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Expert system for making durable concrete for aggressive carbon-dioxide exposure

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ABSTRACT: This paper describes development and main features of a prototype expert system that gives recommendations on making durable concrete exposed to harmful carbonation. Knowledge was acquired from various textual sources and human experts. The acquired knowledge was represented in the form of production rules and frames. The system gives recommendations on issues like water-binder ratio, strength requirement, cover requirement, curing requirement and so on. It has explanation facilities, can be incrementally expanded, and has an easy to understand knowledge base. The system can be used as a tool for making durable concrete and teaching students and inexperienced practitioners.

1 INTRODUCTION

Although extensive research has been carried out on the deterioration of concrete, persistent problems still occur with the durability of concrete structures (Clifton and Oltikar, 1987). For example, when concrete or mortar is exposed to carbon dioxide, a reaction producing carbonates takes place that is accompanied by shrinkage. Carbonation may result in deterioration and a decrease in the pH of the cement paste leading to corrosion of reinforcement near the surface. Exposure to carbon dioxide during the hardening process may affect the finished surface of slabs, leaving a soft and dusting, less wear-resistant surface (ACI Committee 201, 2002). Extensive research on carbonation of constituents of hydrated cement paste has been carried out which has greatly increased the understanding of the factors affecting carbonation process. If the results of these and future research are properly disseminated, then fewer incidents of premature deterioration in new concrete structures should be observed.

Expert system appears to be an effective means for transferring knowledge gained through these research and field experience to individuals responsible for design, construction, and maintenance of concrete structures. Although a few expert systems have been developed for making durable concrete, none of these systems give recommendation on making durable concrete exposed to carbon dioxide (Clifton and Olitkar, 1987; Clifton et al., 1985; Clifton and Kaetzel, 1988; Kaetzel and Clifton, 1988; Kaetzel et al., 1993). This paper discusses development and main features of a prototype expert system called the *Carbonation-Resistant Concrete Consultant (CRCC)*. The system is expected to improve the process of selecting concrete constituents and other related procedures to obtain durable concrete for aggressive carbon dioxide exposure.

2 DEVELOPMENT OF THE PROTOTYPE

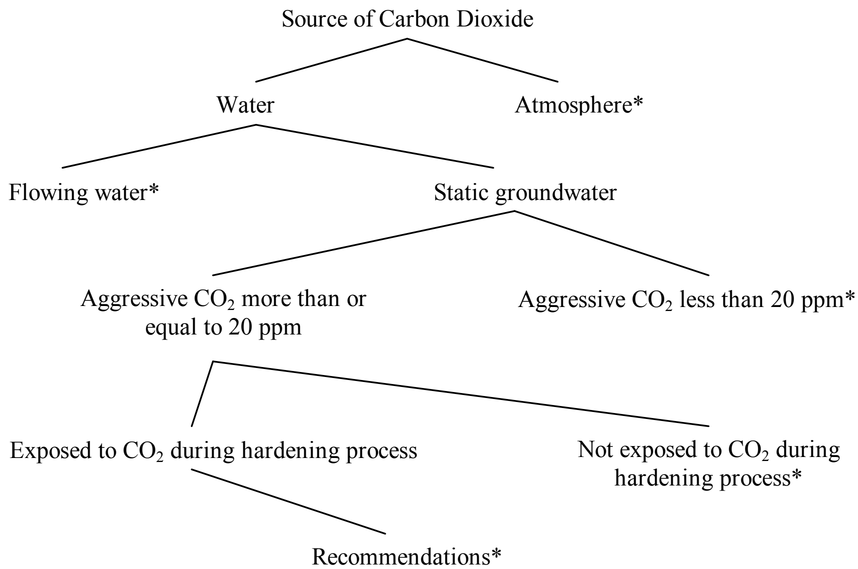
2.1 *Knowledge acquisition*

Knowledge for the CRCC was acquired from multiple sources of expertise. These include classical textbooks and manuals, experts involved in concrete production, and research papers from journals and conference proceedings (ACI Committee 201, 2002; Neville, 1995; Nawy, 1996; Shah and Ahmad, 1994; Aitcin, 1998; Malier, 1992; Mehta, 1991). The major factors controlling the response of concrete to deterioration processes in carbon dioxide environment and recommendation measures to minimize their deleterious effects are given in these sources. It may be mentioned here that acquiring knowledge from these sources was felt to be the most difficult and time-consuming task in the prototype development process.

