DEVELOPMENT OF AN EXPERT SYSTEM FOR MAKING HIGH PERFORMANCE CONCRETE USING HYBRID KNOWLEDGE REPRESENTATION SYSTEM

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PEMBANGUNAN SISTEM PAKAR UNTUK MEMBINA KONKRIT PRESTASI TINGGI MENGGUNAKAN SISTEM PERWAKILAN PENGETAHUAN HYBRID

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TESIS YANG DIKEMUKAKAN UNTUK MEMPEROLEH IJAZAH DOKTOR FALSAFAH

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DECLARATION

I hereby declare that the work in this thesis is my own except for quotations and summaries which have been duly acknowledged.

21 July 2004

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P19842

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ABSTRACT

An expert system prototype, called the *High Performance Concrete Advisor (HPCA)*, was developed to aid the making of high performance concrete. The prototype development process for the HPCA has adopted a modular approach, which covered the tasks of mix design and mix performance adjustment as well as giving recommendations on various durability aspects of high performance concrete. The process comprised of the first trial batch, trial batch for laboratory, batch composition, mix performance adjustment, and cost estimation for the selected mix. The durability module included corrosion, alkali-aggregate reactivity, sulfate attack, seawater exposure, acid attack, carbonation, abrasion and freeze-thaw aspects. An expert system shell, Kappa-PC, was preferred as the building tool for the development of the prototype because of its object-oriented approach that allowed knowledge representation by hybrid techniques, i.e. production rules and objects. It was also found to offer advantages with respect to ease of manipulation, increased productivity and a true windowing capability to run on personal computers. The main issues addressed in the expert system development were the knowledge acquisition process and the building of the prototype. The major steps involved were problem definition, implementation and testing. The knowledge used in the system was acquired from many sources such as textbooks, manuals and guides, journals, reports, and domain experts. In the HPCA consultation process, the user can design and adjust high performance concrete mixes for various performance requirements using available local materials. A summary of the system's recommendations and additional information on each aspect of durability module was given at each stage of the consultation process. Several case studies were carried out to evaluate the system. In these case studies, the overall performance of the HPCA was found to be satisfactory in dealing with the intended scope of work and its appropriateness to the end-user. The primary end-users of the HPCA would be consulting engineers, construction engineers, construction managers and decision-makers, who would use it as an aid to the decision making process. The system can also be utilized for educating students and inexperienced practitioners in getting familiar with the mix design and durability aspects of high performance concrete. The research demonstrated that the domain of high performance concrete could be successfully modelled using an expert system technology.

ABSTRAK

Satu prototaip sistem pakar, dinamakan *High Performance Concrete Advisor (HPCA)*, telah dibangunkan untuk membantu penghasilan konkrit prestasi tinggi (high performance concrete). Proses pembinaan prototaip HPCA ini adalah menggunakan pendekatan modular, di mana ia meliputi kaedah campuran rekabentuk, campuran pengubahsuaian keupayaan dan seterusnya memberikan cadangan untuk pelbagai aspek ketahanan konkrit prestasi tinggi. Proses ini terdiri daripada kelompok percubaan pertama, kelompok percubaan untuk makmal, kelompok kandungan, campuran pengubahsuaian keupayaan dan anggaran kos untuk campuran yang telah dipilih. Modul ketahanan ini termasuklah pengaratan, aktiviti tindakbalas aggregat-alkali, serangan sulfat, pendedahan kepada air laut, serangan asid, karbonasi dan aspek pencairan. Satu kelompok sistem pakar iaitu Kappa-PC menjadi pilihan sebagai alat pembinaan untuk membangunkan protaip. Ini disebabkan ia menggunakan pendekatan orientasi-objek yang membolehkan penyampaian pengetahuan melalui teknik-teknik kacukan/hybrid seperti penghasilan peraturan dan objek. Ia juga dapat memberikan kelebihan bagi memudahkan manipulasi, meningkatkan produktiviti dan kebolehan sebenar tetingkap untuk menjalankan proses komputer peribadi. Isu utama di dalam pembangunan sistem pakar ini adalah proses memperolehi pengetahuan dan pembinaan prototaip tersebut. Langkah penting yang terlibat adalah definasi masalah, pelaksanaan dan ujian. Pengetahuan yang digunakan dalam sistem ini diperoleh daripada banyak sumber seperti buku teks, manual dan panduan, jurnal, laporan dan kepakaran dalam bidang tersebut. Di dalam proses perundingan HPCA, pengguna dapat merekabentuk dan melaraskan campuran-campuran konkrit prestasi tinggi untuk disesuaikan dengan pelbagai keperluan keupayaan menggunakan bahan-bahan tempatan. Ringkasan cadangan kepada sistem ini dan maklumat tambahan pada setiap aspek modul ketahanan diberikan di setiap peringkat proses perundingan. Beberapa kajian kes telah dijalankan untuk menilai sistem ini. Di dalam kajian kes ini, pencapaian keseluruhan sistem HPCA adalah memuaskan dari segi skop kerja yang telah dirancangkan dan kesesuaiannya kepada pengguna. Pengguna utama HPCA adalah dijangkakan jurutera perunding, jurutera pembinaan, pengurus pembinaan dan pembuat keputusan, di mana mereka dijangkakan menggunakan sistem ini dalam membantu proses untuk membuat keputusan. Sistem ini boleh digunakan dalam pengajaran kepada pelajar dan kepada pengamal (practitioner) yang kurang berpengalaman dalam membiasakan diri dengan campuran rekabentuk dan aspek ketahanan konkrit prestasi tinggi. Penyelidikan ini membuktikan yang bidang konkrit prestasi tinggi dapat dijadikan contoh sepenuhnya dengan menggunakan sistem pakar.

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LIST OF SYMBOLS

B	mass of binder in kilogram per cubic metre
cm/s	centimetre per second
d	superplasticizer dosage as a percentage of the mass of solids in comparison to the total mass of cementitious materials
f_c'	compressive strength of concrete cylinder; also specified or design concrete strength
f_{cr}'	average required concrete strength
G_c	specific gravity of cement or cementitious materials
GPa	gigapascal
G_{SSD}	aggregate specific gravity in saturated and surface dry condition
G_{sup}	specific gravity of liquid superplasticizer
kg	kilogram
l/m^3	litre per cubic metre
m	metre
mm	millimetre
MPa	megapascal (= N/mm^2)
M_{sol}	mass of solids in superplasticizer
ppm	parts per million
psi	pound per square inch
s	total solid content of superplasticizer in percent
V_{liq}	volume of liquid superplasticizer
V_{sol}	volume of solids in superplasticizer
V_w	volume of water in liquid superplasticizer
W	mass of water in kilogram per cubic metre of concrete
w_{abs}	absorbed water in aggregate in percent

w_h	moisture content of aggregate in percent ($w_h = w_{tot} - w_{abs}$)
w_{tot}	total water content of aggregate in percent
^0C	degree Celsius
σ	standard deviation
μm	micrometre
%	percent

LIST OF ABBREVIATIONS

AAR	Alkali-aggregate reaction
AASHTO	American Association of State Highway and Transportation Officials
ACI	American Concrete Institute
ASTM	American Society for Testing and Materials
FA	Fly ash
GGBS	Ground granulated blast furnace slag
HPC	High performance concrete
HPCA	High Performance Concrete Advisor
KLCC	Kuala Lumpur City Centre
MSA	Maximum size of aggregate
RHA	Rice husk ash
RILEM	International Union of Testing and Research Laboratories for Materials and Structures
SF	Silica fume
SFFA	Silica fume-fly ash
SHRP	Strategic Highway Research Program
SSD	Saturated and surface dry
W/B	Water-binder ratio

CHAPTER I

INTRODUCTION

1.1 BACKGROUND

The history of concrete goes back to ancient times (Davidovits 1987). Today, concrete is the most commonly used construction material. It is used in almost every construction project, from highways, bridges, buildings, and dams to floors, sidewalks, and even works of art (Bai 1992). The use of concrete is unlimited and is not even earthbound, as indicated by recent interest by the National Aeronautics and Space Administration in concrete lunar structures (Kosmatka & Panarese 1990). Concrete, good, bad, or indifferent, has been the leading construction material for nearly a century (Neville & Aitcin 1998). There is no economically viable competitor in sight. It is also expected that good concrete will serve the world for a long time to come.

The term high performance concrete (HPC) was first used by Mehta and Aitcin (1990) for concrete mixtures possessing three characteristics, namely high workability, high strength, and high durability (Mehta 1999). Thus, a primary distinction between high strength concrete and high performance concrete was the mandatory requirement of high durability in the case of HPC. As high durability under severe environmental conditions cannot be achieved unless a structure remains free from cracks during its service life, the concrete mixture ought to be designed for high dimensional stability.

The making of high performance concrete is affected by many factors e.g., selection of ingredients, mix design, mixing, placing and curing practices and so on.

Among these, concrete mix design considering strength, workability and durability aspects is the first step in making high performance concrete. Concrete mix proportions for high performance concrete have varied widely depending upon many factors. The strength level required, test age, material characteristics, and type of application have influenced mix proportions. In addition, economics, structural requirements, manufacturing practicality, anticipated curing environment, and even the times of year have affected the selection of mix proportions (ACI Committee 363 1995). High performance concrete mix design is a more critical process than the design of normal strength concrete mixtures. Usually, especially selected pozzolanic and chemical admixtures are employed, and the attainment of a low water-cementitious ratio is considered essential. Many trial batches are often required to generate the data that enables the researcher to identify optimum mix proportions (ACI Committee 363 1995).

Since many factors affect concrete mix design, it is almost impossible to make the design right the first time (Bai 1992). Adjustment is always performed based on the results of concrete quality control tests. Concrete mix design and adjustment made to the mix design are complicated issues and the correct ways to perform this can be achieved with expert advice and experience. However, the scarcity of human expertise to design an appropriate high performance concrete mix is a rather pressing issue in most construction companies. Experts are not always available, nor do they always have the time to consult all possible references, review available data, etc. In some companies, they do not have personnel with the experience to make the necessary decisions regarding high performance concrete mix design and the necessary adjustments. Construction managers who are not familiar with the domain may require the assistance of a support tool that could provide solutions to these technical problems. Expert systems have the potential to capture the expertise, and their widespread use may be of far greater importance in mix design of high performance concrete as compared to the other fields of concrete technology. Therefore, development of an expert system for mix design including durability aspects in order to assist the user in the making of high performance concrete would be a valuable tool.

1.2 EXPERT SYSTEMS

An expert system is a sophisticated computer program that manipulates knowledge, facts, and reasoning in an attempt to solve problems efficiently and effectively in a narrow problem area that would normally require the services of expensive human experts (Basri 1999). Like human experts, these systems use symbolic logic and heuristics to find solutions. Expert systems make mistakes but they have the capacity to learn from their errors. This artificial expertise has some advantages over human expertise in that it is permanent, consistent, easy to transfer, and often cheaper. By linking the power of computers to the richness of human experience, expert systems enhance the value of expert knowledge by making it readily and widely accessible.

Expert system technology is a branch of artificial intelligence research that has many potential usages in civil engineering design (Firebaugh 1988). It has the potential to program applications that use reasoning and the conceptual aspects of engineering design process, whereby the engineer often faces situations with too much information for effective comprehension and judgment. In addition, expert systems preserve and disseminate knowledge efficiently at reasonable costs. This function is particularly crucial in high performance concrete where mix design practices are generally complicated, often inappropriate, inaccurate and economically unacceptable. These undesirable scenarios are further compounded by lack of technical expertise for the successful mix design and construction of high performance concrete structures, and secondly, authorities tend to follow sophisticated mix design specifications and formula from developed countries when it is unnecessary or inappropriate for the local materials and environment in consideration.

Research and development into the application of expert system technology in high performance concrete should help to alleviate this problem, and hence, could offer an appropriate solution to one of the major problems faced by construction industries. Although mix design is considered as a simple process, it is actually a combination of adjustments of various conflicting issues such as strength, workability and durability. The selection of mix proportion for high performance concrete is a difficult problem because the relationship between strength and water-binder ratio which is the backbone of mix proportion methods for ordinary concrete is not sufficient to meet all the requirements of high performance concrete (Mehta & Aitcin 1990). It is a combination of various distinct tasks in vastly diverse subject areas especially for high performance concrete. Due to its multidisciplinary nature that involves specialized expertise in various fields such as engineering, chemistry, mathematics, statistics, geology and economics, the application of knowledge-based expert systems is very appropriate.

1.3 RESEARCH OBJECTIVES

The objective of the research was to develop an expert system for making high performance concrete with particular emphasis on its strength, workability and durability. More specifically, the aims of the research were:

- to review literature on expert systems technology and high performance concrete mix design, with particular emphasis on strength, workability and durability;
- to acquire expertise for the knowledge base using suitable techniques from various textual sources, human experts and field observations;
- to build a prototype based on appropriate prototyping methodology and hybrid knowledge representation technique by using the object oriented Kappa-PC expert system shell (Version 2.4);
- to produce a working prototype that consisted of several modules; and
- to evaluate the expert system's capability for solving mix design problems and to give recommendations on mix performance adjustment and various durability aspects related to high performance concrete.

The proposed end-users of the program were consulting engineers, construction engineers, construction managers, construction coordinators, decision makers and civil engineering students. Its main aim was to design the first trial mix, to adjust the mix for field conditions of aggregates, to obtain batch composition and to give recommendations on mix performance adjustment and durability aspects of high performance concrete.

