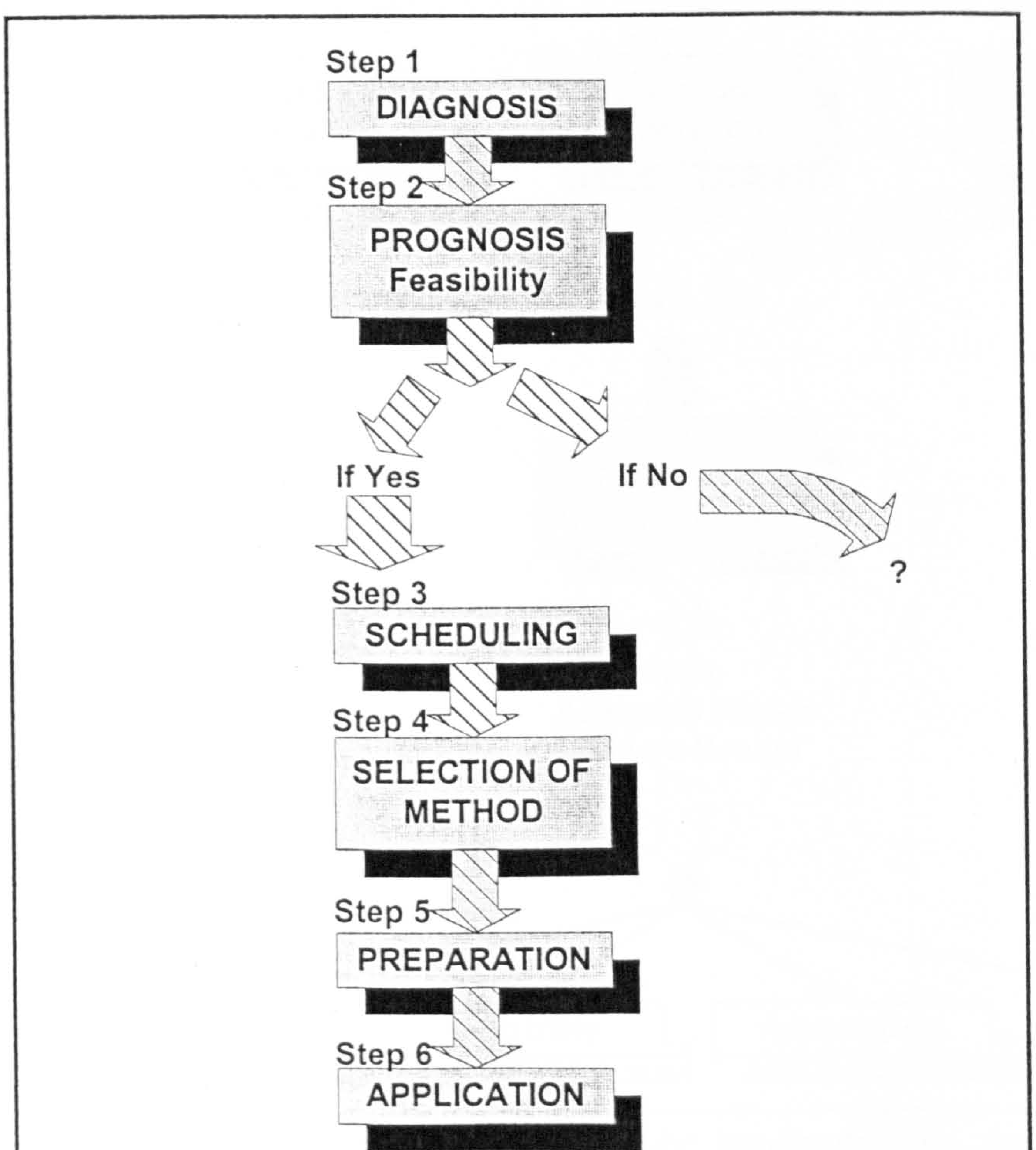


Figure 2.13 - Basic steps of a concrete repair program (Waddell, 1980).

It is very important that a correct diagnosis of the cause of impairment be made because an incorrect diagnosis can lead to the selection of an inadequate repair method that could lead to premature failure of the repair. Correct diagnosis should lead to selecting sound materials, thorough preparation and proper application method alongside consideration of compatibility of repair materials and existing concrete to have a durable repair system. Factors affecting satisfactory repair are shown in Figure 2.14 (Emmons, 1994; Waddell, 1980).

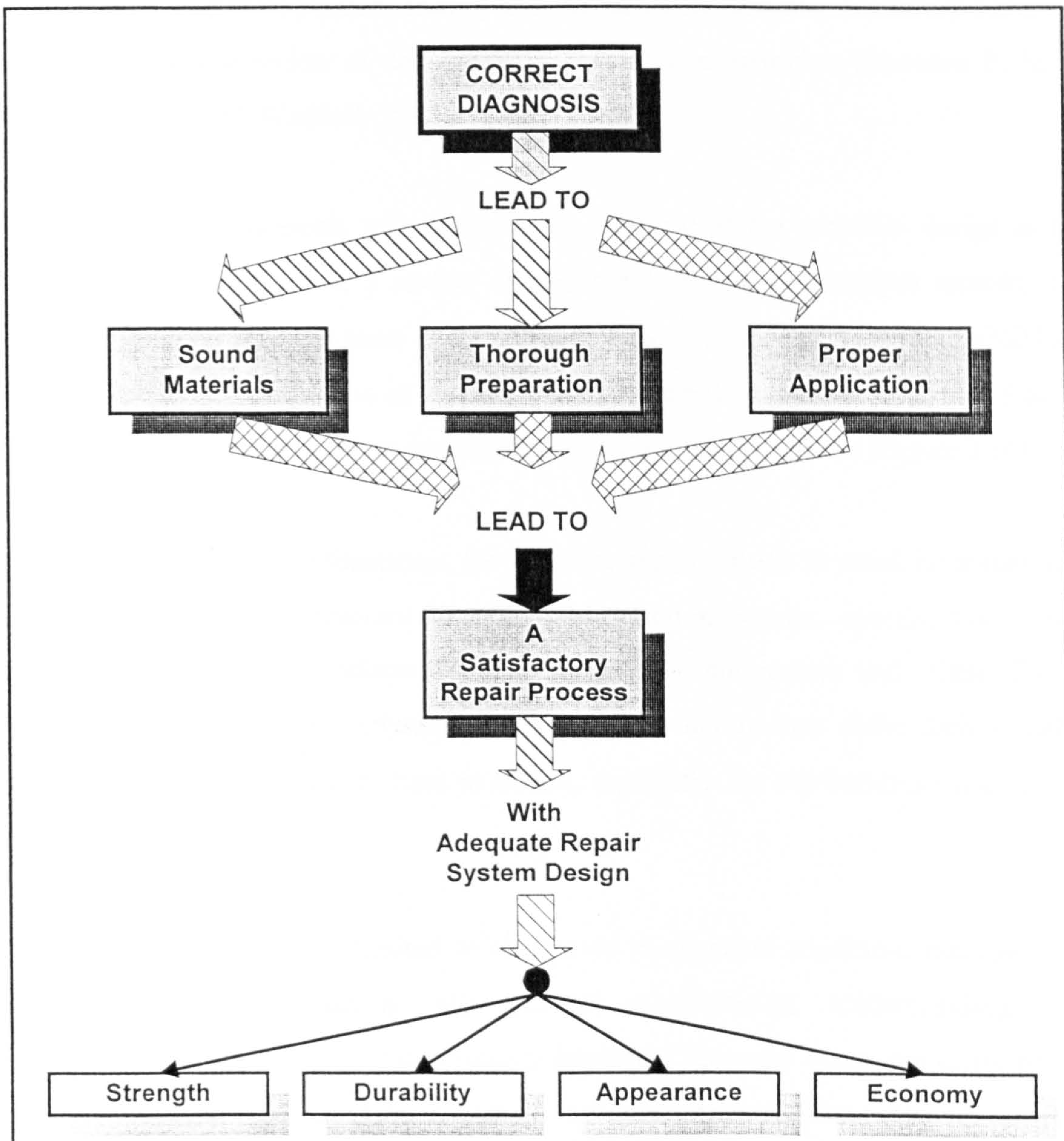


Figure 2.14 - Satisfactory repair with the necessary basic requirements (Waddell, 1980).

2.10 Diagnosis

There is a very wide divergence of opinion and practice as to when concrete structures should be subjected to regular inspection. The evaluation of concrete structures can be either a reactive or proactive process. Generally, evaluation takes place as a result of some visible signs of distress, causing structural and/or durability concerns of poor functional performance, which, in turn results in safety concerns. The procedure for a typical diagnosis of the concrete structure is shown on the flow chart in Figure 2.15. This includes in-situ inspection, testing and the taking of samples, laboratory testing and analysis, and a review of documents of construction operation (Emmons P. H., 1993; Perkins, 1997; Waddell, 1980).

The objectives of diagnosis will generally be a review of the available design and construction documentation, a review of the operation and maintenance records, a visual inspection, an evaluation of the structure by non-destructive testing (NDT) means, a laboratory evaluation of the condition of concrete specimens recovered from the structure, and finally a report and feasibility study of the prognosis (Figure 2.16).

In terms of background information, the engineer should obtain as much information as possible about the structure including construction reports, specification and drawing, and gaining of information from engineers, contractors and client. This information should be in the hands of the engineers before they make their visual inspection, although it is very hard to obtain, especially for old buildings (Perkins, 1997).

Concrete evaluation is not limited to studies of its physical condition, mechanical properties, chemical make-up, and external manifestation. Understanding its interaction with the environment is equally important. In many cases, the cause of a concrete problem is related to a service or exposure condition. Any thorough investigation starts with a visual inspection which will usually involve an overall survey of the structure. Key indicators of problem may include the features of impairment such as cracking, surface distresses (spalling, scaling, disintegration and honeycombing), water leakage, discolouration and rust staining and making some photographs. Typical concrete members of each category of defect, damage and deterioration can be selected for detailed study. The preliminary inspection of the structure may show that the structure's impairment would not amount to a structural weakness and the structure does not require strengthening (Emmons P. H., 1993; Perkins, 1997).

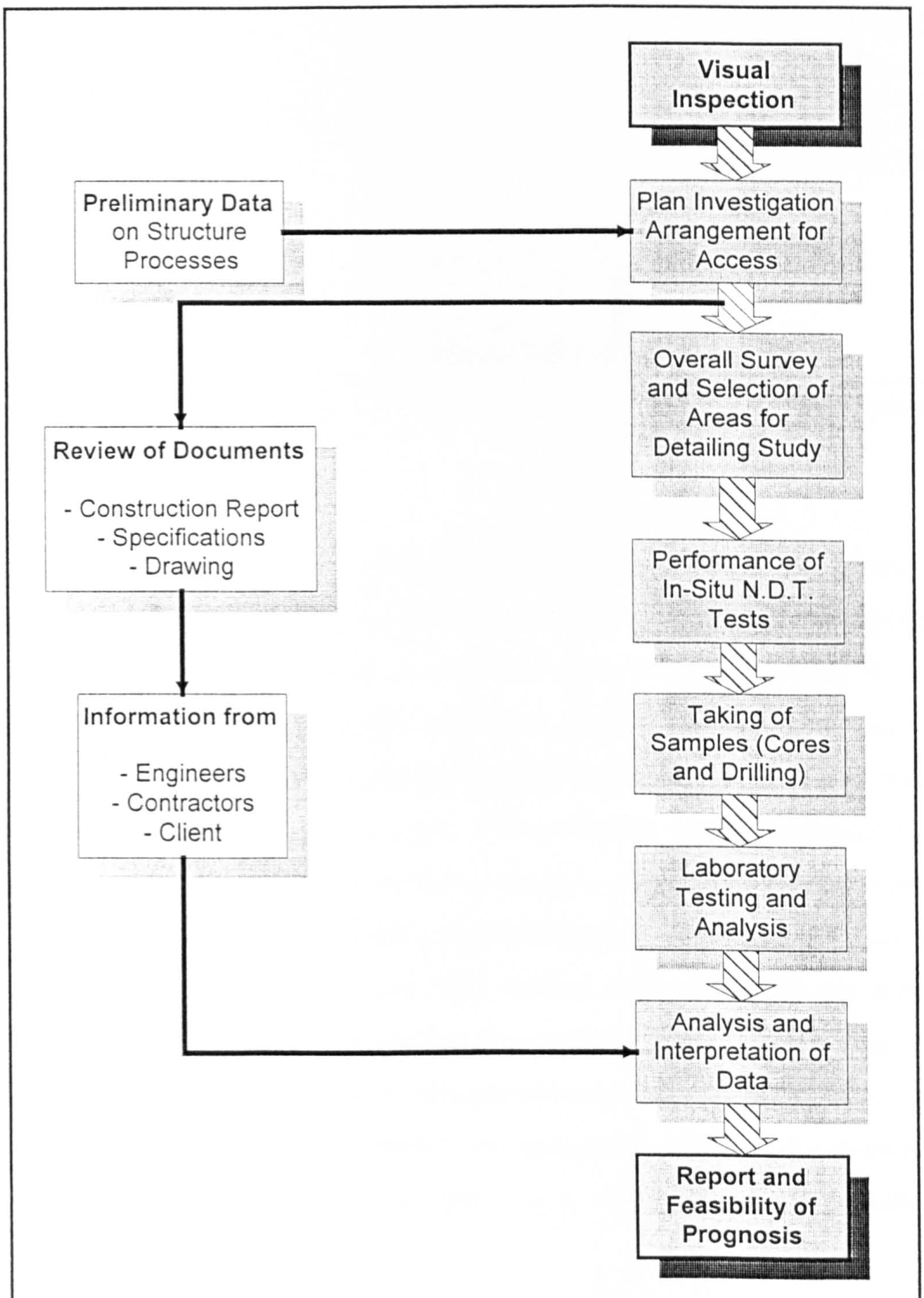


Figure 2.15 – Flow Chart for a typical diagnosis of distress in concrete structure.

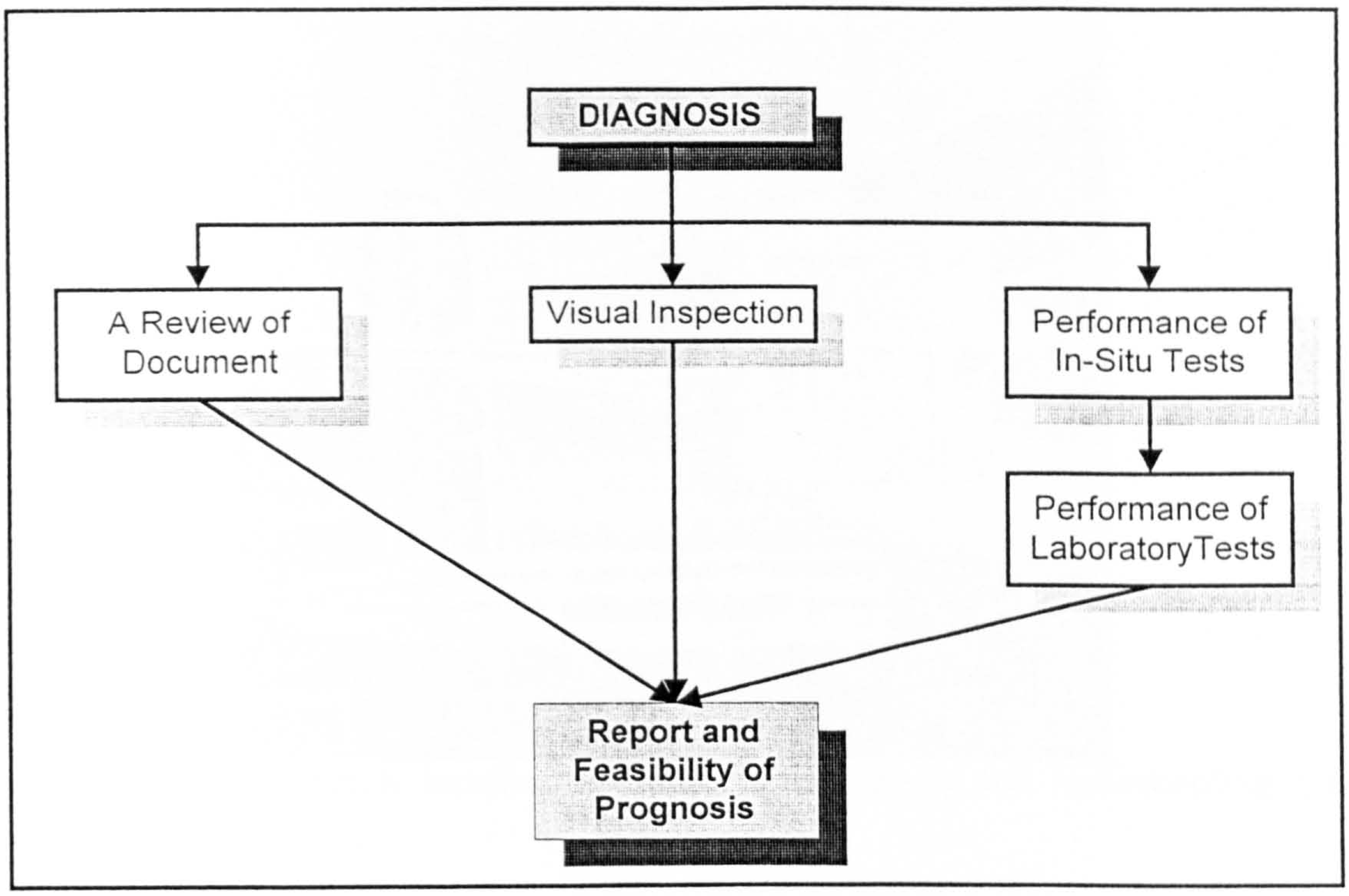


Figure 2.16 - The objectives of investigation and diagnosis of damaged concrete structures.

The purpose of non-destructive testing (NDT) is to determine the various relative properties of concrete such as strength, modulus of elasticity, homogeneity, and integrity, as well as conditions of strain and stress, without damaging the structure. Selection of the most applicable method or methods of testing will require good judgement based on the information needed, size and nature of the project, site conditions and risk to the structure. The commonly used non-destructive testing techniques for the evaluation of in-situ concrete include the Schmidt hammer test (Figure 2.17), carbonation depth, crack microscopic examination, covermeter test, Ultrasonic Pulse Velocity (Figure 2.18), drilling in depth for chloride and sulphate ions content and half-cell potential test (Figure 2.19). Test methods are also classified into those used to assess in-place strength and those used to locate hidden defects. It may be possible that the engineer will take some core samples in this stage in order to do some tests in laboratory (ACI, 1996; Allen, 1993; Bungey, 1989; Mallett, 1994; Perkins, 1997; USACE, 1995).

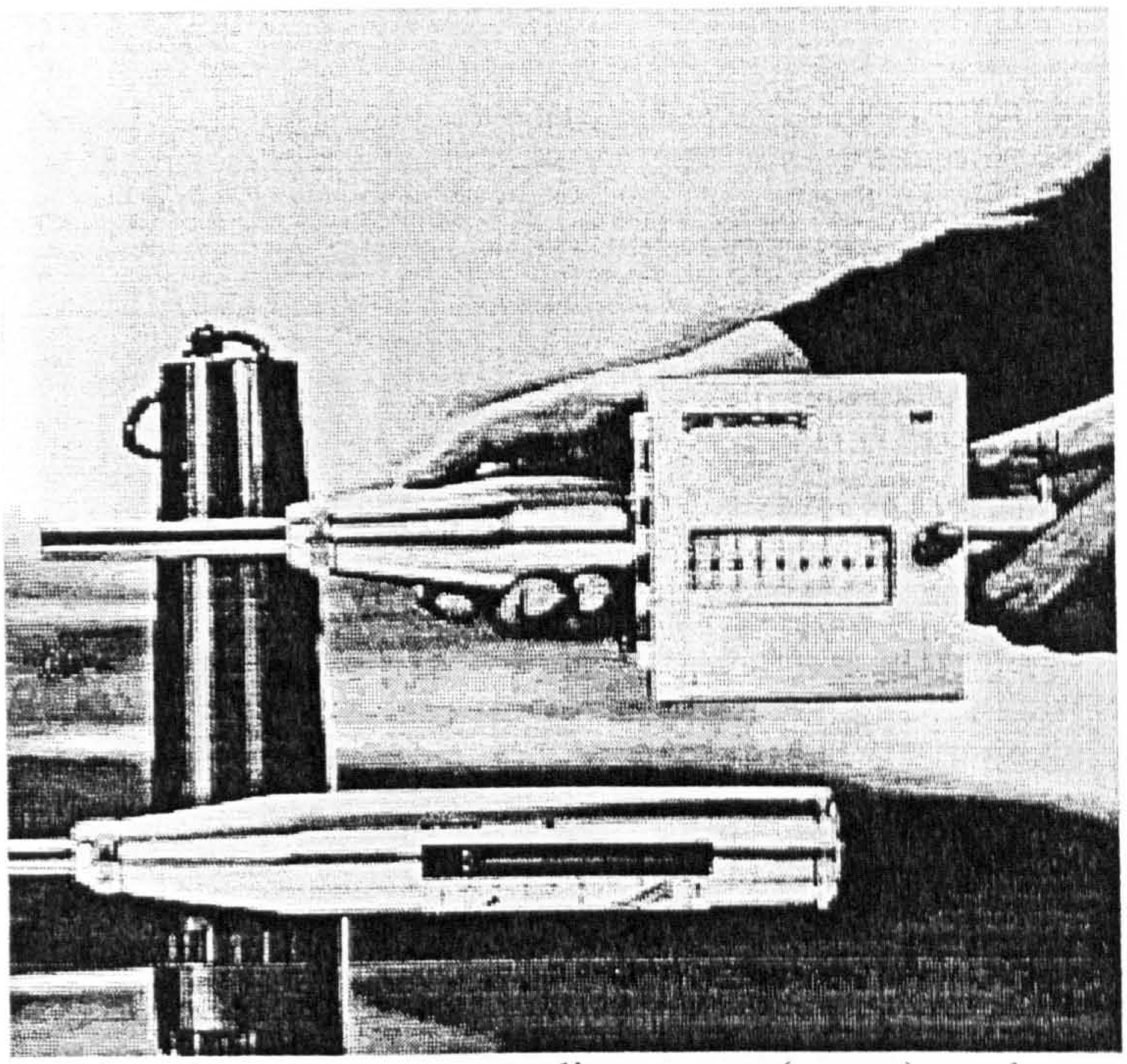


Figure 2.17 - Schmidt hammer: recording type (upper) and non-recording type (lower).

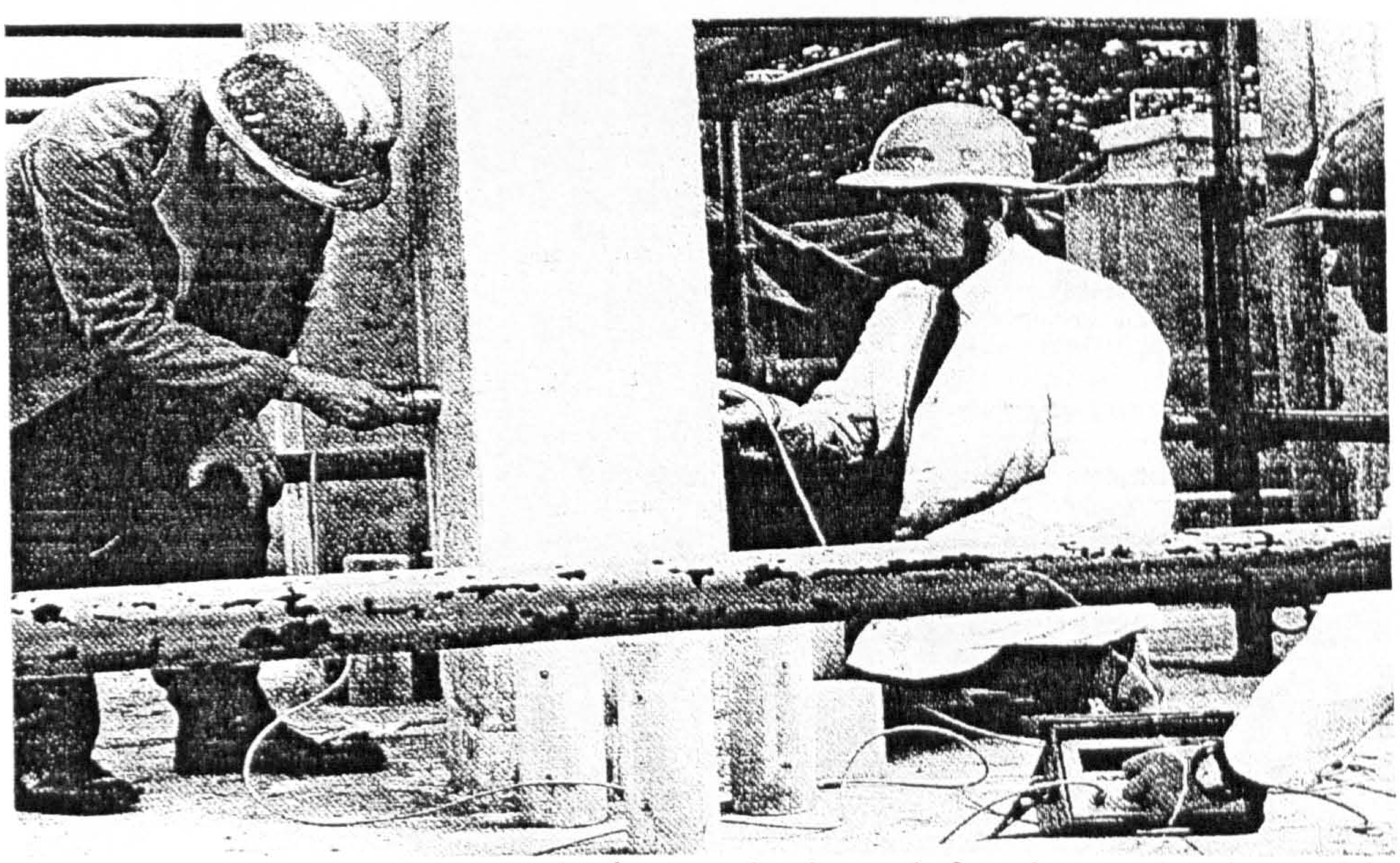


Figure 2.18 - Ultrasonic Pulse Velocity method used for the evaluation of in situ concrete.

The laboratory work will include some standard tests to determine the physical and mechanical properties of the concrete such as compressive and tensile strengths; density and permeability; and chemical analysis such as pH content; chloride and sulphate ions to characterise the nature of attack. All of the issues discussed above are shown in Figure 2.20.

Figure 2.19 - Multicell for half - cell potential measurement.

2.11 Prognosis

After detection, the importance of concrete defect, damage and deterioration must be evaluated, in order to determine the necessary action to be taken (Gemert et al., 1988). At this point, it must be decided whether the structure can be repaired or not. In order to answer this question, a generic rating system should be made for the different forms of defect, damage and deterioration of concrete structure depending on the type of structure, design and construction, type of structural elements and causes of concrete problem.

As an important part of repair and maintenance strategies, efforts have been made to classify the degree of the particular concrete impairments. Gemert et al. (1988) in their rating suggest four categories for the evaluation various levels of damage.

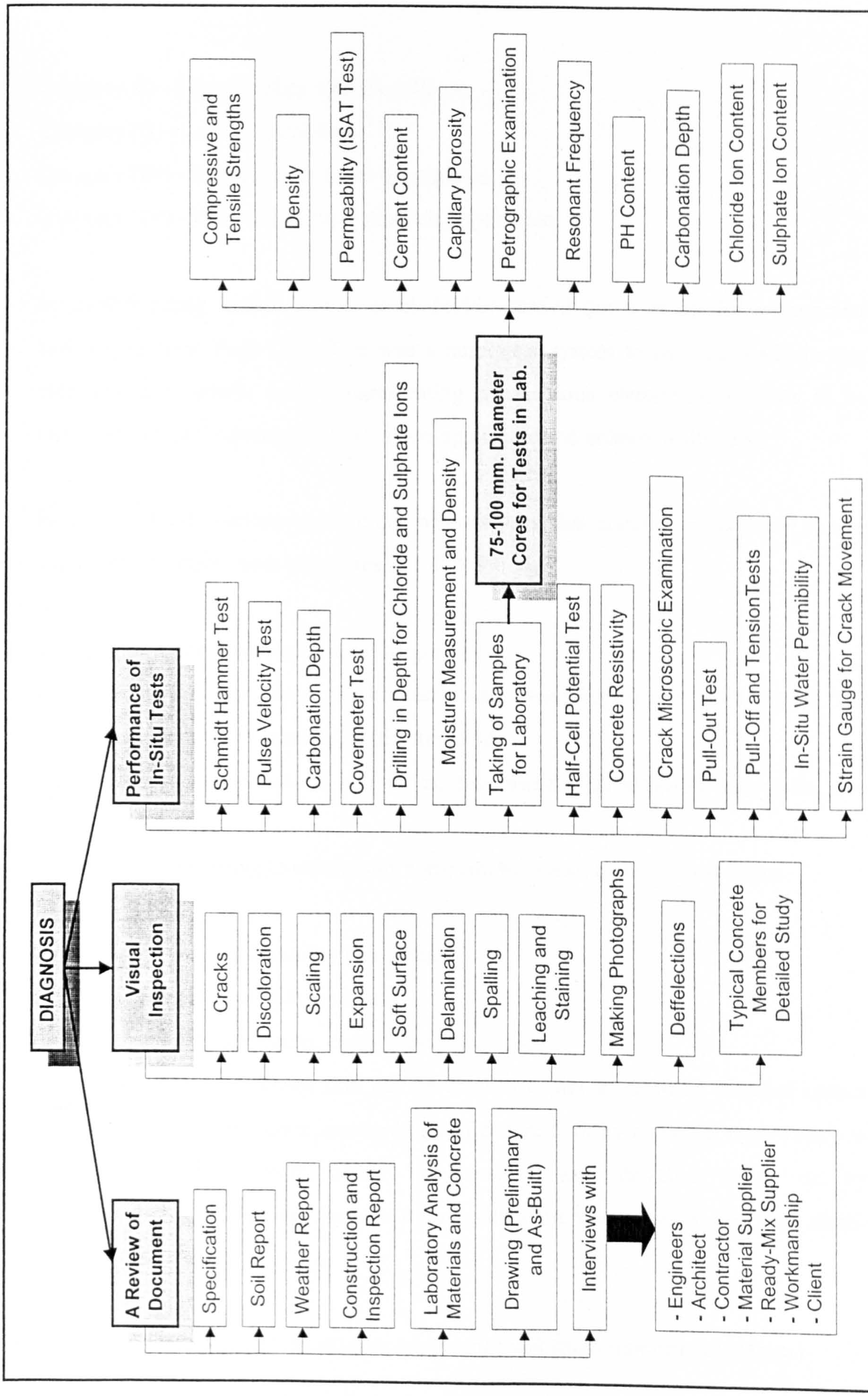


Figure 2.20 - The issues of detailed inspection, sampling and testing for diagnosis of impairment of concrete structures.

They are:

Category (I) - Loss of safety against collapse.

Category (II) - Loss of durability.

Category (III) - Damage to exterior appearance.

Category (IV) - Effect of damage of small importance.

In another rating model, Sabnis et al. (1990) carried out a rating for a particular building in New York City. This was a numerical system to rate the load-carrying elements in 9 levels, with 1 representing a hazardous element that needs to be removed, whilst 9 represented both a non-applicable and unknown situation.

From a study of previous work, it can be concluded that concrete impairment can be classified into three main categories as follows:

<u>Category I</u> - Lack of strengthening (Major)

(a) Defect owing to improper workmanship and unsuitable construction method. The concrete skin can be cracked or disintegrated.

(b) Damage owing to natural calamities, fire, settlement, abrasion, explosion, and impact.

(c) Deterioration owing to continuous corrosion by water, acids or frost action.

<u>Category II</u> - Lack of durability (Moderate)

(a) Defect due to unsuitable materials.

(b) Damage due to shrinkage, creep, punch-out.

(c) Deterioration of concrete skin can be cracked or delaminated by physical causes such as insufficient cover, permeability of concrete, or by chemical causes such as sulphate and chloride attack, carbonation and de-icing salts, or by physical/chemical causes such as freezing-thawing, corrosion of steel and alkali-silica reaction.

<u>Category III</u> - Impairment to exterior appearance and small impairment (Minor)

(a) Defects can be by poor concrete specification and quality.

(b) Damage can be by thermal incompatibility and temperature changes.

(c) Deterioration resulting from surface popouts and cracking, incomplete curing and joint deterioration.

2.12 Compatibility of Concrete Repair Materials

The choice of adequate repairing materials for a satisfactory repair program is usually more involved and imperative than it is for new construction. The range of common materials used is usually broader than just ordinary concrete materials (reinforcing steel and Portland cement). Hence, the rehabilitation engineer has to be concerned with the compatibility of the various materials with each other and with the existing substrate (Tracy et al., 1989). According to Tracy's work (1989), the properties of cementitious materials, as modified by polymers or other admixtures, should be considered. These properties include for example compressive and shear stresses, modulus of elasticity, coefficient of thermal expansion, shrinkage, creep and durability of repair materials. In the case of compatibility of repair materials with existing concrete, Vaysburd (1990) emphasises the change of volume of material due to temperature and moisture changes, tensile and compressive stresses, differential shrinkage and different modulus of elasticity.

The term "compatibility" is used commonly in the repair of concrete structures and is a favourite topic of discussion in conferences (Morgan, 1996). Emmons et al. (1993) stated that:

> "Compatibility can be defined as a balance of physical, chemical and electrochemical properties and dimensions between a repair material and the existing substrate that will ensure that the repair can withstand all the stresses induced by volume changes and chemical and electrochemical effects without distress and deterioration over a designated period of time."

Therefore, it can be concluded that compatibility can be broadly classified into physical (structural and mechanical), chemical, durability and electrochemical properties and dimensional in order to balance the properties of repair materials with original concrete. This balance is necessary if the repair system is to withstand all anticipated stresses applied at any time in a structure's service life.

Dimensional compatibility is one of the most critical components of concrete repair. Restrained contraction of repair materials, the restraint being provided through bond to the existing concrete substrate, significantly increases the complexity of repair projects as compared to new construction. Cracking and debonding of the repair material are often the result of restrained contractions caused by volume changes. Therefore, the specified repair material must be dimensionally compatible with the existing concrete substrate to minimize the potential for failure. Those material properties that influence dimensional compatibility include drying shrinkage, thermal expansion, modulus of elasticity and creep (Emmons, 1994; Vaysburd, 1990; USACE, 1995).

Repair materials require mechanical properties to carry and transfer loads similar to the concrete which is being repaired. In addition to externally applied loads, repair materials must also absorb and resist stress caused by restrained volume changes, including drying shrinkage and thermal expansion or contraction. In physical compatibility, also tensile stresses are induced in one material and compressive stresses in the other causing a substantial shear at the interface. In addition, the repair materials must resist the chemical action of the concrete and the influence of humidity in the concrete.

Durability of Portland cement concrete is defined as its ability to resist weathering action, chemical attack, abrasion, and any other conditions of service. If a repair becomes necessary because of deterioration of the existing concrete, it is essential to establish the cause and extent of deterioration. In most cases, good bond between the repair and the existing concrete substrate is a primary requirement for a successful repair. A properly prepared substrate will almost always provide sufficient bond strength. Also the permeability and the sufficient adhesion between repair material and existing concrete must be considered (Emmons, 1994; ICRI, 1996; USACE, 1995). The critical factors that widely govern the compatibility of concrete repair in practice are shown in Figure 2.21.

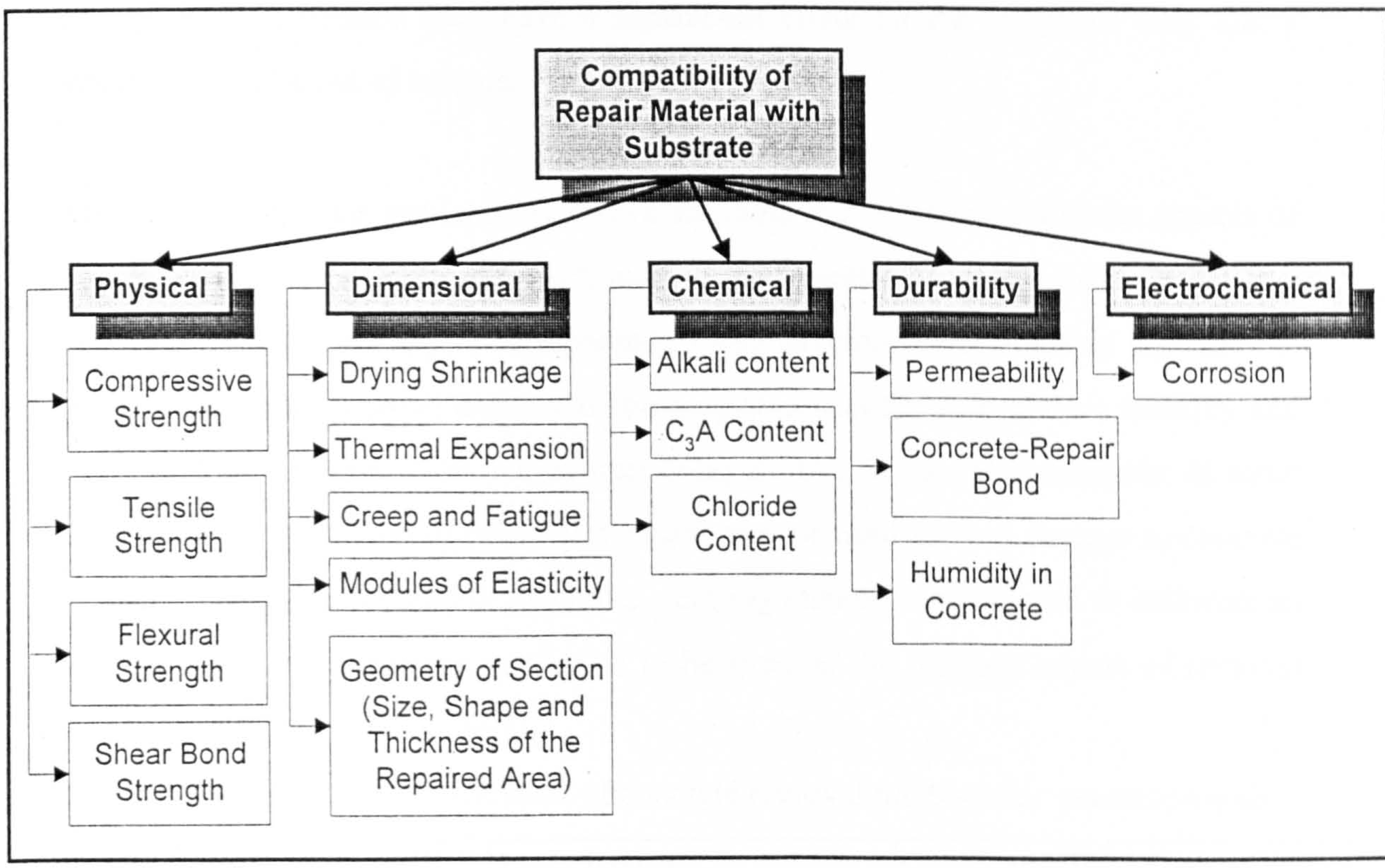


Figure 2.21 - Factors affecting compatibility of repair materials and existing concrete.

2.13 Concrete Removal and Preparation for Repair

Most repair projects involve the process of conditioning the existing concrete to receive repair materials. Conditioning is required to remove deteriorated, contaminated, or damaged concrete to provide surfaces that will promote bonding of the repair materials. Regardless of the cost or complexity of the repair method or of the material selected, the care with which the distressed concrete is removed and with which a concrete surface is prepared will often determine whether a repair project will be successful. Therefore, the surface preparation process is one of the most critical phases of site work (Emmons, 1993; USACE, 1995).

Usually, a repair or rehabilitation project will involve removal of the distressed concrete. However, for many maintenance and repair projects, concrete is removed to a fixed depth to ensure that the bulk of the deteriorated concrete is removed. But in some cases, this requirement would cause a significant amount of sound concrete to be removed. Selected concrete removal methods should be safe and economical and should have as little effect as possible on concrete remaining in situ. Selection of a proper removal method may have a significant effect on the length of time that a structure must be out of service.

Many techniques are available as shown in Table 2.1 to perform various aspects of concrete removal and cleaning. Each method has specific advantages and limitations. However, new technology is continuously being developed but much of the removal work is still done by small hand-held chipping hammers because of their mobility and versatility. Hydrodemolition and hydromilling are two of the latest methods. In some instances, a combination of removal methods may be used to limit damage to concrete that is not being removed. For example, a cutting method may be used to delineate an area in which an impacting method is to be used as the primary means of removal (Emmons, 1993; USACE, 1995).

Table 2.1 - A general classification of concrete removal methods for concrete repair.

Category	Description	Specific Methods
Blasting	Blasting methods employ rapidly expanding gas confined within a series of boreholes to produce controlled fracture and removal of concrete.	Explosive blasting
Crushing	Crushing methods employ hydraulically powered jaws to crush and remove the concrete.	Mechanical crushing: ➢ boom-mounted ➢ portable
Cutting	Cutting methods employ full-depth perimeter cuts to disjoint concrete for removal as a unit or units.	Abrasive-water-jet cutting Diamond-blade cutting Diamond-wire cutting Stitch drilling Thermal cutting
Impacting	Impacting methods employ repeated striking of the surface with a mass to fracture and spall the concrete.	Mechanical impacting: ➢ Hand-held ➢ Boom-mounted ➢ Spring-action
Milling	Milling methods generally employ abrasion or cavitation-erosion techniques to remove concrete from surfaces.	Hydromilling Rotary head milling
Presplitting	Presplitting methods employ wedging forces in a designed pattern of boreholes to produce a controlled cracking of the concrete to facilitate removal of concrete by other means.	Presplitting: ➢ Chemical-expansive agents ➢ Piston-jack splitter ➢ Plug-and-feather splitter

2.14 Concrete Repair Materials

Concrete repair materials can be formulated to provide a wide variety of properties. Because these properties could affect the performance of the repair, choosing the correct material for a specific application requires careful study. The properties of repair materials generally specified are compressive strength, bond strength, shear strength, and those properties which influence volume changes such as drying shrinkage, modulus of elasticity and coefficient of thermal expansion. Other properties such as resistance to freezing and thawing, low permeability or sulphate resistance may be specified (ICRI, 1992; ICRI, 1996).

The adequate selection of repair material will depend on cause(s) and the extent of the existing impairment, constructibility and service issues and owner and engineering requirements. It is only after these criteria have been defined and the required material properties identified that the selection of specific materials can be made. Selecting materials that meet all necessary properties established by conditions and requirements is difficult. Often more than one material or system of materials will satisfy the established requirements. Final selection of materials is based on the optimum balance of performance, risk and cost factors (Emmons, 1993; ICRI, 1996; Kardon, 1997).

Composites of concrete and various kinds of polymers have been used in many applications in recent years with excellent strength and durability properties (Kardon, 1997). Most used materials for deep repairs uses Portland cement binders and well proportioned aggregates. Durability of these materials can be enhanced using special pozzolans (microsilica), polymers (latex), or admixtures that reduce permeability. According to FIP (1991), Kardon (1997), Mallett (1994) and SP-69 (1981), available repair materials which are being widely used in Polymer Portland Cement Concrete (PPCC), Polymer Concrete (PC), and Polymer Impregnated Concrete (PIC) can be classified as either polymer emulsions or resins. The polymers include acrylics, styrene-butadiene rubber (SBR), epoxies, polyesters, methyl methacrylate (MMA) and polyurethanes. In addition, prepacked cementitious materials such as ordinary

Portland cement, high alumina cement, cement grout, artificial pozzolanic materials such as fly ash, blast-furnace slag-cement and silica fume and fibre materials are broadly used for repair work. Various kinds of repair materials are included in Figure 2.22.

2.15 Application Methods for the Repair of Concrete

After a comprehensive evaluation, the scope of both the cause and effect of concrete defect, damage and deterioration must be conducted in order to determine the necessary actions to be taken. The results of the evaluation, together with the user's needs or requirements form the necessary external information to select the repair method. Selection of repair methods depends on the nature of impairment, consideration of durability, constructibility and compatibility with the existing structure, environment, availability of materials, cost and whether the repair is a temporary restoration or permanent. Following Emmons (1993), FIP (1991), RILEM (1994) and Malletts' (1994) work, the primary procedures can be classified into replacement, repair, strengthening and stabilisation and protection.

- *Replacement* may represent the ultimate repair of those structural elements, which have a lower inherent longevity than the structure's service life.
- *Repair* refers to restoration and modification of impaired elements of a structure in its characteristics of serviceability, the load-carrying capacity and/or to improve its durability.
- *Strengthening* is the modification of a member or of a structure in order to increase the load-carrying capacity. For instance, concrete jacketing of an existing column will add compressive load-carrying capacity. *Stabilisation* is the process of halting a particular unwanted situation from progressing. For example, settlement of a structure can be stabilised by grouting to halt further movement. The differences between "stabilisation" and "strengthening" are somewhat clouded and, in some cases, are used synonymously.

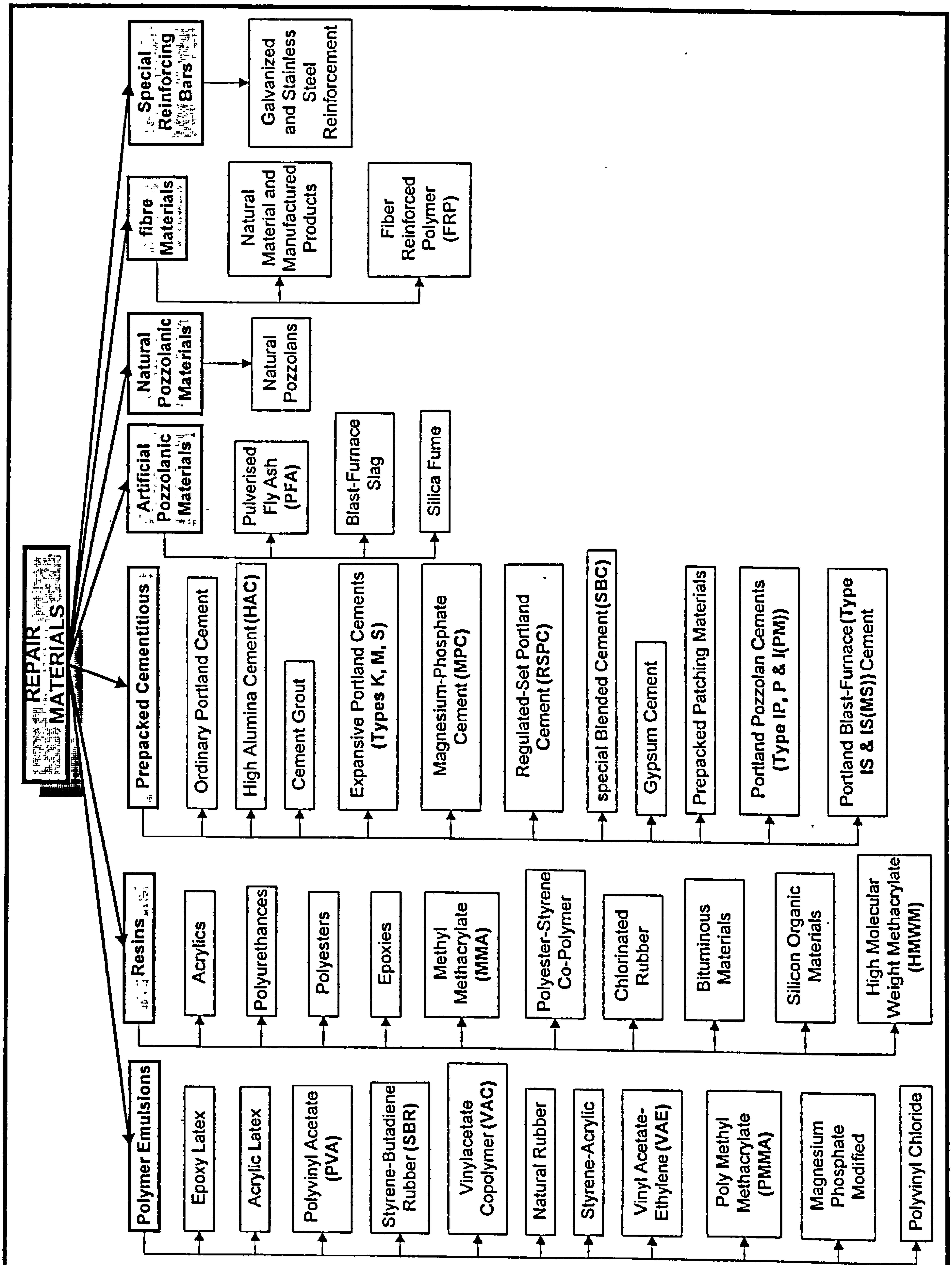


Figure 2.22 - Various kinds of repair materials.

- *Protection* is operations, which intend to prevent damage of the structure or is a method of controlling the cause of distress or user dysfunction by:

    - altering the service exposure conditions,
    - enhancing the physical properties of the concrete to better resist the exposure or service conditions,
    - installing a barrier between the service/exposure condition and the susceptible concrete, or
    - altering the electrochemical behaviour when corrosion of embedded metal is a factor.

  For example, concrete spalling is a form of deterioration that may be caused by an exposure/service condition which promotes reinforcing steel corrosion. Protection of the concrete from the exposure/service condition may be accomplished by utilising sealers, membranes or coatings.

If the structure does not require strengthening, the repair work of the structure may be categorised as following (FIP, 1991):

(a) - Repair of the concrete surface (delamination, spalling and popouts).

(b) - Repair of concrete cracks (physical and chemical).

(c) - Repair of corroded steel reinforcement.

(d) - Repair of joints.

Various application methods for the repair of concrete structures are shown in Figure 2.23.

2.16 Maintenance and Durability Recommendations of Concrete Structures

Preventing concrete impairment is much easier and more economical than repairing distressed concrete. Preventing concrete impairment should actually begin with the selection of proper materials, mixture proportions and placement and curing procedures. If additional protection against impairment is required, the need should be

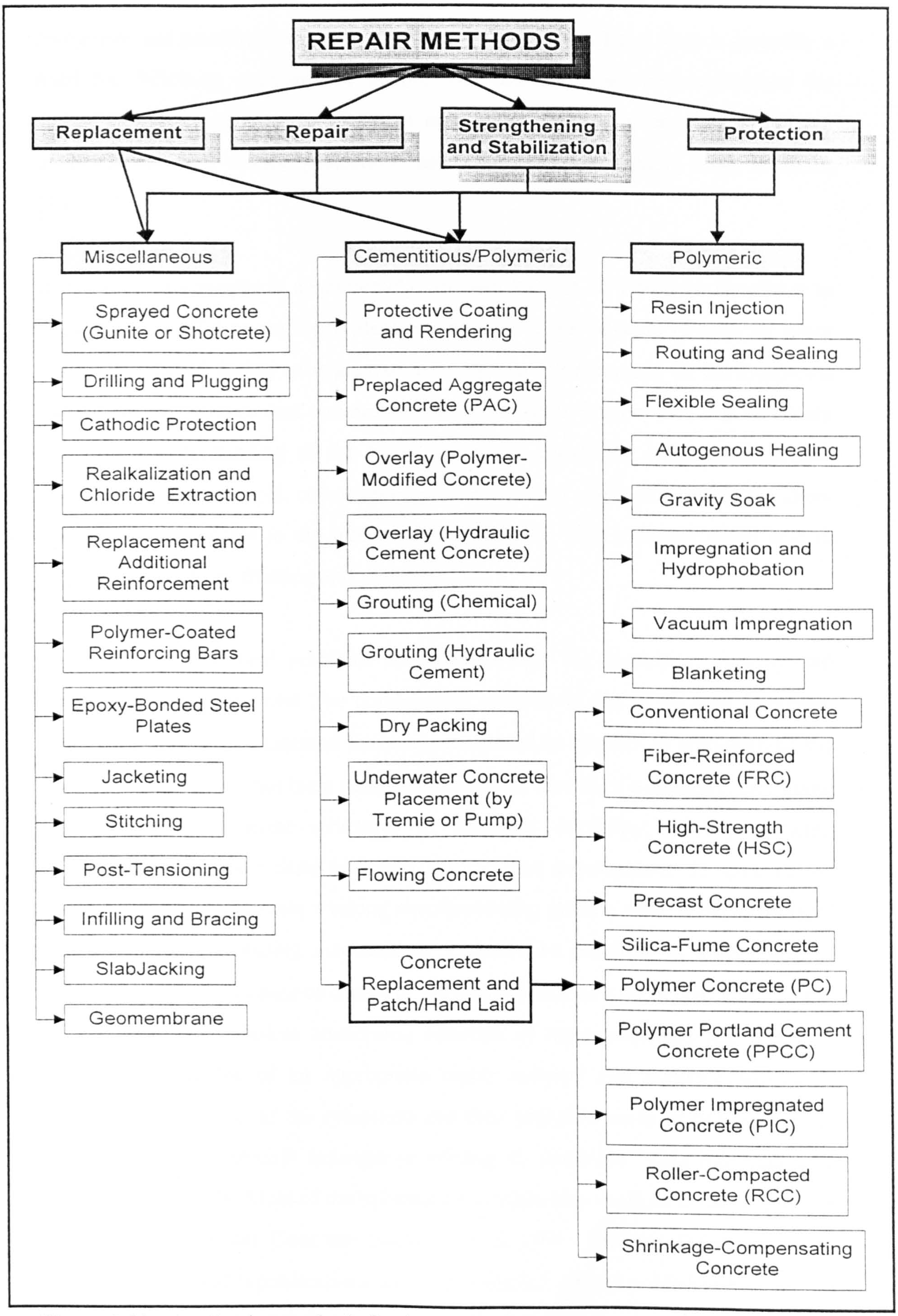


Figure 2.23 - Application methods for the repair of concrete structures.

recognised and provided for during the design of a structure. Thus, there is generally a need for follow-up maintenance action. The primary types of maintenance for concrete include timely repair of cracks and spalls, cleaning of concrete to remove unsightly material, surface protection, and joint restoration (ACI, 1996; USACE, 1995).

Impairment of concrete is an extremely complex subject. It would be simplistic to suggest that it will be possible to identify a specific single cause of distress for every symptom detected during an evaluation of a structure. Since many of the symptoms may be caused by more than one mechanism acting upon the concrete, it is necessary to have an understanding of the basic underlying causes of defect, damage and deterioration. For example, corrosion of reinforcing steel may open cracks that allow moisture greater access to the interior of the concrete. This moisture could lead to additional damage by freezing and thawing.

Structural and functional problems may detract from the durability, integrity and serviceability of a structure. The durability of concrete is one of its most important properties because it is essential that concrete should be capable of withstanding the conditions for which it has been designed throughout the life of a structure. Designing and constructing concrete structures of enhanced durability, thereby reducing maintenance and repair costs has been a focus and development. In spite of the complexity of several causes working simultaneously, given a basic understanding of the various distress-causing mechanisms, it should be possible, in most cases, to determine the primary cause or causes of the distress seen on a particular structure and to make intelligent choices concerning selection of repair materials and methods. Therefore the choice of an appropriate repair material and methods requires a systematic observation of the symptoms and their probable cause or causes together with a source of available information relating to durability. This information is shown in Figure 2.24. Most of the information is taken directly from codes of practice such as the American Concrete Institute (ACI, 1996) and the British Standard Institution (BSI, 1997) publications and from technical reports published by concrete associations (FIP, 1991; RILEM, 1994; USACE, 1995).

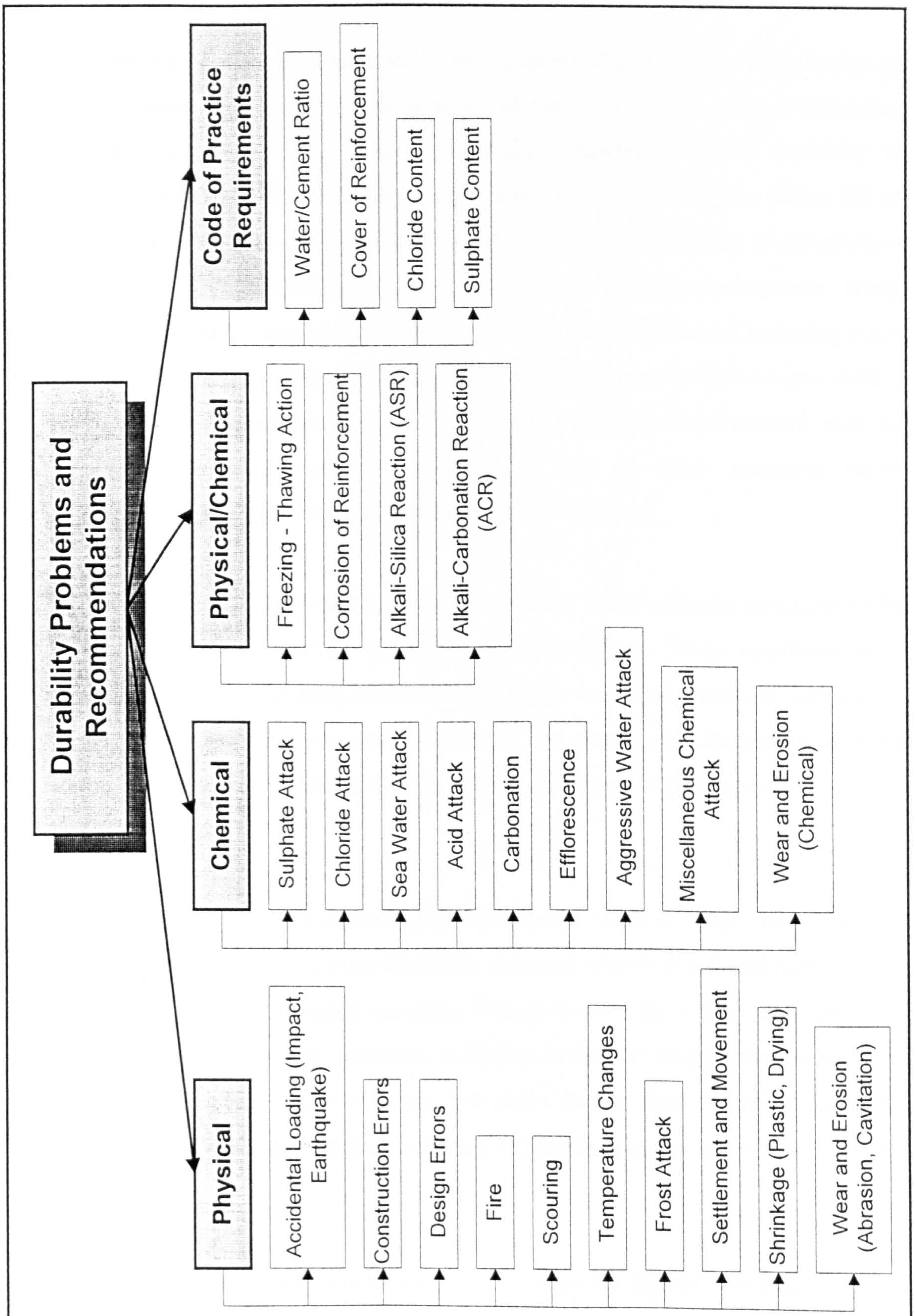


Figure 2.24 - Information relating to durability problems of concrete structures.

2.17 Summary

The durability of concrete is technically and economically one of the main factors in selecting construction materials, so as to avoid damaging factors such as corrosion, Alkali-Aggregate Reactivity (AAR) and freezing-thawing. Lack of durability is common worldwide and it is causing a huge capital cost by reducing the design life of structures. This Chapter has generally reviewed the relevant literature on information and problems in the durability, maintenance and repair of concrete structures. Many aspects relating to the repair of concrete structures have been covered including types of structure, types of design and construction, structural elements and constructibility, and causes and symptoms of concrete distress. Furthermore parameters such as diagnosis, compatibility, removal methods as well as repair materials, repair procedures and durability recommendations are also included.

Inappropriate design and construction methods often cause concrete structures to be affected by lack of durability, integrity and serviceability. These conditions were classified into three main categories Defect, Damage and Deterioration. In addition, in this Chapter a basis for the classification of the causes and symptoms of these conditions has been established. The application developed in this regard is discussed in Chapters 7 and 8.

The evaluation of concrete structure takes place as a result of some visible signs of distress, causing structural and/or durability concerns of poor functional performance, which, in turn, result in safety concerns. The procedure for a typical diagnosis of concrete structure was also reviewed including review of design and construction documentation, visual inspection, non-destructive in-situ tests and laboratory tests. The application developed in the evaluation of distresses in the concrete is discussed in Chapter 9.

To achieve durable repairs it is necessary to consider the factors affecting the design and selection of repair systems as parts of a composite system. These factors must be considered in the design process so that a repair material compatible with the existing concrete substrate can be selected. Detailed discussions of compatibility issue have been highlighted in this Chapter including dimensional, physical (structural and mechanical), chemical, durability and electrochemical compatibility.

The adequate selection of repair material and application methods will depend on the cause(s) and extent of the existing impairment, constructibility and service issues, owner and engineering requirements, compatibility with the existing structure, environment, availability of materials, cost and whether the repair is temporary or permanent. In this Chapter, the most common repair materials such as cementitious and polymers, and application methods in repair, replacement, protection, strengthening and stabilisation of concrete structures have been outlined.

The final part of this Chapter covered a number of issues relating to the durability recommendations in the repair of concrete structures. Most of this knowledge used was based on codes of practice such as the American Concrete Institute (ACI) and the British Standards Institution (BSI) publications and from technical reports published by concrete associations.

It has been shown that the diagnosis, evaluation, maintenance and repair of concrete structures are largely dependent on selection, which makes the subject suitable for the application of Knowledge-Based Expert Systems. It has been shown that the repair process is information and knowledge intensive which makes data management essential for its successful implementation. Most of the options such as causes and effects of distress, inspection and evaluation may best be represented graphically as well as by descriptive information, whilst the advice on material selection and adequate repair techniques along with recommendations to ensure enhanced durability may be best illustrated by descriptive information.

Database Management technology is discussed in Chapter 4. The development of a comprehensive Database Management System for the repair of concrete problems is presented in Chapters 6 and 7.

Chapter 3

An Overview of Knowledge-Based Expert Systems and M.4

3.1 Introduction

This Chapter comprises an overview of the development of Knowledge-Based Expert System (KBES) techniques in the structural engineering field. It deals with the earlier applications in the area of buildings, bridges and pavement design, up to maintenance and repair of concrete structures which are now being used to construct expert systems. The fundamental concepts of the technology including a number of knowledge representation schemes from a theoretical point of view along with applied examples in the various expert systems are discussed. Finally the software tools for building expert system environments, particularly M.4, which is used in this thesis are highlighted.

3.2 Review of Expert System Technology in Structural Design

The maintenance and repair of existing structures in the field of civil engineering is very important and it needs engineers with broad experiential knowledge. The difficulties of structural damage assessment are sometimes more complicated. Under these circumstances, the inspection and determination of the damaged structure require a considerable amount of time in order to take careful assessment of the structure. These conditions make an excellent environment for the development of knowledge based expert systems. These are basically computer programs that can represent human expertise to provide recommendations of a wide range of particular domains and perform the assessment in a much shorter time (Kalyanasundaram P. et al, 1990).

The last few years, the use of knowledge based computer programs in structural engineering applications has significantly advanced. Several common computer programs or software packages have been developed to provide a means for an engineer to use expert systems in the diagnosis of structural damage problems and to be able to recommend maintenance strategies. Adeli H. (1988) presented several expert systems in civil engineering including structural and construction engineering for a satisfactory solution to the problems of diagnosis, fault detection, prediction, monitoring, planning and design. A survey of many of the existing prototype and operational expert systems that have been developed for the construction industry is presented by Kaetzel L.J. et al (1995).

As for the programs used, Mikami et al (1994) used a knowledge based network model analogous to the neural network. Hanna et al (1993) involved two expert system shell programs in their own study, namely EXSYS professional and EXPERT PLUS. Besides object-orientation, Funk and Reinhardt (1992) used the expert system shell for an expert system adopting Contec. Mohsen A. Issa et al (1995) also used the EXSYS professional shell program for the Bridge Rating Expert System (BRES) which is limited to existing highway bridges with prestressed concrete beams or girders.

In addition, several systems such as SCEPTRE, ROSE and ERASME have been developed using EXSYS, an expert development shell that may be applied to pavements (Hanna P. B. et al, 1993). The M.4 as a development shell, was involved in the WAREHOUSE-EXPERT system (Nyambayo J., 1997).

3.3 Expert Systems in the Repair and Maintenance of Concrete Structures

Clifton J. R. et al (1985) developed an expert system called DURCON that gives recommendations on the selection of concrete constituents for the durability areas comprising corrosion, freeze-thaw, sulphate attack and alkali-aggregate reaction. The system also recommends a water/cement ratio and the amount of cover for different environments. It was developed to provide expert knowledge for specifiers of concrete. The embodied knowledge of DURCON uses the American Concrete Institute (ACI) 'Guide to Durability of Concrete', ACI 201.2R-77, and expert knowledge from ACI Committee 201 members.

A prototype expert system known as CRACKS (Kaetzel et al, 1989), a rule-based expert system, was developed at the National Institute of Standards and Technology (NIST) solely for cracks in concrete, and the system incorporates known facts about cracks in concrete as well as the guidelines and opinions of experts. CRACKS deals primarily with non-structural cracks in concrete elements such as slabs, columns, thick sections and thin walls. The CRACKS knowledge base is in three parts comprising facts and rules of thumb, database information and digitized images.

Another rule-based expert system, named CRACK (Wang T. et al, 1989) is designed to diagnose the causes of cracking of cast-in-place concrete structures such as tunnels, tanks and foundation walls. The system also recommends methods for controlling and repairing cracking and contains Chinese design codes and specifications for constructing concrete structures.

Kalyanassundaram P. et al (1990) created an expert system for building repair, namely REPCON whose domain includes diagnosing the cause and suggesting repair methods for cracking, spalling and disintegration in concrete buildings and cracking, dampness and leakage in brick masonry buildings.

An expert system prototype developed at Darmstadt University by Sohni (1991) called REPCON stands for REPair of CONcrete. It 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.

In response to a growing awareness of the repair and maintenance problems of concrete structures, The U.S. Army Corps (1992) initiated the Repair, Evaluation, Maintenance and Rehabilitation (REMR) research program. This program was organised into seven broad problem areas: concrete and steel structures, geotechnical, hydraulics, coastal, environmental impacts, electrical and mechanical and operation management. Studies in concrete and steel structures problem area have focused on methods for assessing the condition of structures above and below water and on techniques for maintaining, repairing and rehabilitating concrete and steel.

A new expert system for the diagnosis and treatment of deteriorated concrete structures was developed by Funk G. et al (1993). This prototype which supports the diagnosing process and the design of repair measures for damage to concrete structures is called Contec^{ES}. The basis of this new expert system is REPCON (Funk G., 1992). It is an object-oriented and rule-based expert system shell. The latest knowledge on concrete technology and information on the essentials of the deterioration process mechanisms are considered as well as the selection of repair measures and surface treatment according to German guidelines. In addition, an extensive set of digital photographs and graphics are part of the knowledge base. The REPCON expert systems reviewed in this Section are totally different pieces of software from the REPCON database described in Chapter 7.

The Strategic Highway Research Program (SHRP, 1994) has developed new software to examine highway pavement distress, namely HWYCON. This is an expert system and fits on a personal computer. This software informs decision-making regarding repair and rehabilitation of concrete pavements and bridge decks and substructures and can help highway agencies to select materials for constructing or reconstructing a concrete structure, complying with design codes and standards for acceptable practice. In addition, the program includes four subsystems: concrete pavement diagnostics (CONPAV-D), concrete bridge deck and substructure diagnostics (CONSTRUC-D), concrete materials selection (CONMAT), and concrete pavement repair and rehabilitation (CONPAV-R) (Harrington-Hughes K., 1993).

The problems of bridge assessment and the requirements for repair, strengthening and replacement are issues which have become increasingly important. Concrete bridge deterioration assessment- COBDA (Cabrera J.G. et al, 1995), is a comprehensive expert system for the diagnosis and prognosis of deterioration of concrete which includes three methods to deal with the uncertainty problems in the evaluation of concrete bridges. PROLOG as a main expert system development tool is used for the development of COBDA. Three different methods are suggested as alternative solutions of uncertainty problems which occur in data processing: Performance Index (PI), Fuzzy Logic and Bayesian Subjective Probability Theory. COBDA knowledge is categorised by sub-domains such as deterioration, inspection, maintenance and repair, assessment and uncertainty problems of inspection data for concrete bridges.

The importance of bridge repair versus new bridge construction has risen in recent decades owing to high deterioration rates that have been observed in these structures. To help rational decision-making, a prototype expert system for concrete bridge management, BRIDGE-1 and BRIDGE-2 was implemented by Brito et al (1997). In BRIDGE-1, the inspection module relies on a periodic acquisition of field information complemented by a knowledge-based interactive system. To optimize management strategies at the headquarters, the BRIDGE-2 module was implemented including three sub-modules: inspection strategy, maintenance and repair.

There is a wide range of knowledge-based expert systems that have been developed for concrete design, condition assessment and repair and rehabilitation of concrete structures. It can be seen that most of the existing prototype expert system applications in the field of concrete repair have been restricted to limited amounts of data and have no facility for sophisticated data management. Database management systems are important components of existing integrated engineering computing systems. Because these two subject areas, i.e. expert system (ES) and database management system (DBMS), have not been integrated previously, the need exists for an interface between the knowledge-based expert systems and DBMS. Therefore, the central feature of this research is the integration of these two areas of Information Technology (IT).

3.4 Knowledge-Based Systems versus Conventional Programming Systems

There are a number of fundamental differences between knowledge-based systems and conventional programming systems. Because it separates knowledge from the inference procedure, the expert system can provide a significant advantage for the developer. In addition, conventional programming systems process data algorithmically while knowledge-based systems involve a heuristic (inferential) process. The end-user can obtain explanatory information while running the knowledge-based system and the system can give the reasons why the program is following a certain operation (Mohsen A. Issa et al, 1995; Kaetzel L. T. et al, 1995; Anumba C. J., 1994).

The characteristic features of conventional computer programs and knowledge-based (expert) systems are summarised in Table 3.1.

Table 3.1 - The general distinctions between expert systems and conventional computer programs.

Conventional programs	Expert Systems
▪ Manipulation and use of large data bases	▪ Manipulation and use of knowledge bases
▪ Control and knowledge integrated	▪ Control and knowledge separated
▪ Algorithmic process	▪ Heuristic process
▪ Representation of data	▪ Representation of knowledge
▪ Give results without explanation	▪ Can provide explanation of results during running
▪ Orientated toward numerical processing	▪ Oriented toward symbolic processing
▪ Calculate results	▪ Make decision
▪ Require complete information	▪ Can work with partial information

3.5 An Introduction to Knowledge-Based Expert Systems

Knowledge-Based Expert Systems (KBES) are computer programs using Artificial Intelligence (AI) techniques, which involve human knowledge and experience in solving difficult problems that would otherwise be solved by an expert in a larger amount of time. Put another way, an expert system is an Artificial Intelligence based program that can play the role of human knowledge using heuristic knowledge or rules of thumb (Adeli H., 1988).

Several factors affect the system architecture for knowledge-based systems. These factors usually depend on the particular application domain, the procedure of direction through the system in solving problems, the software tools (knowledge-based environment, graphical user interface builders, database) and programming language used. A Knowledge-Based Expert System (KBES) comprises three main common components, i.e. the knowledge base, the inference mechanism and the working memory, and also perhaps other expert system development facilities (Adeli H., 1988; Maher M.L. and R. Allen, 1987). The components of a Knowledge Based Expert system are shown in Figure 3.1.

The Knowledge Base is the repository of information relating to a particular task or application derived from a human expert and it comprises documented definitions, facts, rules, procedures and objects. The inference mechanism (also known as the inference engine) carries out the reasoning process to solve definite problems using question-and-answer consultations with factors relating to the application.

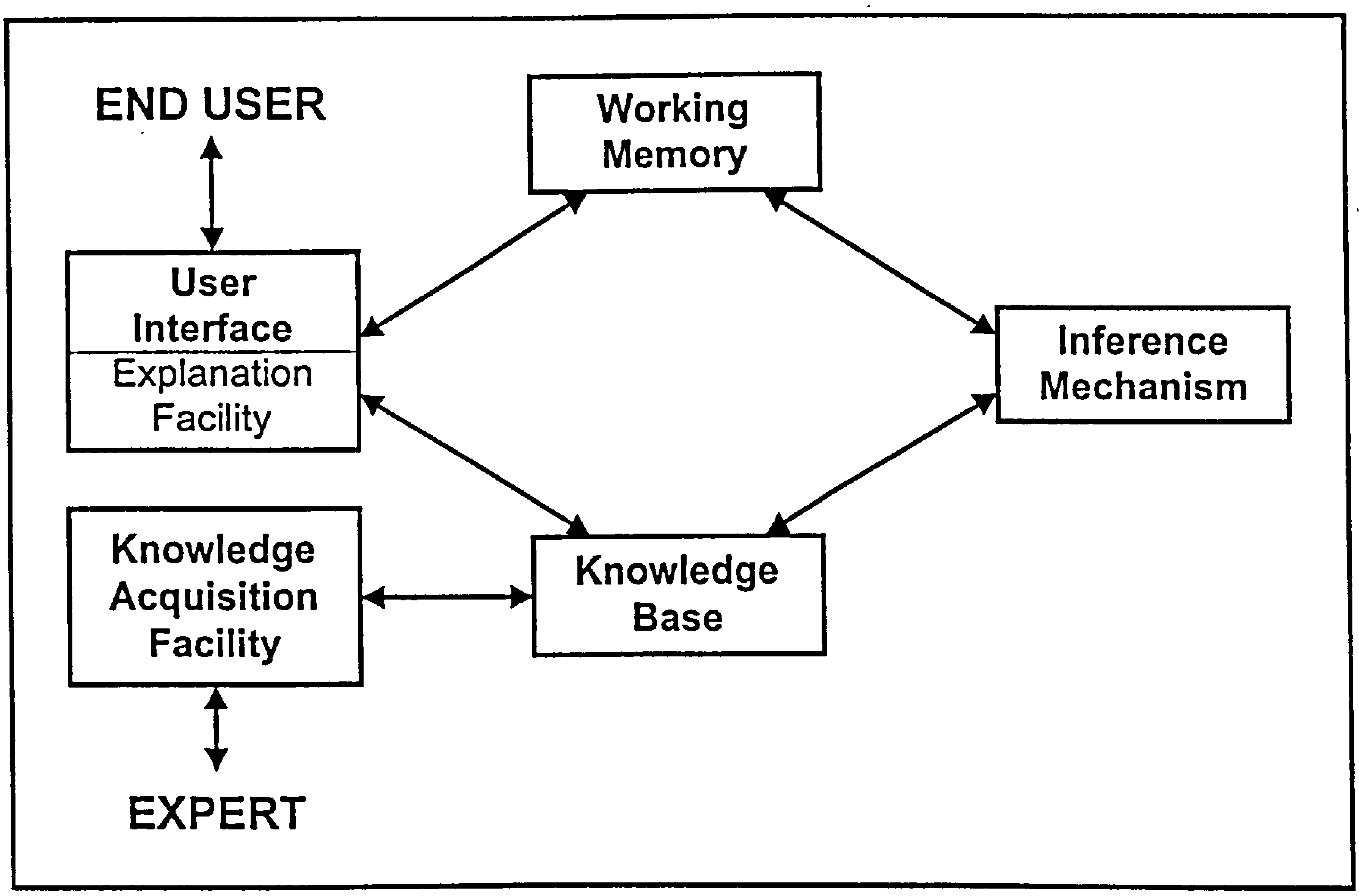


Figure 3.1 - Components of a Knowledge-Based Expert System.

The knowledge base and inference engine is engaged by the knowledge system in order to consider the problems and finally to recommend a conclusion. The working memory of the Expert System is used as temporary storage for facts discovered during a consultation. Its content alters dynamically and comprises information provided by the user about the specific problem and information derived by the system. Other Expert System development facilities include an intelligent user interface, an explanation facility, a knowledge acquisition facility, debugging and help facilities and knowledge base editors.

An organisation can optimise its information and decreases its costs by using Knowledge-Based Expert Systems in decision-making and problem-solving. Hence, knowledge-based systems are becoming more competitive and therefore their applications are available in many areas such as manufacturing, engineering, finance, data processing and management information systems. They fall into five categories: analysis, planning, design, selection and diagnosis (Cimflex, 1991). Construction planning, engineering, and management have been paid high attention as potential domains for knowledge-based systems (Benjamin C.O. et al, 1990).

In the field of civil engineering, Knowledge-Based Expert Systems (KBES) have been developed in areas such as structural analysis and design; especially bridge design (Adeli H., and K.V. Balasubramanyan, 1988), construction management (William C., and De La Garza, 1988), and concrete structures (Reddy R.R. et al, 1993). Within the recent past, Expert Systems (ES) have been employed in the diagnosis of structural damage problems and the recommendations for the repair and maintenance of concrete structures, such as concrete buildings, car parks, and bridges, as well as for the repair and maintenance of highway pavements.

3.6 The Representation of Knowledge

Knowledge in expert systems can be represented in many various ways which depend on the problem-solving techniques (system architecture) supported by the development tools of KBES. The commonly used representations of knowledge for expert systems are production rules (rule-based), semantic network, frame and objected-oriented (Kaetzel L.J. et al, 1995; Adeli H., 1988; Giarratono J., 1994). Combinations of several different techniques are also used and are commonly called hybrid systems.

3.6.1 Production Rules (Rule-Based) Systems

The production rules system has been the most favourable representation approach for building computer expert systems (Adeli H., 1988). A primary objective of the expert system developers is to capture an adequate amount of knowledge from the expert so that the expert systems will have a decision-making capability equal to that expert. It is essential to formulate the knowledge into a rule form within the knowledge base. Knowledge in a production rules system is represented in the form of IF(...) THEN(...) rules. IF part, or premise can be considered as patterns and THEN part, or consequent as conclusion or actions to be taken.

Each production rule in the system represents a single piece of knowledge that relates some known information to other information that can be concluded and inferred to be known. Expert systems of this type involve conducting a session where the systems attempt to find the best goal using information supplied by the user. The sequence of events comprises a question and answer session.

One of the earlier rule-based expert systems was MYCIN (Shortcliffe E.H. et al, 1984) which was used for medical diagnosis. In construction engineering and management, DURCON (Clifton J.R. et al, 1985) is a prototype rule-based expert system for selecting the constituents of concrete exposed to aggressive environment. The knowledge base in DURCON consists of specification rules from the American Concrete Institute (ACI) 'Guide to Durable Concrete' and heuristic knowledge obtained from human experts on the durability of concrete. An example of the rules used in DURCON is shown in Figure 3.2.

IF	**Severe freeze-thaw conditions are anticipated and**
	The nominal size of aggregate is 3/8 in (9.5 mm)
THEN	**the percentage of entrained air should be 7.5.**

Figure 3.2 - An example of rules from DURCON.

In addition, Funk G. (1992) developed an expert system, called REPCON, which is a rule-based expert system designed to help engineers to judge the condition of damaged concrete structures and to recommend repair proposal based on the German Association for Concrete and Reinforced Concrete Regulations.

3.6.2 Semantic Network Systems

It is argued that semantic networks which first were developed for Artificial Intelligence (AI) are the closest models to human memory functions and language understanding (Quillian M.R., 1968). Knowledge representation by semantic network systems graphically consist of a collection of nodes for representation of concepts, objects and/or events and arcs which comprise links connecting the nodes.

In a graphical format of semantic network, the nodes (i.e. objects) are connected to each other by links which show the relationship between them. Phrases like "is-a" and "caused-by" are often used to describe the association between two nodes. A typical component of a semantic network is illustrated in Figure 3.3(a) and an example of a semantic network as applied to construction scheduling is called CONSAS (William C. et al, 1988), is given in Figure 3.3(b).

Formulation of knowledge with semantic networks is simple: each node is related to each other with a phrase. By analysing the network structure closely, the user can easily identify existing relationships between the objects. Because semantic networks are easy to develop and use, expert system developers have adopted the method widely.

One modification of a semantic method is called semantic triples or Object-Attribute-Value (OAV) triples which present a special case of semantic networks. In this type of semantic network, there are only three types of nodes, i.e. objects, which can be physical or conceptual entities, attribute that are general properties or features of objects, and values. Values determine the particular character of an attribute in a specified situation. OAV triples use only two simple relationships, i.e. the object-attribute link and the attribute-value link, while semantic networks may have complicated links.

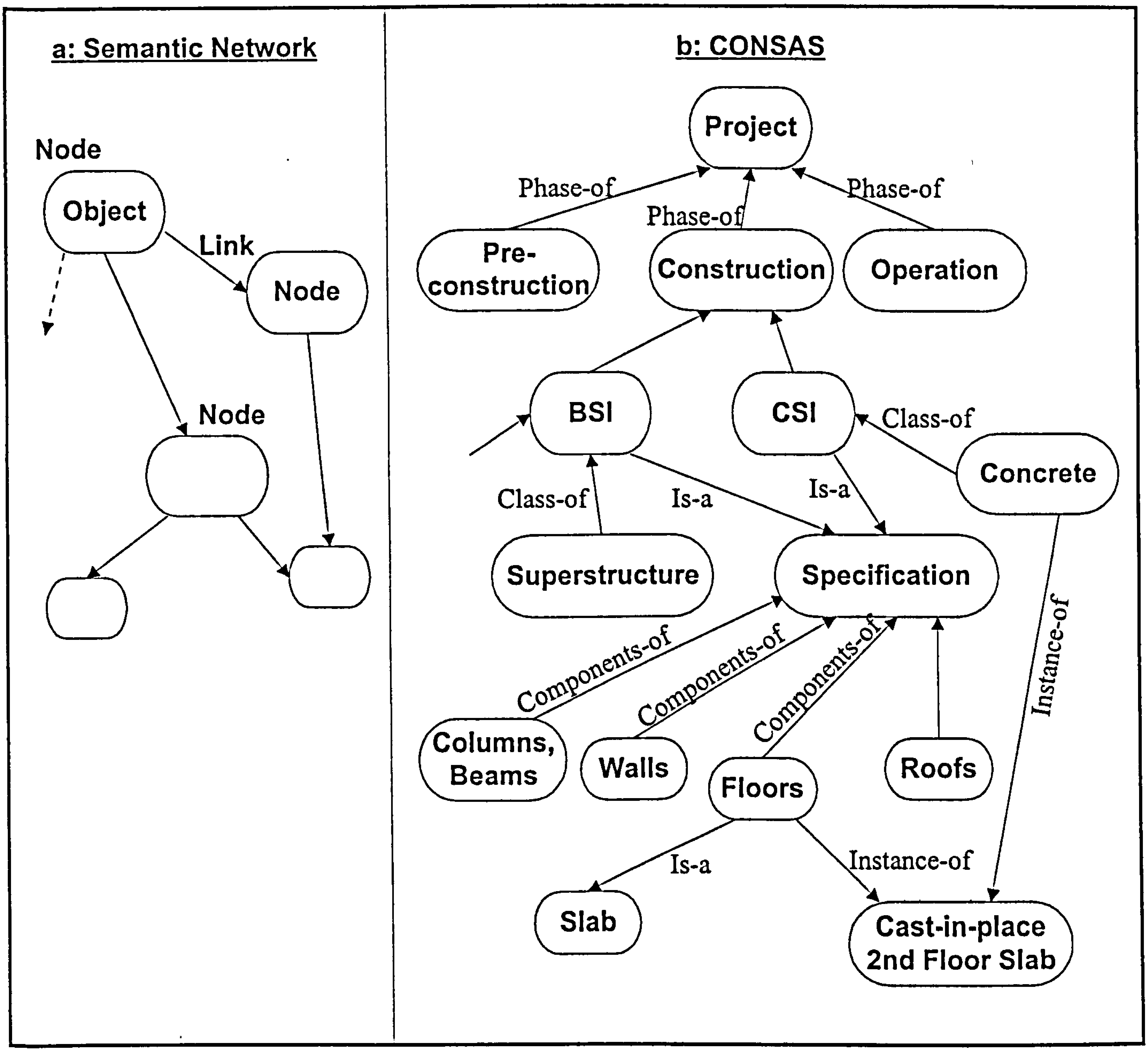


Figure 3.3- (a) Knowledge representation by semantic network (b) CONSAS semantic network.

3.6.3 Frame-Based Systems

A more complex representation of knowledge is performed by the frame-based systems which are powerful tools for knowledge manipulation. The concept of frame-based systems was introduced by Minsky (1975) who described frames as data structures for representing stereotypical knowledge of some concepts or objects.

A frame which is represented by class consists of a group of attributes, called slots, in which different characteristics of an object are described. The first slot in the frame is normally a descriptive object name. Additional slots, which have properties related to the first slot are attached to each other. A frame, therefore, contains related properties of an object such as values, descriptions and introductions to perform a specification and attributes. An example of the structure of a frame is shown in Figure 3.4.

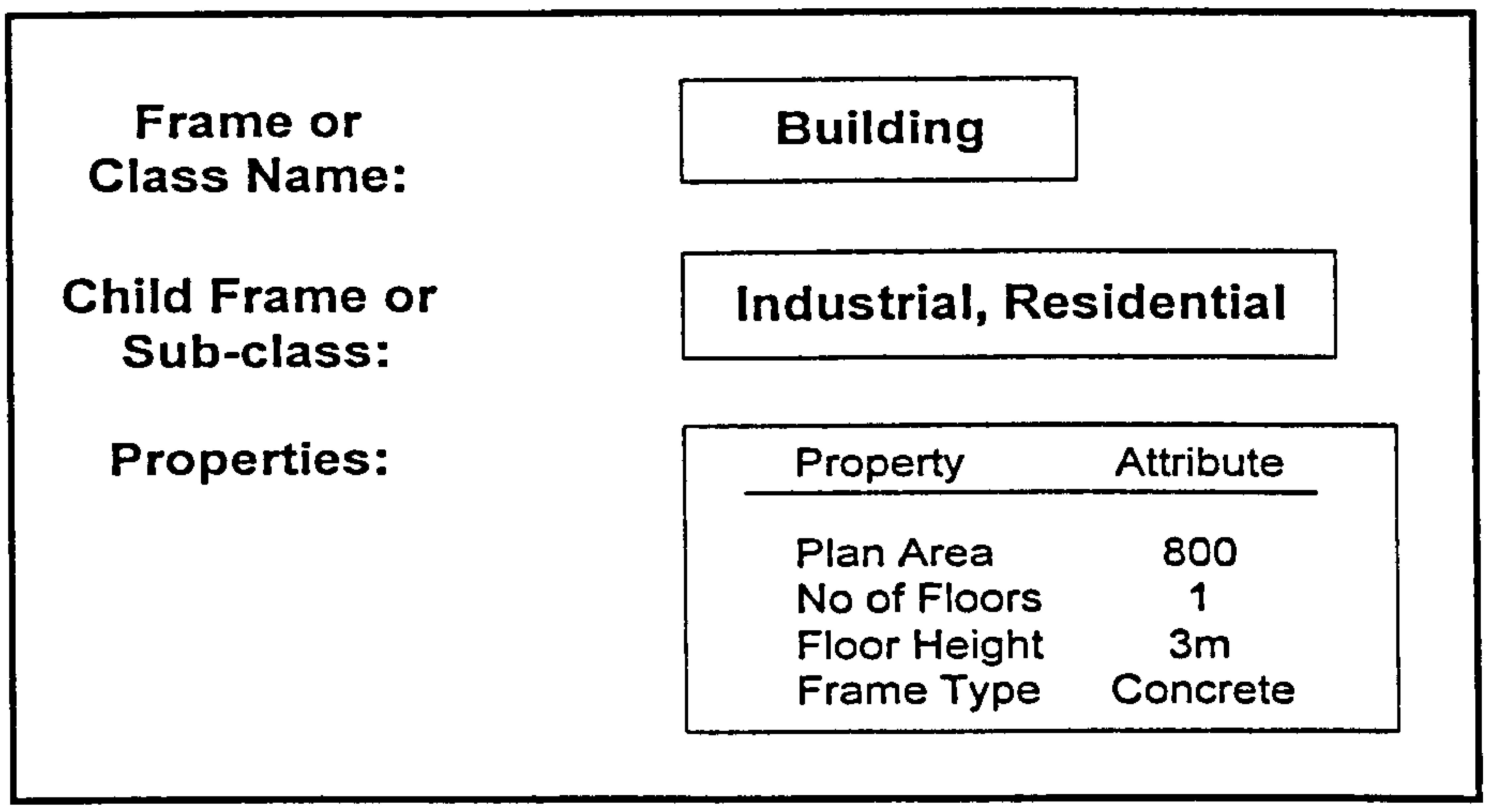


Figure 3.4 - The structure of a frame.

Frames are connected to each other in a manner similar to semantic network structures. While semantic networks are basically a two dimensional representation of knowledge, frames add a third dimension by allowing nodes to have structures. CES-1 and AT-RISE are examples of frame-based knowledge representation in the area of conceptual design of structures (Maher M.L. et al, 1988; Zhang X.J. et al, 1988).

3.6.4 Object-Oriented Systems

In conventional programming languages, knowledge is centred on steps or procedures that lead the program flow. In addition, knowledge is organised by function rather than by a particular entity or object. Conversely, in an object-oriented representation of knowledge information is concentrated around objects, their properties and their behaviours. In object-oriented systems, knowledge is grouped in a way an expert normally thinks of the knowledge domain. An object is a conceptual item with a collection of related attributes. Objects are represented by classes and instances.

Classes describe characteristics and behaviour of objects that can be stored with each instance. Slots are variables which represent important characteristics of classes. An instance is the actual object that has inherited characteristics and a specific value.

Figure 3.5 shows a class and the instance definitions for properties of a residential building object.

The Class Definition

Building
Plan Area
No of Floor
Floor Height
Frame Type

An Instance of Building

Residential Building	
Plan Area	800
No of Floor	1
Floor Height	3m
Frame Type	Concrete

Figure 3.5 - An example of class and instance definition.

All operations and computations on an instance are done by sending a message to objects. The corresponding method will be executed once an instance receives a message. The knowledge engineer would define the methods, which are procedures. These methods can be defined on either a class or an instance, and in most cases are activated by accessing slots. Therefore the creation and deletion of instances, as well as setting, changing or calculating slot values, requires the defining of the desired methods and their execution by sending messages (Adeli H., 1988; Cimflex, 1991; Funk G., 1992).

A class includes superclasses and subclasses. A superclass is an abstract class that defines the slots and methods which comprise all the common information. A subclass defines special information in the form of the slots and methods associated with the object that will override those of their superclass. For example, a class called "failure" may be established and divided further into subclasses for materials related distresses and in-service related distresses. The members of these subclasses share the characteristics and behaviour of the class "failure".

Over the years, frame-based systems have adopted most of the object-oriented programming features so that the two systems are now almost interchangeable. Nowadays, object-oriented systems are becoming more popular owing to the flexibility that exists in drawing relationships between related knowledge and development tools to use the various inference procedures (see Section 3.7) within a single expert system.

3.6.5 Hybrid Representations

Production rules (rule-based) knowledge representation is the most common for first generation expert systems. While this system is adequate for manipulating up to large-scale expert systems, for very large and more complex systems, major difficulties emerged during development. A combination of multiple knowledge representations is called hybrid representation in which the knowledge base may be encoded more efficiently and easily using different formalisms (Nikolopoulos C., 1997).

A hybrid knowledge representation combines production rules, frame-based and object-oriented techniques, facilitating the model based approach to system development and making the development of complex models and class hierarchies much easier than using the production rules approach by itself. This knowledge representation technique is available in most correct expert system shells (see Section 3.10) including ADS, ART and M.4 which employ an object-oriented based hybrid representation scheme.

Funk (1993) developed an expert system, namely Contec^{ES}, for the diagnosis and treatment of deteriorated concrete structures. An object-oriented and rule-based expert system shell has been used for the implementation as well as a set of digital photographs and graphics as part of the knowledge base.

3.7 Inference (Reasoning) Techniques

Inferencing is the common process by which expert systems model the human reasoning to solving problems. It is a process that controls the selection and use of knowledge and the facts in the knowledge base to draw conclusions about the problem. The inference mechanism is normally referred to as the inference engine. It is that part of an expert system which determines how the knowledge is to be used. It achieves this by using procedures that search for problem solutions in one of the two main reasoning processes known as forward chaining (forward reasoning) or backward chaining (backward reasoning). These techniques represent the direction of the search through the knowledge base.

3.7.1 Forward Chaining

In the forward chaining inference technique, sometimes called data-driven search, the expert system uses a set of known facts and attempts to reach a goal state until one is found whose premises match the known facts for the problem entered in the working memory. The rule is then applied and the working memory is updated. This process is repeated until the goal state is achieved or no useable rule is found. The simplest application of forward chaining in a rule-based expert system is shown in Figure 3.6.