2.2 *Knowledge representation*

The rheology model (Bhuiyan et al. 2009; Bhuiyan, 2009) employed in the subsequent numerical analysis is illustrated in Figure 3, where τ and γ are the average shear stress and shear strain of rubber layers, respectively. In this model, the total shear stress is decomposed into three contributions associated with a nonlinear elastic stress, an elasto-plastic stress and finally a viscosity induced overstress. The mathematical description of the model is briefly stated in Eq.(1).

The first step in representing the factual knowledge was the creation of tree (hierarchy) structure. A portion of tree structure for the knowledge of carbonation of concrete is illustrated in Fig. 1. The figure shows that the source of carbon dioxide that can attack concrete can be either water or atmosphere. Again, water may be either static or flowing. Tree structure proceeds further according to concentration of aggressive carbon dioxide and exposure conditions during hardening process. Similar knowledge tree was also developed for the atmospheric carbonation.



* indicates omission of knowledge tree

Figure 1. A portion of Knowledge Tree regarding carbonation of concrete

After the creation of knowledge tree, a hybrid approach of knowledge representation (i.e., rule and frame/object systems) was followed using Kappa-PC expert system shell (IntelliCorp, 1997). In the frame-based structure, **Carbonation** class was defined as subclass to the **Durability** class in the object hierarchy tree. Further, the classification was expanded with respect to the sources of carbon dioxide and created as subclasses and so on. The properties of these objects were created as slots. After the development of object-oriented model of the domain, the knowledge presented in the knowledge tree (Fig. 1) was transformed into a rule-based structure, called workable or production rules. To be workable in Kappa-PC shell, these production rules were translated into KAL (Kappa-PC Application Language) format. The **Carbonation** class, its slots and corresponding slot values in a Kappa-PC class editor window as well as a typical rule in its KAL format in a Kappa-PC rule editor window are available elsewhere (Islam et al., 2003b).

3 MAIN FEATURES OF THE CRCC

The operation of the prototype consists of a series of questions linked by if-then logic. The system runs on typical personal computer configuration, requiring a run-time version of Kappa-PC (for Windows 95 and above). A brief description of the basic components of the prototype is available elsewhere (Islam et al., 2003a). The following section gives general information about the system as well as data input, recommendations and explanation of recommendations for an example session.

3. 1 *General information*

Fig. 2 shows the main interface window of the prototype. The window consists of three transcript images, twelve buttons, six state box images and two text images. The functions of the buttons are consistent with their titles and evidently clear. The first transcript image gives preliminary information about carbonation of concrete and functions of the buttons. It also displays text files regarding advice, source of carbonation, mechanism of carbonation, rate of carbonation, effects of carbonation and effects of pozzolans on carbonation of concrete, 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 particular recommendations. The state box images show the data selected by the user during a consultation session.

In the beginning of the consultation, the first transcript image states that the carbonation of concrete depends primarily on the relative humidity of the environment, temperature, permeability of concrete and concentration of carbon dioxide. Through this transcript image, the user also gets preliminary idea on the sequence of consultation steps. An **Advice** button (Fig. 2) is also available in order to access information in case of need during the consultation process. It gives information about how to use the system efficiently and guides the user to have a consultation in a systematic way. The **Source of Carbonation** button shows, if pressed, the general sources from where carbon dioxide may come in contact with concrete as shown in Fig. 3. The **Mechanism** button opens a text file in the first transcript image describing briefly the carbonation mechanism. The **Effects of Carbonation** button shows the positive and negative effects of carbonation of concrete (see Fig. 4). For example, it states that carbonation of concrete reduces pores and, therefore, reduces permeability of the surface and increases strength, which are positive effects of carbonation.

The **Rate of Carbonation** button displays the relationship between the depth of carbonation in mm and the duration of exposure in year. It also shows the factors that influence carbonation of concrete. The **Effects of Pozzolana** button expresses the effects of supplementary cementitious materials on the carbonation of concrete (see Fig. 5). For example, it states that pozzolans do not have significant effect on the carbonation of concrete. It also explains the reasons for this insignificant effect. These accessory facilities encourage the user to be aware of the potential carbonation situation and train the inexperienced users about carbonation problem