1.4 SCOPE OF RESEARCH

In this study, the main concern was to establish a working prototype for designing high performance concrete mix that concentrated on strength, workability and durability aspects. Various tasks were considered which were divided into several modules for simplicity and ease of knowledge organization. The major issues of concern regarding the research were the knowledge acquisition process and the development of the prototype. The knowledge acquisition process was considered to be the most difficult and time-consuming part of the system development. It is widely acknowledged by artificial intelligence researchers that this is the single most critical obstacle to the development of effective expert systems. The major steps involved included extraction of expertise, its articulation into a format that could be easily understood and programming into computer code. It was a continuous process that began at task analysis and extended to the final stages of the prototype development. The knowledge incorporated into the expert system was taken from technical literature (ACI Manual, ASTM Standards, Journals, textbooks etc.), interviews and field observation. All the interviews were conducted on an informal basis and the conversations were not taped. The experts were chosen because of their knowledge and their experience with the making of high performance concrete.

Another important issue was the prototype development process that utilized Kappa-PC expert system shell (IntelliCorp 1997) as the building-tool. An expert system shell was preferred in the development over other types of building tools since it offered the advantage of ease of manipulation, increased productivity and a true windowing capability to run on personal computers. Firebaugh (1988) suggested for a system developer who is relatively new to the artificial intelligent field and has time limitations, most commercial shells could adequately cater for the needs of the chosen domain. Kappa-PC is a rule and frame based expert system shell. Kappa-PC is able to run on Microsoft Windows, has the advantage of using the application of graphic packages, popular data files and conventional programming language to interface with the user.

The important characteristic of an expert system is that it should have a clearly defined scope. To develop an expert system for making high performance concrete in the present research, it was limited only to the mix design of first trial batch and its adjustment, computation of batch composition for a project, conversion from field composition to SSD (saturated and surface dry) composition and vice versa, cost estimation, and giving recommendations on mix performance adjustment and various durability aspects.

CHAPTER II

HIGH PERFORMANCE CONCRETE TECHNOLOGY

2.1 INTRODUCTION

High performance concrete (HPC) is relatively a new development in building materials technology. It is the latest phrase that comes after high strength concrete and has come more and more into popular use. Many researches have been conducted and the development is still going on. It is hoped that high performance concrete will clarify more of its phases in future. This chapter describes definition, historical perspective and approaches to obtain high performance concrete. This chapter also includes exceptional water-binder ratio, ingredients, production, properties and advantages of high performance concrete.

2.2 DEFINITION OF HIGH PERFORMANCE CONCRETE

High performance concrete is one meeting special combinations of performance and uniformity requirements that cannot always be achieved routinely using conventional constituents and normal mixing, placing and curing practices (Russell 1999). It is a concrete in which certain characteristics are developed for a particular application and environment. Examples of characteristics that may be considered critical for an application are: ease of placement; compaction without segregation; early age strength; long-term mechanical properties; permeability; density; heat of hydration; toughness; volume stability and long-life in severe environments. Because many characteristics of high performance concrete are interrelated, a change in one usually results in changes in one or more of the other characteristics. Consequently, if several characteristics have to be taken into account in producing a concrete for the intended application, each of these characteristics must be clearly specified (Russell 1999).

High performance concrete is a concrete with properties that satisfies the performance criteria usually in terms of workability, strength and durability. Generally, a concrete with higher strength exhibits superiority of other attributes. Hence high strength concrete could be considered as high performance concrete if other attributes are satisfactory in terms of its intended application (Chen & Hon Song 1997). Three influences must be considered to define high performance concrete: the structure in which the concrete will be used including support, the environment in which the structure will be placed and the type and number of loads to which the structure will be subjected.

Other factors should also be considered. Firstly, the concrete must be workable, pumpable and easily compactable within the confines of any formwork or reinforcement. Secondly, the plasticity of concrete should be maintained for the time period necessary to transport, place and consolidate the concrete. Thirdly, good practice must be followed during construction. Fourthly, the interaction of concrete at an early age with the environment and loads must be considered. Thus, "High performance concrete is a concrete made with appropriate materials combined according to a selected mix design and properly mixed, transported, placed, consolidated and cured so that the resulting concrete gives excellent performance in the structure in which it will be placed, in the environment to which it will be exposed and with the loads to which it will be subjected for its design life" (Forster 1994).

Swamy (1997) has defined high performance concrete as "A high performance concrete element is that which is designed to give optimized performance characteristics for a given set of load, usage and exposure conditions consistent with the requirements of cost, service life and durability". Moreover, the dedicated researchers at the Strategic Highway Research Program (SHRP) defined high performance concrete meeting one of the following requirements (Zia et al. 1991):

- 4-hour compressive strength > 20 MPa (3000 psi)
- 24-hour compressive strength > 33.5 MPa (5000 psi)
- 28-day compressive strength > 67 MPa (10 000 psi)
- Water-binder ratio < 0.35.

In addition, the concrete must have a durability factor greater than 80 after 300 cycles of freezing and thawing to meet the definition of high performance concrete (Helland 1993).

The above definitions are not the final ones, because there are still possible areas for improvement in those definitions. However, by most definitions, the concrete should be capable of being produced from readily available materials of high quality using conventional mixing, transporting and placing techniques (Domone & Soutsos 1994). It is hoped that in future there will be a universally accepted and established definition of high performance concrete.

2.3 HISTORICAL PERSPECTIVE OF HIGH PERFORMANCE CONCRETE

High performance concrete is the latest catch phrase in concrete technology. Over the last two decades this type of concrete has come more and more into popular use. Now it seems to be in universal agreement that the production and use of high performance concrete is a worthy goal (Safiuddin 1998).

In 1988, 120 MPa concrete was used in Seattle, USA, to construct the columns for a 52-storey building at Two Union Square. In the same year, 100 MPa concrete went into the columns of the world's tallest concrete building (Aitcin 1995). An experimental column was poured in the La Laurentienne building, Montreal, with 90 MPa concrete in 1984 (Aitcin et al. 1987; Russell 1987). Toronto's Scotia Plaza contains concrete averaging 93 MPa that was completed in 1987 (Ryell & Bickley 1987). The Hibernia offshore platform constructed in Newfoundland, Canada, has incorporated high performance concrete for strength and durability (Aitcin 1995).

High performance concrete was developed for the construction of large offshore platforms and bridges, but very rarely for the construction of high-rise buildings in Europe (Aitcin 1997a). High performance concrete was first used to build huge offshore structures in Norway. It has been used in Norway in constructing enormous drilling platforms for oil and natural gas exploration in the North Sea (NC News 1984). When the technology of high performance concrete was developed, European engineers started to use it, particularly in France for the construction of other structures such as bridges. It is very recently that high performance concrete has been used for high-rise buildings. It is also used in Norway in highway pavement construction for its super-resistance to abrasion (Helland 1990).

In Norway, the concrete industry has acted as a locomotive for the development of high performance concrete for 20 years. There, the research and development of high performance concrete have gone through basically three different phases. The first phase started when silica fume became readily available in the late 1970s and lasted to the mid 1980s. This phase was characterized by pilot tests, basic researches on low water-binder ratio and the construction of a number of full-scale test structures. At the same time, attention was drawn to durability, particularly for marine and highway construction. Therefore, for aggressive environment the limit of water-binder ratio became 0.45. For bridges and highway structures the requirement was further reduced to 0.40. In the second phase, the general building industry was faced with problems in coping with the new material. While introducing the new technology concerning high performance concrete, problems were observed in the field that hardly could have been foreseen in the laboratory or detected during the relatively few numbers of previous full-scale constructions. Both clients and contractors have gained considerable practical and valuable experience through this phase. This phase is often called "the hard way" (Helland 1993). The third phase claims the process of evaluating the experience by investigating the field performance of the first generation structures built a decade ago.

In France, laboratories did much effort for mastering the characteristics and behaviour of high performance concrete. Many researches were conducted in the Laboratorie Central de Recherche (Levy & Boulicaut 1992). Moreover, the Institute of

Reinforced and Prestressed Concrete (IBAP) at the Ecole Polytechnique Federale in Lausanne undertook several research activities concerning the serviceability of concrete structures, particularly in the realm of deformations during the past two decades. This has resulted in advances in the scientific and technological fields of high performance concrete (Farve et al. 1992).

Japan was not far away in the contribution to the development of high performance concrete. The researchers in Japan have developed the super-workable concrete. The research team from the concrete laboratory of the University of Tokyo produced the original idea of the super-workable concrete. In order to improve the reliability of the modern concrete construction, it is necessary to develop a concrete that is not much affected by workmanship during placing or a self-compactable concrete that requires no consolidation. Based on the prototype of self-compacting concrete, "Biocrete 21" has been developed as an example of the super-workable concrete in Taisei Corporation utilizing a new viscosity agent produced by Takeda Chemical Industries (Hayakawa et al. 1994). Southeast Asian countries are also using high strength high performance concrete. For Kuala Lumpur City Centre (KLCC) in Malaysia, 80 MPa concrete was used. For Bioyette Tower of Bangkok, 80 MPa concrete was used to reduce the cost and to ease the construction (Papworth & Ratcliffe 1994). In these two cases, only the high strength issue was considered perfectly.

The development concerning high performance concrete is still going on day by day. Researchers and concrete producers are trying to make the production and placing of high performance concrete easier by studying how to optimise the qualities of its constituents. This great effort is forging ahead to create the next generation of high performance concrete that could cross 150 MPa of compressive strength quite easily (Safiuddin 1998).

2.4 APPROACHES TO OBTAIN HIGH PERFORMANCE CONCRETE

Two approaches are already established as ways to obtain high performance concrete. They differ in their physical and chemical nature as discussed below (Malier 1992):

(a) Deflocculation of cement grains: This is achieved by using organic products such as (i) condensates of formaldehyde and sulphonate melamine, and (ii) condensates of formaldehyde and sulphonate naphthalene. These materials are termed as "high range water reducers" or "superplasticizers". This is the process by which the cement grains in suspension in water can recover their initial grain size. This first approach leads to an appreciable reduction in the quantity of necessary water, since much of this mixing water is no longer trapped in the cement grains flakes. The deflocculation of cement grains due to the addition of superplasticizer is obvious in Figure 2.1. The figure shows that cement grains are more dispersed and deflocculated due to the addition of superplasticizer.

(b) Widening the range of grain size: This approach is achieved by using extremely fine chemically reactive materials such as silica fume, calcareous fillers etc. These fines fill the micro-voids in grain packing, thus improving the compactness of the material and at the same time improving the rheological properties of the fresh mix. It follows that the quantity of water necessary for placing the concrete can be further reduced.

The first approach can be used alone and leads to interesting gains in engineering properties, workability and durability. Obviously, the second approach implies simultaneous recourse to the first, since it is naturally useless to complete the grain size range of the granular material towards very fine elements if priority has not been given to reducing flocculation (Malier 1992).

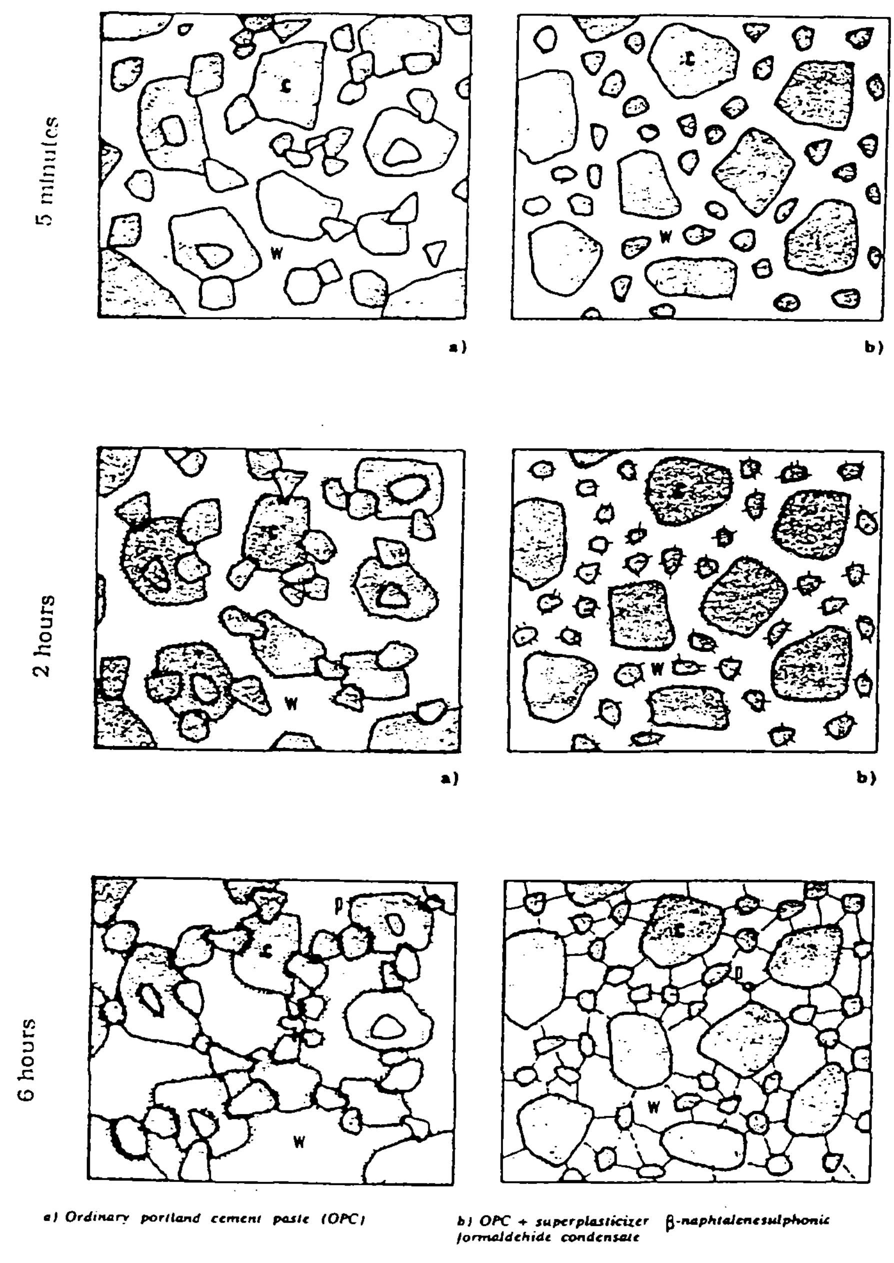


FIGURE 2.1 Deflocculation of cement grains by a superplasticizer

Source: Uchikawa 1986

2.5 EXCEPTIONAL WATER-BINDER RATIO OF HIGH PERFORMANCE CONCRETE

It was impossible to reduce the water-binder ratio of concrete below 0.40 for many years. But during the last two decades, it was realized that the strong deflocculating properties of superplasticizer could be advantageously used to lower drastically the water-binder ratio of concrete. This synthetic polymer is so efficient in deflocculation of cement or binder grains that it is now possible to make flowing concrete having a water-binder ratio as low as 0.25, and in some cases, even as low as 0.20. This technological breakthrough has resulted in the development of a new family of high strength concrete, which is now increasingly referred to as high performance concrete (Aitcin 1993).

