Proceedings of the 5th WSEAS International Conference on Telecommunications and Informatics, Istanbul, Turkey, May 27-29, 2006 (pp121-127)

Expert System For Making Sulfate-Resistant Concrete

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Abstract: - The development and the main features of a knowledge-based expert system for modelling the requirements of durable concrete in sulfate exposure, called the Sulfate-Resistant Concrete Advisor (SRCA), are described. The system was developed to help improve the quality of concrete exposed to sulfate 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 and other decision processes operate on or across objects. The knowledge and experience were acquired from various textual sources and human experts. The system is very useful for civil engineering students as well as practicing engineers.

Key-Words: - Expert system, knowledge-based system, sulfate exposure, durable concrete, object-oriented model.

1 Introduction

Naturally occurring sulfates of sodium, potassium, calcium, or magnesium that can attack concrete are sometimes found in soil or dissolved in groundwater adjacent to concrete structures [3]. When evaporation takes place from an exposed face, the sulfates may accumulate at that face, thus increasing their concentration and potential for causing deterioration of concrete. The reactions between sulfate ion and hydrated cement paste result in an increase in solid volume. The formation of ettringite is the cause of most of expansion and disruption of concrete caused by sulfate solutions. Sulfate attack has occurred at various locations throughout the world, and is a particular problem in arid areas. The chemical deterioration of concrete in seawater, which contains sulfates, has concerned concrete technologists for generations [3].

Experts' advice and experience are prerequisite in the making of sulfate-resistant durable concrete. Serious damage to concrete structure in sulfate exposure may result due to lack of engineering experience and judgment of the designer. Concrete structures suffer from sulfate attack problem on many construction sites particularly those in developing countries 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.

This paper describes the development and the main features of a prototype expert system, the Sulfate-Resistant Concrete Advisor (SRCA), that was developed to give recommendations on requirements of durable concrete exposed to sulfates. Its goal was to improve the quality of concrete produced for the sulfate exposure, by including the views of different expertise sources in the domain.

2 Literature review

Expert systems technology has been applied to the selection of ingredients of durable concrete. DURCON [7,8,9] 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. It was developed originally in the conventional programming languages of FORTRAN and PASCAL, and was designed to run using the DOS operating system. Its knowledge was based on ACI 201.2R-77 guide [1] and experts from ACI 201 committee. Kaetzel et al. (1993) developed a system for highway concrete, called HWYCON, using Level5 Object shell. 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. Its knowledge was based on ACI 201 guide [2] and experts on this field.

However, none of these systems give recommendations on important issues like curing practices, presence of other materials such as calcium chloride and available field performance of concrete, which are included in the ACI 201 guide. These systems were developed on the basis of earlier editions of the ACI 201 guide and do not include knowledge from the recent edition. In both of these systems, the knowledge base for the selection of ingredients of concrete to be resistant to sulfate exposure was developed as a component of integrated systems to complement other durability modules. Thus the knowledge bases of these systems regarding sulfate attack didn’t get the major emphasis and are not considered as complete sources of knowledge for the domain. The SRCA was developed to overcome some of these limitations and to have an expert system dealing completely with the sulfate attack problem.

3. Development of the Sulfate-Resistant Concrete Advisor (SRCA)

3.1. The knowledge engineer

A knowledge engineer acquires knowledge from various sources of expertise and codifies it into an expert system [6]. As a prerequisite for developing knowledge based system in the sulfate-resistant concrete domain, the knowledge engineer has to be familiar with the essential components of expert system technology as well as the domain of sulfate-resistant concrete construction. To develop a successful system, it is also necessary to understand the shell being used. Given the engineering nature of the sulfate-resistant concrete domain, the ‘Engineering Expert Systems’ approach as advocated by Simonovic and Savic (1989) was adopted in the development of the SRCA. In this approach, engineers of the domain (the authors in this case) who have mastery of expert systems technology were to become the knowledge engineers.

3.2. Sources of expertise

Criteria for the selection of sources of expertise are domain specific [17]. For the case of sulfate-resistant durable concrete, there were a variety of expertise sources, e.g. concrete practitioners and technologists, classical texts, manuals and research papers, which were found in scattered locations. Such a situation necessitated the selection of multiple sources of expertise. Knowledge for the SRCA was thus acquired from textbooks [4,14,16,18] and manuals (ACI Committee 201 1995) written by experts and related professional institutions, experts involved in concrete production, and research papers [11,13,15] from journals and conferences. However, the system was largely based on the information contained in the ACI Guide to Durable Concrete (ACI Committee 201 1995) because of its wide acceptability to concrete technologists. This edition of the guide contains updated knowledge compared to those used in DURCON and HWYCON. Acquiring knowledge from these sources was felt to be the most difficult and time-consuming task in the prototype development process.