3.2 Data input

Data input session starts after pressing on the **Data Input** button (Fig. 2). The user inputs data by selecting from a list of slot values displayed by the system. A typical data input form is shown in Fig. 6. This type of input form helps the user avoid input errors. The input form of the user interface includes **Comment** button (see Fig. 6) which helps the user, if pressed, by expanding the meaning of a question or data as shown in Fig. 7 and thus aids the user in responding more efficiently to the prompts of the consultation. This facility also makes the system suitable for educational purposes. Another feature of the system is that the data input is self-consistent. For example, if the user selects water as the source of carbon dioxide, then the system further asks whether source is static water or flowing water. Table 1 shows the data required by the system for a particular consultation session and the corresponding response of the user. In this example session, the following data were selected: source of carbon dioxide was atmosphere and the relative humidity was within 50-75%. These data constituted the key information for the user's situation.

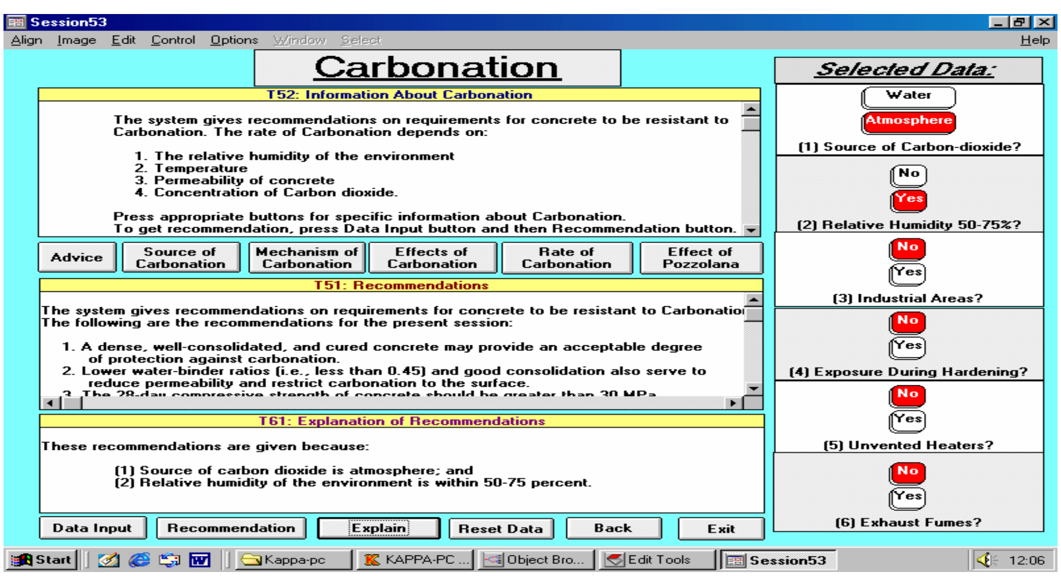


Figure 2. Main interface window of the prototype

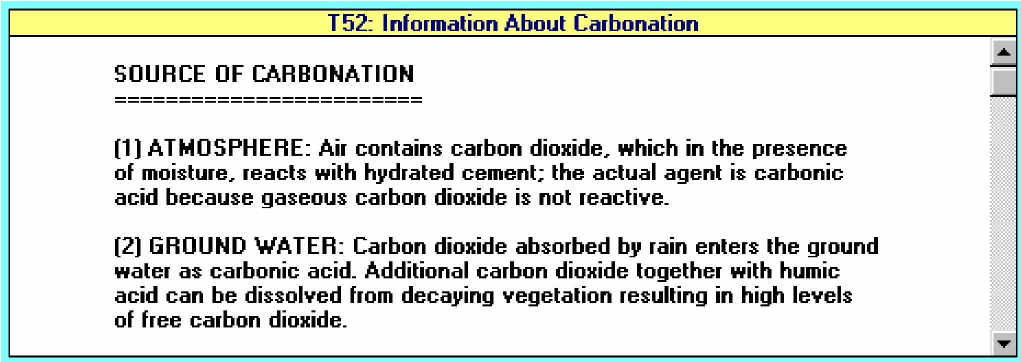


Figure 3. Information about source of carbonation (after pressing ***Source of Carbonation*** button of Fig. 2).