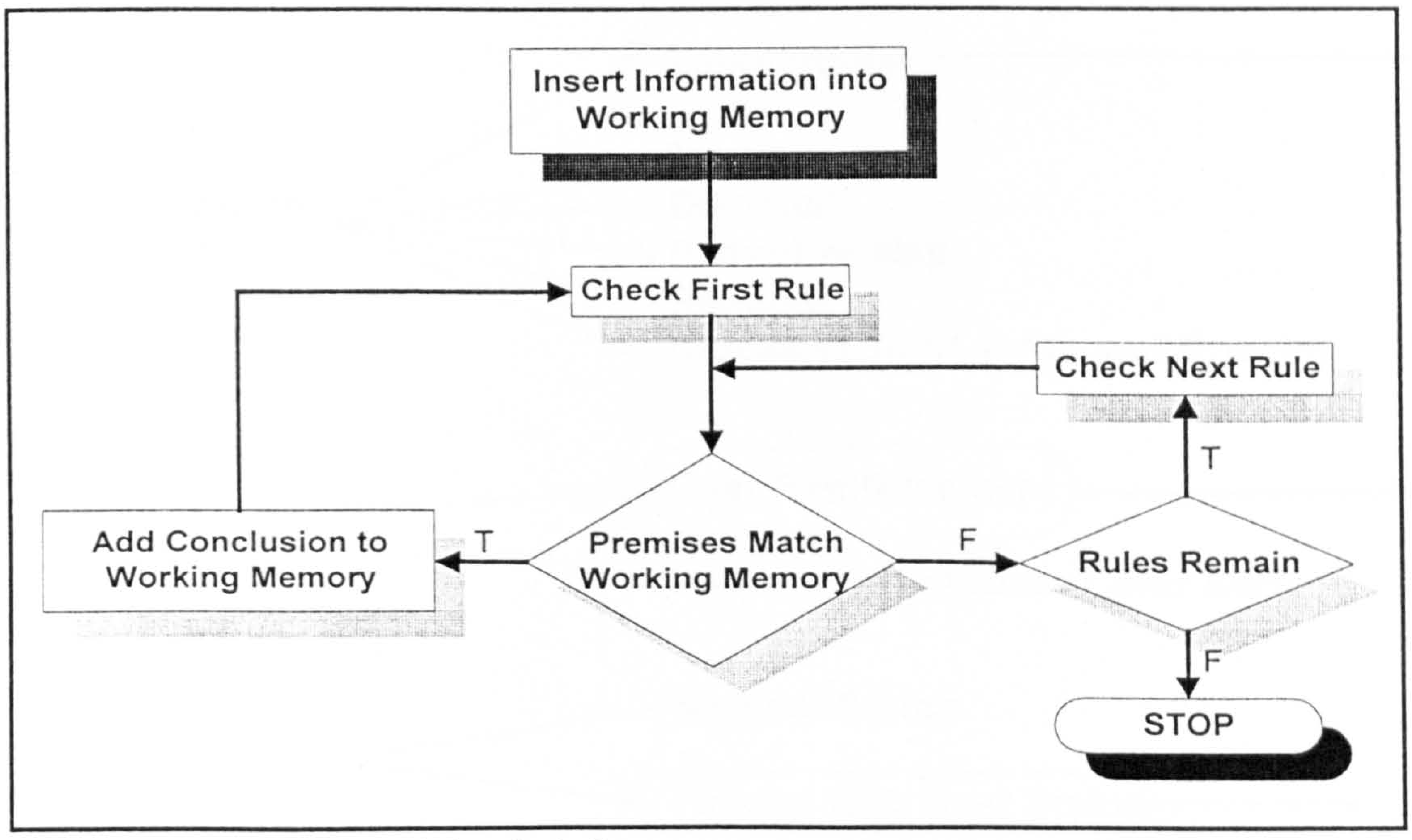


Figure 3.6 - Forward chaining in inference process.

3.7.2 Backward Chaining

The backward chaining inference technique is most commonly used in expert systems known as goal-driven problem-solving systems. This inference technique starts with a hypothesis or goal and then attempts to verify it by the information gathered. Backward chaining is often employed in diagnostic expert systems. For example, an engineer may suspect some problems with a distress in concrete (e.g. corrosion of reinforcement) and attempts to prove it by looking for certain symptoms (e.g. rust stain in generally straight cracks). This style of reasoning is modelled in an example using goal-driven search and in Figure 3.7.

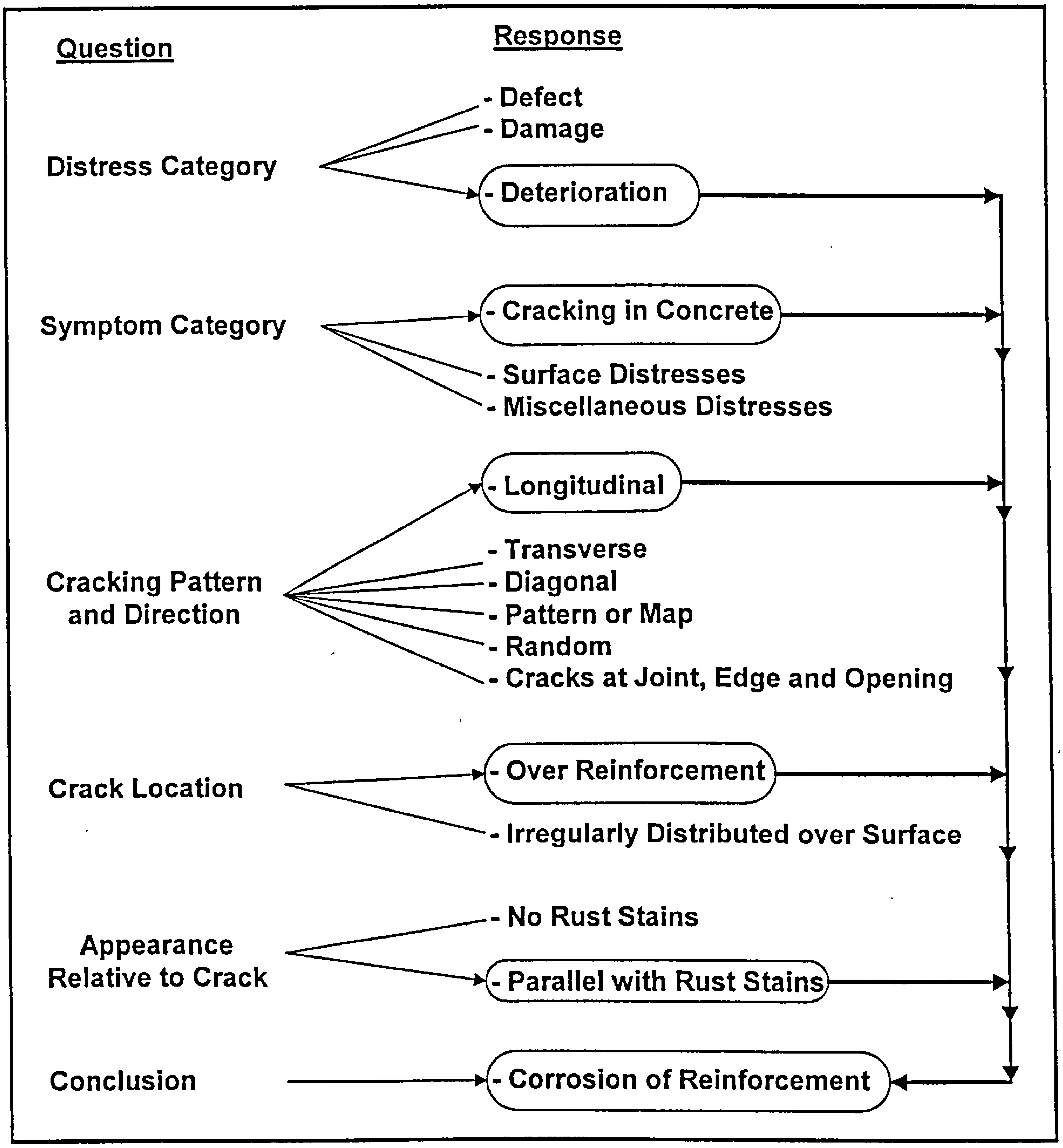


Figure 3.7 - An example of backward chaining inference process.

3.7.3 Combination of Backward Chaining and Forward Chaining

Forward chaining or data-driven reasoning takes the facts of the problem and applies the rules and legal moves to produce new facts that lead to a goal. While backward chaining or goal-driven reasoning focuses on the goal then finds the rules that could produce the goal, and chains backward through successive rules and subgoals to the given facts of problem.

The major difference between forward and backward chaining is that forward chaining checks the rule's premise, not the conclusion. Once the promise is satisfied, forward chaining executes the rule immediately regardless of the contents of the conclusion. In other respects, forward chaining goes through the rules in the order in which they are written in the knowledge base, independent of both premise and conclusion. In addition, forward chaining does not work on only one rule until it determines whether it has "passed" or "failed". It means that forward chaining evokes the execution of all the rules related to the information, unlike backward chaining which searches only the part of the knowledge that is related to the current problem.

A combination of both forward and backward chaining uses advantages from both techniques. In most cases, the mixed chaining technique, which first starts with backward chaining, is the most suitable application for obtaining the maximum performance from expert systems. In this technique, a new rule is assigned to any variable by backward chaining and the search algorithm is switched to forward chaining. Forward chaining goes through the rules and picks up the rules for a new known fact. Once the procedure passes through the knowledge base, backward chaining is resumed. Again, when a new value is assigned, forward chaining is initiated. Therefore, all rules are analysed by both backward and forward chaining. Furthermore, mixed chaining eliminates the disadvantages of backward chaining by introducing forward chaining.

3.8 Search Strategies

In addition of specifying a search direction discussed in Section 3.7 a search algorithm must determine why a particular solution path is preferred over the other. In Artificial Intelligence a problem's knowledge (Problem State) can be graphically examined in a state space (Figure 3.8). The state space is a tree or graph comprising a set of nodes that represent the state of the problems, and arcs or links that represent the possible paths to move from one state to another. To illustrate the way an expert system searches through a state space to solve a problem, two different search strategies can be adopted comprising the depth-first search and the breadth-first search.

3.8.1 Depth-First Search

In depth-first search when a parent state is explored, it always expands along one path at the deepest level of the state space before examining any other path until it either reaches the goal or a dead end. When a dead end is encountered it then backtracks to the last node in the same order from left to right of the state space. If another dead end is revealed or no more unexamined paths from a node (state) exist, by a backtracking technique a search begins at the start node and pursues a path until either a goal or another dead end is found. Figure 3.8 illustrates a depth-first search algorithm, which corresponds very closely to backward chaining which starts with a desired conclusion and decides if the existing facts support the derivation of a value for this conclusion.

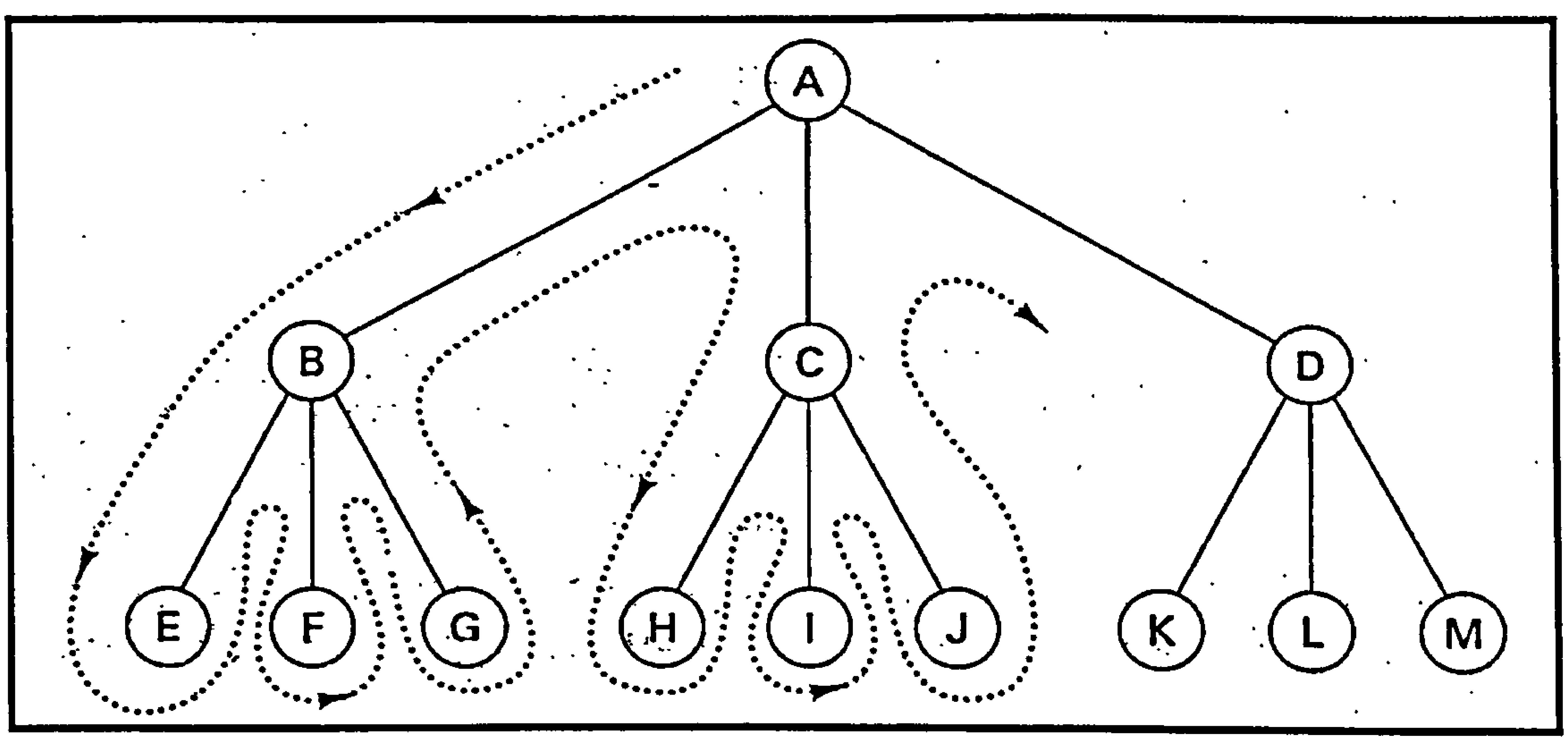


Figure 3.8 - Depth-first search of a tree.

3.8.2 Breadth-First Search

Breadth-first search, in contrast, examines all nodes at the same hierarchical level using some arbitrary rule (e.g. left to right) before proceeding to the next level. Only when it is unable to find a solution within this level and there are no more states (nodes) to be examined it drops down to the next level and searches in the same manner. A breadth-first search algorithm, which is more common in forward chaining or data-driven reasoning, is shown in Figure 3.9.

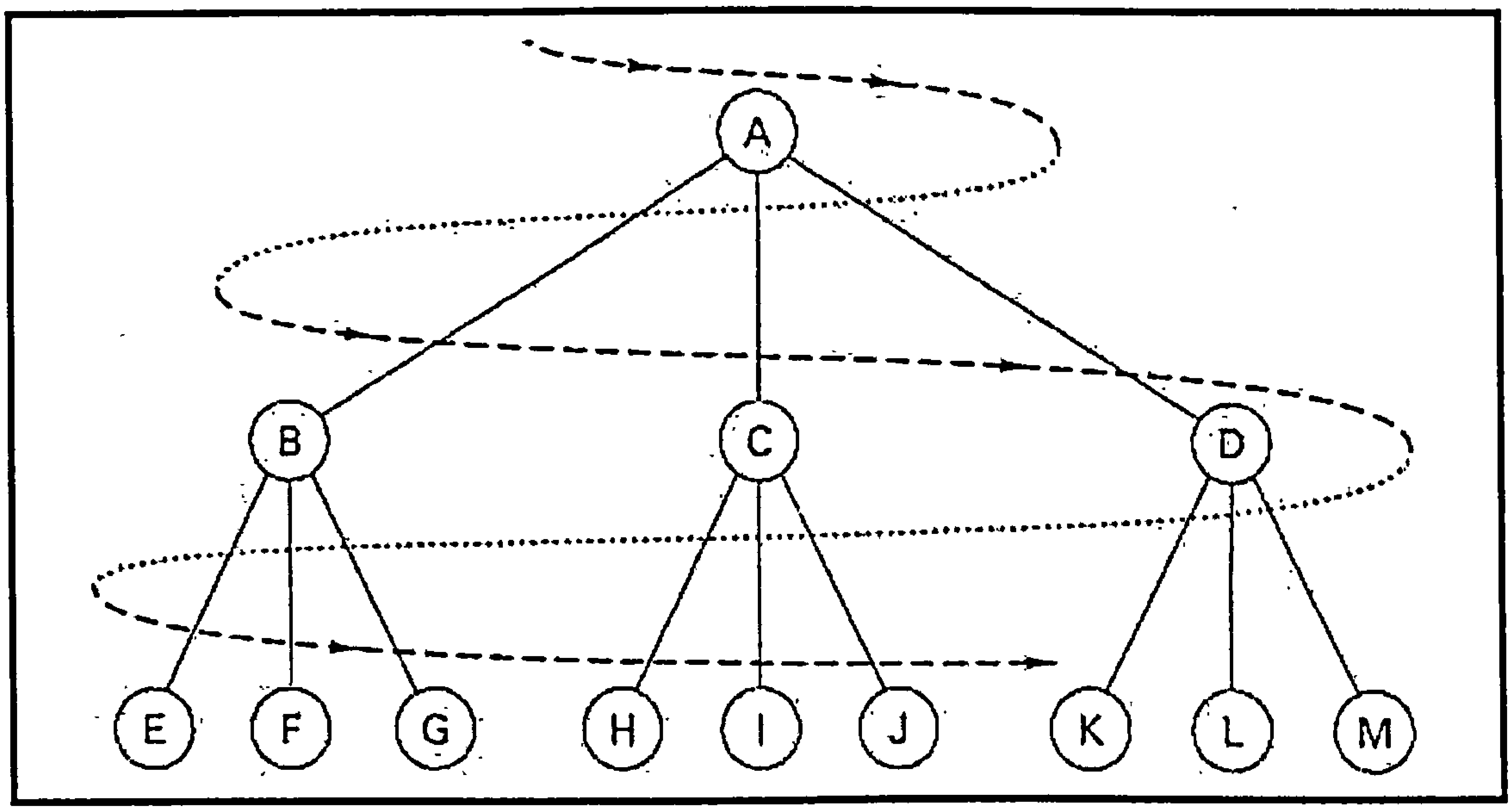


Figure 3.9 - Breadth-first search of a tree.

3.8.3 Heuristic Search

Both depth-first and breadth-first search techniques explore a state space without any knowledge about the state of the problem to help guide their search. Therefore, they imitate the search method blindly which may be time consuming in large state spaces that do not correspond with human reasoning.

A search that uses one or more items of domain-knowledge about the problem to traverse a state space graph is called a heuristic search. The simplest way to implement a heuristic search is through a procedure called hill climbing (Luger G.F. et al, 1998).

In expert systems, when a heuristic search requires a more informed algorithm this is provided by best-first search. During the search of a state space, at each node a best search employs a heuristic (a rule of thumb) method that can choose which system knowledge to process next and which path to take next. The advantage of a heuristic search is that the search is faster than the blind searches as less promising solution paths are eliminated before they are examined.

3.9 Knowledge Acquisition

In the development of expert systems, knowledge acquisition is a crucial aspect of developing knowledge bases and it is important that the source of knowledge for any system is carefully selected. Buchanan et al (1983) defines knowledge acquisition as the transfer and transformation of potential problem-solving expertise from some knowledge source to a program.

Acquiring knowledge from an expert person heuristic experience is a difficult task. Therefore, the use of multiple sources is considered beneficial for validation and for ensuring that the correct representation of knowledge is accomplished. Primary sources of knowledge for providing some information on the given problem include technical publications, published codes of practice, standards, domain experts by interview and/or questionnaire, textbooks and case histories.

Knowledge engineers face difficulties when they deal with heuristic knowledge and most experts have trouble explaining their ideas. In many engineering fields, questionnaire is used as a means of gathering information and data collection. Interviews often take place between the knowledge engineer and the expert person. Data survey methods and procedures adopted in developing a questionnaire used in this research are discussed in Chapter 5.

In addition to expert knowledge, information contained in guides, published standards and the literature is also used in knowledge acquisition and expert system developments. For example, DURCON (Clifton J.R. et al, 1985) is an expert system which uses the American Concrete Institute (ACI) 'Guide to Concrete Durability - 201' and expert knowledge from ACI Committee 201 members as its knowledge base.

3.10 Selection of Expert System Development Environment

Programming languages, representation languages, and expert system shells are development environments available for expert system development. Amongst these, the expert system shell is the most popular development environment that is used in the field of structural engineering.

A shell is a completely developed expert system with all its facilities but without its knowledge base. Most shells are developed using programming languages for use on personal computers. The established shell environment includes the knowledge representation structure, inference engine, explanation, and debugging facilities. Because a working inference engine already exists, the shell user is not directly involved in developing the control strategy or explanation facility (Hanna P. B., 1993; Nyambayo J., 1997).

After the PROLOG language was introduced, a number of expert system shells were developed using this new language as well as LISP. Although LISP and PROLOG are the predominant languages used for writing expert system shells, other languages such as PASCAL, BASIC, C, and C++ are also used. With the growth of expert systems technology, the list of shells is rapidly expanding whereby, nowadays, the primary task is not to find a shell but to choose a suitable shell for the given application. Choosing the most suitable shell for any given application depends on the type of application being performed and the functions required from the expert system shell.

There are several shells which can be used in the field of structural engineering, such as EXSYS Professional, Instant Expert Plus and M.4. EXSYS Professional is a generalised expert system development shell that can be used for any type of problem solving where the decision is based on logical rules. Shell programs such as EXSYS and Instant Expert Plus contain a variety of user-friendly features and flexibility in terms of adjusting and expanding the knowledge base (Hanna P. B. et al, 1993; Mohsen A. Issa et al, 1995).

M.4 may be used as a development shell: it is powerful and adopts PC-based knowledge system software that is being developed and used on microcomputers. Because of its compatibility with the C programming language, novice computer programmers without previous experience in knowledge system technology or special LISP programming capability can use M.4 quickly and effectively.

Knowledge systems created with M.4 use a similar structure to gain adequate solutions. M.4 is a cost-effective software tool for companies to develop and use a knowledge system so that they can rapidly appreciate the utility of using knowledge systems in business (Cimflex, 1991). Table 3.2 shows a comparison between shell programs.

A knowledge base of facts, rules, procedures, objects relating to a particular task or application, and an inference engine that enables the system to reason about the domain in order to solve specific problems is used to design M.4's knowledge systems. A programmer can create a text file of facts and objects for describing the relationships between factors in the application, rules and procedures for applying these facts and objects to certain situations by using any text editor. After being loaded into M.4, this file can be used as a knowledge base file to solve problems by means of the inference engine. With respect to knowledge system delivery, a programmer can build end-user knowledge systems for delivery into application environments by M.4. In this view, an end-user knowledge system includes the M.4 inference engine, one or more knowledge base files in delivery format, and an M.4 configuration file.

3.10.1 M.4 Features

M.4 as a development shell is a powerful and versatile PC-based knowledge system for microcomputers. M.4 consists of the Inference Engine, Knowledge Base and Working Memory as an essential part and a User Interface. M.4 runs on PCs under widely used operating systems with database integration and links to C, Visual Basic, and Visual C++.

Table 3.2 - Comparison between shell programs.

Criteria	EXSYS Professional	Instant Expert Plus	M.4
▪ Environment	PC-DOS IBM	Macintosh	IBM PC, XT, AT, 386, 486, MS-DOS 3.3, Microsoft Window 3.0
▪ Control Strategy	Backward and forward chaining	Backward, forward and mixed mode	Backward, forward and mixed mode
▪ Explanation Facility	- Respond to HOW by displaying the chain of fired rules. - Respond to WHY by displaying the rules attempt to fire	- Respond to WHY by displaying the candidate rules.	- Respond to HOW by displaying the current conclusion was reached. - Respond to WHY by displaying a question is being asked. -Respond to WHAT by displaying a rule is being considered.
▪ External Programs	Yes	Yes with other Mac. Graphics.	External function calls such as: dBase III, Embeddable DOS and Microsoft Windows Libraries, Dynamic Data Exchange (DDE), and Dynamic Link Library (DLL).
▪ Easy of Rules Input	Yes	No	Yes
▪ Confidence	Three mode: • Yes / No • 0 – 10 • -100 to 100 Confidence appears in conclusions only	One mode only: • Yes / No • Unknown • 0 – 10 Confidence appears in question and conclusions.	Four mode: • yes / NO • 0 – 20 • -100 to 100 • unknown Confidence appears in question and conclusions.
▪ Graphics	No graphic capabilities.	Good graphic capabilities.	Good graphic capabilities.
▪ Ease of Modification	Easy, changing qualifiers will automatically change the corresponding rules.	No easy, must change the rules one by one.	Easy, changing qualifiers will automatically change the corresponding rules.

Knowledge Representation - M.4's main knowledge representation is production rules (discussed in Section 3.6.1) with object-oriented and procedural features (discussed in Section 3.6.4). The maximum knowledge base size varies widely based on the mix and complexity of the knowledge base entries, such as facts, rules, objects and procedures. These knowledge base entries can be used with symbolic variables in the knowledge base. These variables can be automatically replaced with values during a consultation, whereby the number of rules used in a knowledge base is greatly decreased. An illustration of the use of variables in a rule, which selects a bolt of a certain size; given that some constraints concerning length; diameter and thread pitch can be satisfied, is shown in Figure 3.10. Upper case expressions denote variables.

```
if      recommended_type = bolt and
        recommended_length = LENGTH and
        recommended_diameter = DIAMETER and
        recommended_thread_pitch = PITCH and
        faster_bolt_LENGTH_DIAMETER_PITCH = BOLT
then    recommended_faster = BOLT.
```

Figure 3.10 - Use of variables in M.4.

Procedures in M.4 - Knowledge engineering applications may be in the form of problem-solving strategies for actions, or steps to take in problem-solving techniques. Such knowledge can be divided into three categories: Factual, Procedural and Heuristic knowledge.

Procedures that are often represented as a group of instructions are the typical forms of code in M.4 as well as in a regular programming language. These procedures use the same syntax as the conventional C programming language.

M.4 procedures are used for seeking the values of expressions in order to assign them to variables, and also for executing M.4 commands in the promise of a rule. The instructions within the body of the procedure may be executed once, iteratively or recursively by using the *do while* loops and *forall* statements. In addition, inside an

M.4 procedure, the developer can display text to the end-user, create an instance of a class, and send a message to an instance. Figure 3.11 shows an example of procedure used in the M.4 knowledge base.

```
procedure(repair_method) = {
        find message(repair_considerations,[]);
        NATURE := active_dormant;
        CRACK := nature_crack;
        find message(repair_method,[NATURE,CRACK]);
        if (NATURE == active) {
            if (CRACK == pattern_cracking) {
                eval(active_pattern_cracks);
                break;}
            else {
                eval(active_isolated_cracks);
                break;}
        }
        else {
            if (CRACK == pattern_cracking) {
                eval(dormant_pattern_cracking);
                break;}
            else {
                eval(dormant_isolated_cracking);}
        }
    }.
```

Figure 3.11 - An M.4 procedure for selecting a repair method for cracking in concrete.

Object Oriented in M.4 - In conventional programming languages, knowledge is centred on steps or procedures, whereas in an object-oriented representation of knowledge (discussed in Section 3.6.4), information is concentrated around objects, their properties and their behaviour. Object-oriented programming allows elements within an M.4 application to be described as objects. The M.4 object-oriented programming capability supports the definition of classes of objects and the creation of instances. M.4 objects also support inheritance of slots, slot values, and methods as well as message passing between objects.

Inference Engine - In the main M.4's body, the inference engine is a mechanism for seeking values for expressions by methodically considering previously stored conclusions, relevant knowledge base entries and user-supplied information. Under these circumstances, the M.4 inference engine initially uses a backward chaining or reasoning process that works with input information and rules in the knowledge base in order to gain conclusions. In addition, forward chaining is another inference strategy that enables it to activate a special set of high-priority goals once conclusions matching a specified prototype are made. Forward chaining is supported in M.4 with the *whenfound* and *whencached* constructs, which cause actions to be taken after values for an expression have been sought. The action taken can be conditional, and may involve the invocation of a procedure or the initiation of backward chaining.

The search strategy in M.4 is heuristic and the inference is triggered by a *goal* or *initialdata* statement. A goal is the ultimate expression to be evaluated, or hypothesis to be proven. An *initialdata* is an intermediate goal.

Control in M.4 - A control strategy is a method of controlling the performance of a consultation. In M.4 the control strategy is implemented through meta-rules and procedures.

3.11 Summary

Advances in computer hardware technology and software development make it feasible to develop expert systems that are an effective decision-making tool for concrete structures involved in diagnosing distresses, designing and in making decisions related to the selection of repair and rehabilitation procedures and materials. A review of the application of expert system technology in structural engineering design and repair and maintenance of concrete structures has been presented in this Chapter. It has been shown that the knowledge normally used by concrete experts in computerized systems can be developed in the form of pictures, drawing, databases, guides and specifications.

The fundamental components of an expert system, which have changed little since expert systems were introduced, are also highlighted. The knowledge representation, which is known as problem solving techniques, the inference engine and/or the logic portion that operates on the knowledge and the knowledge acquisition are presented as the three basic components. Perhaps the most significant change in expert systems architecture is the representation of the knowledge within the computer and its interrelationships. Nevertheless, most knowledge is presented in the form of procedure rules. Development tools in use today make use of this form of knowledge representation in combination with other techniques such as semantic networks. This hybrid system is often called an object-oriented system which uses multiple inference procedures.

The final part of this Chapter covers the selection of a development tool that allows flexibility for incorporating different knowledge forms and provides a high level of programming productivity. In this thesis an expert system shell, called M.4, is used as a development tool that provides a platform for further enhancement and the addition of knowledge as well as providing a high level of programming productivity.

In this thesis it is intended that pictures are used to lead the end-user in identifying causes of distress, using site investigation apparatus, selecting repair materials and methods and the corresponding remedies. It gives room for multimedia assistance in the selection of parameters and it gives rise to an architecture that is not centred around the expert system but one which is centred on the user interface. It is also proposed that the communication of the information through files enables other applications to manipulate the same data, for example storage and retrieval of concrete repair problems from a database. Database Management Systems (DBMS) technology and Expert Database Systems (EDS) are discussed in the next Chapter and their role in the application of multimedia assistance to design in a knowledge-based environment is considered.

Chapter 4

Review of Database Management Systems

4.1 Introduction

Chapter 3 considered the fundamental concepts of Knowledge-Based Expert System technology. The need for data management in the field of concrete repair in a Knowledge-Based Expert System was highlighted.

This Chapter examines Database Management System (DBMS) technology by establishing an initial definition for some of the major concepts of database management architecture and data models such as hierarchical, network, relational and object-oriented. Furthermore, "Microsoft Access", a commercially available DBMS used in this research is discussed. Finally, various architectures for interfacing knowledge-based expert systems with database management systems are reviewed.

4.2 Database System

Databases and database systems have become an essential component of everyday life in modern society (Elmarsi R. et al, 2000). A database system is a computerized record-keeping system whose overall purpose is a structured repository collection of information shareable between different users which allows them to retrieve and update that information on demand. The information in question could be anything that is needed to assist in the general process of running the day-to-day activities of an organisation (Beynon-Davies P., 2000; Date C.J., 2000).

Databases were originally developed to marshal all available data in a common format so that the users could perform a variety of operations rapidly and conveniently. A database system usually involves four major components comprising data, hardware, software, and users. These components, shown in Figure 4.1, are briefly considered in the following sections.

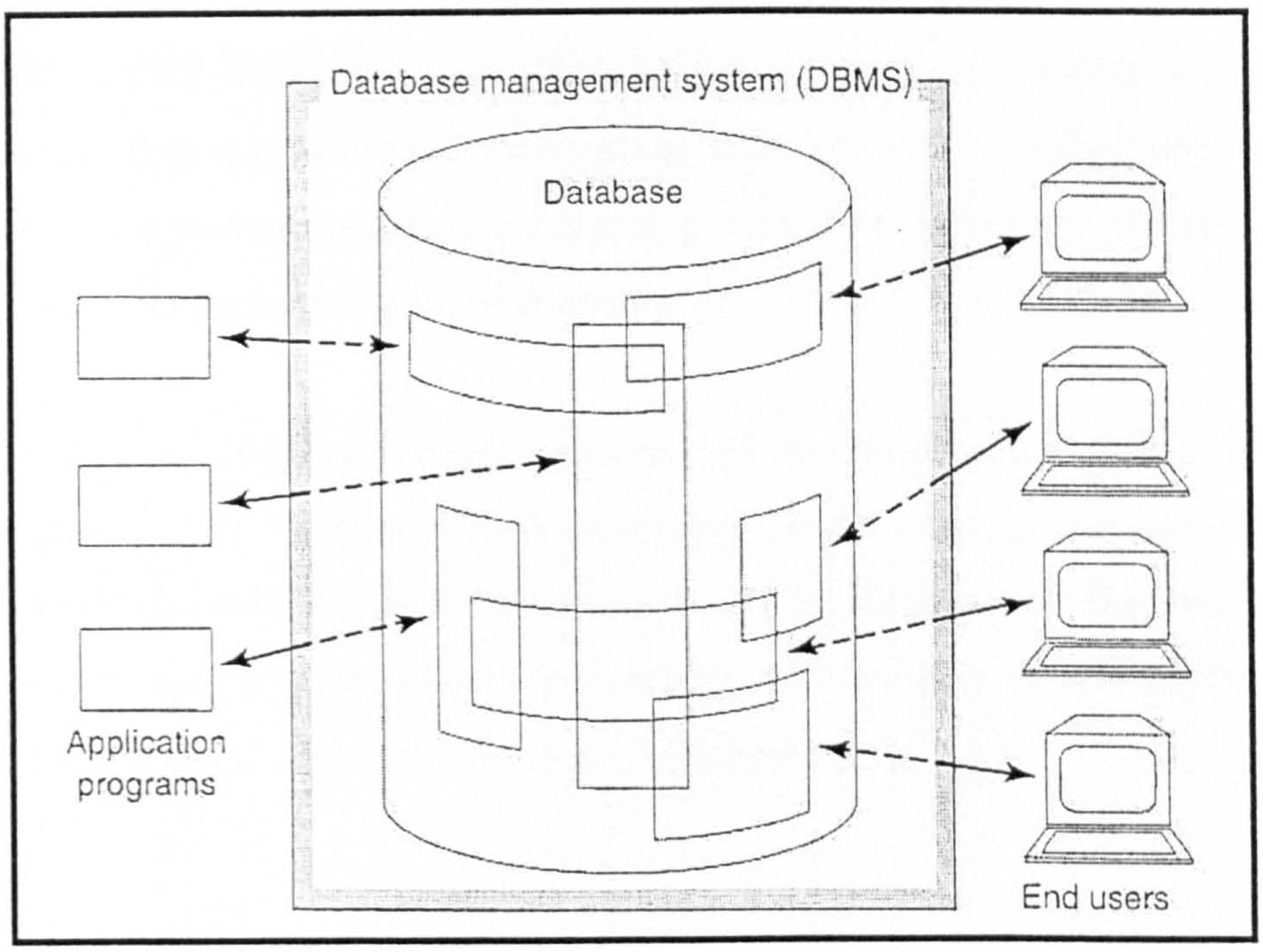


Figure 4.1 - Simplified picture of a database system (Date C.J., 2000).

4.2.1 Data

The most important component of a database system, certainly from the end-user's point of view, is the data so that the data act as a bridge between the machine components and the end-users. Therefore, the data structure is of fundamental importance to a database system which implies a series of related properties comprising data sharing, data integration, data integrity, data security, data abstraction and data independence (Date C.J., 2000; Beynon-Davies P., 2000). These properties are explained briefly below.

Data Sharing - Individual pieces of data stored in a database can be shared among different users and are expected to be accessible concurrently.

Data Integration - One of the major characteristics of database usage is to ensure that the data is integrated. "Integrated", means that the database which should be a collection of data can be thought of as a unification of several otherwise distinct files with any redundancy among those files at least partly deleted.

Data Integrity - Property arising as a consequence of shared data is that a database should display integrity which refers to the accuracy or correction of data in the database. This means that if relationships exist for data in a database then changes made to one partner in such a relationship should be accurately reflected in changes made to other partners in that relationship.

Data Security - One of the primary ways of ensuring the integrity of a database is restricting access. In other words protecting the database against users who are not authorised to access either certain parts of a database or the whole database. Therefore, in a database system the security and integrity control of the database is one of responsibilities of the Database Administrator (DBA).

Data Abstraction - A database can be viewed as a model of reality. The information stored in a database is usually an attempt to represent the properties of some objects in the real world.

Data Independence - The concept of data independence can be defined as the immunity of application programs to changes in the way the data is physically or logically stored and accessed.

4.2.2 Hardware

The hardware components of a database system consist of:

- Secondary storage volumes, often magnetic disks that are used to hold the stored data, to communicate with the associated I/O devices, device controller, I/O channels and so forth; and
- The hardware processor and associated main memory that are used to support the execution of the database system software.

4.2.3 Software

Between the database itself - i.e. the data as physically stored and the user of the system is a layer of software. This software is known variously as the database manager or database server or most commonly the Database Management System (DBMS) described in Section 4.4. The user can access the database and can perform a variety of operations through the DBMS. The facilities provided by the DBMS include adding and removing files, retrieving data from and updating data in such files, inserting data and/or changing data in existing files.

4.2.4 Users

Users can be broadly divided into three categories according to the way in which they use the system. Firstly there are application programmers who are responsible for writing database application programs in some programming languages such as COBOL, PL/I, C++, fourth-generation language and Java.

Second there are end-users (naïve and sophisticated) who interact with the system from online workstations or terminals. Naïve end-users may merely access the database without any awareness of the applications programs which attempt to make the operations as simple as possible. Sophisticated end-users are familiar with the structure of the database and the facilities offered by the DBMS.

A third category of users are Database Administrators (DBA's) who are responsible for the physical database design and implementation, security and integrity control, maintenance of the operational system and ensuring satisfactory performance for the applications and end-users.

4.3 Database System Architecture

A major aim of a database system is to provide users with an abstract view of data, hiding certain details of how data is stored and manipulated. Since a database is a shared resource of information, each user might require a different purpose of the data held in the database. To satisfy these requirements, database system architecture is useful for describing general database concepts and for explaining the structure of specific database systems.

The architecture of most commercial database systems available today is based to some extent on the so-called ANSI/SPARC architecture (Date C.J., 2000; Connolly T.M. et al, 2000; Beynon-Davies P., 2000). Although this architecture does seem to fit most systems reasonably well it is not claimed that every system can be neatly matched to its particular framework.

The ANSI/SPARC architecture which was proposed by the American National Standard Institute Standards Planning and Requirements Committee in 1975, is divided into three levels known as the Internal, Conceptual and External levels (Figure 4.2).

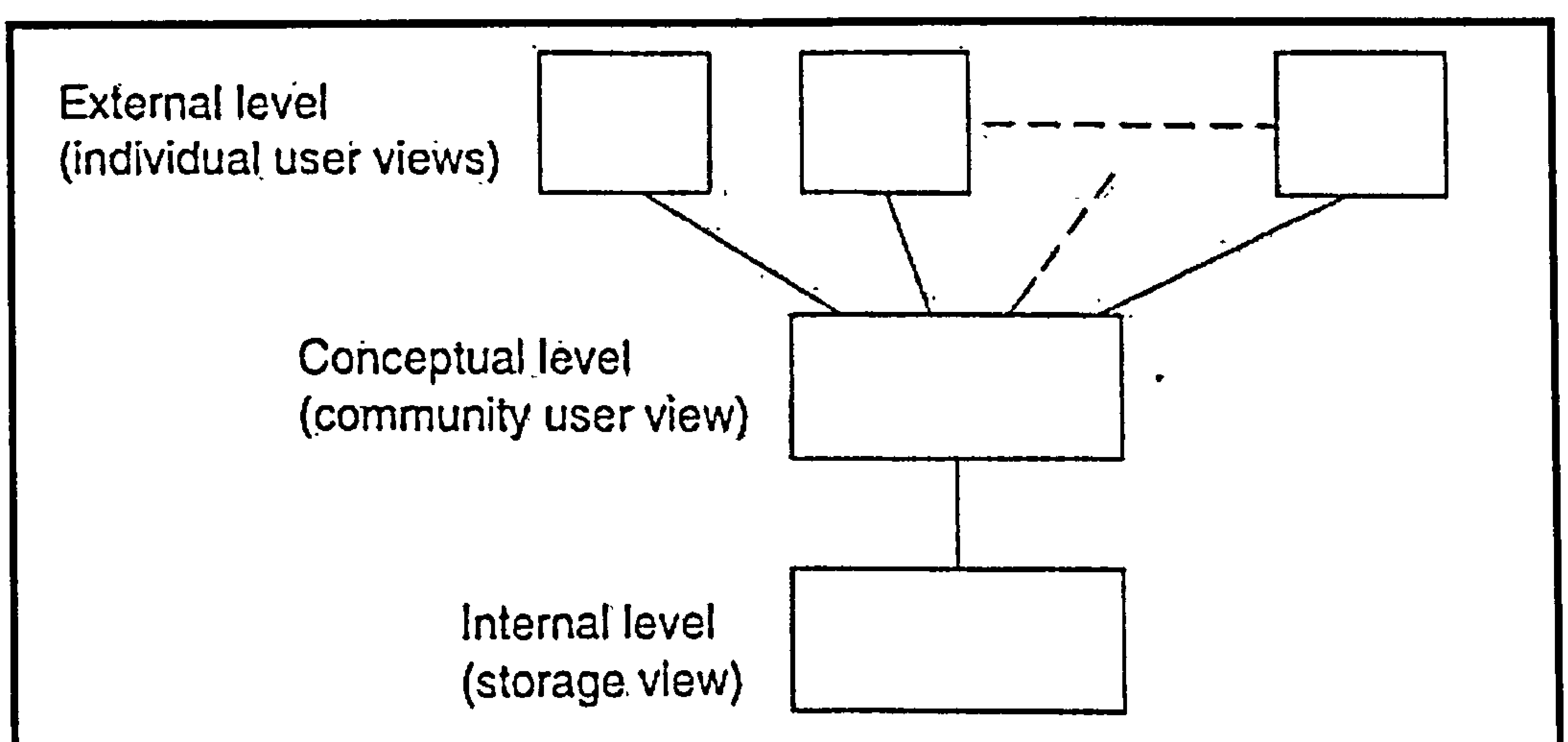


Figure 4.2 - The three levels of ANSI/SPARC system architecture (Date C.J., 2000).

These levels which are sometimes referred to as schemas or views, are briefly described as follows:

- The internal level (or physical level) is the one concerned with the way in which the data is physically stored and the way in which the data might be accessed.
- The external level (or user level) describes the user's or application programmer's view of the database individually.

- The conceptual level (or logical level) is a level of indirection between the other two. This level describes the organisation's view of all the data in the database, the relationships between the data and the constraints applicable to the database.

In addition to these three levels, the architecture involves with two types of mapping, one conceptual/interval mapping and several external/conceptual mappings (Date C.J., 2000).

Conceptual/interval mapping defines the correspondence between the conceptual level and the stored database. It specifies how conceptual records and fields are represented at the internal level. If the structure of the stored database is changed then the conceptual/interval mapping must be changed accordingly so that the conceptual schema can remain invariant. In other words, the effects of such changes must be isolated below the conceptual level in order to preserve physical independence.

External/conceptual mapping defines the correspondence between a particular external level and the conceptual level. In general, the differences that can exist between these two levels are analogous to those that can exist between the conceptual level and stored database.

The major components of the ANSI/SPARC architecture and their interrelationships are shown in Figure 4.3.

4.4 The Database Management System (DBMS)

Databases were originally developed to marshal all available data in a common format so that the users could perform a variety of operations rapidly and conveniently. Database Management System (DBMS), which is the software - i.e. an organised set of facilities for accessing and maintaining one or more databases, organises and structures data so that it can be retrieved and manipulated by users and application programs.

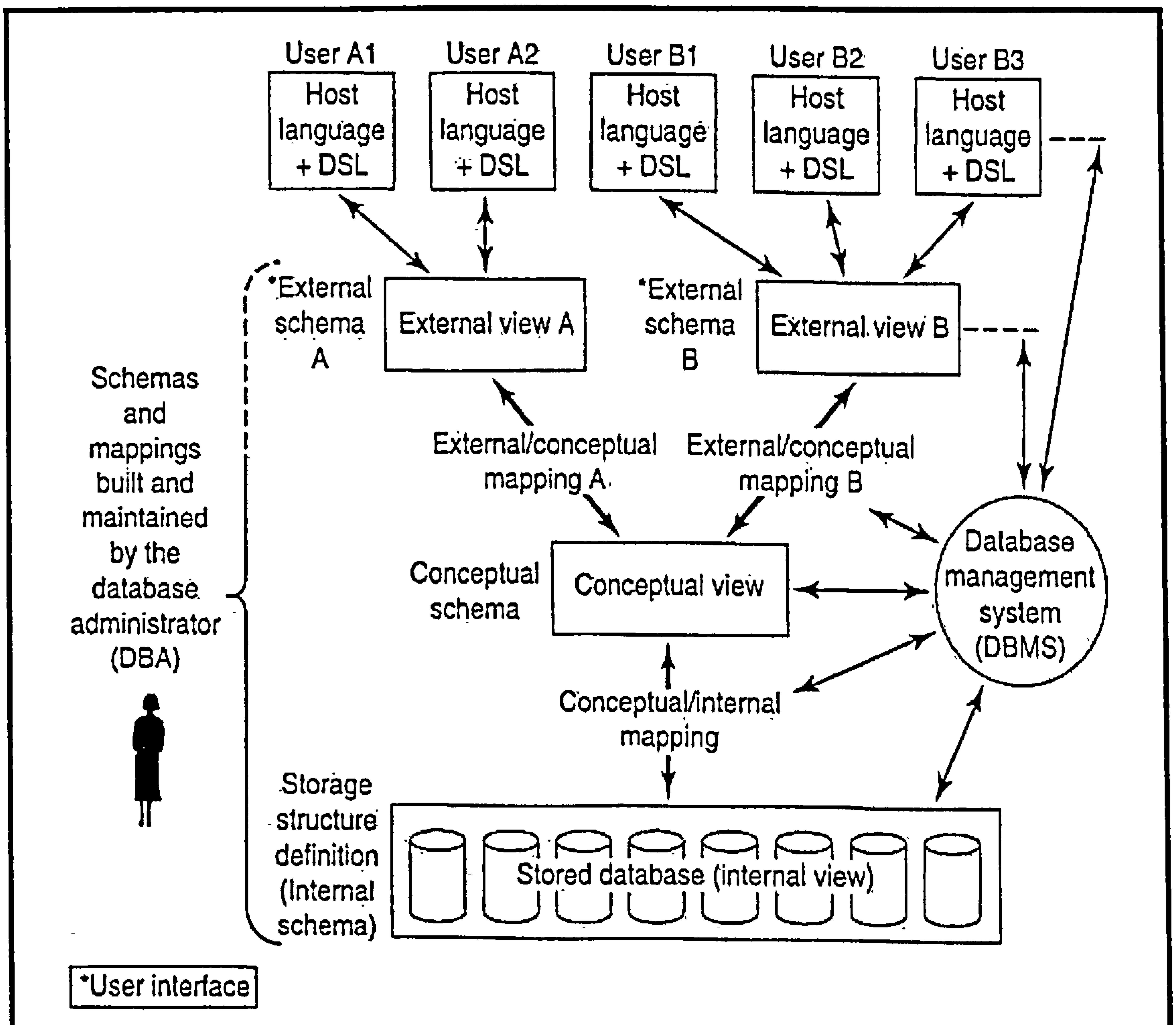


Figure 4.3 - Detailed database system architecture (Date C.J., 2000).

A DBMS surrounds a database or series of databases as a shell through which all interactions take place with the database. The facilities provided by DBMS include data maintenance (adding and removing files, inserting new data into the database, modifying existing data), retrieving data from such files for use by application program, and data administration. The interaction created between a database, a Database Management System and DBMS facilities are shown in Figure 4.4.

4.5 Database Management System Architectures

Over the last decade, the architecture of DBMS packages has evolved from the early monolithic systems, where the whole DBMS software package is one tightly integrated system to the modern DBMS packages that are modular in design, with a client-server system architecture (Elmasri R. et al, 2000).

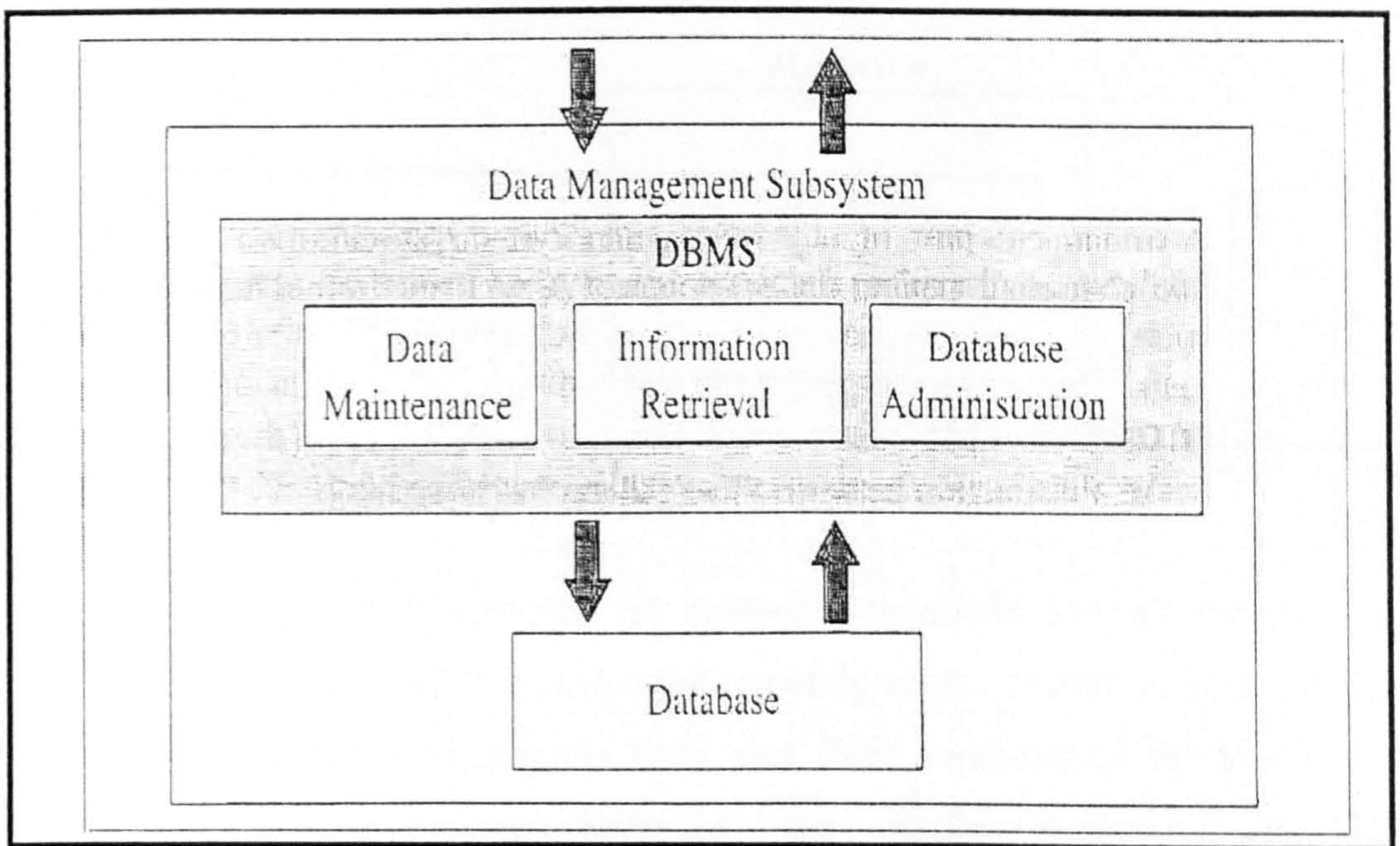


Figure 4.4 - Facilities of a DBMS (Beynon-Davies P., 2000).

A client module is typically designed so that it will run on a user workstation or Personal Computer (PC). Typically, application programs and user interfaces that access the database run in the client module. Hence, the client module handles user interaction and provides the user-friendly interfaces such as forms or menu-based Graphical User Interfaces (GUI). The other kind of module, called a server module, typically handles data storage, access, search, and other functions. This section deals with the various DBMS architectures which include centralized, file-server, and client-server.

4.5.1 Centralized Architecture

One of the earlier and basic system architectures that are used in database systems is centralized DBMS architecture. This architecture is used in mainframe system and minicomputers to provide the main processing for all functions of the system including user application programs, user interface programs as well as all the DBMS facilities. This traditional database architecture was used by DB2, SQL/DS and minicomputer databases such as Oracle and Ingres (Groff J.R. et al, 1990). An example of centralized DBMS architecture is shown in Figure 4.5.

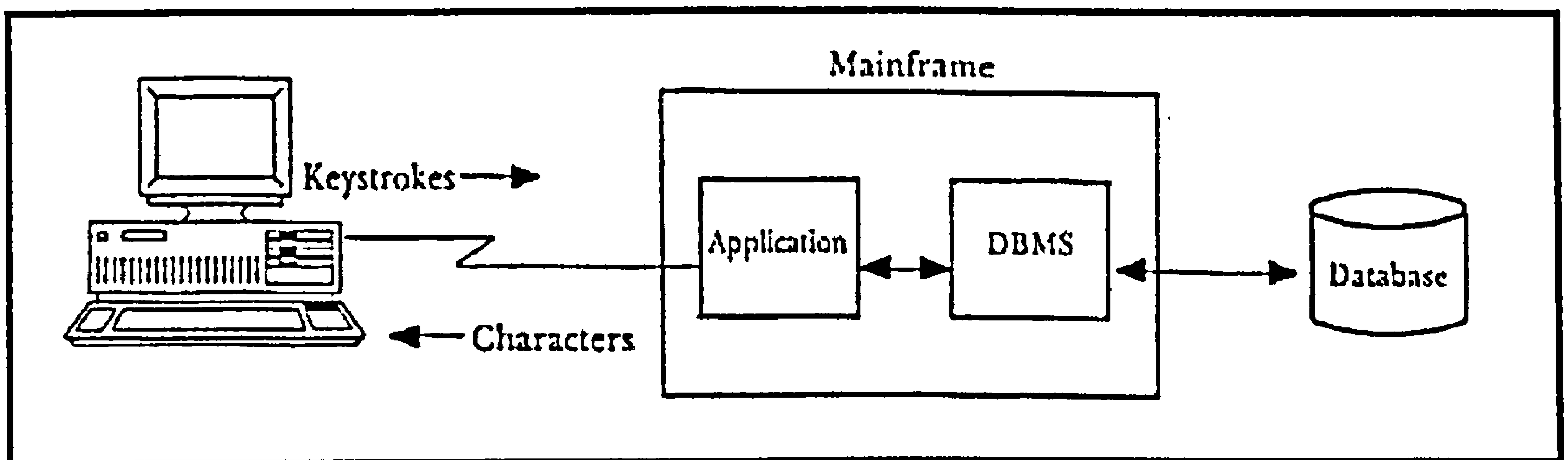


Figure 4.5 - Database Management in a centralized architecture (Groff J.R. et al, 1990).

The user accessed such systems via computer terminals and all the processing (application and database) was performed remotely on the central computer and only displayed information and controls were sent from computer to the user's screen. Since the application program execution, user interface processing and DBMS functionality were carried out in one machine, if the system is shared by many users, the communication slows down drastically.

4.5.2 File-Server Architecture

In a file-server environment, all processing (application programs and DBMS functionality) are distributed from a Local Area Network (LAN). In this architecture, the file-server keeps the files required by application and DBMS while all processing are run on a PC (LAN) as illustrated in Figure 4.6.

The DBMS on each workstation sends requests to a file-server which simply acts as a shared hard disk drive for blocks of data that are requested by DBMS. This data, which is stored on disk, is then constructed to the required form by DBMS running on a PC (LAN). Several requests are made by various numbers of users to the file-server before the DBMS reconstructs the data into the requested form - i.e. it can generate a considerable amount of network traffic loading to performance problems. Furthermore, because of multiple DBMS accessing the same files in this architecture, concurrency, recovery and integrity controls are more complex.

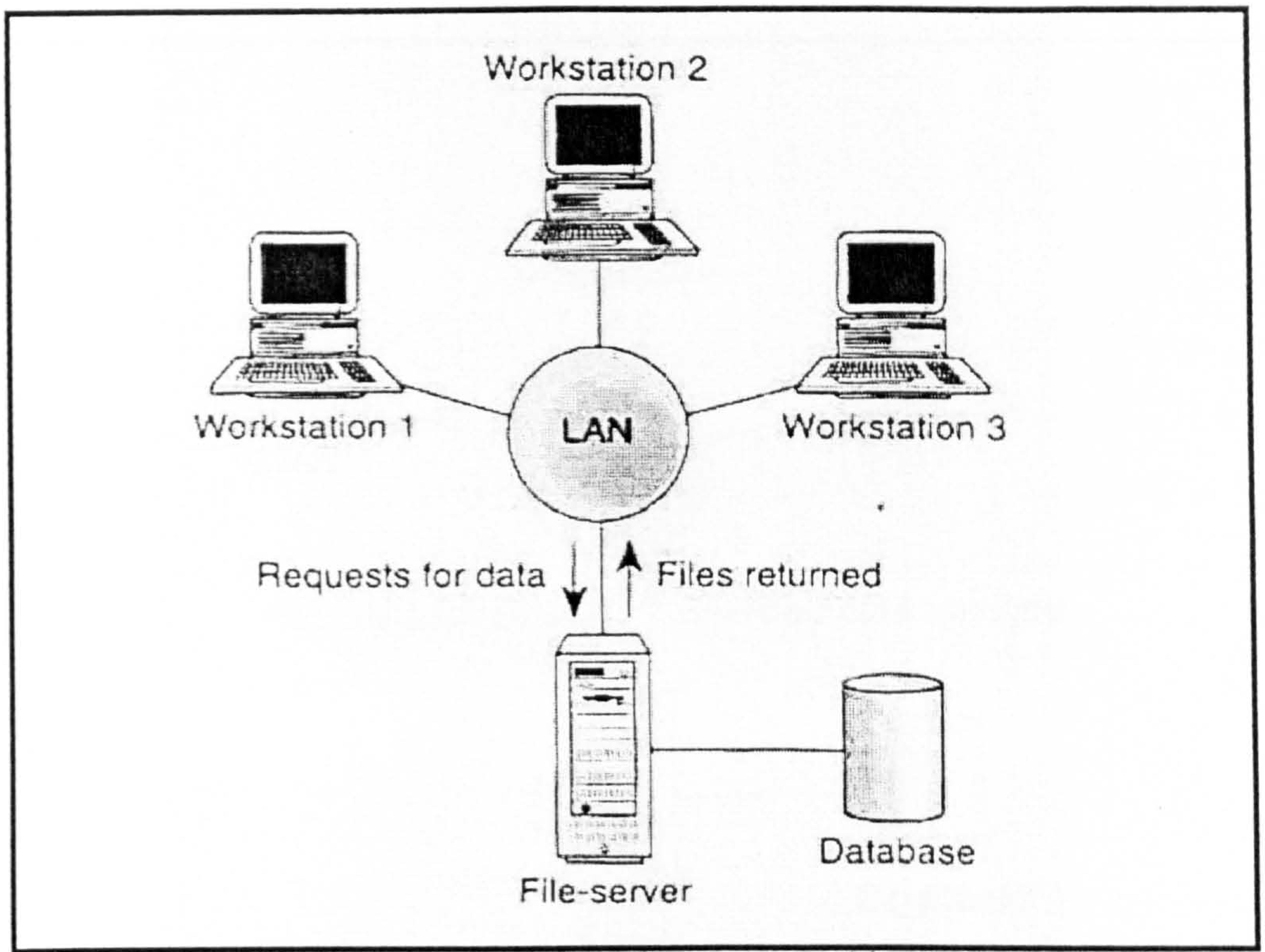


Figure 4.6 - Database Management in a file-server architecture (Connolly et al, 2000).

4.5.3 Client-Server Architecture

The client-server architecture is increasingly being incorporated into commercial DBMS packages (Elmarsi R. et al, 2000). To overcome the disadvantages of the previous architectures, client-server architecture was developed with a Local Area Network (LAN) of personal computers (clients) and a Database Management System (server). Therefore, a database system can be split into a very simple two-part structure, comprising the front-end (a server) and the back-ends (a set of clients). Figure 4.7 illustrates the client-server architecture for DBMS.

The server, which is just the DBMS itself, supports all the basic DBMS functions discussed in Section 4.4 such as data definition, data manipulation, data security and integrity, as well as all of the external, conceptual and internal levels of support discussed in Section 4.3. The clients are the various applications, which reside on the PCs, comprising the application programs, the report writers, query tools and the user interface.

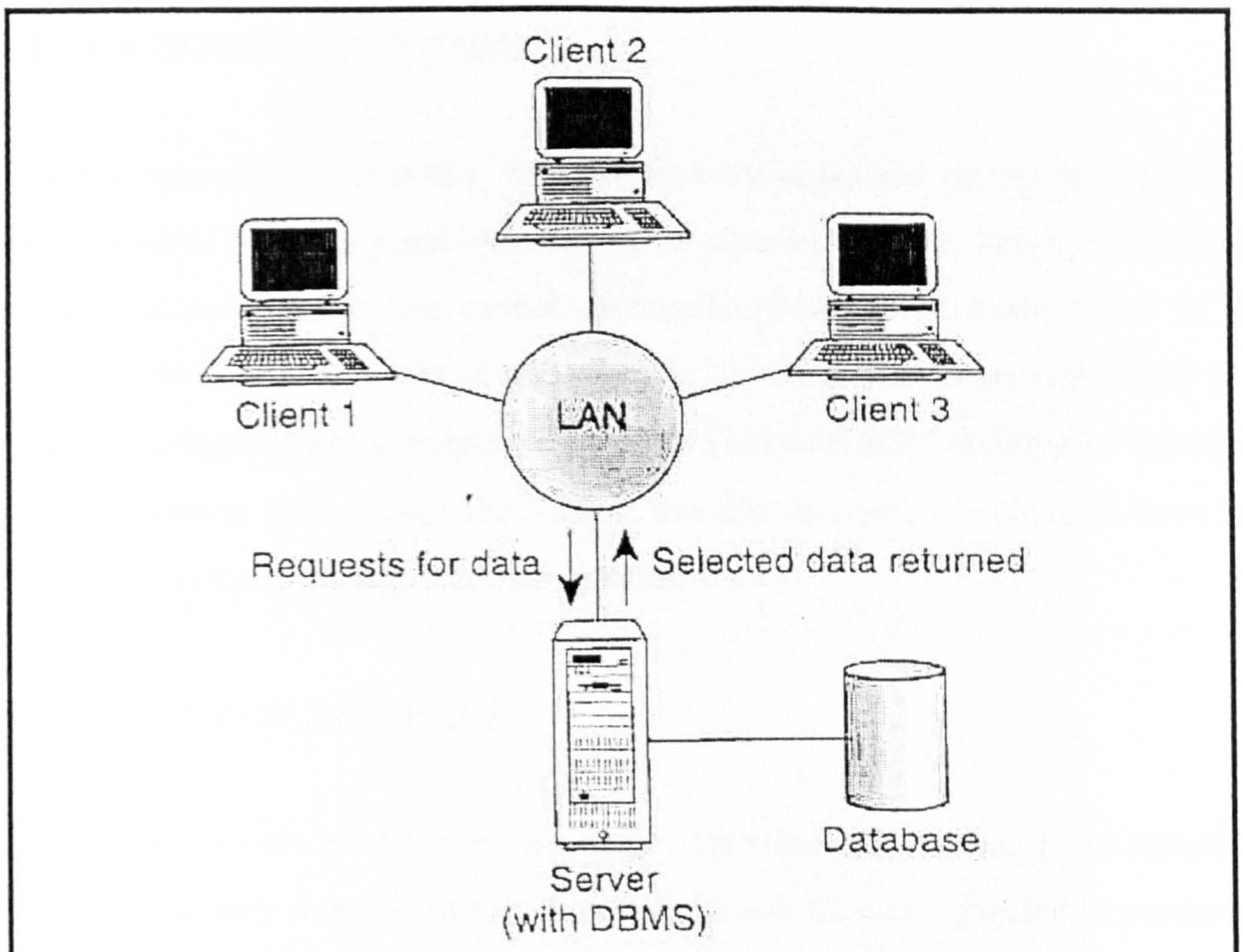


Figure 4.7 - Database Management in a client-server architecture (Connolly et al, 2000).

In this architecture, the Structured Query Language (SQL), which was proposed by Codd (1990), has become the standard database language for communication between the front-end tools and back-end engine. In addition, the network traffic is less than file-server architecture so that the server accepts and processes the requested data into a required form and then transmits the results back to the client as a simple reply.

4.6 Data Models

In the previous sections, the interactions catered for by most existing DBMS were presented while this section deals with how the data is organised in the database itself. In the following sections a number of alternative data models for defining data structures, data integrity and for manipulating data are briefly reviewed. All database software is built on an underlying data model which is a general architecture for data organisation. The proposed data models include record-based data models such as file management, hierarchical, network, and relational data models and object-based data models like deductive and object-oriented data models (Beynon-Davies P., 2000; Connolly T.M. et al, 2000; Groff J.R. et al, 1990; Elmarsi R. et al, 2000).

4.6.1 File Management Systems

In the file management systems, files are directly organised on the storage disk by keeping track of the names and locations of the files on the disk. This system basically has no data model and thus cannot distinguish between different types of files. Therefore, the knowledge about the contents of a file has to be embedded in the application programs that manipulate the data. The main disadvantages of this type of data management is that once the data in the file changes, the changes have to be effected manually in the application programs.

4.6.2 Hierarchical Data Model

The hierarchical data model uses two main data structuring concepts as records and parent-child relationships. In this data model, the records are organised in parent-child relationships. A record type is a named data structure composed of a collection of named field. A parent-child link is a one-to-many relationship (see Section4.6.4) between two record types which means that a data type can have "children" data types, but each child can have only one "parent" data type. The retrieval of the data involves navigation through the hierarchical structure. This model is not suitable for data with complex structures. The hierarchical data model is a restricted type of network data model.

4.6.3 Network Data Model

Like the hierarchical data model, in the network data model, data is represented as a collection of records which are organised in multiple parent-child relationships known as sets. In this model, the data can be stored in multiple values or be represented as a composite of values which repeat. To use the network model, therefore, the user is required to be familiar with the structure of the database and to know where the data are stored. This model is still not very flexible in that the relationships and the structure of the records are pre-set.

4.6.4 Relational Data Model

The relational data model which was first proposed by E. F. Codd in 1970, has emerged from the research and development as the most popular commercial and industrial product (Beynon-Davies P., 2000; Desai B.C., 1990). This model is based on the mathematical concept of a relation with which the data and relationships are physically represented as a two-dimensional table. Each table has a number of columns with a unique name, known as field, and data is stored by means of rows in the table. A primary key field is one or more known common columns of a table whose values are used to uniquely identify each of the rows in a table. These primary key fields relate the tables to each other.

Unlike the previous data model, to use the relational model users do not need to know the exact physical structures to use the database. It can be said that a relational database is a collection of related data where all data are strictly organised as tables of data values and where the entire database operations work on these tables. Figure 4.8 shows a relational database table of the various concrete distresses. A row represents the cause and symptom of each distress while columns or fields represent the various items that constitute the cause and symptom.

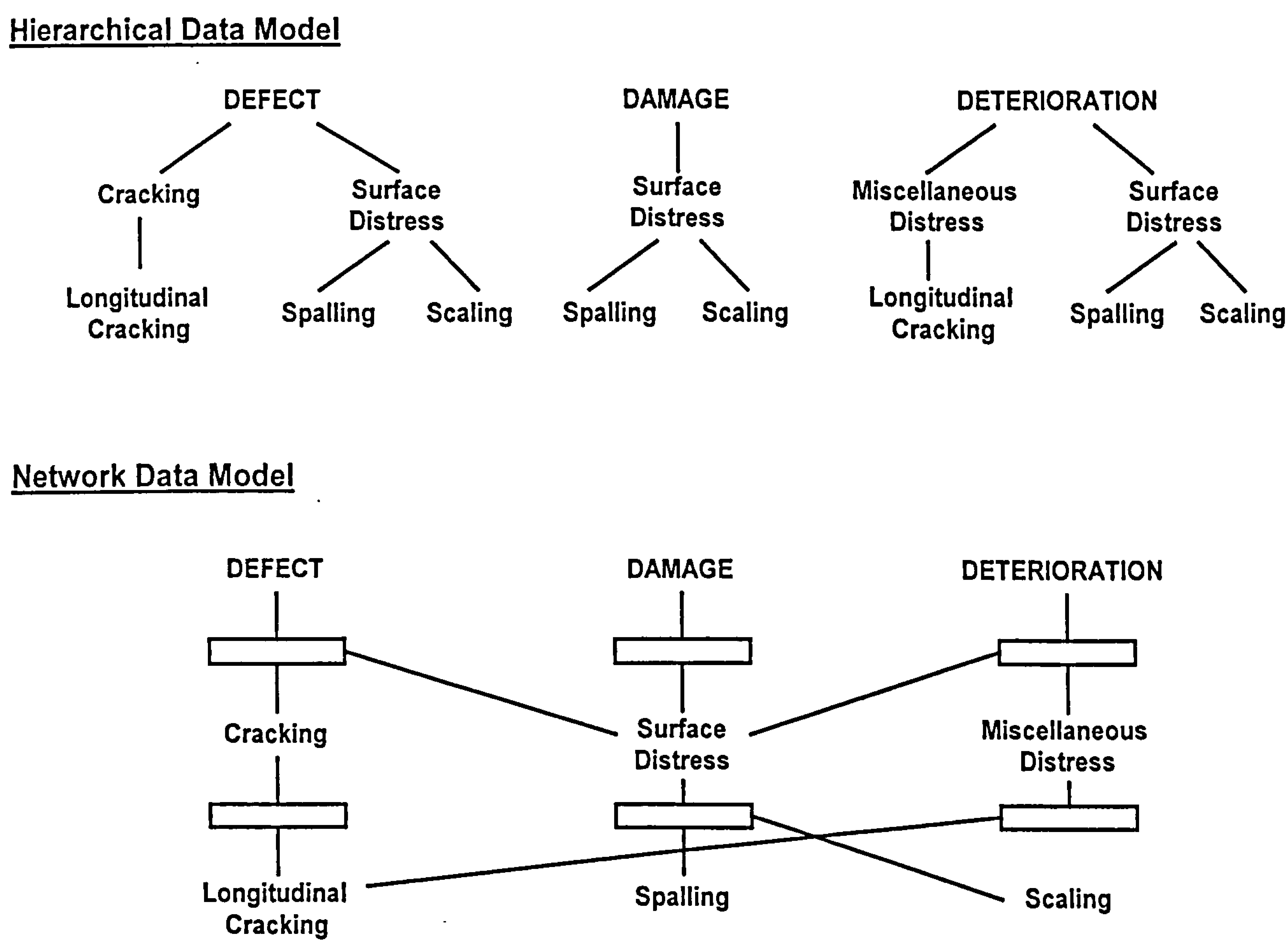
Table: concrete distresses

Concrete Distress ID	Distress Name	Cause Category	Main Cause	Symptom Type	Symptom Category
DETPB	Deterioration	Physical	Insufficient Cover	Bond failure Cracking	Miscellaneous Distress
DETPC	Deterioration	Physical	Scouring	Scaling, Disintegration and Removal of Materials	Surface Distress
DETPD	Deterioration	Physical	Scouring	Polishing of Aggregate	Surface Distress
DETPE	Deterioration	Physical	Aggregate D-Cracking	Pattern or Map Cracking	Cracking in Concrete
DETPF	Deterioration	Physical	Joint Deterioration	Joint Related Spalling or Faulting	Surface Distress
DETPG	Deterioration	Physical	Frost Attack (D-Cracking)	Cracks at Joint, Edge and Opening	Cracking in Concrete
DETPH	Deterioration	Physical	Frost Attack	Pattern or Map Cracking	Cracking in Concrete

Record 146 of 151

Figure 4.8 - A Relational Database table of causes and symptoms of concrete distress.

A comparative example of hierarchical, network and relational data models is shown in Figure 4.9.



Relational Data Model

Distress Category

Dist ID	Name
1	Defect
2	Damage
3	Deterioration

Symptom Category

Sym ID	Symp. Name
C	Cracking
S	Surface Distress
M	Miscellaneous Distress

Symptom Type

Type ID	Type Name
LC	Longitudinal Cracking
SP	Spalling
SC	Scaling

Distress/Symptom Category

Dist ID	Sym ID
1	C
1	S
2	S
3	S
3	M

Symptom Category/Symptom Type

Sym ID	Type ID
C	LC
S	SP
S	SC
M	LC

Figure 4.9 - A comparative example of various data models.

The Relational Database Management System (RDBMS) has become the dominant data-processing software in use today (Connolly T.M. et al, 2000). For creating a RDBMS, several types of relational data models, which depend on the type and the condition of data, can be used. The main relational types, shown in Figure 4.10, are considered in the following three categories (Viescas J.L., 1994):

- One-to-one relationship is used when a record of one table is related to no more than one record of another table.
- One-to-many relationship is used when a record of one table is related to many records of another table.
- Many-to-many relationship is used when a record of one table is related to many records of the second table, and many records of the second table are related to many records of the first table.

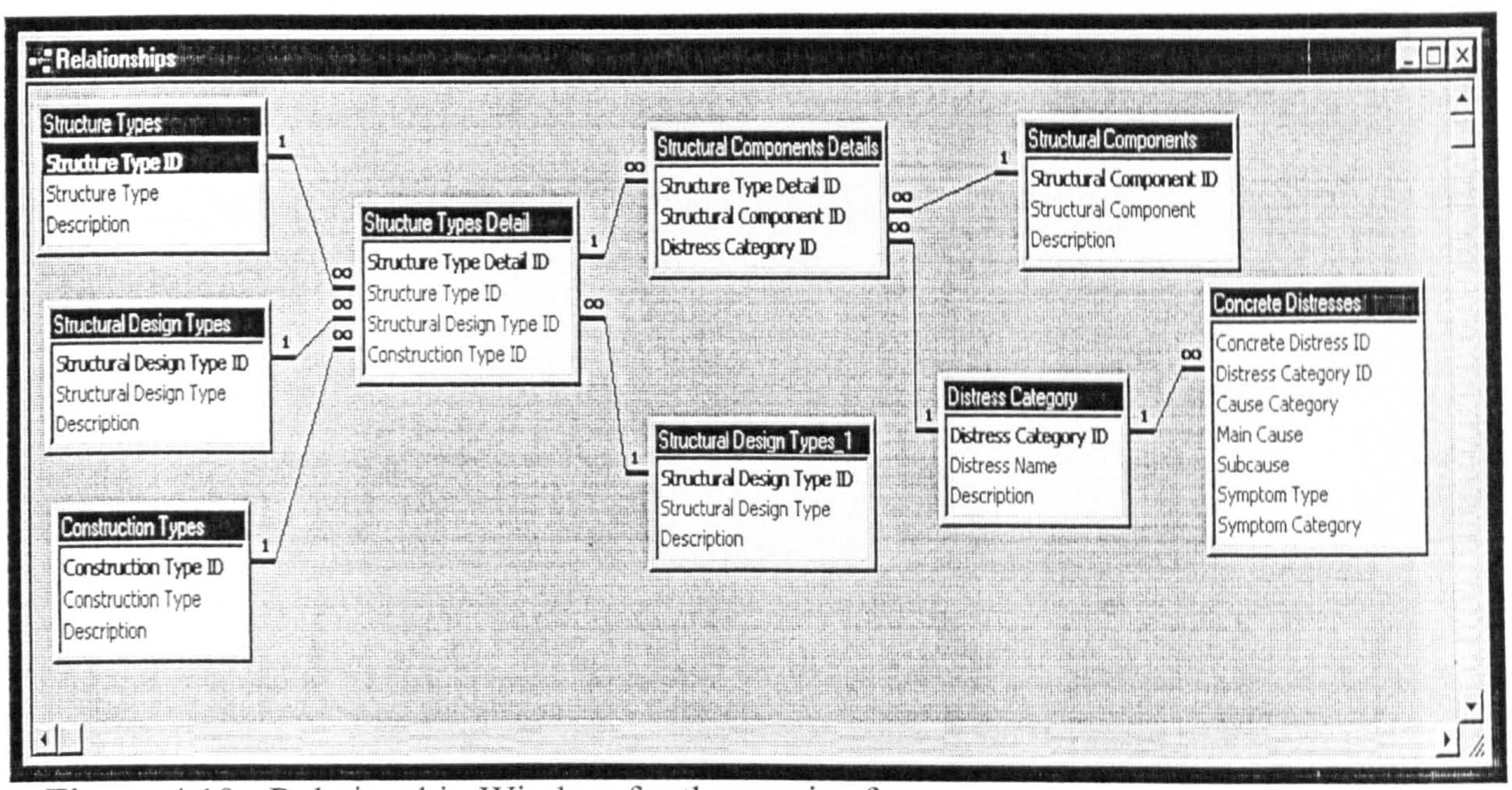


Figure 4.10 - Relationship Window for the repair of concrete structures.

Structured Query Language (SQL) is the standard language for dealing with relational database and is supported by just about every database product on the market today (Date C.J., 2000). SQL may be used as an integral part of a database management system, as a database programming language and/or as a tool for communicating with DBMS. An example of a query statement which may be used to return the main cause, symptom type in where the distress is deterioration, in where the cause category is physical and in where the symptom category is cracking in concrete from the table shown in Figure 4.8 is:

SELECT DISTINCTROW [concrete distresses].[Distress Name], [concrete distresses].[Cause Category], [concrete distresses].[Main Cause], [concrete distresses].[Symptom Type], [concrete distresses].[Symptom Category]

FROM [concrete distresses] **WHERE** (([concrete distresses].[Distress Name]="deterioration") AND ([concrete distresses].[Cause Category]="physical")) AND ([concrete distresses].[Symptom Category]="cracking in concrete"));

The result of the query is shown in Figure 4.11.

Select Query: Query1

Distress Name	Main Cause	Symptom Type	Symptom Category
Deterioration	Frost Attack	Pattern or Map Cracking	Cracking in Concrete
Deterioration	Frost Attack	Longitudinal Cracking	Cracking in Concrete
Deterioration	Frost Attack	Random or Multiple Cracking	Cracking in Concrete
Deterioration	Differential Thermal Strains	Random or Multiple Cracking	Cracking in Concrete
Deterioration	Differential Thermal Strains	Cracks at Joint, Edge and Opening	Cracking in Concrete

Record: 1 of 8

Figure 4.11 - Result from the SQL selection.

4.6.5 Deductive Data Model

A deductive database is a combination of a relational database system and logic programming and is one of the approaches to building intelligent database systems as described in Section 4.8.1. The deductive data model involves Prolog as its Artificial Intelligence (AI) language which consists of facts and rules for manipulating data. Prolog offers both an inference engine and a relational connection with the relational data model. Prolog uses backward chaining as discussed in Section 3.7.2 and a depth-first search strategy (see Section 3.8.1). A variation of Prolog is called Datalog which is a deductive query language similar to Prolog but is more suited to database applications (Codd E.F., 1990; Elmarsi R. et al, 2000; Lafue G.M.E., 1983).

4.6.6 Object-Oriented Data Model

Existing relational database management systems are inadequate to handle complex database applications such as Computer Aided Design (CAD), Computer Aided Software Engineering (CASE) and Geographic Information System (GIS) (Connolly T.M. et al, 2000). Object-oriented techniques are more recent methods of software construction: they have great impact on the database and data modelling, they show considerable promise for solving some of these complex applications of software development.

An object-oriented model is a package of data and procedures. Data is presented by an object whose properties and relationships are governed by its attributes. Procedures are defined by an object's method which is activated by messages passed between objects.

In this data model, a class is a group of objects with the same properties and is used to define the common attributes, methods and relationships of a group of objects. Because the objects of a class can be stored and manipulated directly, there is no need to transform application objects into tables. An object-oriented database management system (ORION) was reported by Kim (1991).

4.7 PC-Based Database Management Systems

For many users, the process of selecting the best PC-based DBMS package can be difficult because, with the increasing power of PCs, most DBMSs are able to run on PCs.

Besides the Relational Database Management Systems (RDBMS) mentioned in Section 4.6.4, many implementations of the relational data model emerged on the Personal Computer (PC) platform in the 1980s (Elmarsi R. et al, 2000; Connolly T.M., 2000). Examples of PC-based RDBMSs include Dbase IV, Paradox, OS/2, SQL server, and most recently Microsoft Access.

In this research, a PC-based database is implemented using the Microsoft Access application which is described in the following section.

4.7.1 Introduction to Microsoft Access DBMS

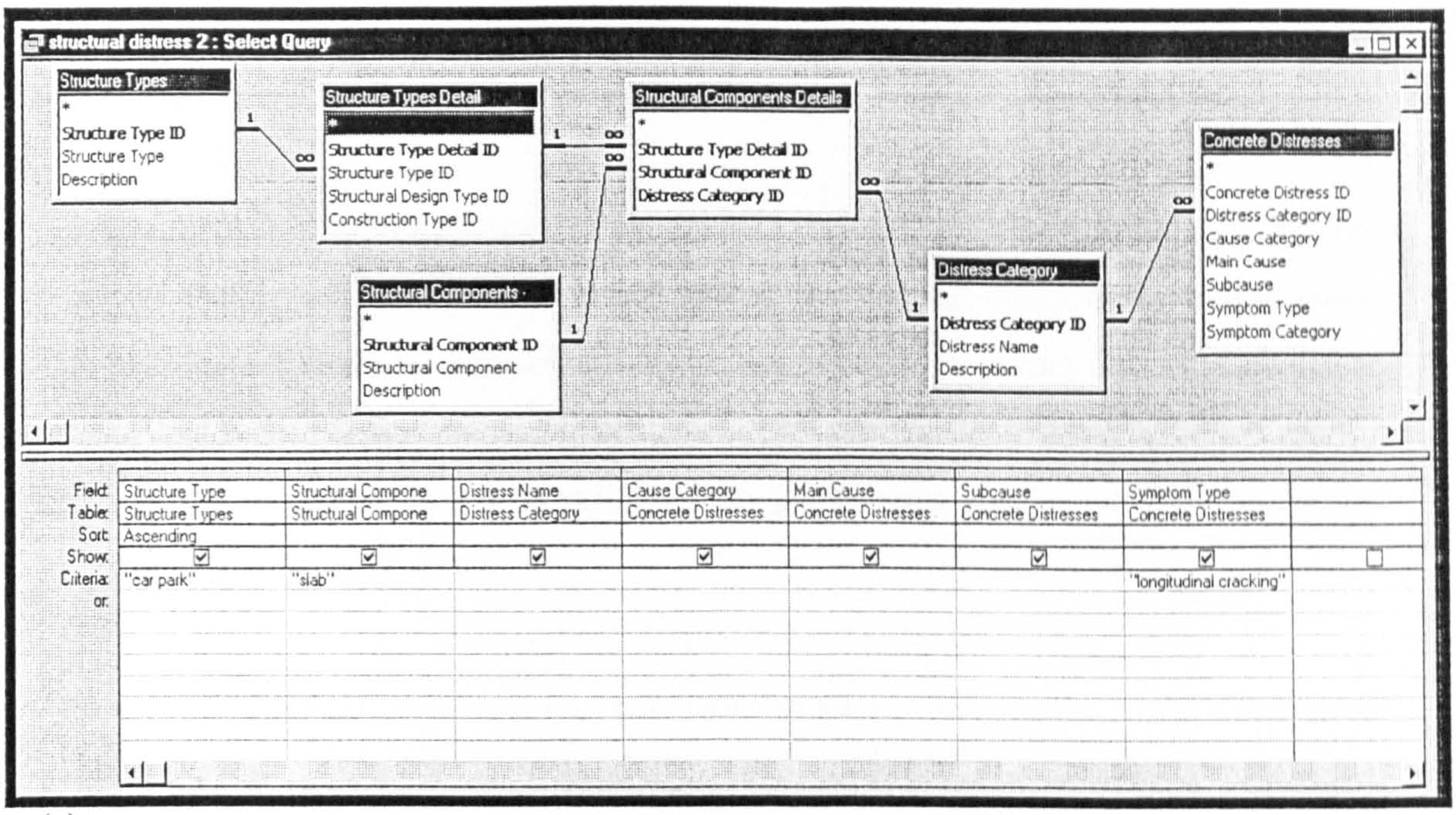
Microsoft Access is a typical PC-based DBMS originally created for desktop computers and designed to be used by non-sophisticated database users. Access can be run as a stand-alone system on a PC or as a multi-user system across a network of PCs. It is one of the best known implementations of the relational data model (described in Section 4.6.4) on the PC platform where the relationships are established through key fields.

Access allows data management and application development can be divided into two facility categories. Data management facilities comprise the creating of tables, relationships and queries. Access checks the integrity of the relationships during construction of a database and illustrates how relationships are built graphically (Figure 4.10). Thus, it eliminates errors during the retrieval of data. In addition, Access works like a complete application development environment in which the users can quickly develop forms and reports for input/output operations in a standard database system.

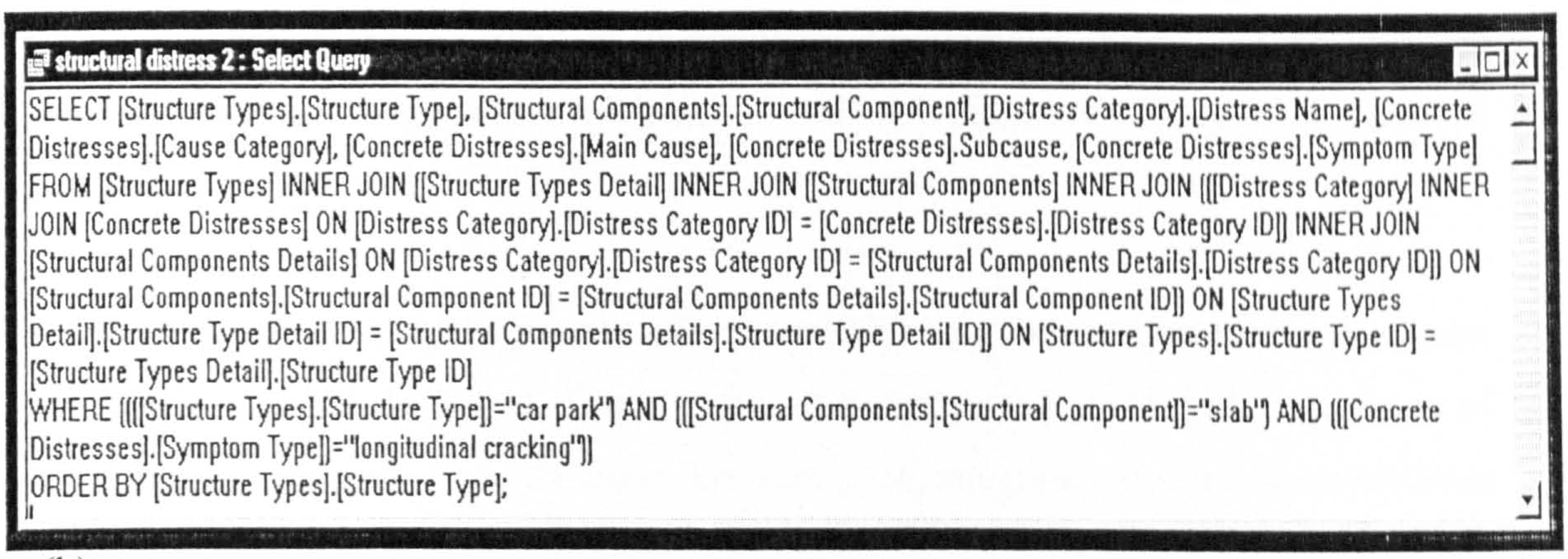
Data definition and manipulation in Access is provided by a database engine and a Graphical User Interface (GUI) with the power of Structured Query Language (SQL) (defined in Section 4.6.4). The Access GUI provides a graphical method to defining tables and relationships among them. A table, which can be created directly in a *design view*, contains the formatting of the field layout. The data types for fields include text, memo, number, date/time, currency, counter, yes/no and OLE objects. The text data type is any text string of fewer than 255 characters long while a memo data type can be any text of fewer than 64 kilobytes. Using Object Linking and Embedding (OLE) technology allows programmers to link an object from an application (like spreadsheets) into another application (like word processing document). OLE is described in detail in Chapter 6.

Data manipulation operations of the relational model are divided into retrieval queries and updates (insert, delete, and modifying operations). To ask a question about data in a database, a query is designed by Access which can be implemented either graphically through a Query-By-Example (QBE) interface or programmatically through Access SQL, micro and/or module. A QBE is a graphical method for developing a simple query in the design view of the database. While the user then has the ability to switch to the SQL view to examine the SQL query generated by Access. Figure 4.12 shows the query both in QBE and SQL. Access provides for update operations through forms that are built by the application programmer by direct manipulation of the tabular data in database view, or through the Access Basic programming language.

A micro in Microsoft Access is an object that is a structured definition of a set of actions which can automate common tasks in cases where defined events in the database perform repeatedly. Modules are units of code written in the Access Basic programming language. It is often used to automate and customize the database in very sophisticated ways in cases where the queries are too complex to be implemented as a macro. Modules can be stand-alone objects containing functions or they can be called from anywhere in application, or they can be directly associated with forms and reports to respond to events on the associated form or report. Modules are implemented in Visual Basic for Application (VBA) programming language.



(a)



(b)

Figure 4.12 - Defining a query (a) Access QBE and (b) Access SQL.

4.8 Knowledge-Based Expert System and DBMS Interaction

The Knowledge-Based Expert System (KBES), which was reviewed in Chapter 3, is based on two fundamental principles; (1) the appropriate representation of domain knowledge, and (2) the control of this domain knowledge. A database management system (DBMS) which is a pool of shared facilities used to access and manipulate a database, acts as the interface between end-users, application programs and the database. Data models that have been developed for database share the same overall objectives as knowledge representation schemes for Expert Systems. Obviously, the interaction of the expert system (ES) and the database would benefit for both these technologies.

Knowledge-based expert systems or expert systems (ES) in general, will contribute to database systems in providing a useful reasoning ability in query optimization tasks. The DBMS technique will contribute to expert systems in giving them the ability to access large collections of facts and also to apply features such as concurrency control, data security and optimized access to knowledge base items (Beynon-Davies P., 1991; Jarke M. et al, 1984).

The combined use of database management systems (DBMS) and knowledge-based expert systems (KBES) is potentially very valuable for modern engineering applications. The large body of facts usually required in information systems can be made available to an ES through an existing commercial DBMS. Furthermore, the DBMS itself can be used more intelligently and operated more efficiently if enhanced with ES features.

Therefore, in this section a variety of ways in which an expert system might interact with a database are reviewed. These ways can be organised along with a spectrum of architectures ranging from database systems with integrated deductive capabilities (e.g. an enhanced database system), to expert systems with integrated database management facilities (e.g. an enhanced expert system), finally to the coupling independent expert system and database management system.

4.8.1 Database Systems with Integrated Deductive Capabilities

The deductive data model fundamentally involves the application of formal logic to the problems of data definition, data manipulation and data integrity. Variants of standard Prolog known collectively as Datalog have been used in most deductive databases. Prolog, or more generally logic programming is an artificial intelligence language designed to implement aspects of formal logic as a programming environment. Datalog is a variant of Prolog specially designed for database work (Beynon-Davies P., 2000).

Therefore, a deductive component is joined with a DBMS to have the possibility of significantly improving the productivity of information systems development and maintenance. It is noted that involving the Prolog language for a relational DBMS is one of the approaches to building an Expert Database System (EDS) (Beynon-Davies P., 2000). Some specific programs are used by Walker (1983) to show that Prolog is a practical language for bringing together apparently diverse techniques in databases and expert systems. In addition, Lafue (1983) discussed basic decisions about linking of a particular ES to DBMS with comparing between Prolog as logic programming and STROBE as an object-oriented language. Furthermore, it is being attempted to extend Datalog to produce deductive object-oriented system.

In this expert database system (EDS), which is sometimes referred to an Intelligent Database System, there are possible ways of linking deductive components to a DBMS (Jarke M. et al, 1983; Beynon-Davies P., 1991):

1- Embedding. Deductive routines are embedded with the DBMS itself and act as one more facility of the DBMS (Figure 4.13).

2- Filtering. User and application program queries are directed through a deductive component before being processed by the DBMS. In this sense, the deductive component acts as an interface between the DBMS and the user or application programs (Figure 4.14).