Water-binder ratio is very important for workability of fresh concrete and also for strength of hardened concrete. In case of ordinary concrete, water-binder ratio varies from 0.50 to 0.75, but for high performance concrete it ranges from 0.20 to 0.40 and rarely 0.50 (Aitcin 1997a). This reduction in water-binder ratio is not only obtained by increase in the amount of binder, but also by simultaneous decrease in the amount of mixing water by using superplasticizer. The limits of water-binder ratio to achieve targeted compressive strength are shown in Figure 2.2.

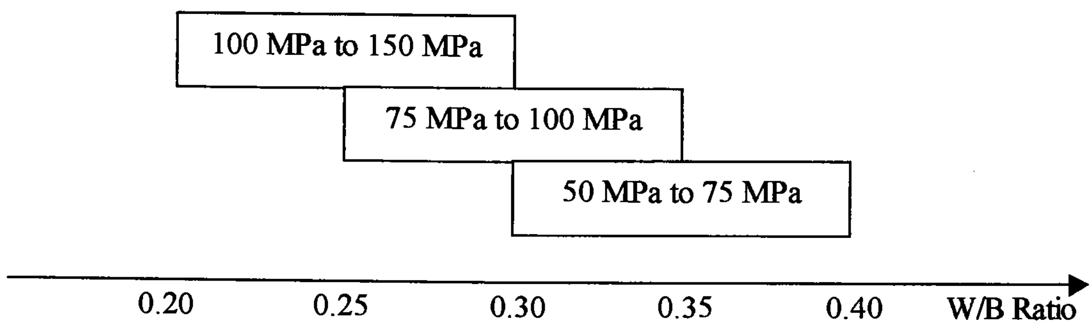


FIGURE 2.2 Range of water-binder ratio necessary to get required compressive strength

Source: Lessard et al. 1995

Exceptional concretes of compressive strength of 300 MPa with water-binder ratio close to 0.16 are currently obtained in the laboratories (Pliskin 1992). But still they are laboratory concretes; their application has not been started yet in practical works.

2.6 INGREDIENTS OF HIGH PERFORMANCE CONCRETE

High performance concrete includes all the ingredients that ordinary concrete contains. The significant difference is the use of two new concrete ingredients: superplasticizer and silica fume. Superplasticizer results in a drastic decrease of the amount of water required getting concrete of a desirable workability (Aitcin et al. 1994). It is possible to obtain self-compacting flowing concrete by using superplasticizer. The second ingredient that offers facilities for the production of high performance concrete is obviously silica fume (Khayat & Aitcin 1992). For higher strength, it is necessary to use silica fume. Moreover, it allows easier rheological control.

High performance concrete may also contain other cementitious materials such as fly ash, ground granulated blast-furnace slag (GGBS), rice husk ash (RHA) or metakaolin as a partial replacement of cement or an addition to cement. Besides, from durability point of view, high performance concrete may have air-entraining agent as one of the ingredients. This agent also helps to maintain workability. Viscosity agent and segregation inhibiting agent may also be used as ingredients of high performance concrete (Sirivivatnanon 1997). Thus, high performance concrete contains both primary and secondary ingredients. The primary ingredients are: (1) coarse aggregate, (2) fine aggregate, (3) cement, (4) water, (5) silica fume, and (6) superplasticizer. The secondary ingredients include: (1) supplementary cementitious materials, (2) air-entraining agent, (3) viscosity improving agent and (4) segregation inhibiting agent.

The production of high performance concrete that consistently meets requirements for workability and strength development places more stringent requirements on material selection than for lower strength concrete. Quality materials are needed and specifications require more enforcement. High performance concrete has been produced using a wide range of quality materials based on the results of trial mixes. Previous selection of materials to produce high performance concrete can be considered critical if success is desired. Therefore, correct and appropriate selection of materials based on the results of trial mixes is necessary. The following sections describe, in brief, component materials to be used in producing high performance concrete.

2.6.1 Aggregates

Aggregates give body to concrete, reduce shrinkage and affect economy. The mere fact is that aggregates occupy 65 to 75% of the volume of concrete. So, special consideration should be paid both for coarse and fine aggregates in producing high performance concrete.

Coarse Aggregate: Coarse aggregates largely influence the strength of hardened concrete, as they comprise the largest segment of all constituents. Hard aggregate should be used for high performance concrete so that the aggregate would contribute at least the strength of the cement gel. The aggregate size should be decreased to achieve higher strength. This is because the size reduction process often eliminates internal defects in aggregate such as large pores, micro-cracks and inclusions consisting of soft minerals.

Experience shows that it is difficult to produce high performance concrete mixes using coarse aggregate larger than 25 mm size. With most natural aggregates it seems that, for making high performance concrete, 10 mm or 12 mm size aggregate is probably the optimum maximum size aggregate. This does not mean that aggregates of 19 mm maximum size cannot be used. When the aggregate is sufficiently strong and homogeneous, 19 mm or 25 mm maximum size aggregates can be used without adversely affecting the workability and strength of concrete (Mehta & Aitcin 1990).

Besides, coarse aggregates should have a low absorption value, a good shape coefficient and a gradation that is allowed. Low coefficient of absorption equal to or less than 1% and a shape coefficient around or above 0.25 are required to improve the consistency of the mix. To improve strength, aggregate should comply with a Los Angeles coefficient equal to or less than 15 and a crushing index equal to or less than 13 (Gutiérrez & Cánovas 1996). Moreover, it should be sound, rough textured and free from deleterious substances. Usually high performance concrete has been produced using normal weight aggregates. Among normal weight coarse aggregates, generally crushed rock and gravel are being used in practice.

Fine Aggregate: Fine aggregates with a rounded particle shape and smooth texture have been found to require less mixing water in concrete and are preferable in high performance concrete. A fineness modulus in the range of 2.5 to 3.2 is recommended for high strength high performance concrete to facilitate workability. Lower values result in decreased workability and a higher water demand (Nawy 1996). Sand with fineness modulus of about 3.0 gives the best workability and compressive strength (ACI Committee 363 1995). Fine aggregates in flowable high performance concrete should be increased to improve the cohesiveness of very fluid mix and coarse aggregates should be reduced slightly (Dodson 1990). Besides, fine aggregates to be used should be sound, low absorbent, damp free and free from deleterious materials. Normal weight natural river sand or mine sand can be used in most cases to produce high performance concrete.

2.6.2 Cement

The choice of Portland cement for high performance concrete is extremely important. It is highly durable and produces high compressive strength in mortar and concrete. Its specific gravity ranges from 3.12 to 3.16 and it weighs 1208 kg/m^3 (94 lb/ft^3). Its fineness measured by particle size ranges from 10 μm to 50 μm (Nawy 1996).

Commercial cements meeting the ASTM Standard Specification C-150 for Type-I Portland cement (ASTM C-150 1992) vary considerably in chemical composition and fineness. This variation influences the water requirement for normal consistency. As the effect of cement characteristics on water demand is more noticeable in high performance concrete because of its higher cement content, the uniformity of cement should be maintained throughout the work. If tricalcium silicate (C_3S) content varies by more than 4%, ignition loss by more than 0.5% or fineness by more than 375 cm^2/g (Blaine), then problems in maintaining a uniform high strength may result. Sulfate levels should also be maintained at optimum with variations limited to ±0.2% (ACI Committee 363 1995). A further consideration is the optimization of the cement-admixture system. The exact effect of a water reducing agent on water requirement depends on the cement characteristics. Therefore cement-superplasticizer compatibility should be desired.

The performance of concrete is also a function of cement content. Common cement content in high performance concrete ranges from 392 to 557 kg/m^3 (ACI Committee 363 1995). However, it is advisable to use cement content below 500 kg/m^3 (Gutiérrez & Cánovas 1996). Because higher cement content causes increased shrinkage and cost.

2.6.3 Water

Water is essential in the production of concrete to initiate chemical reaction with cement, to wet aggregate and to lubricate the mixture for easy workability. Normally, drinking water is used in mixing. Water having harmful ingredients, contamination, silt, oil, sugar or chemicals is destructive to the strength and setting properties of cement. It can disrupt the affinity between the aggregate and the cement paste and can adversely affect the workability of a mix (Nawy 1996).

Water for high performance concrete usually comes from three sources: added water, moisture present in aggregates and moisture present in liquid superplasticizer. The added water is generally required to comply with the standard set forth by British Standard Institution (BS 3148 1980). According to this standard, added water should preferably be potable or clean, fresh and free of obvious contaminants. If mortar cubes made with the water in question are at least equal to 90% of the compressive strength of the specimens made with distilled water, the water then can be considered acceptable to ASTM C 94 (ACI Committee 363 1995). Some specifications also accept water for making concrete if the pH value of water lies between 6 and 8 and the water is free from organic materials (Shetty 1993). Water containing less than 2000 ppm (parts per million) of dissolved solids generally can be used for making concrete. Although concentrations exceeding 2000 ppm (parts per million) are not always harmful, they can affect certain cements adversely (White 1977).

2.6.4 Silica Fume

Silica fume is the by-product of the manufacture of elemental silicon and ferrosilicon alloys. Because of its extreme fineness and high glassy SiO_2 content, it is a highly reactive pozzolanic material (Dodson 1990). The size of silica fume particles as a measure of its fineness is 0.1 μm.

Silica fume seems to attain high early age strength in 3 to 7 days with relatively less increase in strength at 28 days. The addition of silica fume to concrete mixture can produce significantly increased strength, increased modulus of elasticity and increased flexural strength. The proportion of silica fume in concrete mixes varies from 5 to 30% by weight of cement depending on the strength and workability requirements. However, water demand is greatly increased with increasing proportion of silica fume (Nawy 1996). The optimum silica fume content for obtaining high strength is consequently around 20 to 25% of weight of binder. However, considering the cost of silica fume and of other admixtures, the practical and economic optimum content is located rather towards 10% silica fume in relation to cement weight (de Larrard 1992).

2.6.5 High Range Water Reducers or Superplasticizers

This type of admixture provides a far greater degree of water reduction in concrete through dispersion without causing excessive retardation of time of setting and without entraining large amounts of air (Dodson 1990). These admixtures can reduce the quantity of mixing water required to produce concrete of a given consistency by 12 to 25% (ACI Committee 363 1995). Superplasticizers exert their action by decreasing the surface tension of water and by equidirectional charging of cement particles. This property, coupled with the addition of silica fume, helps concrete to achieve high strength and water reduction without loss of workability (Nawy 1996).

Superplasticizers can change zero-slump concrete to concrete with a slump of almost 200 mm, but matching this admixture to the cement both in type and dosage often seems problematic. The slump loss characteristics of superplasticizer determine whether it should be added at the plant, at the site or following the combination of each. Experience shows that high performance concrete of 200 mm slump can be obtained using superplasticizer with a solid content dosage between 0.75% and 1.50% by weight of total binder (Aitcin 1992).

2.6.6 Fly Ash

Fly ash is the finely divided residue that results from the combustion of ground or powdered coal (Dodson 1990). It is composed of siliceous and aluminous ingredients and possesses limited cementitious properties unless so finely divided that its fineness is at least equal to or less than the fineness of the cement with which it is mixed. In the presence of water in mix, it reacts with calcium hydroxide at ordinary temperature and thereby forms compounds that have high cementitious qualities (Nawy 1996).

Fly ash for high performance concrete is divided into two classes: Class-F and Class-C. Class-F fly ash is normally produced from burning of anthracite or bituminous coal and has pozzolanic properties but little or no cementitious properties. Class-C fly ash is normally produced from burning of lignite or sub-bituminous coal and has some autogeneous cementitious properties (ACI Committee 363 1995). However, most fly ashes that are being used in concrete production are Class-F. The use of fly ash in concrete influences compressive strength, workability, heat of hydration, sulfate resistance, permeability and alkali-silica reaction of concrete (Ellis 1992).

The replacement of cement by fly ash in producing concrete is possible up to 50%. However, many concretes containing Class-C fly ash in the range of 20 to 40% of the total cementitious material show equivalent or higher strength than concretes containing Portland cement only (Ellis 1992). The replacement between 30 and 50% by weight of cement gives better result.

2.6.7 Ground Granulated Blast-Furnace Slag

Ground granulated blast furnace slag (GGBS) is a waste product in the manufacture of pig iron, about 300 kg of slag being produced for each tonne of pig iron (Neville 1995). When this slag is rapidly quenched and ground, it will possess latent cementitious properties. After processing, the material is known as GGBS whose hydraulic properties may vary and can be separated into grades noted in ASTM C 989 (ACI Committee 211 1991). Slag can be interground with cement or used as additional cement at the batching facility (ACI Committee 363 1995). Fineness of GGBS is usually greater than 350 m^2/kg and occasionally in excess of 500 m^2/kg. Specific gravity is 2.9 (Neville 1995).

