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An expert system for making durable concrete for chemical exposure

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Abstract. The development and the main features of an expert system for modeling the requirements of durable concrete in chemical exposure, called the Durable Concrete Advisor for Chemical Exposure (DCACE), are described. The system was developed to help improve the quality of concrete exposed to chemical environment by minimizing mistakes and deficiencies in selecting concrete constituents. Using Kappa-PC expert system shell, an object-oriented model was developed where the rule-based reasoning operates on or across objects. The American Concrete Institute manual of concrete practice was chosen as the main source of knowledge. Other textual sources were also consulted for knowledge acquisition. The major objectives of the research were acquisition and formalization of the relevant knowledge and building an expert system for making durable concrete for chemical exposure regarding sulfate attack, acid attack, seawater attack and carbonation. Similar to most expert systems, this system has explanation facilities, can be incrementally expanded, and has an easy to understand knowledge base. The performance of the system is demonstrated by an example session. The system is user-friendly and can be used as an educational tool.

Keywords: expert system; durable concrete; sulfate attack; acid attack; seawater attack; carbonation.

1. Introduction

Concrete will perform satisfactorily when exposed to various atmospheric conditions, to most waters and soils containing aggressive chemicals, and to many other kinds of chemical exposure. There are, however, some chemical environments under which the useful life of even the best concrete will be short, unless specific measures are taken. An understanding of these conditions permits measures to be taken to prevent deterioration or reduce the rate at which it takes place. Major areas of concern are exposure to sulfates, seawater, acids, and carbonation (ACI Committee 201 2003). The procedure of making durable concrete in these cases involves many factors that include materials properties, environmental parameters, construction details as well as the function and use of concrete. The lack of engineering experience and judgment almost always results in dissatisfaction with the process, and may also result in serious damage to concrete structures. On many construction sites, particularly those in developing countries, the quality of concrete does not meet the requirements of the exposure condition. The resulting concrete quality often suffers from

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the lack of durability. This is especially relevant in a developing country where technical and financial resources are generally lacking. Expert system can greatly help improve this situation by preserving and disseminating the much-needed expertise effectively at reasonable costs. They are most useful when the knowledge is based on heuristics, which is often the case in making durable concrete for chemical exposure.

This paper describes a prototype expert system, the Durable Concrete Advisor for Chemical Exposure (DCACE), which gives recommendations on reducing the effect of harmful chemical attack on concrete. Its goal was to improve the quality of concrete to be relatively resistant to external chemical attack, by including views of different expertise sources in the domain. It is assumed that the user is educated and trained in this area. In addition, the educational features of the system may be useful to educate and train the inexperienced users.

2. Literature review

The applications of expert systems in the field of concrete are mainly in structural analysis and design, concrete mix design, construction management, and diagnosis of problems and suggestion of repairs (Abideen, *et al*. 1999). Since the making of durable concrete for chemical exposure is somewhat complicated, time-consuming and tedious task, and also because it is not always possible to be helped by the experts, there were some efforts to develop expert system for making durable concrete. DURCON (Clifton, *et al*. 1985, Clifton and Oltikar 1987, Kaetzel and Clifton 1988, Clifton and Kaetzel 1988) is an expert system that gives recommendation on the selection of concrete constituents for durability problems regarding corrosion, freeze-thaw, sulfate attack and alkali-aggregate reaction. Kaetzel, *et al.* (1993) developed a system for highway concrete, called HWYCON. Its concrete materials (CONMAT) component gives recommendations on the selection of materials for the design of durable concrete in corrosive, freeze-thaw, sulfate and alkali-aggregate environments. Islam, *et al.* (2003) described an expert system dealing exclusively with corrosion problem. Most of these systems are rule-based systems and work using DOS operating system. None of these systems can give recommendations on making durable concrete in chemical exposure regarding acid attack, seawater attack and carbonation. Therefore, these systems cannot be used for making durable concrete for these chemical exposures.

3. Development of the DCACE

The following sections describe the sources of expertise and knowledge representation techniques that were used for the development of the DCACE.

3.1. Sources of expertise

Knowledge for the DCACE was acquired from various textbooks and manuals written by experts and research papers from journals and conference proceedings (ACI Committee 201 2003, Mehta 1991, Neville 1995, Aitcin 1998, Aitcin 1997, Al-Amoudi 2002, Al-Rabiah, *et al.* 1990, Bader 2003, Balayssac, *et al.* 1995, Collepardi 2003, El-Hawary 1999, Fattuni and Hughes 1983, Haque and Al-Khaiat 1997, Ho and Lewis 1987, Hobbs 2003, Khatri, *et al.* 1997, Kumar 2000, Kumar and

Kameswara Rao 1995, Marchand, *et al*. 2002, Memon, *et al.* 2002, Neville 2004, Plowman and Cabrera 1996, Rodríguez-Camacho and Uribe-Afif 2002, Saetta and Vitaliani 2004, Saetta, *et al.* 1993, Thomas and Matthews 2004, Zivica and Bajza 2001, Mehta 2000). However, the system was largely based on information contained in the ACI Guide to Durable Concrete (ACI Committee 201 2003) because of its wide acceptability to concrete technologists.