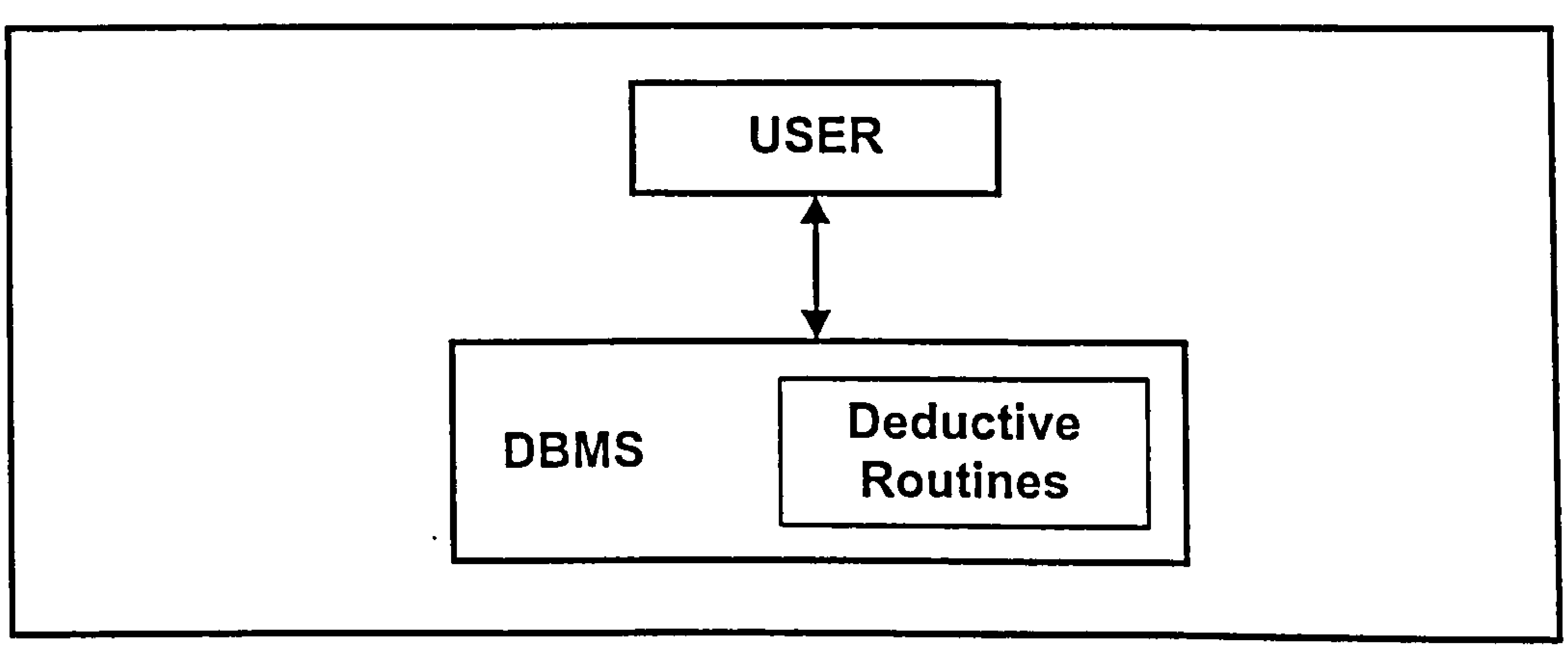


Figure 4.13 - Intelligent Database System: Embedding.

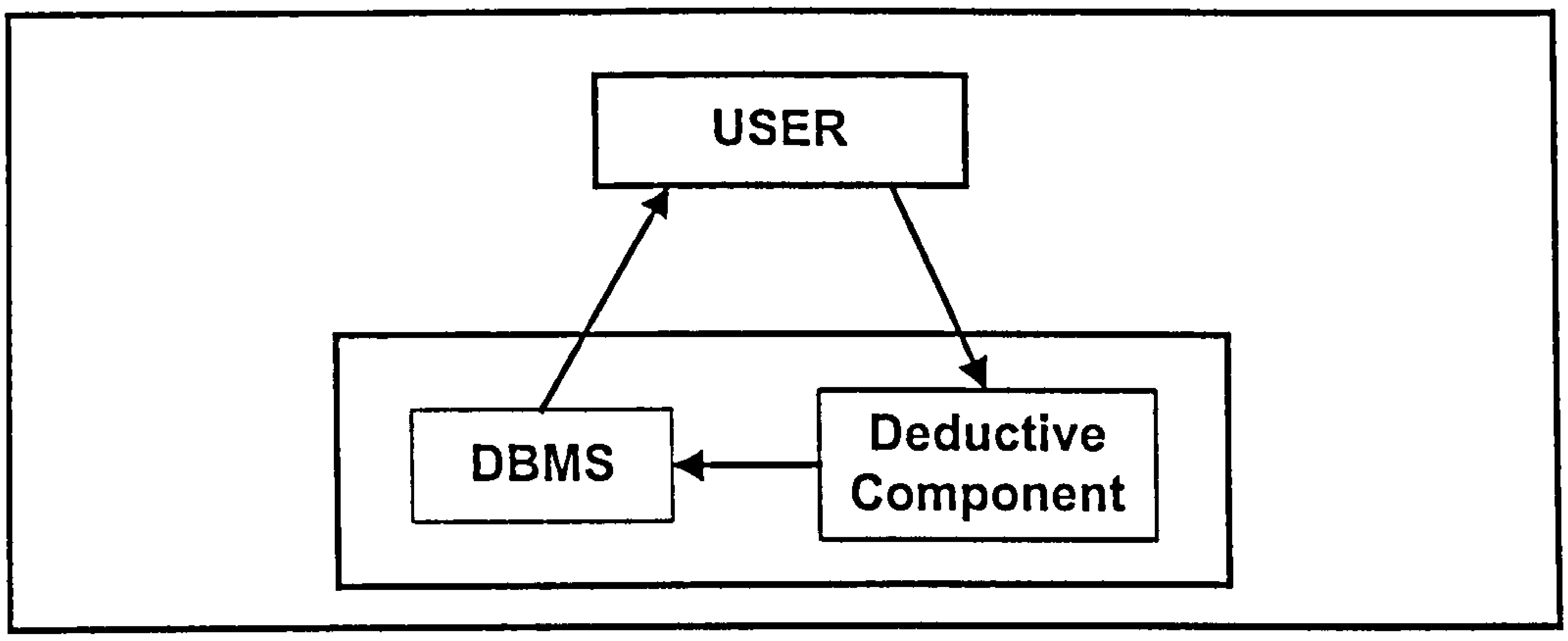


Figure 4.14 - Intelligent Database System: Filtering.

3- Interaction. The DBMS, rather than the user or application programs interacts with the deductive component (Figure 4.15).

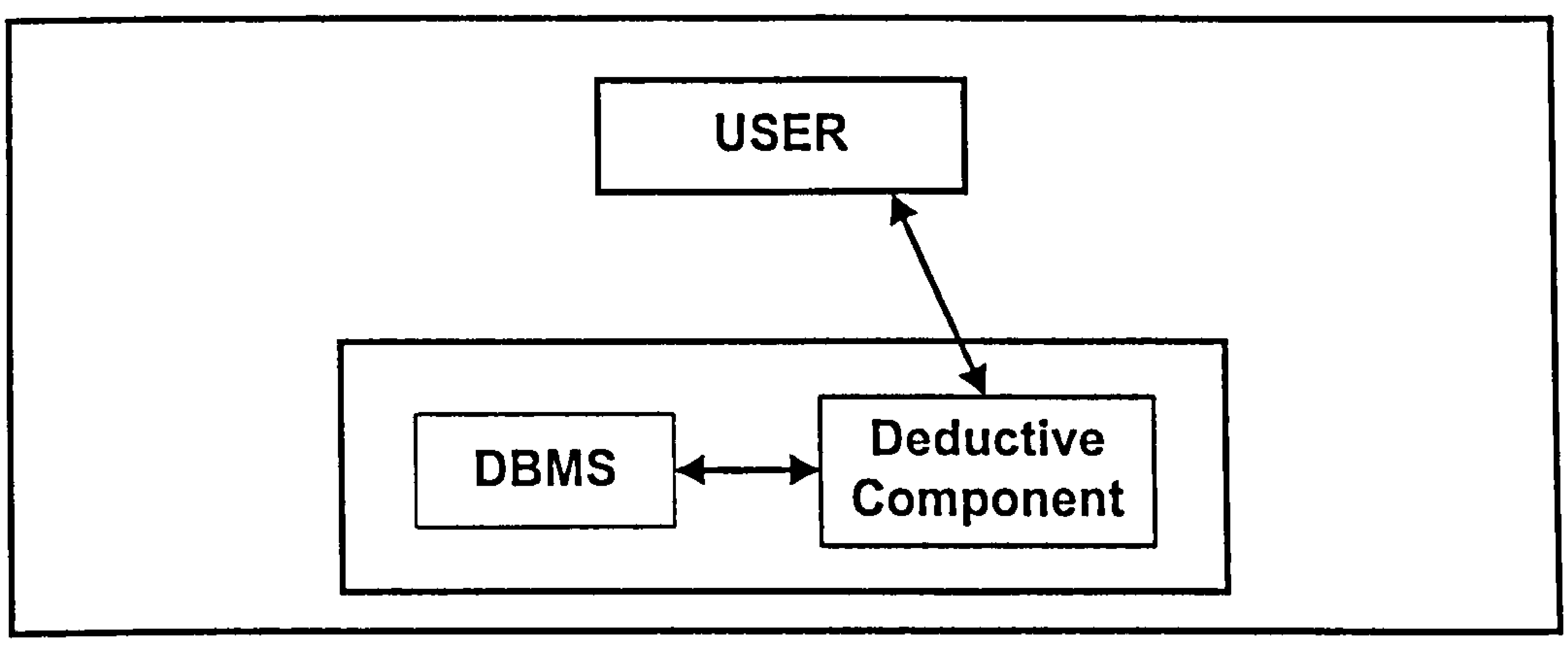


Figure 4.15 - Intelligent Database System: Interaction.

4.8.2 Expert Systems with Integrated Database Management Facilities

In this expert database system (EDS), the enhancement of an expert system can be internally or externally done by extending its data management facilities (Jarke M. et al, 1983; Beynon-Davies P., 1991).

1- Internal enhancement. These are systems which extend the programming language or environment in which the expert system is written (e.g. Prolog). An example of an expert system with internal DBMS is shown in Figure 4.16.

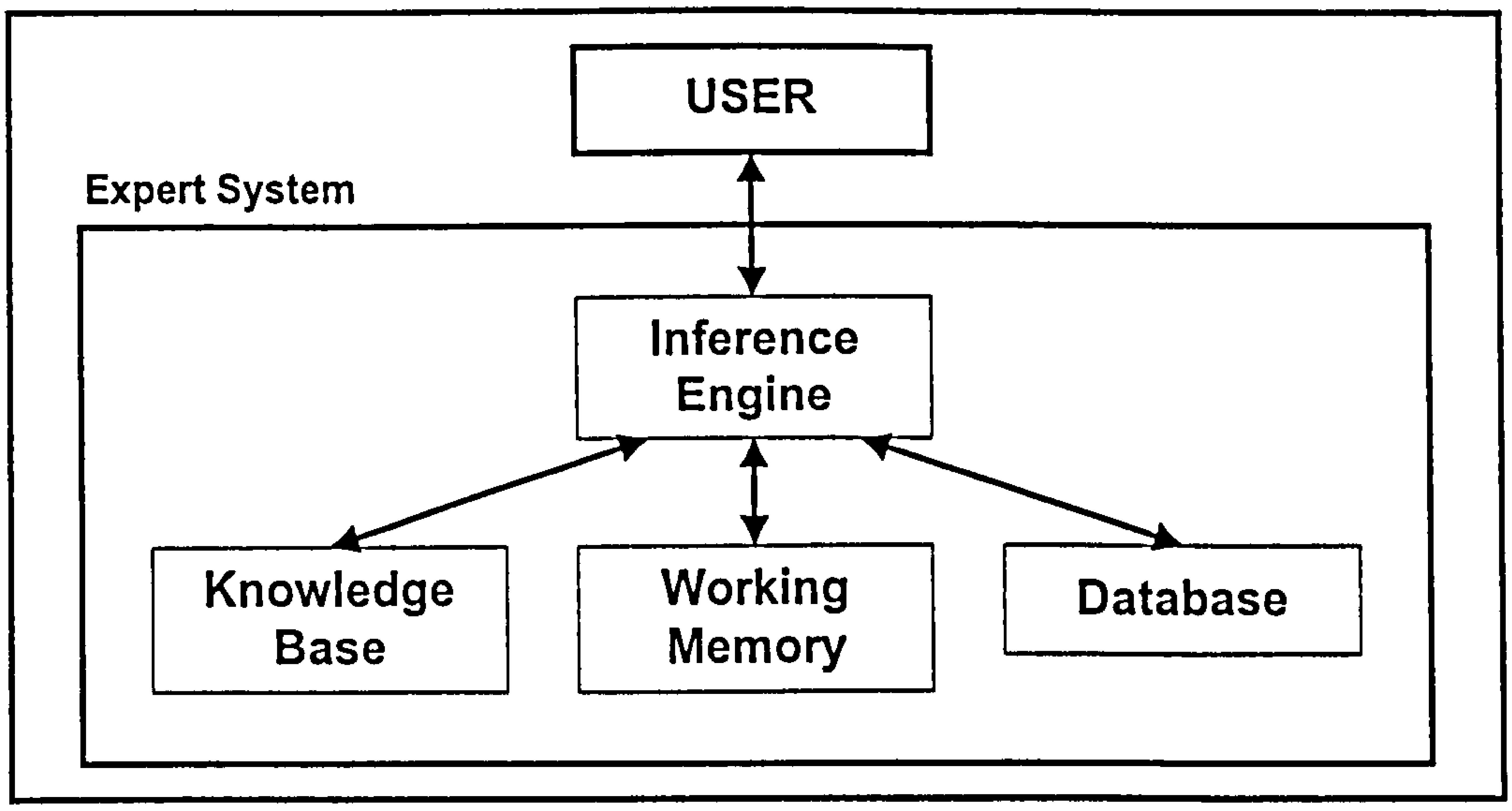


Figure 4.16 - Internal enhanced expert system.

2- External enhancement. An Expert System (ES) can be evolved to incorporate DBMS facilities with external links. These two systems may be loosely or tightly coupled.

➢ Loose coupling. In a loosely coupled system, as shown in Figure 4.17, a dynamic link does not exist between the expert system and database. It means that the DBMS is used to store data which is not required as part of the knowledge base. Therefore, the data is usually delivered statically to the expert system from the database prior to the execution of the expert system.

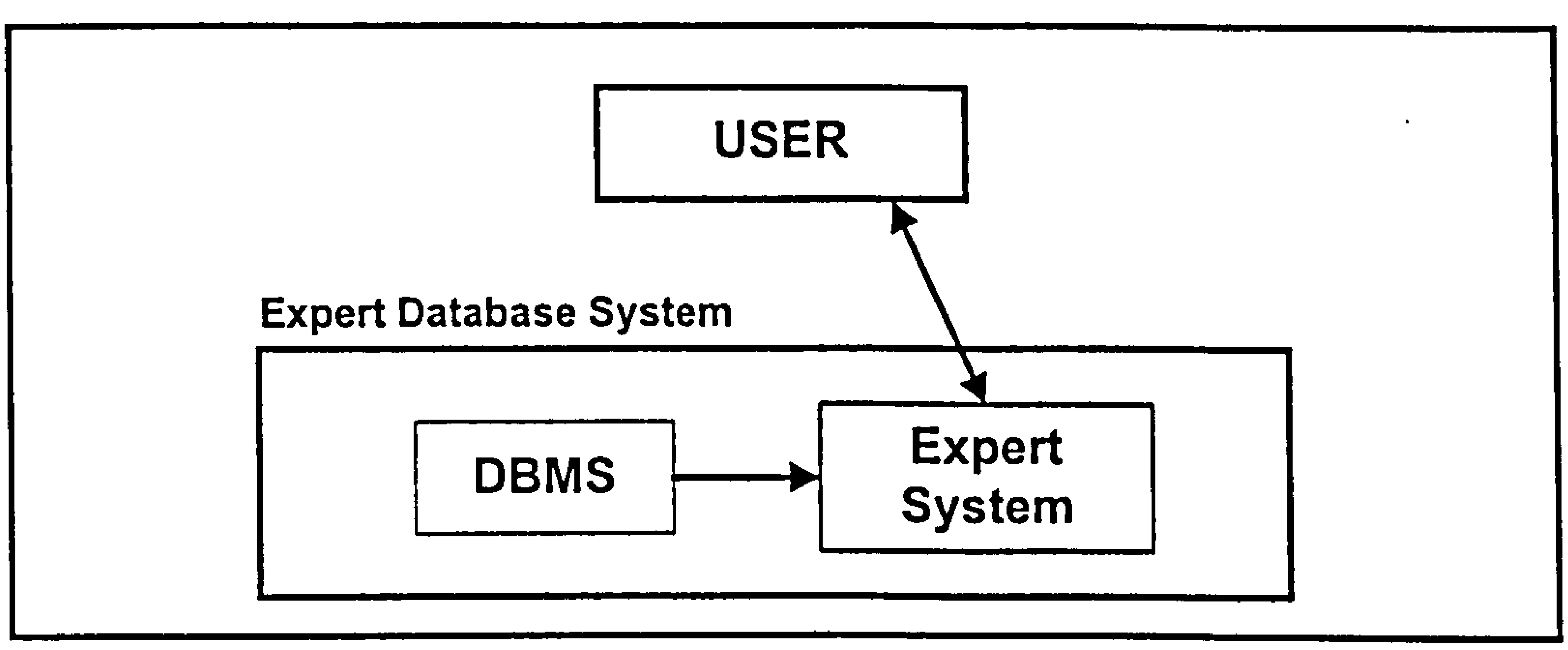


Figure 4.17 - External enhancement of an expert system, loose coupling.

One of the main advantages of this method is its ability to use existing database and avoid replicating data unnecessarily. While the separation of the deductive phase and data retrieval phase is one of the major disadvantages of this approach.

- Tight coupling. Tight coupling occurs when data is retrieved from the database as a part of knowledge during the execution of an expert system. In this approach, the DBMS acts in the capacity of a slave to the expert system in which this overcomes many of the advantages of loose coupling. In contrast, such free interaction can cause a severe slowing down of the expert system performance. An example of a tightly coupled approach is shown in Figure 4.18.

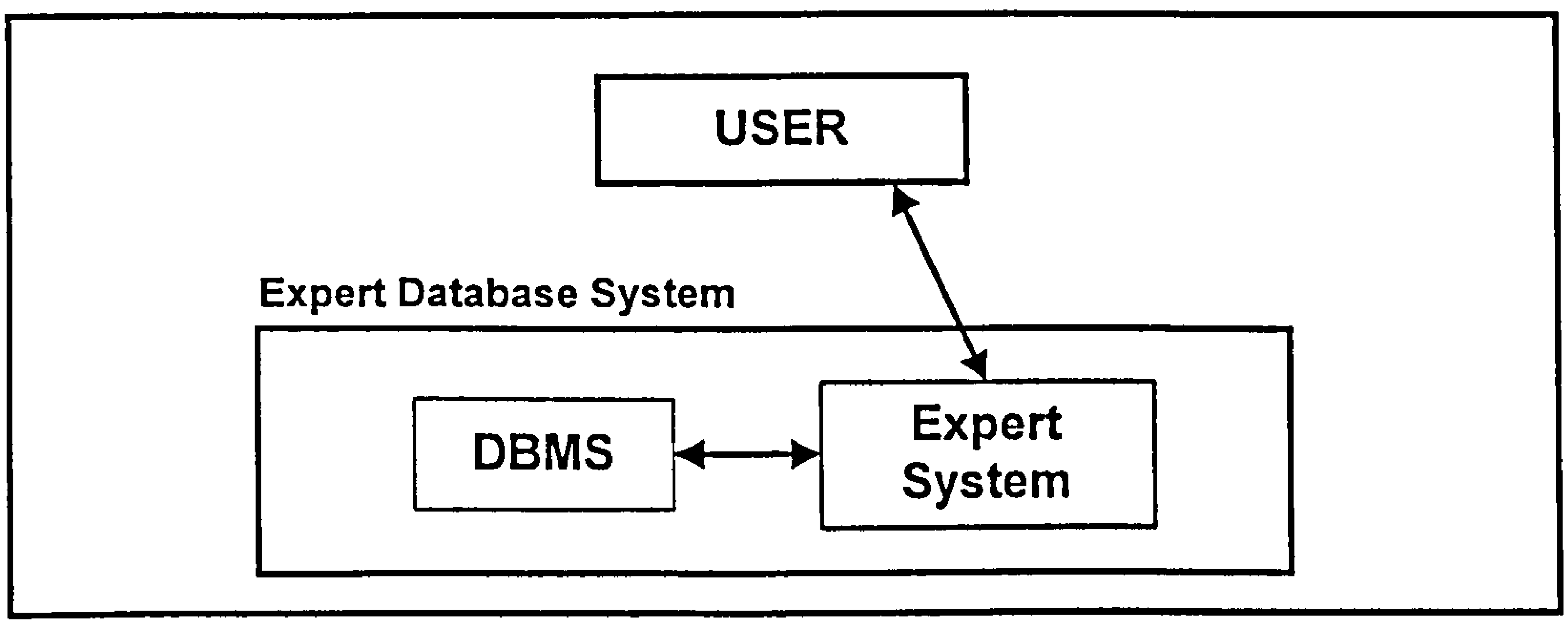


Figure 4.18 - External enhancement of an expert system, tight coupling.

4.8.3 Coupling Independent Expert System and Database Management System

In this type of expert database system (EDS), the expert system and the database are coupled as an independent system that operates either as two entirely separate systems with their own set of users or as a two co-operating systems. Three possible architectures for the coupling of independent systems have been known (Beynon-Davies P., 1991; Jarke M. et al, 1984).

A first strategy is for a total distribution of processing and control such that both systems can operate independently and can interact by exchanging messages. An advantage of this architecture is a large degree of application and system independence allowing for transportability to other ES and DBMS, whereas inevitable problems arise in the areas of data integrity and redundancy. A simplified architecture is shown in Figure 4.19.

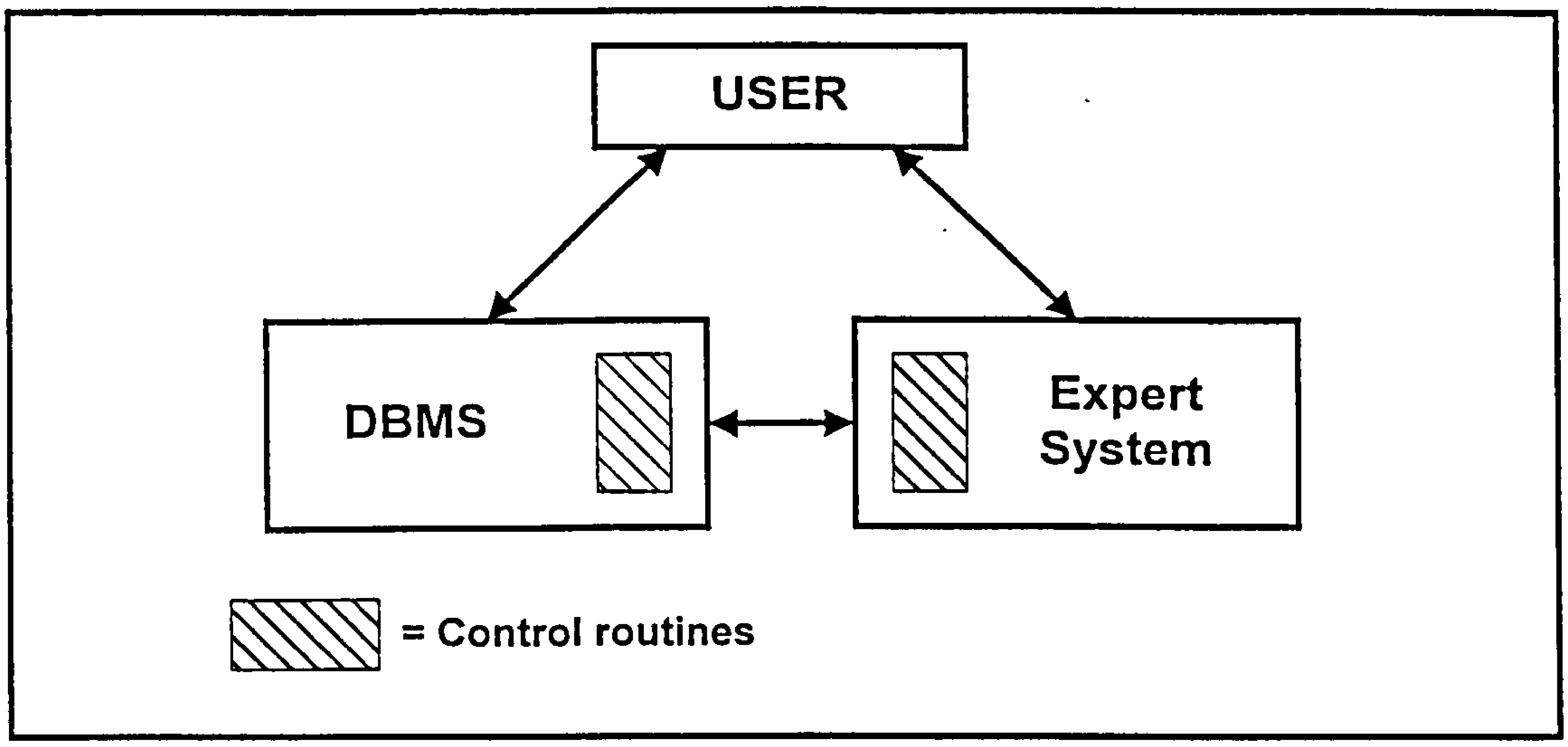


Figure 4.19 - Coupling independent ES and DBMS, distributed processing and control.

A second possibility, as shown in Figure 4.20, is that either the DBMS or the expert system may be assumed to dominate. This approach can generally be followed by researchers who focus on one direction of the interaction between ES and DBMS. This is likely to be more flexible architecture but the integration of addition further subsystems is difficult.

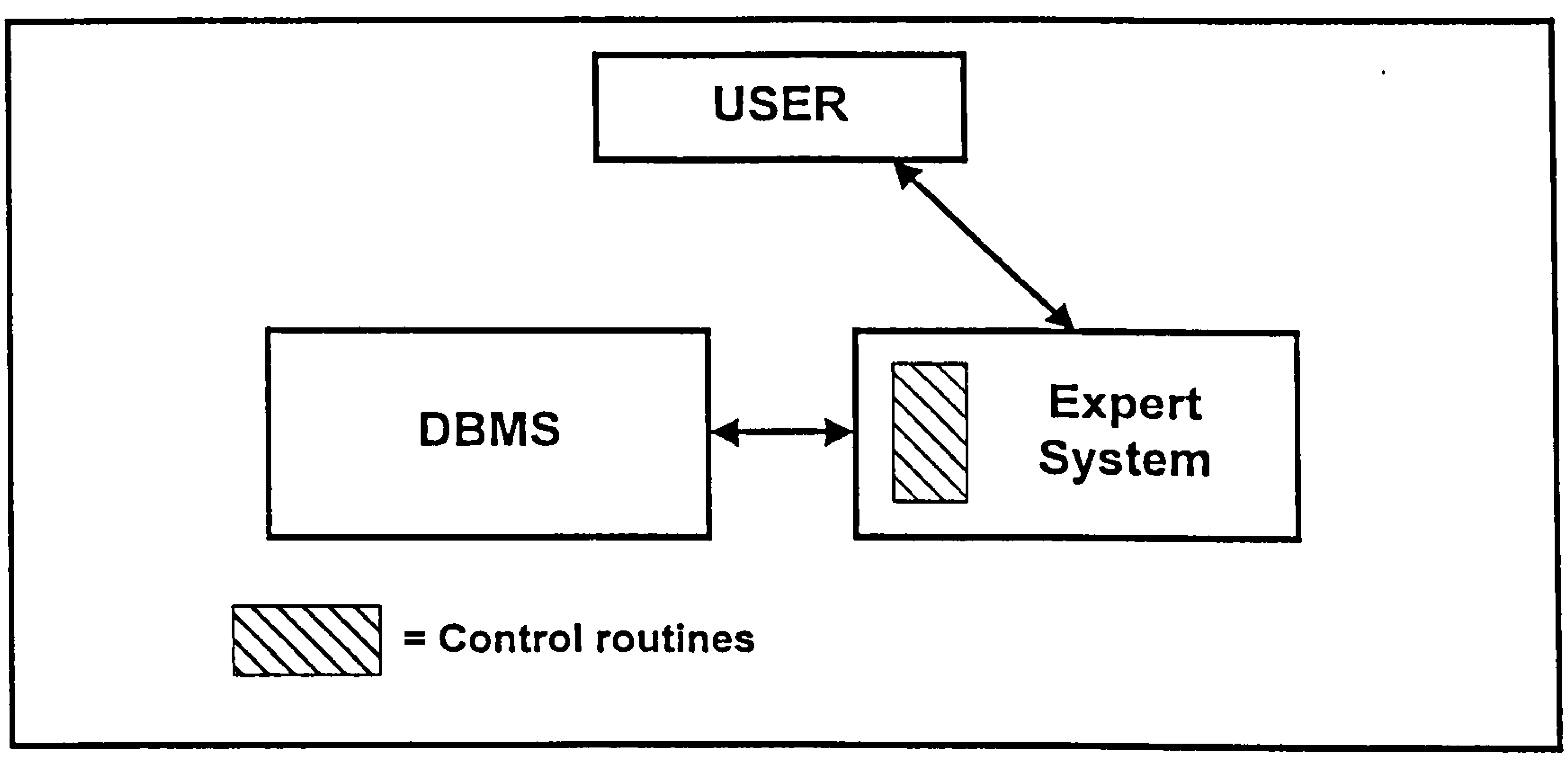


Figure 4.20 - Coupled independent ES and DBMS, domination of control.

Finally, in a third architecture (Figure 4.21) processing method is distributed, but control is the responsibility of an independent subsystem which performs all of the necessary steps for interfacing the ES with the DBMS and manages the interaction between them.

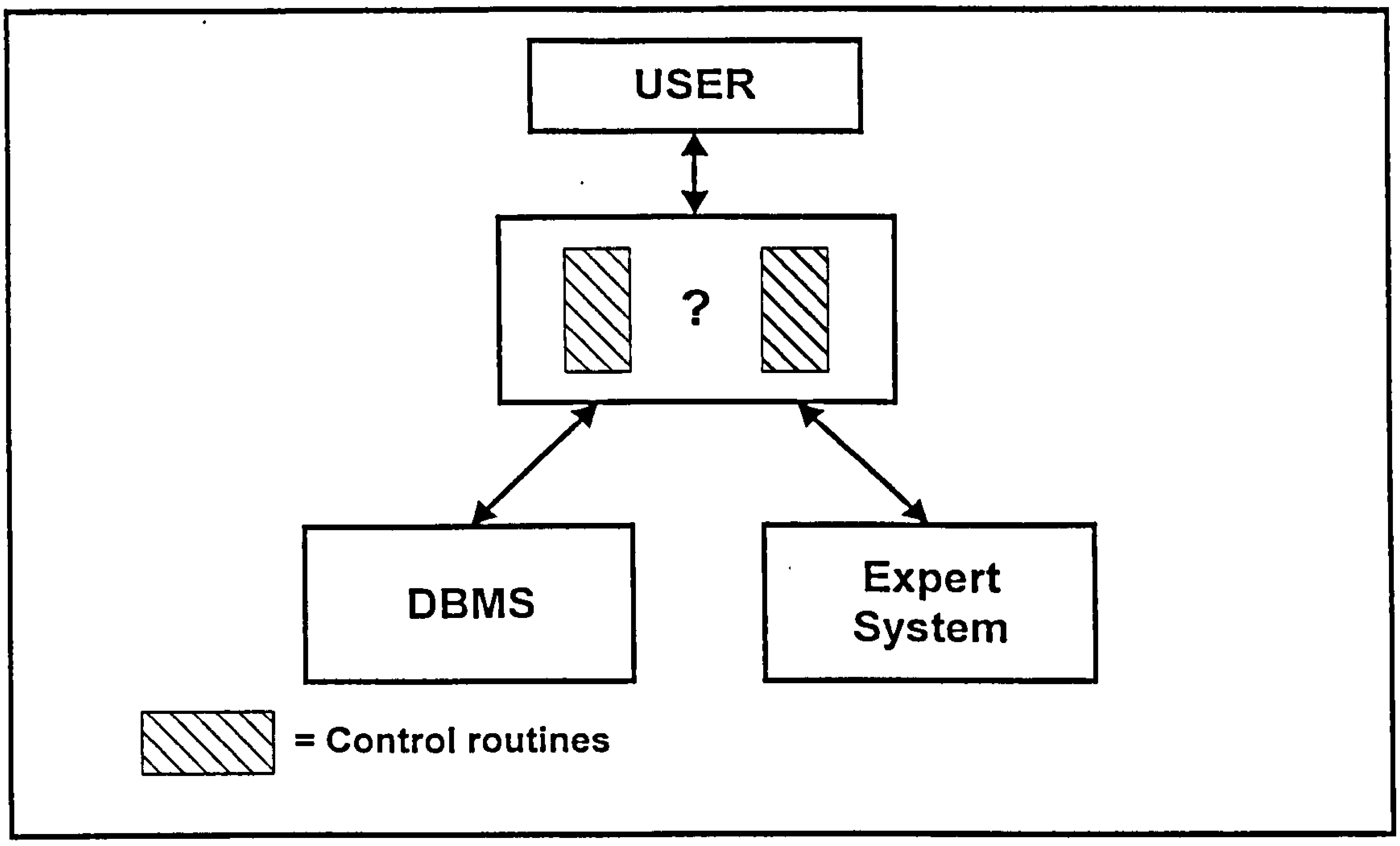


Figure 4.21 - Coupled independent ES and DBMS, independent subsystem.

A prototype of such architecture called KADBASE (Howard H.C. et al, 1986) has been implemented for interfacing expert systems with database management systems. Application components of this prototype system are taken from the structural engineering domain in which multiple expert systems and multiple databases can communicate as independent self-descriptive components within an integrated engineering CAD (Computer Aided Design) system operating in a network-computing environment.

There are a number of advantages inherent in the use of a subsystem to handle the problem of coupling independent expert systems and database management systems (Beynon-Davies P., 1991). These advantages are summarised as follows:

- Flexibility. It enables the user to run expert system and database systems independently or interdependently.
- Efficiency. It allows expert systems the capability of managing large volumes of data without overloading the expert system.
- Versatility. The subsystem architecture allows the users to add pre-existing expert systems or database systems incrementally.

➢ Functionality. Expert systems can exploit the data management facilities of the DBMS such as efficient retrieval, concurrency control and integrity mechanisms.

4.9 Summary

In this Chapter, database management system (DBMS) technology has been reviewed from an architectural point of view. Many aspects relating to the database systems were covered including database management architecture, data models, PC-based database application and an overview of Expert Database Systems (EDS).

First, a database system can be thought as a computerized record-keeping system. Such a system involves the data itself (stored in the database), hardware, software (in particular DBMS), and the users.

A typical database system architecture, so-called ANSI/SPARC, was highlighted. Such architecture divides a database system into three levels comprising the internal level, which is the one closest to physical storage; the external level, which is the one closest to the users; and the conceptual level, which is a level of interaction between the other two levels providing a community view of the data.

This Chapter has taken a closer look at database management system (DBMS) architectures. Database systems can be conveniently thought of as consisting of a server (the DBMS itself) and a set of clients (the applications). Client and server can and often will run on separate machines, thus providing one simple kind of distributed processing. In general, each server can serve many clients, and each client can access many servers.

Database systems can be based on a number different data models. The data model adopted for this research is the relational data model (discussed in Section 4.6.4) because of its flexibility in establishing new relationships in the data at runtime. This is envisaged to be particularly suitable for application to repair of concrete structures as the diagnosis is based on the selection of various parameters (discussed in Chapter 7). The relational data model can be converted to most knowledge base representation models. RDBMSs are the logical first step in building knowledge-based systems, however, natural connections have been made with the whole area of logic programming and knowledge-based systems.

A PC-based architecture is used in the application developed in this thesis because it can mostly be used on PCs or PC networks. Microsoft Access, the commercially available DBMS that was used in this research, is reviewed in this Chapter with particular emphasis on its data management and application development facilities. The ability of Microsoft Access to store and manipulate multimedia data makes it suitable for developing a multimedia database and the need of which is highlighted in the Chapter 3.

Finally, the interaction of an expert system and a database system reviewed in this Chapter shows that the integration of expert systems into the existing database management systems can avoid frictions and duplication of effort. A number of architectures which are currently being used are compared. A coupled independent subsystem connection between the DBMS and the expert system (ES) is considered for use in this research because of the need for flexibility and functionality in the interaction between the expert system, database and the user.

Chapter 5

Development of a Questionnaire

5.1 Introduction

The acquisition of knowledge for expert systems is most frequently impeded by a lack of communication between the expert and the knowledge engineers involved in building such systems. This is sometimes rooted in the knowledge engineers' lack of understanding of the specialist terms of domain as well as the fact that the knowledge engineer cannot ask the relevant questions of the expert. This Chapter presents data survey methods and discusses procedures adopted in developing a questionnaire for the eliciting of knowledge. It also includes the process of selecting the survey method, defining the subjects to be covered by the questions, preparing the questionnaire and selecting the survey samples. The aim of survey was to gather state of the art information on repair products in the UK.

5.2 Information System

Information systems are accepted as an essential prerequisite to the successful fulfilment of the aims of any organisation. A project concerned with the performance of concrete structures may involve many organisations with differing opinions and aims. Groups engaged in this effort include the client, construction contractors, consulting engineers and construction material suppliers.

Contractors, consulting engineers, and material manufacturers are concerned with the execution, analysis, design, and supply of materials in a project to an acceptable level of quality within a specified time period. All of these groups will typically require information to perform a multitude of tasks.

Information is basic to the successful execution of each project and especially to the repair of a concrete structure. However, there has always been a view that the correct diagnosis of the cause of damage to a concrete structure presents difficulties to engineers. This may be for many reasons including the general lack of good quality information. In many engineering fields, the questionnaire is used as a means of gathering information or data.

5.3 Selection of the Survey Method

Rea and Parker (1992) state that survey research, direct measurement and observation are used for primary data collection. As the main techniques, they also claim that "there is no better method of research than the sample survey process for determining with a known level of accuracy, information about large populations."

In the case of social research, Smith (1991) states that statistical procedures have become the most used methods. He supports his view with the following reasons:

- The survey method is a good procedure for the explanation of individuals' attitudes, values, beliefs and motives.
- It can be structured in order to obtain specific information from a broad population.
- Data collection through the survey method is very cheap, simple and easy to administer.
- There are several standard statistical procedures for the analysis of data.

Amongst the numerous methods of data collection, according to Oppenheim (1992), interviews led to the basis of a structured questionnaire, and questionnaires distributed by mail are widely used for data collection. Similarly, Baker (1994) states "Using questionnaires and giving interviews are based on a set of questions. In the questionnaire, these questions are written down and the respondent reads them and give written answers. In an interview, the interviewer asks the questions as they are written in an interview schedule and then records the respondent's answers either by writing them down or recording them electronically." According to Assadi (1997), both methods have advantages and disadvantages. He summarises the advantages and disadvantages of interviews and questionnaires as follows:

- *Interviews*

- To have the opportunity of selection each respondent. (advantage)
- To clarify any ambiguity in question or response immediately. (advantage)
- Bias: the interviewer may carelessly alter the direction of questions during the interview by a change in tone of voice or other subtle means. (disadvantage)

- *Mailed questionnaire*

- Cheaper than other data collection methods. (advantage)
- A greater coverage is achieved by a broadly spread sample. (advantage)
- To avoid problems such as interviewer bias. (advantage)
- Mailed questionnaires are suitable for questions needing a considered response and requiring consultation of documents rather than an immediate answer. (advantage)
- It is the most appropriate way for the respondent who can complete the questionnaire in his/her own time. (advantage)
- The questions need to be relatively simple. (advantage)
- The method may suffer from poor response rates or response bias. (disadvantage)

Finally, relating to the issues discussed and the fact that questions to be asked are relatively simple; it is recognised that greater coverage is possible by questionnaire mail. Therefore, it is considered that the most appropriate method for data collection in the field of repair materials is likely to be through the use of a mailed questionnaire.

However, one of the most important problems concerning the mail questionnaire is an acceptable rate of response. By comparing Nachmiass' work (1976) with Weisberg et al (1996), the typical response rate for a mailed questionnaire is between 10% and 50%. Nevertheless, using self-addressed envelopes and conducting a follow-up process are techniques to be used to improve the response rates. In addition, it is expected that the questionnaire will provide:

- Data needed for objectives and hypothesis in relation to a repair and maintenance for a concrete structure research program.
- An opportunity to gather appropriate knowledge that will inform expert advice about improving the repair scheme (materials and techniques) in order to ensure a durable repair.

In the repair and maintenance of concrete structures research program a decision was made to elicit the views of the groups involved in this area i.e. repair contractors, repair consulting engineers and repair materials suppliers.

The nature of the questions to be addressed to the repair material suppliers differed slightly from those to be addressed to repair contractors and consulting engineers. Therefore, two questionnaires were designed for use in this project.

5.4 Defining the Question Area

According to Rea and Parker (1992), the main objective prior to the development of a questionnaire is to gather preliminary information about the subject concerning interested parties and key individuals. This was, actually, the main issue discussed in Chapter 2 (the general problems in the repair and maintenance of concrete structures). The questions were presented in a sequence designed to elicit the most useful responses. From the preliminary investigation into the general problems in repair and maintenance of concrete structures, a number of interesting questions emerged about which useful information could be gathered.

5.5 Information Gathering

The following issues were specified as information gathering questions to be included in the questionnaire. Some of these items are not relevant to repair materials and thus, were excluded from the questionnaire. The specified issues are classified into six main areas as follows:

5.5.1 General

- Questions including the main areas of experience, number of years involved in repair and maintenance of concrete structures and size of contracts being supervised by those participating in the survey.
- Policies adopted by the companies relating to repair and maintenance (materials and techniques).

5.5.2 Repair and Maintenance – General

- Identifying any specific problems in the repair and maintenance of concrete structures.
- Identifying how the repair and maintenance procedures in concrete structures could be improved.
- Specifying problems that are affected in repair and maintenance.
- Specifying how technical records are kept for repair material.

5.5.3 Repair and Maintenance – Causes and Impairments

- Identifying the most important conditions that affect concrete integrity or serviceability.
- Identifying the causes resulting in structural effects, concrete damage and concrete deterioration.
- Specifying the most common impairments that manifest in concrete structures.
- Specifying the impairments manifest in concrete structures including structural effects, concrete damage and concrete deterioration.

5.5.4 Repair and Maintenance – Diagnosis and Repair Techniques

- Identifying how an impairment of a concrete structure could be assessed.
- Identifying some information which should be obtained about the background of a structure.

- Specifying how information should be obtained through interview with engineers, material suppliers, and workers.
- Identifying the most important issues which may be considered in a visual inspection.
- Identifying tests which are often performed during in-situ investigations and laboratory investigations.
- Specifying the factors that might affect the selection of repair methods.
- Indicating the techniques that usually apply in the repair of concrete structures.
- Specifying the repair systems that often apply in the repair of concrete structures.
- Identifying various kinds of procedure that are often applied in the techniques of repair of concrete structures.

5.5.5 Repair and Maintenance – Materials

- Identifying the factors that might affect the selection of repair materials.
- Identifying the various kinds of polymer which are often used in Polymer Portland Cement Concrete (PPCC), Polymer Concrete (PC), and Polymer Impregnated Concrete (PIC).
- Identifying the various kinds of cementitious and pozzolanic materials which are usually used in the repair of concrete structures.

5.5.6 Repair and Maintenance – Miscellaneous

- Identifying any constraints in restoration projects.
- Identifying the compatibility of the repair materials with each other and with the existing concrete.
- Identifying the various factors that affect the compatibility of repair materials.

5.6 Developing the Questionnaire

Having specified the objectives of the survey questions, the next stage involved writing up the questions (Assadi, 1997). By comparing Rea and Parker's work (1992) with Baker's (1994), it can be concluded that the development of a questionnaire is an essential component of each survey research process with respect to considerations such as unambiguous, clear, and simple questions that make up the questions.

There are two types of question format that can be used in order to achieve the objectives stated, i.e. open-ended and closed-ended forms of questions. An open-ended question format permits respondents to assert his/her beliefs, feelings and recommendations. Whereas, closed-ended questions may constrain the respondents to select from a specific number of responses (Assadi, 1997).

Both question formats have distinct advantages and disadvantages. Therefore, it was decided to use both types of questions in order to make up the questionnaire in repair and maintenance of concrete structures. This is considered to be beneficial in gathering information and in reducing the effects of the disadvantages of both procedures.

In the next stage, the structure of the questionnaire is organised by the identified questions in an intelligent manner. Amongst so many researchers, Weisberg et al (1996) recommend organising the questions so that they flow smoothly. For example, early questions should not be threatening and should not direct later answers. Taking such advice into consideration, the repair and maintenance of the concrete structures questionnaire was structured and presented in nine sections as follows:

- Section A covers questions regarding the respondents' background.
- Section B covers questions regarding company policies.
- Section C covers questions concerning repair and maintenance of concrete in general.
- Section D covers questions concerning the most important causes of defect, damage and deterioration of concrete.
- Section E covers questions regarding the most important impairments in concrete structures.
- Section F covers questions relating to the assessment of impairments of concrete structures.
- Section G covers questions relating to techniques of repair of concrete structures.

- Section H covers questions relating to the use of various kinds of material in the repair of concrete structures.
- Section I covers questions regarding miscellaneous issues relating to repair and maintenance of concrete structures.

The repair materials questionnaire was also structured and presented in six sections as follows (see Appendix A):

- Section A covers questions regarding respondents' background.
- Section B covers questions concerning company policies.
- Section C covers questions regarding repair materials in general.
- Section D covers questions concerning technical records in repair materials.
- Section E covers questions relating to the use of various kinds of material in the repair of concrete structures.
- Section F covers questions regarding miscellaneous issues relating to repair materials.

5.7 Selecting the Survey Sample

The questionnaire is designed to study the repair and maintenance of concrete structures and this category of the construction industry organisations would normally include civil engineering contractors, consultants and material manufacturers. It was decided to select organisations from the Concrete Repair Association (CRA), the International Concrete Repair Institute (ICRI) and other civil engineering contractors, consultants and material suppliers in the U.K. Details of contact addresses were available for 30 consulting engineers and concrete repair contractors and 36 material manufacturer in the U.K.

5.8 Conducting the Main Survey

A considerable effort was made to produce the questionnaires in the most efficient professional manner. Each of the questionnaires was prepared in booklet form and introduced by highlighting the importance of the respondent's contribution to the study as well as assuring him that all responses would be treated confidentially. A stamped self-addressed envelope was also enclosed with each questionnaire to encourage quick response. By the end of few weeks after the original mailing, about 50% of the questionnaires were returned. Of amongst these, only 35% of the questionnaires were usable. Table 5.1 shows the summary of the results from these questionnaires of which their contents were contributed in the database.

Table 5.1 - Summary of the results from the questionnaires contributed in the database.

Company Name	Contributed Comments	Included Products	Number of Products
Structural Chemical Limited	Repair Materials, Repair Methods, Compatibility of Repair Materials, General Comments	Epoxy, Polyurethane	45
sbd Limited	Repair Materials, Repair Methods, Compatibility of Repair Materials, Concrete Distresses, Investigation and Diagnosis, General Comments	Polyester, Epoxy, Polymer, Cement, Acrylic, SBR, Cementitious Materials, Polyurethane, Silicon	45
TAM International Consultants Ltd.	Repair Materials, Repair Methods, Compatibility of Repair Materials, Site Investigation	Polymer, Cement, Acrylic, Cementitious Materials, SBR, Polyurethane, PVC, Epoxy	18
Harris Specialty Chemicals (HSC) UK Ltd.	Repair Materials, Repair Methods, Compatibility of Repair Materials, Concrete Distresses, Investigation and Diagnosis	Cement, Polymer, Epoxy, Acrylic, Silicon Organic Materials	17
Fullstop Technology Limited	Repair Materials, Repair Methods	Polymer, Cement	5
Atraverda Limited	Repair Materials, Repair Methods, Compatibility of Repair Materials, Investigation and Diagnosis, General Comments	Polymer, Cement	1

Table 5.1 (Continued).

Company Name	Contributed Comments	Included Products	Number of Products
Ronacrete Ltd.	Repair Materials, Repair Methods, Compatibility of Repair Materials, Site Investigation	Cement, Acrylic, Epoxy, Polymer, SBR	16
Don Construction Products Ltd	Repair Materials, Repair Methods, Compatibility of Repair Materials, General Comments	Polymer, Silicate, Acrylic, Cement (PFA, HAC, Microsilica), Bituminous Emulsion, Epoxy, Polyester, Aggregate, Polyurethane, SBR, Styrene-Acrylic	62
Feb MBT	Repair Materials, Repair Methods, Compatibility of Repair Materials, Site Investigation	-	-
Perma Rock Products Ltd.	Repair Materials, Repair Methods, Compatibility of Repair Materials, Concrete Distresses, Investigation and Diagnosis	-	-
Astor-Stag Limited	Repair Materials, General Comments	-	-

5.9 Summary

Knowledge acquisition is the most crucial and difficult part in the development of an expert system. It needs highly skilful manipulation to extract and assemble the information and knowledge used to solve a specified problems (Cabrera, J. G. et al, 1995). After reviewing the relevant problems discussed in Chapter 2 and describing the preliminary studies carried out to develop a knowledge base (Chapter 3) and to create a database (Chapter 4), this Chapter has described the procedures adopted in developing the instrument used for collecting a part of the research data. It included the process of selecting the survey method, defining the question areas, and preparing the final version of the questionnaire.

This collected research data contributed to develop the knowledge base (discussed in Chapter 8) that would guide specifiers, owners and contractors in the choice of effective and durable repair schemes for reinforced concrete structures. Another of the main features of this collected research data will be to help in creating a database of repair materials and techniques, discussed in Chapter 7. The purpose of the database is to provide storage of material specifications along with manufactures' general information and application information for repair materials in the UK.

Chapter 6

Overview of DEMAREC: Diagnosis, Evaluation, MAintenance and REpair of Concrete structures

6.1 Introduction

The central feature of this research is the integration of two hitherto separate areas of Information Technology (IT). Firstly, integrated engineering computing systems have evolved and these are based upon sets of algorithmic programs that interact with a central database management system (DBMS). Secondly, knowledge-based programming techniques or expert systems (ES) are applied to a wide range of engineering problems. Because these two subject areas have not been integrated previously, most of the prototype expert system applications in engineering have been restricted to limited amounts of data and have no facility for sophisticated data management. As expert systems are integrated into complex engineering computing environments, the database management capabilities of the integrated systems must be adapted to serve these new components.

The need exists for an interface between the knowledge-based expert systems and DBMS. It has been shown in Chapters 2, 3 and 4 that the maintenance and repair of concrete structures represent a classical problem for the application of expert systems in collaboration with database management system (DBMS). The Diagnosis, Evaluation, MAintenance and REpair of Concrete structures - DEMAREC application, which is presented in this Chapter, is developed as a new software and focuses on integration of concrete distresses (including cracking, surface and miscellaneous distresses), investigation and diagnosis problems, repair materials and methods and given recommendations relating with them. Effectively, Chapters 2, 3 and 4 deal with the DBMS and ES aspects of this research and this Chapter deals with the their interaction with each other and the environment.

6.2 Windows Environment and its Features

Microsoft Windows 95 is a graphical operating system with several features such as multithreading and multitasking. In process-multithreading, the system allows more than one instance of the same application to run simultaneously. While in process-multitasking the system enables more than one application to run simultaneously through the communication features of the Windows environment. These features include Dynamic Link Libraries (DLL), Dynamic Data Exchange (DDE) and Object Linking and Embedding (OLE).

A Dynamic Link Library (DLL) is an executable module comprising functions used by the applications to perform certain tasks, to communicate with the Windows environment and to make use of Windows resources. DLL supports multitasking i.e. a copy of a DLL function can be shared by several applications.

Dynamic Data Exchange (DDE) known as a DDE conversation is a method by which applications exchange data in a Windows environment. A DDE Link is used by applications which are closely coupled e.g. an expert system and a database application (see Section 4.8). The disadvantage of using DDE is that it requires programming to establish a link between applications.

In Object Linking and Embedding (OLE) which is an alternative to DDE, an object from one application can be incorporated into another application. The application supplying the object is called the source application while the application receiving the object is called the container application. An object is either linked to or embedded into the container application. Linked objects can be updated automatically each time the source file changes while embedded objects can be edited from within the container application. In the application developed in this research, the Microsoft Power Point application was linked to the main application through the OLE.

6.3 Visual Basic as an Interface Development Environment

Like the Windows environment, Visual Basic takes advantage of the communication features such as Dynamic Link Libraries (DLL), Dynamic Data Exchange (DDE) and Object Linking and Embedding (OLE). Visual Basic makes use of the standard Windows tools e.g. toolboxes, buttons and dialogue boxes by accessing the appropriate DLLs. For instance, Visual Basic can make use of the Windows dialogue boxes which reside in the *commondialog.dll* file. Apart from the Windows features, Visual Basic supports its own class of controls known as Visual Basic Controls. Visual Basic enables the application developer to access the powerful features of Windows. The communication and data sharing features presented in this Chapter form the basis for the communication and data sharing between the component applications of DEMAREC software.

6.4 System Description

DEMAREC is a Visual Basic interface in which a multiple production rules expert systems (DEMAREC-EXPERT) is coupled to an independent database management system (REPCON) and evaluation program (ECON). The main features demonstrated in this research software include:

- Evolving knowledge and database.
- The integration of pictures and descriptive information in a way that makes problem solving easier.
- The creating of Graphical User Interface (GUI) gives inexperience users the ability to access the full range of DEMAREC program capabilities in order to control the communication between the components of the program.
- An environment in which both experts and their added data can be evaluated and tested to ensure that the evolving system retains its integrity.

The architecture of DEMAREC, shown in Figure 6.1, consists of knowledge-based system interfaces for each knowledge-based expert system (DEMAREC-EXPERT), database interface for REPCON database management system and an evaluation management interface for evaluation of concrete (ECON).

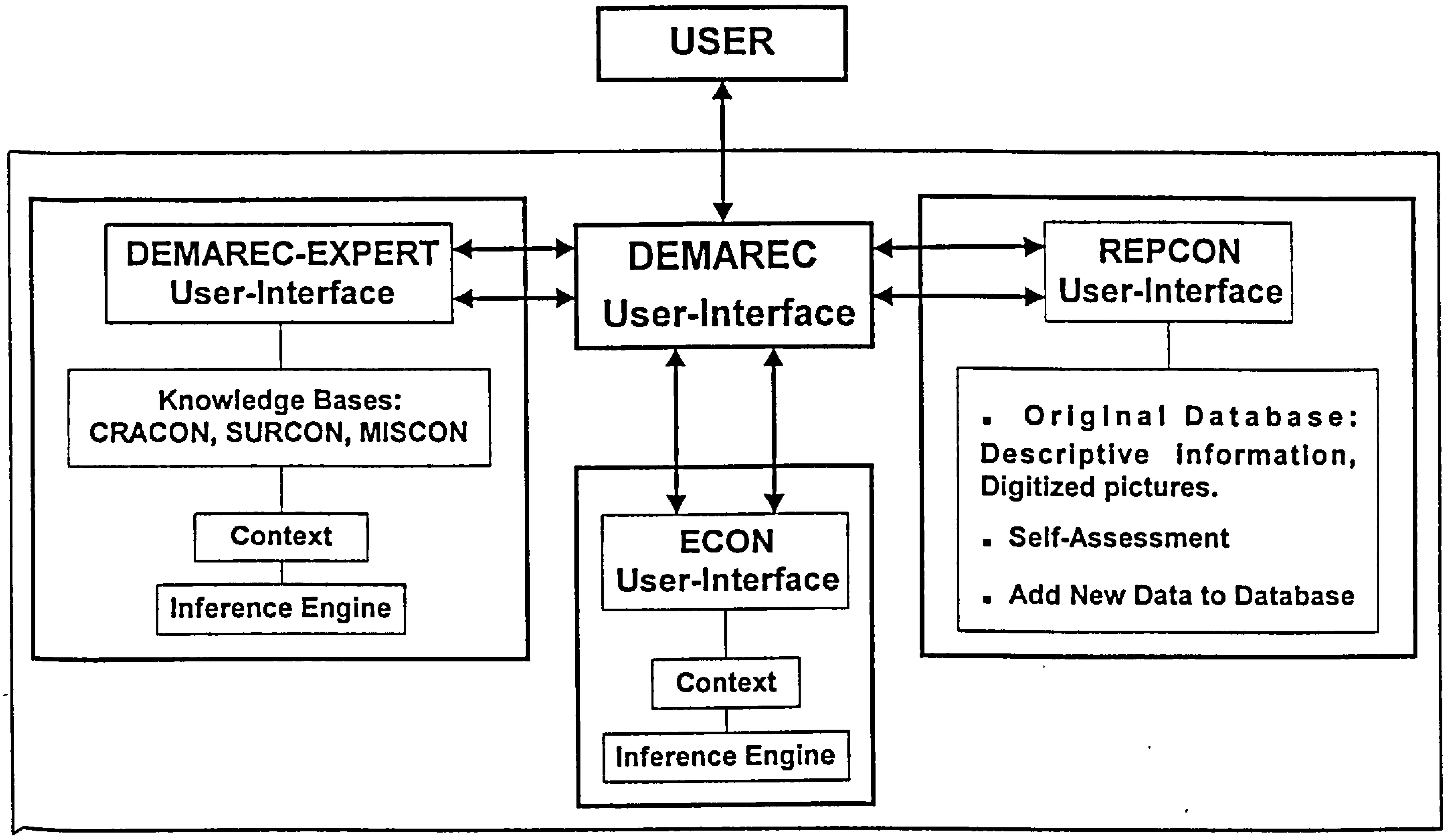


Figure 6.1 - DEMAREC architecture.

6.4.1 REPCON Database

The connection between the REPCON database and the DEMAREC user-interface enables retrieval of data for use by both the user and the expert system. The REPCON imagebase consists of digitized photographs and drawings saved in a file in binary format. The binary file is then loaded into the database using the standard Visual Basic "*Appendchunk*" procedure. This information is obtained from field investigation and technical reports. Images are used in the vicinity of the expert system for the visual display of distress problems. This visual display assists the user in determining the type of distress which relates to the specific problem by allowing the user to view many types of distress.

More importantly the REPCON management system is designed to be an effective support tool for experts whose data can be evaluated and tested to ensure that the evolving database retains its integrity. By providing a quantitative and consistent means for evaluating both new data and the person contributing it, the confidence level (CL) allows the new knowledge and experience to be gathered and monitored overtime. It is shown how a computerized database management system can allow an initial database to evolve and to become a forum for exchanging ideas in the field of concrete repair.

6.4.2 Knowledge-Based Expert System

The expert system comprises production rules knowledge modules controlled by procedures. The modules are dynamically loaded and unloaded into the working memory as and when required by the application. Different forms of knowledge are needed to make expert decisions about the condition of a structure. A wealth of information regarding causes and effects of concrete distress has been gathered in three individual knowledge-based expert programs which can be run in the visual edit screens at the same time as the database is used. Facts, expert opinions, guidelines, rules of thumb and descriptive information are forms of knowledge that are used to make these knowledge bases. These prototype knowledge bases are designed to identity the various causes and problems related to cracking (CRACON), surface distresses (SURCON), and other miscellaneous forms of distress (MISCON) that occur in concrete structures.

6.4.3 Evaluation of Concrete

Condition assessment of concrete structures is apparently far more difficult than the analysis of design (Cabrera J. G. at al, 1995). Though the structure physically exists and the data for testing and examination of the concrete are available, evaluation involves uncertainties owing to the difference between reality and design concepts, heterogeneous concrete material and the complexity of distress mechanisms. Therefore, a thorough and logical evaluation of the current state of the concrete in a structure is the first step of a repair or rehabilitation work. A visual inspection of the exposed concrete is the first step in an in-situ examination of a structure. One objective of an evaluation management system (EMS) is to create assessment procedures that will allow the current condition of the structure and its components to be expressed numerically so as to take the best course of action in the repair and maintenance management.

For this purpose, a quantitative rating system for the condition of concrete in a structure would make possible the determination of which components within a structure most merit repair. The confidence level (CL) prescribed in this program applies to concrete structures in general. The rating system described allows the confidence level to be determined by visual inspection using limited equipment such as binoculars, covermeter and ruler. The rating is related to structural integrity and serviceability of the structure.

6.5 DEMAREC Inference Procedure

The DEMAREC inference procedure is divided into two parts. The main implementation part includes input and reporting system, expert system development environment, database management system and the evaluation management system. The second part is the user-interface. DEMAREC is a flexible application which can be used in four modes: evolution mode, diagnostic mode, evaluation mode and education mode.

6.5.1 Implementation

Input and Report System

The input comprises a full description of the user requirements such as structure and component types, structural design and construction types and visual inspection data such as distress and symptom categories. In this part the help option in each section provides assistance for users in the form of pictures, text and/or combination thereof.

The reporting system summarises the consultation result in the form of a visual edit screen. These results comprise the conclusion from the expert system including causes and effects of distress, repair materials required, methods and recommendation from the database and conclusions from the evaluation process.

Expert System Development Environment

All consultation modules are configured by M.4 which is a commercially available Expert System Development Shell (discussed in Section 3.10). It can be run under the Windows or DOS environment. The shell is integrated into the Visual Basic Graphic User environment through the Visual Basic Controls. In this control there exist procedures which are called by the M.4 Kernel when the Kernel requires data from the Visual Basic application or needs to send data to the application. These procedures control the initialising and termination of an M.4 expert system consultation. The DEMAREC-EXPERT consultation module includes three knowledge bases: CRACON cracking in concrete, SURCON surface distresses and MISCON miscellaneous distresses.

Database Management System

The REPair of CONcrete (REPCON) database is developed using Microsoft Access which is a relational database management system running within Microsoft Windows. The structure of REPCON database comprises thirteen tables which deal with the following themes:

- Structural Types
- Structural Components
- Construction Types
- Structural Design Types
- Concrete Distresses
- Symptom Categories
- Investigation and Diagnosis
- Compatibility of Repair Materials
- Concrete Removal for Repair
- Repair Methods
- Repair Materials

- Repair Material Suppliers
- Durability and Maintenance Recommendation

This user-friendly software is developed to run on a personal computer and a user-interface is provided in the form of visual edit screens which embody the Visual Basic programming language. Microsoft Access database was linked to Visual Basic through the data control in cases where the data did not require any subsequent manipulation. Some databases were linked to the application through the Structured Query Language (SQL) code in cases where there was need to manipulate the data. The database can be accessed by the user independently of the expert system.

Evaluation Management System

The evaluation of concrete (ECON) is implemented in the form of visual edit screens which embody the Visual Basic programming language. The criteria for the evaluation of a concrete structure consist of cracking, disintegration and scaling, and spalling and delamination. The assessment procedures of concrete structures that enable the user to consider the current condition of the structure and its components are the main objective of an evaluation management system (EMS). These procedures are expressed numerically using a confidence level (CL) to take the best recommended action in the repair and maintenance management.

6.5.2 The User-Interface

The user-interface is an important component of the computer software responsible for the interaction with the user and is fundamental to the effectiveness of the program in fulfilling its primary objectives. In view of this, the user-interface is designed to make the program flexible, easy to learn and use and it contributes to the success of the program when carefully designed.

Traditionally, the development of computer software for civil and structural engineering applications addressed by software developers has focused far more on the functional aspects of these systems than on user-interface design issues. With increasing complexity of engineering problems, the design of the user-interface has become a major problem in software engineering. For example, knowledge-based expert systems share with other applications the problems associated with an inadequate user-interface. The user-interface should be user-friendly and natural in its dialogue with the user and should be matched with the experience and needs of the user. It also supports the explanation facility which provides for concise and helpful responses to users' queries and allows the user to interact with the system to seek explanations.

DEMAREC User-Interface

The DEMAREC user-interface shown in Figure 6.2 is developed in Microsoft Visual Basic. The user-interface is not designed as a separate component of the program but it is essentially a menu driven system. Rather, the user-interface is a domain visual edit screen and consists of the various interface operations defined with the domain objects. One of the attractive features of Visual Basic is its access to the Microsoft Access Database Engine through Structured Query Language (SQL) (see Section 4.6.4) and data control and its access to the M.4 Visual Basic User through data control and its communication features. It consists of graphical forms and controls through which the user wants to perform with an object. The main interface comprises three various interfaces such as REPCON, DEMAREC-EXPERT, and ECON interfaces.

Chapters 7, 8 and 9 are devoted to a detailed presentation of the DEMAREC components.

The REPCON user-interface is provided with all objects in repair of concrete database. It is used to present the user with viewing the original database, to introduce the self-assessment process, to add to the database and to search in the database. The REPCON user-interface is shown in Figure 6.3.

Figure 6.2 - Main screen of the DEMAREC application.

The DEMAREC-EXPERT user-interface is an interface which allows the user to apply an expert system to a specific problem. It is used to present the user for selecting one of the three knowledge bases namely CRACON (cracking in concrete), SURCON (surface distresses) and MISCON (miscellaneous distresses). This user-interface is shown in Figure 6.4.

The Evaluation of the CONcrete (ECON) user-interface shown in Figure 6.5 is structured with three different objects such as cracking, scaling and disintegration and spalling and delamination. It is used to allow the user to create assessment procedures for the current condition of the structure and its components.

Figure 6.3 - The REPCON user-interface.

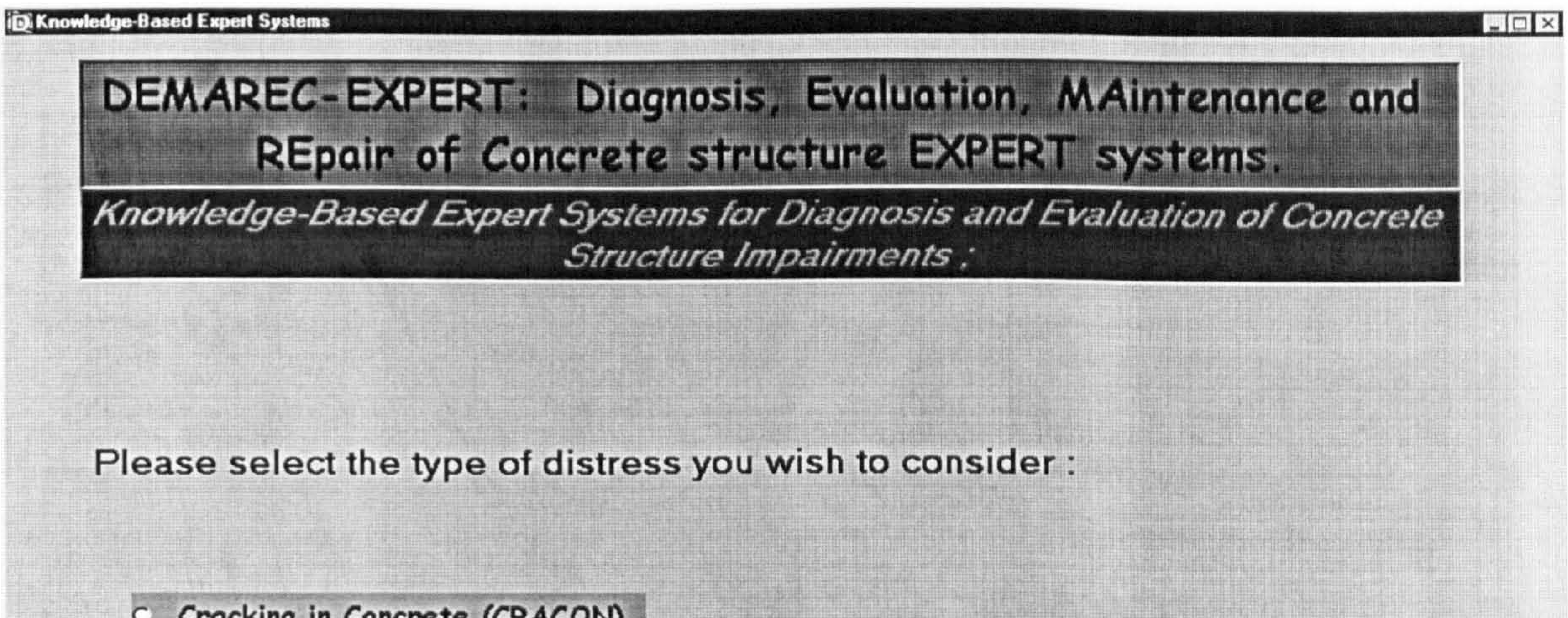


Figure 6.4 - The DEMAREC-EXPERT user-interface.

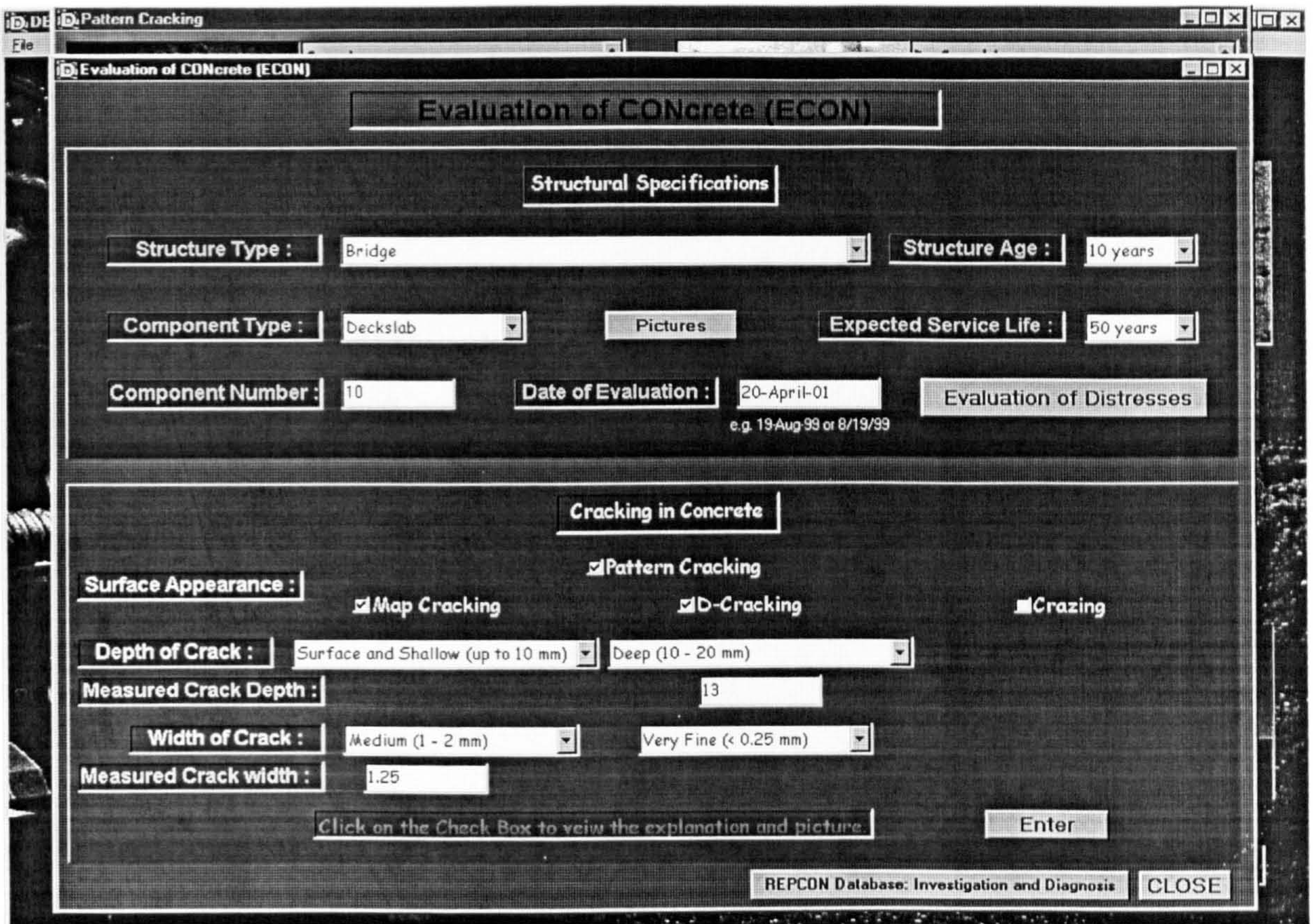


Figure 6.5 - The ECON user-interface in DEMAREC application.

6.6 Summary

In this Chapter, the DEMAREC application has been reviewed from a configuration point of view. Many aspects relating to the application were covered comprising system description, inference procedures, and user-interface.

The development of the system consists of three modules which deal with the repair of concrete database, solving concrete repair problems with expert system and assessment of uncertainty problems in the evaluation of a concrete structure.

The DEMAREC inference procedure is divided into the main implementation part and the user-interface part. The main implementation part is characterised by an input and reporting system in the form of a visual edit screen, development an expert system using M.4 as a shell, creating a database using Microsoft Access and the evaluation of uncertainty problems in concrete structures which embody Visual Basic programming.

It can be seen from the foregoing that several important factors need to be considered in the design of user-interfaces in structural engineering applications. Flexibility, ease of system usage and learnability and the effectiveness of the programs are factors which influence the quality of the user-interface. Advantage should be taken of recent developments in the use of multimedia techniques to improve the quality of user-interface. The DEMAREC application is implemented in Microsoft Visual Basic and is manipulated using multimedia techniques for developing the user-interface.

Chapter 7

REPair of CONcrete (REPCON) Database Structure

7.1 Introduction

Designing and constructing concrete structures of enhanced durability, thereby reducing maintenance and repair costs, has been a focus for research and development. Lack of concrete durability is common worldwide and it is causing a huge capital loss by reducing the design life of structures (Miyamoto et al, 1999; Evbuomwan et al, 1994). In many developed countries, emphasis has been given to the maintenance and repair of existing concrete buildings as well as on the concept of designing and constructing with a view to durability. The choice of an appropriate repair material and method requires a systematic observation of the symptoms and their probable cause together with a source of available information relating to durability.

DEMAREC uses a database called REPCON, which deals with the diagnosis, evaluation, maintenance and repair of concrete structures. The need for a database in the repair and maintenance of concrete structures is highlighted in Chapter 2 and 4. The purpose of the REPair of CONcrete (REPCON) database developed in this research is to guide civil engineers, owners and contractors in the correct diagnosis of the causes of the impairment and in the choice of effective and durable repair materials and techniques.

This Chapter begins with a presentation of the structure of the database, followed by a description of the contents of the database, the methods developed in this research for handling pictures in the database and finally explains how an initial database can be enhanced by the inclusion of additional information provided by experts in the field. It is shown how the REPCON management system is designed to be an effective support tool for experts whose data can be evaluated and tested to ensure that the evolving database retains its integrity. By providing a quantitative and consistent means for the assessment of both new data and the person contributing the knowledge, it is also shown how the REPCON could accelerate the turnover of knowledge.

7.2 Repair of Concrete and Database

Over the last decade, there has been considerable interest in the durability and maintenance of concrete structures thereby reducing maintenance and repair costs. Inappropriate design and construction methods often cause concrete structures to be affected by lack of durability, integrity and serviceability. Durability is technically and economically one of the main factors in selecting construction materials, so as to avoid damaging factors such as corrosion, Alkali-Aggregate Reactivity (AAR) and freezing and thawing (ASTM, 1980).

During the last few years, the repair of deteriorated concrete structures has become a matter of concern for civil engineers and contractors so that an increasing proportion of the funds being spent on construction, especially concrete bridges, is used for the repair of damaged concrete structures. In addition, a significant number of companies are involved in the development and supply of repair products, in damage appraisal in product selection and in the execution of repair and maintenance techniques. Many companies promote themselves as experts in the field of concrete repairs. It is not uncommon in view of the above for a client to appoint an inexperienced or incompetent repair contractor, or to become the victim of an inappropriate repair technique.

A consideration of the foregoing issues led to the development of a diagnosis, maintenance and repair advisory management system for reinforced concrete structures. Modern engineering technology provides procedures for performing condition surveys, consistent and quantitative condition assessment and database management. Database Management Systems (DBMS) organise and structure data so that it can be retrieved and manipulated by users and application programs. The initial reason for the development of a database was to marshal all available data in a common format so that the user can perform a variety of operations rapidly. Therefore, the development of a comprehensive Database Management System (DBMS) is essential not only for the diagnosis and evaluation of concrete distress but also as a maintenance and repair source of knowledge which takes into account the choice of effective and durable repair materials and techniques.

The REPair of CONcrete (REPCON) database includes information which is provided as information gathering and data to arrive at a realistic and proper diagnosis of the cause(s) of distress. REPCON provides advice on materials selection and adequate repair techniques along with recommendations to ensure enhanced durability. It is envisaged that this system when eventually developed will inter-alia provide a factual, logical, economic and expert recommendation to intending concrete repair clients, while also acting as a useful first hand guide to concrete repair specialist, contractors and consultants.

7.3 The Database Structure

REPCON is developed using a database management system (DBMS), Microsoft Access 2.0 which is a relational database (see Section 4.6.4) management system running within Microsoft Windows. This user-friendly software is developed to run on a personal computer and a user interface (Figure 6.3) is provided in the form of visual edit screens which allow the user to use the Visual Basic programming language. The system has been developed for PC computers and is maintained on a host computer that can be accessed via the Internet, thus making it easily available to intended users.

The REPCON database contains two types of information. The first type of data comprises the original database which reflects knowledge in the year 2000 and which features pictures and diagrams to assist users in selecting structural types and construction techniques in diagnosing the causes of concrete distress and to improve their knowledge of the subject. The second type of data is that which has been contributed by skilled users. This contributed data has been assessed by the REPCON Database Management System and a confidence value has been assigned to it. The architecture of the REPCON Database is shown in Figure 7.1. The key elements of the database and its potential benefits are now discussed.

All communications with the database is controlled by the user application or Graphic User Interface (GUI). The knowledge-based expert system manipulates the data from the database through the Visual Basic display controls, events and procedures. This has two advantages, firstly the user has control over the communication between the expert system and the database and secondly the user can interact with the database independently of the expert system. The explanation facility helps the users to learn about the software as well as learning about concrete distresses and repair. The help facility provides step-by-step instructions to help and guide the user in the use of the database. Bibliographic references are also included in each of the REPCON tables. Push buttons contained in the help facility of each table provide access to a bibliography for the data which will assist users in further investigation and analysis.

7.4 REPCON Management System

The REPCON management system is the interface between the user and the physical database. All user requests for access to the database are handled by the REPCON management system. Viewing and adding, retrieving data from and updating data in the database are accomplished by the database management system so ensuring that the evolving database retains its integrity.

The primary objective of the REPCON management system is to allow a user to contribute experience and knowledge to the database thereby evolving the database. The modular REPCON management system allows the user to review existing documents and to contribute new knowledge. The user can diagnose the causes and effects of impairment through the DEMAREC-EXPERT program, can evaluate the current condition of concrete by the ECON program and can select repair materials

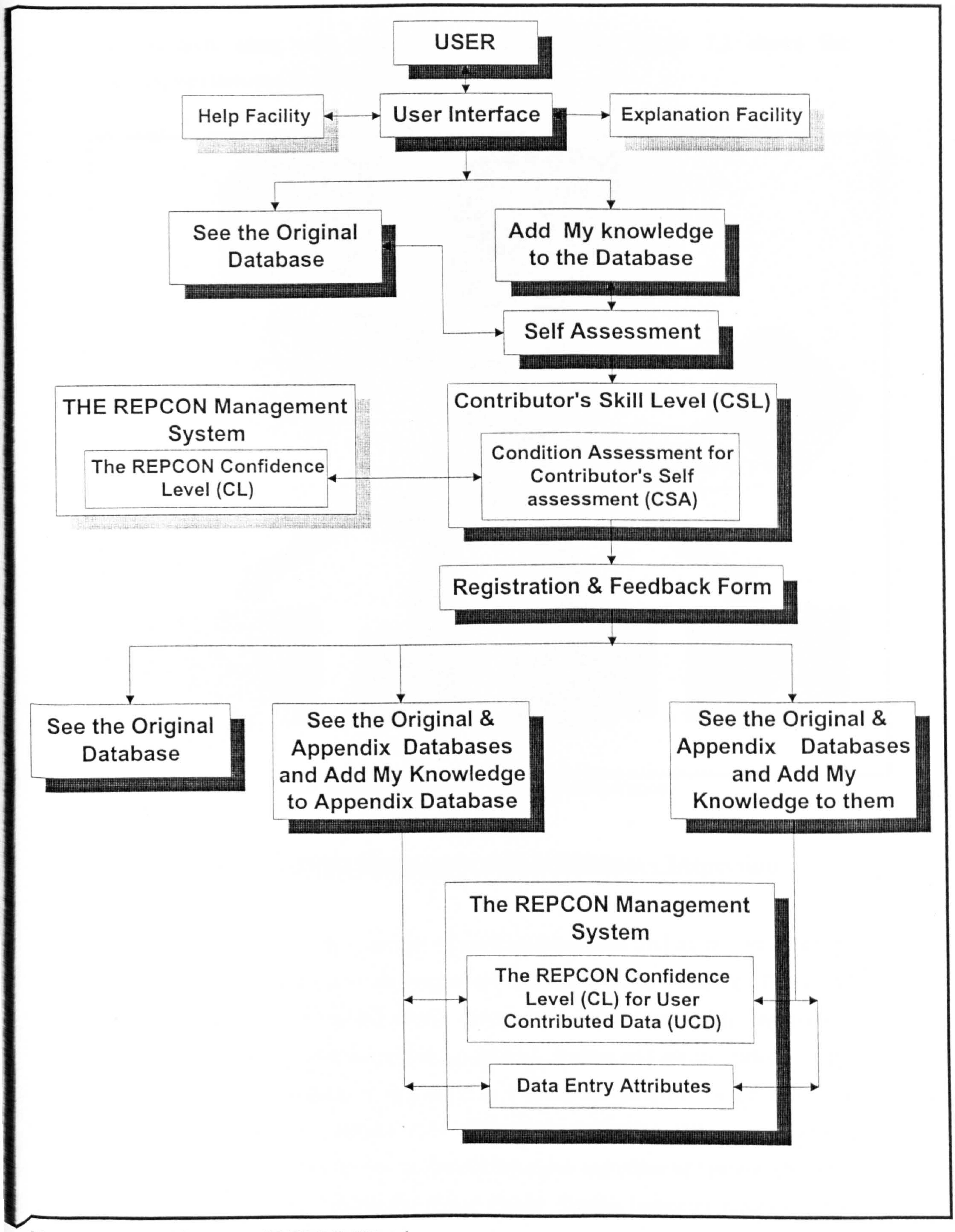


Figure 7.1 - Architecture of REPCON Database.

and methods along with durability recommendations. Figure 7.2 shows the relationships between these features.

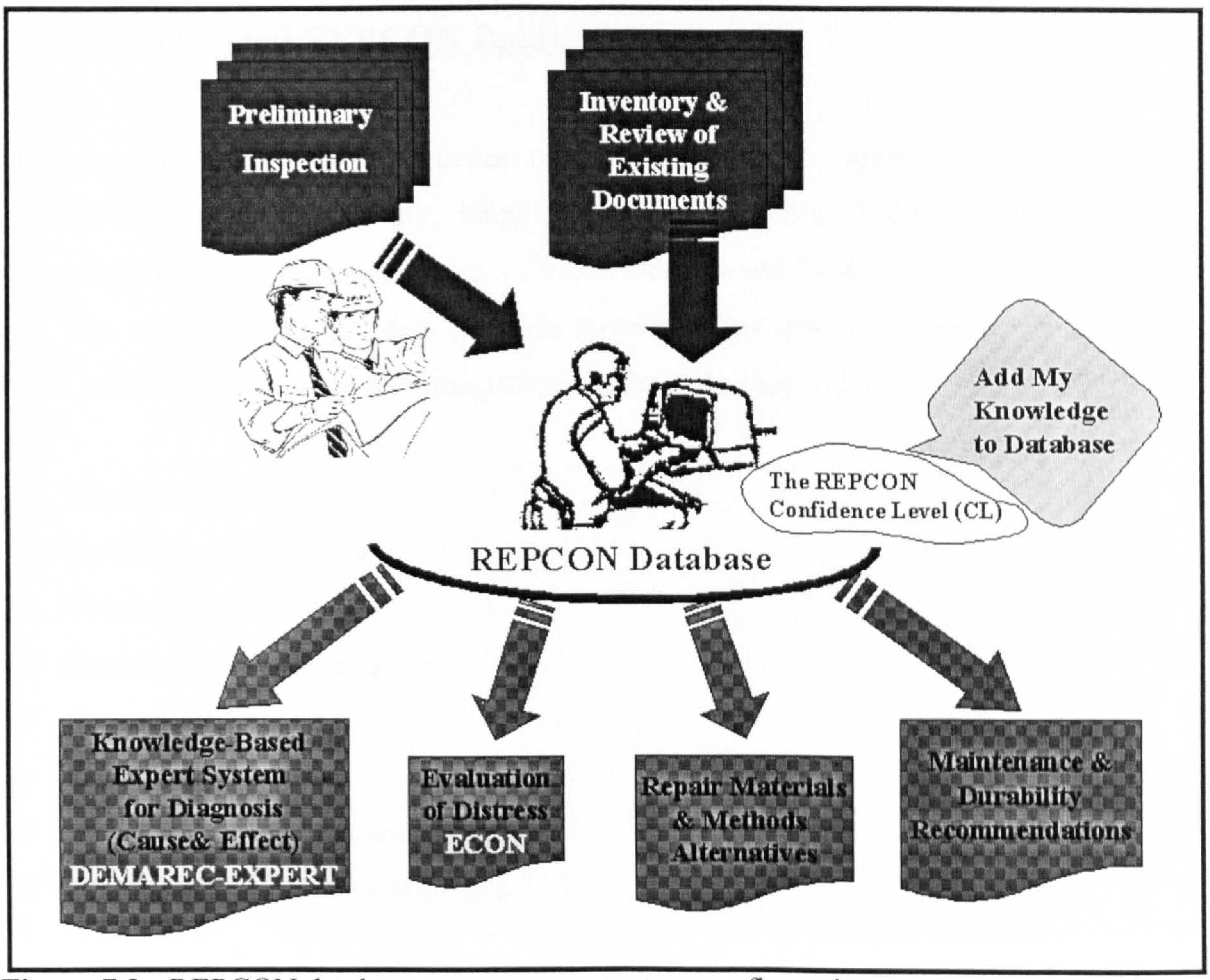


Figure 7.2 - REPCON database management system configuration.

7.5 Review of Existing Documents and Preliminary Inspection

A user session begins with a review of existing documents and an inspection of the user's structure according to the procedure described in the database. The visual inspection usually involves an overall survey of the structure, which may include location and extent of concrete cracking, spalling, scaling and disintegration. Firstly, this inspection information is entered into a computer program called ECON to determine a condition Confidence Level (CL) for the evaluation of the current state of the structure. Secondly, it is used to identify the cause and effect of distress which has been diagnosed by the Knowledge-Based Expert System computer program called DEMAREC-EXPERT. Therefore, the REPCON Management System allows the user to take engineering and management decisions and undertakes a comprehensive investigation and condition survey including in-situ and laboratory tests.

7.6 The Original REPCON Database

Inappropriate design and construction methods often cause concrete structures to be affected by lack of durability, integrity and serviceability. These conditions are classified into three main categories: - Defect, Damage and Deterioration (see Chapter 2). The original REPCON data exists in thirteen tables shown in Figure 7.3 which deal with these conditions according to one of the following themes:

- Structural Types
- Structural Components
- Construction Types
- Structural Design Types
- Concrete Distresses
- Symptom Categories
- Investigation and Diagnosis
- Compatibility of Repair Materials
- Concrete Removal for Repair
- Repair Materials
- Repair Methods
- Repair Material Suppliers
- Maintenance and Durability Recommendations

Most of the REPCON data comes from documented material. However it was often difficult to use information which was unclear and contradictory. The use of multiple sources was considered in developing REPCON in order to ensure the validity of the data stored. Therefore, the data has been obtained from codes of practice, manuals, textbooks, technical reports, journals and conference proceedings, the internet, civil work reports and experienced concrete specialists (see Chapter 2).

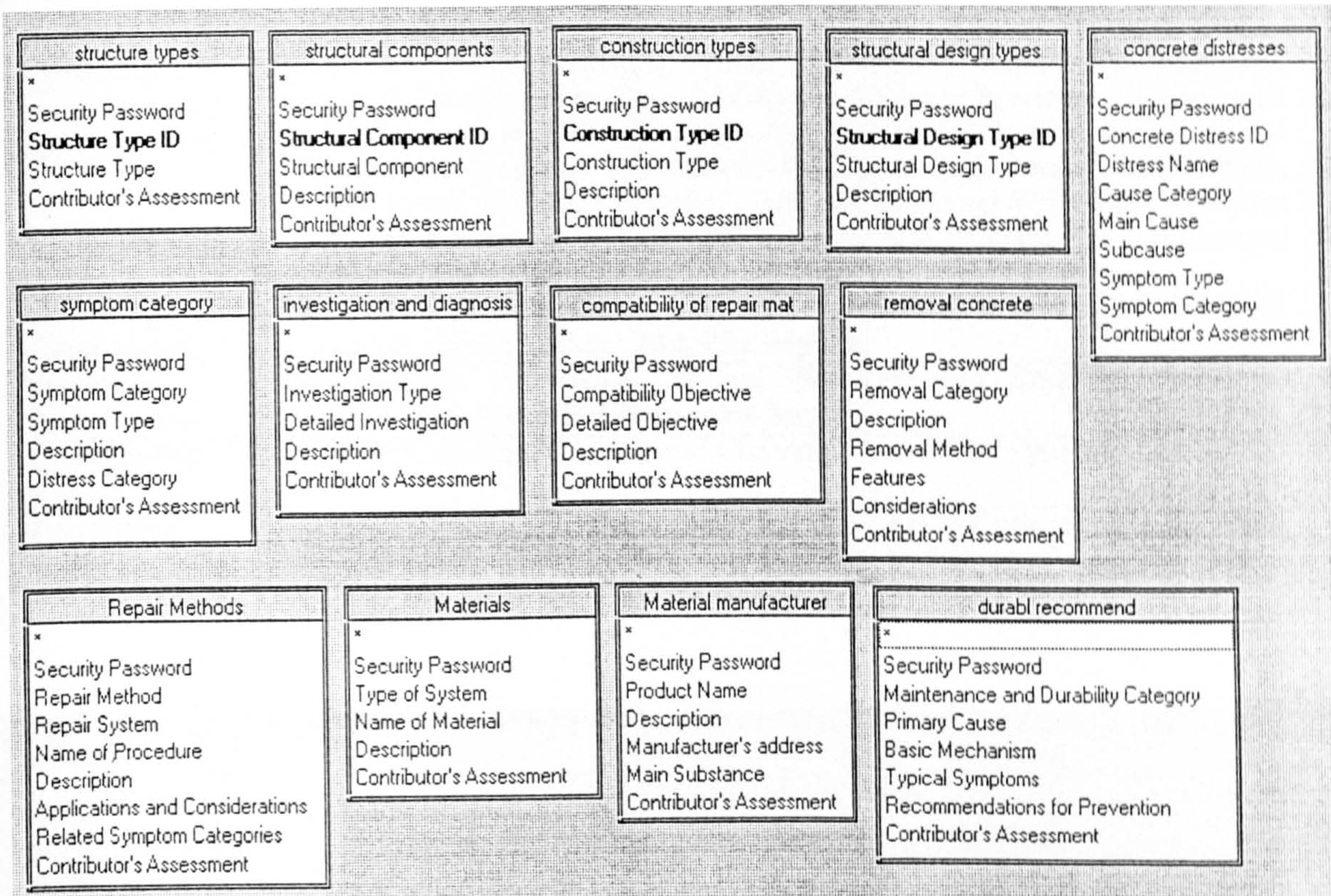


Figure 7.3 - A schematic representation of the REPCON database tables.

7.6.1 Structural and Construction Data

In this database, there are tables which describe the structure types, structural components, structural design types and construction types. The history of the structural type and design, its current use and its originally intended use need to be considered since changes in use may have resulted in changes in loading. A knowledge of the conditions experienced during construction can be included in the investigation, particularly where defects are seen during the construction period or early in the life of a structure. This information shown in Table 7.1 may have a significant affected on the repair and maintenance of concrete. The database comprises pictures such as the one shown in Figure 7.4, representing various structural types and construction methods.

7.6.2 Concrete Distresses Data

Many factors may contribute to or cause the impairment of concrete structures. These are described in detail in the concrete distresses' table shown in Table 7.2.

Table 7.1 - REPCON Database - Structure and Construction.

Structure Type	Reinforced concrete Building (Public, Residential, Commercial, Historical, Industrial), Bridge, Power Plant, Airfield and Highway Pavement, Concrete wall (Canal, Retaining or Bulkhead), Grain Silo and Material Handling Facilities, Dam and Barrier, Underground Structure and Tunnel, Car Park, Smeltery and Refinery, Cooling Tower, Hydraulic Structure (Tank and Reservior, Wastewater Treatment Plant), Marine Structure (Wharf, Offshore Concrete Platform, Jetty, Submerged Reinforced Concrete).
Structural Components	Beam, Column, Slab, Connection, Wall, Foundation, Joint Related, Deckslab, Surface, Abutment, Pedestal, Pier, Pile, Segment.
Structural Design Types	Conventionally Reinforced Concrete, Post-Tensioned Concrete, Prestressed Concrete, Mass Concrete, Combination System.
Construction Types	Cost-In-Situ, Precast, Unreinforced Concrete, Combination System
Description	The function of the structure, location and usage amongst other factors, the design type and nature of construction; and the level of distress of structural element markedly affected in the repair and maintenance of concrete.