3.3. Flow diagram of acquired knowledge

After acquiring the knowledge from multiple expertise sources, a flow diagram for making sulfate-resistant concrete was developed as shown in Figure 1. This flow diagram was used to develop objects and rules for the knowledge base. The diagram shows that the sulfate environment was broadly divided into two categories: sulfate in soil and sulfate in water. Both types of sulfate exposure were further divided into four categories according to the concentration of sulfate ions: mild, moderate, severe and very severe. The type of binders may be Portland cement or blended cement. Again, Portland cement may also include pozzolans such as fly ash, silica fume or both. On the other hand, blended cement may be of two types: slag modified or pozzolan modified.

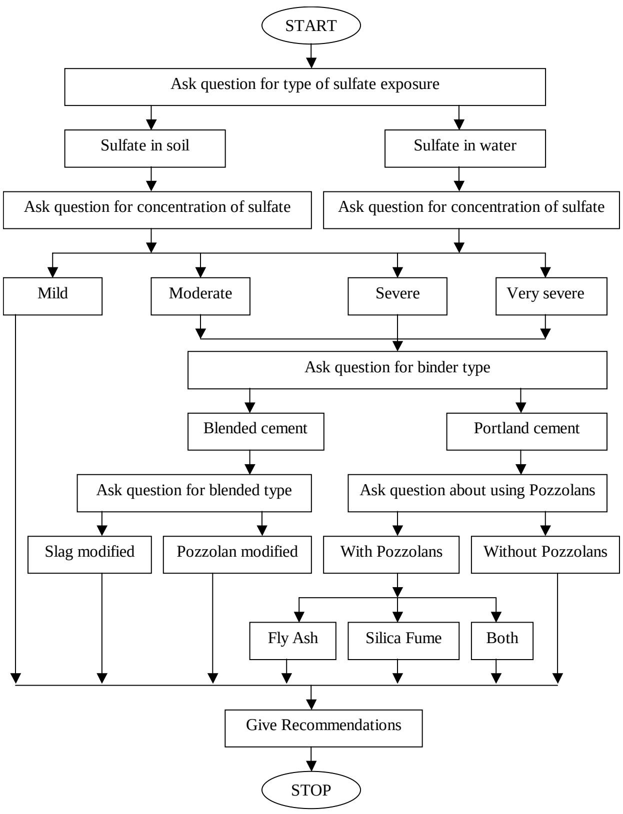


Figure 1. Flow diagram of knowledge for making sulfate-resistant concrete

3.4. Prototype development tool

For the development of the SRCA, an object-oriented expert system shell, Kappa-PC [10], was preferred over conventional programming languages. Apart from its powerful object-oriented capabilities, Kappa-PC also allows representation of knowledge using production rules. In Kappa-PC, the rule facilities allow for interactive editing, automatic tracing, and graphical debugging. It also provides a variety of user options. Moreover, Kappa-PC shell was chosen after considering several available shells because of its proven reliability and knowledge engineers' familiarity of working with this shell. Since most commercial shells could adequately cater for the knowledge representation needs of the chosen domain, the key consideration in the choice of expert system shell was thus reduced to its reliability, and neither the degree of complexity nor the capacity of its problem-solving techniques.

3.5. Object-oriented model of the domain

The sulfate-resistant concrete domain was modelled using the object-oriented approach. The created objects represent their real world counterparts, hence allowing a more realistic and clear representation of domain knowledge. The attributes of these objects were defined as object slots, which also represent the current state of the problem at hand. For example, Figure 2 shows a typical instance editor for the instance **SulfateInSoil** of the parent class **SulfateAttack** in Kappa-PC editor. Interactions between objects, instructions from one object to another, and processes of objects, were codified in the form of functions, methods and rules.