3.2. Knowledge representation

Through the efforts of researchers in artificial intelligence, a number of effective ways of representing knowledge in a computer were developed (Durkin 1994). The selection from these knowledge representation techniques depends on the nature of the expertise to be computerized, as well as the practical capabilities and facilities of the expert system tool used (Islam, *et al.* 2003). In developing DCACE, a hybrid approach of knowledge representation (i.e. rule and frame systems) was followed using Kappa-PC expert system shell (IntelliCorp Inc. 1997). Thus, the domain of making durable concrete in chemical exposure was modeled using object-oriented approach and production rules.

3.2.1. Knowledge representation by frame

A frame is a method of representing knowledge in the form of objects or class of objects that contain slots for all kinds of information about them (Durkin 1994, Basri 1994, Basri 1999). Classes, subclasses and instances are objects representing entities (physical or conceptual) of the knowledge domain. Fig. 1 shows the top-level object-hierarchy of the DCACE. The figure shows that the DCACE class is comprised of four major subclasses or modules, i.e., *SulfateAttack*, *AcidAttack, SeawaterAttack* and *Carbonation*. Each of these classes was further divided into subclasses and instances. Further description of these modules is given in Section 4.

Slots can be thought of as descriptions about a particular object. They add detail structure, list

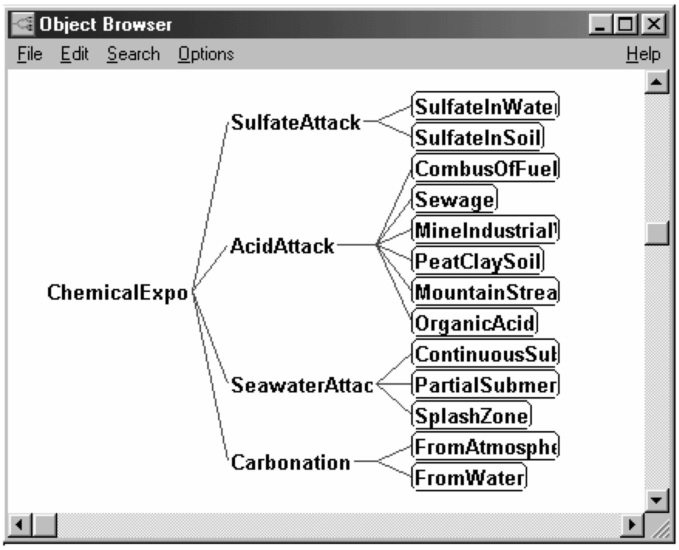

Fig. 1 Top-level object hierarchy of the DCACE

Table 1 Instance description using slot

Instance: SulfateInSoil, Parent Class: SulfateAttack	
Slot Name	Slot Value
ContentOfSulfateIons	0 to 0.01 percent (mild exposure) 0.01 to 0.20 percent (moderate exposure) 0.20 to 2.00 percent (severe exposure) More than 2.00 percent (very severe exposure)

attributes or properties which can be pre-defined, restricted to a range or set of pre-specified possible values, user-defined or determined from user consultations with system. For example, a slot of the instance *SulfateInSoil* (Fig. 1) is *ContentOfSulfateIons* in percent. Table 1 shows this slot and the corresponding slot values. Interactions among the objects, instructions from one object to another, and processes of objects were codified in the form of functions and rules.

3.2.2. Knowledge representation by production rules

After the construction of the object-oriented model of the domain, the heuristic component of knowledge was transformed into a rule-based structure, called workable or production rules. Production rule is the simplest and most widely used knowledge representation technique (Durkin 1994, Basri 1994, Basri 1999). Rules are also more easily understood than conventional programming code because they are typically written with a more structured syntax. They also have the advantage of having specialized debugging and explanation tools for developers and the end users. The general form of a production rule is:

If: Logical conditions are satisfied (antecedent)
Then: Take the indicated action (consequence).

Below is an example of a rule written for the *Sulfate Attack* submodule of the DCACE:

If: (1) Concrete will be exposed to water and
(2) Content of sulfate ion in water is between 150 to 1500 ppm and
(3) Portland cement will be used without pozzolanic admixture,
Then: (1) Water-cement ratio should be less than 0.5 and
(2) Cement should be Type II (ASTM C 150).