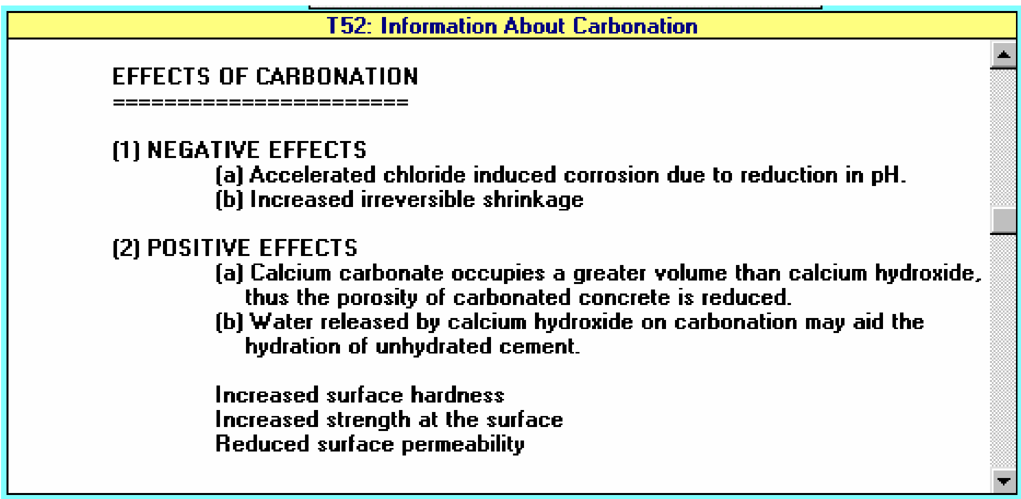


Figure 4. Information about effects of carbonation (after pressing **Effects of Carbonation** button of Fig. 2).

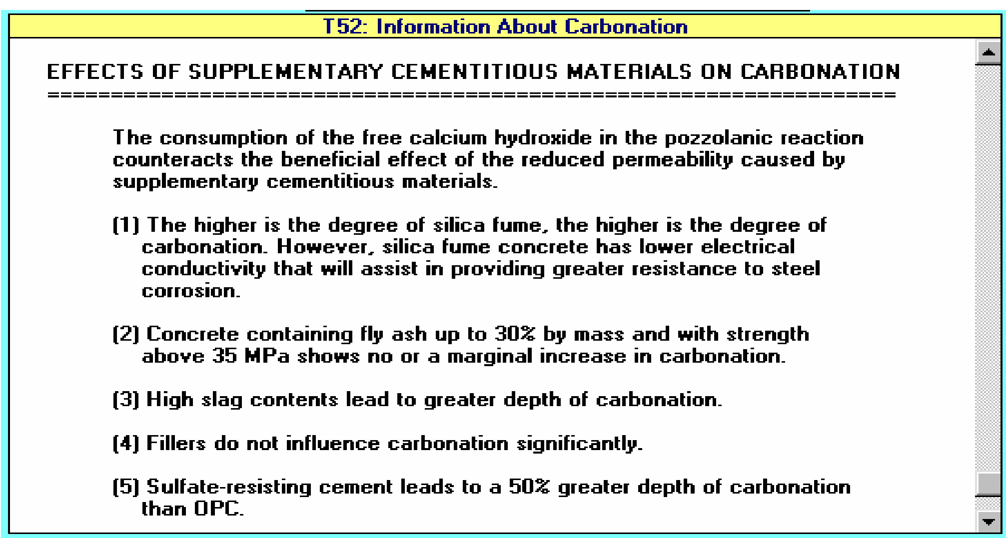


Figure 5. Information about effects of supplementary cementitious materials (after pressing ***Effects of Pozzolana*** button of Fig.2).