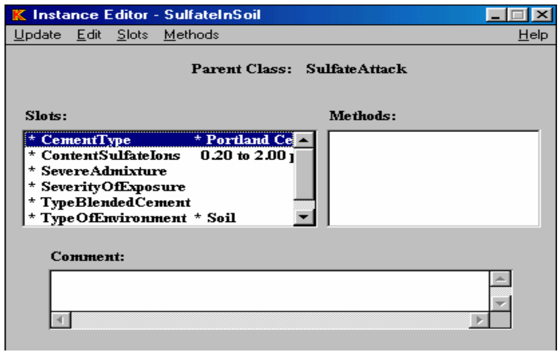


Figure 2. Instance editor for the instance **SulfateInSoil** of the parent class **SulfateAttack**

3.6. Production rules of the acquired knowledge

After the construction of the object-oriented model of the domain, the knowledge presented in the flow diagram (Figure 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. Figure 3 presents a portion of a rule named **SulfateSevere8** in its KAL format in a Kappa-PC rule editor window from the knowledge base of the SRCA. All parameters of a KAL rule must have single or multiple values. Such values were defined in the properties of the frame/object to which the KAL rule belongs.

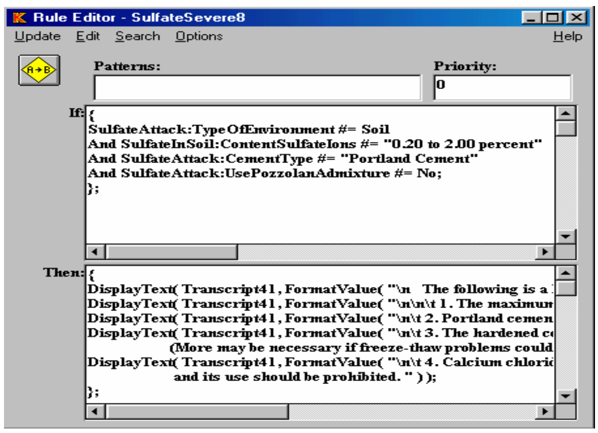


Figure 3. A portion of the **SulfateSevere8** rule in a Kappa-PC rule editor window

4. Main features of the SRCA

The operation of the SRCA consists of a series of questions linked by if-then logic. Its control system supports a forward-chaining procedure. The SRCA expert system runs on typical personal computer configuration, requiring a run-time version of Kappa-PC (for Windows 95 and above) and at least a 486 CPU. The following sections give the general information about the system, input information required, typical output in the form of recommendation, and overall evaluation of the system.

4.1. General information

Figure 4 shows the main window of the SRCA. This gives brief information about the system. To start formal consultation, the user needs to press on the **Continue** button (Figure 4) that opens a new window as shown in Figure 5. This window (Figure 5) consists of two transcript images, one bitmap image and eight buttons. The first transcript image gives preliminary information about sulfate attack and functions of the buttons. The second transcript image displays recommendation and explanation, occurrence and mechanism of sulfate attack, and associated advice if the user presses appropriate buttons. The bitmap image shows the reactions associated with sulfate attack of concrete.

Accessory facilities are available in the SRCA with the general objective of enhancing the performance of the consultation process. For example, the possible reactions of sulfates with hardened cement paste are displayed in the bitmap image of the interface window. The **Occurrence** button shows the general situation where sulfate attack may be a problem as shown in Figure 6. After consulting the sources of sulfate problem using this button, the user will be aware about his/her situation whether it will be subject to sulfate attack or not. On the other hand, the **Mechanism** button opens a text file in a transcript image describing briefly the sulfate attack mechanism as shown in Figure 7. An **Advice** button (Figure 5) 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. These accessory facilities encourage the user to be aware of the potential sulfate attack situation and train the inexperienced users about sulfate attack problem. Accessory facilities like information about occurrence and mechanism of sulfate attack as well as display of associated reactions are some of the improvements of the SRCA over other existing systems in the domain.