The possible beneficial effects of incorporating GGBS in the mix are (Neville 1995): improved workability; lower peak temperature; denser microstructure; reduced water permeability (about 100 times lower); reduced chloride ion diffusivity (about 10 times lower); reduced risk of alkali-silica reaction and sulfate attack; and improved long-term strength and durability performance.

Slag modifies the flocculation of cement, with a resulting reduction in the water demand. It reduces bleeding but leads to retardation at normal temperature, typically 30-60 minutes. The reactivity of GGBS at higher temperature is considerably increased. Steam curing of concrete containing GGBS can, therefore, be used. Prolonged moist curing of concrete containing GGBS is particularly important. Very good development of strength of concretes containing 50-75% of GGBS, with a total content of cementitious material between 300-420 kg/m^3 (300-500 lb/yd^3) has been reported (Neville 1995).

2.6.8 Rice Husk Ash

Rice husks are by product of the rice paddy milling industry, and the husks make up about one fifth of the weight of the dried rice paddy. The current yearly world production of rice paddy is approximately 500 million tonnes, thus about 100 million tonnes of rice husks are available for disposal. It is recognised that about 90% of the total rice paddy is produced in the Asian region and the potential of using this material in concrete in this region is enormous. On the average, each tonne of rice husks, on completion of combustion, produces 200 kg of ash. As ash produced by uncontrolled combustion is generally crystalline and of low pozzolanic value, controlled incineration at about 500 to 700 ^{0}C is needed to make the ash highly pozzolanic. Chemical analyses of the ashes produced by the incineration of rice husks show that the silica content ranges from 90-95% (Mahmud 1997). Rice husks have very high silica content, and slow firing at a temperature of 500 to 700 ^{0}C results in an amorphous material with a porous structure. Thus the specific surface (measured by nitrogen adsorption) can be as high as 50 000 m^2/kg, even though the particle size is large: 10 to 75 μm (Neville 1995).

The rice husk ash (RHA) particles have complex shapes, reflecting their plant origins and they, therefore, have a high water demand. RHA is reported to contribute to the strength of concrete at 1 to 3 days. However, to achieve adequate workability, as well as high strength, the use of superplasticizers may be necessary. This negates the economic benefits of the use of RHA in less affluent areas of the world where collection of the husks for processing may also present problems. The use of rice husks leads to increased shrinkage. No country has issued a standard for the use of RHA yet (Mahmud 1997).

2.6.9 Air Entraining Admixture

An air-entraining admixture is simply one that is added to Portland cement paste, mortar or concrete for the purpose of entraining air in the respective masses (Dodson 1990). Air entraining admixtures incorporate millions of non-coalescing air bubbles which act as flexible ball bearings and modify the properties of plastic concrete regarding workability, segregation, bleeding and finishing quality of concrete. It also modifies the properties of hardened concrete regarding its resistance to frost action and permeability.

The common air entraining agents are Vinsol resin, Darex, Airalon, Orvus, Teepot, Petrosan and Cheecol. Amongst these, the most important air entraining admixtures, which at one time enjoyed worldwide market, are Vinsol resin and Darex. The dosage of air entraining admixture should not exceed 1 to 2% by weight of binder (Nawy 1996). However, the appropriate percentage should be chosen on the basis of water-binder ratio and the maximum size of aggregate.

2.7 PRODUCTION OF HIGH PERFORMANCE CONCRETE

High performance concrete can be produced using the same equipment as used for ordinary concrete. However, in high performance concrete, the selected materials perform at their critical level and, therefore, a very efficient quality control program has to be maintained. In producing high performance concrete, the first objective is to find out the cement-superplasticizer combination in order to get satisfactory slump control and the possible highest strength (Aitcin 1997a). The use of silica fume is fundamental for obtaining very high strength high performance concrete (Nawy 1996). The choice of supplementary cementitious materials and aggregates are also important as described in the previous sections. The following sections describe the importance of compaction and curing in producing high performance concrete.

2.7.1 Compaction of High Performance Concrete

Compaction of concrete is the process adopted for expelling the entrapped air from concrete (Shetty 1993). The overall economy demands full compaction with reasonable compacting efforts available in the field. In order to achieve full compaction and maximum density, it is necessary to use a mix with adequate workability. How compaction together with water-binder ratio affects the compressive strength of concrete is shown in Figure 2.3.

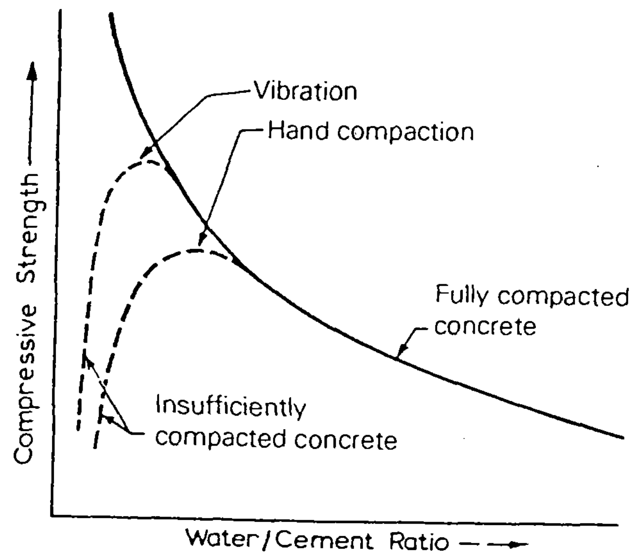


FIGURE 2.3 Effect of different compaction methods and water/cement ratio on the compressive strength of concrete

Source: Juvas 1994

High strength HPC generally exhibits good workability. For HPC having a slump of more than 190 mm, theoretically compaction is not required since it is self-compactable whereas HPC of having slump between 100 mm and 190 mm needs some means of compaction. In the field, vibrator can be used. But it should be kept in mind that excessive vibration can create internal bleeding which results in weak transition zone around coarse aggregates, weak bonding to reinforcing steel and a porous skin at the contact of formwork (Aitcin 1993). HPC has to be vibrated but not too much. It is sufficient only to consolidate it until it is in place. An average slump of 180 mm to 230 mm seems to be a good compromise to get optimum compaction (Aitcin 1997a).

2.7.2 Curing of High Performance Concrete

The quality of concrete improves with efficient uninterrupted curing. If curing is neglected in the early period of hydration, the quality of concrete will experience a sort of irreparable loss. It will exhibit visual defects and suspected long-term strength and durability (Mohd. & Diah 1997). An efficient curing in the early period of hydration can be compared with good and wholesome feeding given to a newborn baby.

Large surfaces of HPC will crack very rapidly and deeply if they are not properly cured. As HPC has a low water-binder ratio, it is not prone to bleed and its surface is very sensitive to plastic shrinkage cracking (Aitcin 1993). Therefore, appropriate curing measures must be taken to prevent plastic shrinkage cracking. The curing of HPC has to begin much earlier than the curing of usual concrete, not after 24 hours but rather just after the placing and finishing. If a sufficient amount of water is provided to HPC just after its placing, plastic shrinkage can be completely prevented and autogeneous shrinkage can be reduced drastically, at least in the covercrete which is the most important and sensitive part of concrete elements to ensure good durability (Aitcin 1997a).

As for ordinary concrete, water curing should also be highly recommended for HPC due to its low water-binder ratio employed. At water-binder ratio below 0.4, the ultimate degree of hydration is significantly reduced if free water is not provided. Water curing will allow more efficient, although not complete, hydration of cement. Curing lowers the porosity of the concrete structure, enhance impermeability and thereby durability, lowers water absorption (Gowripalan et al. 1992). So curing must be practiced properly for the sake of any and especially HPC.

2.8 MICROSTRUCTURE OF HIGH PERFORMANCE CONCRETE

From the microstructural standpoint, it is helpful to consider hardened concrete as made up of three phases, namely aggregate, bulk cement paste and the transition zone (Mehta & Aitcin 1990). Microstructural examination of fractured samples of ordinary concrete shows that the hydrated cement paste contains many large pores. During hydration, massive hexagonal lime crystal plates develop quickly within these large pores. Ettringite needles, monosulfonaluminate platelets and fibrous calcium silicate hydrates (C-S-H) are also seen (Aitcin 1997a). In high performance concrete, these hexagonal lime crystals, ettringite needles and fibrous C-S-H crystals are few or do not develop at all. They are eliminated by a more homogeneous dense paste. This is due to the processes of filling in capillary pores or extracting the excess water by pressure or reducing the water-binder ratio with superplasticizer. This fact is illustrated in Figure 2.4 considering two types of concrete.

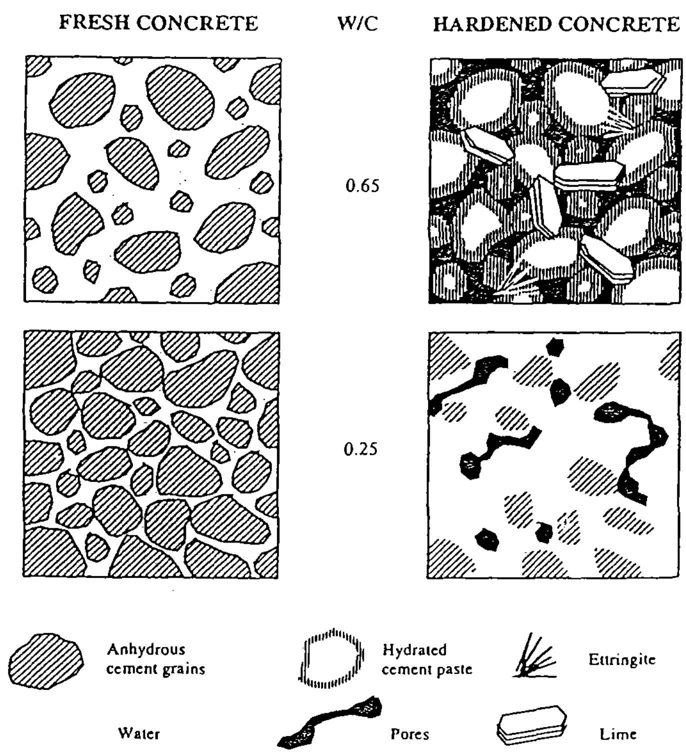


FIGURE 2.4 Schematic representation of the microstructure of two 0.65 and 0.25 W/B ratio fresh and hardened cement pastes

Source: Aitcin 1997a

The aggregate-hydrated cement paste interface in ordinary concrete is better crystallized, more porous and less resistant than the matrix because of excess water (Regourd 1992). Characteristics of this interface correspond to the fracture surface, cracking, composition and texture of hydrates. All these evidently drive the ordinary concrete to be a poor concrete composite. In high performance concrete, a very intimate contact between the aggregate and the hydrated cement paste develops. The hydrated cement paste in the interface has the same texture as in between the aggregates. This results in more compact concrete elements. Figure 2.5 summarizes how high performance concrete achieves rich microstructure.

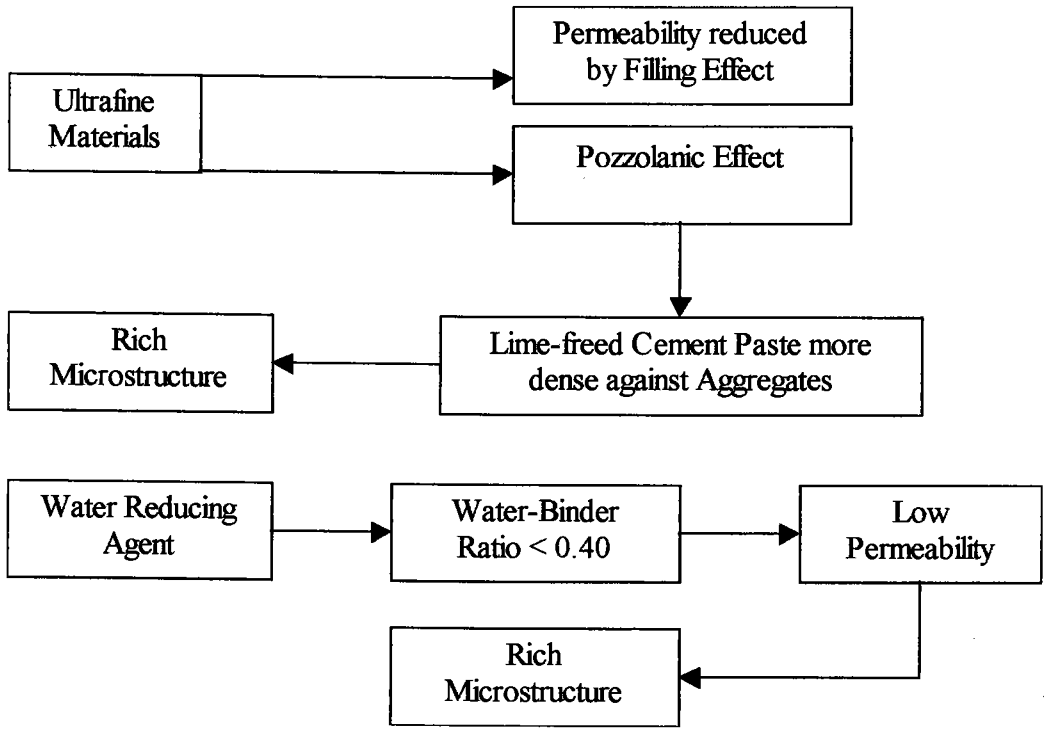


FIGURE 2.5·Development of rich microstructure in high performance concrete

Source: Grandet 1992

The transition zone plays a great role in concrete strength. In high performance concrete, unlike that in ordinary concrete, strength increases drastically as there is no weak transition zone and therefore aggregates can participate actively in the stress transfer (Aitcin & Mehta 1990). In the microstructure of high performance concrete there remains no preferential channels of penetration through which aggressive agents can enter concrete. This is why high performance concrete shows extra-ordinary durability.