Rules are appropriate for use in selective situations where reasoning predominates. For example, the selection of cement type requires many non-mathematical considerations such as exposure of concrete, availability and extent of sulfate ion in water, and use of pozzolanic admixtures etc. In this case, a production system can be applied. The inference engine decides which production rules should be invoked to solve problem based on the knowledge in the knowledge base. There are two approaches for evaluating production rules: backward chaining and forward chaining (Durkin 1994, Basri 1994, Basri 1999). The DCACE uses a data-driven or forward-chaining inference mechanism.

4. Knowledge base modules of the DCACE

The DCACE knowledge base consists of four modules namely *Sulfate Attack, Seawater Attack,*

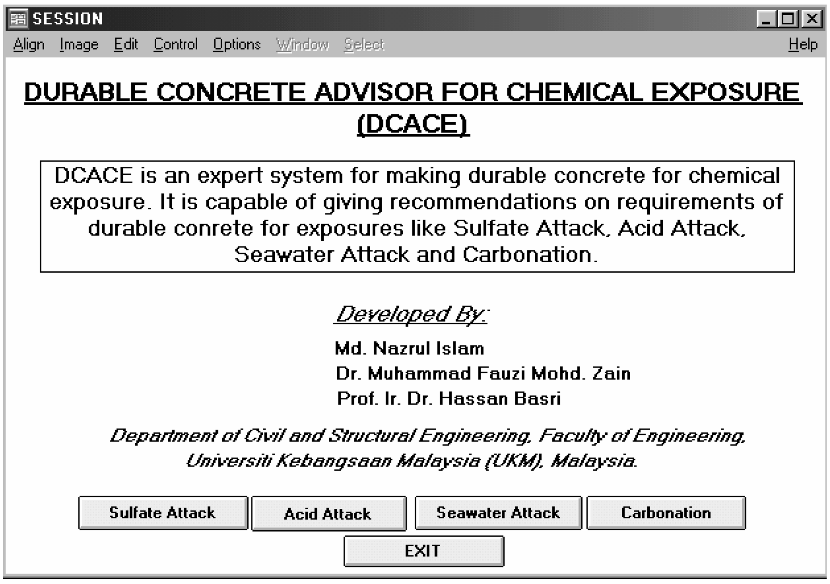

Fig. 2 Main interface window of the DCACE

Acid Attack and *Carbonation* modules. The modules can be accessed from the main interface window of the DCACE shown in Fig. 2. A brief description of each of the above modules is given in the following sections.

4.1. Sulfate Attack module

If it is expected that the concrete will be exposed to sulfate environment, then the consultation can be done using this module. The interface window of this module is shown in Fig. 3. The window consists of one text image, two transcript images, one bitmap image, and eight buttons. The functions of the buttons are consistent with their title and evidently clear. The *Occurrence* button shows the general situation where sulfate attack may be a problem. The *Mechanism* button opens a text file in the second transcript image describing the sulfate attack mechanism. An *Advice* button is also available in order to access information in case of need during the consultation process. The first transcript image displays preliminary information about sulfate attack. The second transcript image displays occurrence, mechanism, advice, recommendation and explanation of recommendations if the user presses appropriate buttons. The bitmap image shows the reactions of sulfates with hardened cement paste. It describes the reactions that are associated with sulfate attack.

The recommendation is obtained by pressing *Recommendation* button after completion of data selection. The reasoning process uses a set of rules from knowledge base that consider factors such as types of environment, concentration of sulfate ion, types of binders etc. The recommendations include, among others, water-binder ratio, compressive strength for light-weight concrete, air content in percent, type of binders and type of pozzolans with appropriate standards like other expert system in the domain. The recommendations also include required curing practices and use of available information regarding field performance of existing concrete structures. After getting recommendations, the user may ask for explanation about the recommendation by pressing on *Explain* button.