Figure 4. Main window of the Sulfate-Resistant Concrete Advisor (SRCA)

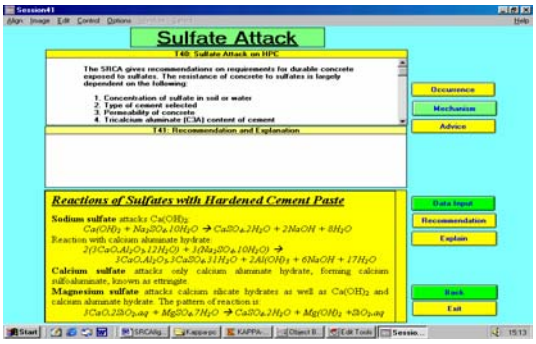


Figure 5. Interface window of the Sulfate-Resistant Concrete Advisor (SRCA)

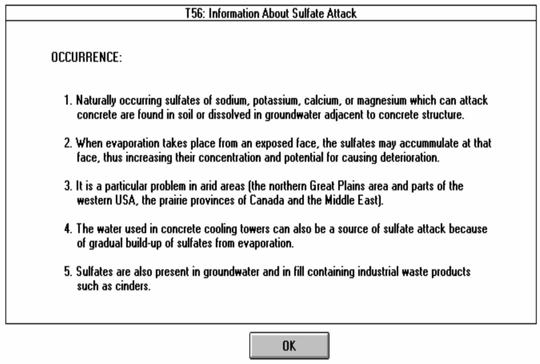


Figure 6. Information about occurrence of sulfate attack after pressing **Occurrence** button of Figure 5

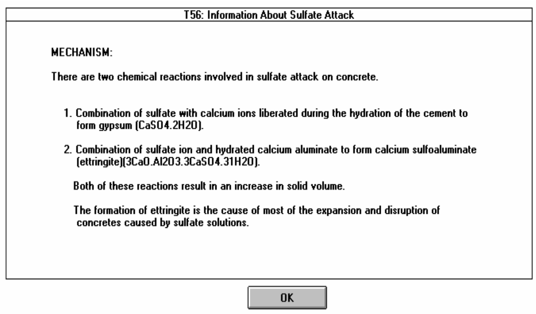


Figure 7. Information about mechanism of sulfate attack after pressing **Mechanism** button of Figure 5

4.2. Data Input

Data input session starts after pressing on the **Data Input** button (Figure 5). The user inputs data by selecting from a list of slot values displayed by the system. A typical data input form is shown in Figure 8. This type of input form helps the user avoid input errors. The input form of the user interface includes **Comment** button (see Figure 8) which helps the user, if pressed, by expanding the meaning of a question or data as shown in Figure 9 and thus aids the user in responding more efficiently to the prompts of the data input procedure. 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 blended cement as binder, then the system further asks whether blended cement is pozzolan modified or slag modified.

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 by the user for his/her situation: type of environment is soil, content of sulfate ion is in the range of 0.20-2.00 percent (severe sulfate exposure), and binder is Portland cement with pozzolan. These data constituted the key information for the user's situation.