The microstructure of high performance concrete clarifies the following facts: formation of a continuous lattice of dense particles; formation of an amorphous and homogeneous matrix; very negligible micro-cracking; least porosity; smaller pore sizes; no weak transition zone and the hydrated cement paste has about the same texture as in between the aggregates; very little free water; low free lime content; a state of self-stresses illustrated macroscopically by the endogenous shrinkage, which leads to a powerful confinement of the aggregates (Safiuddin 1998).

2.9 PROPERTIES OF FRESH HIGH PERFORMANCE CONCRETE

The properties of freshly mixed HPC are affected by mix proportion, aggregate size, type and gradation of aggregates, water content, the presence of cement replacement material, the use of superplasticizer and air entraining agent and obviously mixing procedure, order, time and temperature. The good and adequate properties of fresh concrete undoubtedly help to get hardened concrete of superior quality. Major properties of fresh HPC are described below.

2.9.1 Workability

Slump gives the indication of workability of concrete. Though a slump of 100 mm provides adequate workability, it is no longer realistic since it demands high salaries for construction workers. When the slump of HPC is kept within the 150 mm to 200 mm range, there is almost no risk of segregation, since the mix is quite rich and quite thixotropic. However, it will be quite prudent if a 200 mm slump is specified (Aitcin 1997a). For slump values above 200 mm there is a risk of segregation: the higher the slump, the greater the risk (Aitcin 1993). In such a case colloidal agent can be used to prohibit segregation and to get self-placing concrete mixes of super-slump (i.e., more than 200 mm).

High strength HPC requires a dense, void-free mass with full contact with the steel reinforcement. Slumps have to be compatible with this fundamental need to achieve high performance. To do so, mix proportioning should provide a workable mixture, which is easy to vibrate, and fluid enough to be able to pass through closely placed reinforcing bars. A slump of 100 mm should provide adequate workability although many high strength HPCs with 200 mm to 250 mm slump have been used (Nawy 1996).

Water content is very low in the case of HPC, but the use of high range water reducer or superplasticizer compensates for that and gives the concrete an excellent workability. Besides, addition of some cement replacement materials reduces water demand and offers increased workability (Hobbs 1980). Moreover, incorporation of air entraining agent helps to maintain good workability.

For HPC, the following cases are very important to get required workability: (1) selection of materials, especially aggregates, cement and cement replacement materials; (2) use of superplasticizer; (3) Portland cement reactivity; and (4) cement-superplasticizer compatibility.

According to ASTM standard specification, concrete that is characterized by a slump greater than 190 mm while maintaining a cohesive nature and which otherwise meets the specified requirements is termed as flowing concrete (ASTM C 1017 1992). The flowability of HPC contributes to the fresh concrete itself to be self-levelling and self-compacting, to be spread through thick reinforcement and formwork, to have a high rate of strength gain, to be dense and to have a low permeability and not to suffer from any bleeding (Mcleish 1994). The flowability of HPC can be achieved by using proper mix proportion, aggregates of allowable small maximum size, fitted superplasticizer, some sorts of cement replacement materials such as fly ash, slag etc. and air entraining agent.

Addition of superplasticizer eliminates the shear threshold in the fresh cement paste and leads to the concrete to flow easily and makes the placing and pumping operations much easier (Malier 1992). For the contribution of superplasticizer, in spite of water contents that are much lower than usual, HPCs most often exhibit a slump of approximately 200 mm in the Abram's cone. Moreover, it is possible to have a slump of up to 270 mm, which is the indication of high workability and flowability of HPC.

2.9.2 Air Content

The recommended air content in a given concrete is a function of the purpose for which the concrete is going to be used and its location and climatic condition, the maximum size of aggregate and the richness of the mix. For HPCs, which are to be used in non-freezing environment like that of Malaysia, theoretically there is no need for entrained air. However, in order to improve handling, placeability and finishability of concrete, it is strongly suggested to use a few amount of entrained air (about 1.5 to 2%) in fresh concrete (Aitcin 1997b). But to be resistant to freezing and thawing cycles, HPC needs to contain 3.5 to 4.5% entrained air (Aitcin 1998).

2.9.3 Unit Weight

The unit weight of fresh HPC is slightly higher than that of lower strength concrete made with the same materials. It is mainly controlled by the aggregate type, size, gradation, mix proportion, aggregate-cement ratio, degree of compaction, and air content. Generally, the unit weight of normal weight HPC is in the order of 2200 kg/m^3 to 2600 kg/m^3 (Shetty 1993).

2.9.4 Concrete Temperature

Quality of fresh HPC is also a function of temperature. The higher is the temperature, the higher are the evaporation, the loss of water content, the loss of air content and, thereby, the lower is the workability. The temperature should be maintained within the range of 15 ^{0}C to 25 ^{0}C (Aitcin 1993). It is well known that the control of the parameters of the air bubble system becomes rather difficult when concrete temperature is higher than 25 ^{0}C. Besides, the 15 ^{0}C lower limit must be placed because naphthalene superplasticizers lose some of their efficiencies below 10 ^{0}C due to a significant increase in viscosity.

2.10 PROPERTIES OF HARDENED HIGH PERFORMANC CONCRETE

The exceptional mechanical properties of HPC proceed due to its reduced porosity. Porosity and permeability are the governing parameters, which account for its extra-ordinary mechanical performance. Some of its mechanical properties are mentioned below.

2.10.1 Compressive Strength

This is the most important of the material's functional properties. The kinetics of strength increase in HPC is notably faster than that of conventional concrete (Wolsiefer 1984). In general, for a given cement and acceptable aggregates, the strength that may be developed by workable, properly placed mixture of cement, aggregate and water under the same mixing, curing and testing conditions is influenced by the factors mentioned ahead: (1) water-binder ratio; (2) aggregate-binder ratio; (3) grading, surface texture, shape, strength and stiffness of aggregate particles; (4) maximum size of aggregate; (5) curing temperature; (6) period of curing; and (7) method of curing. However, water-binder ratio primarily affects the strength whereas other factors indirectly affect the strength of concrete by affecting the water-binder ratio (Shetty 1993).

For high strength HPC, the compressive strength ranges from 42 MPa to 100 MPa, for very high strength HPC it ranges from 100 MPa to 150 MPa and for ultra high strength HPC it is above 150 MPa (Nawy 1996).

2.10.2 Tensile Strength

Strength of concrete in compression and tension are closely related. Concrete with higher compressive strength shows higher tensile strength, but the rate of increase of tensile strength is of decreasing order. At low strength, the tensile strength may be as high as 10% of the compressive strength but at higher strength it may be reduced to 5%. The tensile strength depends, among others, on the type of aggregate and the use of pozzolanic material. The tensile strength is about 8% higher for crushed-rock-aggregate concrete than for gravel-aggregate concrete (ACI Committee 363 1995).

2.10.3 Bond Strength

Bond strength between paste and reinforcement is proportional to the tensile strength of concrete. It is therefore a function of compressive strength: the higher the compressive strength, the higher is the bond strength. This means HPC with higher bond strength allows a reduced anchorage length of the reinforcement (Pliskin 1992). The strength of concrete is derived from the bond between paste and aggregate (Shetty 1993). This bond strength depends upon the surface texture of the aggregate, mineralogical nature of the aggregate and the specific surface of the gel. Cement, which consists of a higher percentage of C_2S, will give higher specific surface of gel and thereby higher bond strength. The inherent micro-cracks that are generated within the body of the concrete also influence the bond strength between paste and aggregate.

2.10.4 Modulus of Elasticity

HPC exhibits higher values of elastic modulus. The stronger the concrete, the stronger is the gel and hence the less is the strain for a given load. Because of lower strain, the higher is the modulus of elasticity (Shetty 1993). Aggregates having higher modulus of elasticity produce concretes of higher modulus of elasticity. The modulus of elasticity of high strength HPC ranges from 31 GPa to 45 GPa depending mostly on the methods of determination (ACI Committee 363 1995).

2.10.5 Poisson's Ratio

Poisson's ratio tends to increase with decreasing water-binder ratio. Using dynamic measurements, it was found that values for Poisson's ratio of concrete ranged from

0.23 to 0.32 regardless of compressive strength, coarse aggregate and test age for 17 MPa to 79 MPa concretes (ACI Committee 363 1995).

2.10.6 Shrinkage

Many laboratory and field studies have shown that shrinkage of high strength HPC is similar to that of lower-strength concrete. However, Nagataki and Yonekura (1978) reported that the shrinkage of high strength HPC containing high range water reducer was less than that for lower strength concrete (ACI Committee 363 1995). Drying shrinkage is considerably less in high performance concrete due to lower water-binder ratio (Aitcin 1998).

2.10.7 Creep

The creep of HPC is smaller than that of ordinary concrete. The creep co-efficient decreases as the strength increases. For ordinary concrete, the value of the creep co-efficient is generally taken equal to 2.0 when loading is applied at 28 days. It seems that this co-efficient may be as low as 1.0 for some C60 (60 MPa compressive strength) concretes and 0.50 for some C100 (100 MPa compressive strength) concretes (Pliskin 1992).

2.10.8 Permeability and Absorption

The permeation properties of concrete are important since they give the durability indication of concrete. The permeability and water absorption of HPC are considerably lower than that of usual concrete. It is resulted from reduced porosity, sound compactness, better uniformity and lower water-binder ratio. Other influencing factors are gradation and type of aggregates and nature of curing. But above all, the lower water-binder ratio is the major controlling factor, which contributes least permeability and absorption to high strength HPC. HPC is so impervious to water that it is almost impossible to measure its water permeability. For normal weight high strength HPC obtained by using small aggregates of maximum size 9.5 mm, permeability can be as low as 5 x 10^{-11} cm/s (Safiuddin 1998).

The dense and compact microstructure of HPC resulting from lower water-binder ratio contributes its lowest permeation properties such as absorptivity, permeability and diffusivity. For example, HPC having compressive strength more than 41.4 MPa due to lower water-binder ratio shows absorptivity less than 0.25 ml/m^2/s (Safiuddin 1998). According to the Concrete Society Report, it would be classified as a low absorptive concrete (Concrete Society Working Party 1986).

2.11 ADVANTAGES OF HIGH PERFORMANCE CONCRETE

The main characteristic of high performance concrete is not the high strength; it is the reduced porosity, which makes high performance concrete a new material with multiple advantages. It is possible to categorize the main advantages of high performance concrete as follows (Pliskin 1992; Aitcin 1995, 1997a; Safiuddin 1998):

(1) **Ease of placing:** By the introduction of a superplasticizer, high performance concrete eliminates the shear threshold in the fresh concrete by introducing superplasticizer and leads the concrete to flow easily. So, placing and pumping operations become easy and less costly.

(2) **Productivity increase:** Ease of placing and having of high early age strength lead to higher productivity and therefore to a greater competitiveness of concrete.

(3) **Early age strength:** High performance concrete makes it possible to meet the requirements of contractors who ask for high early strength in order to achieve a quicker reuse of formwork or to enhance production rates.

(4) **High compressive strength:** High performance concrete offers high compressive strength resulting from a very compact mix. High performance concrete reaches easily 60 to 90 MPa compressive strength.

(5) **Impermeability:** High performance concrete having low water-binder ratio offers lower permeability and hence better durability.

(6) **Porosity:** High performance concrete lowers the capillary porosity and makes the whole matrix a perfectly homogeneous one.

(7) **Durability:** High performance concrete providing increased durability constitutes the most important contribution to construction. It gives more durability than ordinary concrete.

(8) **Corrosion resistance:** High performance concrete increases the electrical resistivity of concrete, which restricts the galvanic current and therefore steel corrosion.

(9) **Immunity to chemical attack:** High performance concrete shows better resistance to chemical attack than traditional concrete. It is also recommended in the case of a potential reaction between the alkalis of the pore solution and reactive aggregates.

(10) **Abrasion resistance:** High performance concrete has exceptionally high abrasion resistance rivalling that of the hardest rock. This is of particular interest in road and pipe construction.

(11) **Freeze-thaw resistance:** High performance concrete shows enhanced freeze-thaw resistance. The pore structure of this concrete is so fine that ice cannot form during freezing even if the concrete is saturated with water.

(12) **Creep:** Creep in high performance concrete is much less than that in ordinary concrete so that from a constructability point of view, it presents the great advantage of eliminating practically almost all long-term deformations.

(13) **Quality improvement:** The use of high performance concrete will pull the construction industry up to higher levels of quality due to less problem regarding durability.

(14) **Costs:** Concrete quantity savings and productivity improvements largely balance the increased cost of high performance concrete. Indirect benefits are also gained through durability improvements leading to maintenance savings.

Although high performance concrete is made with the same basic components that are used in ordinary concrete, its much higher quantitative and qualitative performances make it a new material. It offers different advantages over ordinary concrete. This is why it is termed as "High performance concrete".

2.12 SUMMARY

Definition, historical perspective and approaches to obtain high performance concrete are described in this chapter. Exceptional water-binder ratio, ingredients, production, properties and advantages of high performance concrete are also presented. An important property of high performance concrete is its high durability. High performance concrete is more durable than ordinary concrete, which is discussed in detail in the next chapter.

CHAPTER III

DURABILITY OF HIGH PERFORMANCE CONCRETE

3.1 INTRODUCTION

The durability of concrete may be defined as the material's capacity to maintain its physical characteristics and mechanical performance in conditions of satisfactory safety throughout the service life of the construction (Grandet 1992). It refers to the long-term performance of a particular material, in a particular environment, in a particular service condition.

The expression "durability of concrete" is usually used to characterize, in general terms, the resistance of concrete to the attack of physical or chemical aggressive agents. The nature, intensity and mechanism implied in each of these different attacks could vary considerably, which is why the expression durability of concrete is sometimes perceived as too vague an expression. There does not exist any standardized method of measuring the durability of concrete in general. There are no units in which to evaluate the durability of concrete (Aitcin 1998).