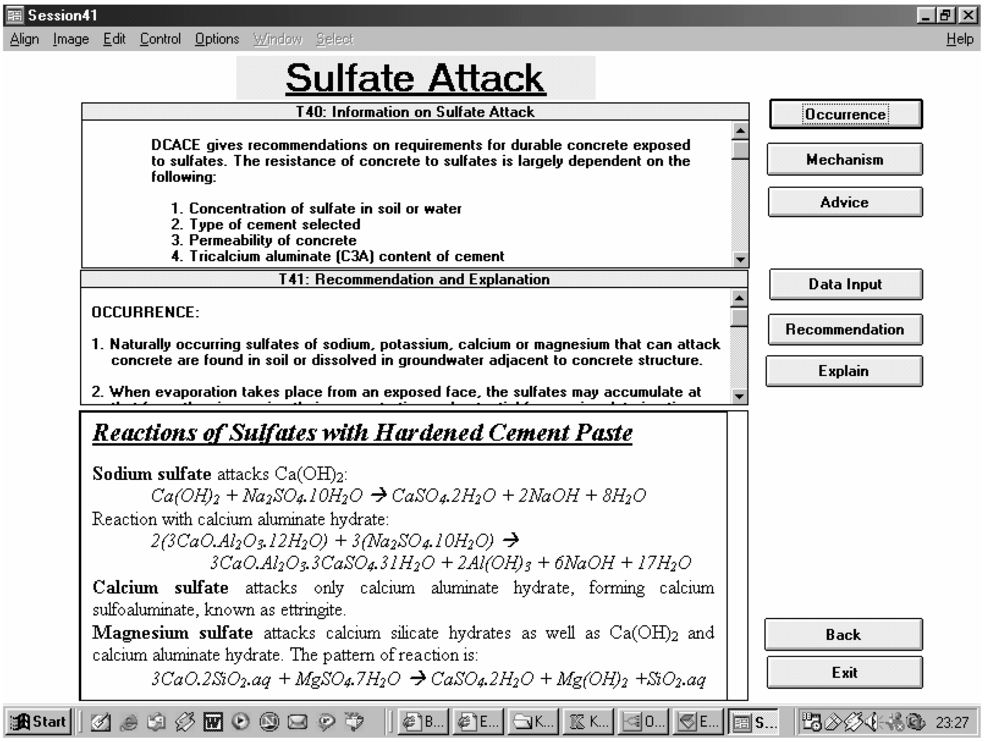

Fig. 3 Interface window of the *Sulfate Attack* module

4.2. Acid Attack module

This module covers the acid attack problem that may be encountered by concrete. The sources of acid that can attack concrete are divided into six major categories: combustion of fuels, collection of sewage, water draining from mines or industries, soil containing pyrite, mountain streams containing carbon dioxide or hydrogen sulfide, and organic acids from farm silage or industries. The ways of

Table 2 Sources and ways of acid attack on concrete

Source of Acid	Ways of Attack on Concrete
Combustion of fuel	The products of combustion of many fuels contain sulfurous gases that combine with moisture to form sulfuric acid.
Sewage	Sewage may be collected under conditions that lead to acid formation.
Water from mine/ industry	Water draining from some mines, and some industrial waters, may contain or form acids, which attack concrete.
Soil	Peat soils, clay soils, and alum shale may contain iron sulfide (pyrite) which, upon oxidation, produces sulfuric acid. Further reactions may produce sulfate salts, which can produce sulfate attack.
Mountain streams	Mountain streams and some mineral water containing CO_2 or H_2S, or both, can seriously damage any concrete.
Organic acid	Organic acids from farm silage, or from manufacturing or processing industries such as breweries, dairies, canneries, and wood-pulp mills, can cause surface damage.

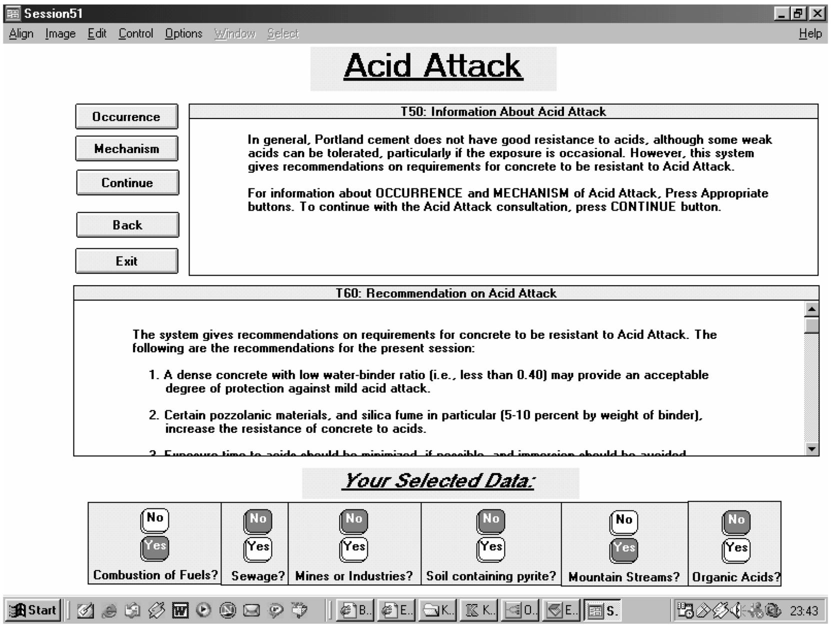

Fig. 4 Interface window of the *Acid Attack* module

acid attack on concrete arising from these sources are summarized in Table 2. The interface window of this submodule is shown in Fig. 4. The interface window consists of one text image, five buttons, two transcript images and six state box images. The first transcript image displays general information about acid attack, and occurrence and mechanism of acid attack if the user presses corresponding buttons. The second transcript image displays recommendations of a consultation session. The state box images display data selected by the user and thus make the system transparent during consultation process.