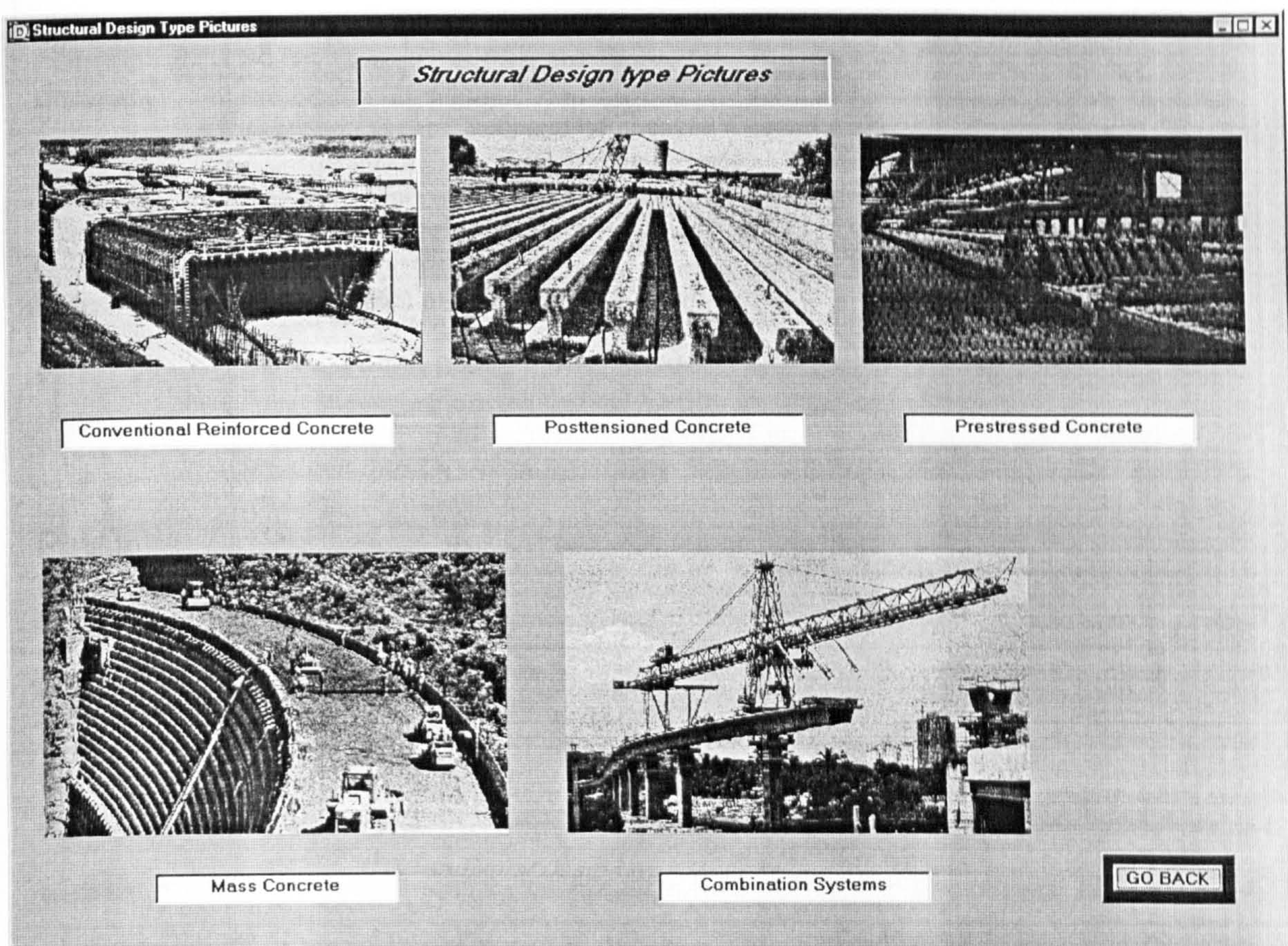


Figure 7.4 - A screen dump showing various structural design types in concrete structures.

It is important to distinguish between defects, damage and deterioration. Defects are usually impairments of a structure which may be compounded by inadequate training and supervision of site operations or workmanship problems. Damage is impairment of a structure caused by external mechanical factors while a structure is in service.

Deterioration can be caused by a combination of factors that lead to long-term durability problems. These three conditions often affect concrete integrity, serviceability and durability.

Table 7.2 - REPCON Database – Concrete Distresses.

Concrete Defect	**Unsuitable Construction Method** - Unsuitable scaffolding and shoring, High slamp, Incompleted curing, Misplaced reinforcement, Unsuitable scoure prevention, Handling and Placing Concrete (Segregation, Careless placing procedures, Inadequate and over vibration) **Improper Workmanship** – Faulty design (Improper size of riprap, inaccurate estimation of flood level and its velocity, Assumptions, Analysis, Calculations, Detailing), Incorrect Concrete mixture (Low cement content, High water content, Incorrect admixture, Dosage, Batching error). **Unsuitable Materials** – Reinforcement (Wrong kind, Incorrect size), Aggregate (Unsound, Reactive, Contaminated), Cement (Wrong type, Manufacturing error, Contaminated, High Alumina Cement), Admixture (Wrong kind, Substandard, Contaminated), Water (Organic contaminant, Chemical contaminant, chemical contaminant, Dirty)
Concrete Damage	Flood, Earthquake, Fire, Explosion, Impact, Drying and Plastic Shrinkage, Plastic settlement, Over load (Tensile, Shear, Flexural and Abnormal deflection cracking), punchout, Creep, Temperature changes, Ground movement, Foundation movement, Thermal incompatibility, Wear and Erosion (Abrasion and Chemical erosion in floor and pavement), Wear and Erosion (Cavitation, Abrasion and Chemical erosion in hydraulic structures).
Concrete Deterioration	**Chemical** – Sulphate Attack, Chloride Attack (Ingress), De-icing Salts, High Chloride level of additives, Soft Water Attack, Sea Water Attack, Brine (cl⁻) Attack, Acid Attack. **Physical** – Insufficient Cover, Scouring, Aggregate D-cracking, Joint Deterioration, Frost attack, Differential thermal Strains, Incompleted Curing. **Physical/Chemical** – Freezing-Thawing, Corrosion of Reinforcement, Alkali-Silica Reaction (ASR), Alkali-Carbonate Reaction (ACR), Alkali-Aggregate Reactivity (AAR).
Description	Conditions, which affect concrete integrity or serviceability and can occur at any time in a structure's service life can be broadly classified into: Defect, Damage and Deterioration.

7.6.3 Symptom Categories Data

Any thorough preliminary investigation starts with a visual inspection which will usually involve an overall survey of the structure noting the occurrence and location of the principal signs of impairment or distress. The visual survey is required in order to effect a repair or rehabilitation after a distress has occurred or to assess whether immediate action is needed. It is important that the observed conditions be described in unambiguous terms so that conclusions will be based on the best observations and information available. Key indicators of problems may include features such as cracking in concrete, surface distresses and miscellaneous distresses such as those shown in detail in Table 7.3.

Table 7.3 - REPCON Database – Symptom Categories.

Cracking in Concrete	Longitudinal and generally Straight, Diagonal, Transverse, Pattern or Map, Random and Multiple (Irregularly distributed over the surface), Crazing, Cracks at Joint, Edge and Opening.
Surface Distresses	Spalling, Popouts, Scaling, Disintegration and Removal of Materials, Pothole, Honeycomb, Discoloration and Efflorescence, Joint Related Spalling or Faulting, Dusting, Polishing of Aggregate, Wear and Erosion.
Miscellaneous Distresses	Structural Related Distresses, Stratification, Segregation and Bleeding, Collapsed Member, Punchout, Rust Staining, Scouring, Dampness and Leakage, HACC (High Alumina Cement Concrete), Pitting.
Description	When the condition of a structure indicates that major repair or rehabilitation is probably necessary, a comprehensive evaluation of the structure should be required. Therefore, a visual inspection of the exposed concrete is the first step in an on-site investigation with the purpose of definition areas of distress. It is important that the conditions observed be described in unambiguous terms that can later be understood by others who have not inspected the concrete. These terms that are typically used during a site investigation, categorised into Cracking in Concrete, Surface Distresses and Miscellaneous Distresses.

One of the main problems in the diagnosis of damaged concrete is the inconsistency of the terminology in describing distress. In this research pictures are used to present modes of distress in order to overcome this problem. The user can simply compare his symptom of distress in his concrete against the pictures in the database to identify them. An example of a failure resulting from cracking in concrete is shown in Figure 7.5.

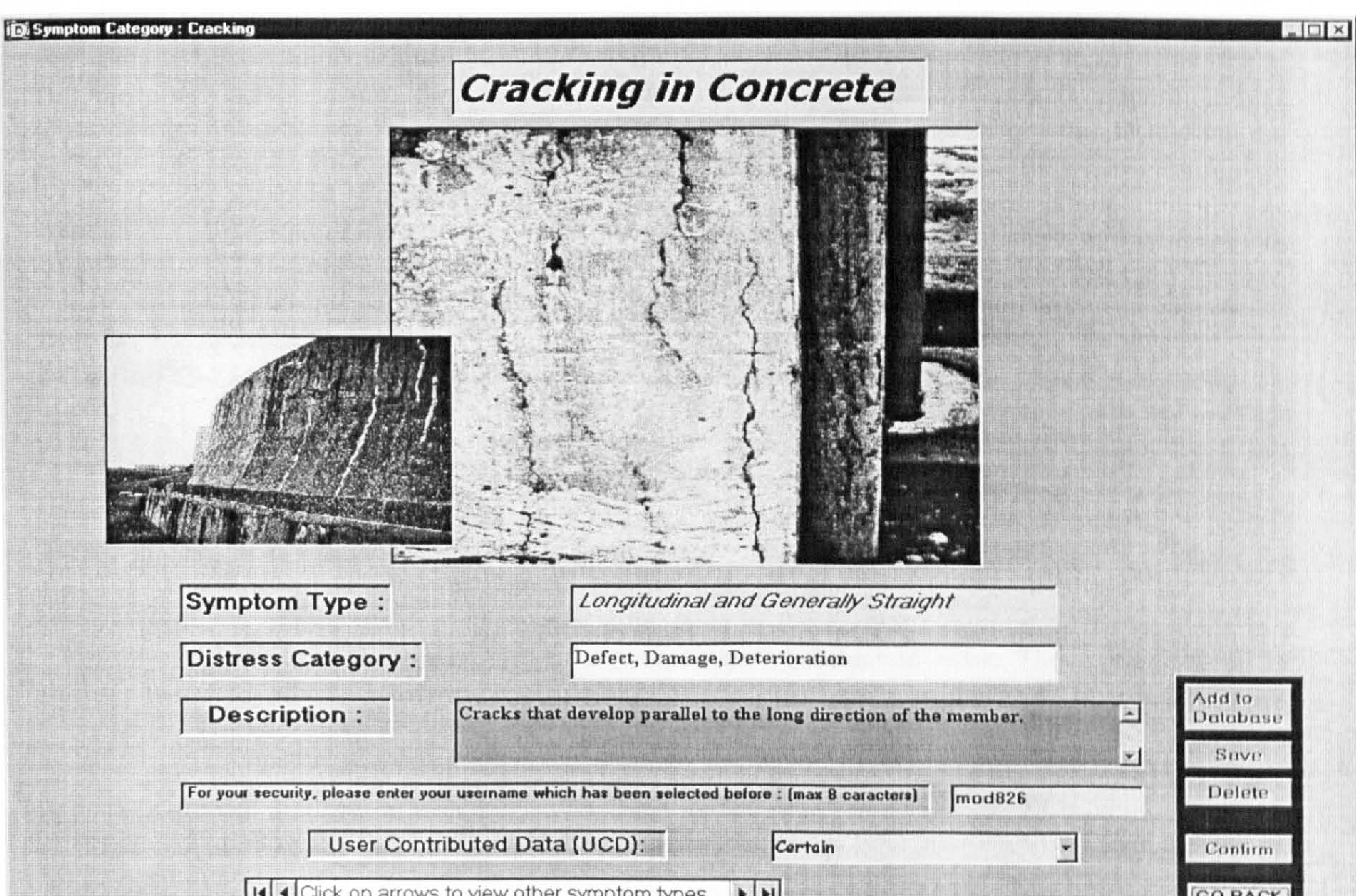


Figure 7.5 - A screen dump showing longitudinal cracking in concrete.

Identifying distresses and determining their causes are important parts of any concrete assessment program. The data available in Tables 7.2 and 7.3 is also included in the DEMAREC-EXPERT program (discussed in Chapter 8). The system assists in the diagnosis by first identifying the distress such as cracking in concrete. Then it attempts to draw a conclusion about the cause of the distress and in the selection of a durable replacement material or the proper rehabilitation method. In some cases, the expert system cannot make a determination of the cause of the distress and then recommends appropriate tests which are based upon the available data in Table 7.4.

7.6.4 Investigation and Diagnosis Data

The data shown in Table 7.4 presents information on how to conduct an evaluation of concrete in a concrete structure. This database is targeted at inexperienced users to enhance their understanding of the various items of test equipment and their use. Furthermore, in cases where the availability of the investigation equipment is a limiting factor, this database can be of assistance in evolving a procedure that is appropriate for the available equipment.

Table 7.4 - REPCON Database – Investigation and Diagnosis.

Review of Documents	Specification, Soil Report, Weather Report, Construction and Inspection Report, Laboratory Analysis of Material and Concrete Samples, Drawing (Preliminary and As-built), Interviews with Engineers, Architect, Contractor, material Suppliers, Ready-Mix Supplier, Workmanship and Client.
Visual Inspection	Cracks, Discoloration, scaling Expansion, soft Surface, Delamination, Spalling, Leaching and Staining, Making Photographs, Typical Concrete specimens for Detailed Study.
In-Situ Tests (NDT)	Schmidt Hammer Test, Pulse Velocity Test, carbonation Depth, Covermeter Test, Drilling in Depth for Chloride and Sulphate Ions, Taking of Core Samples for Laboratory Analysis, Half-Cell Potential Test, Concrete Resistivity, Crack Microscopic Examination, Pull-Out Test, Pull-Off and Tension Test, Strain Gauge for Crack Movement, In-situ Water Permeability, Moisture Measurement and Density.
Laboratory Tests	Compressive and Tensile Tests, Resonant Frequency, Density, Permeability (ISAT) Test, Cement Content, Capillary Porosity, Petrographic Examination, PH Content and Carbonation Depth, Chloride and Sulphate Content.
Description	A comprehensive and logical evaluation of the current condition of the concrete in a structure is the first step of any repair or rehabilitation work. This evaluation of the structure should be conducted to determine the scope of the work required. Such an evaluation could include the following: a review of the available design and construction documentation; a visual inspection of condition of the concrete; in-situ non-destructive tests; and laboratory tests of the concrete specimens.

A thorough review of all documents relating to a structure and the current condition of the concrete should be carried out. It is crucial to consider how design, construction, operation and maintenance have interacted over the years since the structure was designed and constructed. Visual inspection of a structure for the purpose of identifying and defining areas of distress plays a significant part in the early stages of the investigation and diagnosis process. The information derived from this part of the data is used in the evaluation of concrete (ECON) program (discussed in Chapter 9) as well as an understanding of the distress process which will enable an appropriate repair strategy to be selected.

The aim of any testing program should be to fill in the gaps in the information on the structure for a condition assessment and to assess its future performance. These may be in-situ tests comprising destructive or non-destructive tests (NDT) and/or laboratory tests carried out on retrieved samples. The principal techniques and tests available are listed in Table 7.4 and are shown in Figure 7.6.

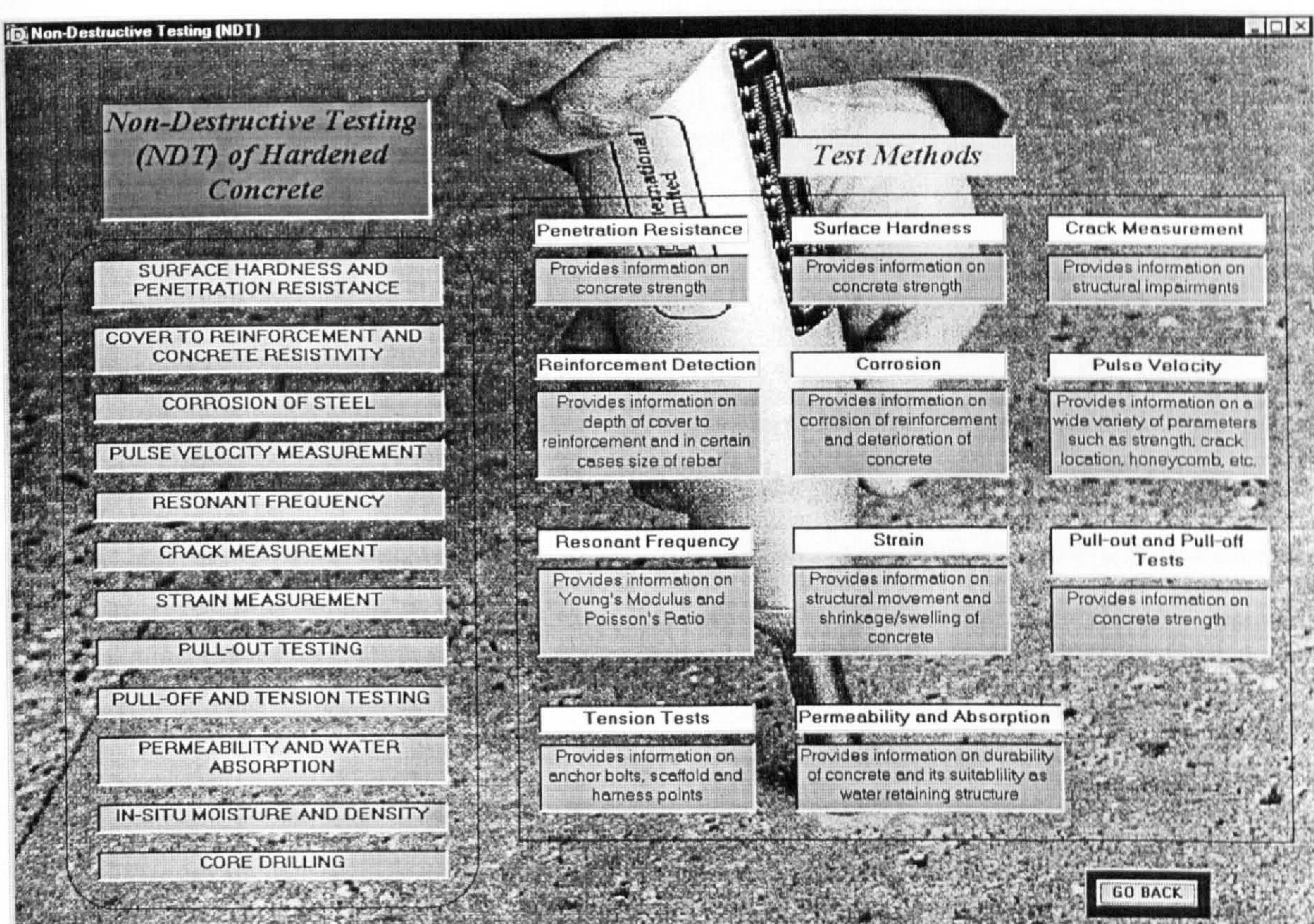


Figure 7.6 - Non-destructive testing (NDT) data screen.

7.6.5 Compatibility of Repair Materials Data

To balance the properties of repair materials with those of the original concrete for achieving durable repairs it is necessary to consider the factors affecting the selection of repair systems comprising materials and methods as part of a composite system. The critical factors that considerably govern the durability of concrete repair in practice are shown in Table 7.5. This information is useful for the education of the user.

Table 7.5 - REPCON Database – Compatibility of Repair Materials.

Physical Compatibility	Compressive, Tensile, Flexural and Shear Bond Strengths.
Dimensional Compatibility	Drying Shrinkage, thermal Expansion, Creep and Fatigue, Modules of Elasticity, Geometry of Section (Size, Shape and Thickness of the Repaired Areas).
Chemical Compatibility	Alkali Content, C_3A Content, Chloride Content.
Durability Compatibility	Permeability, Concrete-Repair Bond, Humidity in Concrete.
Electrochemical Compatibility	Corrosion.
Description	To achieve durable repairs it is necessary to consider the factors affecting the design and selection of repair systems as parts of a composite system. These factors must be considered in the design process so that a repair material compatible with the existing concrete substrate can be selected. Compatibility is defined as the balance of physical, chemical, and electrochemical properties and dimensions between the repair material and the concrete substrate.

7.6.6 Concrete Removal for Repair Data

Usually any repair or rehabilitation project will require removal of the distressed concrete except for situations where the distressed concrete does not threaten the integrity of the structure. Selection of a proper removal method may have a significant affect on the structure's reduction in service, safety, economy and on the concrete remaining in situ. The techniques shown in Table 7.6 are available to perform various aspects of concrete removal and preparation for repair.

7.6.7 Repair Materials Data

Many factors have to be taken into account when choosing an appropriate repair material. These factors depend on the cause and extent of the existing distress, constructibility, service issues and owner and engineering requirements. A variety of repair materials have been formulated to provide a wide range of properties. These can be concluded under five headings shown in Table 7.7. Final selection of materials that meet all necessary properties established by project conditions and requirements is based on the optimum balance of performance, risk and cost factors.

Table 7.6 - REPCON Database - Concrete Removal for repair.

Blasting	Explosive Blasting
Crushing	Mechanical crushing including Boom-Mounted and Portable
Cutting	Abrasive-Water-Jet Cutting, Diamond-Blade Cutting, Diamond-Wire Cutting, Stitch Drilling, Thermal Cutting
Impacting	Mechanical impacting comprising Hand-Held, Boom-Mounted, Spring-Action
Milling	Hydromilling, Rotary Head Milling
Presplitting	Chemical-Expansive Agents, Piston-Jack Splitter, Plug-and-Feather Splitter
Description	Most repair project involves removal of deteriorated, contaminated or damaged concrete to provide surfaces that will promote bonding of the repair materials. The surface preparation process is one of the most crucial phases of site work. Many techniques are available to perform various aspects of concrete removal and cleaning. These techniques may be categorised by the way, which the process acts on the concrete.

Table 7.7 - REPCON Database – Repair Materials.

Polymer Emulsions	Acrylic Latex, Epoxy Latex, Polyvinyl Acetate, Styrene-Butadiene Rubber (SBR), Co-Polymer Latex, Natural Rubber, Styrene-Acrylic, Vinyl Acetate Ethylene (VAE), Polymthlmethacrylate (PMMA), Magnesium Phosphate Modified, Polyvinyl Chloride.
Resins	Acrylic, Polyurethane, polyester, Epoxy, Low Viscosity Polyester, Low Viscosity Epoxy, Methlmethacrylate (MMA), Polyester-Styrene Co-Polymer, Chlorinated Rubber, Bituminous Materials, Unsaturated Polyester, Silicones, High Molecular Weight Methacrylate (HMWM).
Prepacked Cementitious	Ordinary Portland Cement (OPC), High Alumina Cement (HAC), Magnesium-Phosphate Cement (MPC), Expensive Portland Cement (Types K, M, S), Regulated-Set Portland Cement, Special Blended Cement, Gypsum Cement, Prepacked Patching Materials, Cement Grout.
Pozzolanic Materials	Pulverised Fly Ash (PFA), Blast-Furnace Slag-Cement, Microsilica (Condense Silica Fume), Trass, and Diatomite.
Fiber Materials	Steel, Plastic and Glass Fibers.
Description	Most repair projects will have unique conditions and special requirements that must be thoroughly examined before the final repair material criteria can be established. A variety of repair materials have been formulated to provide a wide range of properties. These materials are widely classified to polymer emulsions, resins, prepacked cementitious, pozzolanic materials, and fiber materials. The adequate selection of repair material will depend on the nature of distress, the performance of repair, and the utilisation of the structure. But selecting the correct material for a specific application requires careful study.

7.6.8 Repair Material Suppliers Data

One of the main purposes of the REPCON database is to provide storage of material specifications along with manufactures' general information and application information for repair materials in the UK. These commercial repair products comprise 210 products from 8 companies. For end-user products, the main substance category identifies the basic type of material of which the product in composed. The product users identify the type of use(s) for which the product is applicable. This table has been constructed by product name, product uses, manufactures' address and main substance. Product information provided by the manufactures is published for listing purposes only.

7.6.9 Repair Methods Data

Once the distress has been identified, several repair materials and alternative methods can be reviewed. Information relating several different methods for repair or rehabilitation of concrete structures has been gathered and stored in the database. These alternatives shown in Table 7.8 are called upon in the knowledge-based expert system section of the application. Selection of repair methods can be affected by the nature of impairment, consideration of durability, constructibility and compatibility with the existing structure, environment, availability of materials, cost and whether the repair is a temporary restoration or permanent.

Table 7.8 - REPCON Database – Repair Methods.

Miscellaneous Systems for Replacement, Repair, Strengthening and Protection Methods	Sprayed Concrete; Gunite or Shotcrete, Drilling and Plugging, Cathodic Protection, Desalination and Realkalization, Stitching, Reinforcement Replacement, Jacketing, Bonded Steel Plates, Post-tensioning, Infilling and Bracing, and Slabjacking.
Cementitious/Polymeric Systems for Replacement, Repair, Strengthening and Protection Methods	Preplaced Aggregate Concrete, Overlay, Grouting, Dry Packing, Patch/Hand Laid and Concrete Replacement (Fiber Reinforced Concrete (FRC), High Strength Concrete (HSC), Precast Concrete, Conventional Concrete, Polymer Concrete (PC), Polymer Portland Cement Concrete (PPCC), Polymer Impregnated Concrete (PIC), Roller-Compacted Concrete (RCC), Shrinkage-Compensating Concrete, Silica Fume Concrete).
Polymeric Systems for Repair, Strengthening and Protection Methods	Resin Injection, Resin Bonded External Reinforcement, Routing and Sealing, Flexible Sealing, Autogenous Healing, Protective Coating and Rendering, Blanketing, Vacuum Impregnation, Hydrophobation and Gravity Soak.
Description	Selection of repair methods and systems depends on the nature of distress, compatibility of the proposed method, environment, availability of materials, cost and whether the repair is a temporary or permanent. However, the primary procedures are classified into replacement, repair, strengthening and protection, but they may not be used directly in project specifications because each repair project may require unique remedial action.

7.6.10 Maintenance and Durability Recommendations Data

Structural and functional problems may detract from the durability, integrity and serviceability of a structure. Information shown in Table 7.9 regarding maintenance and durability of concrete structures has been stored in the database. Most of the information is taken directly from codes of practice such as the American Concrete Institute (ACI, 1996) and the British Standard Institution (BSI, 1997) publications and from technical reports published by concrete associations. This data does not interact with other database sections in anyway. It is strictly for information to inform the user who may be conducting research on developing his preliminary strategies.

Table 7.9 - REPCON Database – Maintenance and Durability Recommendations.

Physical	Accidental Loading (Impact, Earthquake), construction Error, Design Error (Inadequate Structural design, Poor Design Details), Fire, Temperature Changes, Frost Attack, Settlement and Movement, Shrinkage (Plastic, Drying), Wear and Erosion (Abrasion, Cavitation).
Chemical	Sulphate Attack, Chloride Attack, Acid Attack, Aggressive Water Attack, Wear and Erosion (Chemical).
Physical/Chemical	Freeze-Thaw Action, Corrosion of Reinforcement, Alkali-Silica Reaction (ASR), Alkali-Carbonation Reaction (ACR), Alkali-Aggregate Reactivity (AAR).
Material Recommendation	Cementitious Materials (Portland Cement, Blended Cement, Pozzolanic materials), Aggregate, Mix Water, admixture, Polymer Materials.
Description	Preventing concrete impairment is much easier and more economical than repairing distressed concrete. Preventing concrete impairment should actually begin with the selection of proper materials, mixture proportions and placement and curing procedures. If additional protection against impairment is required, the need should be recognised and provided for during design of the structure. Thus, there is generally a need for follow-up maintenance action. The primary types of maintenance for concrete include timely repair of cracks and spalls, cleaning of concrete to remove unsightly material, surface protection, and joint restoration.

7.7 Manipulating Pictures in Database

Pictures are used as visual aids in the selection of parameters in the diagnosis, evaluation, maintenance and repair of concrete structures. Each set of pictures represents available options in structural and construction systems, concrete distresses, symptom categories, investigation and diagnosis, compatibility, repair methods, and maintenance and durability recommendations.

Loading a picture into the database at design time resulted in an object of OLE (see Section 6.2) data type being stored in the database. These OLE objects could be loaded into the Visual Basic Graphic User Interface (GUI) through the data control. Whereas, the ability to add pictures at run time was a major requirement in this application, loading a picture resulted in a long binary data format of the picture being stored in the database.

There are two methods used for loading pictures at run time, one a crude method and the other a more refined one. In the crude method, a picture is loaded into a picture box which is linked through a data control to an OLE field in the database. As the data control moves its focus to the next record in the field, the current field is updated automatically and in doing so the current picture in the picture control is loaded into the picture box.

In the more refined method, the picture is loaded into the Visual Basic picture control from the source application then saved into the database using the standard Visual Basic "*Appendchunk*" procedure. In this procedure the file is appended into the database field in chunks of 64kb. Therefore, the solution was to store all the pictures in their long binary form instead of OLE data type so that all pictures in the picture databases could be loaded at runtime.

7.8 Add New Knowledge to the Database

The REPCON management system allows an experienced user to contribute experience and knowledge to the database. The heart of this system is the concept of confidence level (CL) which deals with users' skill level and with the integrating of the data being contributed by them. By providing a quantitative and consistent means for evaluating both new data and the person contributing it, the confidence level (CL) allows new knowledge and experience to be gathered and monitored over time.

To contribute new data to the system, a self-assessment process has been included in order to assess the competence of the user. By allowing new data to be added, the system evolves in line with the state of the art of concrete repair. Indeed, the existence of the database will become a catalyst to the development of knowledge and experience in the field of concrete repair. This is one of the main aims in the development of the system.

For instance, to add new data to the *Damage* Section, select the *Distress Categories, Damage* option in the main database screen. The damage category screen appears and the system allows the data to be added and also to select any part of the data to be viewed. To add new data, click on the *Add to Database* button. After editing the new data, click on the *Save* button and a confirmation box is displayed comprising the information about the user, his skill level and a breakdown of previous added data (Figure 7.7). The system also allows a second expert user to be able to subsequently relegate data to a secondary storage site by using the *Delete* button if, for example, it was superseded.

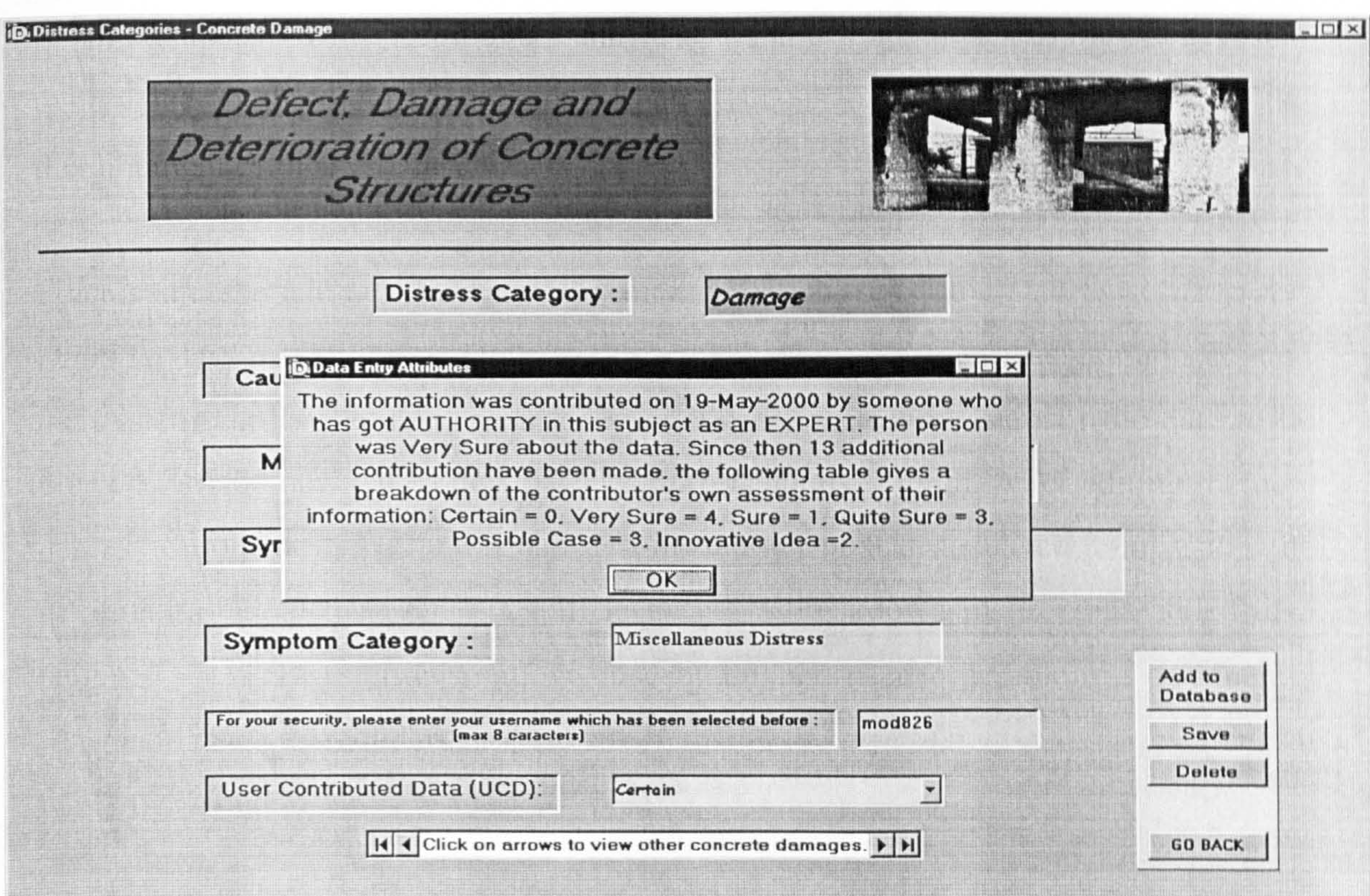


Figure 7.7 - A screen dump showing added new data to *Damage* Section.

7.8.1 Self-Assessment Process

If the user wants to contribute his/her experience and knowledge and add them to the database, he/she has to take a short test by clicking on *Self-Assessment* process in the main database screen in order for his/her competence to be assessed. The process comprises five questions which are randomly chosen from over 20 questions, relating to distresses in concrete such as:

- Sulphate attack
- Alkali-Silica Reaction (ASR)
- Plastic and drying shrinkage
- Freezing and thawing action
- Corrosion of reinforcement
- Alkali-Aggregate Reactivity (AAR)
- Creep
- Early thermal contraction
- Frost attack
- Unsuitable construction methods
- Stresses induced by shear forces
- Poor placement of reinforcement

The self-assessment environment is shown in Figure 7.8. Depending on how many questions have been answered correctly, the REPCON management system assesses the ability of the user and thereby assigns him/her a skill and confidence level (CL).

For instance, if all of the questions have been answered correctly, the contributor skill level screen will be presented (Figure 7.9) and user's level of knowledge has been assessed as an Expert who can see the original database and also take his data out of the appendix and put it in the database.

7.8.2 The Confidence Level (CL) for Contributor's Self Assessment (CSA)

The heart of the REPCON Management System is Confidence Level (CL), which is a numerical assessment of the skill of the user. The criteria for a contributor's self assessment (CSA) are shown in Table 7.10. The skill level depends on how many questions the user can answer correctly and is graded from 0 to 5. The REPCON confidence level (CL) extends from 0 to 100, with 0 indicating someone who has no

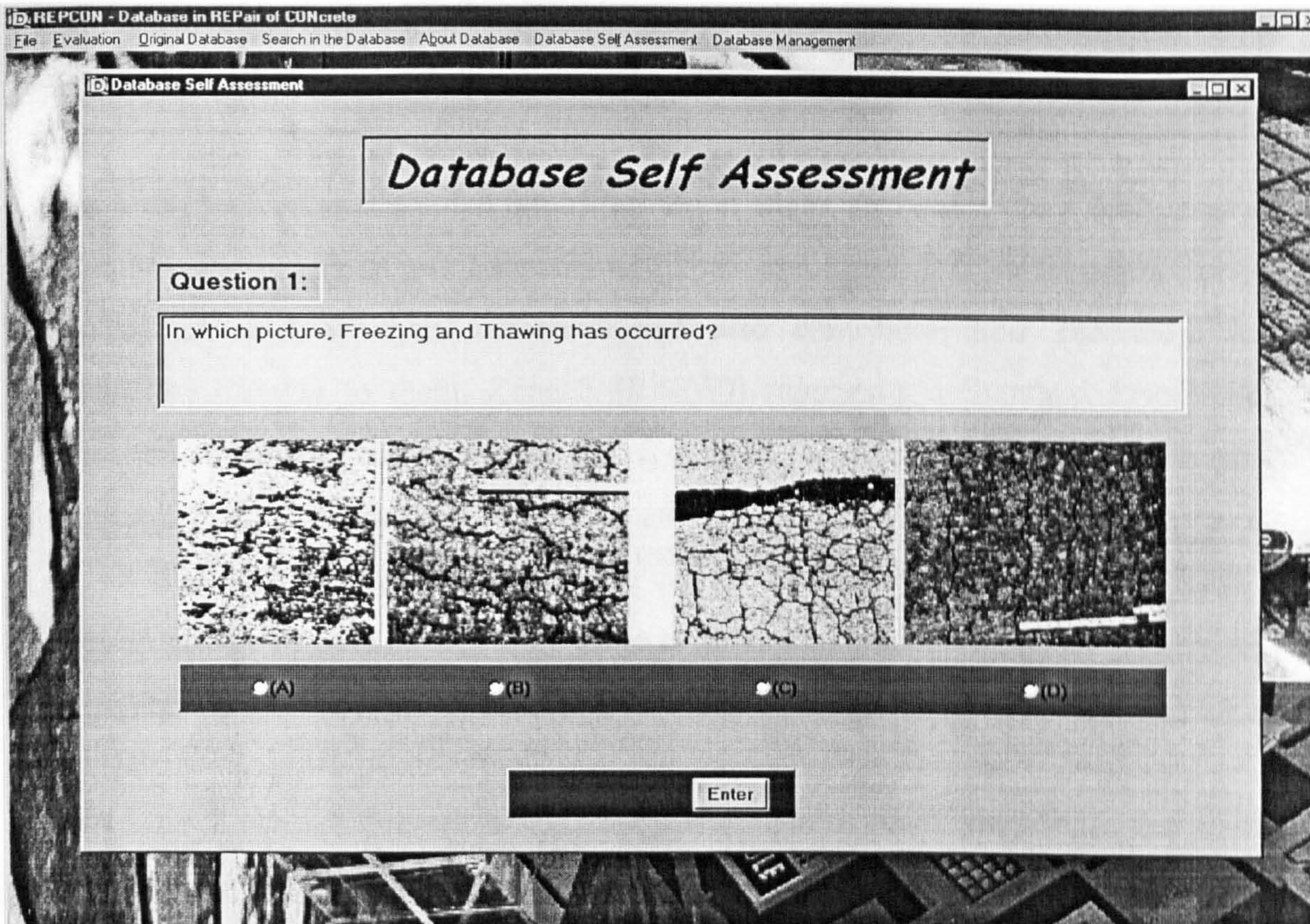


Figure 7.8 - A screen dump of the self-assessment environment.

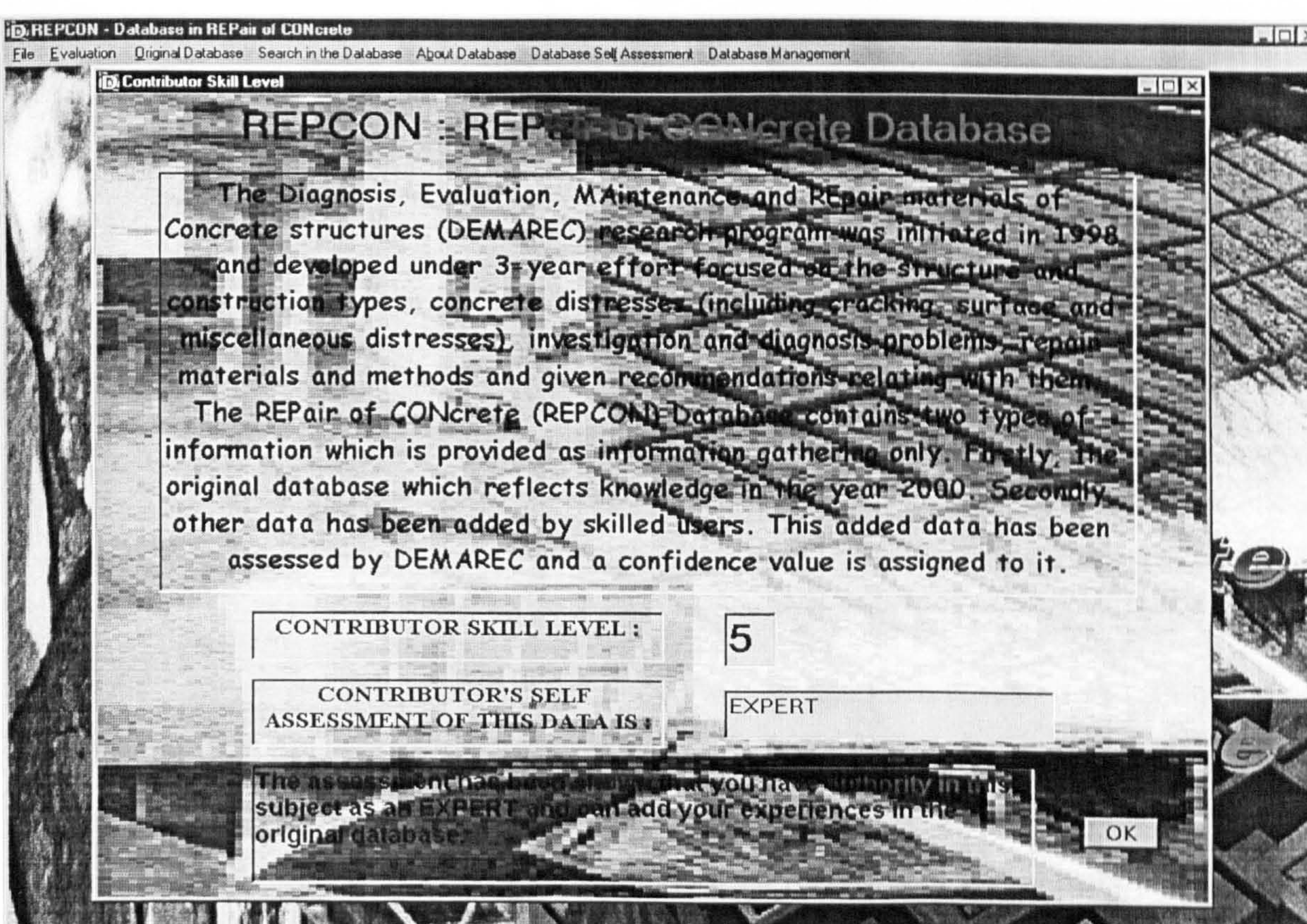


Figure 7.9 - Contributor skill level screen.

experience (a novice) and 100 indicating a user who has authority in the subject as an expert.

The confidence level is divided into three action zones. In Zone 1 (76 – 100), a user's level of knowledge has been assessed as Expert and Specialist. Such people can see the original and appendix databases and also contribute their knowledge and experience directly to them. Zone 3 (0 – 50) represents a Standard Practitioner, Trainee and Novice whose use of the system is restricted to viewing the original database. Zone 2 (51 – 75), represents an Experienced Generalist who may be an expert in a related subject. Such a person can see the original and appendix databases and can also contribute his/her knowledge to an appendix database which an expert or specialist can later upgrade to full database status.

Table 7.10 - The REPCON confidence level (CL) for contributor's self assessment (CSA).

Zone	Skill Level	Confidence Level (CL)	Confidence Description	Recommended Action
1	5	91-100	**EXPERT:** Authority in the subject.	See the original and Appendix REPCON Database and add my knowledge to them.
	4	76-90	**SPECIALIST:** Significant experience in the subject.	
2	3	51-75	**EXPERIENCED GENERALIST:** Expert in related subject seeking to transfer expertise to the subjects in hand	See the original and Appendix REPCON Database and add my knowledge to Appendix Database.
3	2	31-50	**STANDARD PRACTITIONER:** Some experience in the subject.	See the original REPCON Database.
	1	11-30	**TRAINEE:** Limited experience in the subject.	
	0	0-10	**NOVICE:** No experience in the subject	

The registration process is automated once the user has been assessed as falling into zones 1 or 2. This process has been completed by the user completion details in the feedback form. The user must enter information into all of the fields and choose a username. This username is unique to him/her and is required for contributions' data and will be also used for next sections.

7.8.3 The Confidence Level (CL) for User Contributed Data (UCD)

Another important component of the REPCON management system is the quality assessment of user contributed data (UCD) shown in Table 7.11. UCD is a numerical indicator and descriptive function of the new added data. A confidence level (CL) must be chosen and entered in a prepared field when the user wants to contribute his/her knowledge and experience to the database (see Figure 7.7). The quality level extends from 0 to 100 with 0 representing hypotheses and 100 representing accepted state-of-the-art information.

Table 7.11 - The REPCON confidence level (CL) for user contributed data (UCD).

Zone	Confidence Level (CL)	Confidence Description	Sources of Information
1	91-100	**CERTAIN:** Accepted state-of-the-art information.	Codes of practice and manuals.
	76-90	**VERY SURE:** Significantly established information in general practice.	Textbooks and technical reports.
2	51-75	**SURE:** Accepted information, which is growing in acceptance.	Journals and conference proceedings.
3	31-50	**QUITE SURE:** Recommended information and being used tentatively.	Information from internet and professional reports.
	11-30	**Possible Case:** Proposed idea but questioned by someone.	Self-generation and persons contributing unsure information.
	0-10	**INNOVATIVE IDEA:** Hypotheses supported by some evidence.	Just an idea.

The confidence level (CL) is divided into three zones. In zone 1 (76 – 100), the information has been elicited from well-tried codes of practice, manuals or textbooks. In this zone, the confidence levels are Certain and Very Sure. In Zone 2 (31 – 75), Sure and Quite Sure confidence levels have been used for information which is being elicited from journals, conference proceedings and professional reports. The confidence levels of Possible Case and Innovative Idea in Zone 3 (0 – 30), have been introduced for people contributing unsure information or ideas.

7.9 Summary

In this Chapter the use of a database in the diagnosis, evaluation, maintenance and repair of concrete structures has been presented. It has been demonstrated that combining pictures and technical data can be used in a way that makes decision and problem solving easier. The value of visual assistance is in eliminating the misunderstanding that often arises from the varying terminology used in the repair of concrete structures.

More importantly the REPair of CONcrete (REPCON) database is developed to provide technology transfer of information from experts and specialists to other practitioners and vice versa and it provides a common forum for communication between clients, architects, engineers and contractors. Therefore, it is a useful guide to everyone who deals with concrete repair problems. It is an excellent first hand reference guide for a wide range of concrete repair problems leading to accurate diagnosis, the selection of appropriate repair materials and techniques and durable repair recommendations.

The database plays a major role in the education mode of this application. In this mode, an inexperienced user can have access to the data in the database to develop a better understanding of the repair of concrete technology.

One of the innovations in this application is the use of pictures as a basis for the diagnosis of distress in concrete structures. In this mode, the types of distress are represented by pictures. This is expected to solve the problem of inconsistency of terminology in describing modes of distress. This enables even the inexperienced user to diagnose a damaged concrete component by comparing the distress of the concrete against the pictures in the database.

In the evolution mode of the application, the nature of the impairment, repair and maintenance of concrete structures within the extent of the database management system (DBMS) has been assessed. There is a major need for organising, storing and including more effective information and a long-term quality assured information source through the appropriate use of information transfer and a database management system (DBMS).

The REPCON Management System is designed to evolve as the concrete repair community interacts with it. Not only will it include readily available up-to-date information, it should encourage the more rapid development of knowledge and experience in the field of concrete repair. Therefore, this computerized management system could provide an improved and consistent method for evolving each original database and should become a forum for the exchange of expert opinions in this field.

In the diagnostic mode of the application, the inexperienced user can use the data and pictures in the database to assist him/her in the diagnostic process while experienced users can evaluate the performance of the expert system (DEMAREC-EXPERT) by storing their own solution alongside the pre-existing expert system solutions for use by subsequent users. It helps the knowledge engineer to improve the problem solving capability of the expert system by abstracting knowledge from the database. This mode is discussed in detail in Chapter 8.

One of the uses of this application is a thorough evaluation of the current condition of the concrete in a structure. In the evaluation mode, it is important that the conditions observed be described in unambiguous terms that can be used by the user to be able to take engineering and management actions for the repair and maintenance of the structure. The evaluation mode of the application is discussed in Chapter 9.

Chapter 8

DEMAREC-EXPERT: Knowledge Base Representation

8.1 Introduction

In Chapter 7 the structure of the REPCON database comprising its contribution towards the repair of concrete structures is presented. In the DEMAREC software, a database management system works in collaboration with an expert system to solve repair problems. The architecture of the DEMAREC application is shown in Figure 6.1. One of the major goals of the DEMAREC research program is to improve the performance and durability of concrete structures. The role of the expert system in this application is to assist the user in formulating the problem and generating possible solutions of the problem.

The aim of this Chapter is to explain the role played by the expert system component of DEMAREC-EXPERT. This program is created to disseminate knowledge of the concrete distresses and recent advancements in concrete repair problems. DEMAREC-EXPERT is designed to assist civil engineers in three principal areas: 1) diagnosing distresses in concrete structures; 2) assessment of conditions and 3) obtaining recommendations on materials and procedures for repair and rehabilitation.

An overview of the architecture of the expert system environment is discussed in detailed in Chapter 3. Chapter 8 presents the structure of the DEMAREC-EXPERT system which consists of the purpose and scope of the system, its development and implementation, the knowledge acquisition process, the knowledge domain and writing the knowledge bases. The interface between the components of the DEMAREC application is presented in Chapter 6.

8.2 Repair of Concrete and Expert Systems

The repair of concrete structures is complex owing to the need for an accurate assessment of structural conditions and causes of impairment, the level of expertise required for the repair design and specification and the variety of site operations which usually involve the use of specialized materials and methods. Despite these problems, structural engineering has contributed with more or less successful decisions concerning the design and construction of repair or rehabilitation works to existing concrete structures.

Advances in computer hardware technology and software development make it feasible to develop expert systems that are an effective decision-making tool for concrete structures in diagnosing distresses and in making decisions related to the selection of repair and rehabilitation techniques and materials. Computerized systems can be developed that integrate various types of knowledge used in concrete repair such as pictures, drawing, databases, guides and specifications. The knowledge contained in DEMAREC-EXPERT is designed to address diagnostic-related issues and identification and repair or rehabilitation recommendations.

A survey of many of the existing prototype and operational expert systems that have been developed for the repair and maintenance of concrete structures is presented in Chapter 3. This survey identified the three most active areas for concrete structures including concrete design, condition assessment and repair and rehabilitation. Expert systems can aid the designer in the selection of proper constituents for concrete and can assist in design for specific environments, provide information for concrete mix design and can be points of reference to acceptable design practices.

The application of expert systems to diagnostics and repair activities is of benefit to concrete structure inspectors, engineers and decision-makers. It can assist the user in identifying the distresses, diagnosing the cause of impairment, recommending various repair strategies and providing information for budgeting, planning and life-cycle-costs. The application of expert systems in this area is growing rapidly because of enhanced durability thereby reducing maintenance and repair costs, the loss of highly-qualified engineers and advances in data-gathering methods.

8.3 Purpose and Scope of the DEMAREC-EXPERT System

The DEMAREC-EXPERT system is designed to assist engineers in diagnosing distresses and in the assessment of current conditions in concrete structures. It is coupled to an independent database management system (REPCON) for obtaining recommendations on materials and procedures for repair and rehabilitation methods. Recognizing the importance of transferring information to practising concrete engineers, every effort is made to incorporate new concrete technology in the DEMAREC-EXPERT system. The knowledge domain and target user for DEMAREC-EXPERT is illustrated in Figure 8.1.

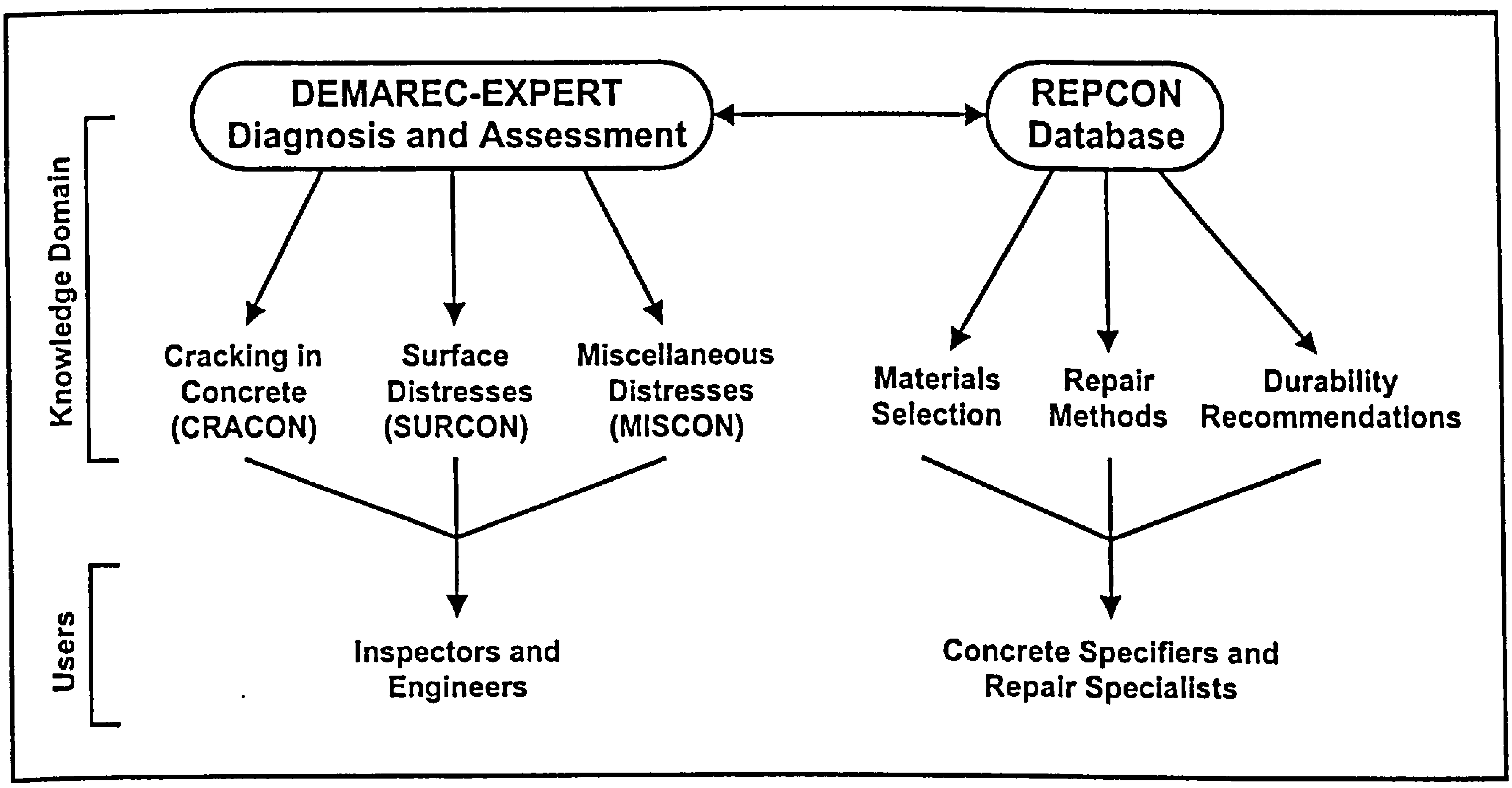


Figure 8.1 – DEMAREC-EXPERT knowledge domain and users.

Examples of distress that occur in concrete structures are those that are induced as a result of exposure to adverse environmental conditions e.g. sulphate attack and freezing and thawing action. For the durability recommendations, knowledge regarding the selection of concrete constituents for different environments is included. Material selection and repair methods include knowledge that relates to the selection of materials and procedures for various repair and rehabilitation methods.

An important factor in developing the DEMAREC-EXPERT was the need to limit its scope so that design criteria can be applied effectively. The system initially accomplishes well-defined goals and then allows for the addition of new knowledge as it becomes available or as the system matures. Such additions would make the system more comprehensive and useful for concrete decision making for both the present and the future.

DEMAREC-EXPERT is designed to assist various users in the field. For instance, it is expected that field inspectors or engineers would use its concrete diagnostics parts (CRACON, SURCON or MISCON) to identify distresses and to determine their causes. The concrete repair and rehabilitation methods would be useful to concrete designers who need recommendations regarding materials and methods for concrete needing repair or rehabilitation. The durability recommendations are useful for anyone involved in concrete repair problems. DEMAREC-EXPERT is considered as a decision-making tool and to be a comprehensive computerized expert system that gives recommendations on concrete structures.

8.4 DEMAREC-EXPERT Development and Implementation

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 which normally takes longer to develop systems using with them. Conversely, expert system shell programs tend to take less time for development and they contain development tools to assist the developer. The M.4 development tool used to develop the DEMAREC-EXPERT is an example of commercial software available and is discussed in Section 3.10.

The fundamental components of an expert system comprising the knowledge domain and the inference engine are presented in Chapter 3. One of the most significant changes in expert systems' architecture is the representation of the knowledge within the computer and its interrelationships. Development tools in use today make use of multiple knowledge representation such as production rules and semantic networks which is often called a hybrid system (see Section 3.6). Object-oriented system as a hybrid system uses multiple inference techniques, both backward chaining and forward chaining inference, discussed in Section 3.7 and allow the knowledge engineer to draw relationships between knowledge components, attach facts and establish inheritance within the knowledge structure. An example taken from the DEMAREC-EXPERT is illustrated in Figure 8.2. The information contained in the ellipses shows the path the system would follow to reach the goal of being "*caused by insufficient cover of reinforcement*". In this example the object attribute "*crack pattern and direction*" is defined and its relationships are established to culminate in "*cracks are caused by corrosion of reinforcement*".

DEMAREC-EXPERT is a knowledge-based expert system which contains all the parts of a typical expert system program (discussed in Chapter 3). The structure of the DEMAREC-EXPERT system shown in Figure 8.3 comprises M.4 as an expert system development shell, knowledge bases, the Visual Basic user-friendly interface and report generation modules. The DEMAREC-EXPERT consultation flowchart is shown in Figure 8.4. The user can read the parameters and answer the questions through the Visual Basic user interface as shown in Figure 8.5. In some of the questions, the user can seek visual assistance in selecting an option by clicking on the *Assist* button. This button activates the picture database enabling the user to view them. The M.4 expert system (see Section 3.10) accesses the knowledge bases and based on the input variables makes a decision. The results are stored as codes in a separate text file and then decoded and fed into the user interface in where the user can review the result. The system is independently coupled to the REPCON database for taking recommendations in durability, repair materials and methods.

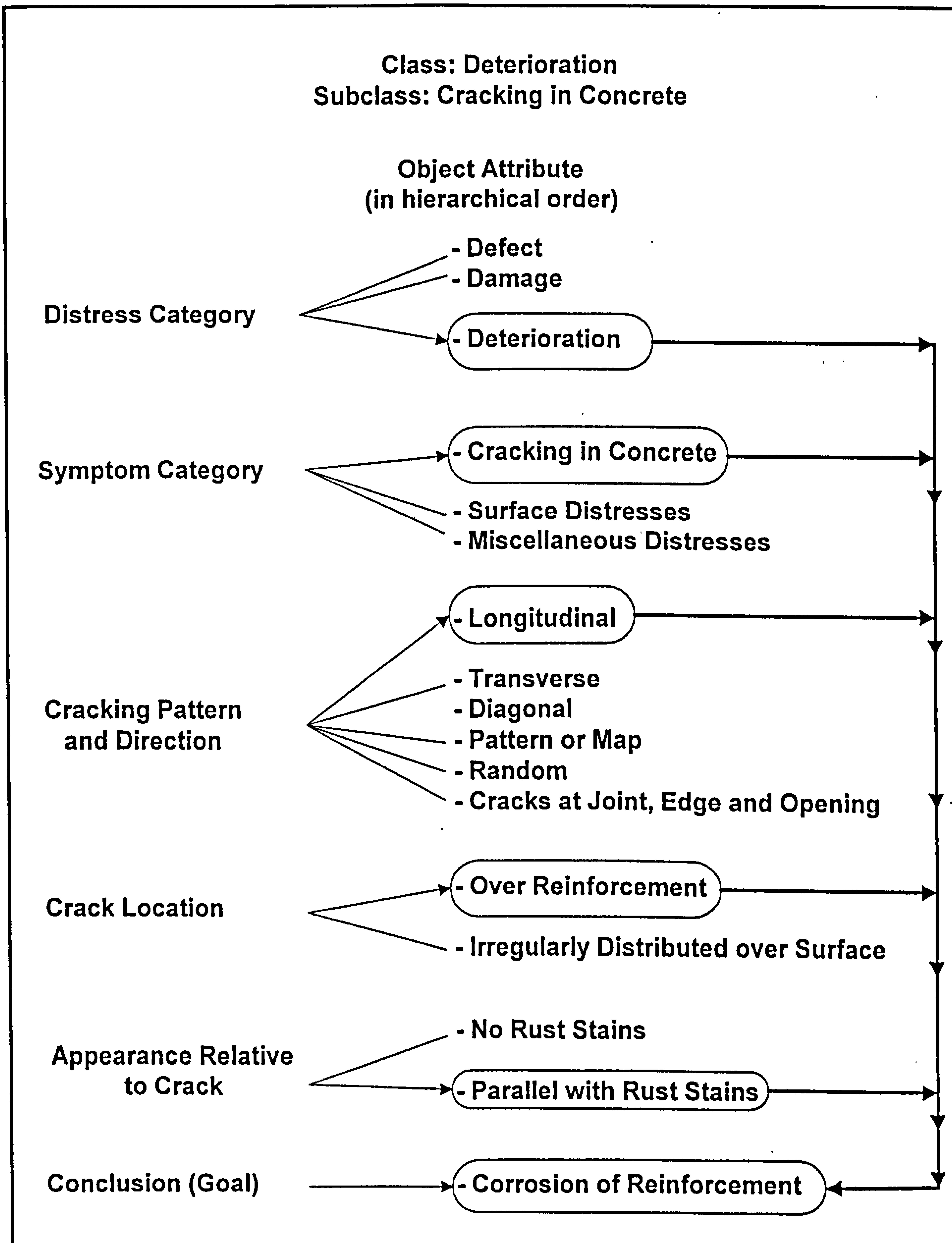


Figure 8.2 - Illustration of an object-oriented knowledge structure.

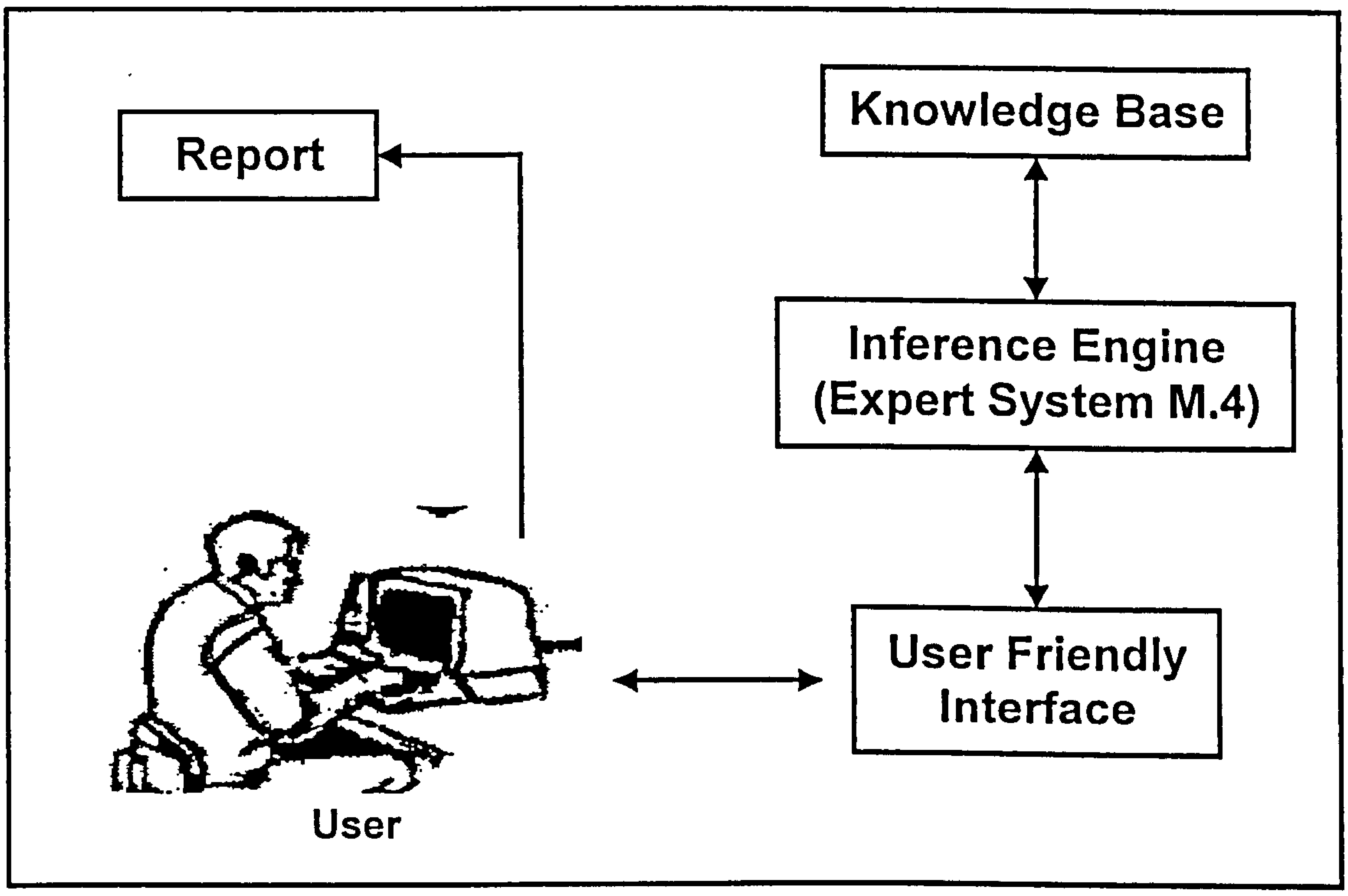


Figure 8.3 - Interaction between the different modules of the DEMAREC-EXPERT.

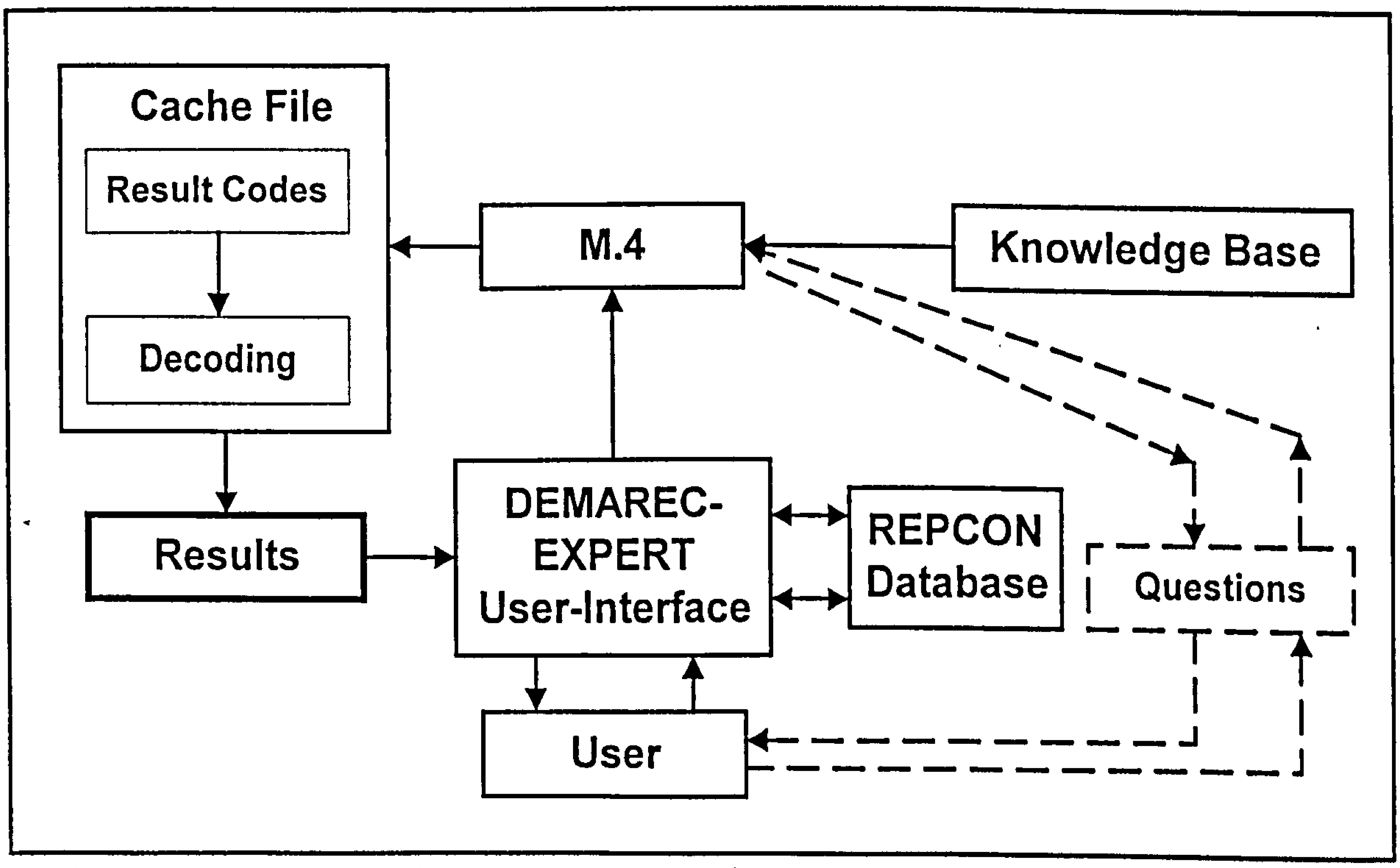


Figure 8.4 - DEMAREC-EXPERT consultation flowchart.

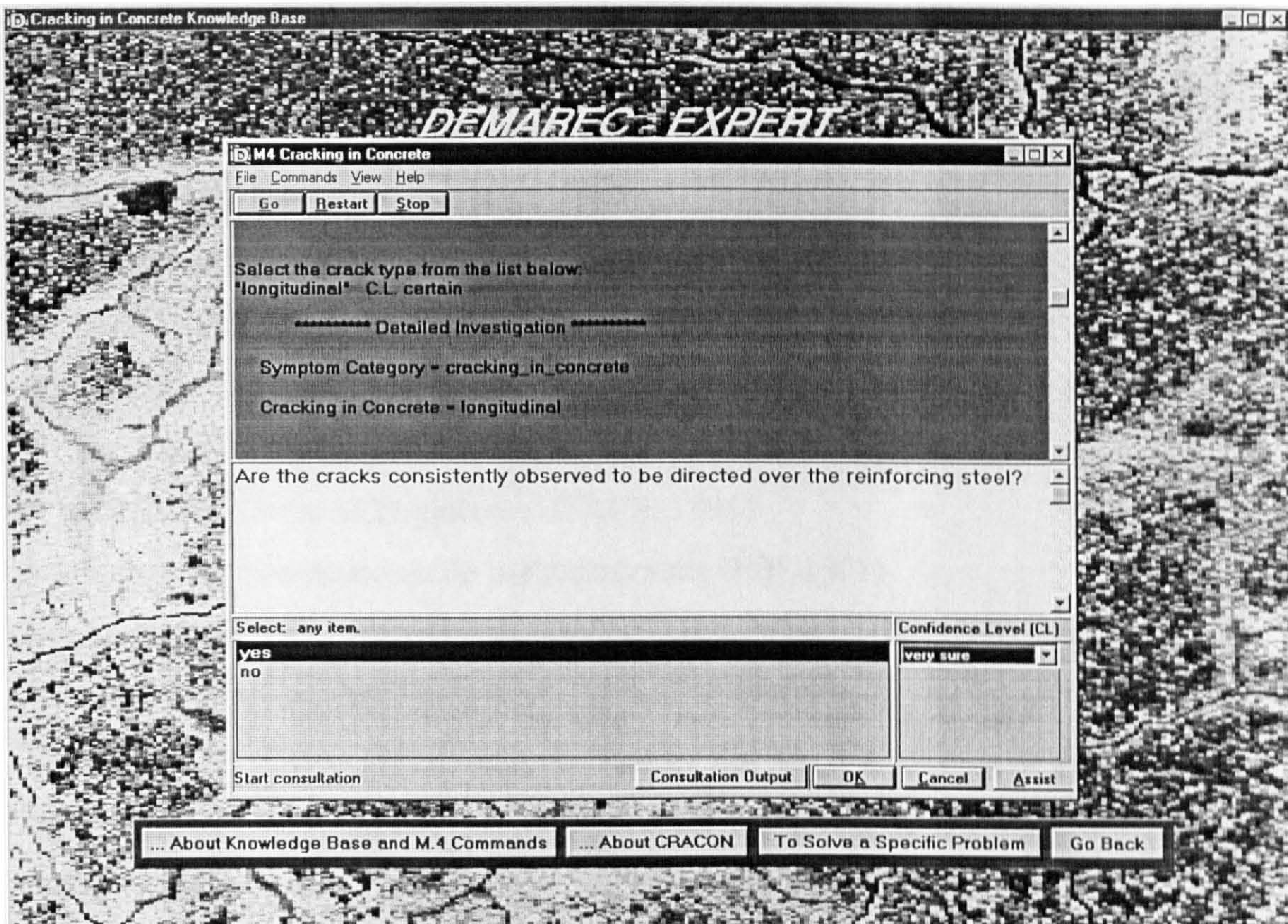


Figure 8.5 - A screen dump of M.4 Visual Basic user interface.

8.5 Knowledge Acquisition Technique

In the development of an expert system, knowledge acquisition is a crucial aspect of developing a knowledge base and it is important that the source of knowledge for any system is carefully selected. The knowledge bases for DEMAREC-EXPERT are developed using what are considered to be best sources available during the development stage. Sources are investigated and used based on the analysis and interpretation of high-level experts. Because of the vast amount of knowledge and the need to assess its validity, acquiring and validating the knowledge is the most crucial and difficult part in the development of an expert system.

For this purpose, the use of multiple sources is considered in developing the DEMAREC-EXPERT knowledge bases. They have been obtained from literature searches, codes of practice, manuals, textbooks, technical reports, journals and conference proceedings, civil work reports and experienced concrete specialists. Most of the knowledge is directly taken from the following major organisations:

- American Concrete Institute (ACI, 1996)
- British Standard Institution (BSI, 1997)
- American Standard Testing for Materials (ASTM, 1980)
- International Concrete Repair Institute (ICRI, 1992; 1996)
- RILEM Draft Recommendation (RILEM, 1994)
- The Concrete Society (2000)
- U.S. Army Corps of Engineers (USACE, 1995)
- Federation Internationale de la Precontrainte (FIP, 1991)
- Strategic Highway Research Program (SHRP, 1994)

The initial step of the development strategy for the knowledge base is to organise the knowledge and then modified it by the author's experience using the approach an expert would take to address the problem or activity. Secondly, a narrative description of the knowledge is developed in a question-and-answer format and conclusions and recommendations are also included at this stage. Then the diagnostic (hierarchical) trees are generated to provide a logical sequence to the knowledge and to represent how the knowledge is linked together. The integrity of the knowledge base lies in the development of the diagnostic trees. The pieces of knowledge in the diagnostic trees are arranged in a manner allowing for an uninterrupted flow of knowledge upon completion of the tress.

The diagnostic tree provides the source document for converting the knowledge to question-and-answer display, explanatory display and for developing the systems rules and procedures. It is also useful as a synopsis for experts and reviewers to review since it provided a *"road map"* for the knowledge contained in the system. Therefore, the sequence of acquiring the knowledge and developing the prototype involved determining the scope of the knowledge to be contained in the category, evaluating the literature, developing the diagnostic (hierarchical) tree and finally developing the computerized version using the expert system development shell program.

This format is made to reflect the most effective method and best knowledge available. Bibliographic references are also included in each of the DEMAREC-EXPERT knowledge bases. These are referenced in explanatory, conclusion and recommendation display. Push buttons contained in the help facility of each knowledge base provide access to a bibliography for the knowledge area which might assist users in further investigation and analysis.

8.6 Knowledge Domain

The Diagnosis, Evaluation, MAintenance and REpair materials in Concrete structures EXPERT system, DEMAREC-EXPERT is a new intelligent computer system which helps the user to select the types of distress which might have occurred. The system gathers information concerning the user's visual inspections and knowledge about the structure and then gives possible causes of the distress. The system also recommends the selection of materials and procedures concerning the concrete repair.

The knowledge contained in DEMAREC-EXPERT includes information and rules on the three categories of distress in concrete structures. Knowledge about cracking in concrete (CRACON) is included to identify the various causes related to cracking that occurs in concrete structures. CRACON attempts to diagnose the cause of cracking. Knowledge related to surface distresses in concrete structures is included in the SURCON knowledge base. In addition, a separate module is developed to address miscellaneous distresses in concrete structures. These distresses can be diagnosed in the MISCON knowledge base. The categories of distress and sub-categories covered by each of them in DEMAREC-EXPERT are shown in Figure 8.6. Tables 8.1 through 8.3 show the distress categories and types along with the cause or probable causes that are included in DEMAREC-EXPERT.

Identifying distresses and determining their causes thereby assisting in the design of durable replacement material or adequate repair methods are important parts of any concrete repair program. It is important to draw conclusions based on the best observations and information available in order to effectively rehabilitate a structure. This information may be obtained from visual inspection observations by an engineer or may be taken from pictures and databases. In some cases, it may be taken from in-situ tests (e.g. non-destructive testing (NDT)) or laboratory tests (e.g. petrographic examination).

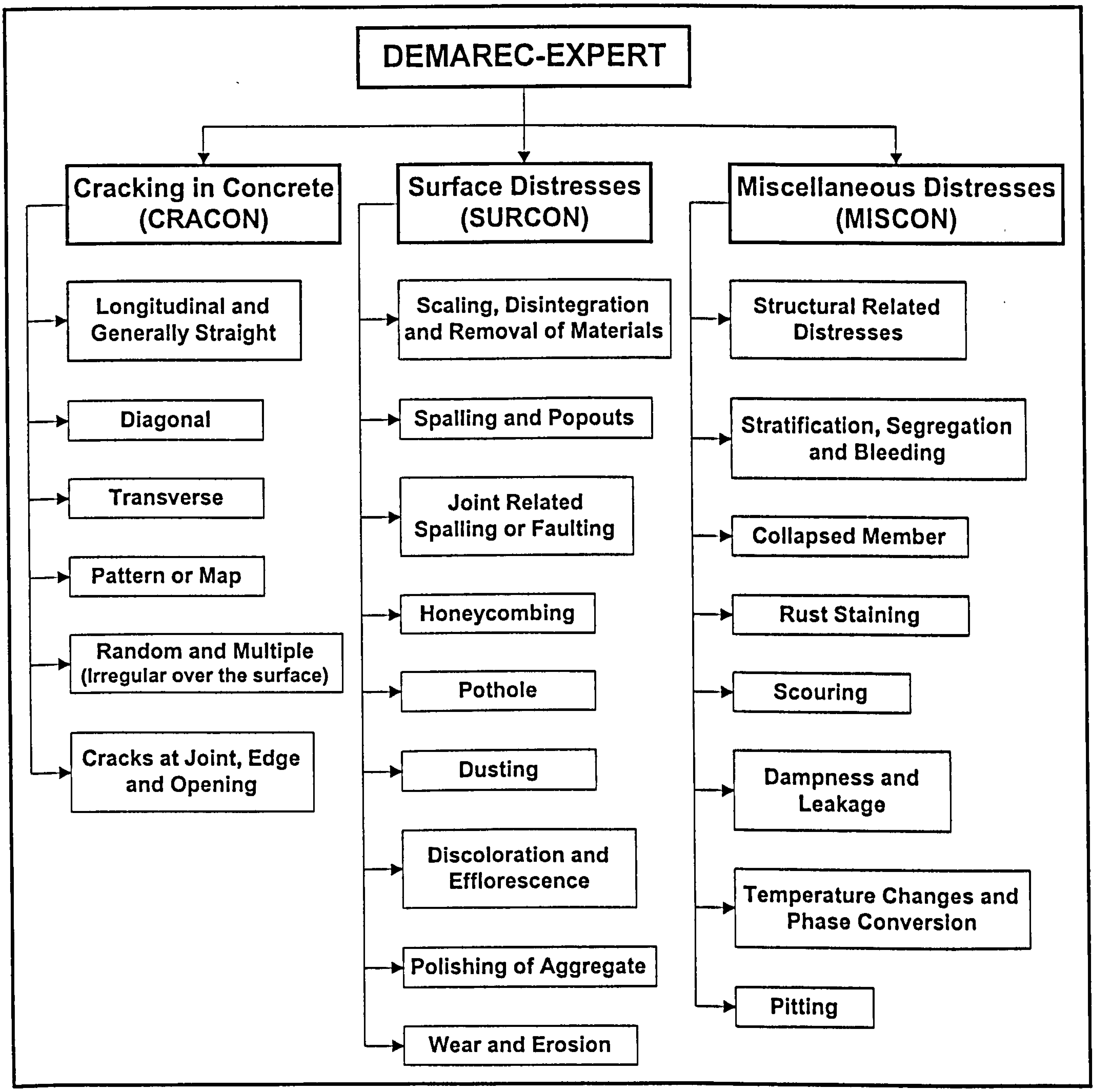


Figure 8.6 - Diagram of DEMAREC-EXPERT knowledge bases.

DEMAREC-EXPERT assists in the diagnosis by first identifying the distress such as map or pattern cracking, scaling or spalling. Then it attempts to draw a conclusion about the cause(s) of distress and, in some cases recommends appropriate tests to determine the cause of the distress. The data available in the REPCON database can assist the user in researching information regarding additional investigation and in-situ and laboratory tests.

Table 8.1 - Cracking in concrete distresses and their associated causes covered by DEMAREC-EXPERT.

Type of Distress	Cause of Distress or Probable Causes
Longitudinal and Generally Straight	Corrosion of reinforcement, Plastic shrinkage, Drying shrinkage, Plastic settlement, Alkali-Aggregate Reactivity (AAR), Alkali-Silica Reaction (ASR), Alkali-Carbonate Reaction (ACR), Frost attack, Sulphate attack, Creep, Compression forces, Early thermal contraction.
Diagonal	Plastic shrinkage, Shear forces, Ground movement, Foundation settlement, Drying shrinkage, Torsion forces, Dead and live loads structural deformation, Restraint to load deformation.
Transverse	Combination of dead and live loads, Drying shrinkage, compressive stresses.
Pattern or Map	Unsuitable construction method, Unsuitable materials, Freezing and thawing action, Sulphate attack, Plastic shrinkage, Drying shrinkage, Alkali-Aggregate Reactivity (AAR), Alkali-Silica Reaction (ASR), Alkali-Carbonate Reaction (ACR), Frost attack.
Random or Multiple (Irregular over the surface)	Ground movement, Plastic shrinkage, Sulphate attack.
Cracks at Joint, Edge and Opening	Corrosion of reinforcement, Lack of expansion joint, Compressive failure (blow-up), Poor joint construction, Thermal expansion, Poor load transfer, Loss of subgrade, Late sawing of joint, Corner break, Omission of bottom crack inducer, Frost attack, Sulphate attack, Alkali-Aggregate Reactivity (AAR), Alkali-Silica Reaction (ASR), Alkali-Carbonate Reaction (ACR).

Table 8.2 - Surface distresses and their associated causes covered by DEMAREC-EXPERT.

Type of Distress	Cause of Distress or Probable Causes
Scaling, Disintegration and Removal of Materials	Corrosion of reinforcement, Chloride attack, Sulphate attack, Freezing and thawing action, Frost attack, Weak concrete surface, Unsuitable construction method.
Spalling and Popouts	Corrosion of reinforcement, Chloride attack, Sulphate attack, Freezing and thawing action, Frost attack, Weak concrete surface, Unsuitable construction method, Generating sufficient stresses, Alkali-Aggregate Reactivity (AAR), Alkali-Silica Reaction (ASR), Alkali-Carbonate Reaction (ACR).
Joint Related Spalling or Faulting	Poor consolidation of concrete, Improper steel placement, Reinforcement rupture, Improper construction method, Foundation settlement, Corrosion of reinforcement.
Honeycombing	Unsuitable construction method, Lack of vibration of concrete, Poor design of formwork.
Pothole	Localized poor concrete, Poor consolidation of concrete.
Dusting	Poor construction method such as sprinkling water on concrete surface during finishing, New timber formwork.
Discoloration and Efflorescence	Poor construction method owing to very permeable concrete.
Polishing of Aggregate	Poor skid resistance of concrete.
Wear and Erosion	Inadequate construction method, Environmental changes, Poor abrasion resistance, Chemical attack, Poor quality of concrete, Poor resistance of aggregate.

8.7 DEMAREC-EXPERT Knowledge Bases

The ability of an expert system to solve a problem has been observed to increase with the extent of its domain knowledge. Undoubtedly the most demanding phase of developing an expert system is obtaining and representing relevant knowledge. DEMAREC-EXPERT consists of three knowledge bases, each of which contains information on the various types of distress in concrete structures. The diagram of the DEMAREC-EXPERT knowledge bases is shown in Figure 8.6. The required knowledge for diagnosing the concrete distresses is formulated as production rules (IF ... THEN) and procedures and is incorporated in the knowledge base structure. These are typical forms of code in conventional programming languages as well as in M.4. M.4 knowledge base entry type procedure uses syntax similar to the C programming language within the body of the procedure.

Table 8.3 - Miscellaneous distresses and their associated causes covered by DEMAREC-EXPERT.

Type of Distress	Cause of Distress or Probable Causes
Structural Related Distresses	Excessive distress in concrete, Overloading beyond the design, Poor construction method, Environmental factors, Deficiencies in shear strength, Inadequate flexural strength, Bond failure during shrinkage, Strain increases with time, Temperature changes, Reduced internal stresses.
Stratification, Segregation and Bleeding	Careless in handling and placing concrete, Inadequate curing, Inadequate and over vibration.
Collapsed Member	Soil failure, Surface rupture, Earthquake loads, Impact, High temperature on structural materials, Fire.
Rust Staining	Corrosion of reinforcement, Poor concrete.
Scouring	Poor choice of foundation location, Meandering riverbed, Inadequate flow area, Inaccurate estimation of flood level and its speed, Lack of scour prevention measures, Improper sizes of riprap protection, Improper designed riprap.
Dampness and Leakage	Poor mix properties used and inadequate construction method.
Temperature Changes and Phase Conversion	Thermal expansion drying, Thermal incompatibility, High temperature, Used High Alumina Cement Concrete (HACC).
Pitting	Corrosion of reinforcement.

The rules are organised on the diagnostic trees developed during the knowledge acquisition process and are arranged in a manner that provides a fast and accurate information flow. The sequence in which the rules are evaluated is controlled by the "*Initialdata*" (Figure 8.7) which is a predefined term makes up the M.4 knowledge representation language. The rule organisation is performed by the following steps:

- The knowledge is represented in diagnostic trees during the knowledge acquisition process. The diagnostic tree indicates how the knowledge is linked together and how the rules are written and organised.
- The rule numbers are assigned in the order which they are created.
- The rules are further arranged by assigning the TYPE and SYMPTOM variables shown in Figure 8.7. These variables control the sequence in which the rules are carried out. The variable SYMPTOM in this rule declares what symptom category has been considered while the TYPE variable is used to assign the value of

distress type such as either longitudinal or diagonal crack in cracking in concrete category.

```
kb-1:
initialdata = [welcome_displayed,consultation_over,
               repair_method,next_step].

rule-2:
    procedure(consultation_over) = {
        TYPE := find_symptom_category;
        find long(cracks_observed(TYPE));
        if (long(cracks_observed(TYPE)) = yes) {
            eval(cracking_corrosion(TYPE));
            break;
        }
        else {
            eval(cracking(TYPE));
        }
    }.

rule-3:
procedure(find_symptom_category) = {
    SYMPTOM :== cracking_in_concrete;
    TYPE := symptom_type(SYMPTOM);
    find message(category,[SYMPTOM,TYPE]);
    return(TYPE);
}.
```

Figure 8.7 - An example of rules showing as a procedure knowledge base entry.

- The results as a message are assigned based on its order of appearance within the diagnostic tree.

It was necessary to extend the capabilities of M.4 by developing special features such as confidence level (CL) that improved the user interface and providing access to external capabilities. The rules and the parameters in the DEMAREC-EXPERT knowledge bases contain confidence level (CL) values to indicate the degree of reliability about the acquired knowledge. The confidence levels can be combined with each other to obtain an overall confidence level for the final recommendation or conclusion. These are a measure of the confidence that can be placed on any given conclusion or recommendation.

The confidence levels (CL) included in the DEMAREC-EXPERT are words and descriptive functions with pre-determined CL value which are used to describe the knowledge. Words such as "Certain", "Very Sure", "Sure", "Quite Sure", "Possible

Case" and "Innovative Idea" conceal specific uncertainty within the meaning. A scale similar to the one shown in Figure 8.8 is used to assign a confidence level as pre-determined value for the DEMATEC-EXPERT rules.

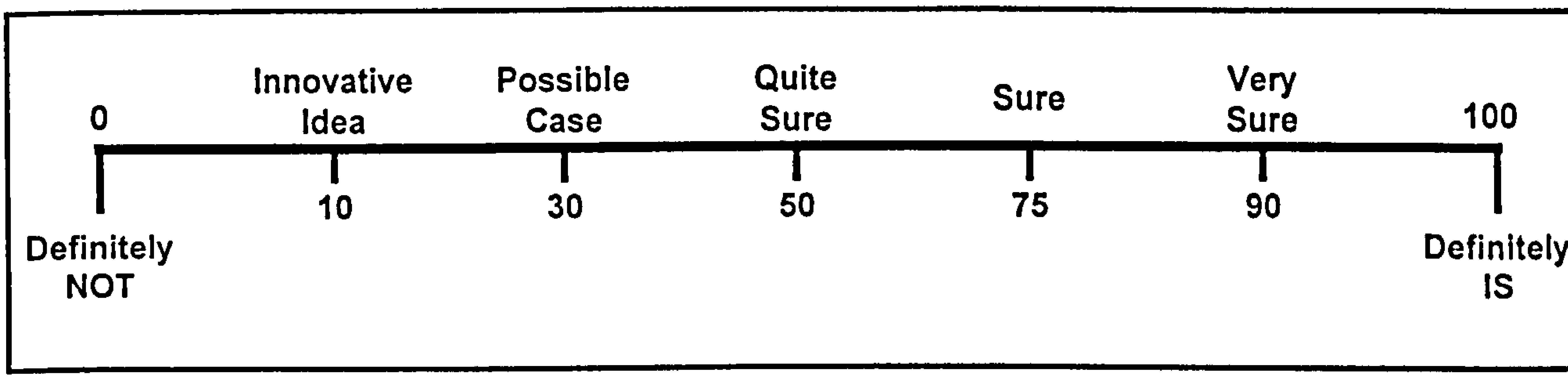


Figure 8.8 - DEMAREC-EXPERT confidence level (CL).

The confidence level should be assessed during the question-and-answer session with the expert system. When a question is asked of the user, the response may include a CL which indicates the unreliability of the answer. If no CL is entered, the program will assign a CL of certain to the parameter.

Other extended facilities provided by DEMAREC-EXPERT are:

- A chronology of the knowledge base development.
- Storage of information during the expert system execution.

The development of these extended capabilities for DEMAREC-EXPERT involved writing computer programs in C and Visual Basic programming languages. Descriptive information about the structure or structural components such as structure and construction types, distress type and category is stored in the database component of the knowledge base. This information is entered by the GUI windows shown in Figure 8.9 and the expert system may be required to assist the user in selecting these parameters. The user can obtain assistance from the REPCON database of pictures attached to some of the user help options. Visual information such as photographs and drawings enhance the interpretation of results and can often describe failure modes for materials and structures.