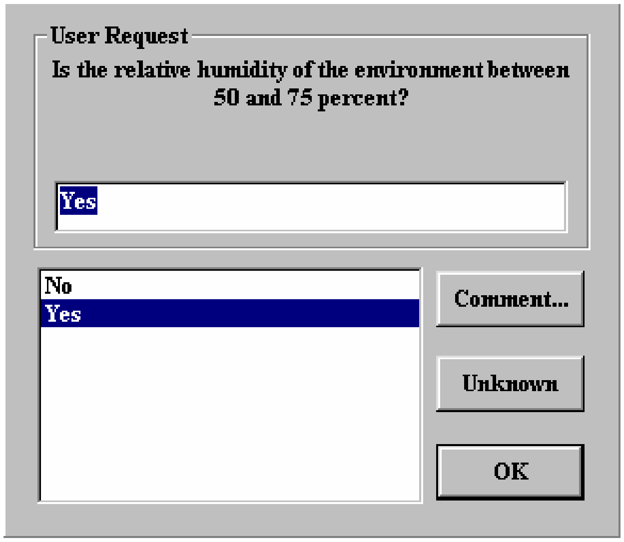


Figure 6. A typical Data Input window of the prototype

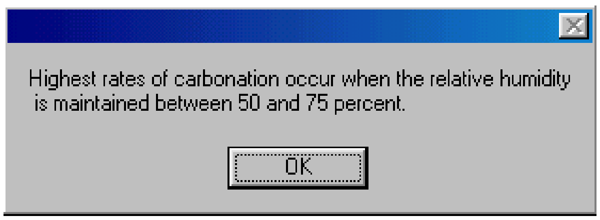


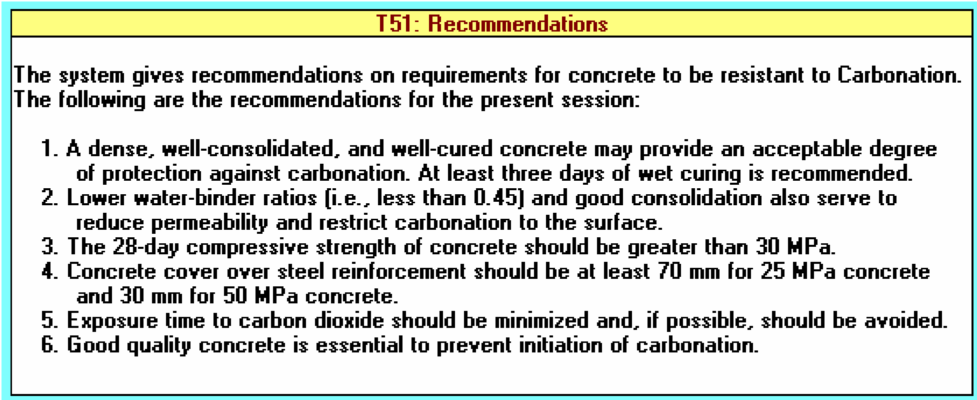
Figure 7. A typical Explanation window during Data Input (after pressing Comment button of Fig. 6).

Table 1. The questions and user's response for an example session

Sl. No.	Question Asked by the CRCC	Options to Select	User's Selection
1	What is the source of CO_2?	(a) Atmosphere (b) Water	(a) Atmosphere
2	Is the relative humidity of environment between 50 and 75%?	(a) Yes (b) No	(a) Yes
3	Is concrete structure located near industrial areas with higher concentration of CO_2?	(a) Yes (b) No	(b) No
4	Will concrete be exposed to CO_2 during hardening process?	(a) Yes (b) No	(b) No
5	Will unvented heaters be used during hardening process?	(a) Yes (b) No	(b) No
6	Is there any possibility of exposure of concrete to exhaust fumes from equipment or other sources?	(a) Yes (b) No	(b) No

(a) Recommendations

After getting the input data from the user, the system produces recommendations by comparing these data with the knowledge contained in its knowledge base. A typical output of recommendation for the input data of Table 1 is shown in the second transcript image of Fig. 2, an enlarged view of which is shown in Fig. 8. The recommendations include that a dense, well-consolidated, and well-cured concrete may provide an acceptable degree of protection against carbonation. Lower water-binder ratio (i.e., less than 0.45) serves to reduce permeability and restricts carbonation to the surface. In addition, exposure time to carbon dioxide should be minimized. Good quality concrete is essential to prevent initiation of carbonation. The recommendations also include compressive strength requirement (i.e., greater than 30 MPa), cover requirement (i.e., 70 mm for 25 MPa concrete and 30 mm for 50 MPa concrete), and curing requirement (i.e., at least 3 days of wet curing) as shown in the figure. These recommendations for the data of Table 1 were considered to be reasonably comprehensive and satisfactory.


T51: Recommendations

The system gives recommendations on requirements for concrete to be resistant to Carbonation.
The following are the recommendations for the present session:

1. A dense, well-consolidated, and well-cured concrete may provide an acceptable degree of protection against carbonation. At least three days of wet curing is recommended.
2. Lower water-binder ratios (i.e., less than 0.45) and good consolidation also serve to reduce permeability and restrict carbonation to the surface.
3. The 28-day compressive strength of concrete should be greater than 30 MPa.
4. Concrete cover over steel reinforcement should be at least 70 mm for 25 MPa concrete and 30 mm for 50 MPa concrete.
5. Exposure time to carbon dioxide should be minimized and, if possible, should be avoided.
6. Good quality concrete is essential to prevent initiation of carbonation.