The system collects information from the user about the sources of acid to produce recommendation. In the information collection process, the system posts user request forms for the required information. The system stores this information in the working memory to produce recommendation for the user. It recommends that a dense concrete with low water-binder ratio may provide an acceptable degree of protection against mild acid attack. Certain pozzolanic materials, and silica fume in particular, increase the resistance of concrete to acids. It also recommends that exposure time to acids should be minimized and immersion should be avoided, if possible. It states that no hydraulic-cement concrete, regardless of its composition, will long withstand water of high acid concentration. In such cases, the system recommends the use of an appropriate protective-barrier system or treatment.

4.3. Seawater Attack module

The objective of this module is to give recommendations on making concrete to be resistant to seawater exposure. Fig. 5 shows the seawater interface window. This window consists of three transcript images, seven buttons, six combo box images and two text images. The first transcript image gives preliminary information about factors affecting durability of concrete in seawater and

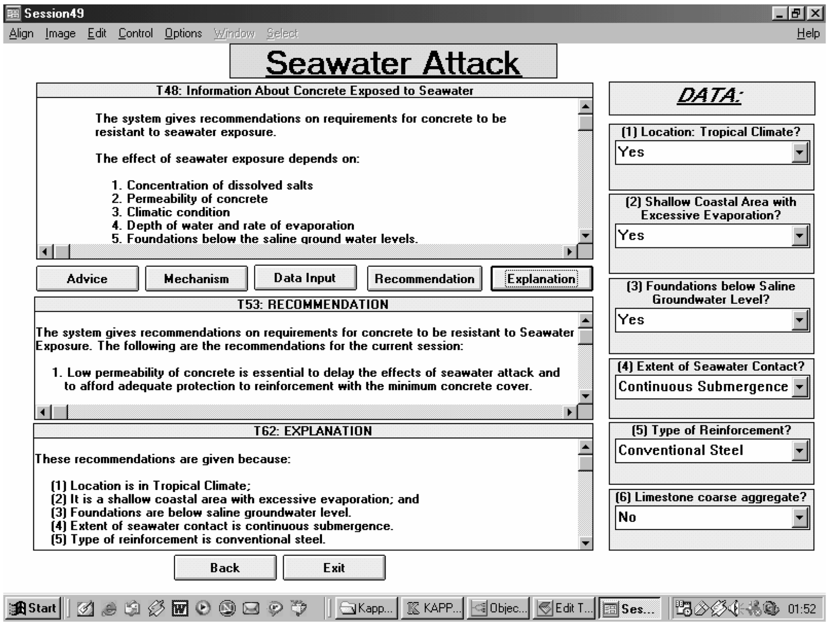

Fig. 5 Interface window of the *Seawater Attack* module

functions of the buttons. It also displays text files regarding mechanism of seawater attack and a brief advice about the system, if the user presses appropriate buttons. The second transcript image displays recommendations of a consultation session. The third transcript image explains the reasons for giving any recommendation. The data selected by the user during a particular session are displayed in the combo box images of the interface window for checking and confirmation. These images can also be used for data input.

The recommendations are based on rules, which consider factors such as climatic condition near the structure, depth of water and rate of evaporation, foundations below the saline groundwater level, extent of seawater contact and type of reinforcement. The system recommends that low permeability is essential to produce durable concrete for seawater exposure. It informs the user of the various ways of achieving low permeability. It further recommends the techniques of minimizing concrete cracks in order to prevent exposure of reinforcement to seawater. In addition, recommendation regarding maturity requirement of concrete and conductive coating as part of a cathodic protection are also mentioned. It also states the disadvantages of the application of coatings in order to make the user aware of the associated problems in selecting those options.

4.4. Carbonation module

The main interface window of this module is shown in Fig. 6. The objective of this module is to assist the user in producing durable concrete for carbonation environment. The first transcript image of the interface window shows that the relative humidity of the environment, temperature, permeability of concrete and concentration of carbon dioxide are the major factors that control carbonation of concrete.