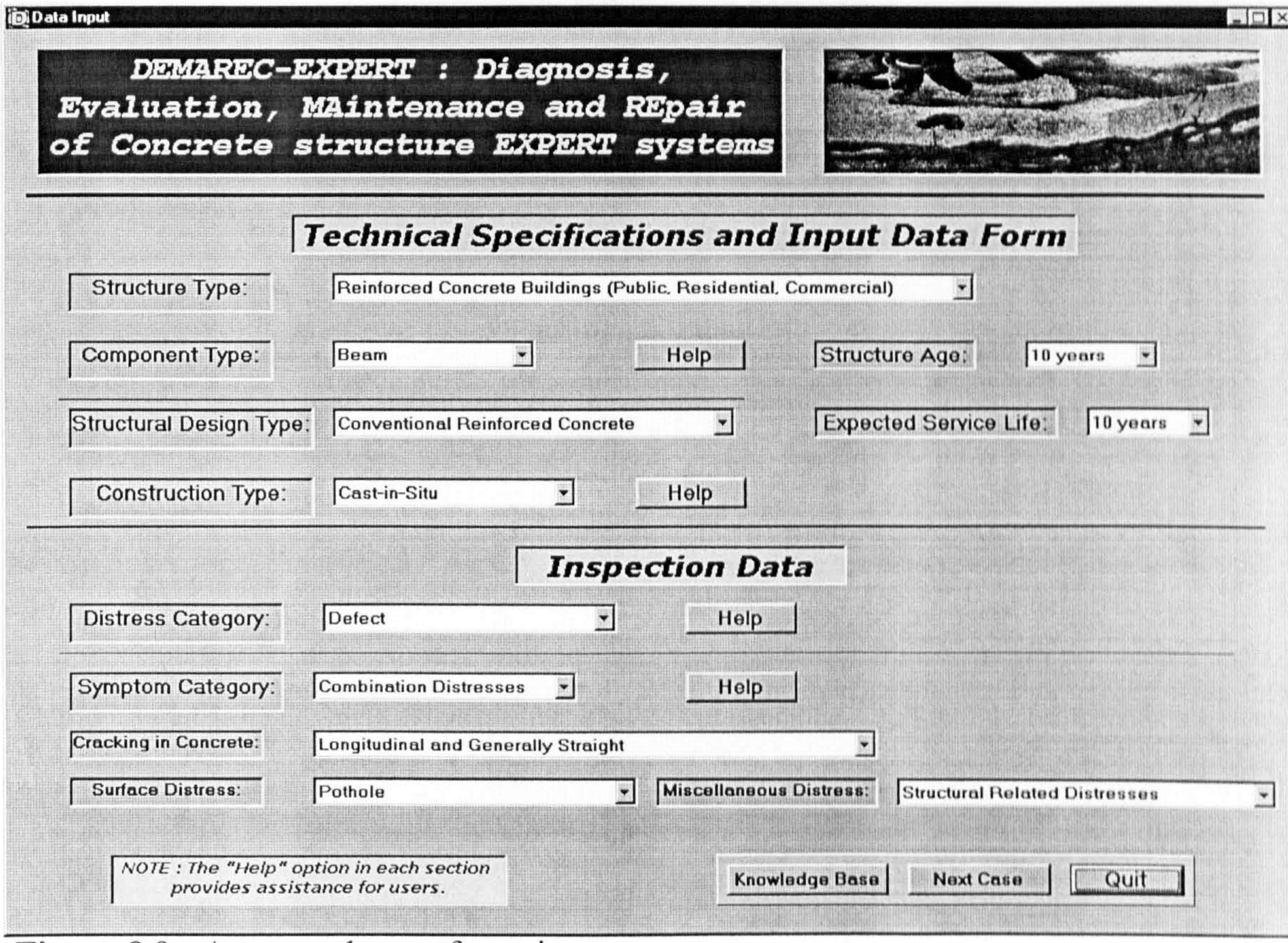


Figure 8.9 - A screen dump of user input.

8.7.1 Cracking in Concrete (CRACON) Knowledge Base

The cracking in concrete (CRACON) knowledge base contains different forms of crack shown in Figure 8.6. The CRACON knowledge base has been developed for identifying the probable cause of cracks in concrete based on their shape and pattern, density and location. The six types of crack are selected because they comprise the most persistent manifestations of premature impairment of concrete. Knowledge contained in the system is obtained from codes of practice, textbooks, experts in the field, photographs taken of actual concrete failures and the classification of the failures into the REPCON database format.

The following definitions summarise the main forms of crack covered by the CRACON knowledge base:

- ***Longitudinal and generally straight:*** Cracks that develop parallel to the long direction of the member.

- *Diagonal:* Diagonal cracks are usually caused by loss of foundation support, base erosion and shear stresses, at about 45 degrees to the natural axis of a concrete member. The formation of diagonal cracks under these conditions may signify ultimate failure in the affected regions.

- *Transverse:* Transverse cracks are usually caused by drying shrinkage or thermal restraint (movement restrained by the reinforcement) that develop at right angles to the long direction of the member. Also, frictional resistance between a pavement and the supporting base may contribute to the formation of transverse cracks.

- *Pattern or Map:* Fine openings on concrete surfaces in the form of a pattern. This results from a decrease in the volume of the material near the surface, or an increase in the volume of the material below the surface, or both.

- *Random and Multiple (irregulars over the Surface):* Several cracks in a reinforced concrete slab showing no regular pattern. Also fine random cracks or fissures in a surface of plaster, cement paste, mortar, or concrete are attributed to crazing.

- *Cracks at Joint, Edge and Opening:* Cracks either at or in the vicinity of transverse and longitudinal joints e.g. within the length of dowel or tie bars or immediately adjacent to them may occur for a number of reasons associated with either their construction, maintenance or design. Cracks at joints which occur as a result of dowel bar misalignment are always secondary to the joint crack. The main types of these cracks are transverse or diagonal cracks in transverse joints, longitudinal cracks at transverse joint and longitudinal cracks at longitudinal joints. Also a series of cracks called D-Cracking occurs in concrete near and roughly parallel to joints, edges and structural cracks.

The first step in representing this knowledge base is the creation of diagnostic (hierarchical) trees. During the development of CRACON, its knowledge was partitioned into six types of crack, each dealing with a major distress problem. Diagnostic trees for knowledge of cracking in concrete are illustrated in Figures 8.10

to 8.15. Then the facts are expressed in the form of production rules and procedures. Within the diagnostic tree of CRACON, several questions are asked concerning the shape and geometry of crack, location, direction and appearance. The inference engine searches for answers by initiating one or more rules within the CRACON knowledge base. The rules are evaluated and recommendations are given based on the current state of the crack.

8.7.2 Surface Distresses (SURCON) Knowledge Base

Structural impairments of concrete structures are shown in the form of various distresses on the concrete surface. In evaluating the existing condition of concrete structures, it is important to define and describe the distresses objectively and consistently. To achieve this objective, the most persistent manifestations of surface distresses in concrete is chosen for creating the surface distress (SURCON) knowledge base. The SURCON knowledge base contains nine different types of surface distress as shown in Figure 8.6.

The following distresses can be chosen as a main visual distress symptom in the concrete surfaces covered by SURCON:

- ***Scaling, disintegration and removal of materials:*** Local flaking or peeling away of the surface layers of hardened concrete. Only in the infrequent cases of severe scaling does the coarse aggregates become detached. Scaling is a type of disintegration that is deterioration into small fragments and subsequently into particles.

- ***Spalling and popouts:*** This is the process of detachment of a concrete fragment, usually in the shape of a flake, from concrete by the action of weather, by pressure or by expansion within the larger mass. This pressure is commonly the result of expansion caused by the corrosion of steel reinforcement. As a surface distress, spalling is usually localised and often shallow. It is rarely deeper than the reinforcing steel or the size of the larger coarse aggregate. A popout is the breaking away of a small portion of concrete at the surface which leaves a

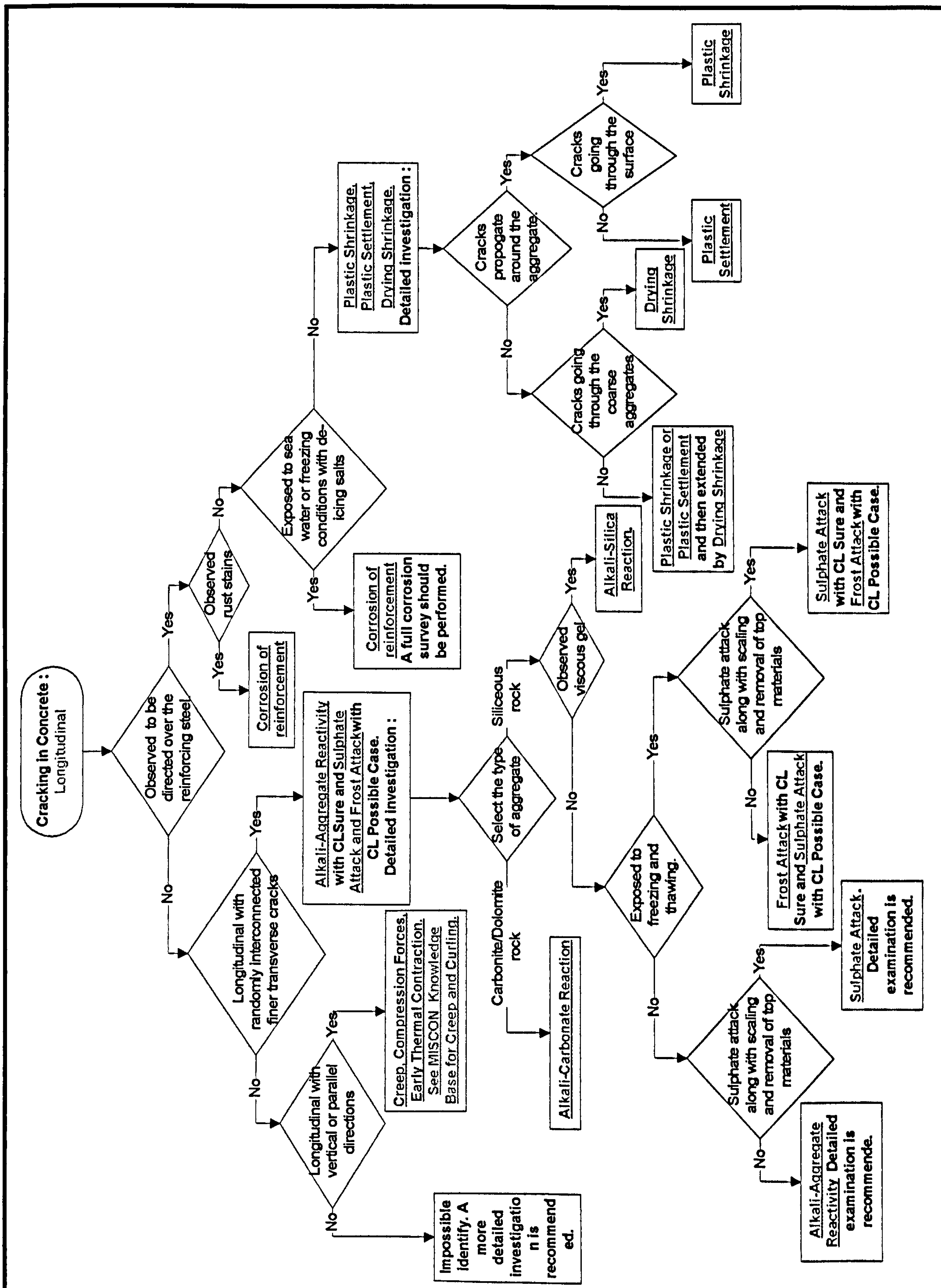


Figure 8.10 - Diagnostic tree for representing of the knowledge of longitudinal crack.

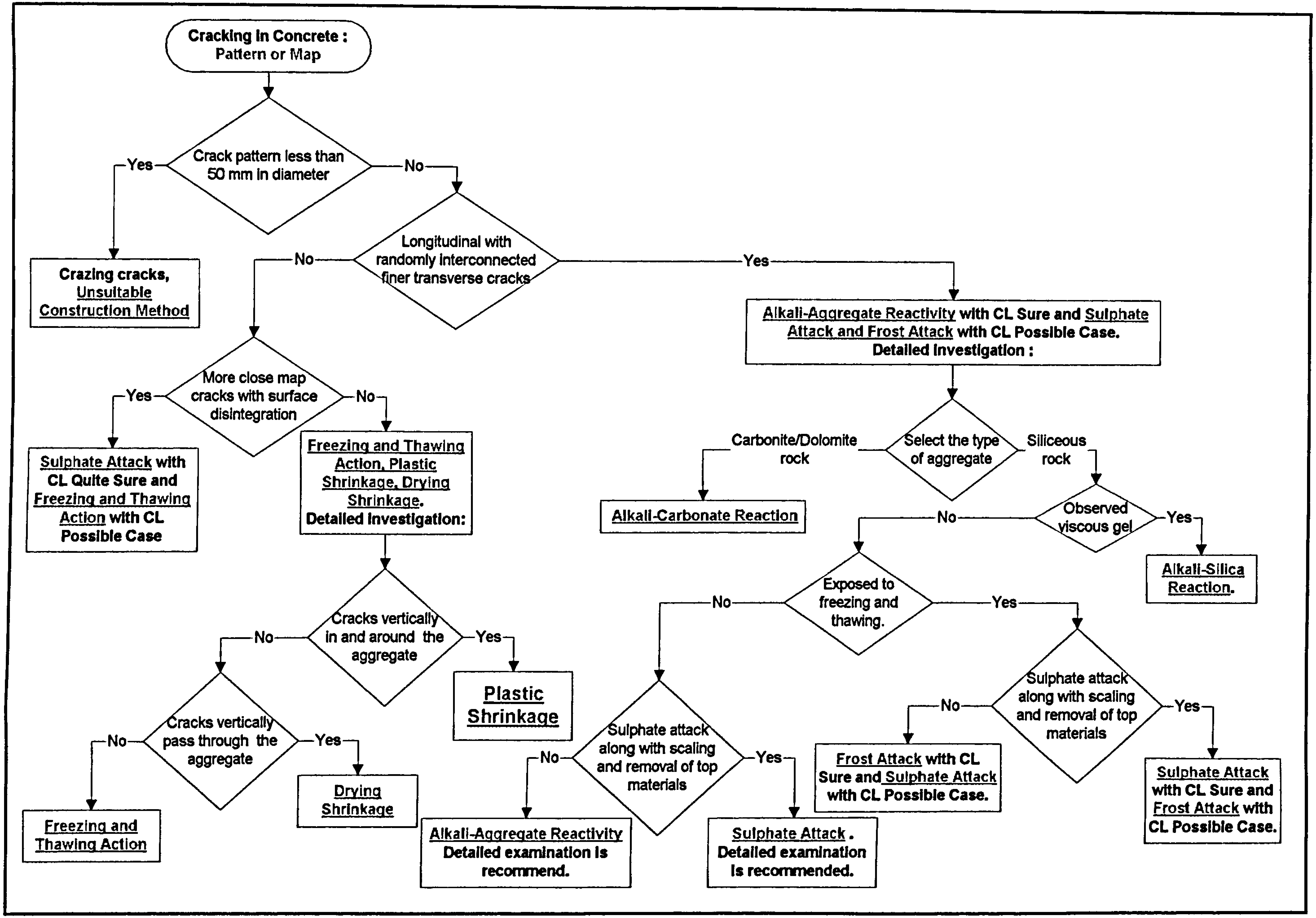


Figure 8.11 - Diagnostic tree for representing of the knowledge of pattern or map crack.

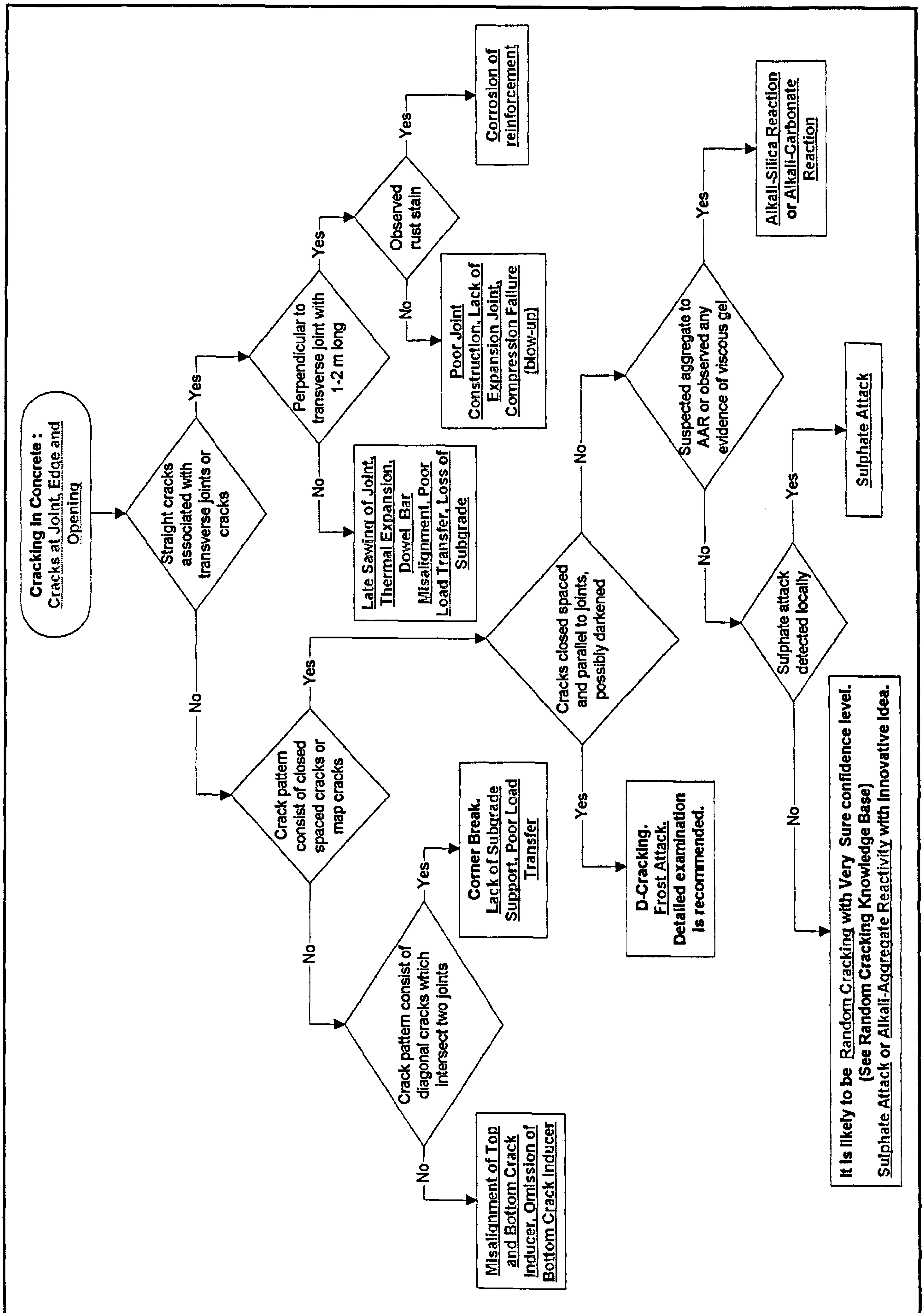


Figure 8.12 - Diagnostic tree for representing of the knowledge of crack at joint, edge and opening.

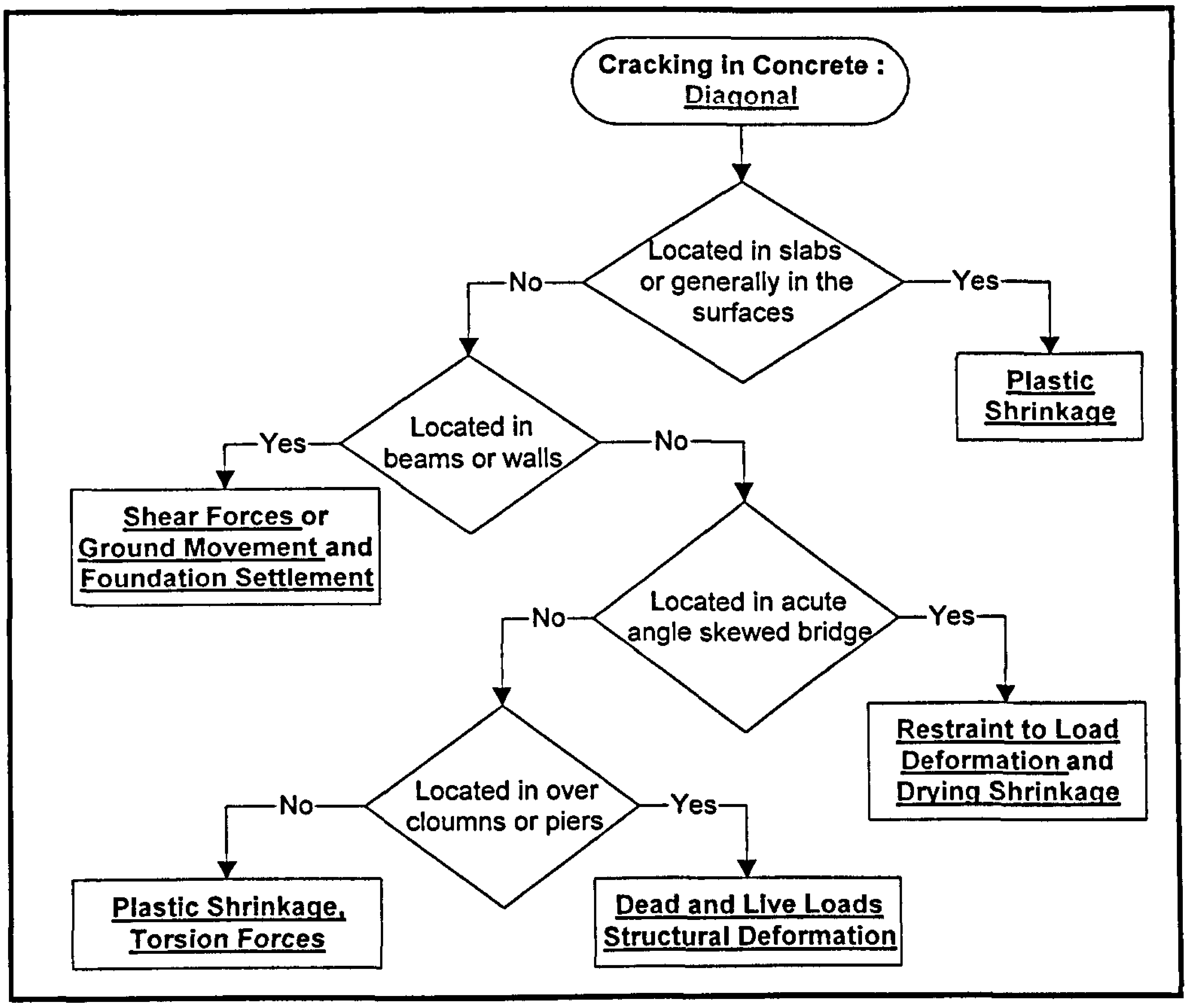


Figure 8.13 - Diagnostic tree for representing of the knowledge of diagonal crack.

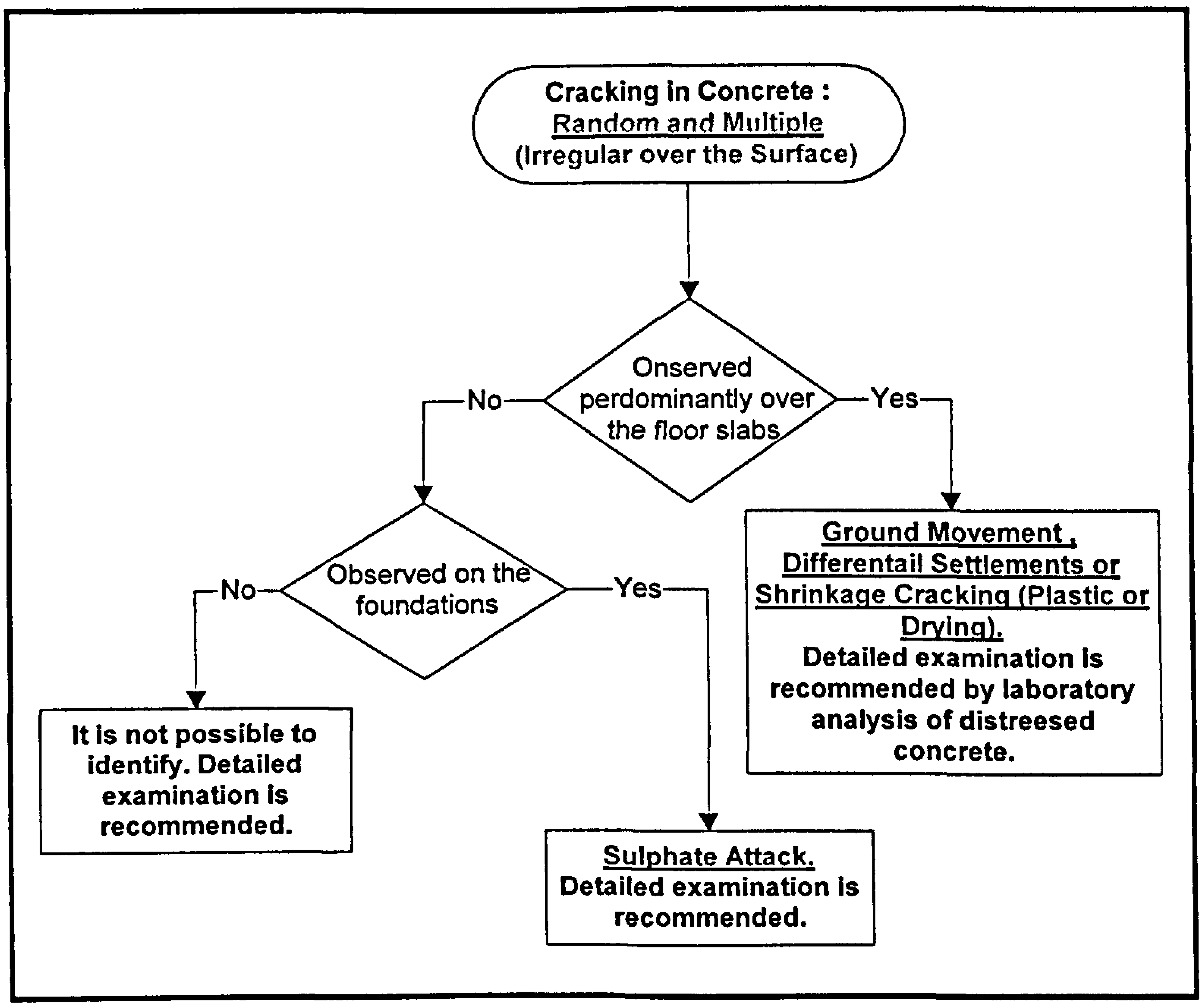


Figure 8.14 - Diagnostic tree for representing of the knowledge of random crack.

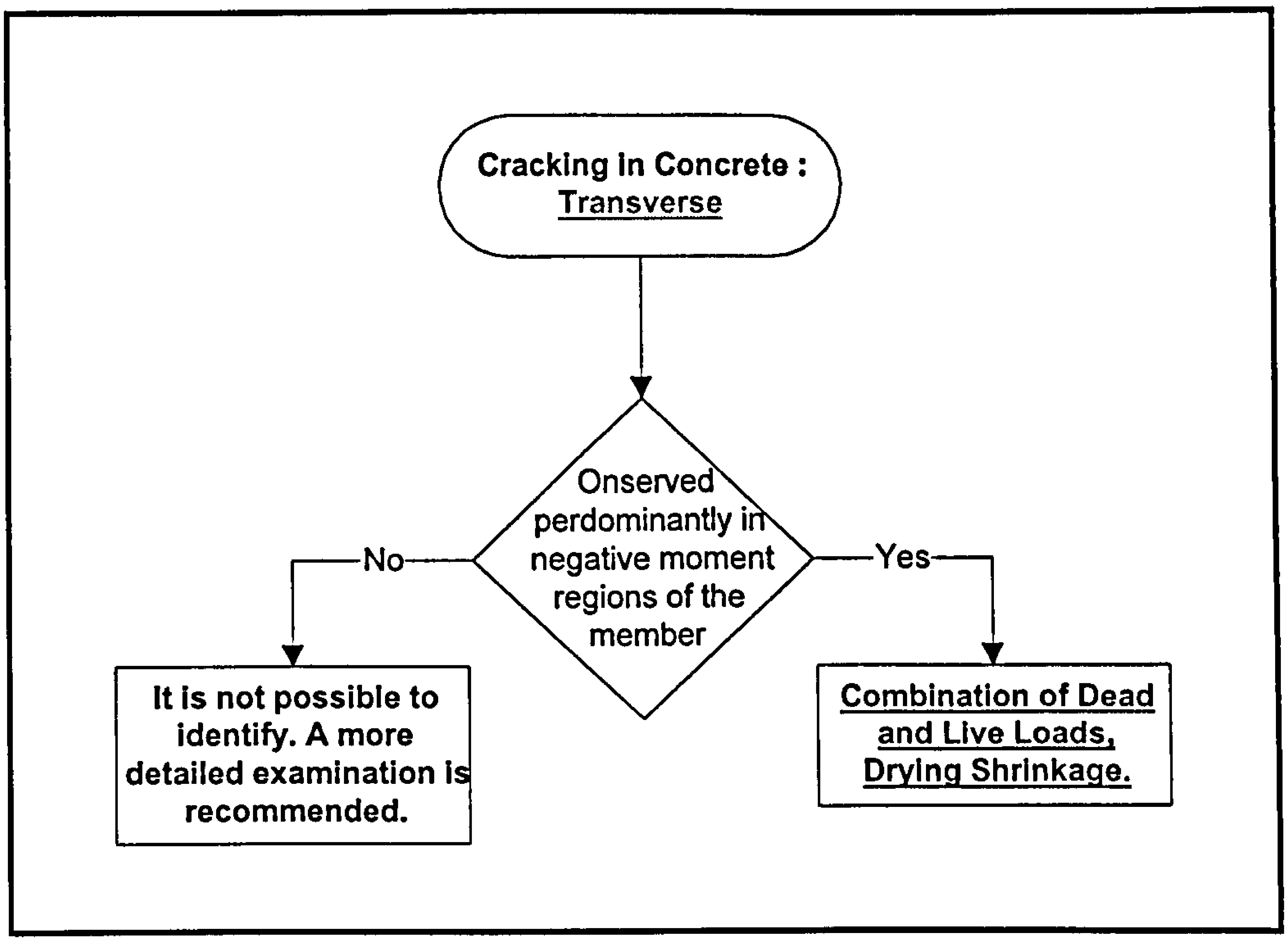


Figure 8.15 - Diagnostic tree for representing of the knowledge of transverse crack.

shallow, typically conical, depression or hole. Popouts are usually caused by the expansion of aggregates which are susceptible to frost action. Small popouts leave holes up to 10 mm in diameter, medium popouts leave holes 10 to 50 mm in diameter and large popouts leave holes greater than 50 mm in diameter.

- ***Joint related spalling or faulting:*** This is a spall adjacent to a joint.

- ***Honeycombing:*** Voids left in concrete owing to failure of the mortar to effectively fill the spaces among coarse aggregate particles. Honeycombing occurs when concrete is not properly consolidated owing either to inadequate vibration or poor design or formwork, allowing pockets of concrete to lie out of the reach of vibration.

- ***Pothole:*** Bowl-shape holes of various sizes in concrete pavement surfaces, which when fully developed are larger than popouts.

- ***Dusting:*** The development of a powdered material at the surface of hardened concrete.

- ***Discolouration and efflorescence:*** Discolouration is loss of colour from that which is normal or desired. Efflorescence is a deposit of salts, usually white, formed on a surface, the substance having emerged in solution from within either concrete or masonry and subsequently precipitated by evaporation.

- ***Polishing of aggregates:*** Surface mortar and texturing worn away to expose coarse aggregate in the concrete, which is glossy in appearance and smooth to the touch.

- ***Wear and Erosion:*** Progressive disintegration of a solid by the abrasive or cavitation action of fluids or solids motion. Abrasion damage is wearing away of a surface by rubbing and friction. Also, cavitation damage is pitting of concrete caused by implosion, i.e., the collapse of vapour bubbles in flowing water which form in areas of low pressure and collapse as they enter areas of higher pressure. Pitting is also the development of relatively small cavities in a surface owing to phenomena such as corrosion, or other types of localised disintegration.

In developing this prototype knowledge base, the diagnostic trees served as the vehicle for communication between the experts who interpreted and organised the knowledge in a hierarchical structure and the knowledge engineer who initially record the knowledge into a question-and-answer sequence form along with a network diagram. Diagnostic trees for representing the knowledge of surface distresses are shown in Figures 8.16 to 8.19.

The SURCON knowledge base may ask many questions during the consultation session for surface distresses and detailed suggestions and recommendations are displayed. The main rules for assigning symptom category and a value (any distress type) to SYMPTOM and TYPE variables respectively are shown in Figure 8.20.

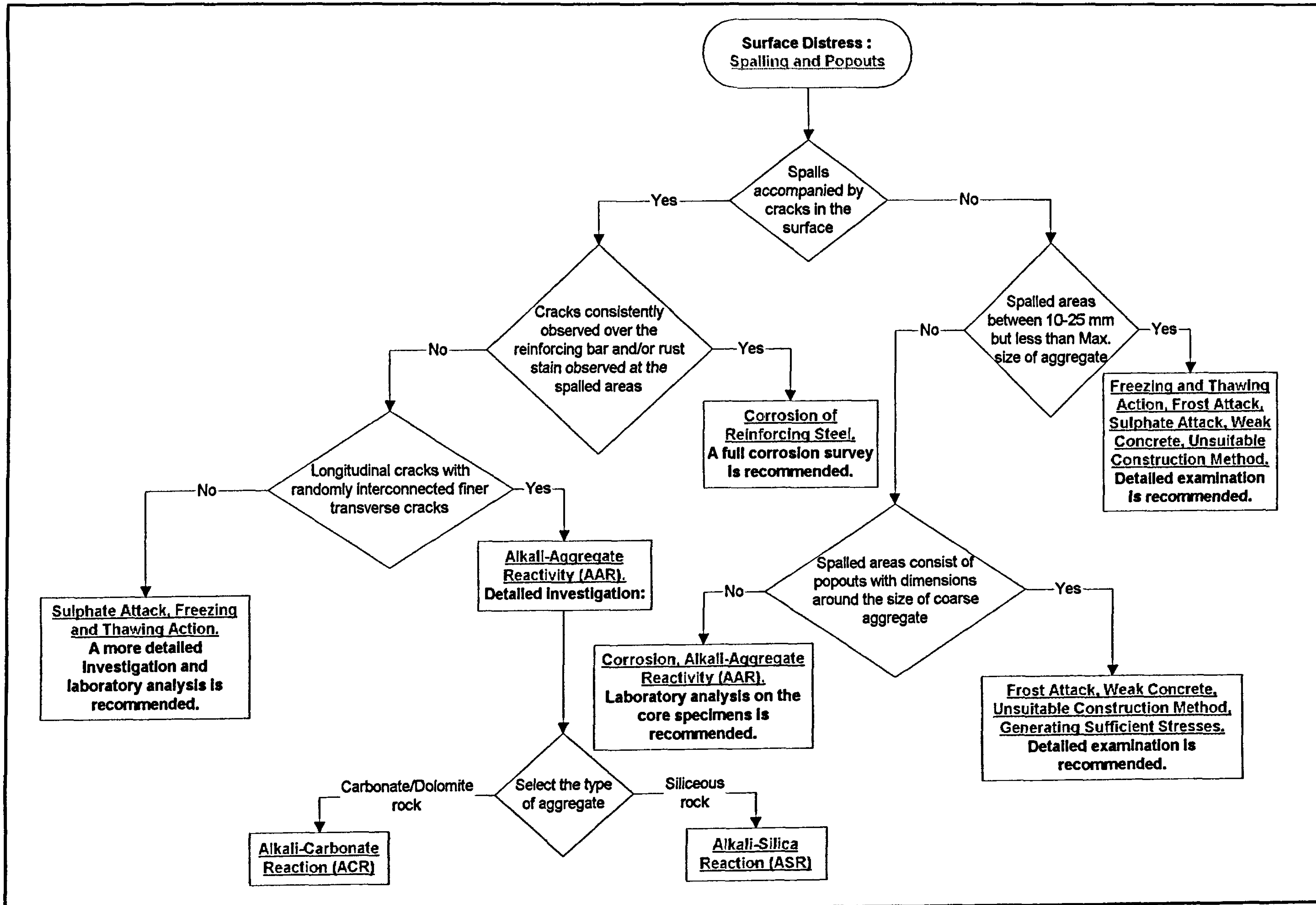


Figure 8.16 - Diagnostic tree for representing of the knowledge of spalling and popouts.

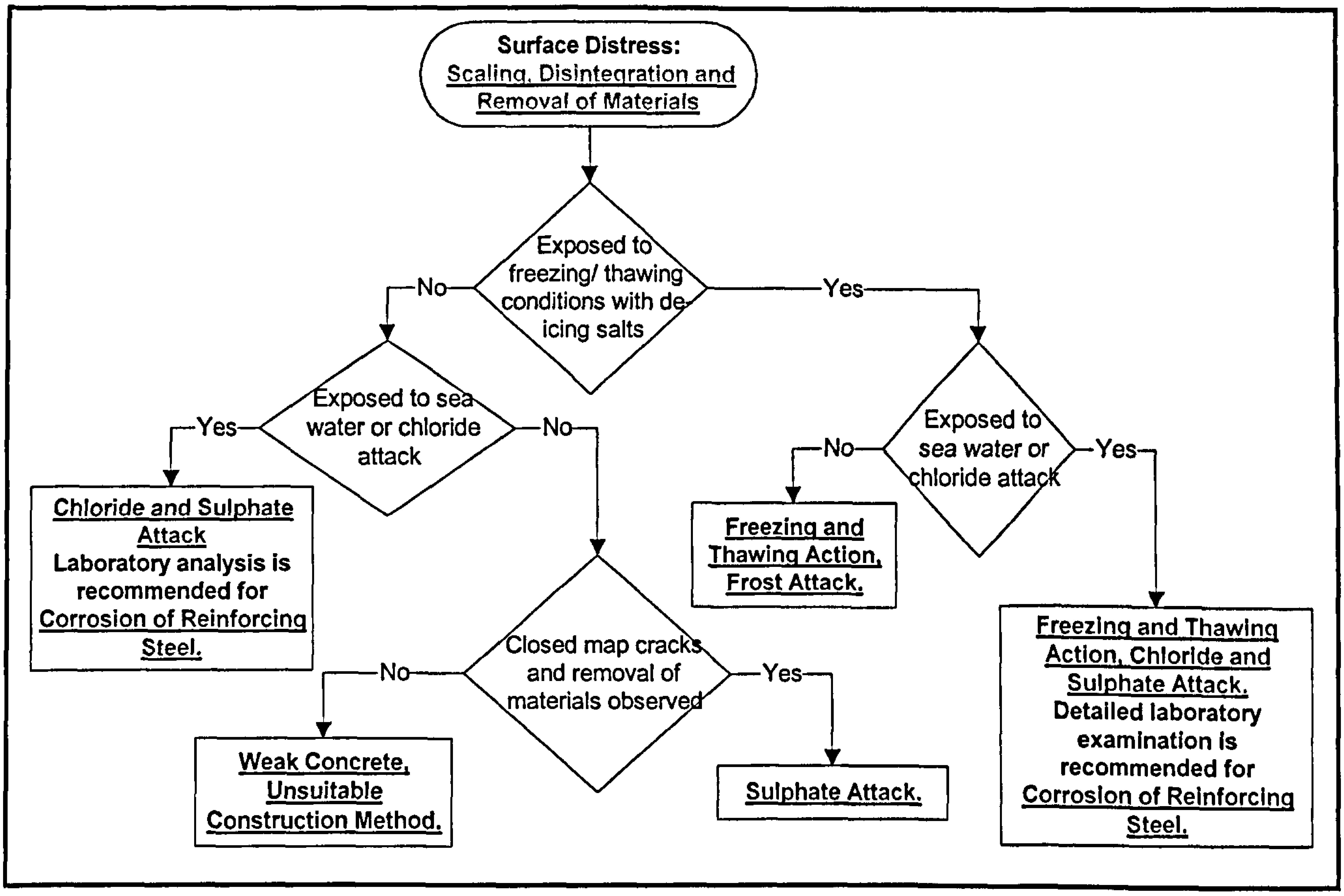


Figure 8.17 - Diagnostic tree for representing of the knowledge of scaling, disintegration and removal of materials.

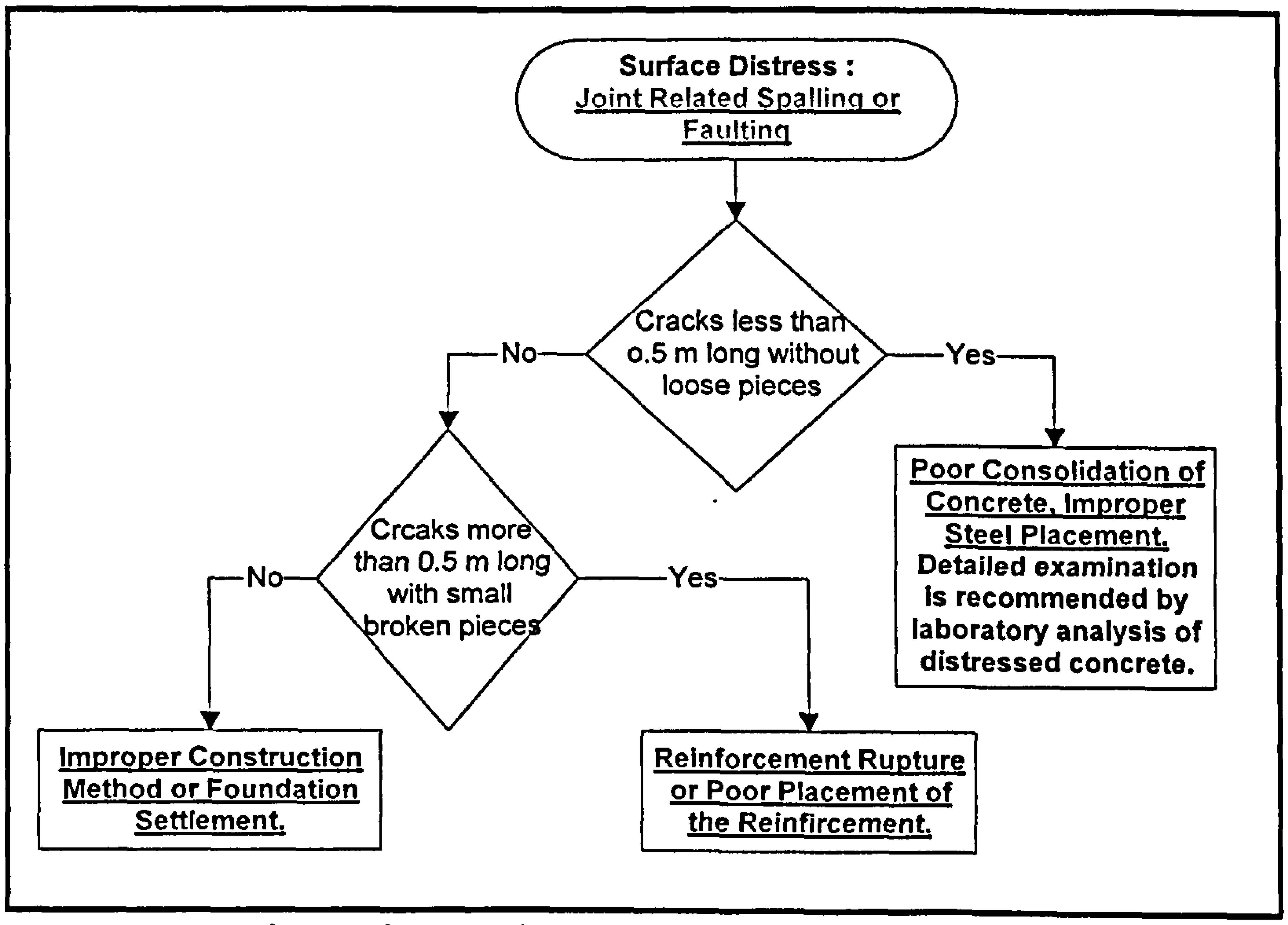


Figure 8.18 - Diagnostic tree for representing of the knowledge of joint related spalling or faulting.

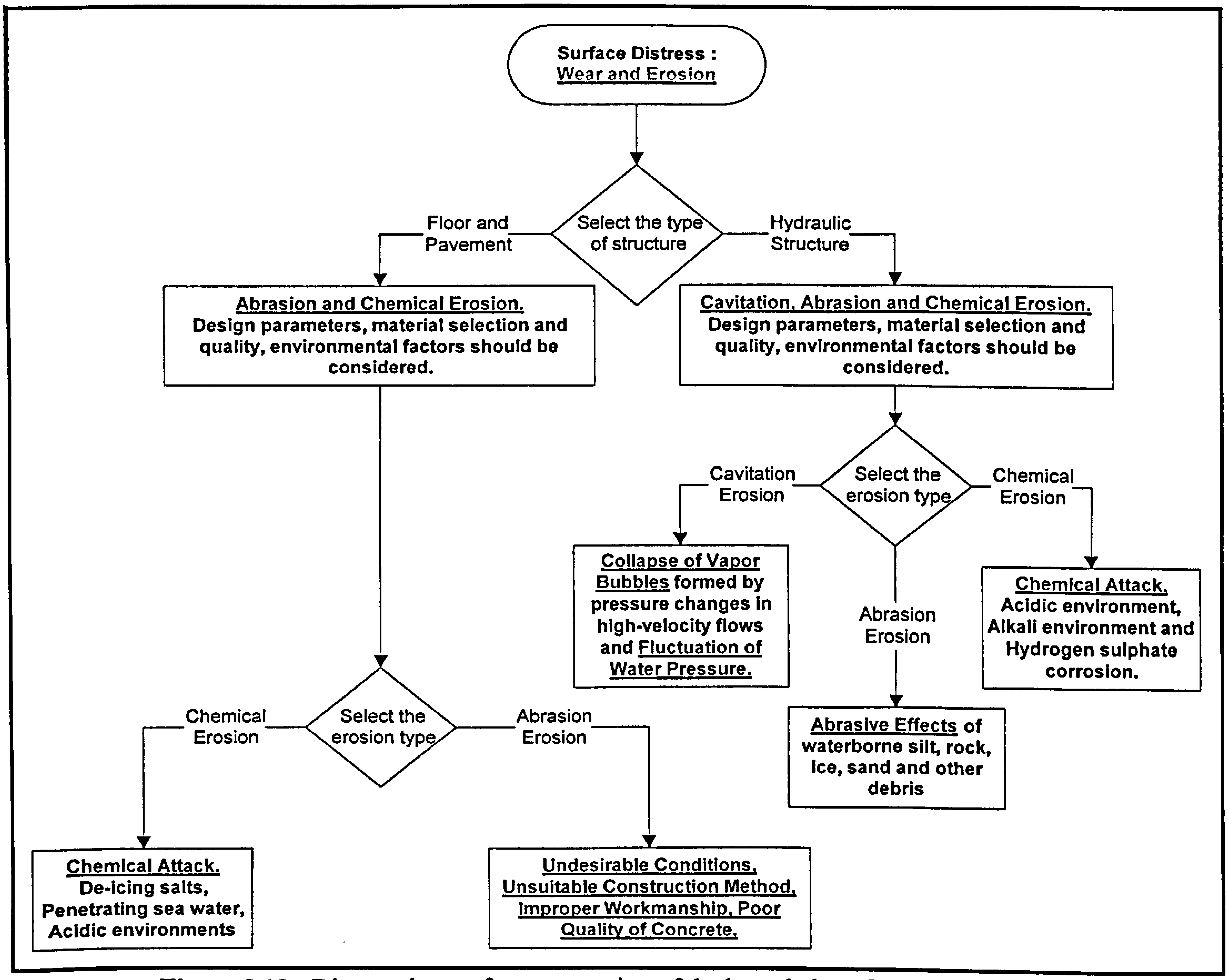


Figure 8.19 - Diagnostic tree for representing of the knowledge of wear and erosion.

Recommendations are written as "message-text" kb-entries in the SURCON knowledge base. Figure 8.21 shows an example of message-text including conclusions and recommendations for surface scaling.

```
rule-2:
procedure(consultation_over) = {
    TYPE := find_symptom_category;
    if (TYPE == polishing_of_aggregate) {
        eval(surface(TYPE));
        break;}
    else {if (TYPE == honeycombing) {
            eval(surface(TYPE));
            break;}
        else {if (TYPE == pothole) {
                eval(surface(TYPE));
                break;}
            else {if (TYPE == dusting) {
                    eval(surface(TYPE));
                    break;}
                else {if (TYPE == discoloration_and_efflorescence) {
                        eval(surface(TYPE));
                        break;}
                    else {find surf(surface_distress(TYPE));
                        if (surf(surface_distress(TYPE)) = yes) {
                            eval(surface(TYPE));
                            break;}
                        else {eval(distress(TYPE));}
                    }
                }
            }
        }
    }
}.

rule-3:
    procedure(find_symptom_category) = {
        SYMPTOM :== surface_distress;
        TYPE := symptom_type(SYMPTOM);
        find message(category,[SYMPTOM,TYPE]);
        return(TYPE);
    }.
```

Figure 8.20 - Main rules shown as a procedural knowledge base entry in SURCON.

```
kb-19:
message-text(scaling_sulphate,[]) = ['===== CONSULTATION OVER
=====',nl,nl,'The surface scaling is caused by SULPHATE ATTACK. This
conclusion can be increased by laboratory analysis which should be
taken on the distressed layer specimens. Sulphates often concentrate
at the surface at a higher level than in deeper regions of the
concrete component.',nl,nl,
'*********************************************************',nl].
```

Figure 8.21 - An example of message-text in SURCON.

In developing of the diagnostic trees shown in Figures 8.10 through 8.19 for representing the knowledge of concrete distresses, detailed investigation mentioned in some conclusions. Table 8.4 shows the summary of these investigations recommended for some of possible causes which are covered by DEMAREC-EXPERT system program.

Table 8.4 - Detailed investigation recommended by DEMAREC-EXPERT for some of possible causes.

Possible Cause	Detailed Investigation Recommended
Alkali-Aggregate Reactivity (AAR)	❑ Taken sample of distressed concrete. ❑ Petrographic examination of aggregates (ASTM C 295) and concrete (ASTM C 856). ❑ Quick chemical test. ❑ Osmotic test.
Sulphate Attack	❑ Taken sample of distressed concrete. ❑ Petrographic examination of concrete (ASTM C 856). ❑ Sulphate content test. ❑ Physical properties test.
Corrosion of Reinforcement	❑ Taken sample of distressed concrete. ❑ Chloride content test. ❑ Carbonation test. ❑ Permeability test. ❑ In-situ half-cell potential test. ❑ In-situ covermeter test.
Weak Concrete, Unsuitable Construction Method, Frost Attack	❑ Taken sample of distressed concrete. ❑ Determining the physical and chemical properties of concrete. ❑ Analysis of concrete contents for contaminated aggregates.
Unknown	❑ Taken sample of distressed concrete. ❑ Determining the physical and chemical properties of concrete.

Once the diagnosis has been made a remedy needs to be recommended. There are many alternative repair materials and methods in the REPCON database and the most appropriate is dependent on the engineering knowledge and experience of the user. This information is chosen alongside brief description and referred to Tables 2.22 and 2.23 in Chapter 2.

8.7.3 Miscellaneous Distresses (MISCON) Knowledge Base

Many other factors may contribute to or cause the impairment of concrete structures. These are described as miscellaneous distresses in this research and are presented in the miscellaneous distresses (MISCON) knowledge base. These forms of distress are as follows:

- ***Structural Related Distresses:*** Distresses in the form of cracking can result from excessive stress levels in the concrete. Overloading beyond the design provision, poor construction or deterioration owing to environmental factors can result in in-situ strength deficiencies in concrete, reinforcement and their interfaces. In addition to the materials, the structural forms themselves can be lacking in strength and robustness owing to inadequate design, detailing and construction. Such deficiencies include shear, flexural, tensile and bond strength failures. Cracks may also result from stresses owing to imposed overloading and abnormal deflection, curling and warping and creep. Abnormal deflection is a variation in position or shape of a structure or structural element resulting from the effects of load or volume change, usually measured as a linear deviation from an established plane rather than an angular variation. Curling and warping is a change in dimension or shape resulting from stress, or the distortion of an originally essentially linear or planar member into a curved shape such as the warping of a slab resulting from creep or to differences in temperature or moisture content in the zones adjacent to its opposite faces. Creep is also time-dependent deformation resulting from sustained load or drying of concrete.

- ***Stratification, Segregation and Bleeding:*** Segregation is the differential concentration of the components of mixed concrete, aggregate, or the like, resulting in non-uniform proportions in the mass. It is the tendency, as concrete is caused to pass from the unconfined ends of shute or conveyor belts or similar arrangements, for coarse aggregate to separate from the concrete and accumulate at one side. It is also the tendency, as processed aggregate leaves the ends of conveyor belts, chutes, or similar devices with confining sides, for the larger aggregate to separate from the mass and accumulate at one side; or the tendency for solids to separate from the water by gravitational settlement. Bleeding channel is the autogenous flow of mixing water within, or its emergence from, newly placed concrete or mortar; caused by the settlement of the solid materials within the mass; also called water gain. Stratification is also the separation of overwet or overvibrated concrete into horizontal layers with increasingly lighter material toward the top.

- *Collapsed Member:* Careless overloading can occur during construction or use, but the direct evidence may have been removed. Accidental overloading can occur due to impact, explosion, earthquake or wind. Serious overloading can be caused by change of use or ill thought through modifications to the structure.

- *Rust Staining:* Rust staining, together with fine cracks, is almost always an early sign of reinforcement corrosion. On the other hand, rust-like stains may also be the result of contamination of aggregates with pyrites (iron sulphide) which oxidizes on contact with air. Stain patches may also result from the rusting of nails and tie wires which have been left in the formwork during casting and rust deposits on the formwork before casting may also show as rust stains on the concrete surface.

- *Scouring:* Excess water rising in the forms can produce stream-like patterns in the surface of the concrete.

- *Dampness and Leakage:* One of the biggest problems with concrete structures is the intrusion of water. Water and dissolved salts attack reinforcing steel, posttensioning tendons, and anchorages, thus greatly affecting the capacity of the structure. Water may enter from cracks in the top slab or from a poorly designed or defective expansion joint. Damp areas on the surface may be the result of leakage through cracks and joints or may indicate the accumulation of water in the behind of surface which is leaching through the concrete.

- *Temperature Changes and Phase Conversion:* Phase changes which involved volume changes can cause disruption of concrete, and in particular the phase change of quartz on heating has been studied because of its importance in concrete subjected to extreme temperature changes. The conversion of one hydrate phase to another in concrete under more usual service conditions is of importance in influencing of the durability of concrete.

Temperature rises, and particularly those that occur at an early age, may be responsible for a great deal of early cracking in structures. Cycles of temperature can have a progressive effect on the reduction of tensile and compressive strengths of which tensile strength is more affected by heat than is compressive strength. During rapid rise and fall of temperature, the response of concrete is affected by the interaction of thermal expansion drying (and hence shrinkage), thermal incompatibility (leading to cracking) and enhanced creep at high temperatures.

High Alumina Cement (HAC) concretes are widely used to achieve high early strength, higher temperature and resistance to chemical attack; especially to sulphate attack. In poor quality conditions (not fully compacted, high W/C ratio, inadequate cured) the strength may fall significantly at later ages. This is associated with the conversion to the stable hydrate of the metastable calcium aluminate hydrates which form first. HAC does not release free lime when mixed with water (as does Portland Cement) and this results in improved resistance to attack by dilute acids but it is vulnerable to attack by caustic alkalis in solution as the alkalis react with the hydration products of the HAC to form calcium hydroxide and other components. If carbon dioxide is present, the calcium hydroxide is converted to calcium carbonate in the presence of moisture, and further complex reactions occur which weaken the concrete and lower the pH.

- ***Pitting:*** Pitting is the development of relatively small cavities in a concrete surface, localized disintegration owing to phenomena such as cavitation, corrosion, or other types of localised disintegration.

In representing the MISCON knowledge base, the diagnostic trees shown in Figures 8.22 and 8.23 are created in order to convert the knowledge to a question-and-answer display which is presented to the user in search of a conclusion or recommendation.

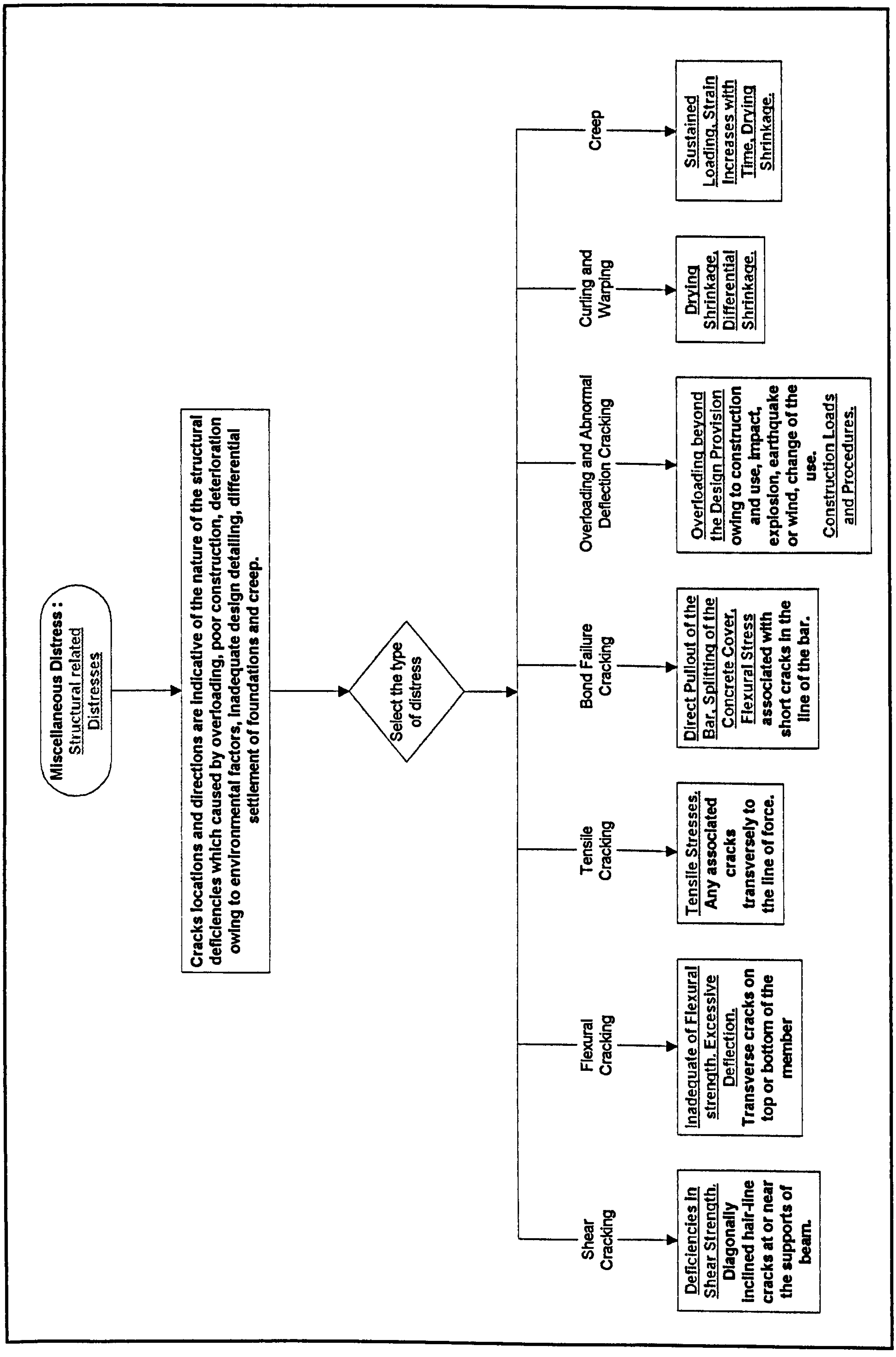


Figure 8.22 - Diagnostic tree for representing of the knowledge of structural related distresses.

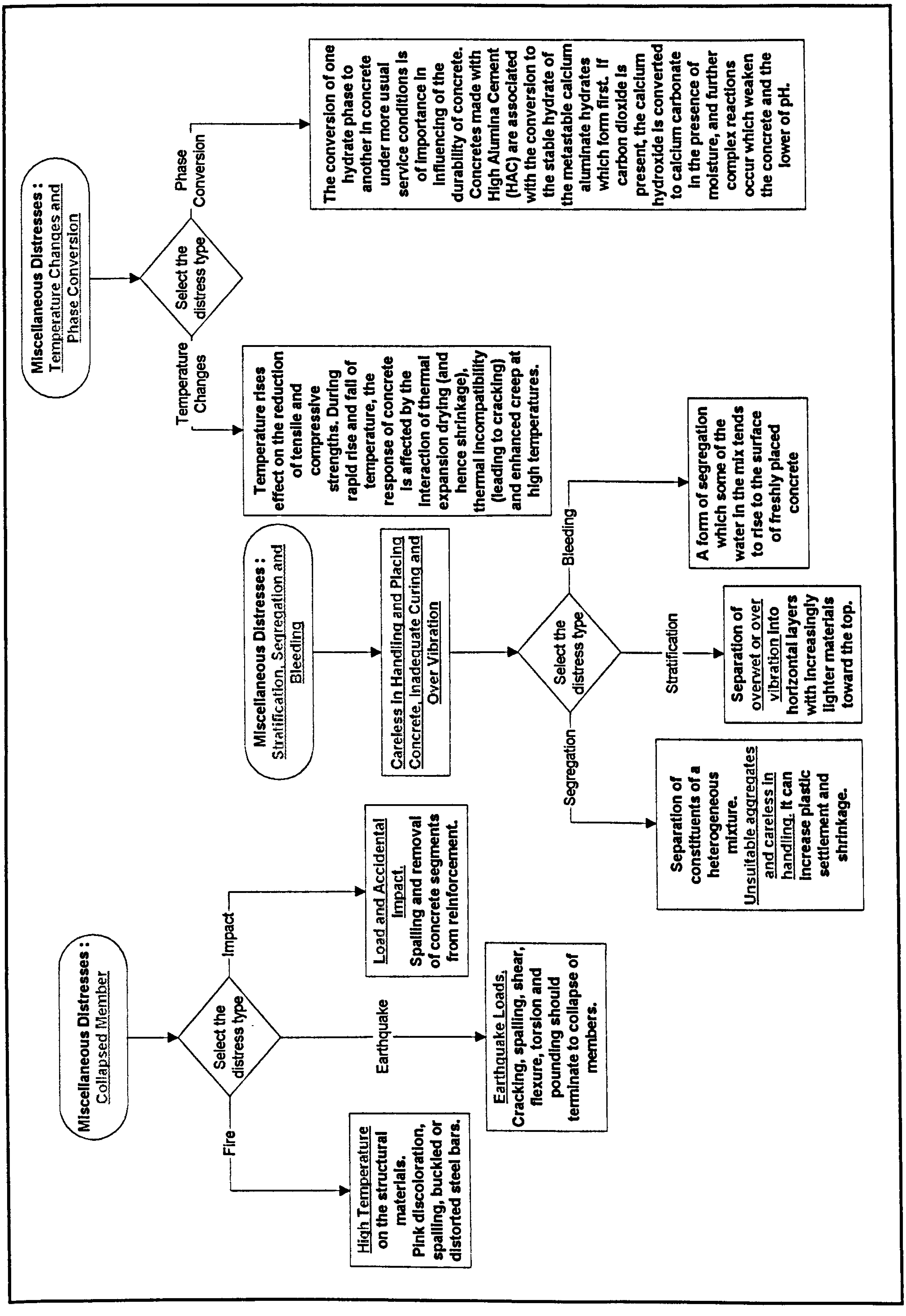


Figure 8.23 - Diagnostic tree for representing of the knowledge of miscellaneous distresses.

8.8 Summary

In this Chapter the components of the expert system DEMAREC-EXPERT have been described. The role of the expert system in this software is to describe the design and implementation considerations of an expert system tool to aid field inspectors in determining the cause(s) of distress in concrete structures. This system is a valuable tool in automating the acquisition of field information, in presenting a hypothesis on how known distresses relate to site specific problems, in preserving the knowledge of experts and in providing a record of the condition of structures at different ages. It also provides much needed guidance for practitioners while serving as a decision support system for other experts and specialists in the field.

It has been shown that the knowledge base for DEMAREC-EXPERT uses a vast amount of knowledge of proven validity.

The knowledge contained in the DEMAREC-EXPERT comprises information on the three main categories of distress and is presented by using both production rules and a procedural approach. In developing these knowledge bases, diagnostic trees are used for converting the knowledge to a question-and-answer display and as a road map for reviewing knowledge and making modifications to the computerized system.

The aim of the expert system is to provide a rapid and consistent method to make decisions from the assessment of concrete structure impairment. DEMAREC-EXPERT is designed to provide the user with recommendations related to the best course required for maintenance and in the selection of materials and methods for the repair of concrete structures. For this purpose, the DEMAREC-EXPERT system is coupled to an independent database management system called REPCON. The REPCON expert systems reviewed in Section 3.3 are totally different pieces of software from the REPCON database described in Chapter 7. The knowledge included in the REPCON database offers information relating to selection of materials and methods for repair and rehabilitation and gives the recommendations to enhance durability. Therefore, it is a valuable tool for engineers and other professionals dealing with the maintenance and repair of concrete structures.

DEMAREC-EXPERT's conclusions and recommendations are meant to be used as a decision-making tool. Miss-perception of the structure's conditions and requirements, miss-statement of the inspectors or the absence of information may cause the conclusions and recommendations to be invalid. This is why users are encouraged to conduct tests and procedures recommended by the REPCON database.

Chapter 9

Condition and Performance Rating Procedures for the Evaluation of Deteriorated Concrete

9.1 Introduction

It is important to gain an understanding of the basic causes and mechanisms of the various forms of distress which may attack concrete. Although impairment of concrete structures is usually a medium to long term process, the onset of distress and its rate may be influenced by the presence of defects which have their origin at the time of construction, or in the very early stage of the life of the structure. Condition assessment of concrete structures is apparently far more difficult than the analysis of design (Cabrera et al, 1995). One objective of an evaluation management system (EMS) is to create assessment procedures that will allow the current condition of the structure and its components to be expressed numerically so as to assist in choosing the best course of action in the repair and maintenance management.

In the DEMAREC software, an evaluation management system (called ECON) works in collaboration with a database management system (REPCON described in Chapter 7) to describe a proposed system for determining a confidence level (CL). CL numerically rates the condition of the concrete on a scale of 0 to 100 (Table 9.1) by evaluating each concrete deficiency.

The main objective of this Chapter is to create uniform procedures for assessing the current condition of structures that numerically rate the condition of the distressed concrete. Information on how to conduct an evaluation of the concrete in a structure was presented in Chapter 2. As described in Chapter 7, the stored data in the

REPCON database directs the user towards a comprehensive evaluation of the structure. Chapter 9 is structured as follows: an overview of the evaluation of concrete structures followed by a description of decision making under conditions of uncertainty, distress simulation and finally a quantitative rating system for evaluating the condition of deteriorated concrete. It will be shown how the procedure developed in this research is related to structural integrity and serviceability of the structure.

9.2 An Overview of the Evaluation of Concrete Structures

The impairment of concrete is an extremely complex subject (May; 1992, Kay; 1992, USACE; 1995). Consideration of failure mechanisms such as brittle or ductile fracture, fatigue, creep, instability or corrosion must take into account the nature and properties of all the materials which together constitute the composite.

In most cases, the damage detected will be the result of more than one mechanism. For example, corrosion of reinforcing bar may cause cracks that allow moisture greater access to the interior of the concrete. This moisture could lead to additional damage by freezing and thawing. In spite of the complexity of several causes working simultaneously, given a basic understanding of the various distresses causing mechanisms, in most cases it should be possible to determine the primary cause or causes of the distress evident on a particular structure. Therefore, it would be simplistic to suggest that it will be possible to identify a specific, single cause of distress for every symptom detected during an evaluation of a structure.

With respect to the evaluation of structural concrete which is related to structural integrity and serviceability, some work has been done. In an effort to improve maintenance techniques and practices for such concrete structures as coastal structures, gravity dams, and retaining walls, the U.S. Army Corps of Engineers (USACE) established the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research program (USACE, 1996). Within the REMR program is a group projects dedicated to the development of computerized maintenance management systems for concrete structures. One of the main objectives of the REMR program was to establish a rational, standard procedure for evaluating the physical condition and to create a method for determining numerical condition and performance ratings which, in turn, would be used to produce Condition Index (CI) values for the structure.

A prototype Bridge Management System (BMS) was developed for deteriorated concrete bridges by evaluating the output results from a bridge rating expert system. The proposed BMS offers various maintenance plans based on a combination of maintenance cost minimization and quality maximization. Genetic Algorithms (GAs) are adopted for solving the optimization (Miyamoto et al, 1999). A program related to the concrete bridge rating expert system was developed by Miyamoto et al (1995) enabling the performance of concrete bridges to be evaluated by visual inspection based on knowledge and experience acquired from domain experts.

Through the 1960's and into the 1970's bridge Maintenance, Repair and Rehabilitation (MR&R) activities were performed on an "as-needed" basis. The Pontis bridge management system is the predominant bridge management system employed in the United State (Thompson et al, 1998). Pontis is both a software system and an organising framework to help bridge managers make the transition from collecting and processing raw safety inspection data to a more sophisticated approach of optimizing the economic efficiency of the bridge network.

To assist airport managers, engineers and maintenance personnel in undertaking pavement design, performance, preventive and remedial maintenance and repair, an advisory circular (AC) has been developed by the Federal Aviation Administration (FAA, 1982). This advisory circular describes a pavement condition index (PCI) limited to flexible pavements and jointed rigid pavements and provides information on the various types of pavement distress together with recommended corrective actions. It also contains guidelines for conducting preventive maintenance inspections and establishing an effective maintenance program.

A performance index (PI) method is developed for fast and cursory evaluation of the physical condition of concrete bridges (Cabrera et al, 1995). This method originally proposed by Cabrera (1988) introduces the concept of quantitative evaluation of concrete performance in order to implement rapid ranking of the overall state of concrete bridges using the result of the observation of signs of distress and weighting scales based on severity and extent. This procedure involves visual inspection of concrete surface or near surface damages which can be described in terms of severity and extent and takes exposure condition into account as modifier.

9.3 U.S. Army Corps of Engineers Approach to the Evaluation of Concrete Structures

With respect to the development of condition rating procedures for the evaluation of concrete structures the U.S. Army Corps of Engineers has developed a system which is now described. A common definition is used to express the condition of facilities. It is called the Condition Index (CI) and it can be applied to all of the structures to be evaluated (USACE, 1996). Engineering judgement and experience are needed to develop the set of criteria and procedures from which the CI of a structure will be established. The process of identifying this set of criteria was done for such structures as dam and lock gates, gravity dams, retaining walls, spillways and jetties. Serviceability and subjective evaluation of safety were the primary factors considered by the experts, whose opinions have been combined and classified into a set of problems or distresses and "expert opinion" rules that are embedded in the evaluation that constitutes the CI (Greimann, 1995). Therefore, great care is taken in the development of criteria and inspection procedures to ensure that the results are consistent and repeatable.

The distresses identified for each structure are quantified by a measurement X. These measurements can comprise actual data-taking or are the result of a subjective evaluation. Typically each distress can be either a problem in itself or an indication of a problem. In most projects which were done by USACE (1996), the individual distress CI is quantified by:

$$\text{Condition Index (CI)} = 100(0.4)^{X/X_{max}} \qquad (9\text{-}1)$$

where X_{max} is some limitation value of X (Greimann, 1995). Engineering judgement, knowledge and experience are needed to describe the measurement of X and limiting X_{max} values for each distress.

Correct diagnosing for each type of distress is a complex issue. Many times a distress may have several possible causes, and often a combination of distresses must be present before a certain cause can be identified. For example, in a lock gate, there are several causes of anchorage deterioration such as:

- Corrosion
- Concrete cracking and spalling
- Anchor bolt elongation or movement
- Loose or missing casting bolts
- Additional load.

If anchorage movement can be detected by visual inspection, this is usually the first indicator of a significant problem. Any structural cracking and spalling of the concrete in this area will reduce the CI by a factor of 0.85. If any of the anchor or casting bolts and nuts is corroded, loose or missing, the CI decreases by a 0.70 factor (Greimann, 1995).

Obviously, subjective judgement and engineering knowledge and experience are required to classify the importance of distresses.

When multiple distresses occur in a part of the concrete structure, weighting factors, w_i, are assigned to each distress. These relative weights reflect in some degree the opinions of experts and engineers. Previous work done by Greimann et al (1995) has suggested that the normalized weighing factors, W_i, are defined by:

$$W_i = \frac{w_i}{\sum w_i} (100) \qquad (9\text{-}2)$$

where $\sum w_i = 100$. The combined CI for all types of distress is given by:

$$\text{Condition Index (CI)} = \frac{[W_1 CI_1 + W_2 CI_2 + ... + W_n CI_n]}{100} \qquad (9\text{-}3)$$

where n represents the total number of distresses. The experts have judged that this equation is always valid unless a crack is detected because a crack in any lock gate component could seriously affect the structural integrity of the gate (Greimann, 1995).

Therefore, a unique formula or equation to calculate the Condition Index is not possible and it depends much more on the type of concrete distress and engineering judgement, knowledge and experience.

In another effort to develop a procedure for the evaluation of concrete structures, Bullock et al (1995) assigned nominal deduct values for most defects in serviceability. The exact method of calculating the Condition Index (CI) from the deduct values was determined by collecting subjective expert ratings based on the condition described by the REMR Management Systems.

Deduct Values for various distress categories that tend to result in cracking such as diagonal, pattern, longitudinal, D-cracking, and in volume loss of concrete such as honeycomb, scaling, spalling, and steel deterioration were determined. Deduct Values are subtracted from 100 to established the CI.

When multiple distresses occur in a part of the concrete structure, to calculate the CI the five largest Deduct Values (DV), with DV_1 the largest value and other values in descending order to the fifth largest, DV_5 were considered. The calculation was based on the following equation (Bullock et al, 1995):

$$CI = 100 - [1.0(DV_1) + 0.4(DV_2) + 0.2(DV_3) + 0.15(DV_4) + 0.1(DV_5)] \qquad (9\text{-}4)$$

9.4 Decision Making under Uncertainty

One of the most important characteristics of successful administrators in all types of organisation is the ability to make the correct decision more often than the incorrect one when confronted with insufficient information (Baird, 1989). Decision making is so pervasive that everyone is involved with it. Industrial, government, academic and scientific administrators all make decisions which might be the choice of a method, adoption of one among various possible ways to pursue, treatment of an illness or repair of damage. Professionally, executives are constantly faced with problems of many varieties and to solve them decisions must be made. Even if a decision that might solve a problem is avoided and no action is taken, that itself is a decision (Baird; 1989, Holloway; 1979).

The best way to judge the competence of any executive is by the quality of decisions made in complex situations when faced with uncertainty. When problems are complicated by uncertainty, gathering information, assessing consequences and making a choice are also complicated. Therefore complications from uncertainty extend to all phases of the decision-making process.

A comprehensive treatment of decision making under uncertainty has been reported (Holloway, 1979). The analytical process, as shown in Figure 9.1, is separated into two parts: Models and Choices. Models provide descriptions of decision problems. When uncertainty is present, these models use the theory of probability. Once the decision problem has been modelled, a choice must be made.

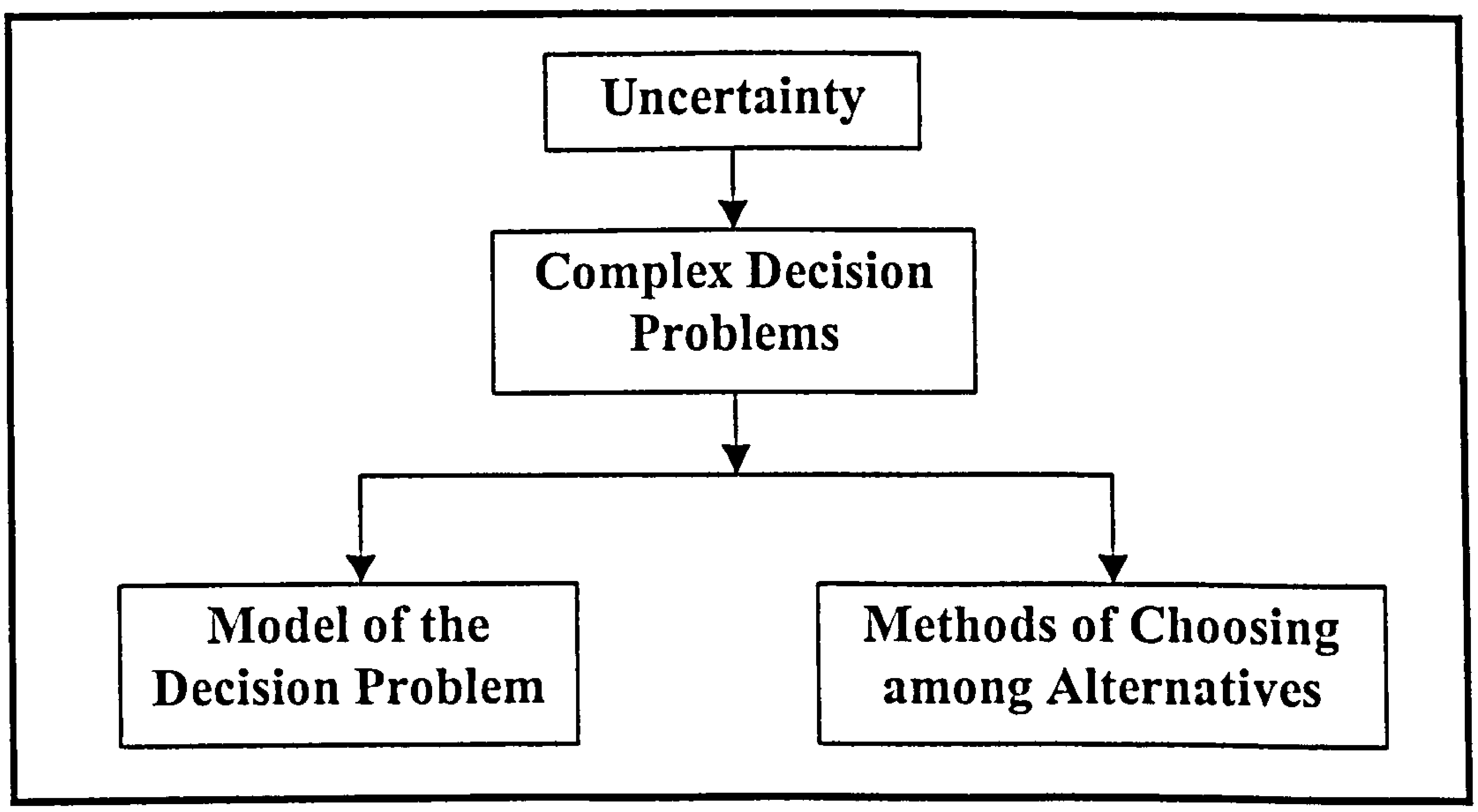


Figure 9.1 - Analytical process of decision making under uncertainty.

Probabilities distinguish decision models under uncertainty from other models and also are required to complete the description of the uncertain events. Probability information is displayed by probability distribution. A probability distribution can also be displayed using a cumulative distribution.

9.5 Random Variables and Classifications

In some works dealing with probability and its applications, the terms "random variable" and "uncertain quality" are used synonymously. A random variable takes on value; thus the random variable is not itself a value but a function whose numerical values correspond to experimental outcomes. Perhaps the concept of random variable would be more comprehensible if it were termed a random function, but this would be at odds with the convention now well established in the literature of probability theory and applications. It is most important to note that the uncertainty exists in the mind of the decision maker who must deal with the random variable (Baird; 1989, Holloway; 1979).

Random variables might be classified into discrete and continuous values. If the outcomes may occur in an infinite or countable number of ways, the term attributes is frequently used. If the random variable under consideration is described in terms of attributes, a limited number of discrete values is possible. Therefore, a discrete random variable can assume a countable number of values.

A random variable that is discrete may assume a "countably infinite" number of values and still be a discrete variable. For example, if a damaged column in a concrete structure is considered until the corrosion appears, what are the possible values of random variable "numbers of distress until corrosion appears"? Therefore, it must be recognised that the values may at times also be a series that is infinite but countable if the count could be continued indefinitely.

Observations may also be measured in terms of continuous values such as time or volume. How long does a particular damage occur in a component of a structure? Obviously the answer to this question could be one of an infinite number of values limited only by our ability to measure very small fractions or very lengthy periods of elapsed time. Therefore, a continuous random variable may assume any value in the interval between any other two values of the variable.

Using probability for the improvement of decision making, both concepts (discrete and continuous) are important. The differences between discrete and continuous random variables are crucial because the probability model is different for each. For instance, the sum of probabilities which may be assigned to the various possible values of a discrete random variable is one, whereas if two values of the continuous random variable are specified, it is not possible to count the number of values in the interval between the specified values. Clearly, this makes it impossible to define a probability for each value assumed by the continuous random variable because there would also exist an uncountable infinite number of these probabilities. Therefore, instead of specific probabilities to be associated with specific values of the variable, a probability density function is described. In some situations it might be interesting to compute the cumulative distribution function of random variables which describe the probability of some specific values (Baird; 1989, Holloway; 1979).

There exist several very useful models of probability in the real world. The binomial, Poisson, hypergeometric, normal and exponential distributions are examples of theoretical distributions used in a large numbers of decision situations. The Poisson and exponential distribution functions are briefly described in the following sections.

9.5.1 The Poisson Distribution

A famous and useful family of the theoretical discrete probability distribution is the Poisson. This distribution is particularly useful in describing the distribution of number of occurrences per unit of volume, area, or time in cases where the average number of occurrences is small. Examples include distresses per component of a concrete structure, failures of machine in a large manufacturing plant containing many such machines, and the numbers of toxic organism in a large volume of fluid. The Poisson probability distribution is described by the function (Baird, 1989):

$$P(X) = \frac{e^{-\lambda}\lambda^{x}}{x!} \tag{9-5}$$

where X = random variable,

$P(X)$ = probability of exactly X occurrence,

e = a constant equal to 2.71828,

λ = average (mean) number of occurrences of X per unit of measurement.

For some fixed value x, it needs to be computed the probability that the observed value of X will be at most x. The cumulative distribution function (cdf) F(x) of a discrete random variable X gives, for every specified number x, the probability $P(X \le x)$. The cumulative distribution function provides the same information as the density function, and one can be derived from the other. It is calculated by summing the probability mass function p(y) over all possible values y satisfying $y \le x$ using the relationship (Devore; 1995, Holloway; 1979):

$$F(x) = P(X \le x) = \sum_{y:y \le x} p(y) \tag{9-6}$$

9.5.2 The Exponential Distribution

Another random variable associated with a Poisson process is the time from one event to the next one. This is a continuous variable whose distribution can be obtained with the aid of the Poisson formula. Therefore, the Poisson distribution may be used to estimate the probability of X occurrences during an interval of measurement. During a production run of one week, what is the probability of exactly 100 defect? During a service life of a structure, what is the probability of exactly six distresses appearing in the structure? The occurrences assume integer values over some unit of measurement such as volume, area or time. In the cases above, the distribution of the unit of measurement, which is occurrences per unit of time, is discrete. Suppose that the questions were reversed. What length of time elapsed between occurrences? Time is continuous and if the process generating occurrences is Poisson in nature, the exponential distribution is appropriate in this case and is characterized by the function (Baird, 1989):

$$f(t) = \lambda\, e^{-\lambda} \tag{9-7}$$

where t = amount of time elapsing before the exact occurrence,

e = constant, 2.71828,

λ = mean of the related Poisson process,

$f(t)$ = frequency (density) of t,

λ and t are positive.

The cumulative distribution function of a continuous random variable gives the same probability $P(X \leq x)$ and is obtained by integrating the probability distribution function f(y) between the limits $-\infty$ and x, thus:

$$F(x) = P(X \leq x) = \int_{-\infty}^{x} f(y)dy \tag{9-8}$$

where for each x, F(x) is the area under the density curve to the left of x (Devore, 1995).

9.5.3 Expected Values of Random Variables

Frequently, in decision situations, the mean or central tendency of random variables is of interest. This is called the mathematical expectation of the random variable or its expected value. To compute expected value, the values of the random variables and the probability that each value will occur must be determined.

The mathematical definition of expected value of a discrete random variable is (Baird, 1989):

$$E(X) = \sum_{i=1}^{n} x_i\, P(x_i) = x_1\, P(x_1) + x_2\, P(x_2) + \ldots + x_n\, P(x_n) \tag{9-9}$$

where E(X) = expected value of the random variable X,

x_i = *i*th value of the random variable X,

$P(x_i)$ = probability of the *i*th value of X,

$\sum_{i=1}^{n}$ = summation of all values of the variable for i=1 to i=n.

To compute the expected value for a continuous random variable, it is summed by integration and the probability mass function (pmf) by the probability density function (pdf) to get a continuous weighted average. Thus:

$$E(X) = \int_{\infty}^{\infty} x.f(x)dx \tag{9-10}$$

where the pdf f(x) is specified as a model for distribution of values in a numerical population (Devore, 1995).

9.6 Modelling Variability and Simulation

Civil engineers have always had to deal with uncertainty, but they are now expected to do so in more accountable ways. Probability theory provides a mathematical description of random variation and enables the user to make realistic risk assessments. Statistics is the analysis of data, and the subsequent filling of probability models.

Simulation is used to define the performance of public transport systems, to investigate the efficiency of control rules for reservoir releases, to examine the response of structures to extreme events and to investigate the propagation of cracks in offshore structures by structural engineers. The advantages over theoretical results are that simulation can be used in complex situations for which appropriate formulas are not known. The disadvantage is that simulation is far less convenient than an algebraic formula (Metcalfe, 1997).

Situations have been considered in which observations are made over a period of time and that are influenced by chance or random effects, not just at a single instant but throughout the entire interval of time or the sequence of times that are being considered. This situation is termed a stochastic process. A stochastic process is a phenomenon that varies to some degree unpredictably as time goes on. A point process is a continuous time model for a stochastic process in which events occur at point in time. The simplest example is a Poisson process, which is characterized by the Markov property. That is, the probability of an occurrence in the next interval, of arbitrary length, is independent of the time of the last occurrence and of the entire history of the process (Metcalfe; 1997, Clarke; 1970).

9.7 Generating a Model for Concrete Distress Simulation (Multiple Distresses)

In the simplest form of model for concrete distress simulation, symptoms of distress which can be a sign of the damage of concrete, occur as a Poisson process with a rate of λ per unit of time (Figure 9.2-a). Each symptom has a random number (C) of causes associated with it (Figure 9.2-b). For example, longitudinal cracking might be owing to corrosion of reinforcing bar, plastic or drying shrinkage, Alkali-Aggregate Reactivity (AAR) or frost attack. Also in the case of the scaling and disintegration of a surface, it might be in association with freezing and thawing, sulphate and chloride attack, unsuitable construction method and frost attack. The number of causes is generated via a Poisson distribution, specifically (C-1) is a Poisson random variable with a mean of (ν-1). The reason for modelling (C-1), rather than C, as a Poisson random variable is to ensure that all symptoms have cause. The parameter ν is the average number of causes per symptom.

The waiting times from the symptom to the causes are exponential random variables. In Figure 9.2-c the causes are assumed rectangular and their size depends on duration and intensity. Therefore, the duration and intensity of each cause are modelled as exponential random variable distributions with a mean of $1/\eta$ and $1/\xi$ per unit of time, respectively. The total intensity (Figure 9.2-d) at any point in time is the sum of the intensities of all active causes at that point and is calculated by cumulative distribution function.

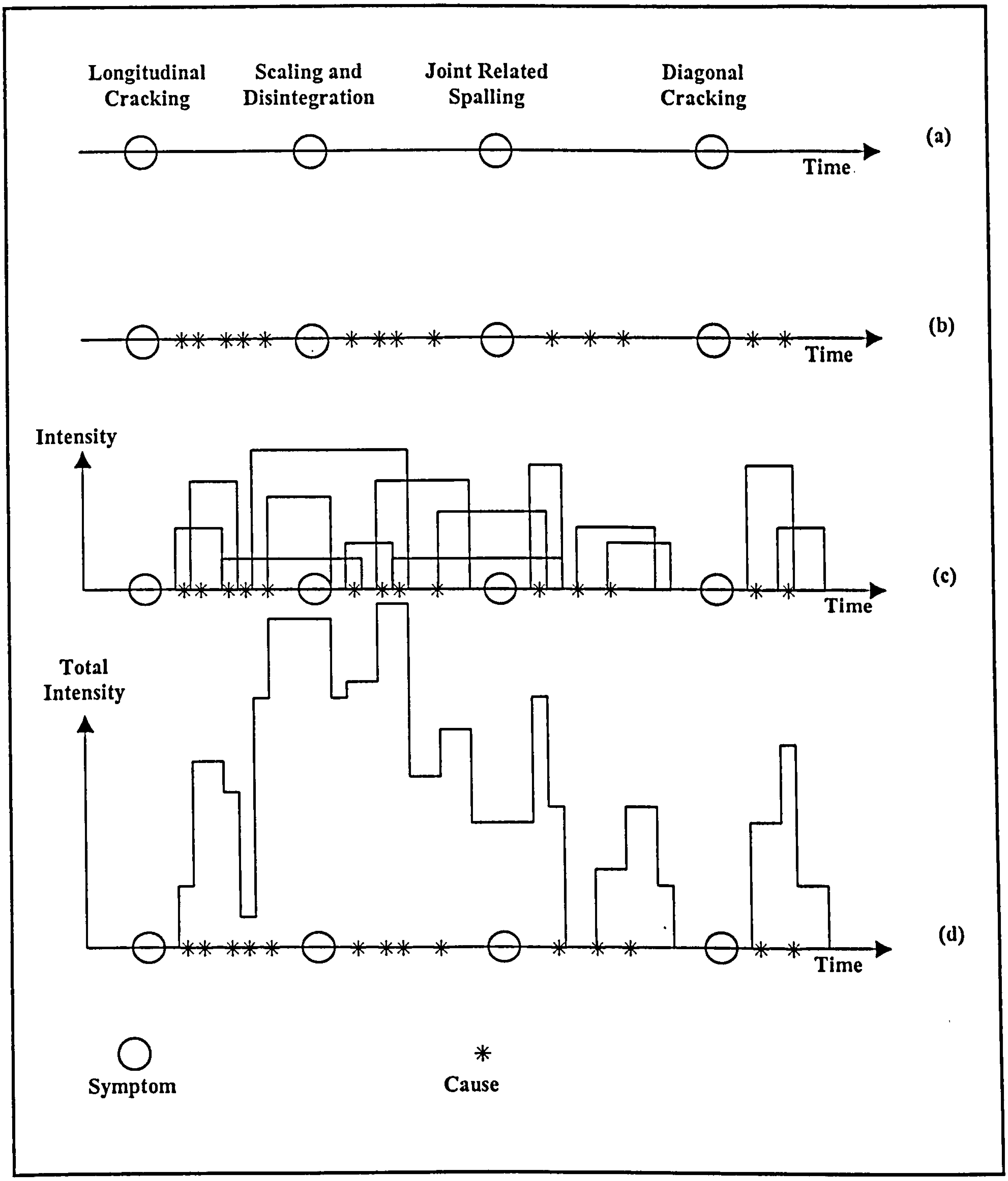


Figure 9.2- A schematic representation of the concrete distress model.

The parameters of the model should be estimated from past records and simulation of concrete distress needs random numbers from Poisson distribution. In the case of the evaluation of concrete, because there are always no past records available, the intensity of each symptom (or value of the random variable) should be estimated by defining a set of criteria such as width and depth of crack and surface appearance. The criteria and also the probability of the value which influences concrete integrity and serviceability could be determined by visual inspection and engineering knowledge, judgement and experience.

9.8 Evaluation of Concrete (ECON) in a Concrete Structure

A thorough and logical evaluation of the current state of the concrete in a structure is the first step of any repair or rehabilitation work. Therefore, a visual inspection of the exposed concrete is the first step in an in-situ examination of a structure. The purpose of such an examination is to locate and define areas of distress or deterioration. A condition survey will usually include a mapping of the various types of concrete deficiencies that might be found such as cracking, surface problems (disintegration and spalling) and joint deterioration.

It is important that the conditions observed be described in unambiguous terms that can be used in the evaluation of the current condition of the structure to be able to take engineering and management actions for the repair and maintenance of the structure. Terms typically used during a visual inspection are listed in Figure 9.3. This information is included for determining the Deduct Values and for producing the confidence level (CL) in ECON program for a good inspection, analysis and evaluation.

The evaluation management interface for evaluation of concrete (ECON) is a Visual Basic interface shown in Figure 6.6 which is structured with three different objects as cracking, scaling and disintegration and spalling and delamination. The user can obtain assistance from the REPCON database of pictures alongside the descriptive information attached to each type of distress. Visual information (photographs and drawings) such as the one shown in Figure 9.4 enhance the interpretation of results and can often describe failure modes for materials and structures.