High performance concrete can be physically or mechanically attacked, such as when exposed to abrasion or freezing and thawing cycles; it can be chemically attacked directly by chloride ions (or chloride ions may attack the reinforcing steel the concrete should have protected), by sulfate ions, or by acidic or other types of aggressive chemicals. It can also be chemically attacked by a gas such as carbon dioxide and even by bacteria. Moreover, it can self-destruct in the presence of alkali reactive aggregates.

Undoubtedly, HPCs are more durable than ordinary concretes because they have a dense microstructure due to their low water-binder ratio. Being less porous and pervious than ordinary concrete, HPC offers a much better durability. In HPC, there is often not enough water available to hydrate entirely all cement grains, so that they contain a fair reserve of unhydrated cement particles when the mixing water has been consumed. If for any reason, structural or environmental, concretes get cracked, then these unhydrated cement particles will hydrate as soon as any water penetrates concrete and will protect further movement of water and thereby aggressive agents. Thus, these unhydrated cement particles offer a self-healing potential for HPC (Aitcin 1993).

3.2 DURABILITY AS A CRITERIA TO CONCRETE DESIGN

One of the principal reasons for the deterioration of many concrete structures stems from the fact that, in the past and even now, too much importance has been given to concrete compressive strength when designing concrete structures and not enough to the environmental factors that the structure will have to face when performing its structural function (Ho & Cao 1993).

When concrete is subjected to external chemical attack, there is only one way to reduce the intensity of this external aggression: to lower the porosity and the permeability of the concrete in order to reduce or to slow down as much as possible the penetration of the aggressive agents. Therefore, in order to offer the best resistance to external chemical attack as well as physical attack, it is necessary that the concrete be as compact and as impervious as possible. To achieve this, it is necessary that the concrete has a low water-binder ratio. In fact it is the water-binder ratio, and not the compressive strength, that has always been and will always be the key factor in controlling the impermeability of a concrete and therefore its durability (Aitcin 1998). If the water-binder ratio necessary to reach such a level of impermeability leads to a high compressive strength, it is the responsibility of the designer to use this additional strength more efficiently.

In spite of the fact that the engineer has no influence on environmental conditions, the engineer can, with appropriate design in certain details, avoid creating artificial catastrophic micro-climatic conditions (Norberg et al. 1993). Therefore, when a concrete structure is designed, it is essential to begin by defining in the best way possible the exact environmental conditions to which the concrete will be subjected during its service life. It is the role of the material specialist to adjust the composition and to select the right materials so that the concrete that will be used can resist these environmental conditions.

3.3 PLACING AND CURING OF CONCRETE

Specifying HPC with a low water-binder ratio is a necessary condition for obtaining a durable concrete, but it is not a sufficient condition. It is also necessary to be sure that this HPC is placed and cured in a correct manner. Even a properly specified and produced HPC will have only a mediocre durability if it is not placed and cured properly. As for any concrete, the durability of HPC is governed by the intrinsic quality of the material and the severity of the environment to which it is exposed, but it is also affected by the care that has been taken during its placing and curing (Aitcin 1998).

The importance of the placing and curing, as well as the difficulty of carrying out these operations properly, is one of the major weaknesses of concrete when compared with other construction materials. Excessive vibration generates internal bleeding even in HPC with a high slump and very low water-binder ratio (lower than 0.30). As mentioned earlier, HPC has to be vibrated but not too much; it is sufficient only to consolidate it until it is in place. An average slump of 180 to 200 mm, and rarely greater than 230 mm, seems to be a good compromise.

Premature drying of the concrete surface can have a catastrophic effect on the durability of concrete in general, and HPC in particular, because, as in the case of excessive vibration, a network of capillaries will appear at the surface of the concrete which will constitute an easy pathway through which aggressive agents will penetrate the concrete. It is absolutely essential to protect fresh HPC surfaces against early drying, because HPC either doesn't bleed or bleeds very little. Wetting the concrete surface in order to prevent it from drying can make all the difference between a durable concrete structure and a structure that will deteriorate quite rapidly (Aitcin 1998).

3.4 COVERCRETE

The disappearance of the transition zone makes HPC a true composite material with good stress transfer between the hydrated cement paste and the aggregate. However, when looking at concrete from a durability point of view, it has been found that the high slumps achieved when using superplasticizer create a new type of heterogeneous zone along the forms or at the top surface of the concrete. This zone has become known as the '**concrete skin**' (Kreijger 1987), '**outer skin**' (Bentur & Jaegermann 1991), '**concrete cover**' (Halvorsen 1993) or simply as '**covercrete**' (Aitcin 1998). In this study, the term covercrete is adopted.

The covercrete does not have exactly the same composition and microstructure as the interior of the concrete, owing to the so-called '**wall effect**'. The packing of the aggregates is less dense adjacent to the forms, or around any solid inclusion in the concrete, so that in these regions the concrete is richer in hydrated cement paste. For a long time, the consequence of this wall-effect has been ignored from a durability point of view because concrete was generally placed with low slumps of 20 mm to 100 mm, resulting in concrete that was very cohesive and not prone to too much segregation and thus not very much affected by the wall-effect. Most HPC are cast with very high slumps using superplasticizer. The covercrete is very rich in paste, owing to the high slump of HPC. When HPC is plastified so that its slump is maintained within the 150 to 200 mm range, there is little risk of segregation, because the mix is quite rich and quite thixotropic, but it is observed that the wall effect is greatly increased when the slump increases.

Moreover, in such fluid concrete, phase segregation within the cementitious phase can occur, especially when supplementary cementitious materials of different specific gravities and grain size distributions are used. The wall-effect and phase segregation of supplementary cementitious materials cause the covercrete to be more absorptive, more permeable and therefore less durable and much susceptible to aggressive agents.

Temperature of the environment also affects the durability of covercrete. In hot weather, where the temperature is about 35^0C (typical for Malaysia), due to thermal cracking the permeability or absorption of covercrete increases and so its durability decreases. Long-term high temperatures such as those found in power plants and chemical plants can also increase the potentiality for reinforcing steel corrosion. This is due to the increased cracking which possibly makes the ingress of corrosive solutions (Zain 1995).

To maintain the strength and to have good durability of concrete, appropriate curing method such as spraying of water or covering with wet sheet on the concrete member is necessary. Besides, the use of permeable forms seems to be an option very often used in Japan to improve the durability and the aesthetic appearance of covercrete (Katayama & Kabayashi 1991).

3.5 DURABILITY AT MICROSCOPIC AND MACROSCOPIC LEVELS

Concrete is, and always will be, a porous material, either because too much water has been used during mixing in ordinary concretes, or in HPC owing to autogenous shrinkage when water hydrates cement particles. It is the total volume of this porosity, and its degree of interconnection, that will make a concrete more or less impervious to its environment, i.e. more or less durable (Aitcin 1998). What makes HPC more durable than ordinary concrete at a microscopic level is its reduced porosity because it is made with a reduced amount of water. Definitely concrete durability is closely linked to hydrated cement paste permeability.

Concrete durability depends not only on the microstructural characteristics of the hydrated cement paste, of the transition zone and of the covercrete, but also on the development of macro-cracks which can originate from drying shrinkage, thermal gradients, autogenous shrinkage, thermal shrinkage and from overloading. If a sufficient amount of water is provided to a HPC just after its placing, plastic shrinkage can be prevented and autogenous shrinkage can be reduced drastically, at least in the covercrete, which is the most important and sensitive part of concrete elements to ensure a good durability.

3.6 DURABILITY ASPECTS OF HIGH PERFORMANCE CONCRETE

In general, HPC is more durable than ordinary concrete. However, as mentioned in the previous sections, this durability of HPC depends on various factors. The following sections describe various durability problems and their remedial measures to improve the performance of concrete.

3.6.1 Corrosion

The corrosion of reinforcing steel has been and still is the major deterioration mechanism for reinforced concrete structures. Corrosion of reinforcing steel occurs whenever the covercrete that was supposed to protect the reinforcing rebars against oxidation or rusting does not fulfil its role for various reasons: high water-binder ratio, poor curing practice or the absence of curing, misplacing of reinforcing rebars too close to the forms, ingress of chloride ions (Neville 1995), bacteria, and carbonation (Hansson & Sorensen 1990), etc.

The loss of passivity when the concrete pH decreases is the basic phenomenon leading to oxidation or rusting of the steel. Steel oxidation or rusting is accompanied by an increase in volume which first generates micro-cracks, or increases the number of pre-existing micro-cracks present in the covercrete owing to inadequate curing. These micro-cracks make the penetration of the aggressive agent easier, corrodes the steel and finally leads to the spalling of the covercrete.

According to Aitcin (1998), a concrete having a specified compressive strength lower than 30 MPa is a pervious concrete, whatever the environment in which it will be used. Any concrete with a water-binder ratio greater than 0.50 is also a pervious concrete that allows penetration of aggressive agents. On the other hand, a concrete having a specified water-binder ratio in the 0.30 to 0.35 ranges is impervious enough to provide proper corrosion protection to ordinary steel if there are an adequate thickness of covercrete and an adequate curing. The thickness of this covercrete has to be adjusted to the severity of the environment.

Of course, such a first step is necessary to solve the steel corrosion problem, but it is not sufficient: this impervious concrete must be well placed and well cured in order to protect reinforcing steel from corrosion. A low water-binder ratio, and adequate placing and curing of the concrete, are the 'price' that has to be paid to protect reinforced concrete structures against the corrosion of reinforcing steel. When looked at on the basis of service life and societal cost, this is not too high a price that has to be paid. This solution is not only feasible but also the most practical, the most economical and the safest to solve the corrosion problem of reinforcing steel if it is properly understood and applied (Aitcin 1998).

The lower the water-binder ratio, the more impermeable the concrete. According to Aitcin (1998), the first step to improving the resistance to corrosion of ordinary steel is to decrease the water-binder ratio, and then to see whether it is still necessary to provide further corrosion protection. The efficiency of silica fume to protect steel reinforcement has also been advocated (Wolssiefer 1991), as well as the use of permeable sheets and surface coatings (Sugawara et al. 1993; Tsukinaga et al. 1993).

Various alternatives to replace ordinary steel reinforcing rebars by 'corrosion-free' rebars have been proposed; different anti-corrosion admixtures are regularly advertised, with some companies even promoting the protection of the entire structure through an expensive cathodic protection. There are some other solutions to corrosion problems that are presently in use: stainless steel rebars; galvanized rebars; epoxy-coated rebars; and glass fibre-reinforced rebars. But these rebars have a few disadvantages including high cost and low bond strength with concrete.

3.6.2 Alkali-Aggregate Reactions

Three conditions are necessary to develop alkali-aggregate reaction (AAR) within a concrete. First, the aggregate must be potentially reactive; second, the concentration of alkalis must be high enough within the interstitial solution of the concrete; and third, the concrete must be humid. It is well known that severe expansion and cracking of concrete take place due to AAR if these conditions are met.

It is most probable that ambient moisture conditions would not be so important in the case of sealed concrete or of HPC having a lower water-binder ratio, which is not much absorptive. As most naphthalene and melamine superplasticizers are neutralized with soda, the use of a high dosage of superplasticizer increases the availability of alkali ions within the interstitial solution and therefore could result in an increase in the expected expansions, as found by Wang and Gillott (1989). This explains why some researchers and agencies are specifically specifying a calcium naphthalene superplasticizer when they have the least doubt or when they do not know the potential reactivity of the aggregates used in the HPC.

In order to fight, or at least to minimize an AAR, it is necessary to act on one of the three conditions necessary for the development of an AAR (Aitcin 1998). First, HPC must be made with a potentially non-reactive aggregate. Second, the total mass of alkalis in the concrete should be limited to a maximum of 3 kg/m^3. Third, the concrete surface should be sealed using a good silane or siloxane, so that the concrete is allowed to dry progressively. It has also been suggested adding some supplementary cementitious materials (e.g., silica fume, fly ash, slag) that are commonly used to fight efficiently or to reduce AAR expansions.

The higher cement content, the lower water-binder ratio and the use of superplasticizer tend to increase the development of an AAR in HPC, while the use of silica fume should reduce the risk. It is possible that the risk of seeing an AAR developing in an HPC could be lower than expected or even zero, because most of the mixing water is used during the hydration reaction so that there is practically no interstitial solution left within an HPC. Moreover, owing to its very low permeability and the poor connectivity of the capillary and pore system, there is a very low risk that a HPC will become saturated. Moreover, HPC has a greater tensile strength and, therefore, it should better resist the expansive pressure developed by the gel (Aitcin 1998).

3.6.3 Various Forms of Chemical Attack

The different hydration products of concrete are usually in equilibrium with the surrounding pore solution until the ingress of external ions modifies the solution equilibrium. A new equilibrium is then reached through the dissolution of certain hydration products as well as the formation of new products. In HPC, the controlling factor for the kinetics of the process is the diffusivity of the paste; the lower the water-binder ratio, the lower the diffusivity. However, HPC cannot create a completely insurmountable barrier to those chemicals that attack ordinary concrete; it can only slow down the process of the chemical attack and increase significantly, in many cases, the durability of the concrete in that particular environment.

It must be remembered also that chemicals penetrate within any concrete element, not only through the capillary network, but also, and more easily, through the cracks that are present in the concrete, whatever their origin. Therefore, any means of decreasing or eliminating concrete cracking should be considered seriously if an HPC has to face an aggressive environment. The following sections describe the various forms of chemical attack e.g., sulfate attack, seawater attack, acid attack and carbonation.