The system states that the sources of carbon dioxide can be either atmosphere or water carrying

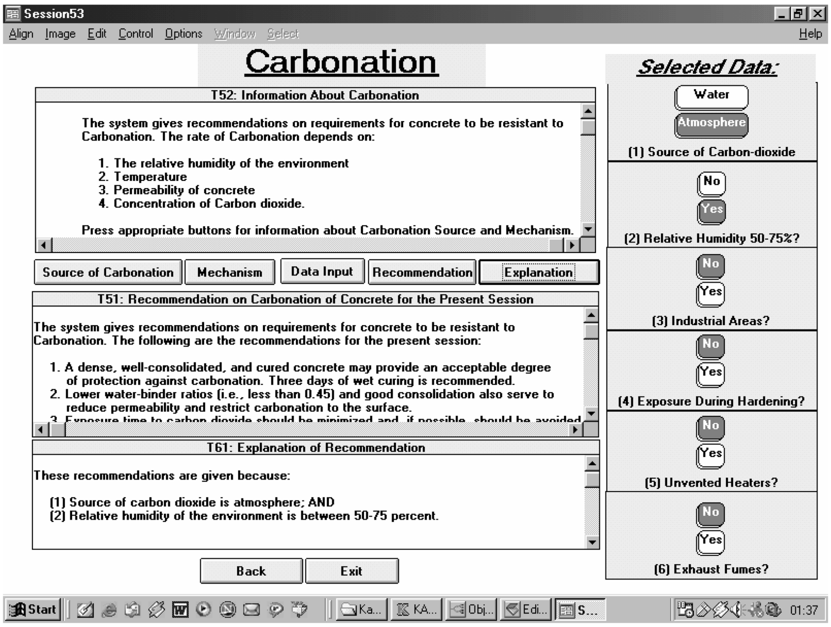

Fig. 6 Interface window of the *Carbonation* module

dissolved carbon dioxide. The highest rate of carbonation occurs when the relative humidity is maintained between 50-75%. Concrete in industrial areas with higher concentration of carbon dioxide in the air is more susceptible to attack. Exposure to carbon dioxide during the hardening process may affect the finished surface of slabs, leaving a soft, dusting and less wear-resistant surface. During the hardening process, the use of unvented heaters and the exposure of concrete to exhaust fumes from equipment or other sources can produce a highly porous surface subject to further chemical attack.

The system recommends that a dense, well-consolidated, and well-cured concrete may provide an acceptable degree of protection against carbonation. Lower water-binder ratio and good consolidation also serve to reduce permeability and restrict carbonation to the surface. Exposure time to carbon dioxide should be minimized and, if possible, should be avoided. It emphasizes that good quality concrete is essential to prevent initiation of carbonation.

5. Example session and evaluation of the DCACE prototype

The operation of the DCACE consists of a series of questions linked by if-then logic. The DCACE expert system runs on typical personal computer configuration, requiring a run-time version of Kappa-PC (for Windows 95 and above). The objective of this example session was to evaluate the performance of the DCACE consultation process and results. The example session was carried out for concrete exposed to a typical seawater attack situation. The user clicked on *Seawater Attack* button of the main interface window (Fig. 2) for getting recommendations regarding this situation. This opened the interface window of the *Seawater Attack* module (Fig. 5). The input data, recommendations and explanations of recommendations are described in the following sections.

These sections also include description about user-friendliness and overall evaluation of the system.

5.1. General information

The first transcript image of the *Seawater Attack* interface window (Fig. 5) displayed that the durability of concrete in seawater depends primarily on the concentration of dissolved salts, permeability of concrete, climatic condition, depth of water, rate of evaporation and foundation below the saline ground water level. Through this transcript image, the user also got preliminary idea on the sequence of consultation steps. An *Advice* button (Fig. 5) is also available in order to access information in case of need during the consultation process. It gave information about how to use the system efficiently and guided the user to have a consultation in a systematic way. The *Mechanism* button opened a text file in the first transcript image describing briefly the mechanism of seawater attack. For example, it stated that concrete exposed to seawater could be subjected to various chemical and physical actions. These include chemical attack, chloride-induced corrosion of steel reinforcement, freeze-thaw attack, salt weathering, and abrasion by sand in suspension and by ice. The presence and intensity of these various forms of attack depend on the location of the concrete with respect to the sea level. These accessory facilities encouraged the user to be aware of the potential problems of seawater attack on concrete and thus trained the users about the seawater situation.

5.2. Data input

An expert system requires some key information for giving recommendation for a particular situation similar to a domain expert. Therefore, the next step of the consultation process was to collect and analyze the required basic data. The user could alter and update the input data at any stage of consultation.