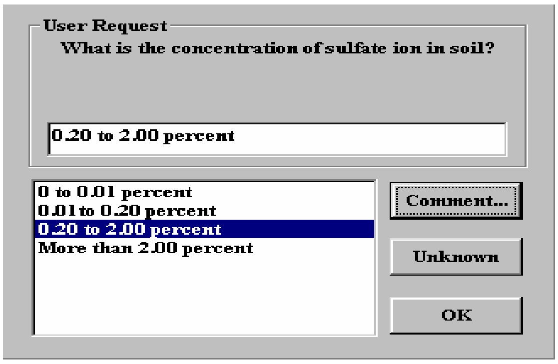


Figure 8. A typical data input form of the SRCA

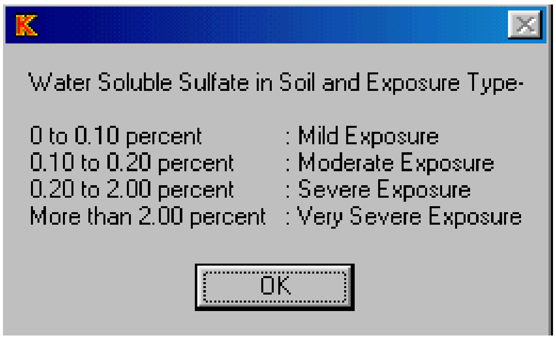


Figure 9. Explanation of the data after pressing **Comment** button of Figure 8

Table 1. Data required and user's selection for an example session

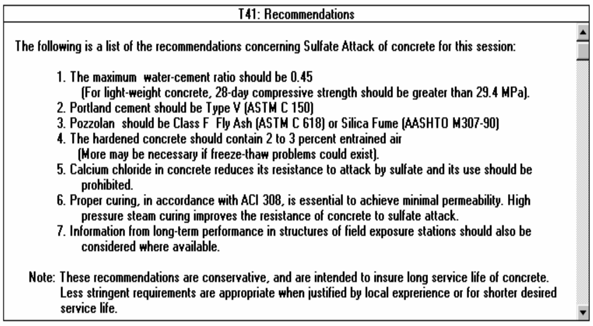
Required Data	Options To Select	User's Selection
Type of environment	Soil Water	Soil
Sulfate ion concentration (%)	0.00-0.01 (mild exposure) 0.01-0.20 (moderate exposure) 0.20-2.00 (severe exposure) More than 2.00 (very severe exposure)	0.20-2.00 (severe exposure)
Type of binders	Blended cement Portland cement	Portland cement
Use of pozzolan admixtures	Yes No	Yes

4.3. Recommendation and explanation

The system gives recommendation in a transcript image according to the data supplied by the user. The SRCA produces recommendations by comparing these data with the knowledge contained in its knowledge base. The method of making recommendations is very similar to the way a human expert would handle the problem.

A typical output transcript image of recommendations for the input data of Table 1 is shown in Figure 10 (enlarged view of the second transcript image of Figure 5). The recommendations includes, among others, water-binder ratio, compressive strength for lightweight concrete, type of binders and type of pozzolans with appropriate standards like other expert systems in the domain. The SRCA recommendations also include required curing practices, use of other materials such as calcium chloride and use of the knowledge of available field performance of concrete. Moreover, the recommendation includes a note which indicates that the recommendations are conservative and are intended to insure longer service life of concrete and so on. These are some of the improvements over the other systems available in the sulfate-resistant concrete domain. The output information or recommendations, like input information, are also self-consistent. For example, if a moderate, severe or very severe exposure condition is selected, then the system recommends the use of air-content in percent as shown in recommendation number 4 of Figure 10.

One of the distinguishing characteristics of an expert system such as the SRCA is the transparency of its reasoning process and knowledge base. This advantage is available to the user through **Explain** button of Figure 5, which displays the reasons for arriving at a particular recommendation. The explanation of the recommendations of the present session (Figure 10) is shown in Figure 11. The explanation facility of the system facilitates verification and validation of results and also makes it suitable for educational purposes.

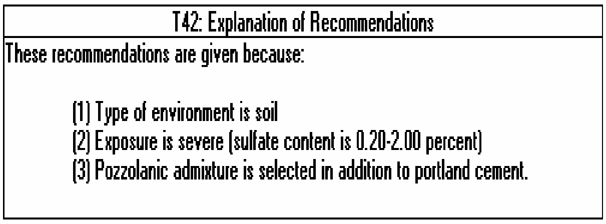

T41: Recommendations

The following is a list of the recommendations concerning Sulfate Attack of concrete for this session:

1. The maximum water-cement ratio should be 0.45
   (For light-weight concrete, 28-day compressive strength should be greater than 29.4 MPa).
2. Portland cement should be Type V (ASTM C 150)
3. Pozzolan should be Class F Fly Ash (ASTM C 618) or Silica Fume (AASHTO M307-90)
4. The hardened concrete should contain 2 to 3 percent entrained air
   (More may be necessary if freeze-thaw problems could exist).
5. Calcium chloride in concrete reduces its resistance to attack by sulfate and its use should be prohibited.
6. Proper curing, in accordance with ACI 308, is essential to achieve minimal permeability. High pressure steam curing improves the resistance of concrete to sulfate attack.
7. Information from long-term performance in structures of field exposure stations should also be considered where available.

Note: These recommendations are conservative, and are intended to insure long service life of concrete. Less stringent requirements are appropriate when justified by local exprerience or for shorter desired service life.

Figure 10. The output transcript image of recommendations for the data of Table 1


T42: Explanation of Recommendations

These recommendations are given because:

(1) Type of environment is soil
(2) Exposure is severe (sulfate content is 0.20-2.00 percent)
(3) Pozzolanic admixture is selected in addition to portland cement.

Figure 11. Explanation of recommendations after pressing **Explain** button of Figure 5

4.4. Overall evaluation of the system

The consultation process of the SRCA was reasonably satisfactory and systematic to the knowledge engineers. The flow of consultation was flexible, allowing the user to go back for a new consultation, to review input values, to repeat rule inferences and other procedures until he/she is satisfied with the results. The ability of the SRCA to run using Windows operating system, to give recommendation on issues like curing requirements and use of the knowledge of available field performance make this system superior to similar other systems in the domain. Moreover, the knowledge of the SRCA was based on the latest edition of the guide compared to those of the similar systems.