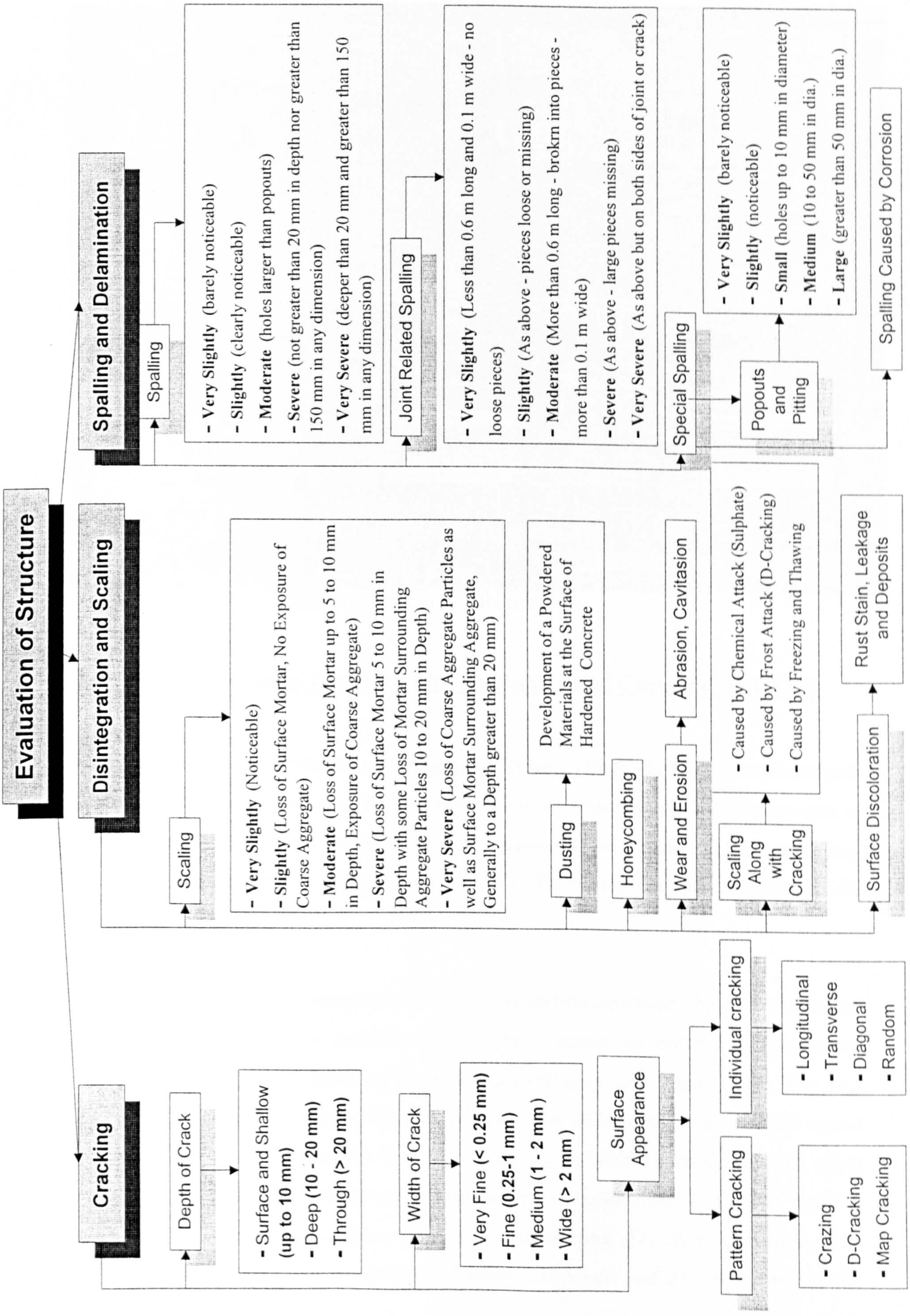


Figure 9.3 - Distress categories used in a visual inspection.

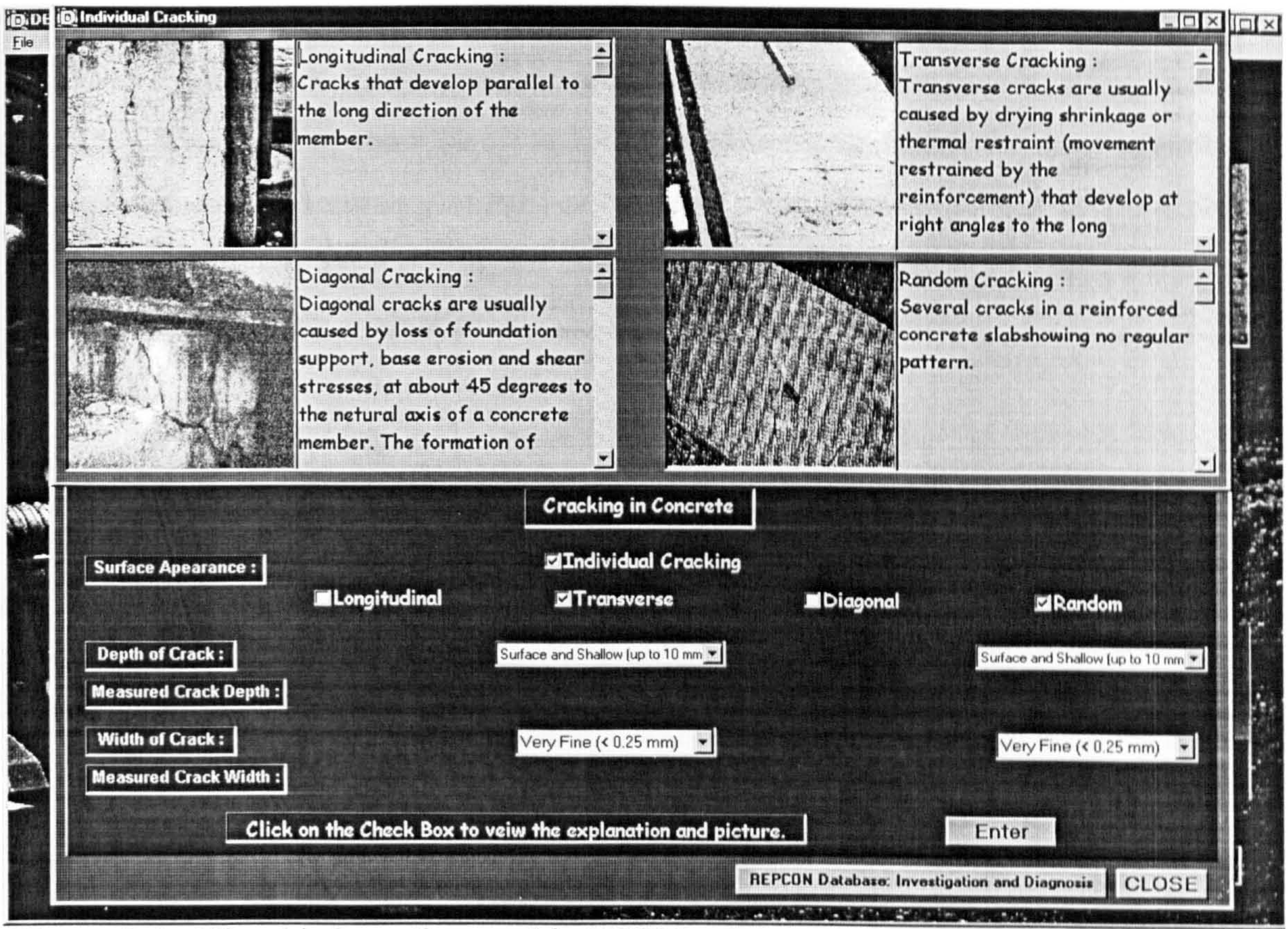


Figure 9.4 - Visual information used in ECON program.

9.9 The Confidence Level for the Evaluation of Concrete (ECON)

One objective of an Evaluation Management System (EMS) is to create assessment procedures that will allow the current condition of the structure, and its components to be expressed numerically to take the best recommended action in the repair and maintenance management. The criteria for the evaluation of a concrete structure are shown in Table 9.1.

Once the condition of the structure is understood and documented, the next step in the maintenance management process is to initiate action to correct unsatisfactory conditions and to begin planning for future maintenance and repair needs. For this purpose, a quantitative rating system for the condition of concrete in a structure would make possible the determination of which components within a structure most merit repair. The Evaluation Confidence Level (ECL) extends from 0 to 100, with 0 representing *Very Poor* condition and 100 representing *Excellent* condition. The Confidence Level (CL) is divided into *Minor*, *Moderate* and *Major* zones. In the minor zone (85-100), condition and function are generally at a level at which only periodic investigation and/or possible protection is needed. Structures falling in the moderate zone (50-70) show *Good* and *Fair* conditions for which the most potential for maintenance and repair alternatives typically exist. The conditions of *Poor* and *Very Poor* in major zone (0-30) are enough to warrant immediate attention and to recommended a safety evaluation.

Table 9.1 - The Confidence Level (CL) for the Evaluation of Concrete (ECON) structure.

Zone	Confidence Level (CL)	Description	Recommended Action
Minor	95 - 100	**Excellent:** No noticeable impairments.	Prompt action is not required, but periodic investigation is recommended. In some cases, protection might be needed.
	85 - 94	**Very Good:** Barely noticeable impairments. Some ageing or dusting may be visible.	
Moderate	70 - 84	**Good:** Clearly noticeable impairments. Only minor defect, damage and deterioration are evident.	Detailed investigation and economic analysis of repair alternatives are recommended. In some cases, appropriate repair and protection methods will be needed.
	50 - 69	**Fair:** Moderate impairments. Some defect, damage and deterioration are evident, but concrete remains serviceable.	
Major	30 - 49	**Poor:** Severe impairments in at least some major components of the structure have been occurred. Concrete remains serviceable.	Detailed investigation and an engineering evaluation should be made to determine the demand for repair, replacement strengthening and stabilisation. Safety evaluation is recommended.
	0 - 29	**Very Poor:** Very severe and extensive impairments in most components of the structure. General failure or a complete failure of structural components.	

The Confidence Level (CL) prescribed here applies to concrete structures in general. The rating system described allows the Confidence Level to be determined by visual inspection using limited equipment such as binocular, covermeter and ruler. Values in each parts of progressing are properly interpreted as representing the current conditions found at the time the structure was inspected and rated. The rating is related to structural integrity and serviceability of the structure. The Confidence Level system is not intended to replace the detailed investigation needed to fully document structural deficiencies, to identify their causes and to formulate plans for correcting them. An extended investigation comprising detailed investigation and analysis, and engineering evaluation should be made when the Confidence Level is less than 50.

One of the main uses of Confidence Level (CL) values is to track changes in condition over time, as illustrated in Figure 9.5. With historical trends and knowledge of the structure environment, future rates of impairment may be estimated and used to plan the timing of repairs and corresponding maintenance expenditure.

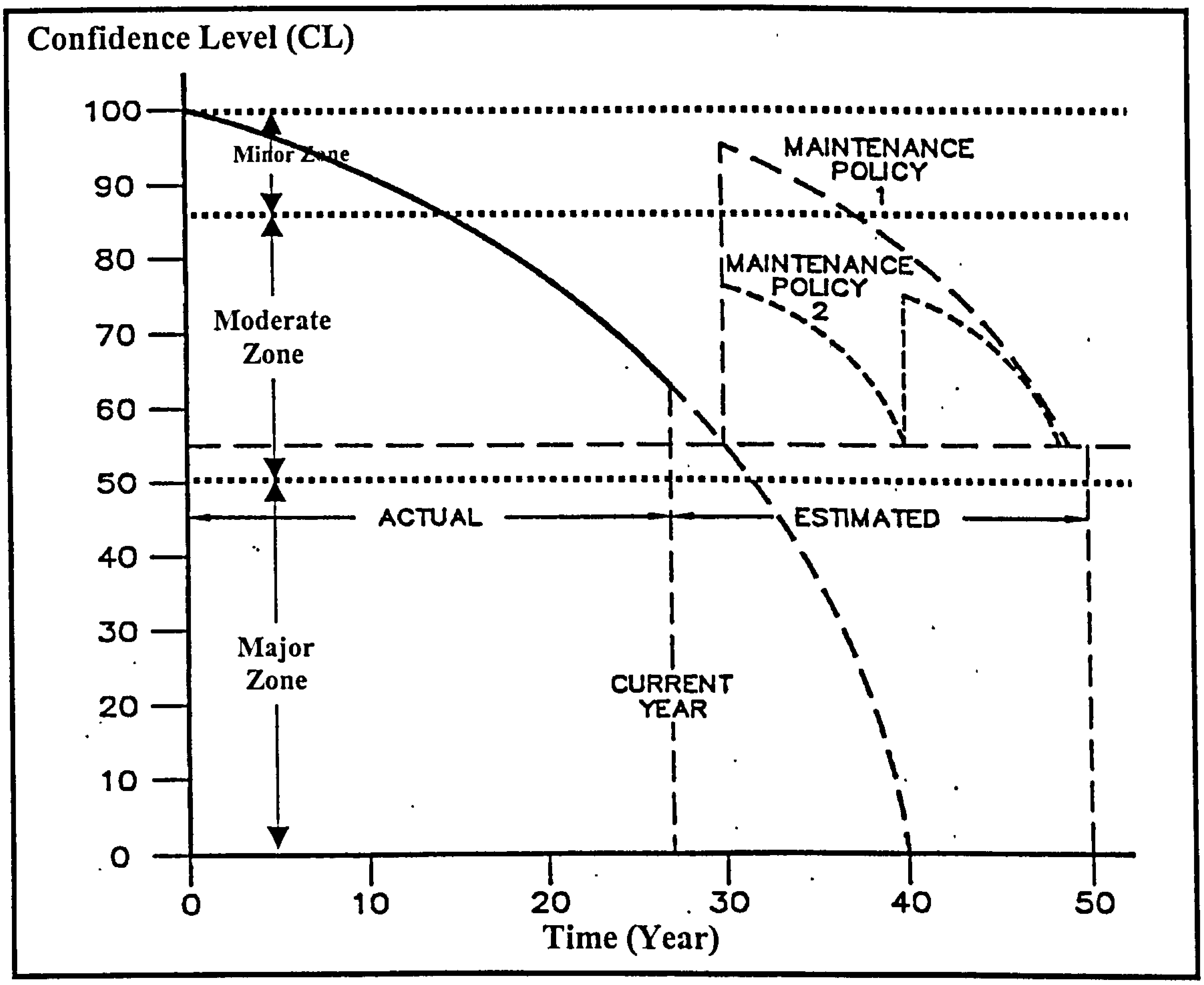


Figure 9.5 - Using Confidence Level (CL) values to track condition changes over time (Oliver, 1998).

9.10 Development of Deduct Values for Various Distresses in Concrete Structures

Confidence Level (CL) is developed by assigning specific Deduct Values to various types of distress in the concrete. These types of distress are defined in Section 9.8 by making a visual inspection of concrete in service. Primary Deduct Values are determined with the intent of obtaining a CL of 50 when the severity of an individual distress caused the safety of the structure to become questionable i.e. 50 is the critical value below which failure occurs. Deduct Values are subtracted from 100 to determine the Confidence Level (CL). The exact calculated Confidence Level from Deduct Values is determined by collecting subjective expert ratings based on the condition described in Table 9.1. The system is designed to be independent of the inspectors. However a combination of the field approach and experience with different inspectors in determining the Confidence Level will influence the quality of their decision. Therefore, a variation of ±10 in the Confidence Level for a structure component can be expected.

The Deduct Value is determined by visual inspection and by recording the information needed in the field inspection. The inspection and condition assessment procedure for determining Deduct Values is based on simple visual inspection techniques. If the condition of the structure being inspected is severely damaged i.e. a Confidence Level of below 50 more detailed investigation and engineering evaluation should be made.

The field inspection generates data for input to the PC-based REPCON Management System for evaluation of the current state of the structure. The REPCON Management System typically comprises modules such as preliminary inspection, inventory and review of existing documents to allow the user to take engineering and management decisions and to undertake a comprehensive investigation and condition survey. Review of existing documents such as construction or as-built drawings of the structure are necessary to determine such factors as physical dimensions and reinforcing details which are needed for the inspection. Some of the required information is not used directly in producing Confidence Level (CL) values but is considered necessary for a good inspection, analysis, and evaluation.

9.11 Distress Categories and Deduct Values

Deduct Values for various distress categories that tend to result in cracking in concrete, disintegration and scaling, spalling and delamination are shown in Tables 9.2 to 9.6. An inspector should be familiar with the types of distress before performing an inspection to determine the Deduct Value. Deduct Values are based on considering previous works done and the author's opinion and experience. They involve two considerations:

(1) The knowledge and experience of expert engineers in the safety of the structure which has been degraded by various types of distress, and
(2) Serviceability of the structure.

9.11.1 Cracking in Concrete

A number of crack categories are provided including individual cracks such as longitudinal, transverse, diagonal and random, and such pattern cracking as crazing, D-cracking and map cracking. Deduct Values for crack categories shown in Table 9.2 are dependent on crack width and depth. By comparing ACI (1996), BSI (1997) and RILEM (1994) reports with U.S. Army Corps of Engineers (1995), crack width is classified into Very Fine (< 0.25 mm), Fine (0.25 – 1.0 mm), Medium (1.0 – 2.0 mm), and Wide (> 2.0 mm). The three categories generally used to describe the depth of cracking are Surface and Shallow (up to 10 mm), Deep (10 – 20 mm) and Through (> 20 mm). This category is based on the author's research, the U. S. Army Corps of Engineers recommendations (1995) and the size of coarse aggregates (19 – 25 mm) used in the concrete.

Table 9.2 - Deduct values for cracking in concrete structures.

Surface Appearance	Type of Crack	Depth of Crack*	Deduct Value – Width of Crack: Very Fine < 0.25 mm	Fine 0.25–1mm	Medium 1 – 2 mm	Wide > 2 mm
Pattern	Crazing	Surface and Shallow	5	10	-	-
	D-Cracking	Surface and Shallow	5	10	-	-
		Deep	10	20	30	40
		Through	15	30	40	50
	Map Cracking	Surface and Shallow	5	10	20	30
		Deep	10	20	30	40
		Through	15	30	40	50
Individual	Longitudinal	Surface and Shallow	5	10	20	30
		Deep	10	20	30	40
		Through	20	30	50	70
	Transverse	Surface and Shallow	2	5	10	15
		Deep	5	10	15	30
		Through	10	15	25	40
	Diagonal	Surface and Shallow	10	20	30	40
		Deep	15	30	40	60
		Through	20	40	60	80
	Random	Surface and Shallow	5	10	20	30
		Deep	10	20	30	40
		Through	15	25	40	60

* **Depth of Crack:** Surface and Shallow (up to 10 mm), Deep (10 –20 mm), Through (> 20 mm)

9.11.2 Types of Surface Distress

Surface distress is categorized into disintegration, scaling, spalling and delamination. A number of concrete surface-loss modes such as those shown in Tables 9.3 to 9.5 is listed including scaling, dusting, honeycombing, wear and erosion, surface discolouration and scaling along cracking. A number of concrete volume-loss categories shown in Table 9.6 is provided comprising spalling, popouts and pitting, joint related spalling and spalling caused by corrosion. Descriptions of surface appearance are provided by comparing ACI (1996), BSI (1997) and RILEM (1994) reports with the U.S. Army Corps of Engineers results (1995). Deduct Values depend on estimated depth, extent and exposure of coarse aggregates.

Table 9.3 - Deduct Values for Textural Features of Surface of Concrete.

Type of Distress	Rating	Description (Surface Appearance)	Deduct Value
Rust Stain	Slightly	Noticeable surface rust staining	10
	Severe	Surface rust staining along with cracking	15
Leakage and Deposits	Very Slightly	Barely noticeable surface discoloration	2
	Slightly	Noticeable surface efflorescence	5
	Moderate	Surface material less than 10 mm thick	10
	Severe	Surface material more than 10 mm thick	15
	Very Severe	Surface material along with stalactite	20

Table 9.4 - Deduct values for scaling and disintegration in surface of concrete.

Type of Distress	Rating	Description (Surface Appearance)	Deduct Value
Scaling	Very Slightly	Noticeable	5
	Slightly	Loss of surface mortar, no exposure of coarse aggregate	10
	Moderate	Loss of surface mortar up to 5 to 10 mm in depth, exposure of coarse aggregate	20
	Severe	Loss of surface mortar 5 to 10 mm in depth with some loss of mortar surrounding aggregate particles 10 to 20 mm in depth	30
	Very Severe	Loss of coarse aggregate particles as well as surface mortar surrounding aggregate, generally to a depth greater than 20 mm	50
Honeycombing	Very Slightly	Barely noticeable	2
	Slightly	Noticeable	5
	Small	Holes up to 10 mm in diameter	10
	Medium	Holes between 10 to 50 mm in diameter	20
	Large	Holes greater than 50 mm in diameter	30
Dusting	Slightly	Any area	5
	Severe	More than 50% of area	10
Wear and Erosion (Abrasion)	Very Slightly		2
	Slightly		5
	Moderate	The same as Scaling	10
	Severe		20
	Very Severe		30
Wear and Erosion (Cavitation)	Very Slightly		5
	Slightly		10
	Moderate	The same as Scaling	20
	Severe		40
	Very Severe		60

Table 9.5 - Deduct values for scaling and disintegration along with cracking in surface of concrete.

Type of Distress	Rating	Description (Surface Appearance)	Deduct Value
Caused by Frost Attack (D-Cracking)	Slightly	Less than 25% of area with fine cracks	5
	Moderate	More than 25% and less than 50% of area with medium cracks	10
	Severe	More than 50% of area with wide cracks	30
Caused by Chemical Attack (Sulphate, ...)	Very Slightly	Noticeable	5
	Slightly	Loss of surface mortar with very fine cracks, no exposure of coarse aggregate	15
	Moderate	Loss of surface mortar up to 5 to 10 mm in depth with fine map cracks, exposure of coarse aggregate	25
	Severe	Loss of surface mortar 5 to 10 mm in depth with some loss of mortar surrounding aggregate particles 10 to 20 mm in depth along with medium map cracks	40
	Very Severe	Loss of coarse aggregate particles as well as surface mortar surrounding aggregate, generally to a depth greater than 20 mm along with wide map cracks	60
Caused by Freezing and Thawing	The same as chemical attack	The same as scaling	The same as scaling

9.12 Calculation of the Component Confidence Level (CCL)

Once the distress modes in each component of the structure to be rated are determined, the Component Confidence Level (CCL) can be calculated. By inputting the distress types into the REPCON Management System software, hand calculation of Deduct Values and the Confidence Level (CL) can be avoided. By considering previous work done, generating a model for concrete distress simulation (Section 9.7) and the author's experience and knowledge, the following formula, which was recommended by Bullock et al (1995), is used for calculating the Component Confidence Level (CCL).

$$CCL = 100 - [1.0(DV_1) + 0.4(DV_2) + 0.2(DV_3) + 0.15(DV_4) + 0.1(DV_5)] \quad (9\text{-}11)$$

Table 9.6 - Deduct Values for Spalling and Delamination in Surface of Concrete.

Type of Distress	Rating	Description (Surface Appearance)	Deduct Value
Spalling	Very Slightly	Barely noticeable	5
	Slightly	Clearly noticeable	10
	Moderate	Holes larger than popouts	20
	Severe	Not greater than 20 mm in depth nor greater than 150 mm in any dimension	30
	Very Severe	Deeper than 20 mm and greater than 150 mm in any dimension	50
Popouts and Pitting	Very Slightly	Barely noticeable	2
	Slightly	Noticeable	5
	Small	Holes up to 10 mm in diameter	10
	Medium	Holes between 10 to 50 mm in diameter	20
	Large	Holes greater than 50 mm in diameter	30
Spalling Caused by Corrosion	Slightly	Any area	30
	Severe	More than 50% of area	60
Joint Related Spalling	Very Slightly	Less than 0.6 m long and 0.1 m wide – no loose pieces	2
	Slightly	As above – pieces loose or missing	5
	Moderate	More than 0.6 m long – broken into pieces more than 0.1 m wide	10
	Severe	As above – large pieces missing	20
	Very Severe	As above but on both sides of joint or cracks	30

The Component Confidence Level (CCL) is based on the five largest deduct values (DV), with DV_1 the largest value and other values in descending order to the fifth largest, DV_5. Table 9.7 shows an example of how the Component Confidence Level (CCL) for a component (such as beam or column) has been calculated.

Table 9.7 - Example of calculation of the CCL for a component.

Step 1: Inspect component to determine distresses and quantities.

Step 2: Calculate Deduct Values for each distress.

Step 3: Rank the Deduct Values in descending order to the smallest. Only the five largest are used in the Component Confidence Level (CCL) calculation.

Distress and Quantity (Step 1)	Deduct Value (Step 2)	Rank (Step 3)
1- Map cracking, deep and 2 mm wide	30	DV1
2- Leakage and deposit, slightly	10	DV5
3- Dusting, slightly	5	-
4- Rust staining, severe	15	DV4
5- Transverse crack, through and 2 mm wide	25	DV2
6- Popouts, medium	20	DV3

Step 4: Calculate the CCL based on the ranked Deduct Values:

$$CCL = 100 - [1.0(DV_1) + 0.4(DV_2) + 0.2(DV_3) + 0.15(DV_4) + 0.1(DV_5)]$$

$$CCL = 100 - [1.0(30) + 0.4(25) + 0.2(20) + 0.15(15) + 0.1(10)] = 52.75$$

The CCL is 53 which is Fair (Table 9.1).

To determine a component confidence level (CCL) by ECON program, the type of information and observations needed to be entered such as the one shown in Figure 9.4 and finally the calculation confidence level for each component is done. Figure 9.6 illustrates the CCL for a bridge deckslab as calculated in Table 9.7.

After identifying the Deduct Value for each distress of a component and determining the confidence level for each component of a structure, the confidence level of structural components is included in a format such as the one shown in Figure 9.7.

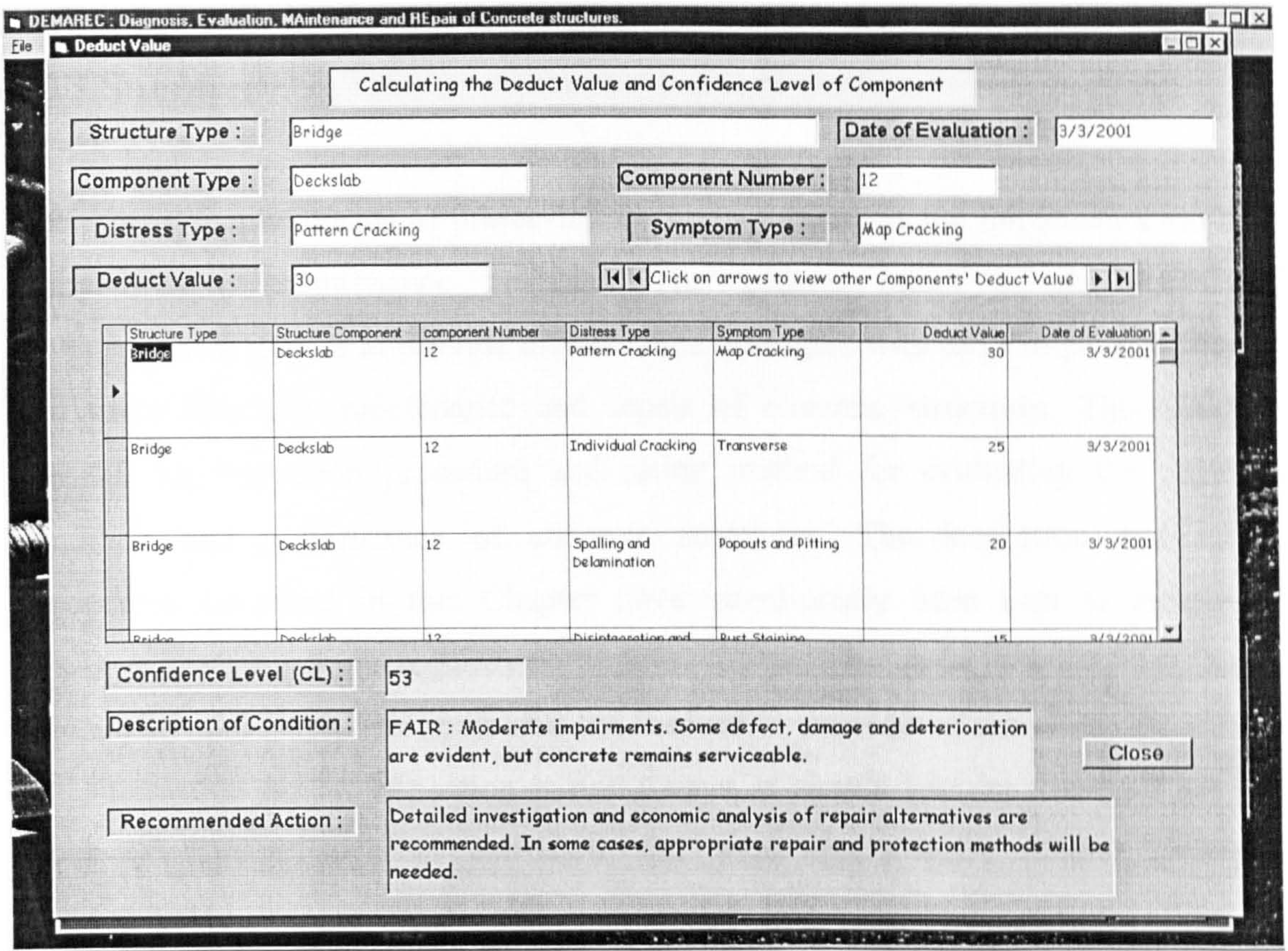


Figure 9.6 - A screen dump of calculation of the CCL for a bridge deckslab as shown in Table 9.7 by ECON program.

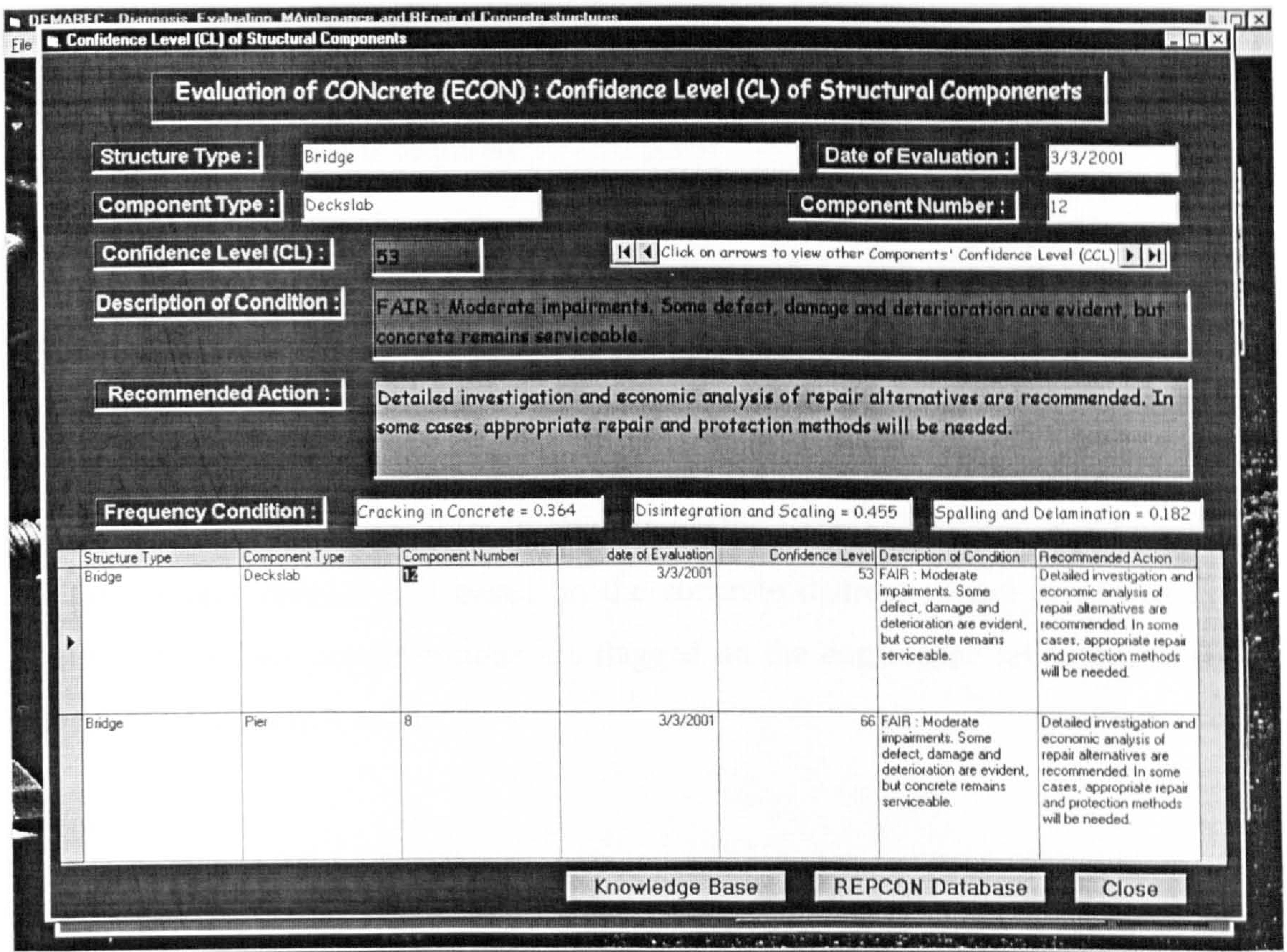


Figure 9.7 - A screen dump of confidence level of structural components.

9.13 Summary

The most effective means of preserving concrete surfaces is the implementation of a comprehensive maintenance program. The general intent of the REPCON management system is to provide maintenance managers with tools to promote easier and more effective maintenance and repair of concrete structures. This Chapter contains an inspection procedure and rating method for evaluating the physical condition and performance of concrete structures. The inspection and rating procedures described in this Chapter have intentionally been kept as simple as possible. The inspections require only simple tools such as a tape measure, dial gauge, covermeter and ruler. The tools and the inspection procedures are relatively simple but preparation for an inspection is not always as simple because there are several types of distress such as corrosion and wear that require several types of measurement.

Once the data is obtained software has been developed to compute the confidence level (CL) directly from the inspection records. The CL is a numbered scale from 0 to 100 that indicates the current state of the structure. Confidence levels below 50 indicate that immediate repair may be necessary or possibly that a more detailed inspection and analysis is required.

Several types of distress reduce the confidence level according to rules based on the knowledge, experience and opinion of experts. They involve two considerations: (1) the knowledge and experience of expert engineers in the safety of category of the structure which has been degraded by various distresses, and (2) serviceability of the structure. A combined confidence level (CL) for each component is calculated by weighting each distress and based on the concrete distress model described in this Chapter. Structural considerations are flagged on the confidence level (CL) table on the basis of subjective safety.

Chapter 10

DEMAREC System Evaluation

10.1 Introduction

The research presented in this thesis is the development of an application which consists of three modules that deal with the gathering of repair of concrete information in a database, solving concrete problems with expert system technology and the assessment of uncertainty problems in the evaluation of a concrete structure. The main implementation part of this application is characterised by:

- an input and reporting system in the form of a visual edit screen,
- development an expert system using M.4 as a shell,
- creating a database using Microsoft Access and
- a performance rating procedure for the evaluation of deteriorated concrete in a concrete structure which embodies Visual Basic programming.

The first part of this Chapter critically evaluates DEMAREC application which is examined the virtues and deficiencies of DEMAREC in terms of its usability and implementation. The experience gained in implementing DEMAREC reveals several insights about the utility and integrity of the system. Then it is followed by the evaluation of DEMAREC in its various components comprising the DEMAREC-EXPERT system, the REPCON database and the ECON evaluation program.

The remainder of the Chapter presents the main outputs from this research work and validates the system through three case studies. In these case studies, it is shown that the results of this research could have been used to enhance the process of determining the causes of failure and in selecting the repair methods.

10.2 Knowledge-Based Expert Systems Evaluation

Knowledge-based expert systems are becoming standard products in engineering applications developed by commercial companies to solve various ranges of problem (Nouas, 1993). Because of increasing commercial interest and future growth of these systems, the reliability of a knowledge-based expert system must be assured before employing a system for practical use. Therefore, it is the responsibility of the developers to come to grips with the problems of accuracy and reliability.

Assessing the performance of the system at its decision-making task is one of the crucial aspects of the evaluation process. The mechanism for performing the needed formal evaluation of knowledge-based systems is provided by verification and validation (Gonzalez et al, 1993). Verification confirms that the system is correctly implemented. It consists of two basic processes; checking for compliance with the specification and checking for the consistency and completeness of the knowledge base (i.e. syntactic and semantic errors). When verifying a knowledge-based system both the inference engine and the knowledge base must be considered.

The system validation is performed in collaboration with the domain knowledge. It ensures that the domain knowledge is correct and the system solves problems within the domain correctly and accurately. The critical criteria to consider in validating the system knowledge base are the correctness and the accuracy of the system output, the correctness of the reasoning techniques and the sensitivity, the reliability and the robustness of the knowledge base. Although the inference engine is an important component of the system, it is presumed that because a commercial shell was used in this research, the inference engine has already been validated and verified by its developers.

The performance evaluation of the knowledge-based systems in most prototype systems is focused on the problem-solving processes. A knowledge-based system should be easy to use so that the user concentrates on solving the problem at hand. Learnability and clarity are both functions of the ease of use requirement and influence the efficiency with which the system is deployed (Anumba, 1994). Concerning the system usability, there is an agreement among developers that knowledge-based systems user acceptance can be increased by incorporating end-users early in the development process (Nouas, 1993).

10.2.1 DEMAREC-EXPERT System Evaluation

This Section is concerned with the evaluation of the DEMAREC-EXPERT system which can be described as a two-stage process; 1) initial prototyping and evaluation and 2) final evaluation after development. The first stage is verification of the rules in the knowledge bases during the development of the system. In this stage the rule structure, organisation and knowledge gaps are identified and corrected. This task was facilitated by the design approach adopted in developing the system.

Further evaluation was carried out in the second stage of the evaluation process and consisted of the validation of the system output. This procedure was performed by synthesising test cases for hypothetical conditions by selecting different types of distress. Final modifications required for the rules and procedures were carried out at this stage. Finally the system usability was evaluated by the developer. In a commercial situation, a customer clinic might be established for this, but within the context of academic research, this was judged to be appropriate.

First Stage – Initial Prototyping Evaluation.

The prototyping technique uses the flexibility and power of commercially available shells to create quickly a working prototype of the envisioned final system. By acquiring and representing knowledge from some limited aspects of the problem domain, the developer is able to create an initial prototype of the final system. Once the initial prototype of the system's knowledge base is developed, the system can be continuously evaluated. Subsequent additions, deletions and modifications are known as incremental development.

The representation technique used in developing the system (see Chapter 8) has significantly eased the evaluation task during development. The modelling of the knowledge base using diagnostic trees has considerably simplified the task of validation of knowledge about domain objects and verifying the code. Indeed, knowledge base objects can be tested by simply observing the behaviour of these diagnostic trees.

The initial evaluation of DEMAREC-EXPERT involved verification of the knowledge base by the developer where the rules are restructured, reorganised and rewritten to eliminate problems with the knowledge base. The syntactic errors in the rules were automatically detected by M.4 as a shell development environment in which the developer can view the actions performed by the inference engine. Tracing the inference engine's actions helps the developer to locate where the problems are originating.

The M.4 development environment offers a number of useful debugging tools to the developer during the creation of a knowledge base. Some of the most useful tools are as follows:

- ability to trace the rule evaluation process along with the search path of the inference engine,
- ability to ask why a rule is used and how a value is assigned to a parameter, and
- an inference monitor window which comprises the events, the reasoning and the conclusions windows. Inference monitor windows are used for monitoring the operations of the inference engine as it steps through the knowledge base.

Expert system developers can observe the entire rule evaluation process simultaneously with the inference engine by the monitoring of rules at run time under the M.4 development environment. First, M.4 identifies the rules which conclude the goal parameter. Until the goal parameter is completely established, the identified rules are individually evaluated in a sequence in which the inference engine locates them. The developer reviews the sequence list and makes necessary corrections to the rules to control the actual order in which the rules are evaluated (Figure 10.1). Setting the correct order of execution enables pruning of the rules by speeding up the inference engine's rule evaluation process, so eliminating the unnecessary questions asked by the inference engine.

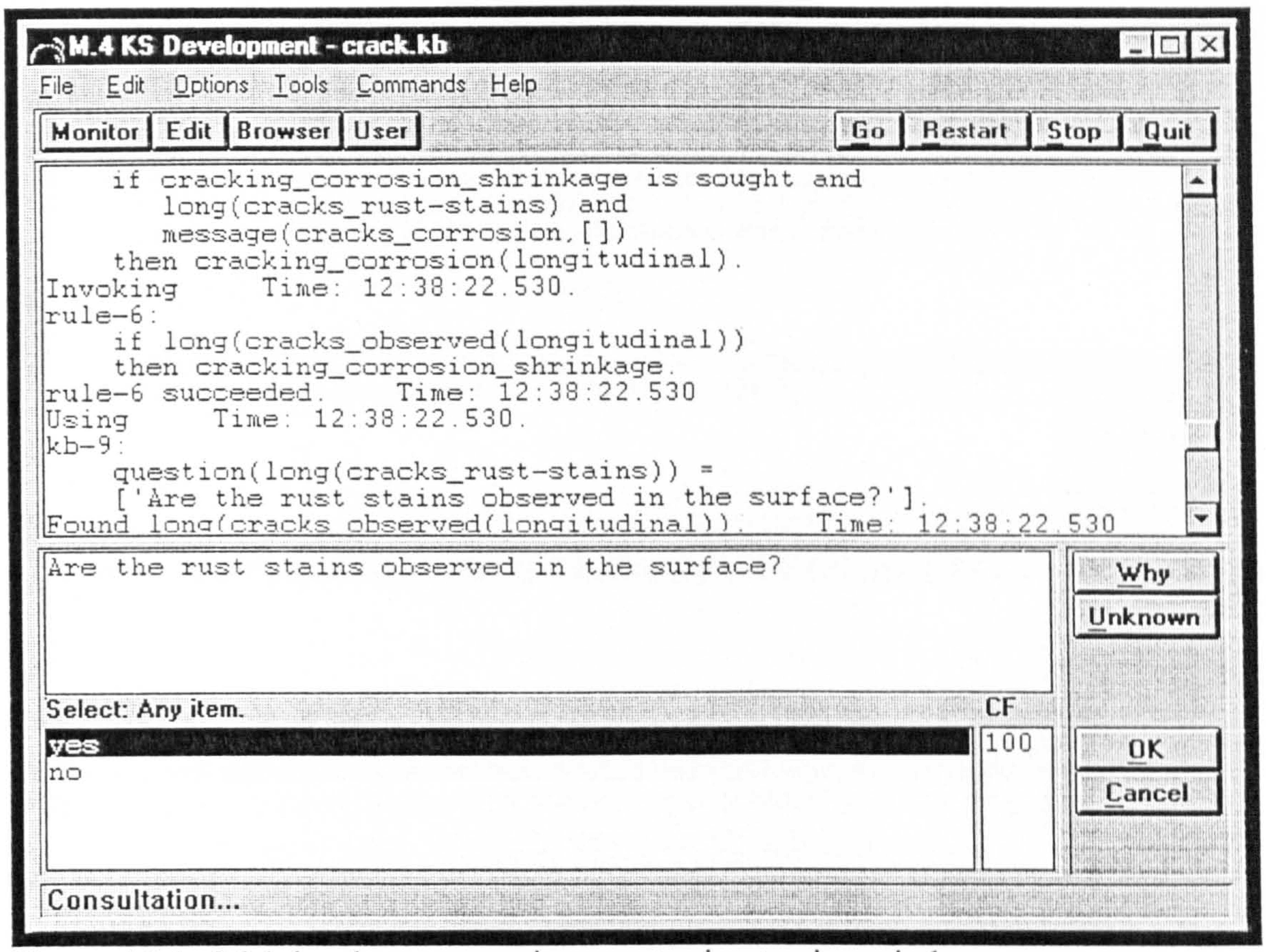


Figure 10.1 - M.4 development environment using tracing window.

During the evaluation process, it was possible to check "why" a particular rule was not used by considering the link between the rules within the knowledge base. This tool allows M.4 to display the rule premise and conclusion as well as the reason for considering that particular rule. The "why" question can also be used for determining why a question is asked during a consultation session (Figure 10.2). Any error in writing the rules can be easily identified in this way and can be corrected accordingly.

Value assignment to parameters can be verified through the interface-tracing tool. In an interface-tracing mechanism, the M.4 development environment replies showing how the parameter received that particular value by displaying the rule which determined the value for that parameter in question. A screen dump of the M.4 development environment using its interface-tracing mechanism is shown in Figure 10.3.

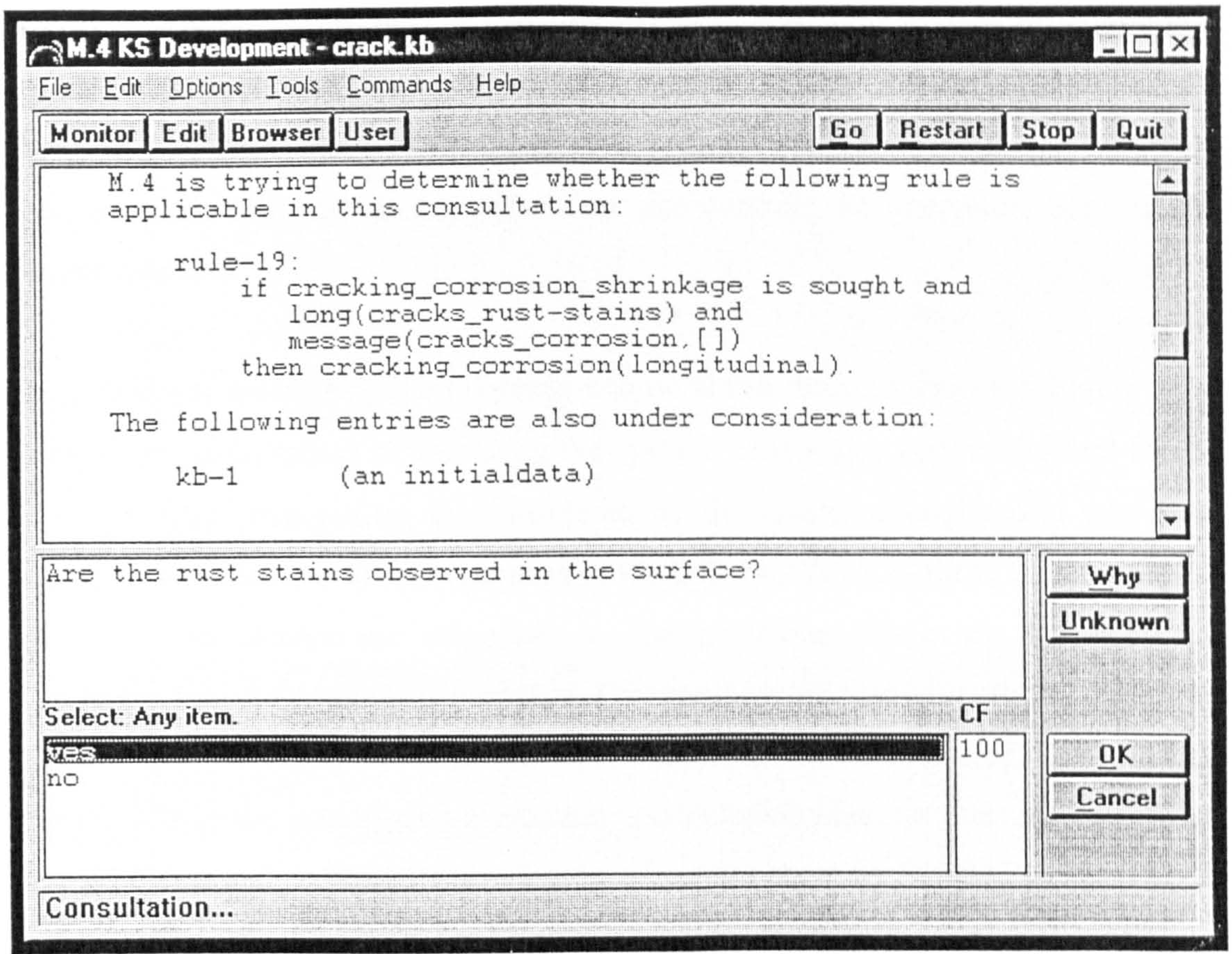


Figure 10.2 - A screen dump of M.4 development environment using *Why* question.

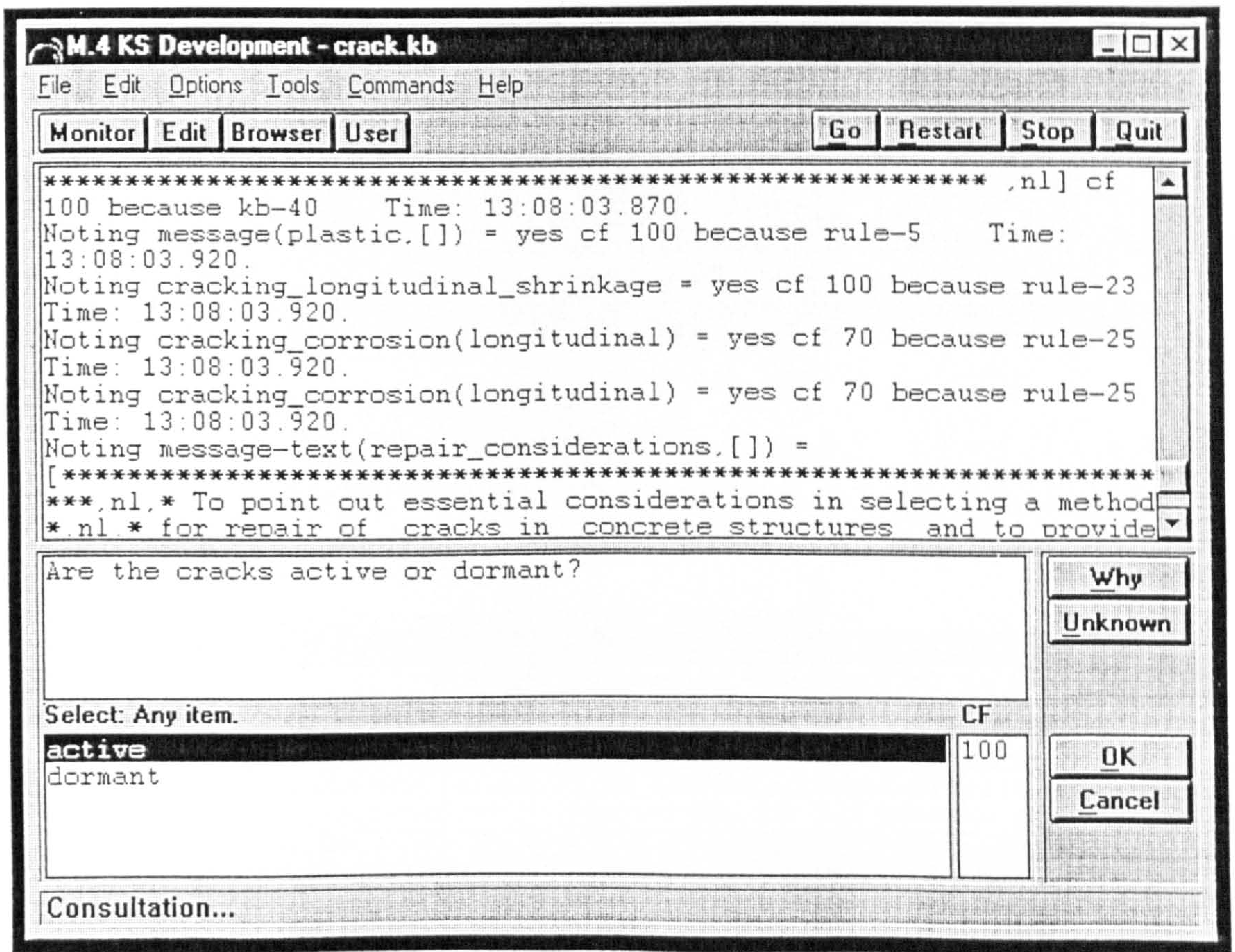


Figure 10.3 - M.4 development environment, interface-tracing tool.

For rule checking for consistency and completeness, the rule base was structured into separate rule sets, each specialising in a particular task. In each task only the corresponding rules are considered by the system. The use of rule sets not only decreases the work load on the system but also controls the interaction between the various rule sets.

The process of monitoring the inference engine at run time, as shown in Figure 10.4, is a very powerful means of validating the system. This was a very useful tool for the developer when many rules are considered by the inference engine and was more manageable in the case of rule sets used in the DEMAREC-EXPERT. In addition, the developer can change the responses to the questions which are listed by the monitoring tool for evaluation purposes. By changing the responses to the questions, the developer can verify the rules that would not have been used during the evaluation process. The initial prototyping evaluation is concluded when no rules are detected to have problems and no more incorrect suggestions are given by DEMAREC-EXPERT.

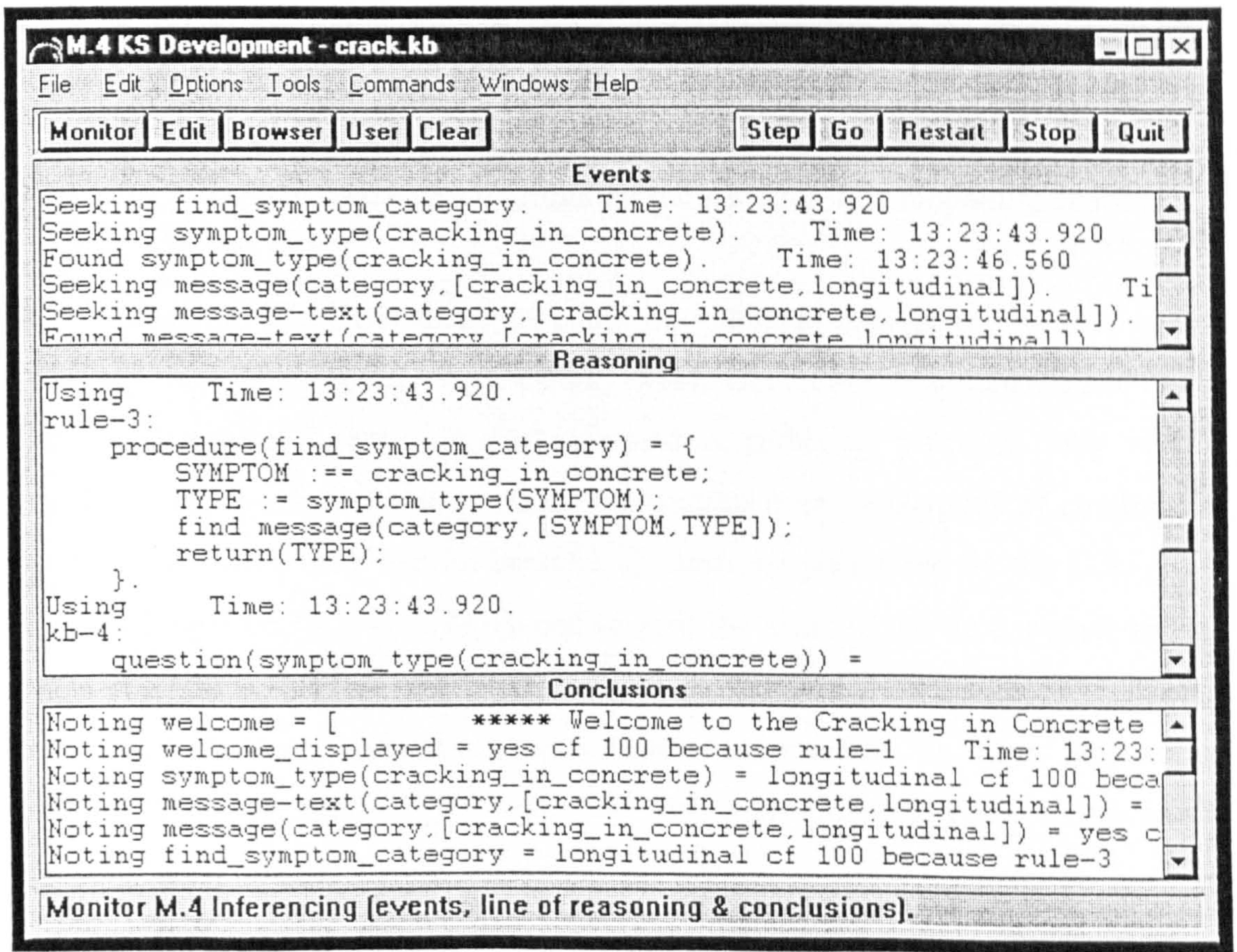


Figure 10.4 - A screen dump of M.4 development environment, inference monitor.

Second Stage – Final Evaluation after Development.

One of the characteristics of the knowledge domain is that no external experts in the repair of concrete domain were used in the validation process. The only experts who were available to validate the system results were those involved in the development of the system.

The final performance evaluation of the system was validated by three case studies shown in Sections 10.5 through 10.7. These case studies are examples of actual cases of concrete diagnosis and repair and of already stated in the literature. The system output was then compared the diagnosis and remedy obtained through DEMAREC-EXPERT system and the diagnosis and remedy actually used.

10.3 REPCON Database Evaluation

The evaluation and validation of the REPCON database in comparison with previous work carried out in the field of the repair of concrete structures is a very difficult task. This is because databases such as that used in COBDA (Cabrera et al, 1995) are used as record keeping database in order to provide a link between the theoretical knowledge and visual inspection information for statistical and modelling analysis.

Only part of the REPCON database could be validated against the repair material database called REMR (U.S. Army Corps, 1992). The REMR maintenance and repair materials database is designed for information gathering purposes only and is developed to provide technology transfer of results from evaluations of commercial repair products and their use for specific applications performed by the U.S. Army Corps of Engineers. It is also developed to give the users in the field a place to find answers to their questions about what might be the best product for their specific needs. The database contains manufacturer's information on uses, application procedures, limitations and technical data for approximately 1860 commercially available repair products.

The REMR database is menu driven and has help windows to facilitate its use. The products in the database are identified as either end-use or additive. An end-use product is a material that is used as purchased to make a repair, whereas an additive product is a material used in combination with other materials to produce an end-use product. The end-use product portion of the database contains products for maintenance and repair of concrete, steel or both. The additive product portion of the database contains products that are Portland-cement admixture, binders, fibres or special filler materials.

Emphasis was placed on comparing the information transfer of data in repair materials and methods. This comparison confirmed that the system (REPCON database) performance was good.

The final performance evaluation of the database was validated in two ways. First, hypothetical conditions synthesised by the developer were used the way in which a user interacts with REPair of CONcrete (REPCON) database by way of a brief example. Second, it is described the detail of a case study which illustrates the innovation features built into the educational and evolution modes of the REPCON management system.

10.3.1 Brief Example

As shown in Figure 10.5, any user can use the original database by reviewing the existing documents or retrieving data from database (For example about shrinkage cracking) and choose the suitable repair methods and materials along with durability recommendations. Then this user could go back to the system and contribute the new knowledge. By the using self-assessment process the competence of the user can be assessed e.g. as Experienced Generalist who might be an expert person in related subject but seeking to transfer his expertise. So this user can contribute the new knowledge in the Appendix database. Then another user which has been assessed as an Expert who can see the Original and Appendix databases and can add the new data to both of them. This expert person might use the system to take that data, which was added by Experienced Generalist, out of the Appendix and put it in the Original database as an accepted information. Because of advancements in concrete repair and evolving the system, another user as second Expert 10 years later would relegate that data to Appendix or somewhere else when it has been superseded. This is the main innovative feature which is built into the REPCON management system.

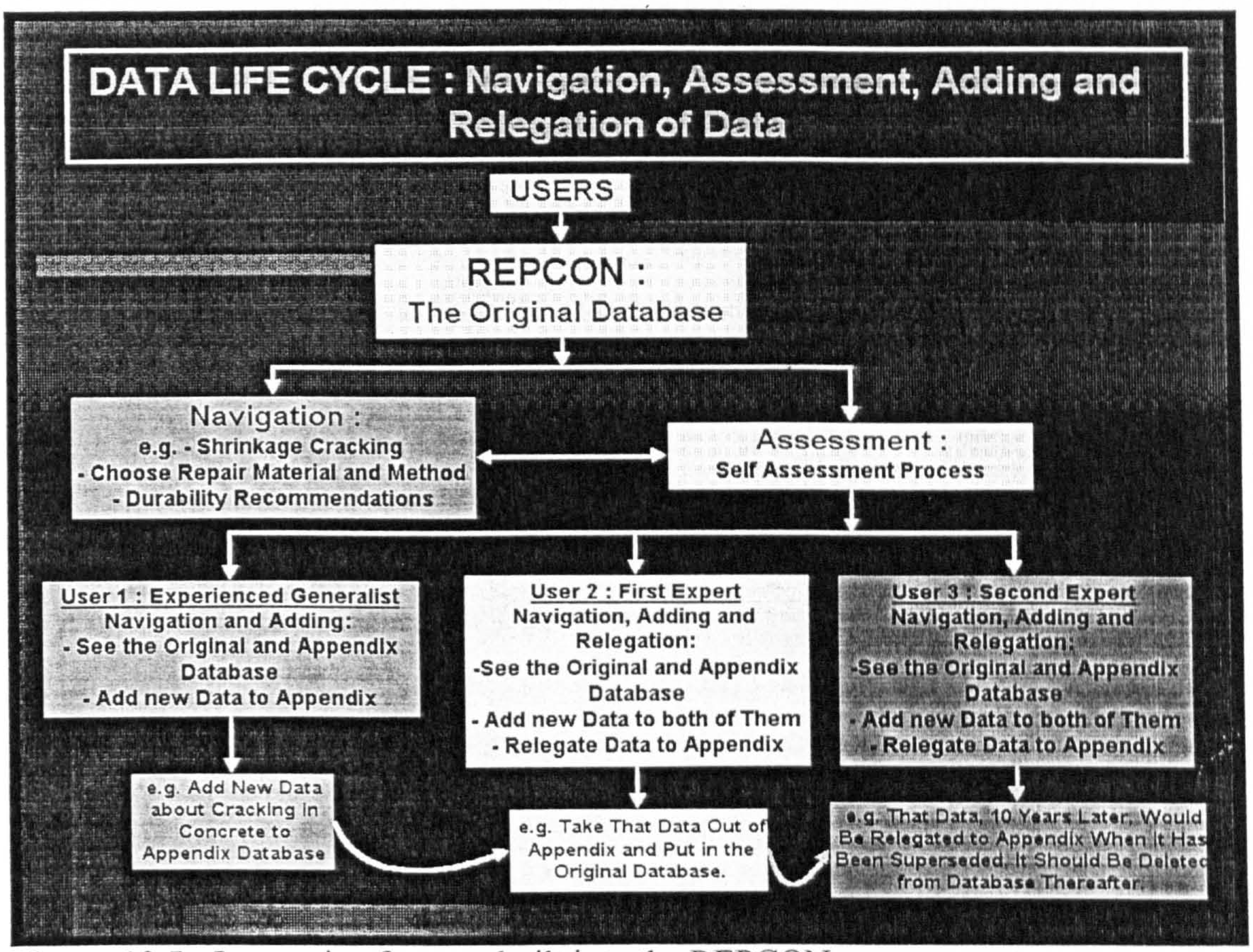


Figure 10.5 - Innovative features built into the REPCON management system.

10.3.2 Case Study

This is a data life cycle case study which represents the REPair of CONcrete (REPCON) database from the user's perspective. In this case study the way in which a user interacts with navigation, assessment, adding and relegation of data is explained and illustrated the innovative features built into it.

Figure 10.6:

In the first mode of application, EDUCATION, system in year 2001 contains information about concrete distresses, investigation and diagnosis problems, repair materials and methods and recommendations in durability. It is envisioned that the system in year 2002 used by a number of users with different levels of ability from expert to novice.

Figures 10.7 through 10.9:

The integration of pictures and descriptive information makes problem solving easier and can allow a better understanding of the repair of concrete problems, particularly for novices, trainees (Figures 10.7 and 10.8). The NDT information (Figure 10.9) is important for experienced generalists and standard practitioners who have some experience in the subject.

Figure 10.10:

Information regarding maintenance and durability of concrete is very useful for structural and construction engineers and users who may be conducting research on developing preliminary strategies.

Figure 10.11:

The modular REPCON management system allows the user to retrieve any information (For example shrinkage cracking) from the database including combined pictures and descriptive information.

Figures 10.12 and 10.13:

It is anticipated that the number of users in year 2005 and 2010 will increase and the system should encourage the more rapid development of knowledge and experience for users with lower levels of ability.

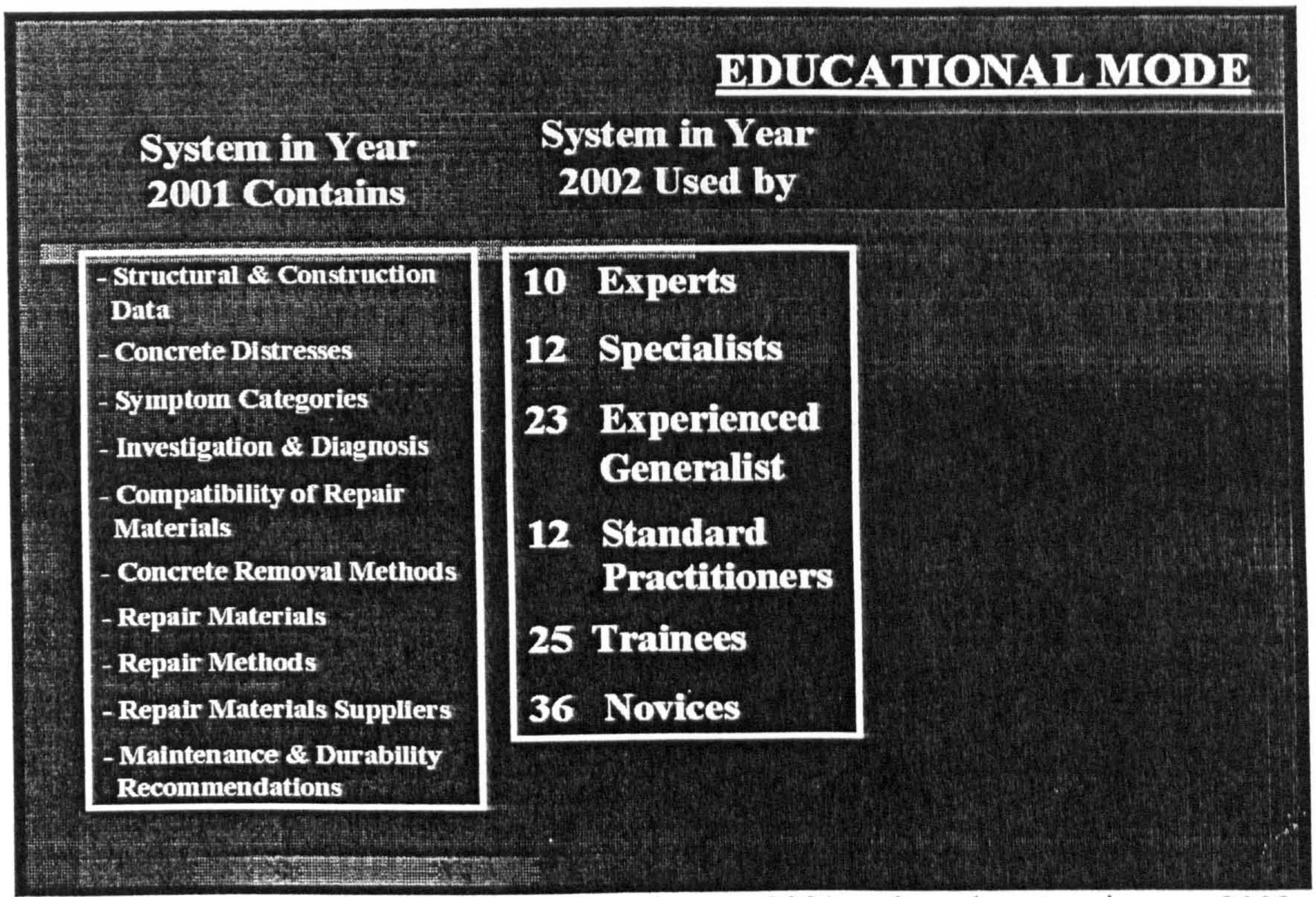


Figure 10.6 - Repair of concrete database in year 2001 and used system in year 2002.

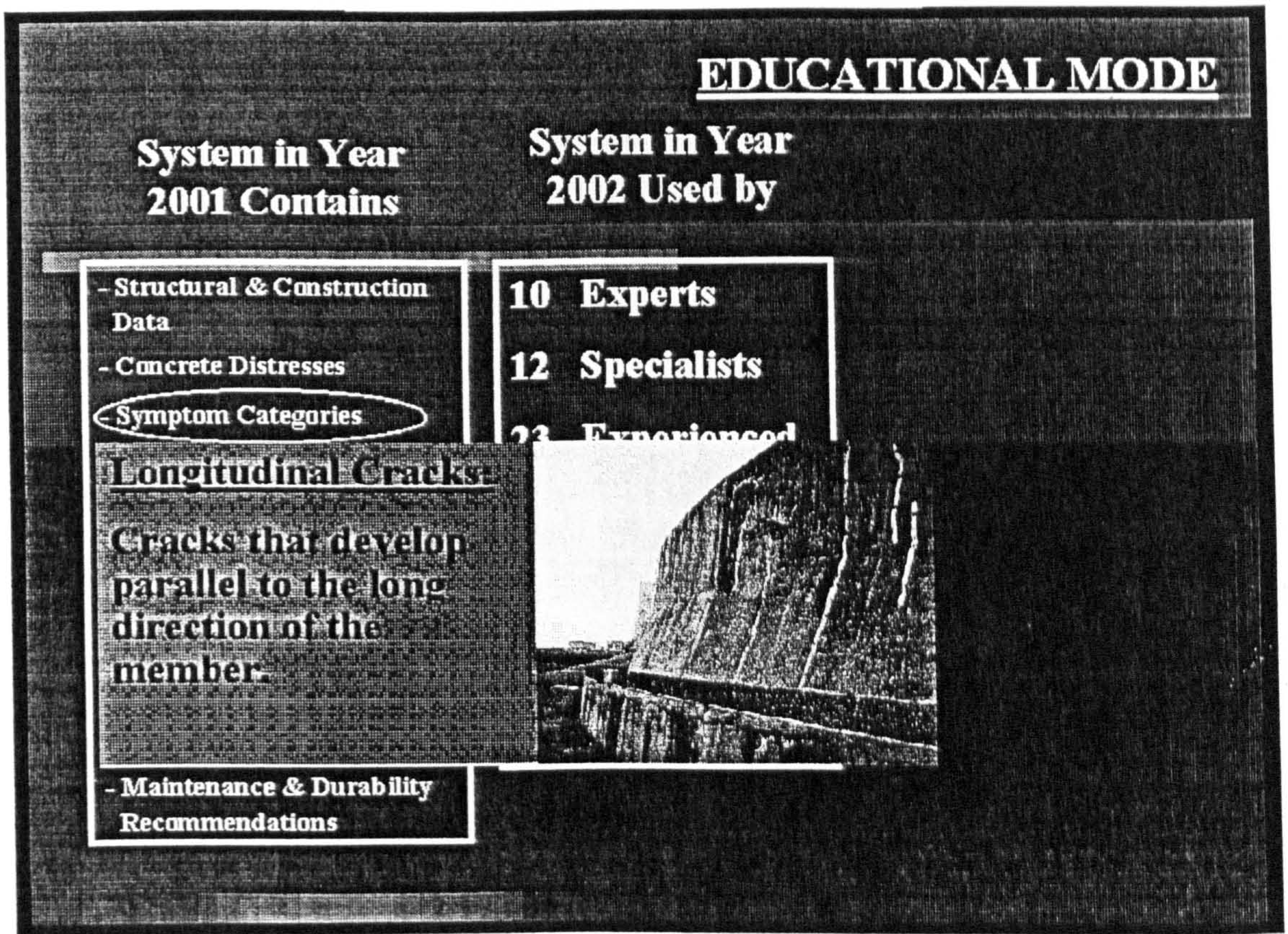


Figure 10.7 - Combination of pictures and descriptive information for better understanding of concrete problems.

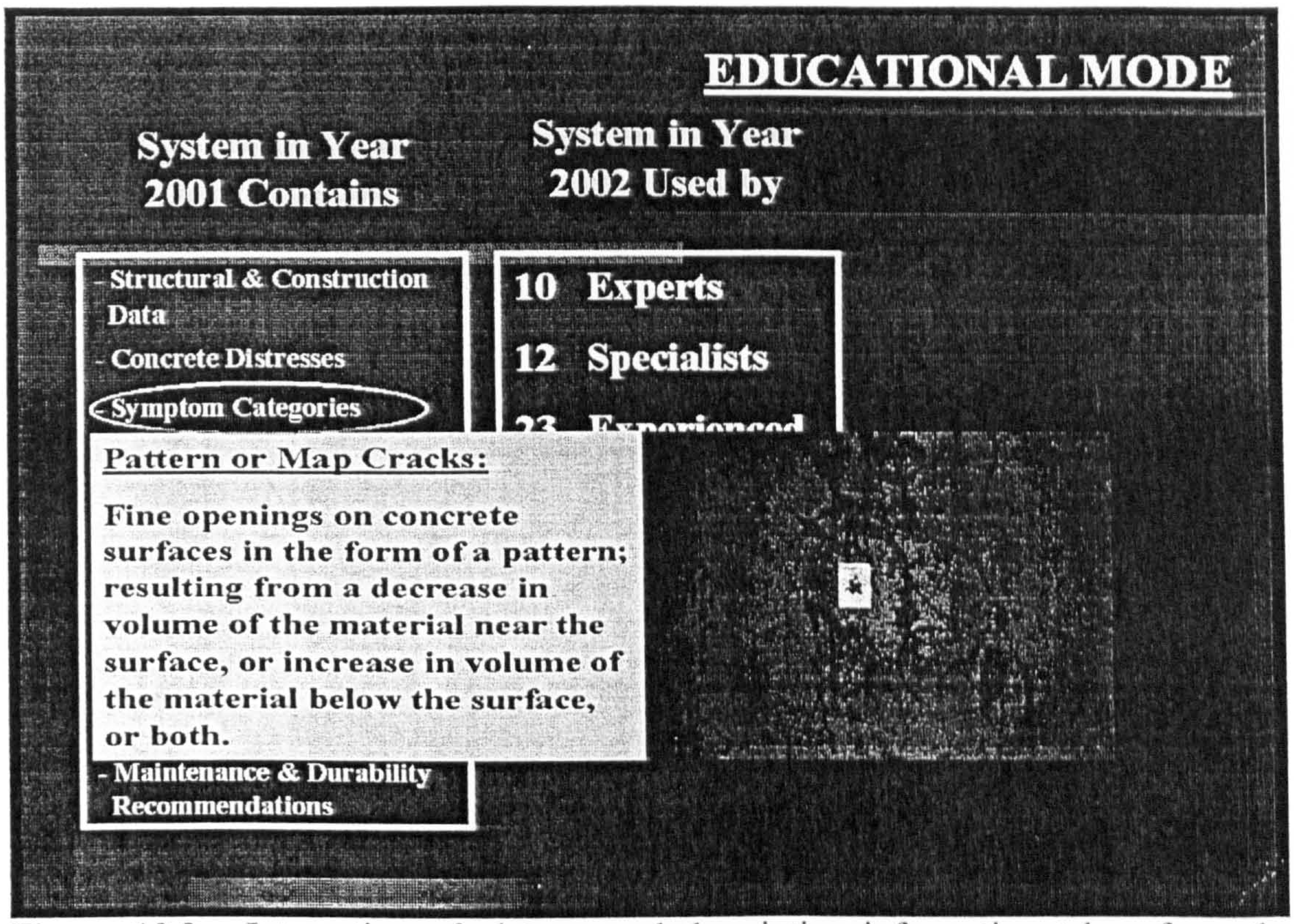


Figure 10.8 - Integrating of pictures and descriptive information taken from the database.

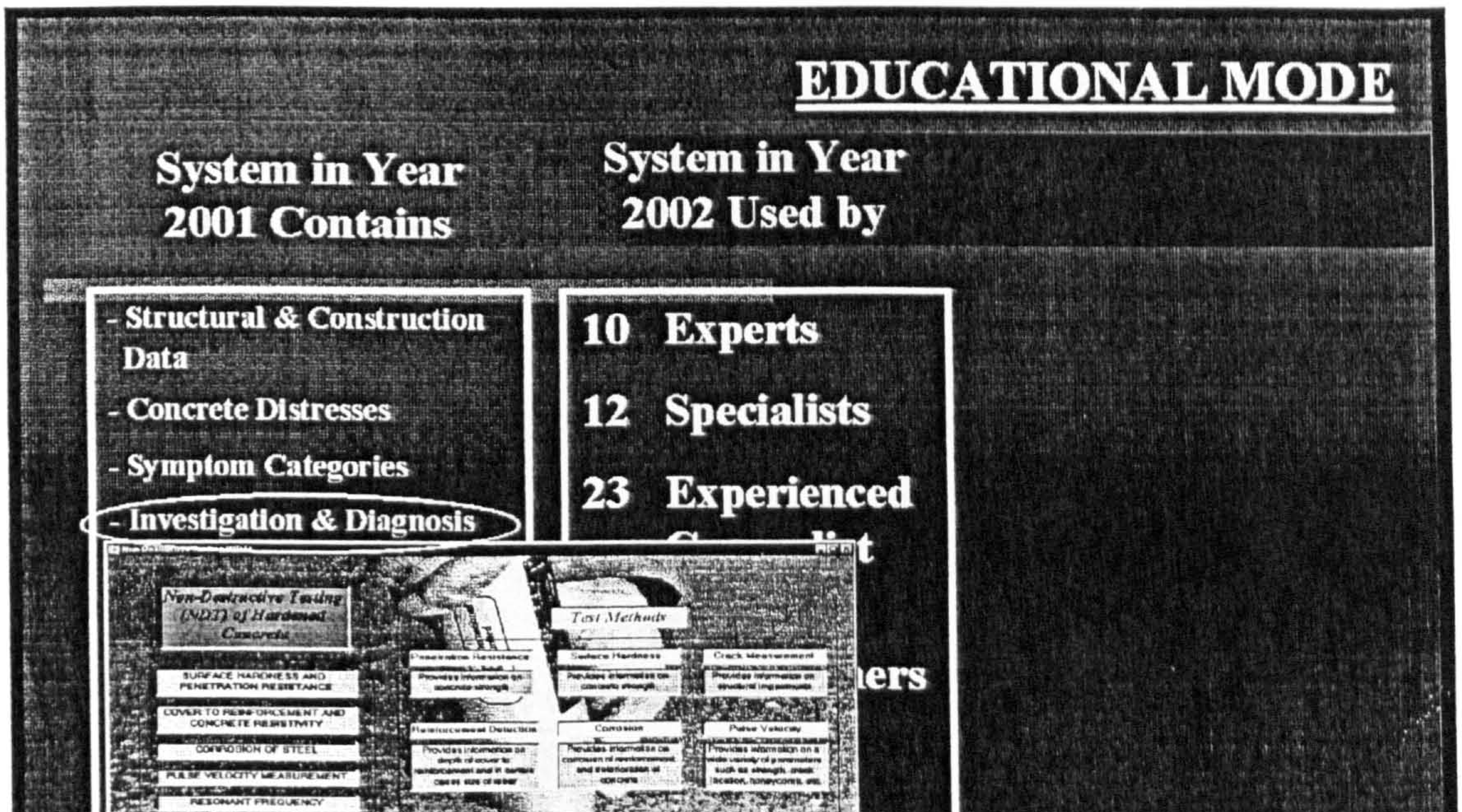


Figure 10.9 - NDT information for making problem solving easier.

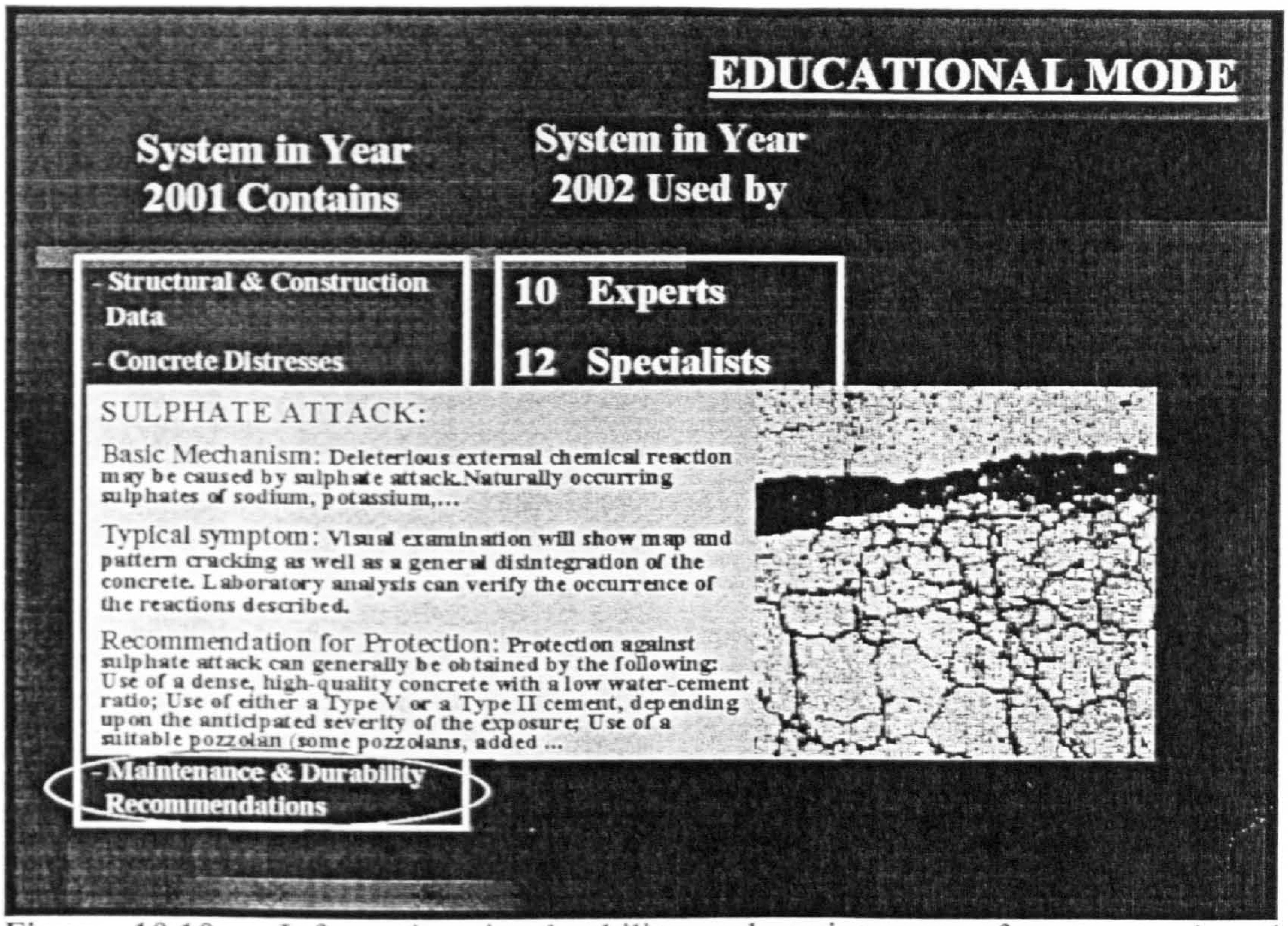


Figure 10.10 - Information in durability and maintenance for structural and construction engineers.

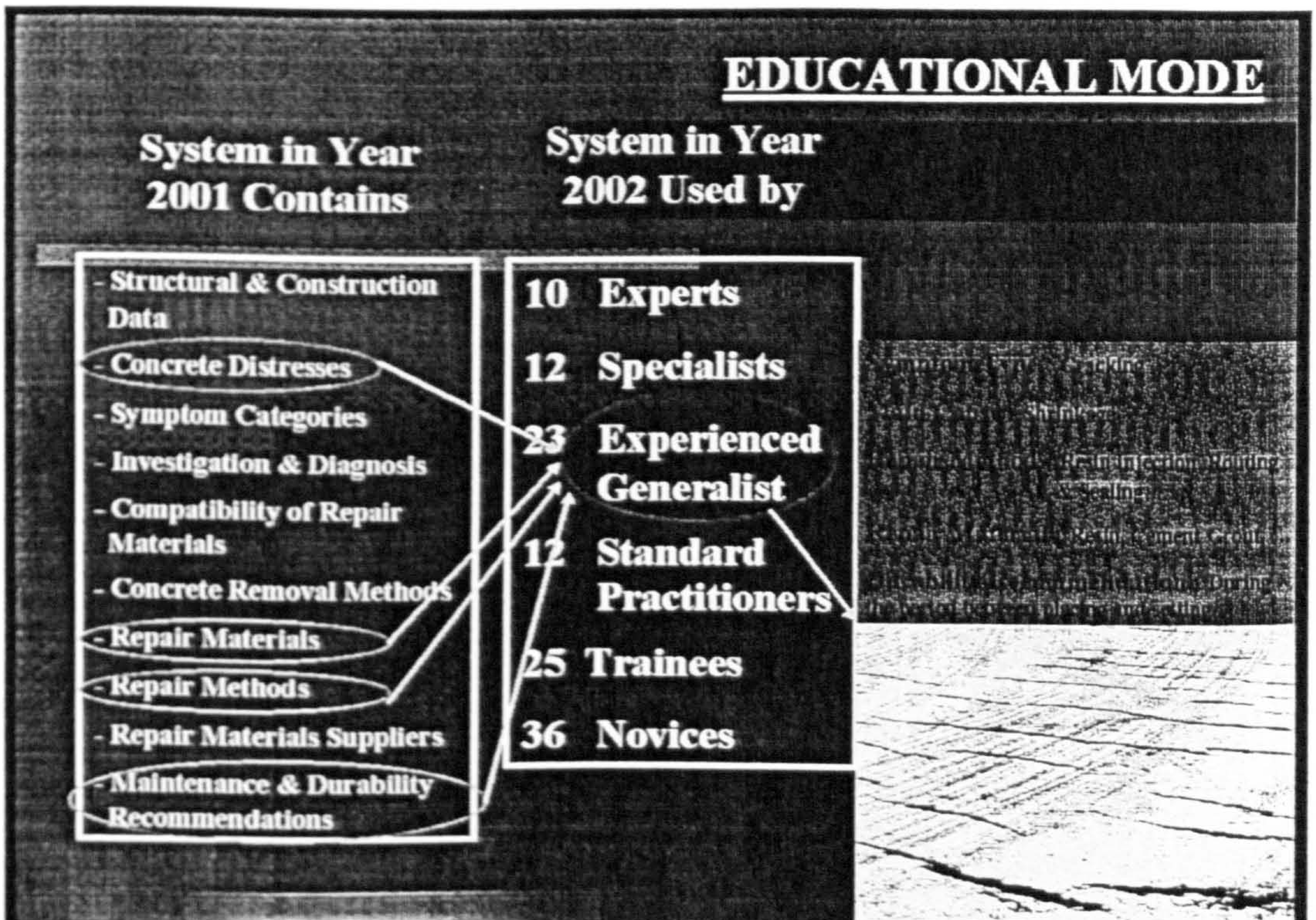


Figure 10.11- Retrieving any data from the database.

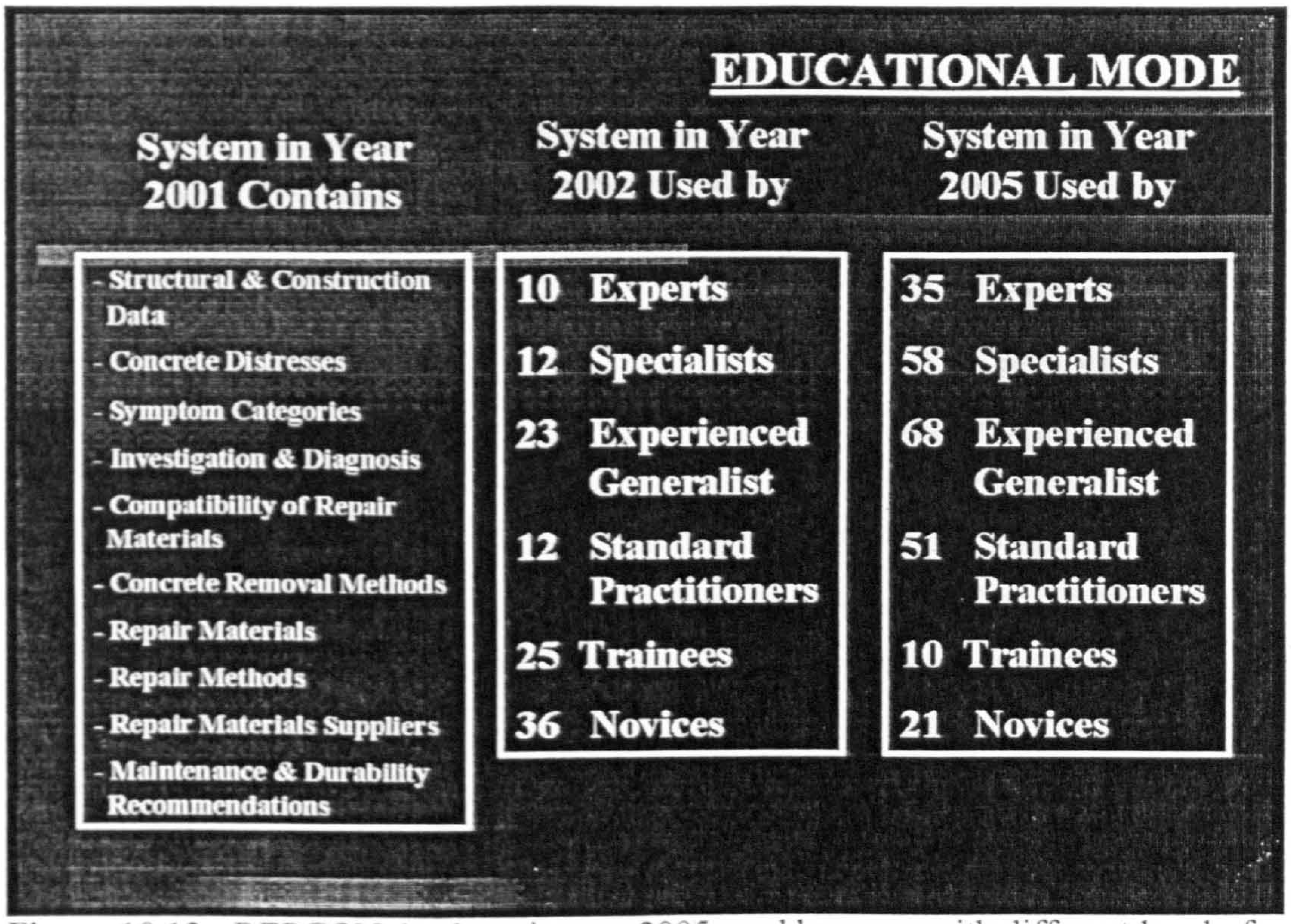


Figure 10.12 - REPCON database in year 2005 used by users with different level of ability.

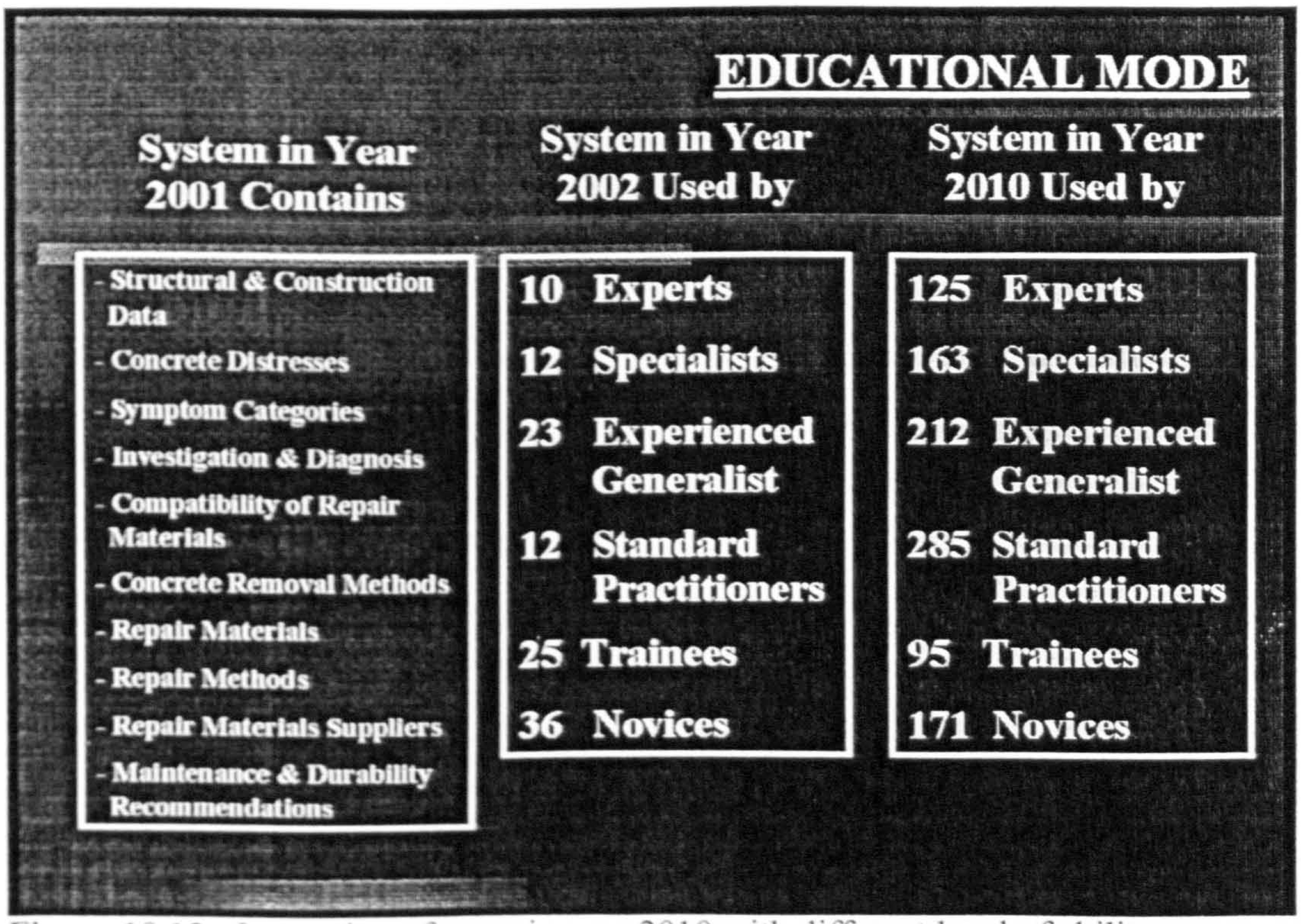


Figure 10.13 - Increasing of users in year 2010 with different level of ability.