Fig. 8. Recommendations of the CRCC for the data of Table 1.

(b) Explanation of recommendations

One of the distinguishing characteristics of an expert system such as the CRCC is the transparency of its reasoning process and knowledge base. This advantage is available to the user through **Explain** button of Fig. 2, 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. 2. The explanation facility of the system facilitates verification and validation of results and also makes it suitable for educational purposes.

4 UPGRADING AND MODIFICATION OF THE CRCC

The consultation process of the prototype was reasonably satisfactory and systematic. The flow of consultation is flexible, allowing the user to go back for a new consultation, to review input values, to repeat rule inferences and other procedures until he is satisfied with the results. However, 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). All expert systems, the CRCC included, cannot claim completeness in their knowledge bases; they are always subject to upgrading, modification and correction. The existing knowledge base of the prototype can be improved by:

(i) refining, expanding, and reinforcing its knowledge base using new findings as reported in literature or new experience from domain experts;
(ii) incorporating further functional capabilities such as knowledge of corrosion, alkali-aggregate reactivity, freeze-thaw, sulfate attack and so on.

5 CONCLUSIONS

A prototype expert system for making durable concrete in aggressive carbon dioxide exposure has been developed. The system helps the concrete technologists make durable concrete based on carbon dioxide source and concentration, and environmental conditions. The knowledge was acquired from textual sources and human experts. Kappa-PC toolkit was used to develop the application, which is supported by object-oriented programming and rule based reasoning. The knowledge was represented by production rules and frames. The system works in full interactive mode and gives information to follow in making carbonation-resistant durable concrete. The system can also be used as a tool for training students and inexperienced concrete technologists.

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REFERENCES

ACI Committee 201 (2002). "Guide to durable concrete", ACI Manual of Concrete Practice: Part 1, American Concrete Institute, Detroit, 41 pp.

Aitcin, P.-C. (1998). High Performance Concrete, E & FN SPON, London.

Clifton, J.R. and Kaetzel, L.J. (1988). "Expert systems for concrete construction", Concrete International, Vol. 10 (11). 19-24.

Clifton, J.R. and Oltikar, B.C. (1987). "Expert system for selecting concrete constituents", Computer Application in Concrete Technology, American Concrete Institute, Vol. SP-98, 1-24.

Clifton, J.R., Oltikar, B.C. and Johnson, S.K. (1985). Development of DURCON, An Expert System for Durable Concrete: Part I, U. S. National Bureau of Standards, Gaithersburg, MD.

IntelliCorp. (1997). KAPPA-PC Ver. 2.4 User's Manual, IntelliCorp Inc., CA.

Islam, M.N., Zain, M.F.M. and Basri, H.B. (2003a). "A knowledge based system for making durable high performance concrete exposed to carbonation". Proceedings of the International Conference on Advances in Strategic Technologies (ICAST), Kuala Lumpur, August.

Islam, M.N., Zain, M.F.M. and Basri, H.B. (2003b). "Development of an intelligent system for durable high performance concrete exposed to carbon dioxide environment". Proceedings of the International Conference on Concrete Engineering and Technology (CONTEC), Sabah, October.

Kaetzel, L.J. and Clifton, J.R. (1988). "Maintenance and implementation of an expert system for durable concrete". ACI Special Publication, Vol. SP 106. 75-86.

Kaetzel, L.J., Clifton, J.R., Klieger, P. and Snyder, K. (1993). Highway Concrete (HWYCON) Expert System User Reference and Enhancement Guide. Research Report No. NISTIR-5184, National Institute of Standards and Technology (BFRL), Gaithersburg, MD.

Malier, Y. (1992). High Performance Concrete: From Material To Structure, E & FN Spon, London.

Mehta, P.K. (1991). Concrete in the Marine Environment, Elsevier Science Publishers Ltd, New York.

Nawy, E.G. (1996). Fundamentals of High Strength High Performance Concrete, Longman Group Limited, London.

Neville, A.M. (1995). Properties of Concrete, Longman Group Limited, Essex.

Shah, S.P. and Ahmad, S. H. (1994). High Performance Concrete and Applications, Edward Arnold, London.