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 [13]. All expert systems, the SRCA included, cannot claim completeness in their knowledge bases; they are always subject to upgrading, modification and correction. The existing knowledge base for the SRCA 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) adding further functional capabilities such as knowledge of corrosion, alkali-aggregate reactivity, freeze-thaw etc; and

iii) adding photographs as bitmap images showing the sulfate attack problem of existing structures and the corresponding recommendation from experts for solving the problem.

5. Conclusions

Concrete ingredients, their proportions and construction procedure largely affect the quality of concrete in sulfate exposure. The use of expert systems can minimize the mistakes and deficiencies in the selection of ingredients and production of durable concrete in this case. The developed prototype expert system, the Sulfate-Resistant Concrete Advisor (SRCA), is an attempt to achieve this objective. Knowledge was acquired from a variety of expertise sources, modeled using the object-oriented approach in combination with rule-inferencing techniques, and codified into software. 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 research has also documented various stages in the prototype development exercise. The prototype can be used by the technical personnel of government authorities and engineering consultancy firms in charge of production of durable concrete for sulfate environment. It can also be used as a tool for educating untrained and inexperienced concrete technologists.

References:

[1]ACI Committee 201 (1977), Guide to durable concrete, ACI Manual of Concrete Practice, Part 1, American Concrete Institute, 1977 (ACI 201.2R-77).

[2]ACI Committee 201 (1991), Guide to durable concrete, ACI Materials Journal, 88, 1991, 544-582

[3]ACI Committee 201 (1995), Guide to durable concrete, ACI Manual of Concrete Practice, Part 1, American Concrete Institute (ACI 201.2R-92).

[4]Aitcin, P.-C. (1998), High performance concrete, E & FN Spon, 1998.

[5]Basri, H.B. (1994), An expert system for preliminary landfill design in developing

countries, Ph.D. Thesis, Department of Civil Engineering, University of Leeds, 1994

[6]Basri, H.B. (2000), An expert system for landfill leachate management, Environmental Technology, 21, 2000, 157-166.

[7]Clifton, J.R. and Kaetzel, L.J. (1988), Expert systems for concrete construction, Concrete International, 10, 1988, 19-24.

[8]Clifton, J.R. and Oltikar, B.C. (1987), Expert system for selecting concrete constituents, ACI Special Publication No. SP-98, 1987, 1-24.

[9]Clifton, J.R., Oltikar, B.C. and Johnson, S.K. (1985), Development of DURCON, an expert system for durable concrete: Part I, Report No. NBSIR-85/3186, National Bureau of Standards, Gaithersburg, 1985.

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

[11]Kaetzel, L.J. and Clifton, J.R. (1988), Maintenance and implementation of an expert system for durable concrete, ACI Special Publication No. SP-106, 4, 1988, 75-86.

[12]Kaetzel, L.J. and Clifton, J.R. (1995), Expert/Knowledge based systems for materials in the construction industry: state-of-the-art report, Materials and Structures, 28,1995, 160-174.

[13]Kaetzel, L.J., Clifton, J.R., Klieger, P. and Snyder, K. (1993), Highway concrete (HWYCON) expert system user reference and enhancement guide, Report No. NISTIR-5184, National Institute of Standards and Technology, Gaithersburg, 1993.

[14]Mehta, P.K. (1991), Concrete in the marine environment, Elsevier Science Publishers Ltd, 1991.

[15]Mehta, P.K. (2000), Sulfate attack on concrete: separating myths from reality, Concrete International, 22, 2000, 57-61.

[16]Neville, A.M. (1995), Properties of concrete, 4th edition, Longman Group Limited, 1995.

[17]Perman, C.D. and Ortolano, L. (1992), A diagnostic aid for wastewater treatment plants, In: Arciszewski, T. and Rossman, L.A. (eds.), Knowledge Acquisition in Civil Engineering, ASCE, New York, 1992, 86-104.

[18]Shah, S.P. and Ahmad, S.H. (1994), High performance concrete and applications, Edward Arnold, 1994.

[19]Simonovic, S.P. and Savic, D.A. (1989), Intelligent decision support and reservoir management & operations, ASCE Journal of Computing in Civil Engineering, 3, 1989, 188-192.