Figure 10.14:

The primary objective of the EVOLUTION mode of application is to allow the user to contribute experience and knowledge to the database thereby evolving the system. It is expected that the system with existing documents could be used by a number of users in year 2002 who will contribute new knowledge. A self-assessment process has been included in order to assess the competence of the users who wish to contribute new data to the system.

Figures 10.15 and 10.16:

An Expert user can add new data such as those illustrated in Figure 10.15 to the Concrete Distress Table of the original database as well as a Specialist who can add new data to the Investigation and Diagnosis Table of the Original database (Figure 10.16).

Figure 10.17:

Also, an Experienced Generalist who is seeking to transfer expertise to the subjects in hand can contribute new experience to the Distress Category Table of the Appendix database.

Figure 10.18:

By allowing new data to be added, the system evolves in line with the state of the art of concrete repair.

Figures 10.19 and 10.20:

An Expert user in year 2003 can use the system to contribute new data to the original database and to upgrade data which was contributed by an Experienced Generalist in year 2002 from the Appendix data (Figure 10.19) to the original database (Figure 10.20).

Figures 10.21 and 10.22:

Because of advances in concrete repair, another expert user in year 2010 could relegate that data to the Appendix or somewhere else when it has been superseded. This means that none of the original knowledge remained as the subject matter is superseded. Indeed, the existence of the database could accelerate the turnover of knowledge.

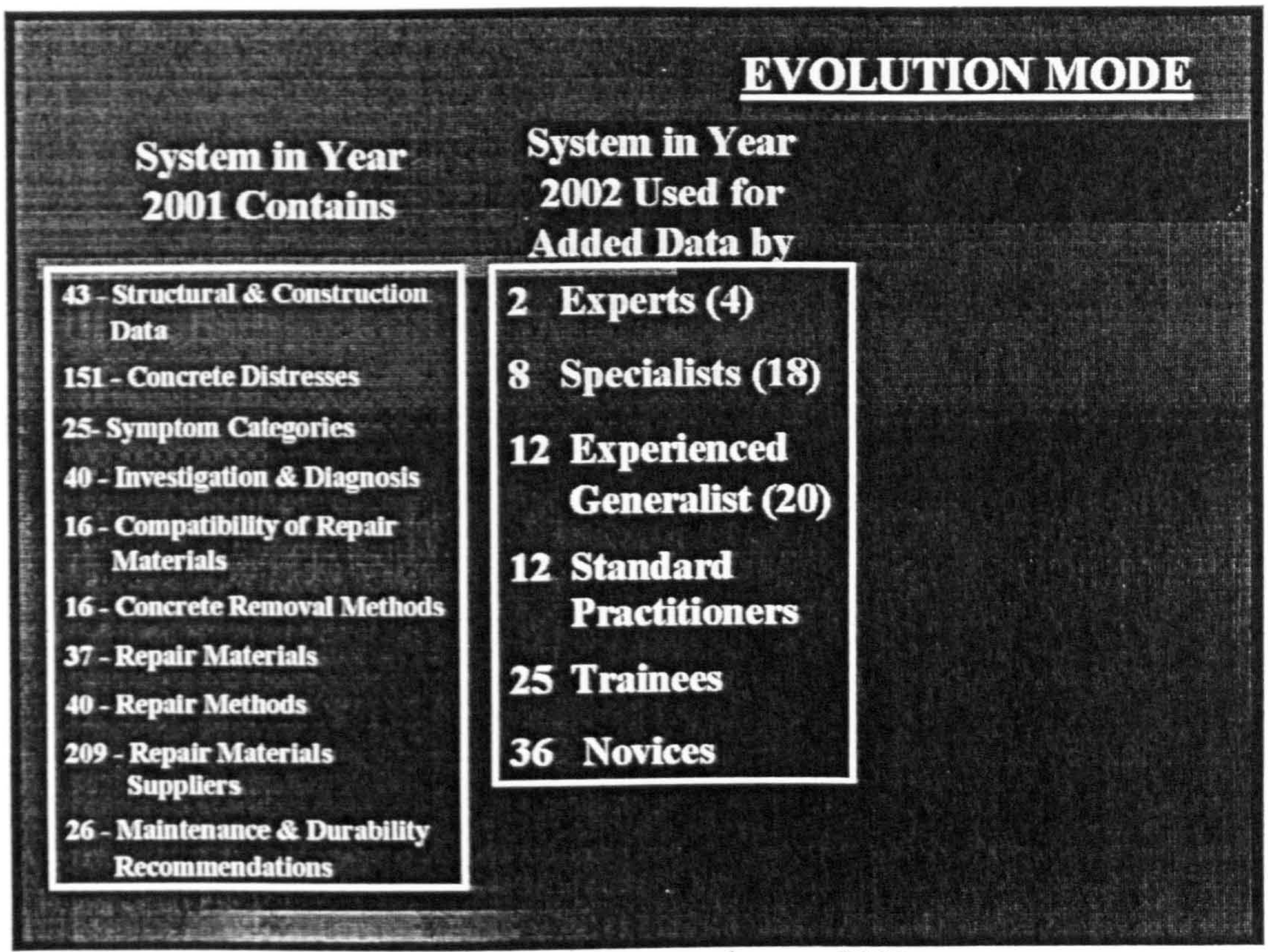


Figure 10.14 - Contributing knowledge by users in year 2002.

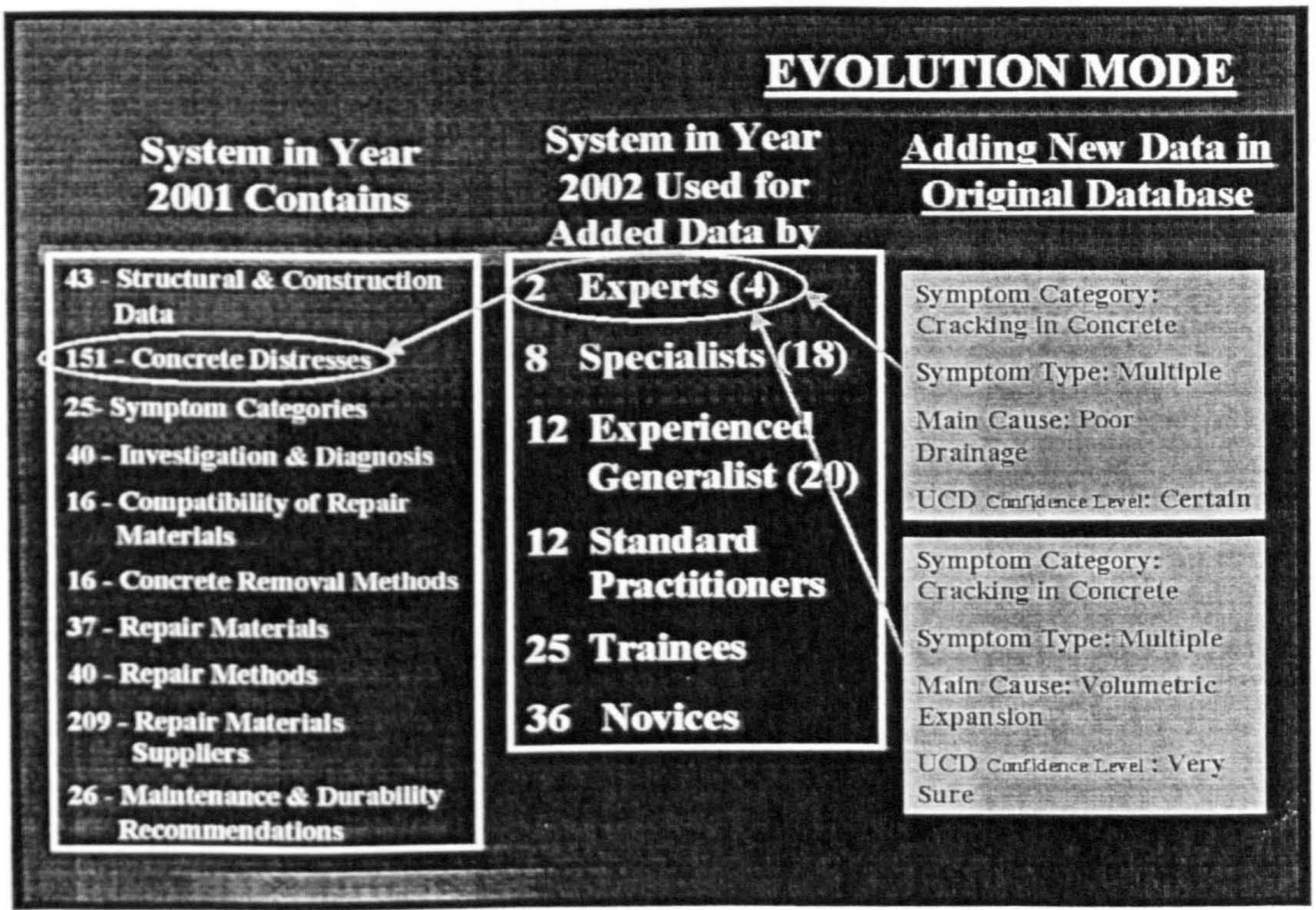


Figure 10.15 - Adding new data by an expert user to the original database.

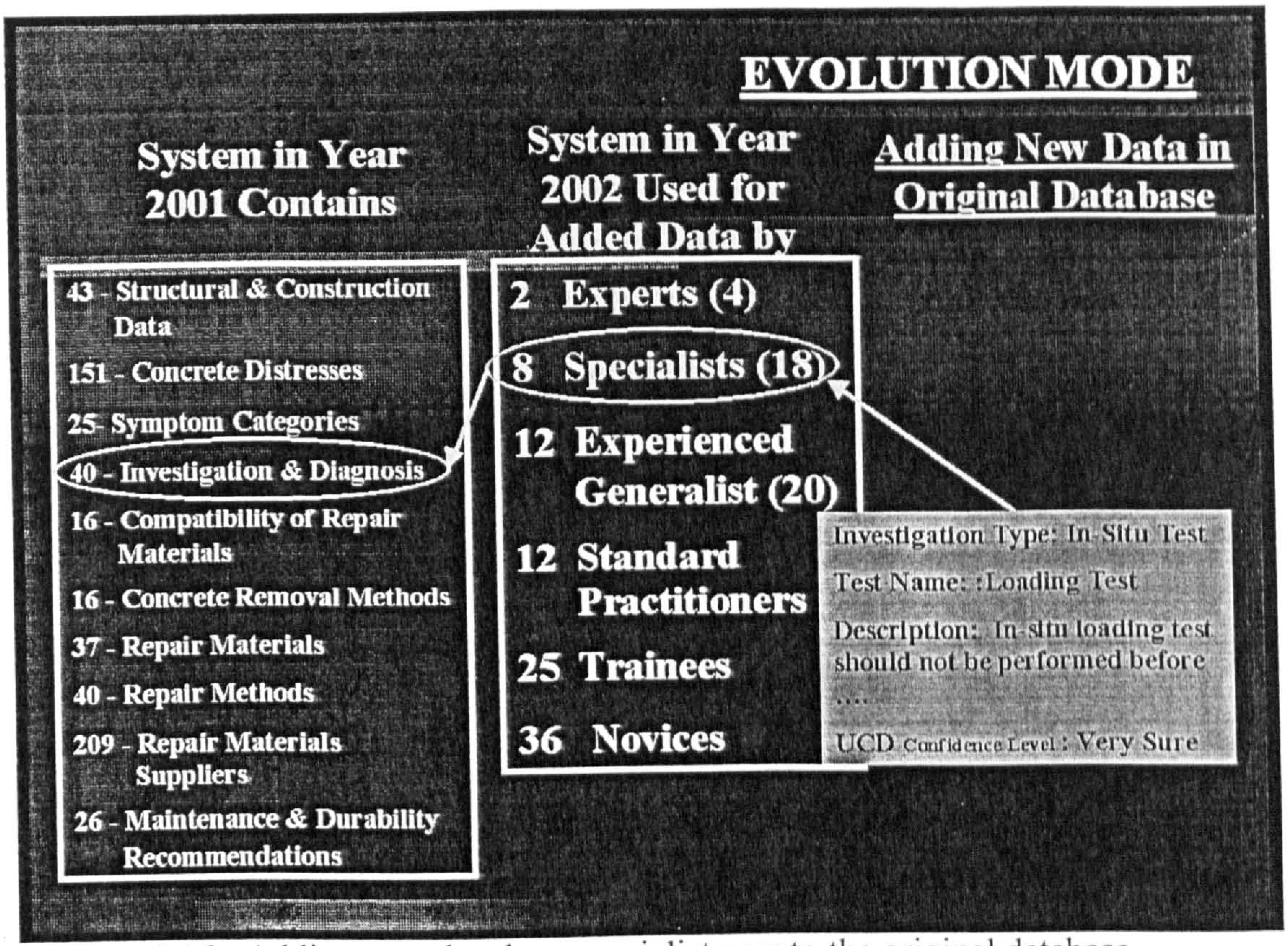


Figure 10.16 - Adding new data by a specialist user to the original database.

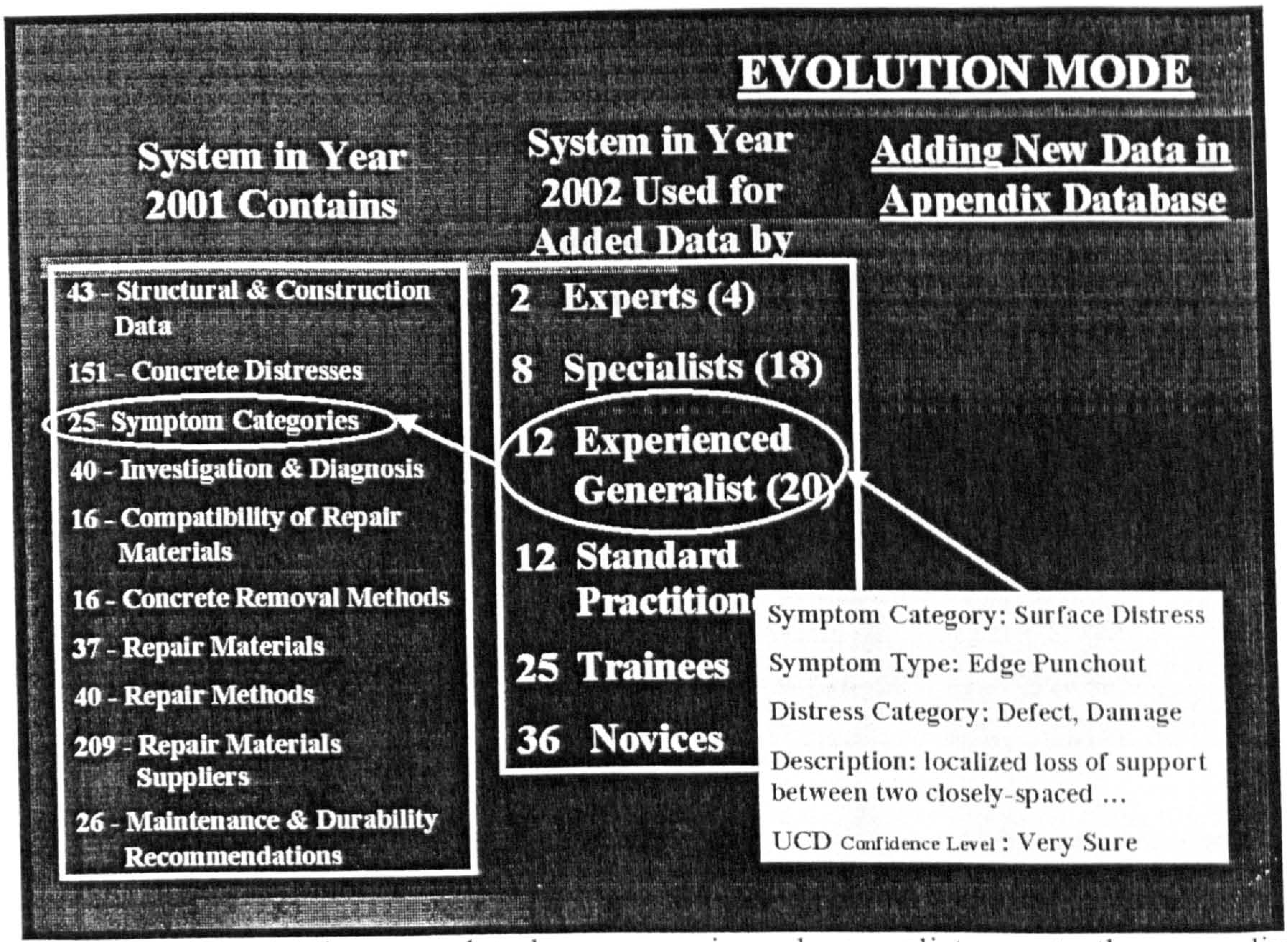


Figure 10.17 - Adding new data by an experienced generalist user to the appendix database.

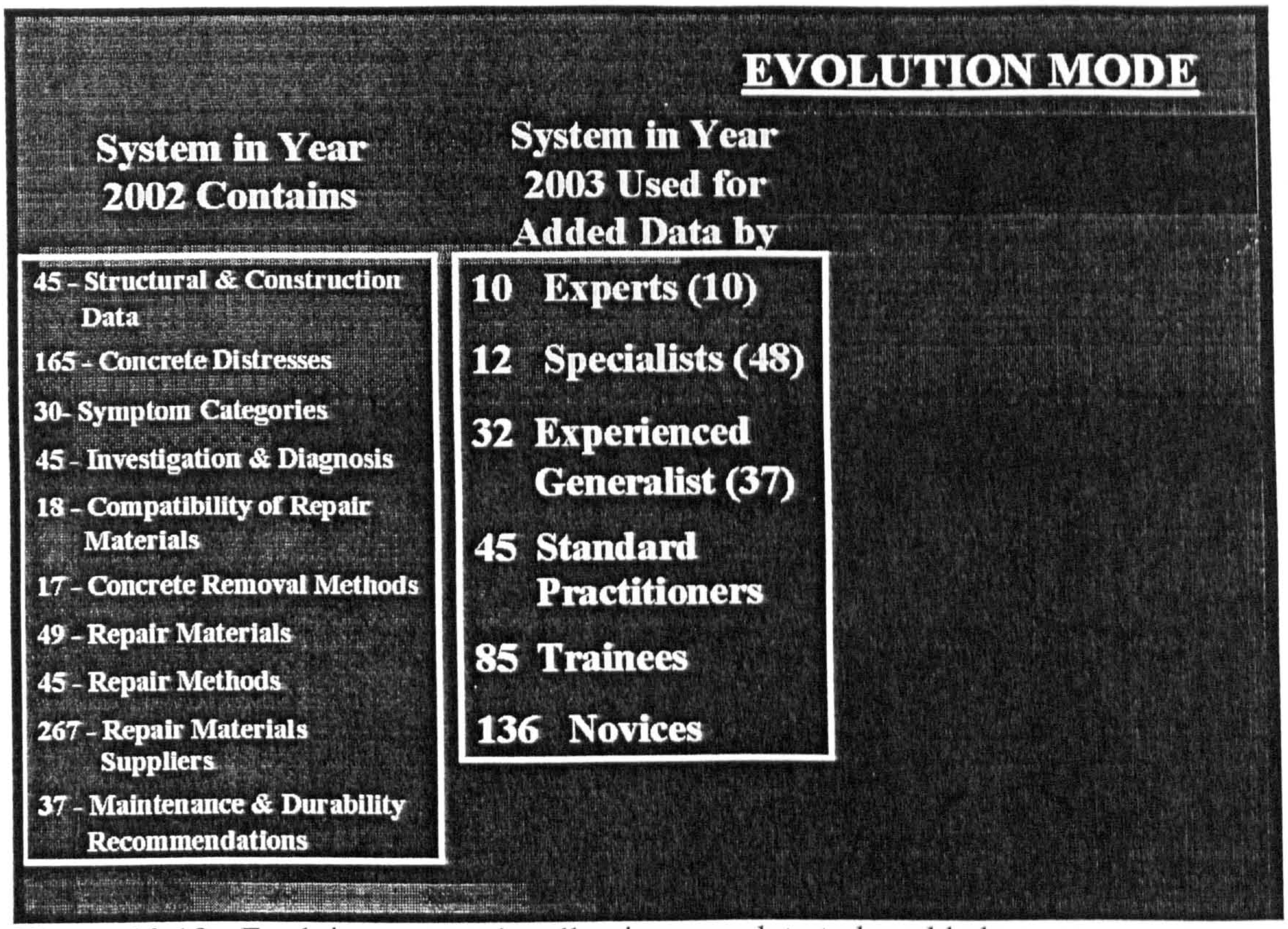


Figure 10.18 - Evolving system by allowing new data to be added.

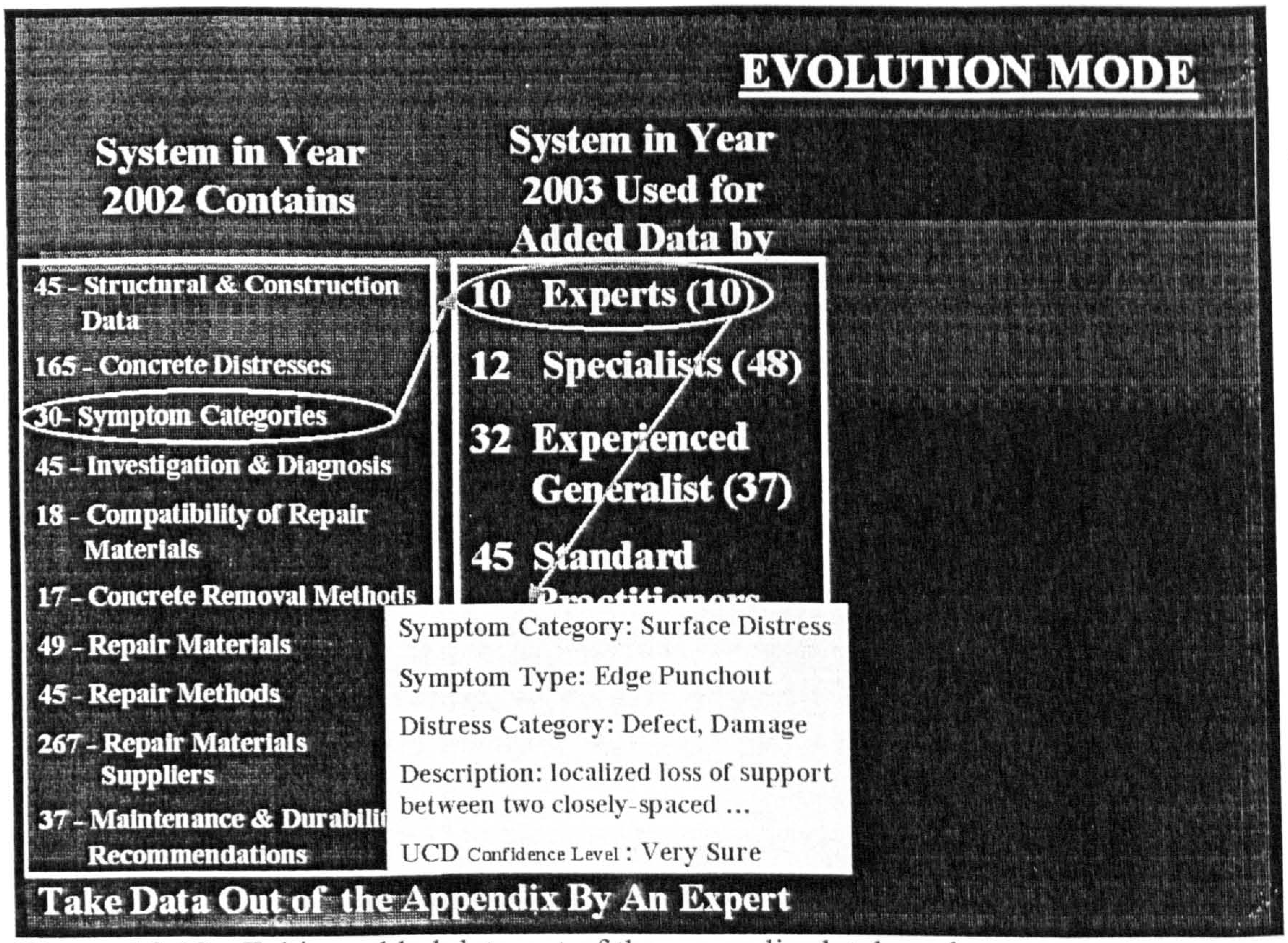


Figure 10.19 - Taking added data out of the appendix database by an expert user.

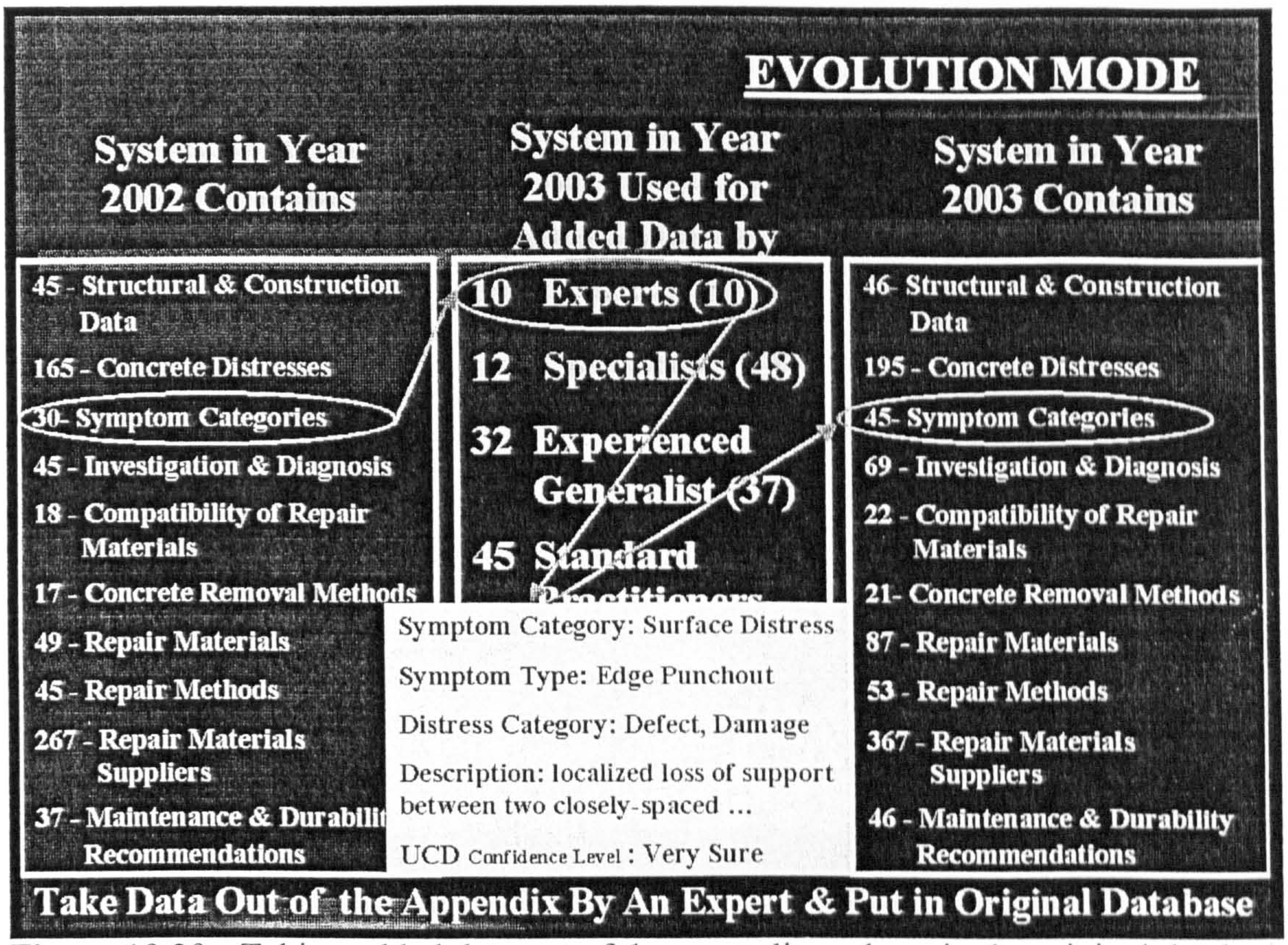


Figure 10.20 - Taking added data out of the appendix and put in the original database by an expert user.

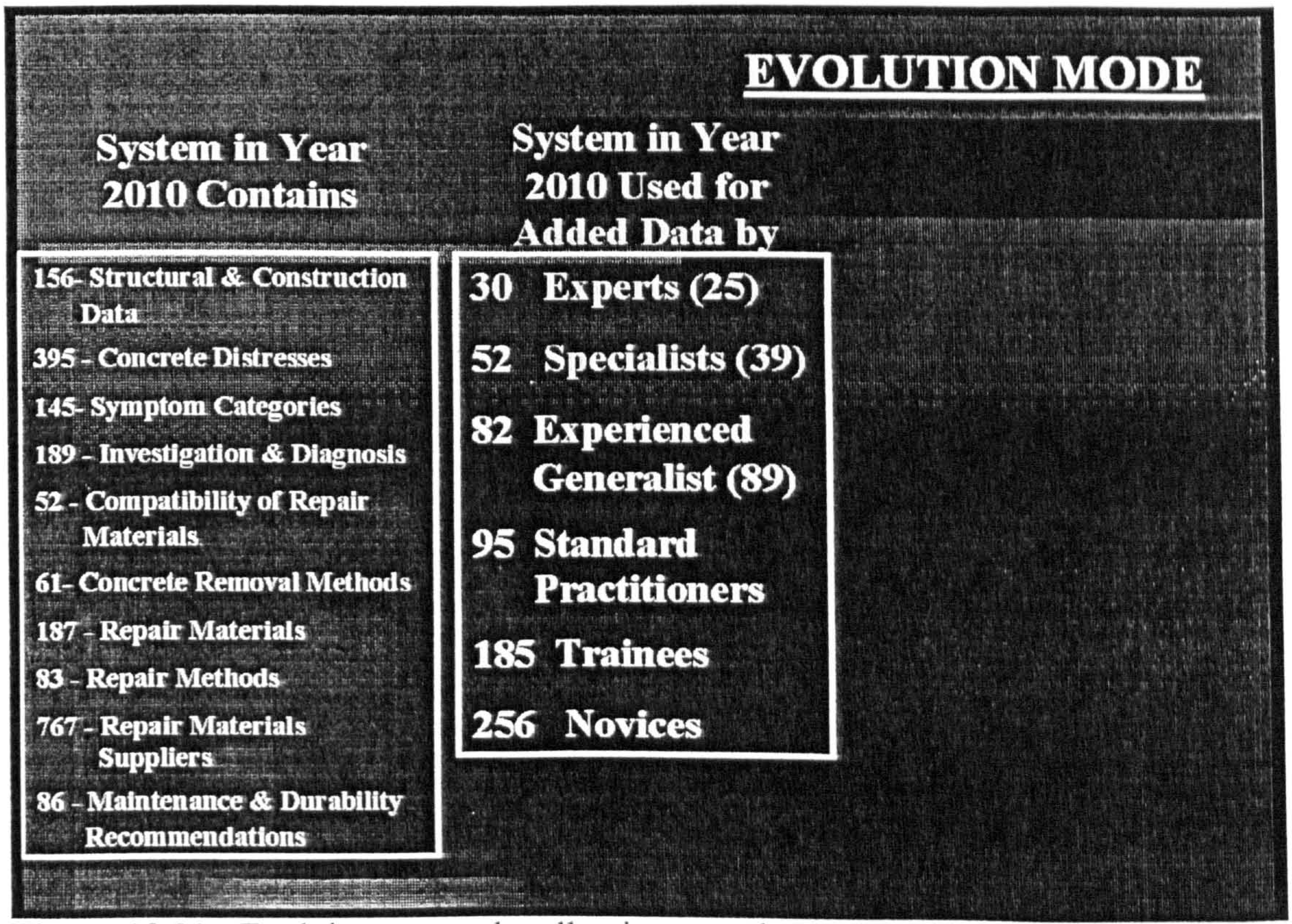


Figure 10.21 - Evolving system by allowing new data to be added in year 2010.

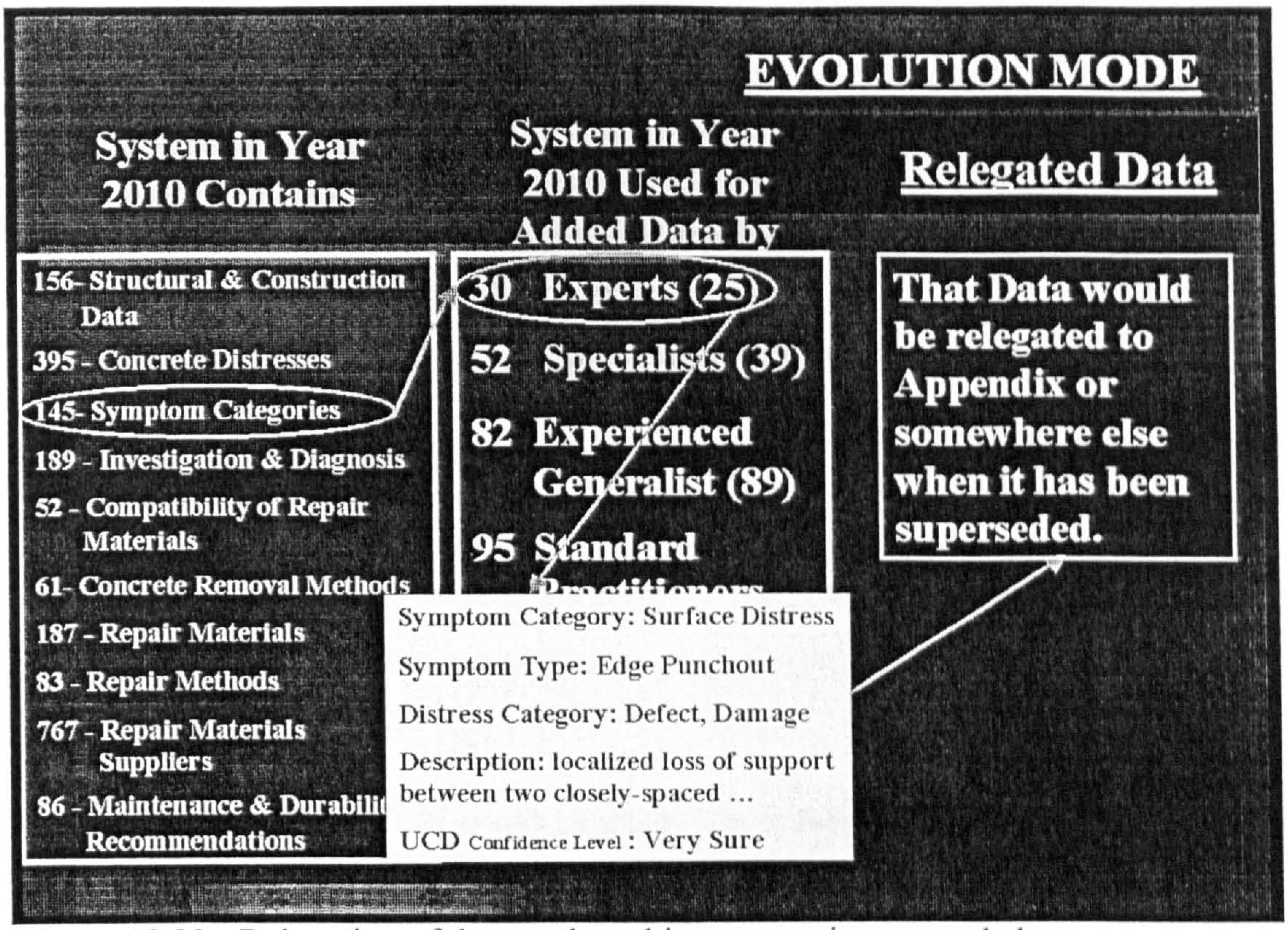


Figure 10.22 - Relegation of data as the subject matter is superseded.

In addition, some special characteristics and purposes of the REPCON database cause the system performance to be unique.

These unique characteristics are summarised as follows:

- It combines pictures and technical data in a way which makes decision and problem solving easier.

- It provides a common forum for communication between clients, engineers and contractors as well as technology transfer of information.

- It facilitates a better understanding of the repair of concrete technology.

- It allows an experienced user to contribute experience and knowledge to the database. By providing a quantitative and consistent means for evaluating both new data and the person contributing it, the confidence level (CL) allows new knowledge and experience to be gathered and monitored over time.

- It is designed to evolve as the concrete repair community interacts with it. This system could provide an improved and consistent method for evolving each original database and should become a forum for the exchange of expert opinion in this field.

- It helps the knowledge engineer to improve the problem-solving capability of the expert system by abstracting knowledge from the database.

- The success of REPCON could be gauged by a future scenario in which none of the original knowledge remained as the subject matter is superseded. Indeed, the very existence of REPCON could accelerate the turnover of knowledge.

- The value of REPCON can be gauged by considering how this acceleration in the turnover of knowledge might impact upon all areas of endeavour.

10.4 Evaluation of Concrete (ECON) Validation

The performance of ECON in the evaluation of concrete section was compared with previous work as described in Chapter 9. Each of the examples of previous work was performed for a special type of concrete structure which is summarised as follows:

- Performance Index (PI) in COBDA (Cabrera, 1985) developed for the evaluation of the physical condition of concrete bridges.

- Pavement Condition Index (PCI) described by FAA (1982) used for the evaluation of airport pavements.

> The Condition Index (CI) procedure developed by Bullock (1995) used for the evaluation of concrete retaining walls and spillways.

> The Condition Index (CI) procedure described by Greimann et al (1995) used for the evaluation of concrete dams and lock gates.

Engineering judgement and experience were needed to develop a set of criteria in order to implement a quantitative rating of the overall state of concrete in each of these structures using the results of the observation of signs of distress and weighting scales based on severity and extent.

In the ECON program, engineering judgement and the author's knowledge and experience are applied to determine Deduct Values (DV) for various distress categories and to develop the Confidence Level (CL). In comparison with the cited research, the Deduct Values and confidence levels prescribed in ECON program apply to concrete structures in general. ECON comprises a powerful user interface by providing pictures during run time. A comparison of ECON confidence levels with other systems is shown in Table 10.1.

Table 10.1 - A comparison of ECON confidence level with other systems.

ECON		Bullock & Greimann		FAA		COBDA	
CL	**Condition**	**CI**	**Condition**	**PCI**	**Condition**	**PI**	**Condition**
95-100	Excellent	85-100	Excellent	85-100	Excellent	95-100	Very Good
						90-94	Good
85-94	Very Good	70-84	Very Good	70-84	Very Good	85-89	More or less Good
70-84	Good	55-69	Fair	55-69	Good	75-84	Fair
50-69	Fair	40-54	Marginal	40-54	Fair	65-74	More or less Fair
30-49	Poor	25-39	Poor	25-39	Poor	50-64	Poor
		10-24	Very Poor	10-24	Very Poor	40-49	Very Poor
0-29	Very Poor	0-9	Failed	0-9	Failed	0-39	Dangerous

10.5 Case Study 1 - External Paving Project

In this project, cracking to the external concrete paving at Unit A, Hams Hall currently being used by Tradeteam as a consumer-products distribution centre is considered. This is an actual project in which a full investigation was undertaken conventionally. In this case study, it is shown that the results of this research could have been used to enhance the process of determining the cause of the failure and in selecting the repair method.

10.5.1 Description of External Paving

The Tradeteam external pavement comprises approximately 26000m^2 of 200mm thickness unreinforced C35 concrete slabs installed over 150mm thickness DTp Clause 803 granular sub-base material. The concrete is specified to have a cement content of 325 Kg/m^3, a maximum free water/cement ratio of 0.55 and a normal maximum aggregate size of 20mm. Non of the above is in any way unusual, indeed it presents the orthodox specification for external hardstanding slabs. The concrete includes polypropylene fibres at the rate of 0.9 Kg/m^3 to enhance the durability of the concrete and reduce the risk of early age cracking (Knapton, 2001).

The hardstanding includes an orthogonal pattern of joints at 8m centres as shown in Figure 10.23. All joints have been formed (as opposed to induced) i.e. they have been cast either against formwork or against the vertical concrete face previously cast. Nearly all of the 8m x 8m bays have cracked typically into longitudinal cracks such as those shown in Figures 10.23 trough 10.25 (near opening and joint) or into a quartered pattern as shown in Figures 10.23, 10.26 and 10.27. The cracks are full depth and move with moisture and temperature variation. Spalling and general deterioration in the slab and near openings and joints is occurring as shown in Figure 10.28.

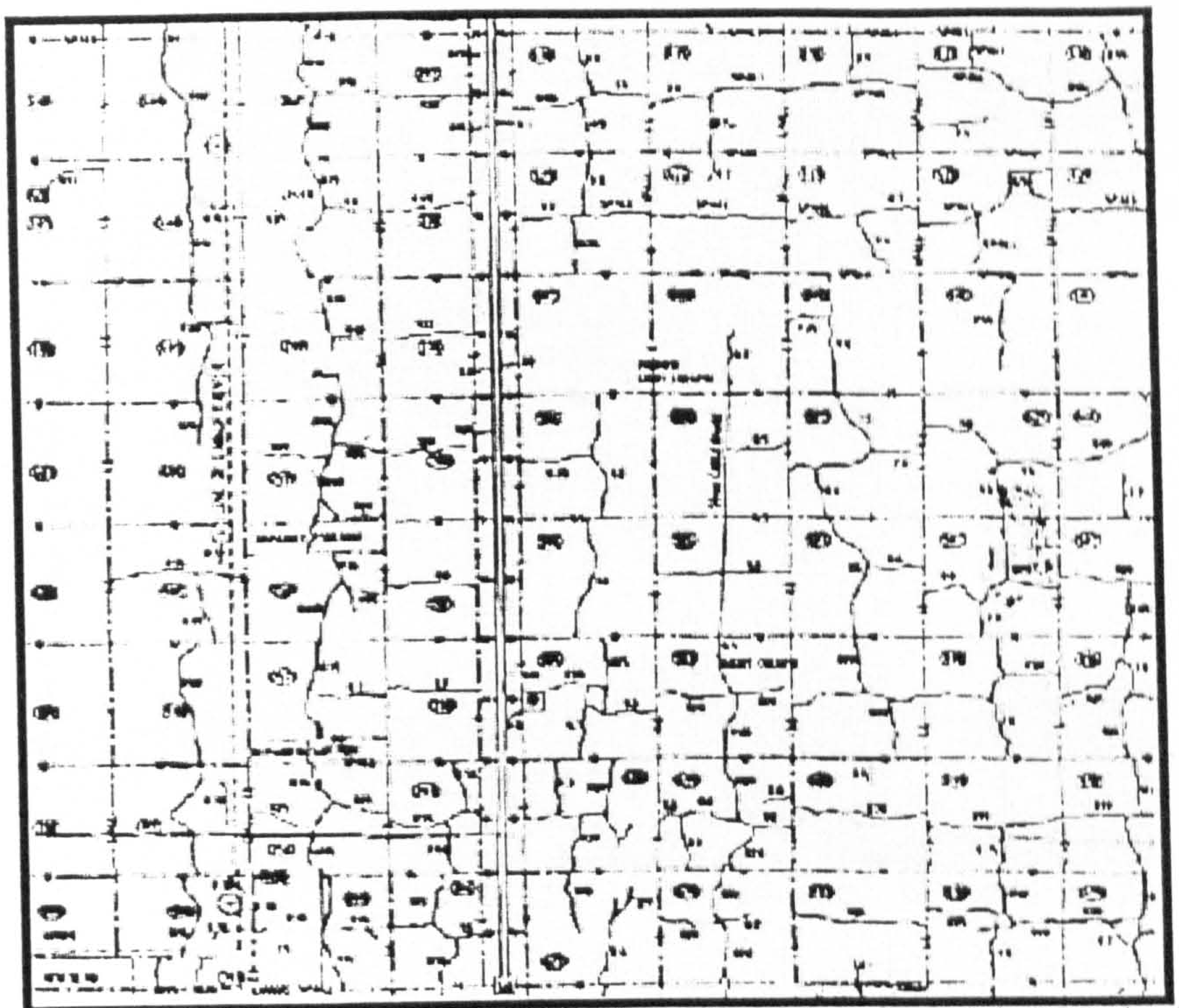


Figure 10.23 - Part of Unit A external hardstanding showing slab 288 shaded (Knapton, 2001).

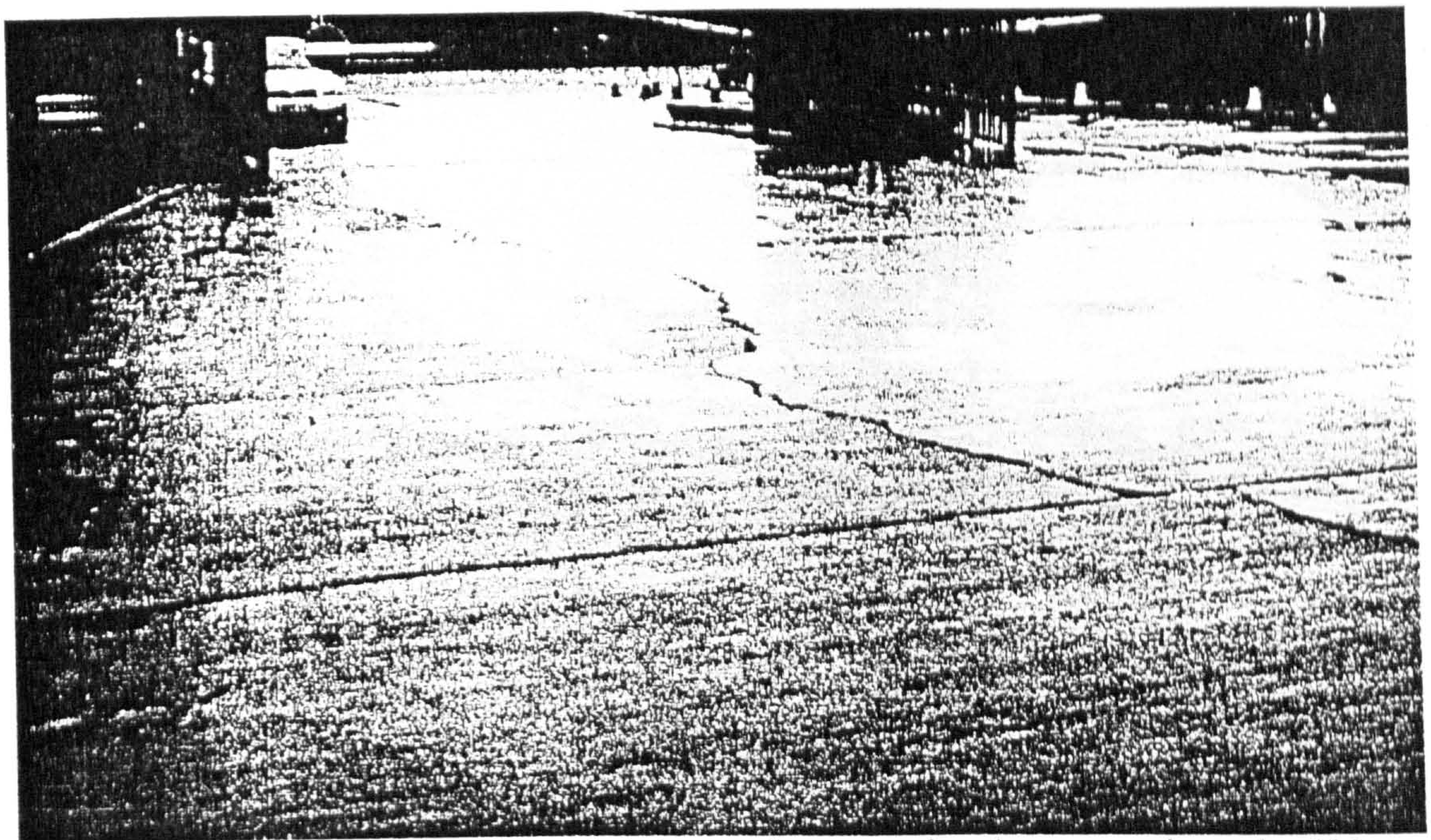


Figure 10.24 - Cracks run through joints, often stepping by approximately 400mm (Knapton, 2001).

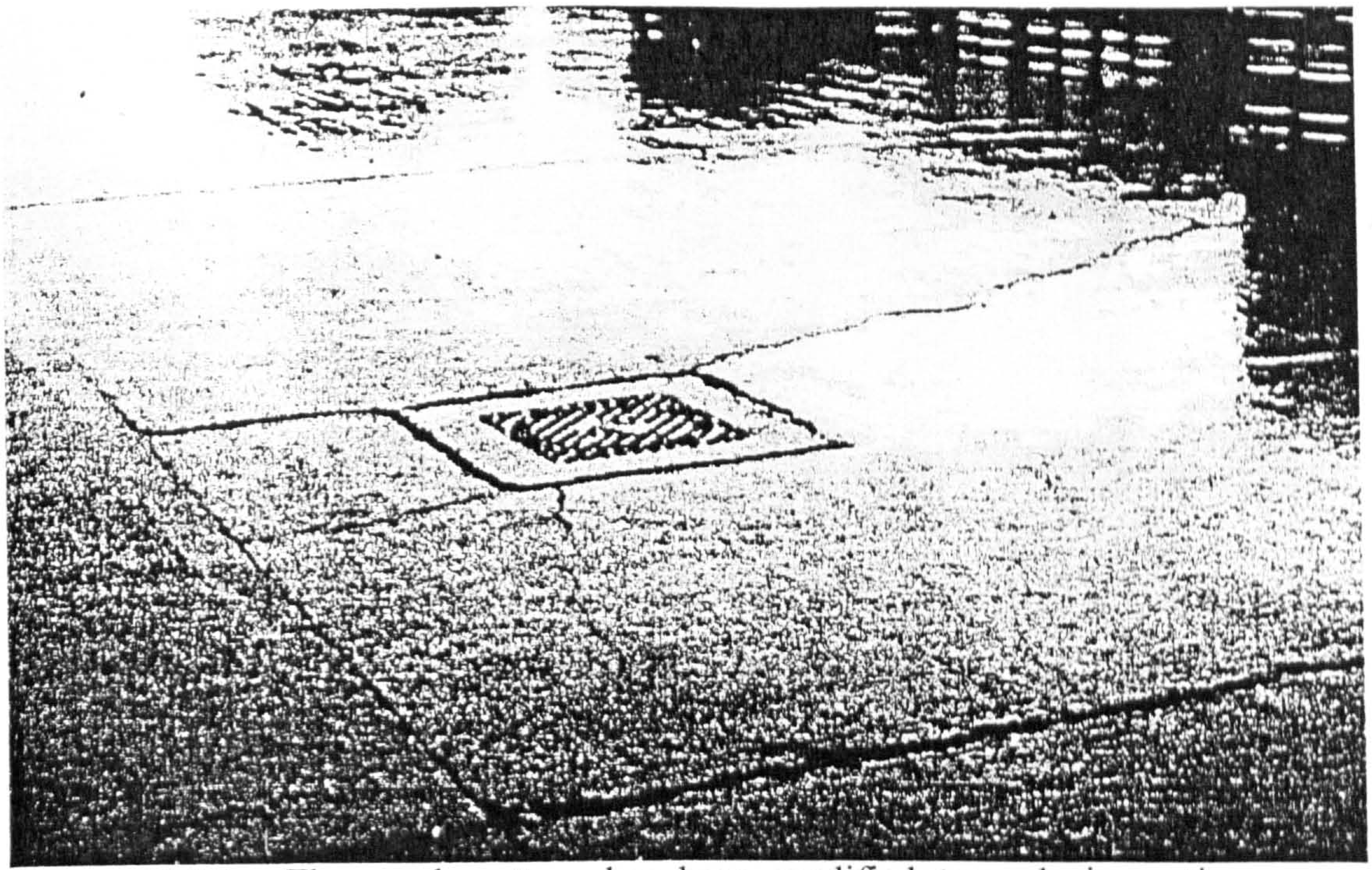


Figure 10.25 - The crack pattern has been modified towards inspection covers (Knapton, 2001).

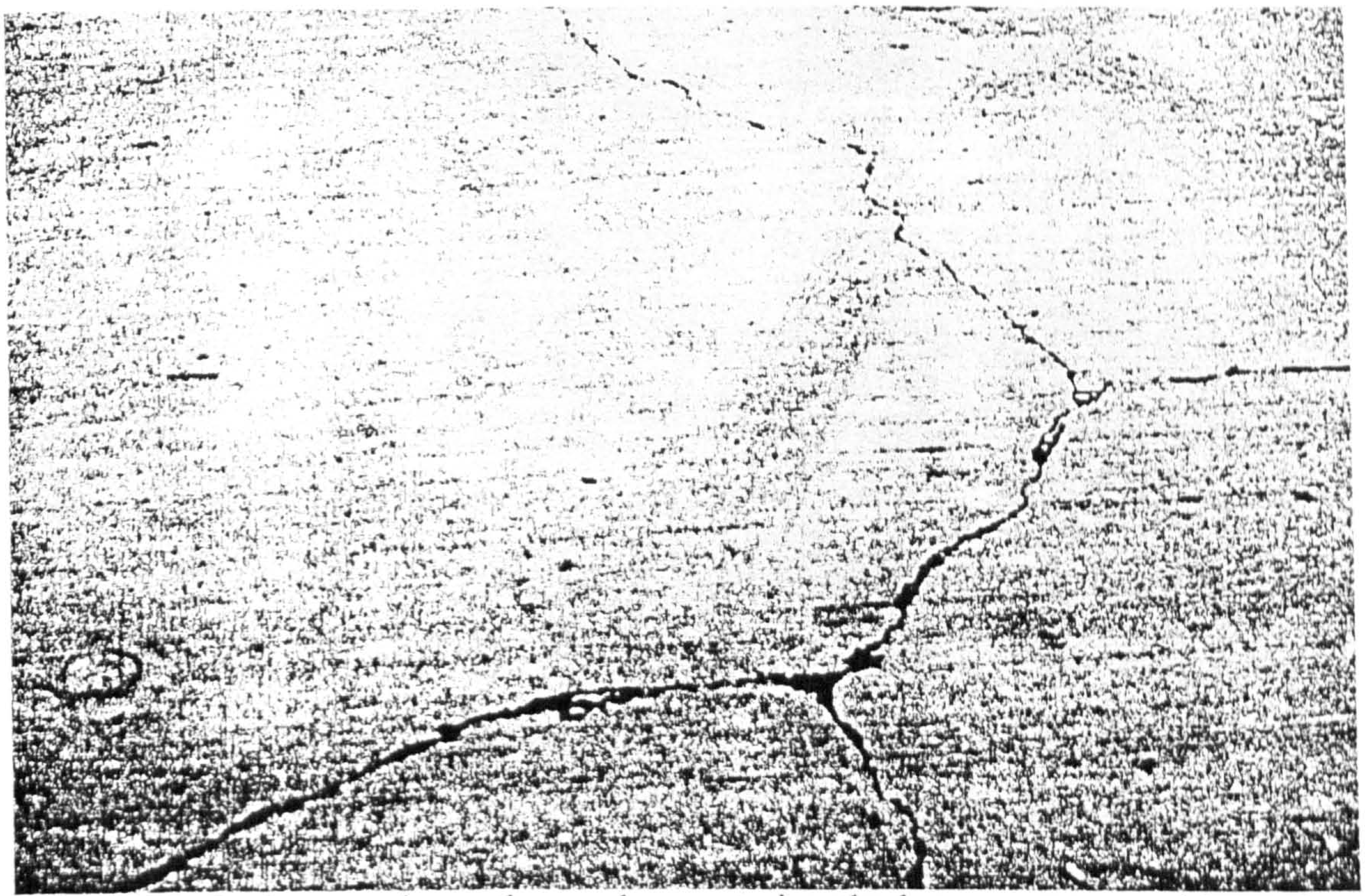


Figure 10.26 - In some bays, the cracks quartering the bay are connected by a short 45 degree crack (Knapton, 2001).

Figure 10.27 - Typical pattern of quartered bays (Knapton, 2001).

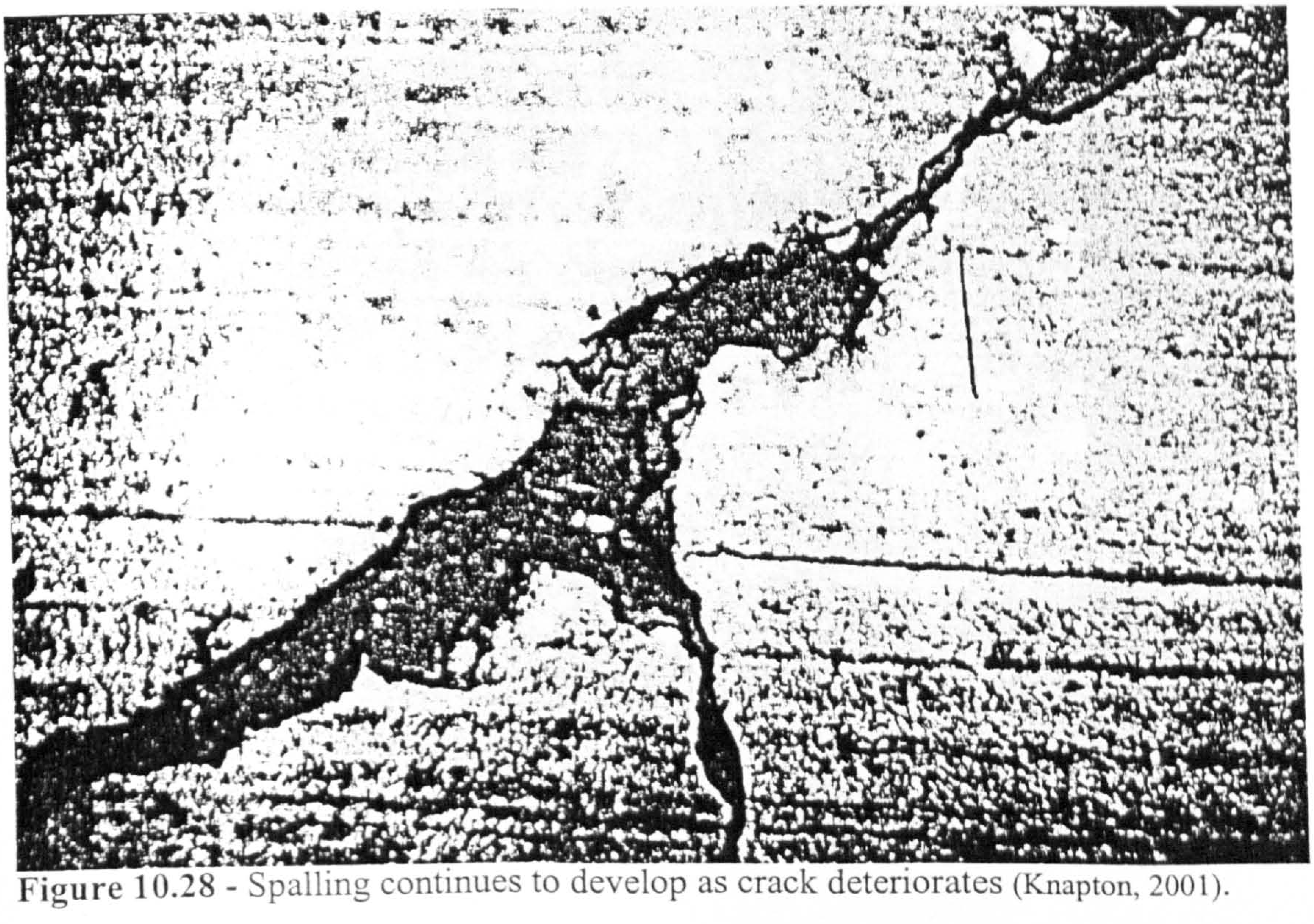


Figure 10.28 - Spalling continues to develop as crack deteriorates (Knapton, 2001).

10.5.2 Assessment of Causes of Cracking

From the pattern of cracking, and from the other test reports, it is clear that there is insufficient release of restraint at the joints for the slabs to operate by the joints moving and thereby accommodating temperature/moisture induced volume changes. Since their casting, the concrete slabs have undergone a complex history of temperature and moisture change and this has led to overall shrinkage and curling. In the main, the slabs have cracked into halves or quarters as a result of thermally induced stresses. A secondary contribution to the development of the cracking has resulted from dowel bar misalignment.

The absence of corner cracking indicates that the hardstanding is sufficiently strong for the loading to date and that there has been no loss of bearing beneath the slabs. The concrete appears to meet its specification requirements and seems to be a suitable external pavement quality concrete. Indeed, the inclusion of polypropylene fibres will have enhanced its durability as an external slab. The absence of overall settlement or differential settlement confirms that there are no geotechnical issues to consider.

10.5.3 Remedial Works

It was recommended that the slabs should be replaced with slabs of similar thickness but with joints spaced on a 6m orthogonal grid with as many joints as possible induced rather than formed. It was recommended that unreinforced concrete should be installed and that either air entrainment or polypropylene fibres should be included in the concrete.

10.5.4 DEMAREC Applied to the Tradeteam External Hardstanding

Evaluation of External Concrete Pavement by ECON Program

Firstly, by using the Evaluation of Concrete (ECON) program the current condition of the concrete slabs can be assessed.

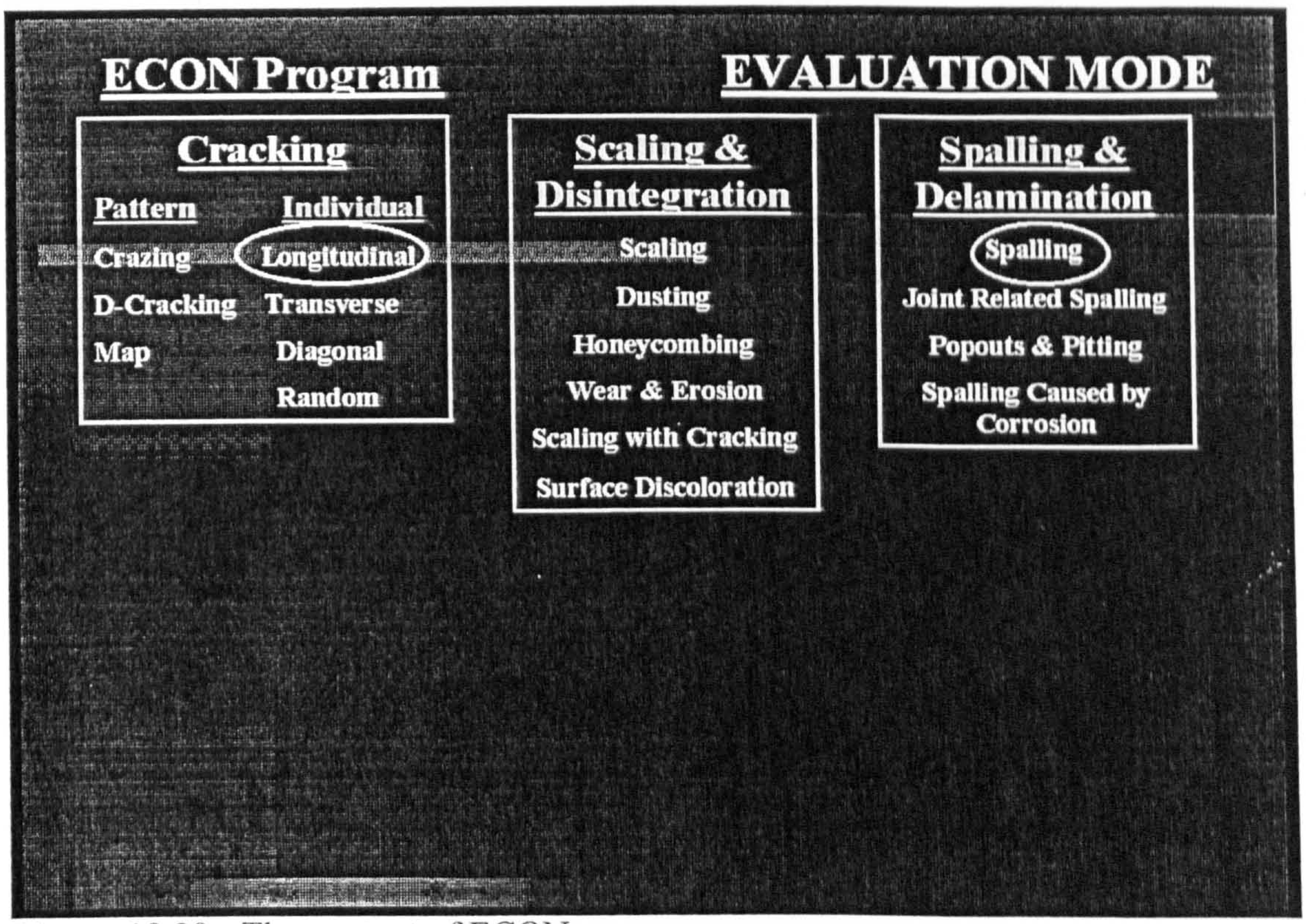


Figure 10.29 - The content of ECON program.

The criteria for the evaluation of a concrete structure are shown in Figure 10.29 and consists of cracking, scaling and disintegration, and spalling and delamination. The observations of signs of distress at Tradeteam comprise longitudinal cracking (wide and through) and slight spalling.

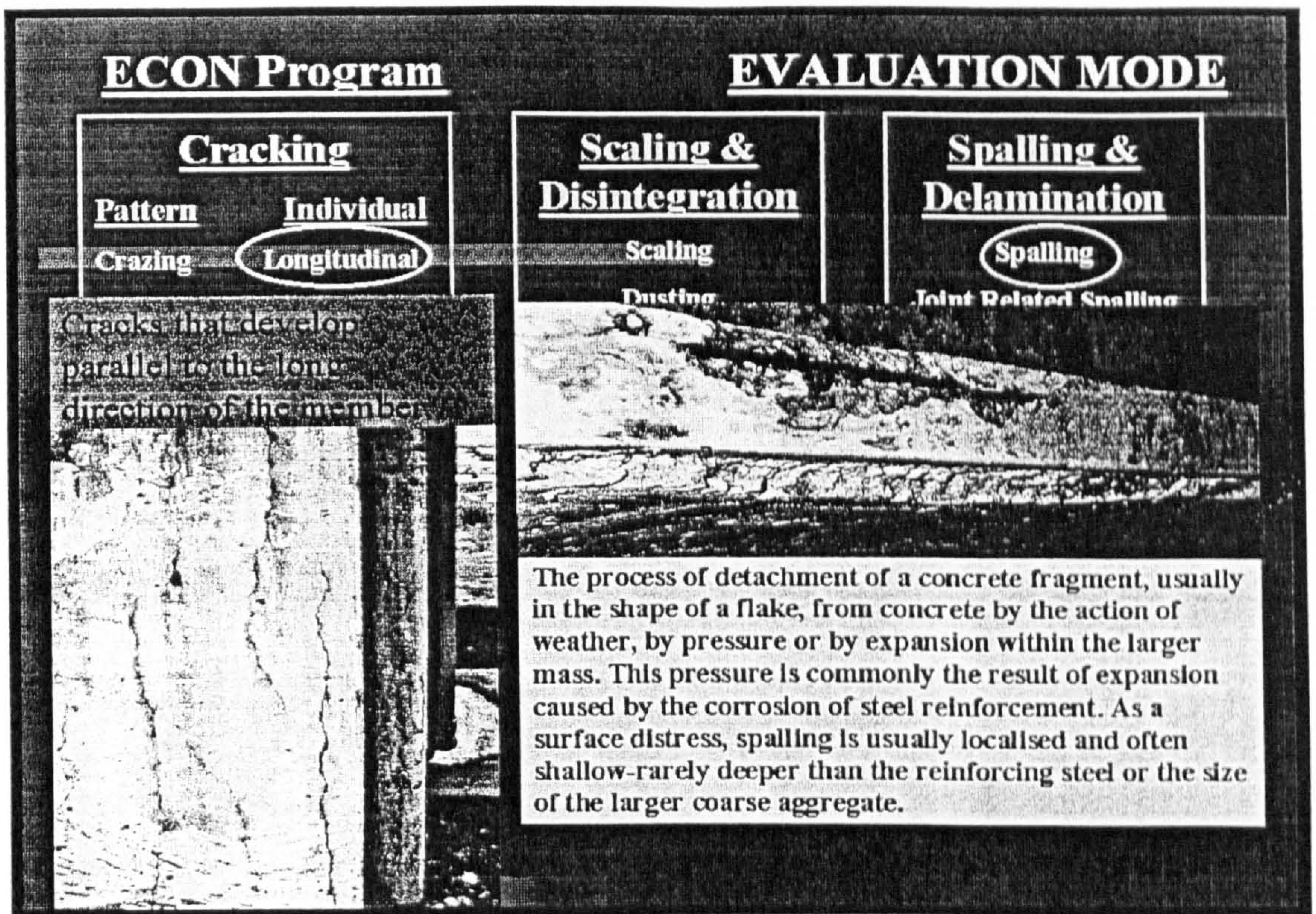


Figure 10.30 - Combining of pictures and descriptive information for better understanding of concrete problems.

Figure 10.30 is taken from the database and illustrates an example similar to Tradeteam. This allows the user to define the type of cracking as longitudinal.

Depending on the severity and extent of each type of distress a Deduct Value has been assigned and finally the slab confidence level and current condition of component is determined to take the best-recommended action for repair and maintenance. The confidence level as shown in Figure 10.31 for slab 488 is 46 with poor condition. Detailed investigation and an engineering evaluation should be made to determine the demand for repair, replacement or strengthening.

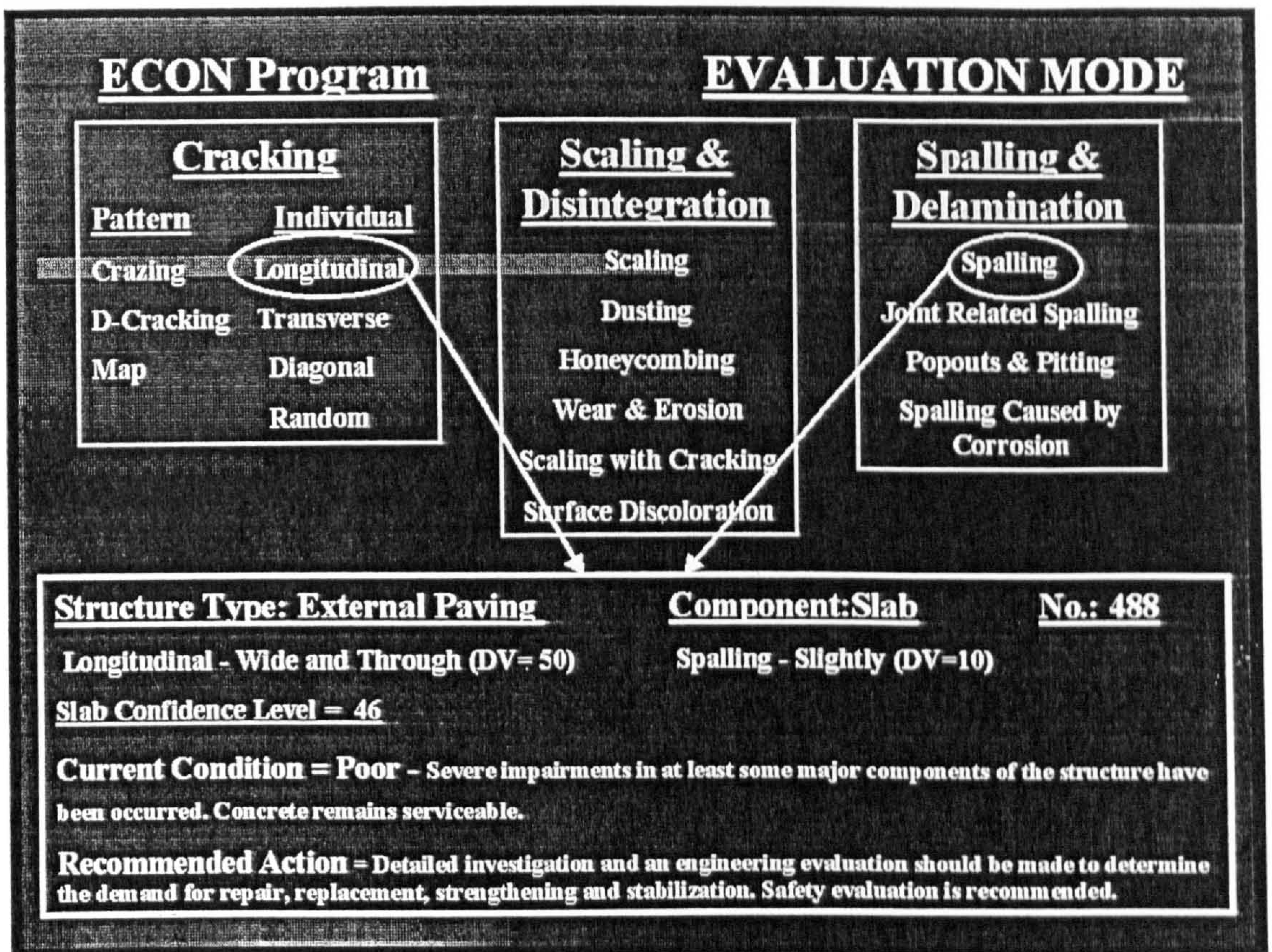


Figure 10.31 - The detailed evaluation of slab 488 by ECON program.

Diagnosis of Cause of Distress by DEMAREC-EXPERT System

Different forms of knowledge as shown in Figure 10.32 regarding causes and effects of concrete distress have been gathered in three individual knowledge-based expert programs which can be run in the visual edit screens at the same time as the database is used. The severity and extent of distresses observed in visual inspection and obtained from evaluation program can assist the user in correctly diagnosing the cause and effect of distress. For slab 488, the main sign of distress is longitudinal cracks.

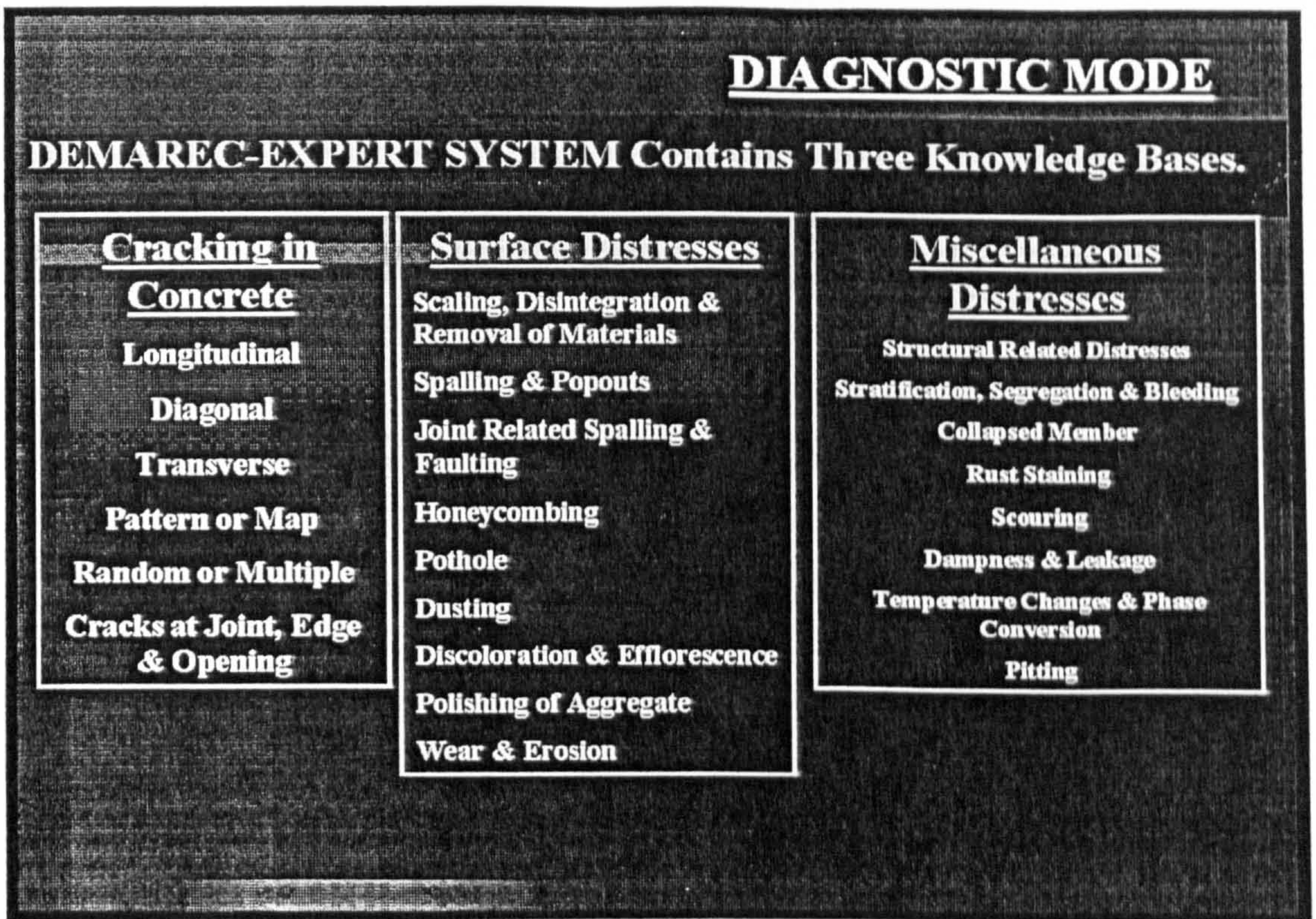


Figure 10.32 - DEMAREC-EXPERT Knowledge bases.

By using cracking in the concrete knowledge base, the user can diagnose the causes and effects of longitudinal cracking and cracks at joints by running the expert system. Several questions might be asked concerning the shape and geometry of cracks, location, direction and their appearance (Figure 10.33). At the end of the longitudinal cracking section, the user is directed to use the MISCON knowledge base for further investigation.

By using the miscellaneous (MISCON) knowledge base, the user can find other possible causes of cracking in slab 488 as shown in Figure 10.34.

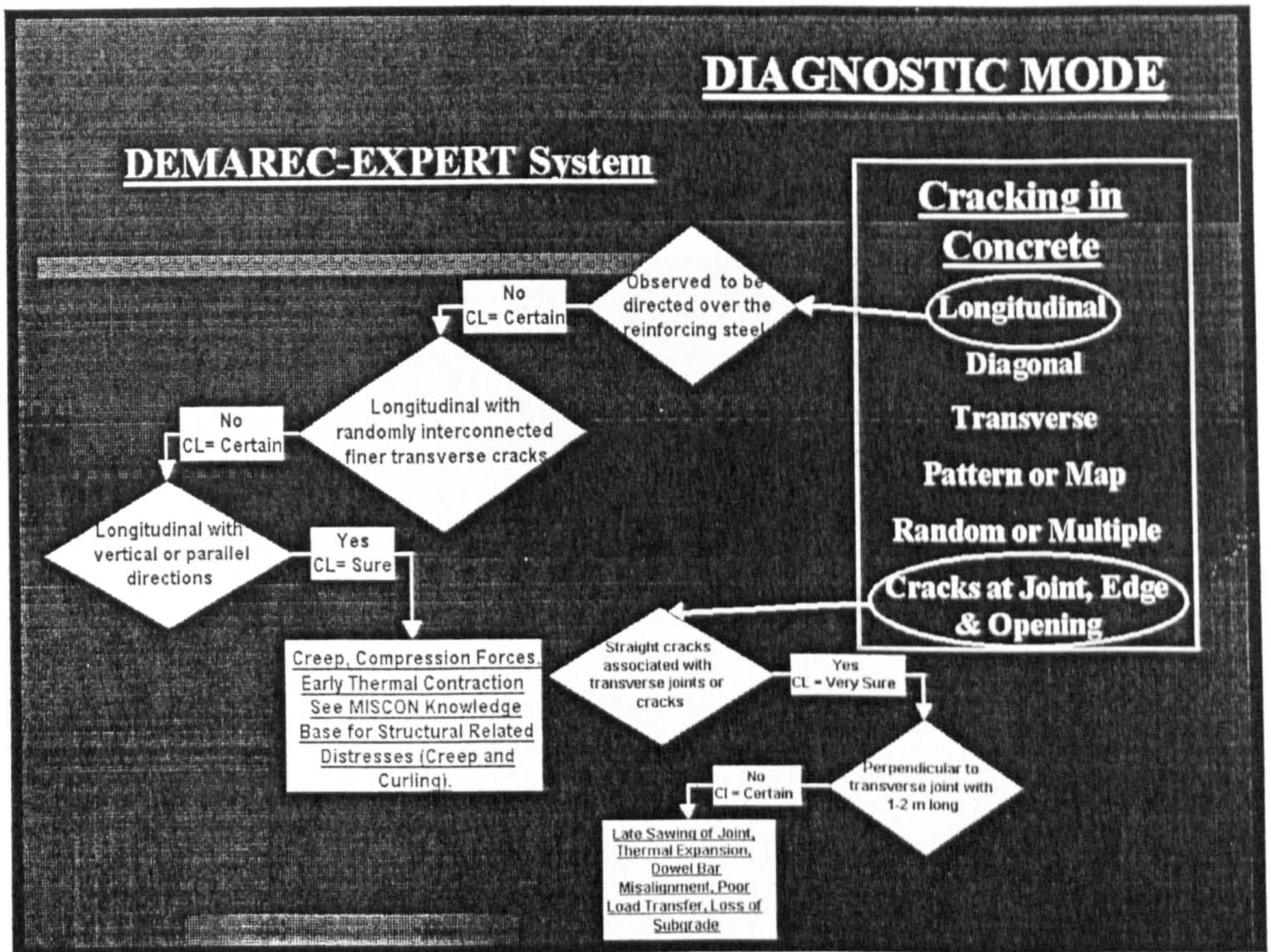


Figure 10.33 - Running cracking in concrete knowledge base.

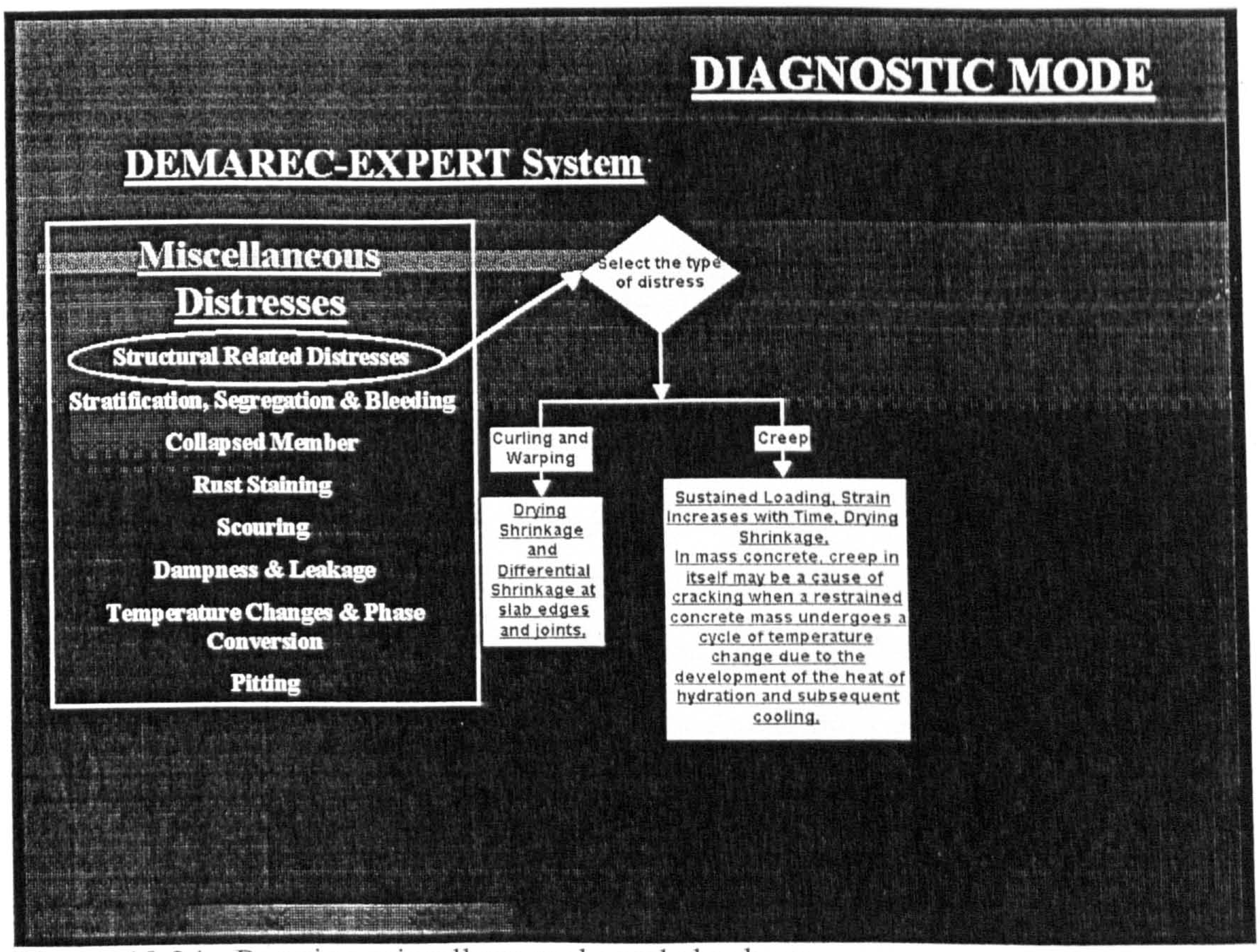


Figure 10.34 - Running miscellaneous knowledge base.

It is concluded that the pattern of cracking in the external slab is a result of the possible causes such as late sawing of joints, dowel bar misalignment, shrinkage, temperature changes, curling, poor load transfer and loss of substrate (Figure 10.35).

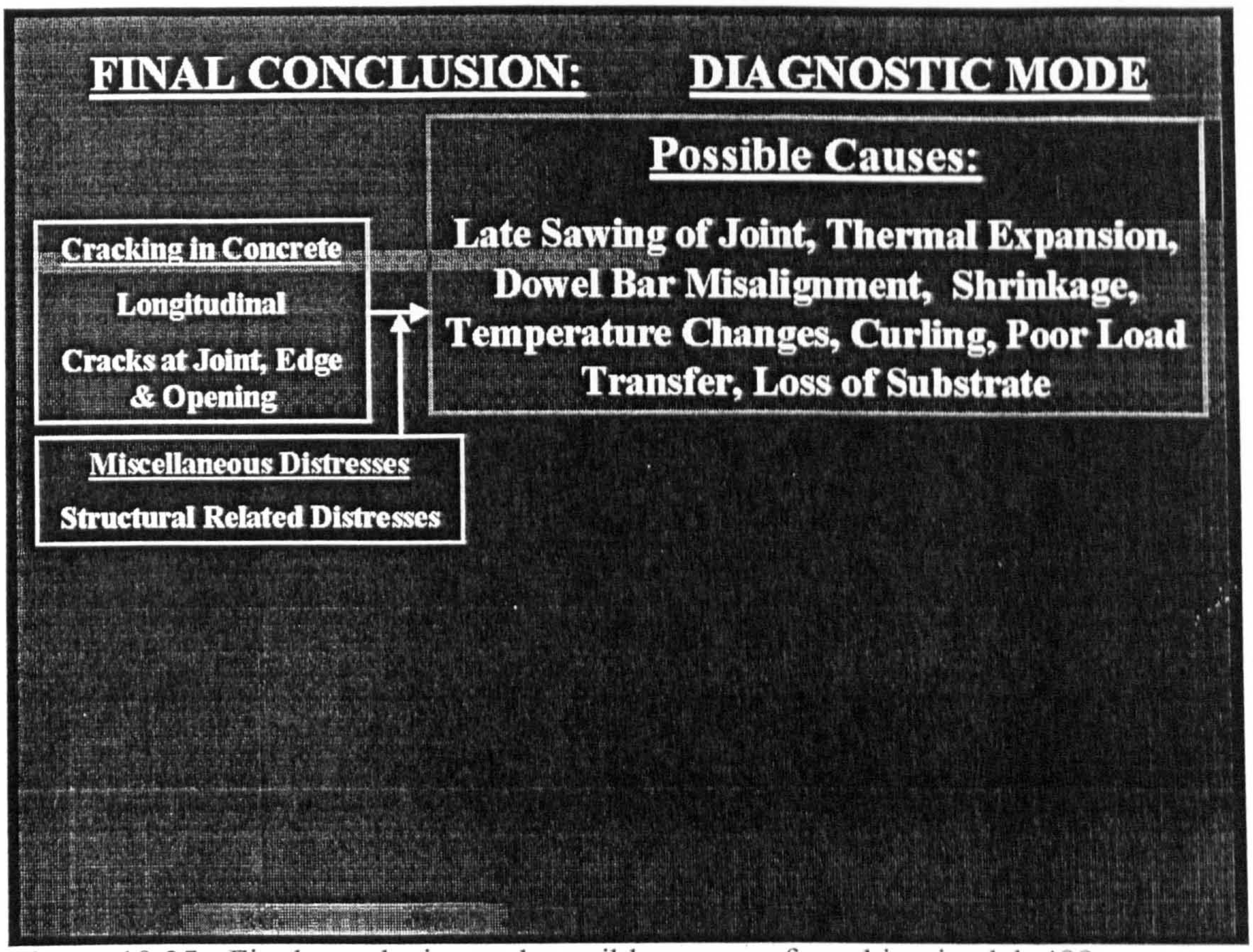


Figure 10.35 - Final conclusion and possible causes of cracking in slab 488.

In view of the data provided by the REPCON database in repair, durability and maintenance of concrete, the user could go back to REPair of CONcrete (REPCON) database as shown in Figure 10.36 and extract the appropriate information on durability and in choosing alternative repair materials and methods. It is recommended that slabs should be replaced with either fibre-reinforced concrete or shrinkage compensating concrete. Recommendations regarding shrinkage and temperature changes could direct the user to design the concrete with specifications relevant to such a concrete slab.

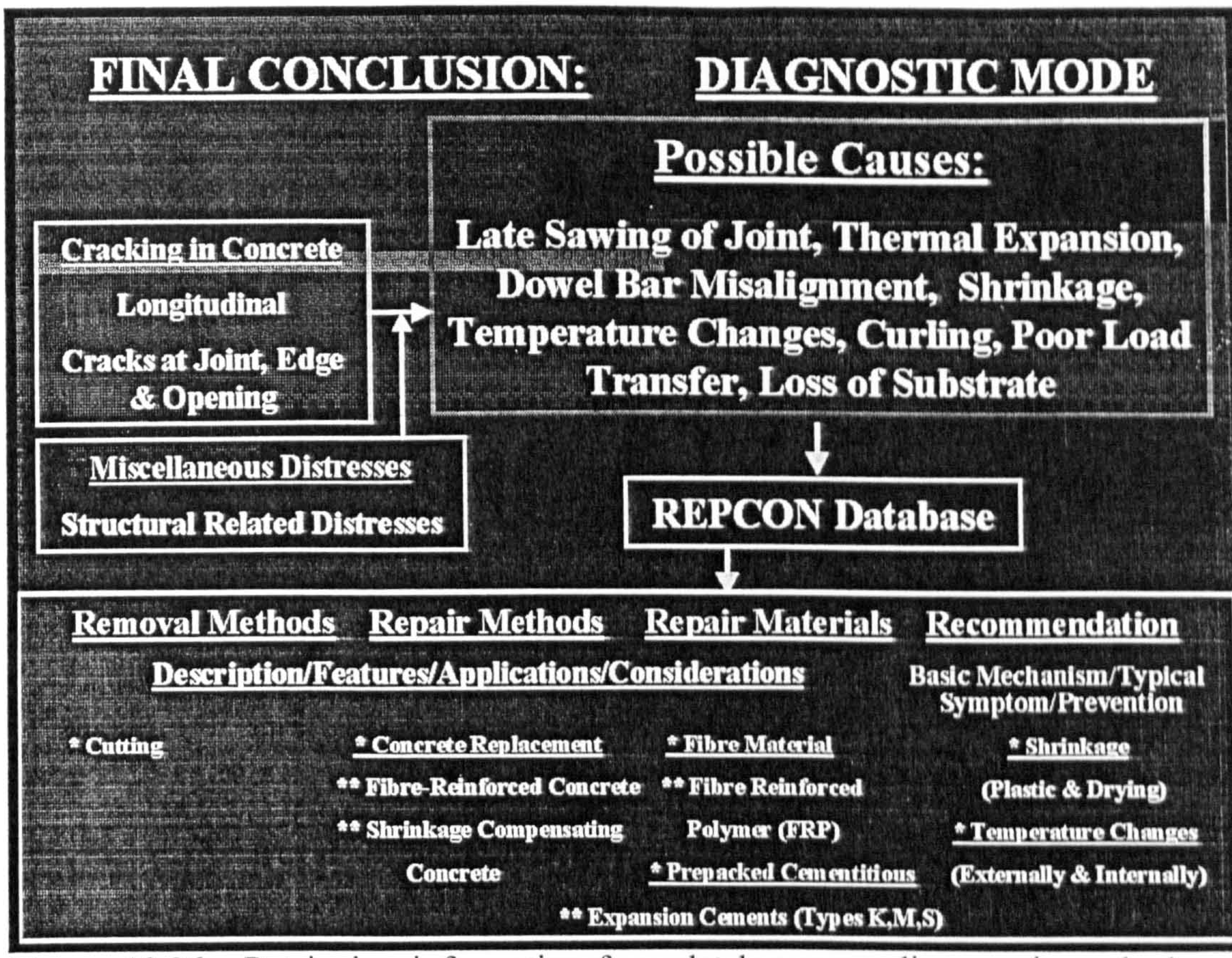


Figure 10.36 - Retrieving information from database regarding repair methods and material and durability recommendation for slab 488.