The user input data by selecting from a list of slot values displayed after clicking on *Data Input*

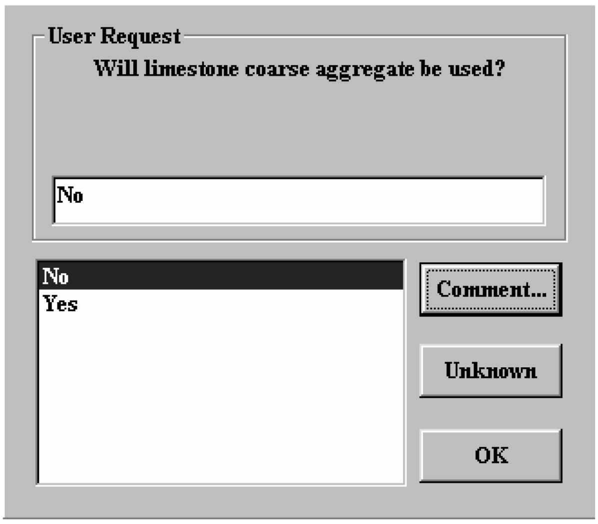

Fig. 7 A data input form of the *Seawater Attack* module

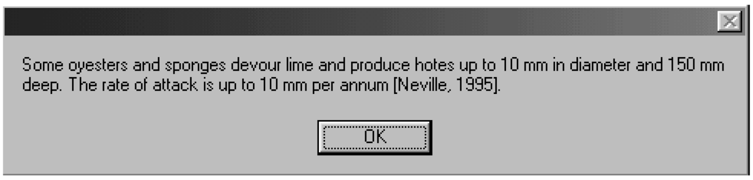

Fig. 8 An explanation window during data input (after pressing *Comment* button of Fig. 7)

Table 3 The questions and user's selection for an example session with the *Seawater Attack* module

Question Asked by the System	Options to Select	User's Selection
(1) Is the proposed location of concrete structure in tropical climate?	(a) Yes (b) No	(a) Yes
(2) Is it a shallow coastal area with excessive diurnal evaporation?	(a) Yes (b) No	(a) Yes
(3) Will foundations be placed below saline groundwater level?	(a) Yes (b) No	(a) Yes
(4) What is the extent of seawater contact?	(a) Continuous submergence (b) Partial submergence (c) Splash zone	(a) Continuous submergence
(5) What type of reinforcement will be used?	(a) Prestressing steel (b) Conventional steel	(b) Conventional steel
(6) Will limestone coarse aggregate be used?	(a) Yes (b) No	(b) No

button (Fig. 5). A typical data input form is shown in Fig. 7. This type of input form helped the user avoid input errors. The input form of the user interface includes *Comment* button (see Fig. 7) which helped the user, if pressed, by expanding the meaning of a question or data as shown in Fig. 8 and thus aided the user in responding more efficiently to the prompts of the consultation. This facility also made the system suitable for educational purposes. The data could also be selected from the combo box images displayed on the right portion of the interface window (Fig. 5). The selected data were displayed in these combo boxes for verification. The questions asked and options to select as well as user's selection for this example session are shown in Table 3.

5.3. Recommendation and explanation

The text containing recommendations were displayed in the second transcript image after pressing *Recommendation* button (see Fig. 5). The system gave recommendation according to the data selected by the user. The DCACE produced recommendations by comparing these data with the knowledge contained in its knowledge base. The recommendations given for the data of Table 3 of the present session are shown in Table 4. The recommendations include, among others, water-binder ratio, minimum cover over reinforcement, maximum chloride ion content, minimum compressive strength requirement, curing requirement, type of binders and type of pozzolans with appropriate standards. It may be observed that the recommendations were consistent with the selected data. For example, since conventional reinforcement was selected as the type of reinforcement, the system recommended that the maximum chloride ion content should be 0.2% by mass of cement (see Table