3.6.3.1 Sulfate Attack

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 (ACI Committee 201 1995). When evaporation takes place from an exposed face, the sulfates may accumulate at that face, thus increasing their concentration and potential for causing deterioration. Sulfate attack has occurred at various locations throughout the world, and is a particular problem in arid areas. The water used in concrete cooling towers can also be a potential source of sulfate attack because of the gradual build-up of sulfates from evaporation, particularly where such systems use relatively small amounts of make-up water. Sulfates are also present in ground water and in fill containing industrial waste products such as cinders. There are apparently two chemical reactions involved in sulfate attack on concrete (Lea 1971; Mehta 1976; Neville 1995):

(1) Combination of sulfate with calcium ions liberated during the hydration of the cement to form gypsum ($CaSO_4.2H_2O$).

(2) Combination of sulfate ion and hydrated calcium aluminate to form calcium sulfoaluminate (ettringite) ($3CaO.Al_2O_3.3CaSO_4.31H_2O$).

Both of these reactions result in an increase in solid volume. The formation of ettringite is the cause of most of the expansion and disruption of concretes caused by sulfate solutions.

The protection against sulfate attack is obtained by using a dense, quality concrete with a low water-binder ratio, and concrete making ingredients appropriate for producing concrete having the needed sulfate resistance. Proper curing, and use of ASTM C 150 Type V (sulfate-resisting) and Type II (moderately sulfate-resisting) cement improve sulfate resistance (ACI Committee 201 1995). The pozzolans normally used in high-strength concrete are very effective in reducing the calcium hydroxide, and hence also greatly enhance the resistance against sulfate attack. In addition to reducing the calcium hydroxide, pozzolans, such as silica fume, also form calcium silicate hydrates, which are able to incorporate aluminium ions, thus reducing the amount of aluminium available for ettringite formation (Shah & Ahmad 1994).

3.6.3.2 Seawater Attack

Where concrete structures are placed on reclaimed coastal areas with the foundations below the saline ground water levels, capillary suction and evaporation may cause supersaturation and crystallization in the concrete above ground, resulting both in chemical attack on the cement paste (sulfate), and in aggravated corrosion of steel (chlorides). In tropical climates these combined deleterious effects may cause severe defects in concrete in the course of a few years (ACI Committee 201 1995).

The reaction of mature concrete with the sulfate ion in seawater is similar to that with sulfate ion in fresh water or leached from soils, but the effects are different (Mather 1966). The concentrations of sulfate ion in seawater can be increased to high levels by capillary action and evaporation under extreme climatic conditions. The presence of chloride ions, however, alters the extent and nature of the chemical reaction so that less expansion is produced by a cement of given calculated tricalcium aluminate (C_3A) content than should be expected of the same cement in a fresh water exposure where the water has the same sulfate ion content. The Corps of Engineers (1985) permits up to 10% calculated tricalcium aluminate (C_3A) for concrete that will be permanently submerged in seawater if the water-cement ratio is kept below 0.45 by mass.

The requirement for low permeability is essential not only to delay the effects of sulfate attack, but also to afford adequate protection to reinforcement with the minimum concrete cover. The required low permeability is attained by using concrete with a low water-cement ratio, well consolidated and adequately cured.

The permeability of concrete with appropriate amounts of suitable ground blast-furnace slag or pozzolan can be as low as one-tenth or one-hundredth that of comparable concrete of equal strength made without slag or pozzolan. The satisfactory performance of concretes containing ground slag in a marine environment has been described in literature (Mather 1981; Vanden Bosch 1980; Lea 1971).

Careful attention must also be given to structural aspects with properly designed and constructed joints to assure that cracking is minimized to prevent the exposure of reinforcement. Additionally, concrete should reach a maturity equivalent of not less that 35 MPa (5000 psi) at 28 days when fully exposed to seawater.

Conductive coatings applied at the time of construction as part of a cathodic protection system may provide additional protection for concrete, which is partially submerged or reaches down to saline ground water. Silane coatings, which are water-repellent, have shown excellent protection characteristics. Caution is required with application of coatings, which significantly restrict evaporation of free water from the interior of concrete and thus reduce resistance to freezing and thawing. HPC has been used extensively to construct offshore platforms in the North Sea for over 20 years, and with great success (Aitcin 1998). Here, too, it is the great compactness of HPC that is responsible for this improved durability.

3.6.3.3 Acid Attack

In general, Portland cement does not have good resistance to acids, although some weak acids can be tolerated, particularly if the exposure is occasional (ACI Committee 201 1995). The deterioration of concrete by acids is primarily the result of a reaction between these chemicals and the calcium hydroxide of the hydrated Portland cement. Where limestone and dolomitic aggregates are used, they are also subjected to attack by acids. In most cases, the chemical reaction results in the formation of water-soluble calcium compounds, which are then leached away by the aqueous solutions (Biczok 1972). In the case of sulfuric acid attack, additional or accelerated deterioration results because the calcium sulfate formed which affect concrete by the sulfate attack mechanism described earlier. If acids, chlorides, or other aggressive or salt solutions are able to reach the reinforcing steel through cracks or pores in the concrete, corrosion of steel can result.

There are various sources of these acids that may attack concrete: the products of combustions of fuels; sewage; water draining from mines and industries; peat soils, clay soils, and alum shale; mountain streams; farm silage; and manufacturing and processing industries (Thornton 1978).

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. In all these cases, however, exposure time to acids should be minimized, if possible, and immersion should be avoided. No hydraulic-cement concrete, regardless of its composition, will long withstand water of high acid concentration (pH of 3 or lower). In such cases, an appropriate protective-barrier system or treatment must be used (ACI Committee 201 1995).

3.6.3.4 Carbonation

When concrete or mortar is exposed to carbon dioxide, a reaction producing carbonates takes place, which is accompanied by shrinkage (ACI Committee 201 1995). 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, dusting, and less wear-resistant surface. During the hardening process, the use of unvented heaters, or exposure to exhaust fumes from equipment or other sources, can produce a highly porous surface subject to further chemical attack. The source of the carbon dioxide can be either the atmosphere or water carrying dissolved carbon dioxide as described below.

Atmospheric carbonation: Reaction of hydrated Portland cement with carbon dioxide in the air is generally a slow process. It is highly dependent on the relative humidity of the environment, temperature, permeability of the concrete, and concentration of carbon dioxide. Highest rates of carbonation occur when the relative humidity is maintained between 50 and 75%. Below 25% relative humidity, the degree of carbonation that takes place is considered insignificant. Above 75% relative humidity, moisture in the pores restricts carbon dioxide penetration. Concrete in industrial areas with higher concentrations of carbon dioxide in the air is more susceptible to attack (ACI Committee 201 1995).

Carbonation by ground water: Carbon dioxide absorbed by rain enters the ground water as carbonic acid. Additional carbon dioxide together with humic acid can be dissolved from decaying vegetation resulting in high levels of free carbon dioxide. Reaction with carbonates in the soil produce an equilibrium with calcium bicarbonate, which can result in solutions with a neutral pH but containing significant amounts of aggressive carbon dioxide (Lea 1971). Water containing more than 20 parts per million (ppm) of aggressive carbon dioxide can result in rapid carbonation of the hydrated cement paste. Freely moving waters with 10 ppm or less of aggressive carbon dioxide may also result in significant carbonation (ACI Committee 201 1995).

Low water-binder ratio and good consolidation serve to reduce permeability and restrict carbonation to the surface. HPC offers much better protection from carbonation than ordinary concrete owing to the compactness of its microstructure in the covercrete area (Levy 1992).

3.6.4 Abrasion

Abrasion resistance can be a critical design factor in certain circumstances, or in certain parts of concrete structures: highway pavements, braking and accelerating zones at toll booths on highways, approaches to urban highway tunnels; some parts of hydraulic structures such as spillways, stilling basins, and bridge piles subjected to the action of water containing solid particles in suspension; and industrial floors. Wind or waterborne particles can also abrade concrete surfaces. There are instances where abrasion is of little concern structurally, yet there may be dusting problem which can be quite objectionable in some kinds of service (ACI Committee 201 1995). Recently, ice abrasion has become a major concern for designers of Arctic offshore platforms and bridges in Canada (Tadros et al. 1996).

The abrasion resistance of concrete is a progressive phenomenon (ACI Committee 201 1995). Initially, resistance is closely related to strength at the wearing and floor wear is best judged on this basis. Resistance can be modified by the use of shakes and toppings, finishing techniques, and curing procedures. As the paste wears, the fine and coarse aggregate are exposed and abrasion and impact will cause additional degradation that is related to aggregate-to-paste bond strength and hardness of the aggregate. With a given concrete mixture, compressive strengths at the surface can be improved by (ACI Committee 201 1995): avoiding segregation; eliminating bleeding; properly timed finishing; minimizing surface water-cement ratio, i.e., forbidding any water addition to the surface to aid finishing; hard trowelling of the surface; and proper curing procedures.

The abrasion resistance of concrete is a direct function of its compressive strength, as well as coarse aggregate volume and hardness (Dhir et al. 1991; Liu 1981; Mehta 1993; Ozturan & Kocataskin 1987). High quality cement paste and abrasion resistant aggregates are essential to produce an abrasion resistant concrete. Moreover, abrasion resistance is closely related to the surface properties of the concrete, which are in turn closely related to the finishing and curing of the surface (Fentress 1973; Kettle & Sadegzadeh 1987). Since abrasion occurs at the surface, it is critical, when possible, to maximize the strength of the surface using high quality aggregates, either by the dry-shake method or as part of a high strength topping. In some extreme cases metallic aggregates are used to provide additional service life (ACI Committee 201 1995).

Two fundamental studies (Gjørv et al. 1987, 1990; Laplante et al. 1991) have clearly shown that HPC has a greater abrasion resistance than ordinary concrete. The main findings of the first study (Gjørv et al. 1987, 1990) were as follows: (a) By increasing the compressive strength from 50 to 100 MPa, the abrasion of the concrete was reduced by roughly 50%; (b) The service life of a 150 MPa concrete is 10 times longer than that of a top quality asphalt pavement under abrasion by studded tyres; and (c) The partial substitution of a sand manufactured from a hard rock for natural sand was found to decrease compressive strength but to increase abrasion resistance.

In the second study (Laplante et al. 1991), it was found that the quality of the coarse aggregate is the most important factor affecting concrete abrasion resistance under the procedure of the ASTM C 779 standard (1993), with the water-binder ratio ranking the second. Silica fume was found to increase the abrasion resistance of concrete. Thus, the use of HPC can be expected to increase significantly the service life of concrete structures exposed to severe abrasion, because this type of concrete is strong and is usually made of high quality aggregates. At a very low water-binder ratio, HPC containing granite coarse aggregate can be nearly as abrasion resistant as the high quality rock alone.

3.6.5 Freezing and Thawing

The best way to make ordinary concrete resistant to repeated freezing and thawing cycles is to entrain a network of closely spaced air bubbles. In fact, it is not the total volume of entrained air that protects concrete against repeated freezing and thawing cycles, but rather the uniform distribution of this air as a multitude of very small bubbles (Aitcin 1998). The space distribution of the air-void system is characterized by the so-called **spacing factor**, which represents very approximately the average half-distance between two adjacent air bubbles, i.e. the average maximum distance that water will have to flow to reach the closest air bubble. When the manufacture, delivery and placing of concrete are well controlled, the spacing factor depends essentially on the total amount of entrained air.

Usually, ASTM C 666 (1993) standard considers that if a ordinary concrete is able to sustain 300 freeze-thaw cycles with a durability factor greater than 60%, it is freeze-thaw resistant. Research done in Canada has clearly established that for an ordinary concrete having a water-binder ratio within the 0.40 to 0.45 range, the critical spacing factor that makes it resistant to the 300 freezing and thawing cycles is around 400 μm (Aitcin 1998). From a practical point of view, it is generally accepted that 200 μm represents a good design value for the spacing factor, although this value can be considered as conservative. This spacing factor limiting value is necessary, but not sufficient, to make concrete resistant to freezing and thawing. To avoid surface scaling, ordinary concrete must also have a water-binder ratio no larger than 0.45 when the class of exposure is the most severe: frequent cycles of freezing and thawing in saturated conditions in the presence of chlorides.

To entrain air in low water-binder mixtures is not easy. It is also difficult to get a spacing factor lower than 200 μm, and it is extremely difficult to maintain such a low value of the spacing factor after pumping a HPC (Lessard et al. 1995). Pigeon (1996) suggested the following guidelines: 'air entrainment is not needed for good frost resistance when the water-binder ratio is lower than 0.25 but it should be used when the water-binder ratio is equal to or higher than 0.30. For intermediate values, tests should be carried out to determine the required air void parameters. These guidelines are of course only valid if good quality and low porosity aggregates are used'.

Aitcin (1998) is strongly convinced that all HPC should contain a small amount of entrained air to improve their workability, placing and finishing. He also believes that this entrained air will efficiently protect most concretes from freezing and thawing damage, under most field conditions. He suggests: (a) a total air content of 3.5 to 4.5%, which implies about 2 to 3% of actual entrained air on top of the 1.5 to 2.0% entrapped air that is present in any case in HPC, and (b) a spacing factor lower than 400 μm. It is obvious that the addition of some air within HPC conflicts with the search for a very high compressive strength. A variation of 1% air content within the 4 to 8% range results in an opposite variation of 5% in compressive strength (Aitcin 1998).

The resistance of non-air-entrained HPC to scaling due to freezing in the presence of deicing salts has generally been found to be very good. This is clearly due to the very low porosity of this type of concrete, which reduces the rate of chloride penetration, and increases the time required for the saturation of the surface layer. Being a surface phenomenon, finishing and curing take on a special importance, since it is possible to weaken considerably the microstructure of the skin of an otherwise adequately air-entrained concrete. A low water-binder ratio is equally important to reduce on the one hand salt penetration, and on the other full saturation of the surface layer. It is clear that HPC shows a very good resistance to scaling (Foy et al. 1988; Gagné et al. 1991; Hammer & Sellevold 1990; Peterson 1986; Zhang et al. 1997).