10.5.5 Comparison of Results

In order to assess the validity of the DEMAREC-EXPERT System results in assessing the reasons for the pattern of cracking in the Tradeteam external pavement, the following conclusion can be reached. Firstly, causes and effects of cracking obtained from the DEMAREC conclusion could conduct the user in correctly diagnosing the distress. Secondly, alternative repair materials and methods from the durability recommendation extracted from the REPCON database allow the user to select the best course of repair and maintenance. Engineering judgement and experience alongside the site investigation and in-situ and laboratory examinations were able to inform the final conclusion. The results are shown in Table 10.2. They confirme that the DEMAREC-EXPERT performance was very good.

Table 10.2 – Comparison of results between DEMAREC application and external paving investigation.

	Possible Causes or Considered	Alternative Materials	Alternative Methods
DEMAREC-EXPERT System	* Dowel Bar Misalignment * Late Sawing of Joint * Thermal Expansion * Shrinkage * Temperature Changes * Curling * Poor Load Transfer * Loss of Substrate	* Fibre Reinforced Polymer (FRP) * Expansion Cements (Types K, M, S)	Concrete Replacement * Fibre-Reinforced Concrete * Shrinkage Compensating Concrete
External Paving Investigation	* Temperature & Moisture Changes Led to Shrinkage and Curling * Dowel Bar Misalignment * Poor Load Transfer * Differential Settlement	* Air Entrainment * Polypropylene Fibre	Concrete Replacement

10.6 Case Study 2 – Warehouse Concrete Floor Project

In this project, the settlement and cracking in a warehouse floor at Chatham Dockyard operated by Nordic Holdings Ltd. is considered. This is an actual project in which the settlement and cracking are proving to be a significant hindrance and a need to undertake a full investigation. In this case study, it is shown that the results of this research work have been able to enhance the process of determining the causes and effects of the distress and in choosing the alternative options for the repair methods and materials.

10.6.1 Description of Warehouse Concrete Floor

The site is located adjacent to the River Medway immediately to the north of No. 3 Basin at the Chatham Dockyard. Referenced to publications of the British Geological Survey indicate that the site is located on the boundary of the Thanet Beds and Upper Chalk, underlying superficial Alluvium deposits. Alluvium is typically a variable sequence of silt, clay, sand and gravel deposits, which is locally organic with beat bands. Thanet Beds are typically a dense locally clayey silty fine sand, and this deposit is underlain by Upper Chalk which consists of a weak, white fine grained limestone with bands of flints. The existing concrete slab is a ground-bearing slab on the basis of CBR test values taken on the subgrade level. A steel fibre reinforced concrete floor also installed in 1996 and an extension installed in 1997 have developed differential settlement which in turn has caused cracking (Knapton; 2001, Contest Melbourne Weeks; 1994).

The concrete slab is laid directly onto prepared ground and sub-base and therefore relies on the resistance of this ground to prevent it from settling (WS Atkins Consultant Ltd, 1997). However, the ground has settled due to the deeper poor ground, but is being held back from settling around the column areas where the pile foundations for the columns are preventing this settlement (Figure 10.37). Thus giving differential settlement at these areas. The floor slab is settling differently on either sides of joint and cracks in the floor as shown in Figures 10.38 and 10.39.

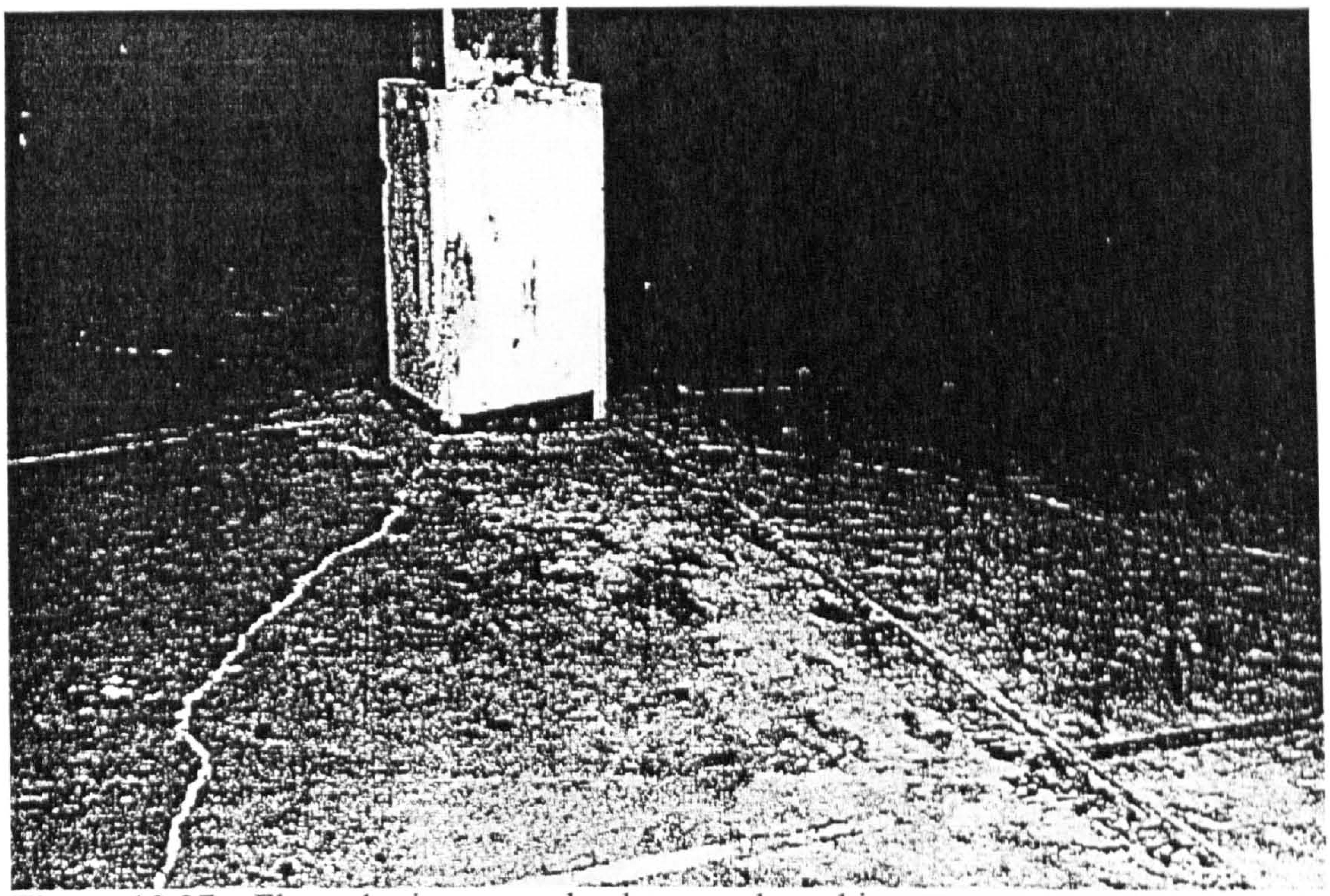


Figure 10.37 – Floor sloping around column and cracking (Knapton, 2001).

Owing to the differential settlements in the slab, floor level now has slopes throughout, therefore the tacked-up rolls of paper in those areas are no longer plumb (Figure 10.40). Figure 10.41 shows a developing crack in which the concrete rarely cracks cleanly. The tearing shown illustrates how small stones break away from the concrete during the cracking process. This tearing has produced small stones which are part of the hindrance.

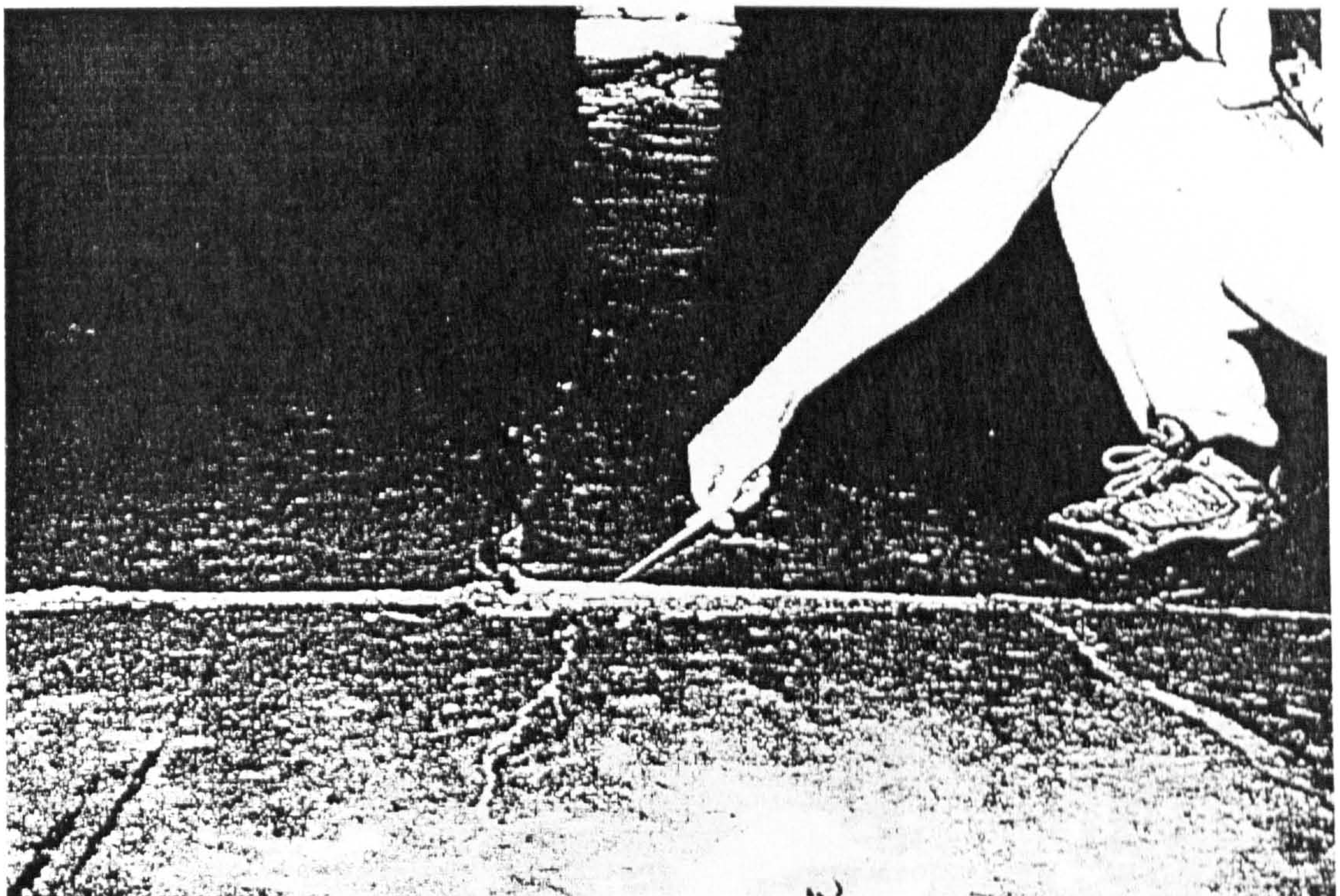


Figure 10.38 – Difference in level at cut joint (Knapton, 2001).

Figure 10.39 – Difference in level at cut joint and spalling at crack (Knapton, 2001).

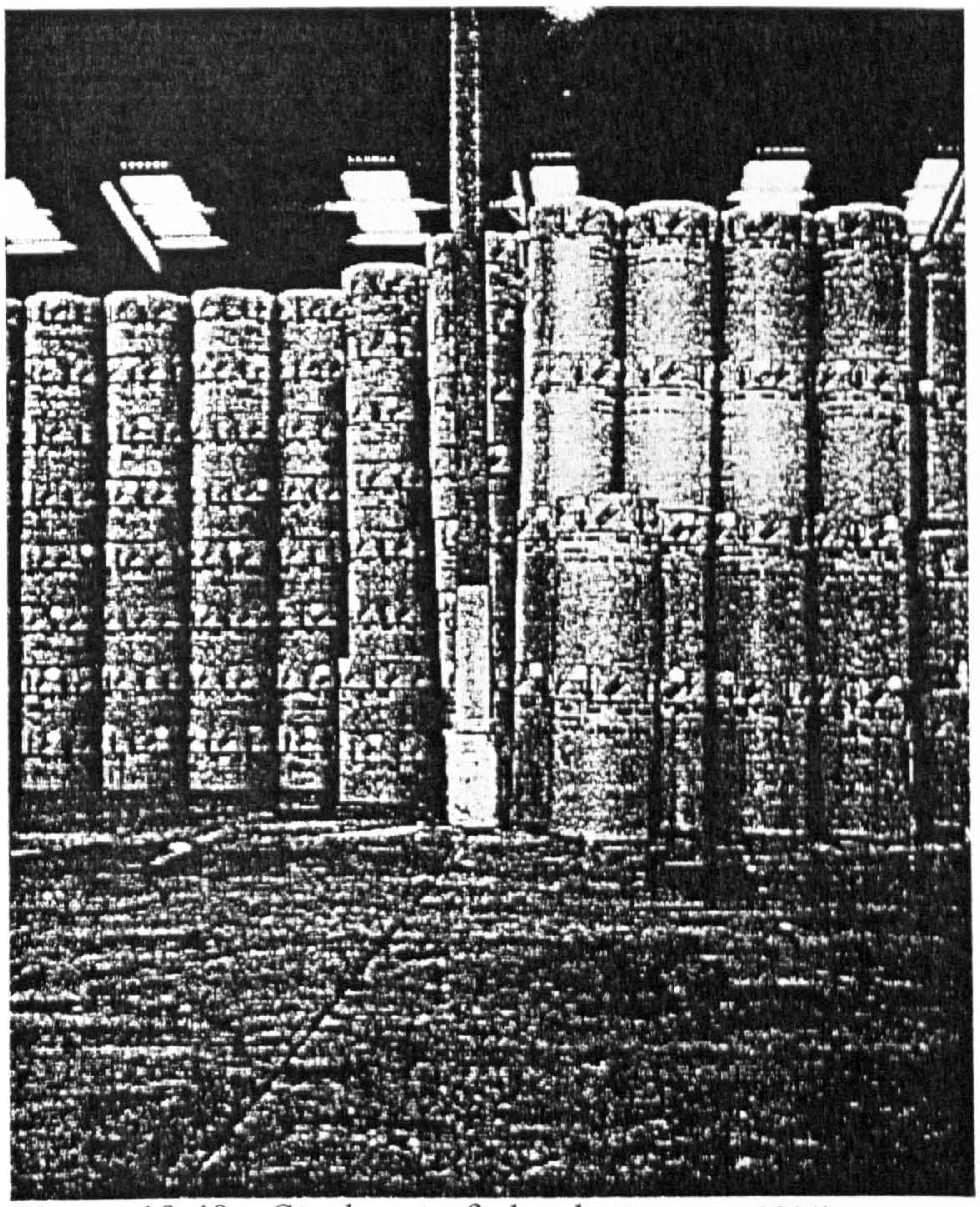


Figure 10.40 – Stack out of plumb (Knapton, 2001).

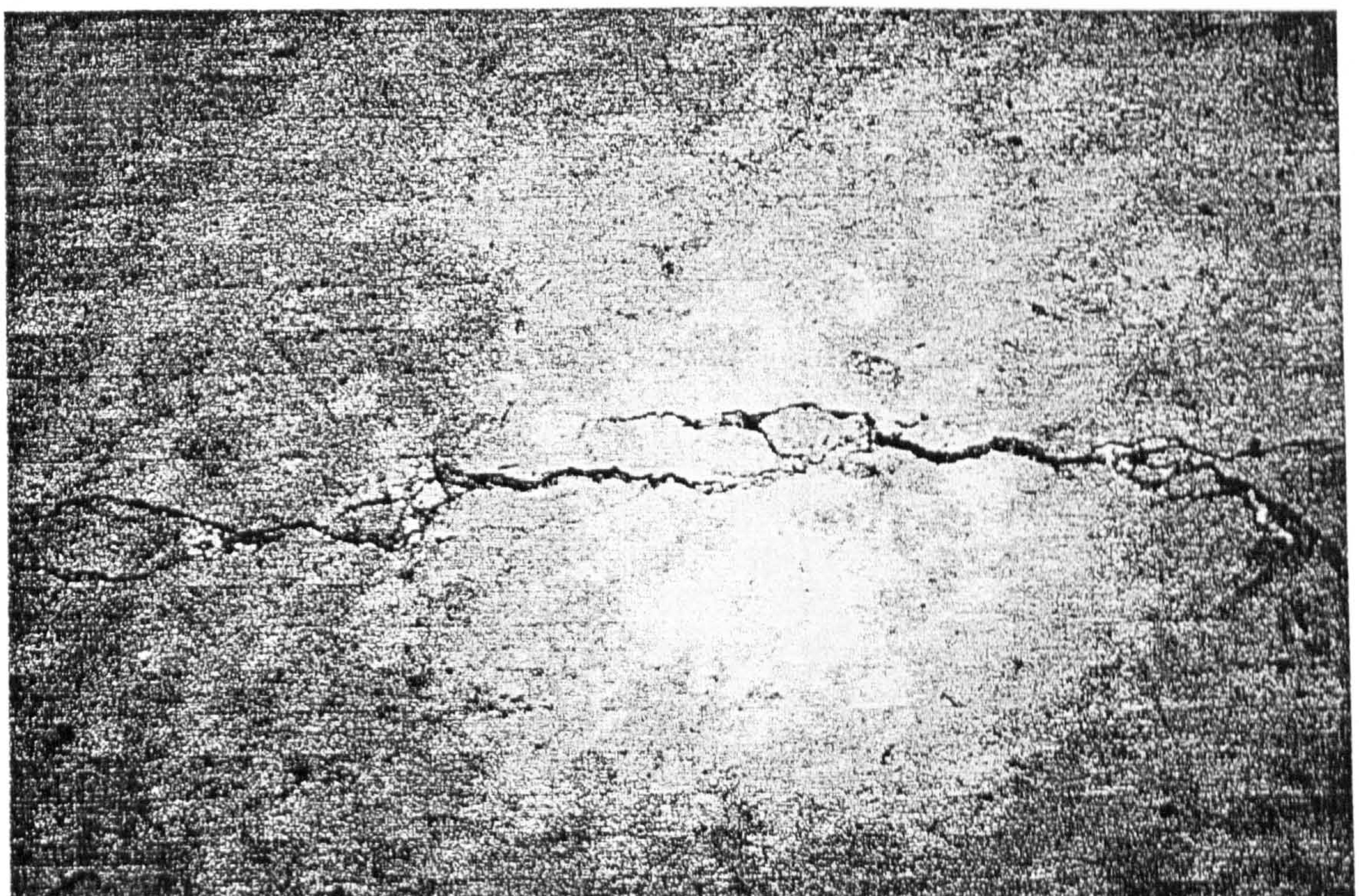


Figure 10.41 – The tearing of the concrete at this cracks leads to loose stones which are proving a hindrance to operations (Knapton, 2001).

Figures 10.42 and 10.43 show typical pattern of cracking at a hard spot. The small area of concrete surrounding the bunch of keys is at its original level and the surrounding concrete is settling. From visual inspection, it is concluded that the cracking occurs because concrete is stiff and cannot bend to accommodate the settlement. Other hard spots under the slab such as the old foundation for the previous electrical sub-station are also preventing the slab from settling evenly with the rest of the slab. Figure 10.44 illustrates the cracking in the vicinity of the electricity sub-station. The foundation of the old sub-station was left in and the new slab cast over, but with the slab settling around and the old foundations not settling. Those foundations are now causing the concrete to settle differentially and crack.

Figure 10.42 – Pattern of cracking around a local hard spot (Knapton, 2001).

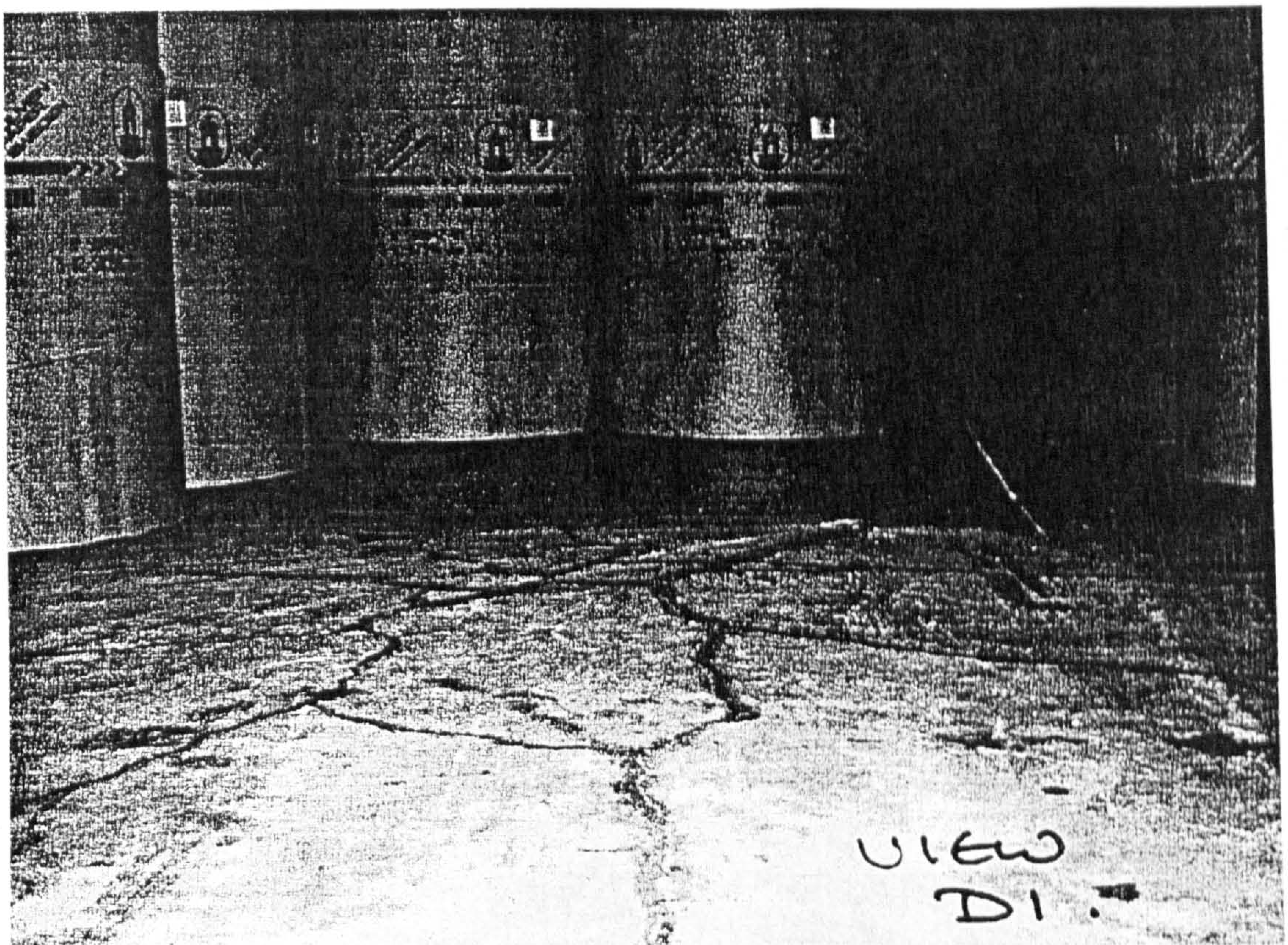


Figure 10.43 – Pattern of cracking around a local hard spot between stacks of paper rolls (Knapton, 2001).

Figure 10.44 – Cracking and differential settlement in the vicinity of the foundation to the old electricity sub-station (Knapton, 2001).

10.6.2 Assessment of Causes of Cracking

It is clear from the patterns of cracking shown in the Figures that the majority of cracking is due to large differential settlement and those that started as shrinkage cracks have developed further owing to the settlements in the slab. With the differential settlements experienced, it is quite possible that either the joints have opened up or a drain has cracked, allowing any water to escape into the ground below, which will increase the rate or compaction of these layers and increase the differential settlement of the slab. With further differential settlement the drainage runs would experience further damage.

10.6.3 Remedial Works

A full range of options was reviewed by WS Atkins Consultants Ltd (1997) and Mott MacDonald Ltd (1996) such as adding a lightweight reinforced screed, construct ground beams and suspended floor slab, expanded head piles and suspended RC floor slab and vibro-replacement stone columns with ground bearing slab. However, for the warehouse to be put back into full service for the full life span of the building it could be recommended that the total slab is replaced with a reinforced suspended concrete slab on a grid of piles or steel fibre reinforced concrete floor. Further comments in relation to remedial work was taken by Knapton (2001) on decoupling of floor and pile-caps, floor flattening and initial monitoring, and crack repair and long term monitoring.

10.6.4 DEMAREC Applied to the Chatham Dockyard Concrete Floor

Evaluation of Dockyard Concrete Floor by ECON program

The criteria for the evaluation of the current condition of the Chatham dockyard concrete floor is shown in Figure 10.45 and consists of cracking, spalling and delamination. The majority of the observations of signs of distress at Chatham comprise random cracking and joint related spalling and faulting. The descriptive information and pictures taken from the database illustrate failure modes of distress similar to the Chatham dockyard concrete floor. This capability allows the user to view examples and see the minor differences in similar distresses such as pattern and orientation of distress.

The current condition of the concrete floor at Chatham dockyard is determined by assigning a Deduct Value to each type of distress as shown in Figure 10.46. The confidence level for the concrete floor at Unit 15 is 38 i.e. poor condition. In-situ and laboratory investigation and engineering judgement should be made to take the best-recommended course for repair, replacement and maintenance.

Diagnosis of Causes of Distress by DEMAREC-EXPERT System

Owing to the differential settlements on either sides of the joints and cracks (Figures 10.38 and 10.39) observed in the visual inspection, the user could be directed to correctly diagnosing the cause and effect of distress at joints by using the cracking in concrete knowledge base and selecting the cracks at joint, edge and opening option.

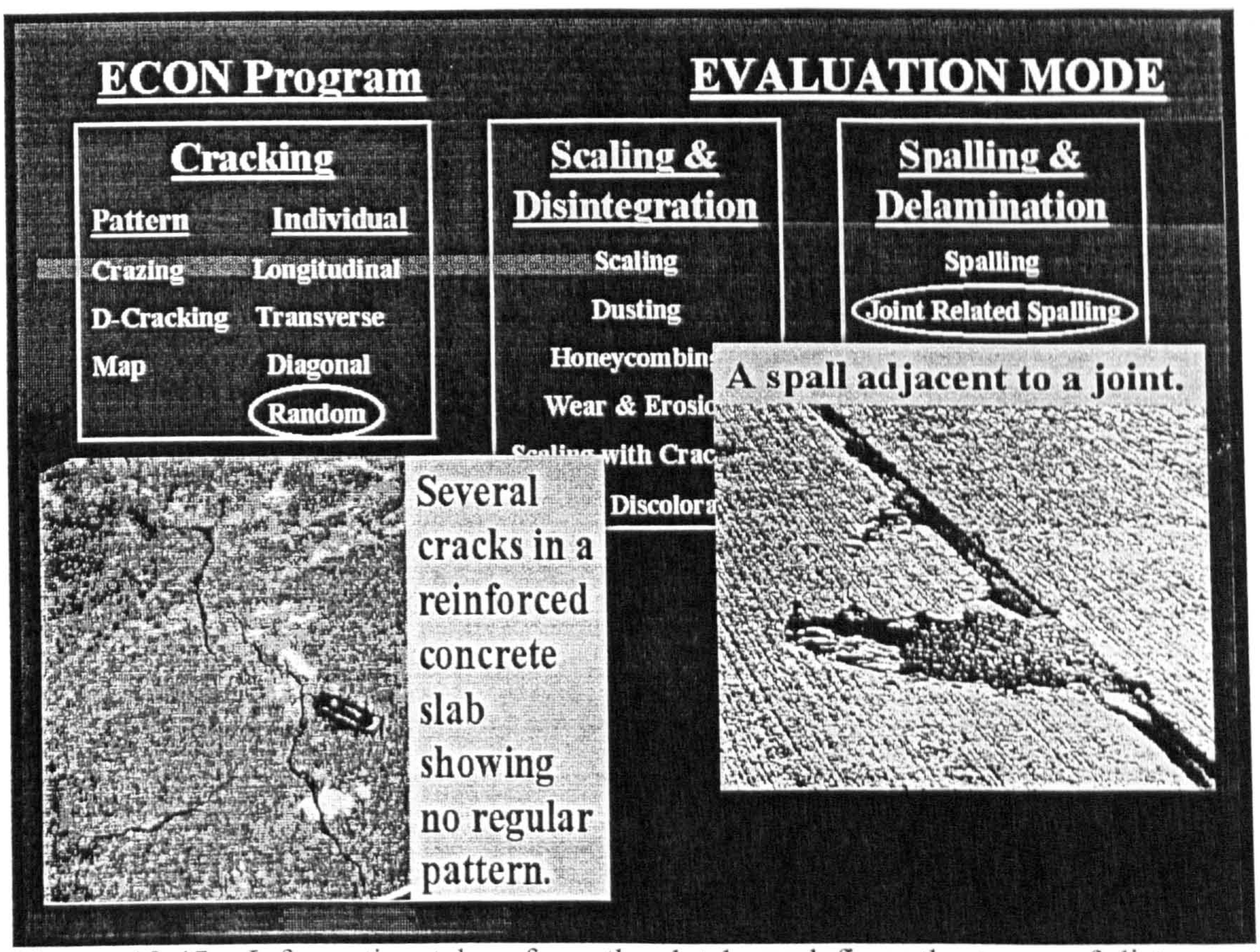


Figure 10.45 - Information taken from the database defines the types of distress at Chatham.

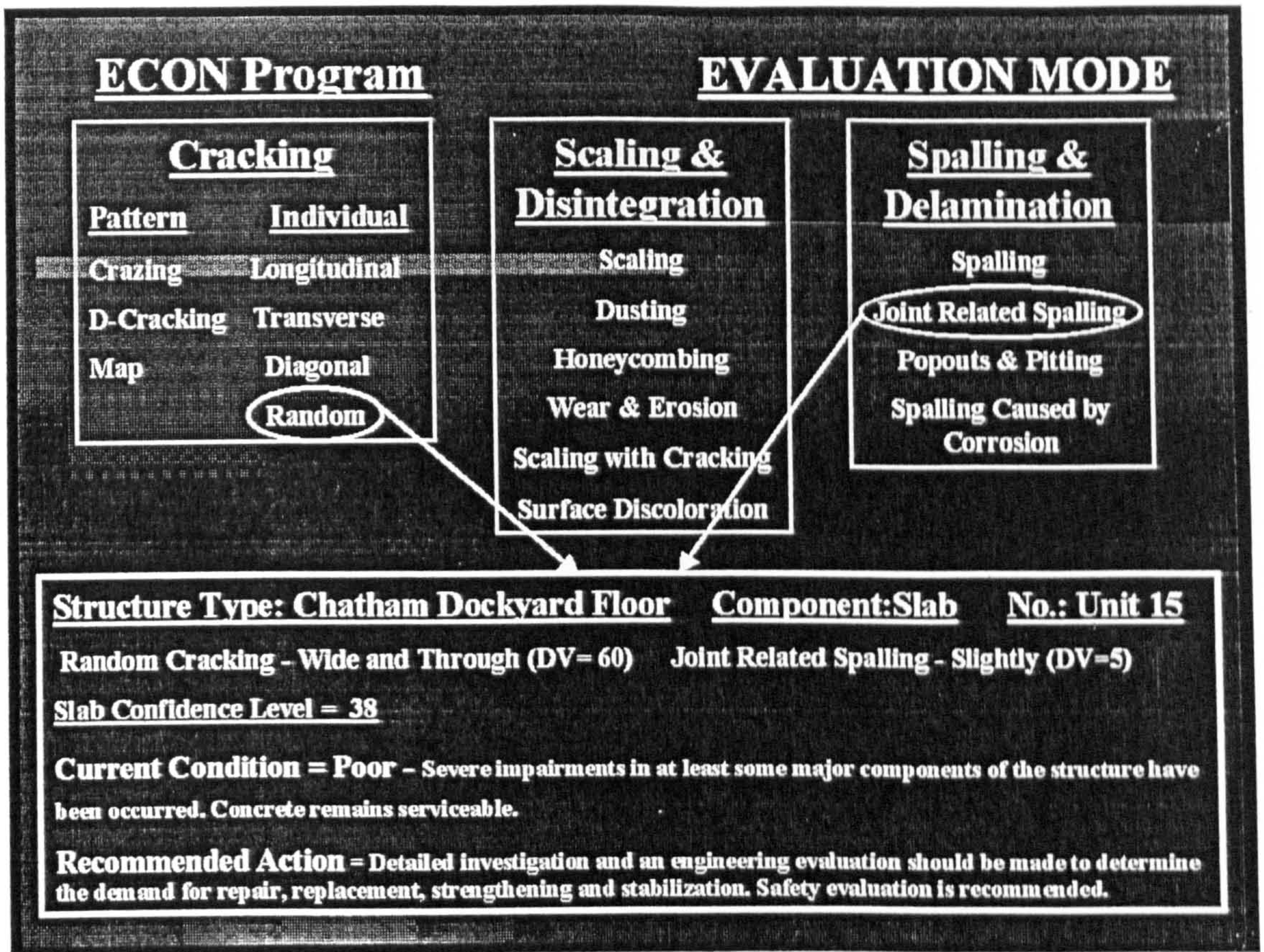


Figure 10.46 - The detailed evaluation of concrete floor at unit 15, Chatham dockyard.

This session may involve questions related to the shape of the cracks, location, direction and their appearance (Figure 10.47). At the end of this session, the user is conducted to use the random or multiple option for further investigation and final conclusion.

By using the random or multiple option at cracking in the concrete knowledge base shown in Figure 10.48, the user can find the possible causes of cracking in the concrete floor of Unit15 at the Chatham dockyard.

It is concluded that the ground movement, the differential settlements and the shrinkage cracking are proving to be the possible causes of distress at the Chatham dockyard floor (Figure 10.49).

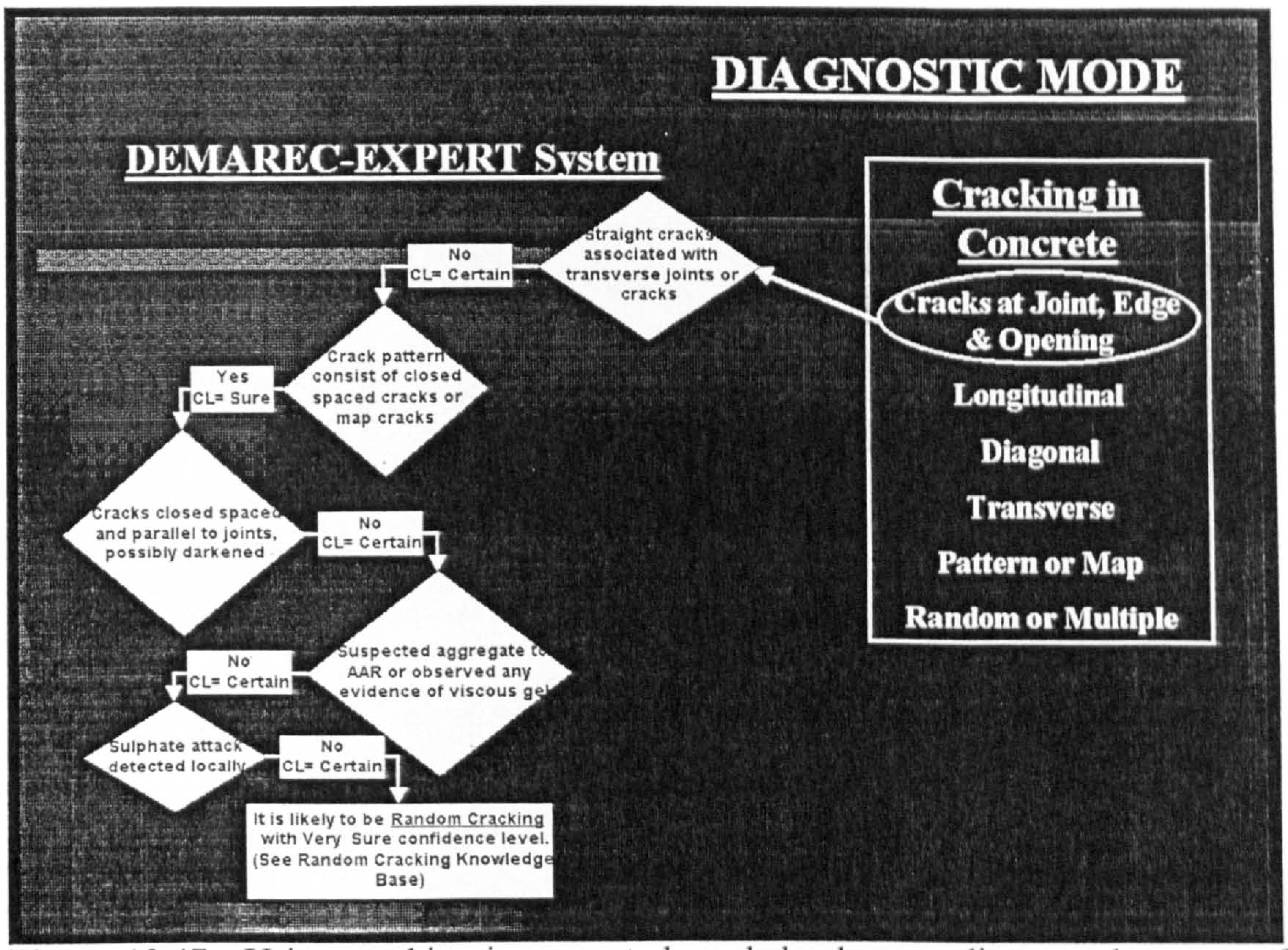


Figure 10.47 - Using cracking in concrete knowledge base to diagnose the cause of distress at joints.

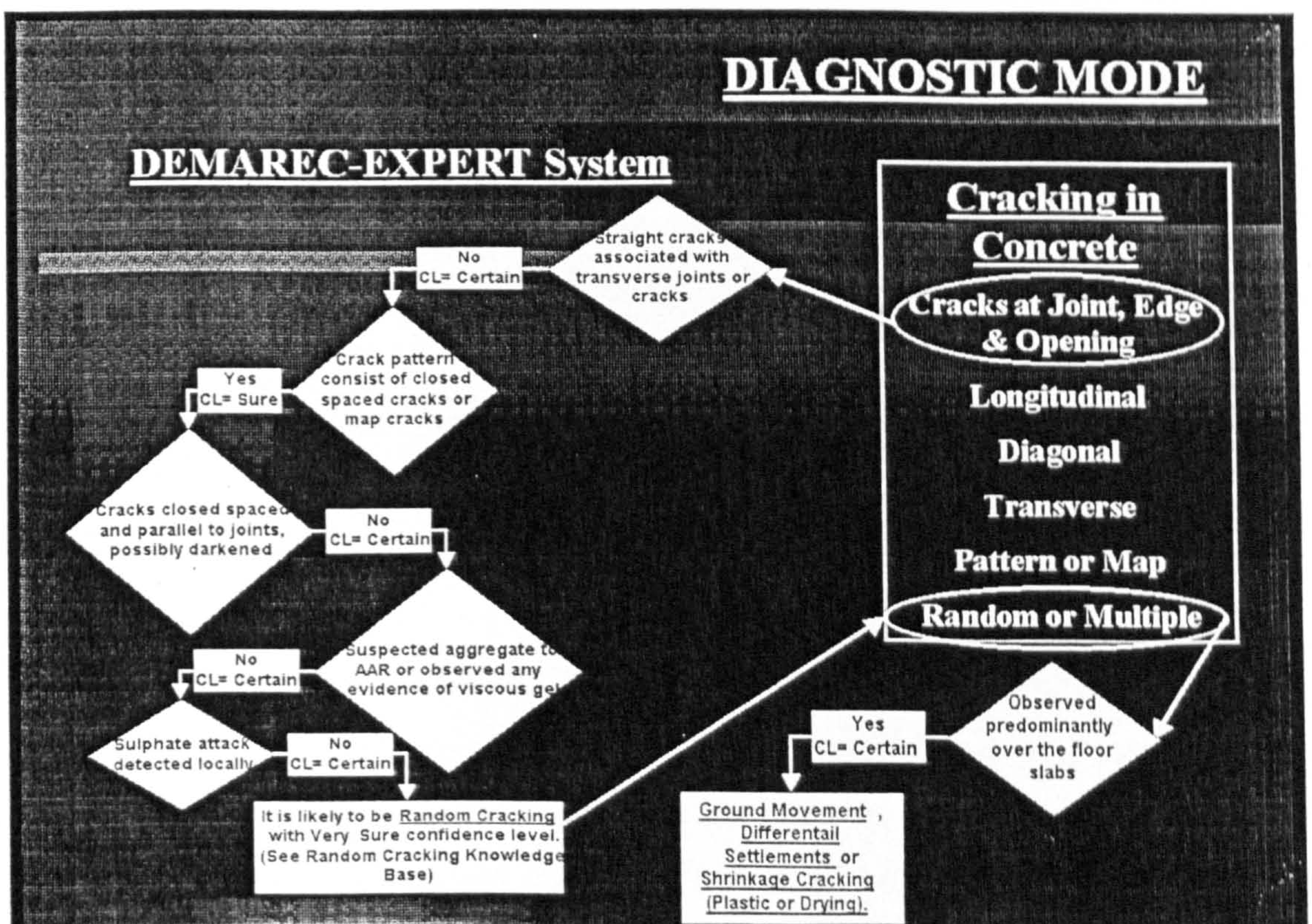


Figure 10.48 - The system directs the user to use random cracking for final conclusion.

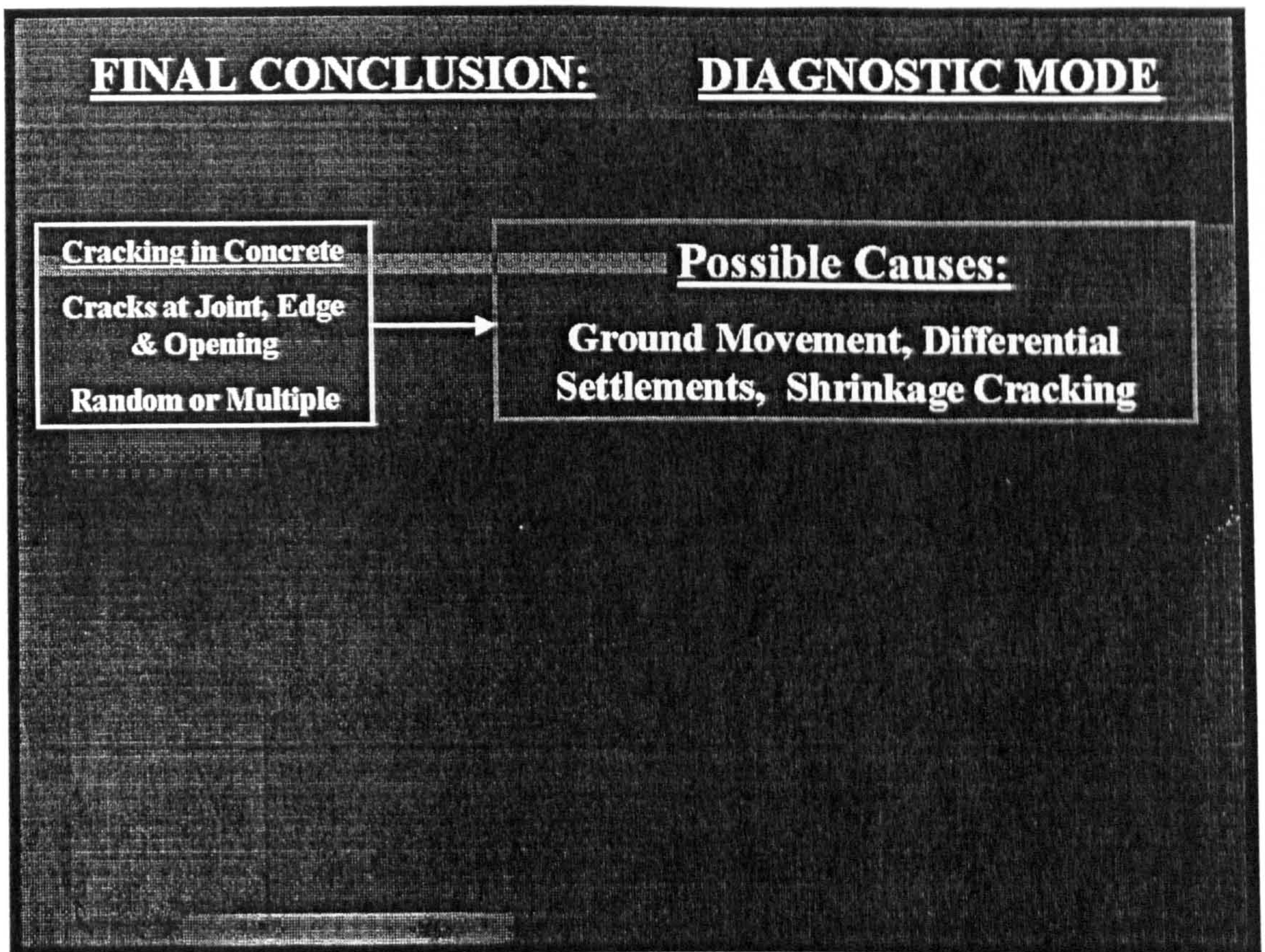


Figure 10.49 - Possible causes of cracking at Chatham dockyard floor concluded by DEMAREC-EXPERT System.

The REPCON database gives recommendations on the selection of materials and procedures for the repair and rehabilitation of concrete floor. It is recommended that the concrete floor at Chatham dockyard should be replaced with fibre-reinforced concrete or should be stabilised by grouting and resin injection of the cracks. Figure 10.50 shows the result of retrieving appropriate information from the REPCON database for the Chatham dockyard concrete floor.

10.6.5 Comparison of Results

To assess the validity of the DEMAREC-EXPERT System results, the emphasis is put on comparing the experimental and actual investigation of causes of distress at the Chatham dockyard concrete floor and those given by the system. Firstly, the causes and effects of cracking obtained from the DEMAREC conclusion could conduct the user in correctly diagnosing the distress. Secondly, alternative repair materials and methods alongside the recommendation regarding durability retrieved from the REPCON database conducts the user to take the engineering judgement and experience for repair and maintenance. This comparison, as shown in Table 10.3, confirmed that the system performance was very good.

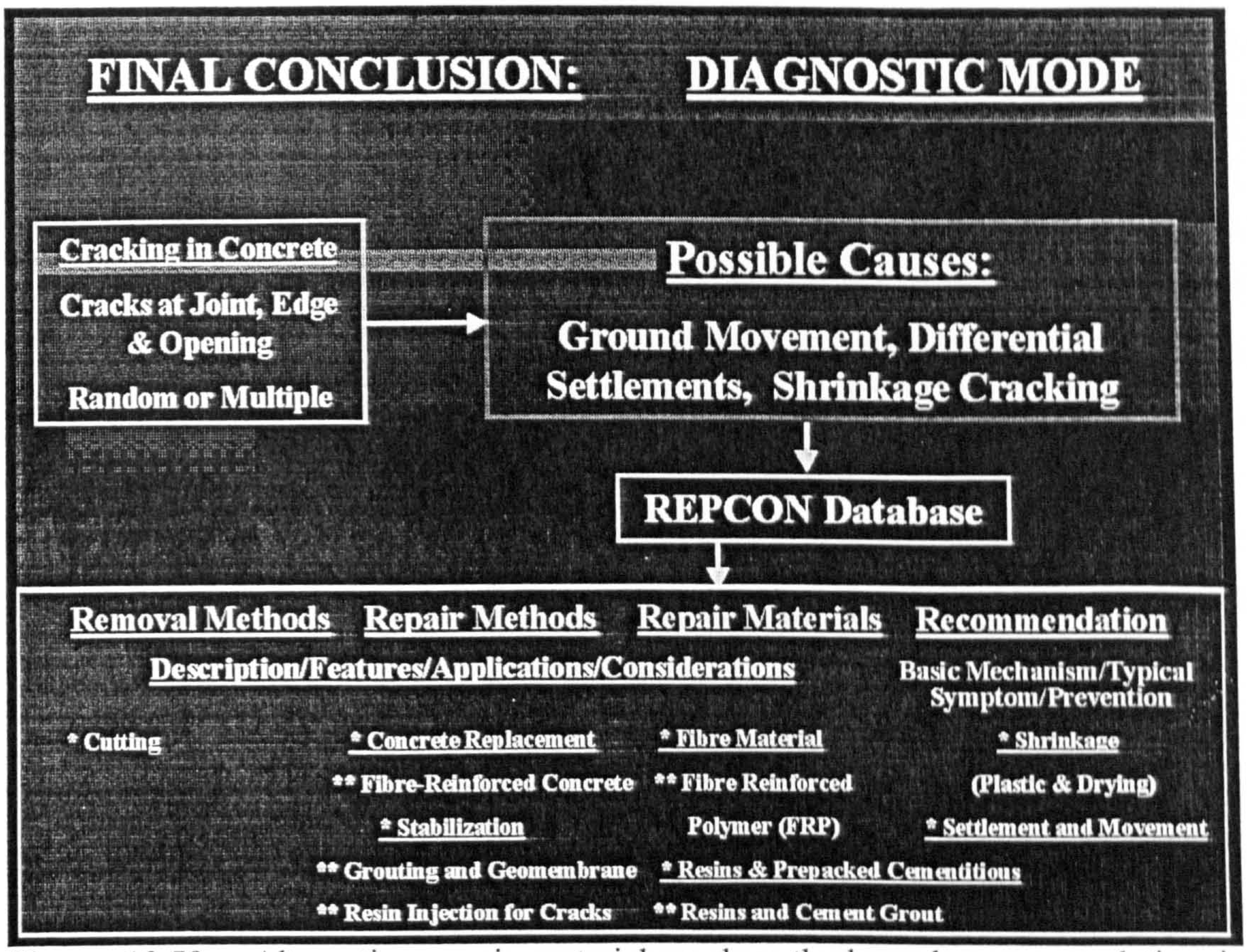


Figure 10.50 - Alternative repair materials and methods and recommendation in durability for the Chatham dockyard floor retrieved from the database.

Table 10.3 – Comparison of results between DEMAREC application and the Chatham dockyard concrete floor investigation.

	Possible Causes or Considered	Alternative Materials	Alternative Methods
DEMAREC-EXPERT System	* Ground Movement * Differential Settlements * Shrinkage Cracking	* Fibre Reinforced Polymer (FRP) * Cement Grout * Resins	**Concrete Replacement** * Fibre-Reinforced Concrete **Stabilization** * Grouting * Geomembrane * Crack Resin Injection
Chatham Dockyard Concrete Floor Investigation	* Differential Settlements * Shrinkage Cracks	* Fibre Reinforced Polymer (FRP) * Resins	**Concrete Replacement** * Fibre-Reinforced Concrete * Reinforced Suspended Concrete slab on piles **Stabilization** * Decoupling * Flattening * Monitoring * Crack Repair

10.7 Case Study 3 – Highway Concrete (HWYCON) Expert System

One of the major goals of the Strategic Highway Research Program (SHRP) was to improve the performance and durability of highway concrete. SHRP Project C-206, Optimization of Highway Concrete Technology, was created to disseminate knowledge of the results of SHRP – sponsored research and recent advancements in concrete materials technology. The products of this project included a synthesis of advances in highway concrete technology, training videos and the expert system Highway Concrete (HWYCON) (SHRP, 1994). HYWCON was designed to assist state highway departments in three areas: 1) diagnosing distresses in highway pavements and structures; 2) selecting materials for construction and rehabilitation; and 3) obtaining recommendations on materials and procedures for repair and rehabilitation methods.

In this case study, the DEMAREC-EXPERT results were validated against concrete repair problems undertaken by HYWCON expert system (SHRP, 1994) stated in the literature involving concrete bridge deck and substructure diagnostics. Emphasis was placed on comparing the knowledge areas, the development and implementation tools and the experimental results obtaining by HYWCON with those given by DEMAREC-EXPERT.

10.7.1 The Knowledge Areas Covered by HYWCON

The knowledge contained in HYWCON includes information and rules on the four individual subsystems. Each subsystem was initially developed and distributed independently in the following sequence:

- Concrete pavement diagnostics (CONPAV-D),
- Concrete bridge deck and substructure diagnostics (CONSTRUC-D),
- Concrete materials selection (CONMAT), and
- Concrete pavement repair and rehabilitation (CONPAV-R).

Knowledge about pavements was represented in all three subsystems CONPAV-D, CONMAT and CONPAV-R. Knowledge related to highway concrete structures was also included, especially for bridge decks and substructures. Substructures include concrete elements such as bridge columns, piers and parapet walls. Information on structures was not as clearly defined as the knowledge on pavement, except in diagnostics subsystem. Separate modules were developed to address distresses in bridge decks (CONSTRUC-D for bridge decks) and CONSTRUC-D for distresses in structures. The CONMAT subsystem was used to select materials for pavements or structures. For repair and rehabilitation, no knowledge was included on structures. Table 10.4 shows the types of pavement and structure and topics covered by each of the HYWCON subsystems.

Table 10.4 – Distress categories and types of structures covered by HYWCON.

Subsystem	Structure Type	Distress Category and Type
CONPAV-D	**Jointed Concrete Pavement (Reinforced or Plain)**	• Cracks at joints, edges and other openings • Random cracking distributed over span • Generally Straight cracks • Sealant failure • Joint related cracking, spalling and faulting • Surface spalling, popouts and scaling • Surface potholes • Polishing of aggregate
	Continuously Reinforced Concrete Pavement	• Cracking (transverse, longitudinal, diagonal, multiple distributed over slab. multiple localised near joint) • Joint related faulting • Edge punchout • Surface spalling, popouts and scaling • Surface potholes • Polishing of aggregate
CONSTRUC-D	**Bridge Deck**	• Cracking (longitudinal, transverse, diagonal, random, Pattern or map) • Surface spalling, popouts and scaling • Polishing of aggregate
	Structures	• Cracking (longitudinal, pattern or map, diagonal, random) • Surface scaling and disintegration

CONMAT gave recommendations on the design of concrete for four areas of durability and included knowledge on three methods. The durability areas included: 1) corrosion of reinforcing steel; 2) sulphate attack; 3) freezing and thawing actions; and 4) alkali-aggregate reactivity. The methods represented in the knowledge base included recycling concrete, permeable bases and fast track concrete. Materials durability knowledge included in CONMAT closely parallel the Guide to Durable Concrete published by the ACI Committee 201. New knowledge from other SHRP projects on freezing and thawing actions, alkali-aggregate reactivity and on high-performance concrete was also included in this subsystem.

The HYWCON subsystem CONPAV-R gave recommendations on the selection of materials and procedures for the repair and rehabilitation of concrete pavements. The program assumed that the procedure has already been chosen. The procedures covered in CONPAV-R included bonded and unbounded overlays, full and partial depth repairs and diamond grinding and milling. CONPAV-R gave recommendations on materials and steps for performing the procedures. The American Concrete Pavement Association has an action program in this area and has published technical bulletins covering this area. Knowledge from this documents and drawings were represented in CONPAV-R.

10.7.2 HYWCON Development and Implementation

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 development tool used to develop HYWCON is an available example of commercial software. One of the advantages of using Level5 Object was the ability to use different inference procedures. HYWCON used both backward and forward chaining inference. But, the major disadvantage of using Level5 Object in development HYWCON is the use of Yes/No mode of confidence level. It means that if the confidence of the user to answer the question is not definitely "Yes" or "No", there is no longer any reason to pursue the hypothesis.

10.7.3 Comparison of DEMAREC-EXPERT Results with HYWCON Subsystems

The knowledge contained in DEMAREC-EXPERT includes information and rules on the three categories of distress in concrete structures. These categories as shown in Tables 8.1 through 8.3 comprise cracking in concrete, surface distresses and miscellaneous distresses in concrete structures. By comparing of Tables 8.1 through 8.3 with Table 10.4, it is observed that the domain of knowledge included in DEMAREC-EXPERT system is much more covered than HYWCON subsystem CONSTRUC-D. It is particularly for surface distresses such as dusting, wear and erosion and discoloration and miscellaneous distresses in concrete structures.

One of the main characteristics of DEMAREC application is that the DEMAREC-EXPERT system is coupled to REPCON as an independent database through the Visual Basic User Interface to access the repair materials and methods and recommendations on durability and maintenance. The data and knowledge included in DEMAREC application in comparison with CONMAT subsystem is covered a wide range of materials and alternative methods on repair of concrete structures.

Information shown in Table 7.9 relating durability and maintenance of concrete structures included in the DEMAREC application in comparison with HYWCON subsystem CONMAT was taken from the American Concrete Institute (ACI, 1996), the British Standards Institution (BSI, 1997) and other technical reports published by concrete associations. This information has been classified in four main categories and gives recommendations on the design of concrete for a wide range of durability areas such as construction and design errors, settlement and movement, frost attack, sulphate attack, shrinkage, chloride attack, alkali-aggregate reactivity, concrete material recommendations.

DEMAREC-EXPERT development and implementation were also validated against development tool used by HWYCON. Emphasis was placed on comparing the development tool and programming productivity. M.4, as an expert system shell, is used as a development tool that provides a platform for further enhancement and the addition of knowledge as well as providing a high level of programming productivity. A comparative example between DEMAREC-EXPERT and HWYCON consultation results is shown in Figure 10.51.

The chief innovative characteristic of DEMAREC-EXPERT in comparison with HYWCON is the introduction of confidence levels (CL). CLs are words and descriptive functions with pre-determined confidence level value which are used to measure the strength of the knowledge and to conceal specific uncertainty within the meaning. If the confidence level of the premise is not "Certain", the conclusion is still noted because there may be good reason to pursue the hypothesis, no matter how uncertain it might be now. Indeed, one of the strengths of the system is the way in which it allows the promotion and relegation of knowledge according to the opinion of users of different levels of ability from expert to novice. This chain of events in which seeking the value of one expression causes M.4 to invoke a relevant rule, and consequently to seek the value of another expression found in the premise of the rule is called backward chaining and is fundamental to the operation of the DEMAREC-EXPERT inference engine. It was concluded that the DEMAREC-EXPERT system performance was very good.

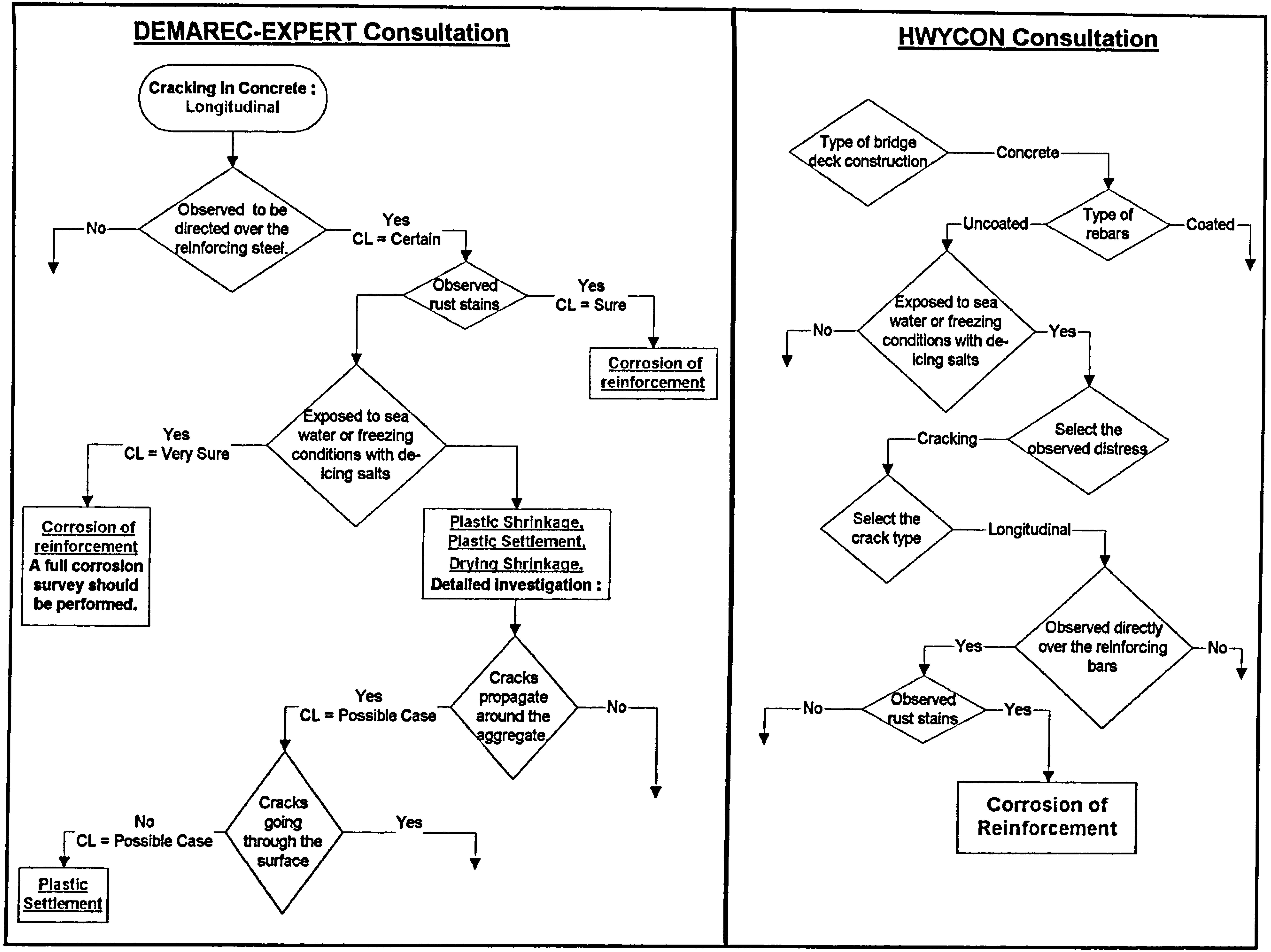


Figure 10.51 - An instance of comparing between DEMAREC-EXPERT and HYWCON consultation.

10.8 Summary

The principal value of DEMAREC is as a platform for the long-term development of an integrated engineering computing environment. The conceptual architecture for the environment consists of multiple knowledge base tools, user interfaces, evaluation program and databases supported on networked processors to form a simple integrated system

The central feature of this research is the integrating of two hitherto separate areas of Information Technology (IT), i.e. a database management system (DBMS) and a knowledge-based expert system (KBES). Certainly the research has succeeded in addressing many of the issues in the coupling of knowledge-based expert systems with database management systems for concrete repair applications. The original focus of research on developing a flexible interface system has been substantially achieved. In the prototype implementation, knowledge-based expert systems may pose arbitrary queries in the context of their own data structures which are then answered using data from the database that is hidden from KBES.

As a database interface for a knowledge-based expert system, a major strength of DEMAREC has proved to be its provisions for handling dynamically added data. In addition, DEMAREC deals with engineering data and the needs of engineering applications with respect to that data in the field of concrete repair. Considerations were given to the design process for DEMAREC. The global schema uses a data model to provide maximum semantic representation capabilities. This is illustrated by comparing pictures and technical data in a way that makes decision and problem solving easier.

In the final part of this Chapter, the DEMAREC results is validated by three case studies taken from actual cases of concrete diagnosis and repair and from the literature. In these case studies, it is shown that the results of this research could have been used to enhance the process of determining the cause of the failure and in selecting the repair material and method.

Chapter 11

Conclusions and Recommendations

11.1 Introduction

The overall aim of the research was to investigate the benefits which would accrue from combining a knowledge-based expert system and a database management system so as to produce an evaluation program for the maintenance and repair of concrete structures. Within the framework of this overall aim, the main objective of the thesis is to explain the development of an integrated engineering computing environment in which a multiple expert system (DEMAREC-EXPERT) is coupled to an independent database management system (REPCON) and an evaluation of concrete program (ECON). The software is called DEMAREC - Diagnosis, Evaluation, MAintenance and REpair of Concrete structures.

The first part of this Chapter presents a brief summary of the research study presented in this thesis. The remainder of the Chapter presents the main outputs from this research work and proposes future work to improve and to extend the system. It also points out areas in repair of concrete where additional research is required. Finally, general comments are given concerning the evolving knowledge and database.

11.2 A Brief Summary of the Research Study

The durability problem of concrete structures is worldwide. It contributes a huge capital loss by reducing the lifetime of structures. Over the last decade, designing and constructing concrete structures of enhanced durability, thereby decreasing maintenance and repair costs, has been the focus of research and development and a wealth of knowledge has been promulgated at various conferences. In view of this, emphasis has been placed to the maintenance and repair of existing concrete buildings as well as on the concept of designing and constructing with a view to durability.

Concrete repair is a complex process, presenting unique challenges very different from those experienced in the field of new concrete construction. Concrete repair must successfully integrate new materials with old materials, forming a composite capable enduring the exposure of use, the environment and time. During the last few years, many companies have involved in the development and supply of concrete repair products as well as damage appraisal and performance of repair and maintenance techniques. Therefore, it is common for a client to appoint an inexperienced contractor and become the victim of an inadequate repair in terms of material and technique.

Extensive research has been conducted to make decisions and to overcome problems associated with the repair of concrete structures by using knowledge based expert systems. With consideration of the foregoing issues, a lack of an advisory management system and a need to marshal all available data in a common format has persuaded authors to use an integrated engineering computing environment to investigate concrete repair problems. Gathering available information and data in the maintenance and repair of concrete structures allows realistic and proper diagnosis of the cause(s) of the distress, provides expertise advice on material selection and enables adequate repair techniques.

An objective of the aim of this research is to investigate an innovative approach designed to improve the performance and durability of concrete structures. The research has included the development of a computer program called DEMAREC which combines information on concrete distresses (including cracking, surface and miscellaneous distresses), investigation technologies, diagnosis methodologies and repair materials and methods. DEMAREC is a Visual Basic interface in which a multiple production rules expert system (DEMAREC-EXPERT) is coupled to an independent database management system (REPCON) and an evaluation program (ECON). DEMAREC provides technology transfer of information from experts and specialists to other practitioners and so provides a platform for the exchange of expert opinions in this field.

DEMAREC is a flexible application which can be used in four modules of evolution, diagnostic, evaluation and education.

The REPair of CONcrete (REPCON) database includes information and data to arrive at a realistic and proper diagnosis of the cause(s) of distress in a concrete structure. It is also designed to be an effective support tool for experts whose data can be evaluated in the enhanced level of confidence to ensure that the evolving database retains its integrity. The confidence level (CL) provides a quantitative and consistent means for evaluating both new knowledge and experience and the person contributing it and so it allows new data to be gathered and monitored over time. To contribute new knowledge to the database, a self-assessment process (see Section 7.8.1) has been included in order to assess the competence of the user. When new data to be added, the system evolves in line with the state of the art of concrete repair and so the database will become a catalyst to the development of knowledge and experience in the field.

In addition, data and pictures have been shown to have an impact in educating the inexperienced user enabling him to develop his confidence in concrete repair technology. The educational mode is predominantly an interaction between the user and the database. The user is enabled to view various aspects of repair of concrete technology in the form of pictures and descriptive information such as those shown in Figures 7.5, 7.6 and 11.1 through the Database button in the main screen of the application (see also Figures 6.2 and 6.3).

The knowledge contained in DEMAREC-EXPERT is designed to address diagnostic-related issues and identification and repair or rehabilitation recommendations and to assist users in the assessment of current conditions in concrete structures. In developing this knowledge-based system, diagnostic trees are used for converting the knowledge to a question-and-answer display and as a road map for reviewing knowledge and making modification to the computerized system. The knowledge included in REPCON as an independent database is coupled to the DEMAREC-

EXPERT. This knowledge offers information relating to the selection of materials and methods for repair and rehabilitation and gives the recommendations to enhance durability. Indeed, this research describes how a knowledge-based expert system and a conventional database have been integrated to produce an innovative platform which will facilitate and encourage the development of knowledge in concrete repair.

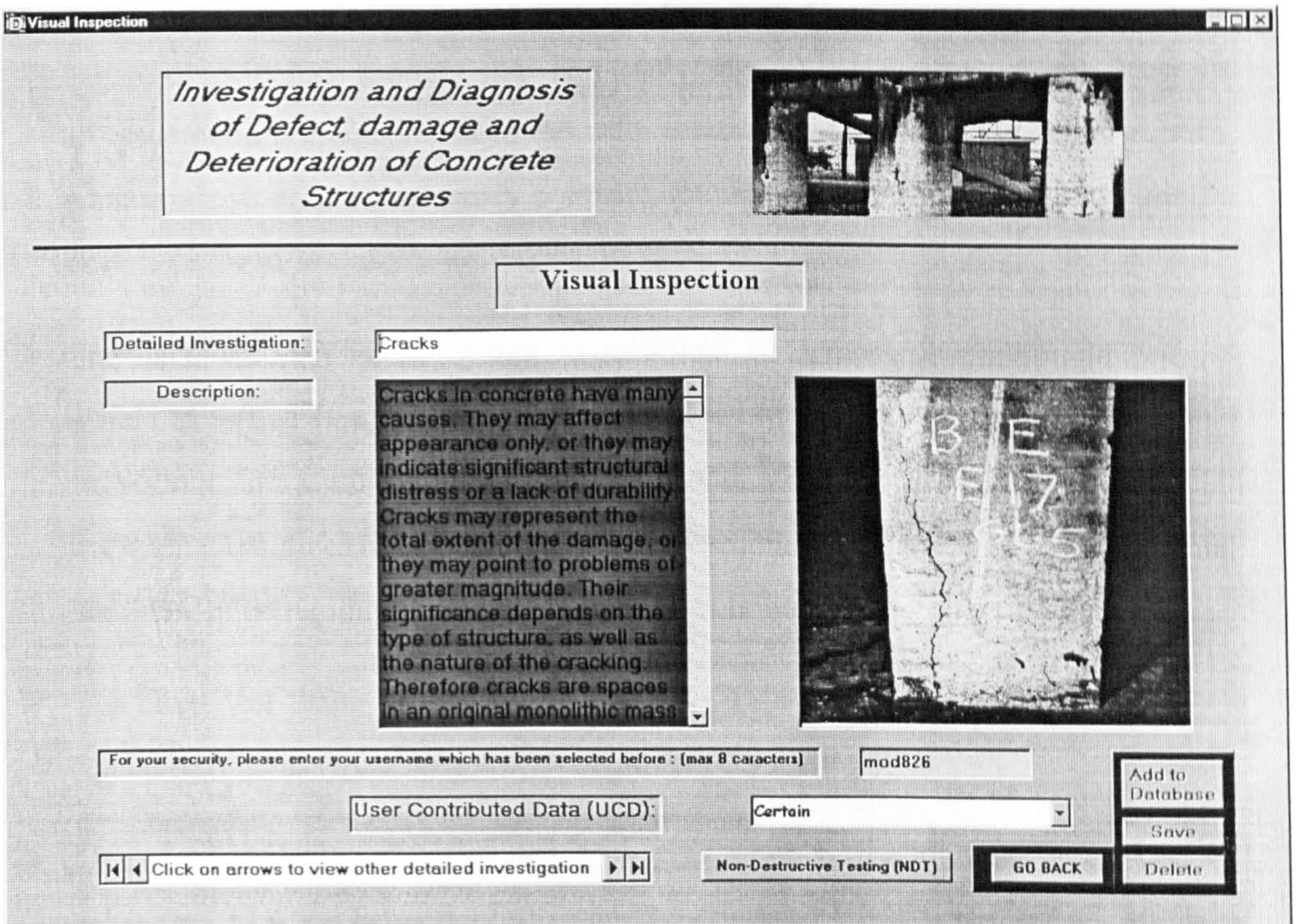


Figure 11.1 - An example of combination of pictures and descriptive information in the REPCON database.

A performance rating procedure is proposed in the ECON program to evaluate the durability of concrete structures which is based on the observation of signs of distress and Deduct Values based on severity and extent. The principle of computing the confidence level (CL) is based on the deduction method where all distress Deduct Values are summed and subtracted from a value of 100. The frequency and extent of distresses in this program directs the user towards the correct use of knowledge and data in DEMAREC-EXPERT and REPCON in diagnosing the cause(s) of distress in a concrete structure.

11.3 Main Conclusion

Based upon the research carried out in this thesis, the following main conclusions are drawn.

- This research has wider implications than within the realm of concrete repair. It presents a radical approach to knowledge engineering: a database is no longer a static resource under the direction of one central organisation. It could be expanded to include models, data and knowledge of which all is shared. It causes all construction organisations to radically review what problem they involve with, what products and services they provide, how to be more competitive and how to exchange the information and expert opinion.

- The database evolves according to informed consensus. It models the way in which expertise has traditionally evolved. More effort has to be placed into supporting the exchange of information and knowledge between the various experts whilst allowing them to work on their respective parts of the knowledge and experience.

- The benefit of using the system lies in the enhanced levels of confidence which can be attributed to the data and to contributors of that data.

- One of the strengths of the system is the way in which it allows the promotion and relegation of knowledge according to the opinion of users of different levels of ability from expert to novice.

- The system is designed to model a true evaluation of a field of expertise but allows that expertise to move on in a faster and more structured manner.

- The new methodology of data/user evaluation could have wider implications in many knowledge rich areas of expertise.

- The methodology can be applied in any area of expertise which is knowledge based. The only impediment to its being extended widely is the initial populating of the knowledge base. Once the system has been established, there is no reason why it should not continue ad infinitum, gathering credibility and value as it evolves.

- A central feature of the system is the opportunity for information to change status. This is important because the value of all knowledge changes with time and may eventually be of no worth. It may be that at sometime in the future none of the original knowledge and information will remain as the subject matter becomes superseded. Indeed, the very existence of the system could accelerate the turnover of knowledge which might impact upon all areas of endeavour.

- It has been already seen how the Internet has improved the accessibility of knowledge, yet has failed to measure the value of the knowledge which it makes available. The ideas embodied within the research could remove this impediment from the Internet. If a user only accesses a record for information and finds they cannot leave it without providing the correct information they can get very annoyed with the system. Because the ideas presented in this thesis use the enhanced level of confidence for the data and contributors of that data, so users will be more likely to use yours because they will feel part of it.

- The development of the prototype knowledge-based system is expected to stimulate research into other aspects of concrete durability.

11.4 Considerations beyond This Research Study

Many studies have been conducted in the construction sector in recent years in order to investigate the relationships between technologies and in particular Information Technology (IT) and processes (Betts M., 1999). Most of these studies have concentrated on IT capabilities and forecasting how IT will be used in the future. Information is the words, numbers, images and voices that impart meaning and inform while Information Technology (IT) is the technological basis for the capture, manipulating, storage and communication of information. IT is the application of systems of information and knowledge to gathering data and creating information that is valuable to users who make decisions.

Information is a key source within any business activity. Researchers, software developers and practitioners are now applying Information Technology to automate different parts of the design and construction processes. The nature of construction activity, its structure and its operating environment are fluid and dynamic. This dynamism is growing at an increasing pace, offering proportionately greater strategic opportunities while posing significant threats. The value of knowledge and the status of information change with time and may eventually be of no worth. A principal feature of how design and construction processes have coped these changes has been to strategically exploit Information Technology (IT). The use of IT in design and construction is becoming increasingly sophisticated with object-oriented techniques, virtual reality, expert systems (ES), database management systems (DBMS), case-based reasoning and neural networks among the latest technological advances. These technologies can be used to enhance the integration and sharing of information between the various processes of design and construction.

The Information Technology (IT) map can be developed in relation to the process requirements. An IT map should support the key themes of visualisation, intelligence, communication and integration which are emerging as the generic technologies for future research. This map should however be used as a stimulator of ideas regarding developing IT solutions for re-engineered design and construction processes.

Of the generic technologies, the research community within this research has made most reference to the technologies of visualisation, intelligence and integration. Multimedia and other visualisation technologies, knowledge-based expert system and database management system are used as specific technologies of research priorities in this thesis.

Knowledge-Based Expert Systems (KBES) or Expert Systems (ES) are sophisticated computer systems which store expert knowledge on specific subjects and can provide answers to questions on these subject areas, thus providing new ways to tackling many existing problems and allowing more complex tasks to be undertaken by using Information Technology (IT). These systems can make a particular expert's knowledge more generally available and can thereby save valuable resources by assisting decision making and multiplying available skills.

Powerful database applications have facilitated the essential capability of sorting data to overcome an increasing information malaise as design and construction processes are faced with too much unstructured information. Knowledge-based systems can be linked to an integrated database. It is the coupling and integration of these technologies which will provide the ultimate benefits to the design and construction processes. Integrating of these technologies can be used to bring a group of experts and specialists in any field of engineering closer together by allowing them to communicate and exchange information and data. Indeed, the exchange of information could accelerate the turnover of knowledge which might impact upon all areas of endeavour. The success of the research program presented in this study is derived from the close co-operating of the groups of user whose origins and experiences are diverse and who are willing to see IT as a means of helping to integrate their efforts as much as in providing a platform for the exchange of information. In addition, a more developed use of this research would have helped in integrating a greater proportion of the information used by the users.

Design and construction processes are highly dependent upon the transfer and exchange of information between the project participants. The flow of information is a key issue since the effectiveness of information transfer could bring about the integration of the project stage. Information Technology (IT) is considered to be a relevant approach for addressing this challenge as it would allow the process to be reviewed and exchange to be adjusted.

The most important way in which the future design and construction processes will differ from the present will be through a greater measure of integration. Many projects in the future will have greatly improved flows of information between their participants. This will encourage the use of divers technologies to work towards the integrated project database concept. This improved information flow will lead to re-engineered and improved processes of design and construction. It will also enable much greater integration of the process of design, construction and facilities management. The construction and future operation of buildings will be assessable at design stage through integrated IT, based on established information and design standards.

The new methodology of data/user evaluation and the modelling of the evolution within a field of expertise which is presented in this research study is to suggest that innovating with Information Technology (IT) can be applied to any areas of design and construction. The respondents to this study have suggested a number of tools that may emerge from future research. The important design tools and integration tools are on-line collaboration, simulation models, tools to capture client's requirements, communication and the Internet. One dominant research issue is improving the access of construction industry participants to information. The other dominant research theme is concerned with improving or visualising the design process.

All generic technologies of visualisation, intelligence, communication and integration need to be supported on a continuous basis for the long term in the strategic interests of construction industry. Visualisation and integration are considered to be the key generic technologies of strategic significance of design and construction. Key tools that are likely to emerge in future academic research and its subsequent development in industry are concerned with building performance, design and integration. Key research themes also include access to information and the review of the design and construction processes.

11.5 Recommendations for Future Works

As concluded in Section 10.4, the greatest contribution of this research is to explore the coupling of knowledge-based expert systems with an independent database management system for the repair of concrete structures. It also shows the integrating of these separate areas of Information Technology (IT) in order to provide technology transfer of information between experts, specialists and other practitioners by allowing them to communicate and exchange information and data. The methodology presented here is simple and demonstrative but it is of pioneering nature. Although the proposed methodology has wider implications in many knowledge rich areas of expertise, there are areas that may be studied further so that a greater understanding as well as improvement of the present research can be achieved. These areas are highlighted as further research:

- In terms of concrete repair, DEMAREC can be used for most concrete structures with any possible concrete distresses. It can however be extended for any special concrete structure, i.e. concrete bridges.

- Other forms of knowledge representation which enable the sharing of knowledge between applications could be investigated. It is recommended that any further research should be complemented on each knowledge base individually.

- Further work on the REPCON database will extend beyond the pictures through OLE technology including video clips and sound files. However more pictures and multimedia clips covering a wide range of failure are required for the database to make a meaningful contribution towards the fault diagnosis and maintenance of concrete structures. Comprehensive data defining maintenance problems and durability recommendations are also required. Furthermore, other specific technologies of visualisation systems such as virtual reality (VR), computer aided design (CAD) and 3D modelling can be used to solve the problems of inconsistency of terminology in describing modes of distress. Indeed, the user should have the ability to view the concrete distresses using virtual reality based on information stored in the database.

- The REPCON database can be extended as a regular record keeping process of repair and maintenance. Record keeping is an essential part of repair and maintenance since the history of the database has a significant effect on the decision-making process. It is important to maintain a log of successful and unsuccessful materials and processes.

- The REPCON database is no longer a static resource and therefore, a case for further investigation is recommended on the merits of adding knowledge to the database and its subsequent evolution.

- The use of statistical and mathematical models enables the expert system program to access the structure's historical characteristics. Based on the analysis of the historical database, invaluable information can be obtained in order to understand the behaviour of the distress. Future development of the DEMAREC simulator will provide an insight into the repair and maintenance process by the information supplied by both mathematical models and the knowledge of experts in the repair of concrete field. IT applications may emerge that integrate visualisation and artificial intelligence technology to produce tools that can model the environmental impact of various concrete distresses.

- DEMAREC could be more effective in the integration of concrete repair and in knowledge elicitation if it is used over a network where it would benefit from wider implications of knowledge. Combination of generic technologies of IT such as integration and communication is being used to automatically capture data on facilities in use and feed this into appropriate area as a basis for the exchange of information and data. In some cases, the Internet communication protocol has improved the accessibility of information, yet has failed to measure the value of information. The ideas embodied within the DEMAREC could remove this impediment from the Internet. Future effort is aimed at developing DEMAREC software which can run over the Internet.

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CIVIL ENGINEERING DEPARTMENT
UNIVERSITY OF NEWCASTLE UPON TYNE

Appendix (A)

The Research Questionnaire

This appendix presents a copy of the repair materials questionnaire:

UNIVERSITY OF
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Department of Civil Engineering
Cassie Building
University of Newcastle
Newcastle upon Tyne NE1 7RU
United Kingdom
Head of Department
Professor B G Clarke

RESEARCH PROJECT IN THE REPAIR AND MAINTENANCE OF CONCRETE STRUCTURES.

Dear Sir;

I am conducting research in the field of construction management under the supervision of Prof. J. Knapton in the Civil Engineering Department of the University of Newcastle upon Tyne. The aim of the research is to develop a knowledge-based system that would guide specifiers, owners and contractors in the choice of effective and durable repair schemes for reinforced concrete structures.

In addition, the system would utilise up-to-date information to assess and accurately diagnose the cause of a concrete defect, and then provide objective, logical and expert advice on the most appropriate and durable repair scheme (materials and techniques) in a given situation.

One of the main features of this research will be to create a database in repair materials and techniques. The purpose of the database is to provide storage of material specifications along with manufacture's general information, application information, manufacturer's technical data and any technical reported data for repair materials in UK. In view of this, I enclose a sample data sheet illustrating the type of data to be stored.

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NEWCASTLE

Department of Civil Engineering
Cassie Building
University of Newcastle
Newcastle upon Tyne NE1 7RU
United Kingdom
Head of Department
Professor B G Clarke

I would very much appreciate any information that you could supply and I would request that you complete the questionnaire so as to ensure that your products and /or methods are included in the database.

It is hoped that the research will lead to publication while will be guidance to specifiers, owners and contractors in the choice of repair materials from your company.

I would be most grateful if you could assist me in this work and will be happy to answer any queries you may have.

Thank you very much for your co-operation.

Yours faithfully;
F. Moodi
Researcher

The Sample of Repair Material Specifications' Data Sheet

Product Name: WATERPLUG

Category: CEMENT

Use(s): CRACK REPAIR AND PATCHING MATERIAL, HORIZONTAL OR NONHORIZONTALSURFACE; WATERSTOP REPAIR MATERIAL

Description: INSTANTLY STOPS RUNNING WATER OR SEEPAGE

Comments: VERY COLD OR VERY HOT WEATHER WILLS RETARD OR QUICKENS SETTING TIME

***************MANUFACTURE'S GENERAL INFORMATION**************

Manufacturer: THORO SYSTEM PRODUCTS
7800 NW 38TH STREET
MIAMI, FL 33166
800-327-1570

Packaging: 2.5 LB CAN, 10 LB CAN, and 50 LB PAIL

Shelf Life: up to 1 year in unopened, undamaged containers.

Colour: GRAY

Availability: USA AND EUROPE WITH EXPORT TO MOST OTHER COUNTRIES

Cost: .0 LB BAG IS APP $45.00

Technical Support: FIELD TECHNICIANS AND TECHNICAL SERVICES DEPARTMENTS

Comments: WILL SET IN 3-5 MIN.

*****************APPLICATION INFORMATION***************************

Surface Prep: ALWAYS UNDER CUT OR CUT SQUARE: DO NOT USE V CUT. OPEN CRACK OR HOLE TO A MIN DEPTH AND WIDTH OF 3/4 IN.FLUSH AWAY ALL CUTTINGS AND DIRT.

Mixture Prop: WATER ADDED TO DESIRED PROPERTIES.ADD WATER TO

POWDER, TO REACH A NO SLUMP, DAMP PACK MORTAR CONSISTENTCY.

Mixing: DO NOT MIX MORE THAN CAN BE PLACED IN 3 MIN. MIX BY HAND IN SMALL MIXING VESSEL.CLEAN VESSEL COMPLETELY AFTER EACH BATCH.DO NOT RETEMPERS.

Application: PLACE WITH MINIMUM WORKING OR RUBBING FORCE INTO CRACK/HOLE BY PUSHING FIRMLY. USE MAXIMUM PRESSURE.

Coverage: 1 LB WILL FILL 7 CU IN.

Precautions: DOES NOT BRUSH OR TROWEL SURFACE.

Curing Time: KEEP DAMP FOR AT LEAST 15 MIN.

Limitation: VERY HOT OR VERY COLD WEATHER WILL RETARD OR QUICKEN SETTING.

*****************MANUFACTURER'S TECHNICAL DATA*****************

COMPRESSIVE STRENGTH: 7 DYS=4,000 PSI, 28 DYS=5,800 PSI
TENSILE STRENGTH: 7 DYS=300 PSI, 28 DYS=350 PSI
FLEXURAL STRENGTH: 7 DYS=600 PSI, 28 DYS=1,500 PSI
DANGER! CONTAINS CEMENTS AND CRYSTALLINE SILICA.AVOID BREATHING DUST. AVOID DIRECT CONTACT WITH SKIN. WEAR IMPERVIOUS GLOVES. WEAR APPROPRIATE PROTECTIVE CLOTHING MEETING THE MOST CURRENT ANSI Z85.1 STANDARD.

Composition: CEMENT BASED

COMP. STR; PSI (ASTM C 109):	20 MIN 1800 1-DAY 4000 7-DAY 5000 28-DAY 5500
TENSILE STR; PSI (ASTM C 190):	7-DAY 300 28-DAY 3500
FLEXURAL STR, PSI (ASTM C 348):	7-DAY 600 28-DAY 1500

Composition: CEMENT BASED

********************TECHNICAL REPORTED DATA*********************

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United Kingdom
Head of Department
Professor B G Clarke

A QUESTIONNAIRE TO INVESTIGATE THE GENERAL PROBLEMS IN THE MAINTENANCE AND REPAIR OF CONCRETE STRUCTURES.

Dear Respondent;

We need your help. The information you provide is an essential part of this investigation that hopefully will result in useful recommendations that will help in the selection the most appropriate repair materials in the repair and maintenance of concrete structures.

The aim of this investigation is to determine general impairment problems currently found in the concrete structures in order to assess and accurately diagnose the cause of a damaged concrete, and then provide useful recommendations about a satisfactory repair process with selection of adequate and durable repair materials and techniques in a given situation.

Please, take the time to complete the enclosed questionnaire and also try to comment whenever you have a view. Please, send your completed questionnaire using the enclosed self-addressed envelope as soon as possible. This form contains an identification number that will be used for follow-up purpose only.
Thank you very much for your assistance. We care about what you think.

Yours sincerely;
F. Moodi
Researcher

Questionnaire { }

Section (A) Personal Details

Q_{A1} Name:............................

Current Position:...................................

Q_{A2} Please indicate the main products which you have produced for repair materials of concrete structures:

- ☐ Admixtures
- ☐ Resins
- ☐ Polymer Emulsions
- ☐ Others (Please specify):
- ☐ ....
- ☐ Grout
- ☐ Prepacked Cementitious
- ☐ Pozzolanic Materials
- ☐ ....
- ☐ ....

Q_{A3} For how many years have you produced repair materials for concrete structures?

☐ 0-5 ☐ 5-10 ☐ 10-20 ☐ Over 20

****

Section (B) Company Policy

Q_{B1} Please indicate whether your company is a member of the following associations.

- ☐ CRA (The Concrete Repair Association)
- ☐ FeRFA (The Federation for the Repair & Protection of Structures)
- ☐ ICRI (International Concrete Repair Institute)
- ☐ Others (Please specify):...
- ☐ ....

Q_{B2} Does your company carry out the quality control on repair materials?

☐ Yes ☐ No

If yes, how often?

(Please specify):..

....

....

Q_{B3} Please specify the standards which your products confirm to?

☐ B.S. ☐ ASTM

☐ ACI ☐ Canadian Code

☐ Others(Please specify):........... ☐ ....

☐ .... ☐ ....

Q_{B4} Please specify whether your products have a special certificate such as ISO 9001, BSI, etc.

....

....

Q_{B5} Does your company use the services of consulting engineers with respect to your products?

☐ Yes ☐ No

If yes, please specify:

....

....

....

****

Section (C) Repair Materials - General

Q_{C1} Do you think that the current repair systems for concrete structures are:

☐ Suitable and adequate.

☐ Inadequate and in need of improvement.

Q_{C2} Are you aware of any specific problems in the repair and maintenance of concrete structures?

☐ Yes ☐ No

If yes, what are these problems?

....

....

....

Q_{C3} Are you aware of the techniques which are applied for repair of concrete structures?

☐ Yes ☐ No

If yes, what are these techniques?

....

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....

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Section (D) Repair Materials - Records

Q_{D1} Please specify how often you represent your products to owners, consultant engineers and contractors

☐ Leaflet ☐ Catalogue

☐ Internet ☐ Others (please specify):............

☐ .... ☐ ....

Q_{D2} Are there any technical records which show the properties of your materials as reported by some contractors and consulting engineers?

☐ Yes ☐ No

If yes, how should such records be used?

....

....

....

Q_{D3} Do you know whether there is any database of repair materials which are produced in U.K.?

☐ Yes ☐ NO

If yes, where is it?

....

....

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Section (E) Repair Materials - Products

Q_{E1} In your opinion, what are the factors that might affect the selection of repair materials?

....

....

....

Q_{E2} The list below sets out various kinds of polymers which are often used in Polymer Portland Cement Concrete (PPCC). Please identify the polymers which your company uses/produces:

- ☐ Acrylic Latex
- ☐ Epoxy Latex
- ☐ Polyvinyl Acetate
- ☐ Vinyl Acetate Ethylene (VAE)
- ☐ Styrene-Butadiene Rubber (SBR)
- ☐ Co-polymer Latex
- ☐ Natural Rubber
- ☐ PolyMethylMethacrylate(PMMA)
- ☐ Styrene-Acrylic
- ☐ Magnesium-Phosphate Modified
- ☐ Others(Please specify):............
- ☐ ....
- ☐ ....
- ☐ ....

Q_{E3} The list below sets out various kinds of polymers which are often used in Polymer Concrete (PC) and Polymer Impregnated Concrete (PIC). Please identify the materials which your company uses/produces:

- ☐ Acrylic
- ☐ Low viscosity Polyester
- ☐ Polyurethances
- ☐ Low viscosity Epoxy Resin
- ☐ Polyesters
- ☐ Methyl Methacrylate (MMA)
- ☐ Epoxies
- ☐ Polyester Styrene Co-polymer
- ☐ Others (Please specify):...........
- ☐ ....
- ☐ ....
- ☐ ....

Q_{E4} The list below sets out various kinds of cementitious materials which are usually used in Shotcrete, Gunit and Patch repair. Please identify the materials which your company uses/produces:

☐ Ordinary Portland Cement	☐ Pulverised Fly Ash (PFA)
☐ High Alumina Cement	☐ Blast-Furnace Slag-Cement
☐ Microsilica(Condensed Silica Fume)	☐ Flowing Concrete
☐ Cement Grout	☐ Trass
☐ Diatomite	☐ Others(Please specify):.......
☐	☐ ....
☐	........☐.................................

****

Section (F) Repair Materials - Miscellaneous

Q_{F1} In your opinion, would it be imperative to consider the compatibility of the repair materials with each other and with the existing concrete?

☐ Yes ☐ No

Comment:..

....

....

Q_{F2} The list below sets out various factors which have affected the compatibility of repair materials and existing concrete. Please identify what you think are the most important factors:

☐ Compressive Strength	☐ Alkali Content
☐ Tensile Strength	☐ C3A Content
☐ Flexural Strength	☐ Humidity in Concrete
☐ Shear Bond Strength	☐ Chloride Content
☐ Drying Shrinkage	☐ Permeability

Counts

☐ Thermal Expansion	☐ Concrete-Repair Bond
☐ Creep and Fatigue	☐ Corrosion
☐ Modules of Elasticity	☐ Geometry of Section
☐ Others (Please specify):	☐ ....
☐	☐ ....

Q_{F3} Would you please, send us a copy of any specification source (leaflet, catalogue, diskette, etc.) for materials produced by your company?

....

....

Q_{F4} Do you want to receive a copy of the results of this study?

☐ Yes ☐ No

Q_{F5} Would you like to add any further comments?

....

....

....

****

We are very grateful indeed for your help. Please return the completed questionnaire in the self-addressed envelope provided:

Mr. F. Moodi,
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Questionnaire { }