Table 4 Recommendations of the *Seawater Attack* module for the data of Table 3

T53: RECOMMENDATIONS
The system gives recommendations on requirements for concrete to be resistant to Seawater Exposure. The following are the recommendations of the current session: a) Low permeability of concrete is essential to delay the effects of sulphate attack and to afford adequate protection to reinforcement with the minimum concrete cover. b) The required low permeability can be achieved by the use of a low water-binder ratio, an appropriate choice of cementitious materials, good compaction, adequate curing (i.e. at least 7 days of curing in fresh water), and absence of cracking due to shrinkage, thermal effects, or stresses in service. c) A 60 mm cover and water-binder ratio below 0.40 or a 75 mm cover and a water-binder ratio below 0.45 are necessary. d) The use of ground granulated blast furnace slag (ggbs) or pozzolan is recommended. Because they reduce permeability by one-tenth or one-hundredth that of comparable concrete of equal strength made without slag or pozzolan. e) Maximum chloride-ion content should be 0.2% by mass of cement. f) Concrete should reach a maturity equivalent of not less than 35 MPa (5000 psi) at 28 days when fully exposed to seawater. g) Coarse aggregate should be dense and should have very low absorption capacity. h) Joints should be designed and constructed properly to assure that cracking is minimized to prevent the exposure of reinforcement. i) Conductive coatings applied at the time of construction as part of a cathodic protection system may provide additional protection for concrete that is partially submerged or reaches down to saline groundwater. Silane coatings, which are water-repellent, have shown excellent protection characteristics. j) Caution is required with the application of coatings that significantly restrict evaporation of free water from the interior of concrete and thus reduce resistance to freezing and thawing.

4). Thus the recommendations of Table 4 for the data of Table 3 were considered to be satisfactory.

One of the distinguishing characteristics of an expert system is the transparency of its reasoning process and knowledge base. This advantage is available to the user through *Explanation* button of Fig. 5, which displays the reasons for arriving at a particular recommendation. The explanation of the recommendations of the present session is shown in the third transcript image of Fig. 5. The explanation facility of the system facilitated verification and validation of results.

5.4. User-friendliness and user interface

The DCACE user interface was designed for user friendliness to enable its efficient utilization in the following ways.

(a) The first *Transcript Image* in the beginning of each consultation session provides information regarding the steps to follow for that session (for example, see Fig. 4). In addition, *Advice* buttons are available in some of the modules (for example, see Fig. 5) to guide the user about design procedure. Moreover, each consultation window contains some buttons to guide the user for the next design steps. Thus the user gets advice on the most appropriate sequence of design steps.

(b) The combo box and state box images display the data selected by the user (see Fig. 5). This facility gives the user confident as the user continues with the data input process.

(c) Each *User Request* form of data input has a *Comment* button attached to it as mentioned earlier (see Fig. 7). This helps the user by expanding the meaning of a question and thus aids the user in responding more efficiently to the prompts of the consultation procedure.

(d) The user can ask for explanation of any recommendation given by the system (for example, see the third transcript image of Fig. 5). This facility explains the reasons for arriving at a particular recommendation and thus facilitates verification and validation of results. It also makes the system suitable for educational purposes.
(e) Some of the other facilities include information about *Occurrence* and *Mechanism* of a particular durability problem (for example, see Fig. 3), and bitmap image showing reactions of sulfates with the hardened cement pastes (Fig. 3). These facilities also make the system suitable for educational purposes.

5.5. Overall evaluation of the system

The consultation process of the DCACE is reasonably satisfactory and systematic. The flow of consultation is flexible, allowing the user to reset data, to go back for a new consultation, to review input values and other procedures until he is satisfied with the results. The ability of the DCACE to run using Windows operating system makes this system superior to similar other systems in the domain. Moreover, the system gives information of data at every stage of data input. It has facilities like *Explain*, *Advice* and *Comment* buttons as well, which make the system very user-friendly. The limitation of the system is that it is not platform independent. The user will need a runtime version of Kappa-PC in order to use the system. However, in future, this limitation can be overcome by using a state-of-the-art platform independent expert system shell.

In order for expert systems not to become obsolete, they must be nurtured and kept current. This involves a mechanism for making modifications as knowledge and needs change, and to include new knowledge (Kaetzel, *et al.* 1993). The existing knowledge base of the prototype can be improved by refining, expanding, and reinforcing its knowledge base using new findings as reported in literature or new experience from domain experts.

6. Conclusions

Concrete ingredients, their proportions and construction procedure largely affect the quality of concrete in chemical exposure. Expert systems can help the user to minimize the mistakes and deficiencies in the selection of ingredients and production of durable concrete in this case. The developed prototype expert system, DCACE, is an attempt to achieve this objective. Knowledge was acquired from various textual sources and modeled using object-oriented approach in combination with rule-inferencing techniques. It has reasonably achieved the objective of harnessing scarce expertise in an important domain, and exploiting the potential of the latest in software technology in order to create a user-friendly expert system. The ability of the system to give comments and advice about an input data makes this expert system very useful for the educational environment. Additional knowledge to expand the scope of the system can be added without major modification of the structure of the program.

The DCACE is potentially beneficial for the intended end-users such as technical personnel and designers of government authorities and engineering consultancy firms in charge of construction of concrete structures in chemical environment. It will also be a good means of transferring knowledge and experience to young, untrained, and inexperienced concrete technologists.

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