For resistance to deicing salt scaling, the type of cement seems to be less important if the C_3A content is kept low, below 6%. Hammer and Sellevold (1990) and Gagné et al. (1990, 1991) found that the use of Type III cement could bring a very rapid resistance to deicer salt scaling. Gagné et al. (1990, 1991) also found that at a water-cement ratio of 0.30 in concrete specimens, a curing period as short as 24 hours could provide resistance to 150 cycles.

3.7 SUMMARY

Concrete durability is still associated with the concrete water-binder ratio, as it has always been, because the water-binder ratio represents the real concrete parameter that reflects its compactness and permeability to aggressive agents. By using superplasticizers and supplementary cementitious materials, it is now possible to make concretes with very low water-binder ratios, so they are as impervious as the most durable rocks. Moreover, as in HPC, as there is not enough water available to hydrate all the cement grains fully, there is a fair reserve of unhydrated cement particles. These unhydrated cement particles have a potential for self-healing. Concrete with low water-binder ratio can be easily made with or without entrained air. As for the extra strength offered by these durable concretes, designers will have to learn how to make the best use of that strength in their designs. They should, however, have to make sure that this potentially durable concrete is placed and cured correctly. It must be emphasized that the covercrete always plays a critical role in concrete durability and that all things that will result in the improvement of the covercrete have to be implemented in order to improve the life cycle of concrete structures. To obtain durable high performance concrete, careful attention must be given in the mix design and adjustment, which is the topic of discussion of the next chapter.

CHAPTER IV

MIX DESIGN OF HIGH PERFORMANCE CONCRETE

4.1 INTRODUCTION

Concrete mix design is the process of selecting suitable ingredients of concrete and determining their relative quantities with the object of producing as economically as possible concrete of certain minimum properties, notably strength, durability, and a required consistency (Neville 1995). The objective of any mixture proportioning method is to determine an appropriate and economical combination of concrete constituents that can be used for a first trial batch to produce a concrete that is close to a good balance between the various desired properties of the concrete at the lowest possible cost (Aitcin 1998). It will always be difficult to develop a theoretical mix design method that can be used universally with any combination of Portland cement, supplementary cementitious materials, aggregates and admixtures because in spite of all the components of a concrete must fulfil acceptance criteria, these criteria are too broad; moreover, to a certain extent the same properties of fresh and hardened concrete can be achieved in different ways from the same materials. This situation must be perceived as an advantage, because in two different locations the same concrete properties can be achieved differently using non-expensive locally available materials (Aitcin & Neville 1993). A mixture proportioning method only provides a starting mix design that will have to be more or less modified to meet the desired concrete characteristics. In spite of the fact that mix proportioning is still something of an art, it is unquestionable that some essential scientific principles can be used as a base for mix calculations.

The production of high performance concrete (HPC) that consistently meets requirements for workability and strength development places more stringent requirements on material selection than for lower strength concrete. Quality materials are needed and specifications require more enforcement. However, HPC has been produced using a wide range of quality materials based on the results of trial mixes. This chapter describes different methods of mix design of HPC in general, and method proposed by Aitcin (1998) in particular. This chapter also discusses the mix performance adjustment criteria of the trial mix.

4.2 BACKGROUND OF MIX DESIGN OF HIGH PERFORMANCE CONCRETE

Concrete is becoming a more complex material than a simple mixture of cement, water and aggregates and it is more and more difficult to predict concrete properties theoretically in spite of the fact that the use of computers facilitates complex calculations. It is interesting to see in the present literature a renewal of interest in mix design and mix proportioning (Day 1996; de Larrard & Sedran 1996; Ganju 1996; Oh et al. 1999; Popovics & Popovics 1996). In fact this renewal of interest only traduces the limitations of the present mix proportioning methods that have been used for ordinary concrete without any problem for many years. As long as ordinary concrete was essentially a mixture of Portland cement, water, and aggregates and sometimes entrained air, these methods could be used with a very good predictive value to design a concrete mixture having a given slump and 28-day compressive strength (Aitcin 1998). This is no longer the case for HPC because of the following reasons.

(1) The range of water-binder ratio of HPC has been drastically extended towards very low values by the use of superplasticizers.

(2) The slump of a HPC is essentially dependent not only on the amount of mixing water but also on the amount of superplasticizer used. The slump can be adjusted to the specific needs by playing with these two values.

(3) HPC very often contains one or several supplementary cementitious materials (e.g., fly ash, slag, silica fume etc.). So the simple relationship linking the 28-day compressive strength to the water-cement ratio used for normal concrete is, in general, no longer valid and must be established in each particular case. For example, silica fume drastically changes the properties of fresh and hardened concrete.

(4) The maximum size of aggregate (MSA) is usually no longer dictated by geometrical considerations. It is also no longer advantageous to select as coarse an aggregate as possible to reduce the amount of mixing water needed to meet a certain slump; rather it is advantageous to select the coarse aggregate as small as possible for placeability considerations and also for concrete strength considerations.

(5) Coarse aggregate content is no longer influenced by the fineness modulus of the sand. The mixture is so rich in paste that, whenever possible, it is better to use coarser sand.

(6) Reference gradation used for normal concrete cannot give good results if applied to HPC mixes.

(7) The suggested air content values given for normal concrete are no longer appropriate to make HPC to be freeze-thaw resistant; it is rather the spacing factor that is the more relevant parameter in designing a freeze-thaw-resistant HPC.

There is no systematic mix proportioning method for HPC similar to those developed for normal concrete. The process of mix proportioning for normal concrete will not be applicable for HPC (Gutiérrez & Cánovas 1996). Since the aggregate types and amounts of admixtures may have a great influence on the strength characteristics of HPC mixtures, a different approach is needed for determining the mix proportions of HPC instead of traditional method (Mehta & Aitcin 1990).

Designing mix proportion of HPC is a difficult and complex task. It comes down to combining the various components that go into the concrete to obtain the required compressive strength while ensuring that the mixture maintains adequate workability until final placement. Balancing these two requirements is often problematic. The situation is rendered even more complex when there is a requirement to create air-void system with specific volume and spacing factor (Lessard et al. 1995).

Moreover, unlike ordinary concrete, HPC can have several characteristics that need to be met simultaneously. Among these requirements are low permeability and high durability, high modulus of elasticity, low shrinkage, low creep, high strength, and high and lasting workability. Because of the large number of mixture components used in HPC and because of the various concrete requirements that can contradict one another, it is very difficult to use a mix design method that gives mix proportions very close to that of the final mixture. Usually it is necessary to make a large number of trial mixtures in order to select the desired combination of materials that should be used to make HPC. Most mix proportions are, therefore, developed from extensive laboratory testing and these proportions are generally applicable to a narrow range of locally available materials that will be used in the test. However, a good mixture proportioning procedure can minimize the number of trial mixtures that are needed to achieve an economical and satisfactory balance between the various desired properties. Therefore, the use of a comprehensive mixture proportioning procedure to produce HPC mixture with the minimum amount of trial batches is very desirable. There have been several attempts to develop systematic methods for mix design of high performance concrete; a few of them are briefly presented in the following sections.

4.3 MIX DESIGN METHODS OF HIGH PERFORMANCE CONCRETE

Several methods have been proposed to calculate HPC mixture proportions and in some cases computerized versions of these methods are commercially available (Addis & Alexander 1990; Aitcin 1997b, 1998; Bharatkumar et al. 2001; Blick et al. 1974; Chang et al. 2001; Day 1996, 1999; de Larrard 1990; de Larrard & Sedran

1996, 2002; Domone & Soutsos 1994; Ganju 1996; Gutiérrez & Cánovas 1996; Haug & Sandvick 1988; Hover 1998; Hughes 1964; Keong 2001; Luciano et al. 1991; McCarthy et al. 2001; Mehta & Aitcin 1990; Peterman & Carrasquillo 1986; Popovics & Popovics 1996; Shah et al. 2000; Shilstone & Shilstone 1993; Welch 1962). In order to show the diversity of the different approaches, three of the methods are chosen and discussed briefly for comparison purposes, i.e. the methods proposed by the ACI 363 Committee on high-strength concrete (1995); by de Larrard in 1990, which is available in computerized version known as BETONLAB and which is widely used in France (de Larrard et al. 1996; Sedran & de Larrard 1996); and a simplified method presented by Mehta and Aitcin (1990). In addition, Section 4.3.4 discusses the method proposed by Aitcin (1998).

4.3.1 ACI 363 Committee Method

The steps of this procedure are as follows:

(1) Slump and required strength selection: A table suggests slump values for concretes made with superplasticizers and for those without superplasticizer. The first value of the slump is 25 to 50 mm for the concrete before adding superplasticizer in order to ensure that sufficient water is used in concrete.

(2) Selection of the maximum size of coarse aggregate (MSA): The method suggests using coarse aggregate with MSA of 19 or 25 mm for concrete made with f_c' lower than 65 MPa and 10 or 13 mm for concrete made with f_c' greater than 85 MPa. The method allows the use of coarse aggregate with MSA of 25 mm with f_c' between 65 and 85 MPa when the aggregate is of high quality. As in the case of ordinary concrete, the MSA should not exceed one-fifth of the narrowest dimension between the sides of forms, one-third of the depth of slab, or three-quarters of the minimum clear spacing between reinforcing bars, bundled bars or tendons.

(3) Selection of coarse aggregate content: This method suggests that the optimum content of coarse aggregate, expressed as a percentage of dry-rodded unit weight (DRUW), can be 0.65, 0.68, 0.72 and 0.75 for nominal size aggregates of 10, 13, 19 and 25 mm, respectively. These values are given for concrete made with a sand of fineness modulus between 2.5 to 3.2.

(4) Estimation of free water and air content: A table gives estimates for the required water content and resulting entrapped air content for concretes made with coarse aggregates of various nominal sizes. These estimated water contents are given for a fine aggregate having a 35% void ratio. If this value is different from 35%, then the water content obtained from the table should be adjusted by adding or subtracting 4.8 kg/m^3 for every 1% increase or decrease in sand air void.

(5) Selection of Water-Binder (W/B) ratio: Two tables suggest W/B values for concretes made with and without superplasticizer, respectively, to meet the specified 28 and 56-day compressive strength. These values are based upon the MSA and f_c' of the concrete.

(6) Cement content: The mass of cement is calculated by dividing the mass of the free water by the W/B ratio.

(7) First trial mixture with cement: The first mixture to be evaluated can be batched using cement and no other cementitious materials. The sand content is then calculated using the *absolute volume method*.

(8) Other trial mixtures with partial cement replacements: At least two different cementitious material contents are suggested to replace some of the cement mass to produce other trial mixtures that can be batched and evaluated. Maximum cement replacement limits are suggested for fly ash and blast-furnace slag; no limits for silica fume are suggested because this method is valid for a maximum f_c' of 85 MPa. These limits are 15 to 25% of the mass of cement for Class F fly ash, 20 to 35% of mass of cement for Class C fly ash, and 30 to 50% of the mass of cement for blast-furnace slag. Again, the unit mass of sand is calculated using the *absolute volume method*.

(9) Trial batches: The mass of aggregates, along with that of the mixing water, are adjusted for actual moisture conditions, and trial batches are made using concretes made with no cement replacement and others using fly ash or blast-furnace slag. The concretes are then adjusted to meet the desired physical and mechanical characteristics.

The main limitation of the method is that it is applicable for concrete compressive strength less than or equal to 85 MPa. Moreover, no limits for the use of silica fume are suggested. This method requires testing of at least three trial batches to start for performance adjustment of the mix.

4.3.2 de Larrard Method

This method is based on two semi-empirical mix design tools. The strength of the concrete is predicted by a formula, which is in fact an extension of the original Feret's formula where a limited number of mix design parameters are used. The workability is assumed to be closely related to the viscosity of the mix, which is computed using the Farris model (de Larrard 1990). The idea behind using the Farris model is that each granular class has the same interaction with the mix containing the liquid phase plus the finer classes as with a homogeneous fluid. From these tools the following assumptions were made:

(1) The strength of a concrete made of a given set of components is mainly controlled by the nature of the binding paste.

(2) The workability of a concrete, where strength grading is fixed, is assumed to be a combination of two terms: the first depending on the concentration of the binding paste and the second on paste fluidity.

The main idea of the method is to perform as many tests as possible on grouts for rheological tests and mortars for mechanical tests. The first step consists of proportioning a control concrete containing a large amount of superplasticizer with the amount of cement corresponding to the lowest water demand possible. This amount of water is adjusted to obtain the right workability as measured with a dynamic apparatus. The second step consists of measuring the flow time of the paste of this control concrete using a Marsh cone. The third and fourth steps involve the adjustment of the binder compositions and of the amount of superplasticizer until the flowing time does not decrease anymore. This amount of superplasticizer is said to correspond to the saturation value. The fifth step involves the adjustment of the water content to obtain the same flowability as in the control mix. The sixth step consists of following the variation of the flow time with time. If the flow time increases too much, a retarding agent should be added. The seventh step corresponds to the prediction of the strength of the HPC using Feret's formula or the measurement of the compressive strength of different mortars. In the eighth step, an HPC is made and its composition is slightly modified in order to get the targeted workability and strength values.

A sample calculation can be found in de Larrard (1990). A computerized programme has been developed from this method and is currently used in France under the trade name of BETONLAB (de Larrard et al. 1995; de Larrard et al. 1996; de Larrard & Sedran 1994; Sedran & de Larrard 1996).

This method has certain limitations. First, extensive tests on cement grouts and mortars are required to predict the strength and workability of concrete mix. Second, the method is based on experiment and needs much experimental works and more trial mixes compared with classical methods to get a mix with the desired workability and strength. This method gives composition that is more expensive than other methods. Moreover, Farris model does not take into account the real grading of granular components and hence does not apply quantitatively to concrete (de Larrard 1990).

4.3.3 Mehta and Aitcin Method

Based on certain assumptions and general considerations, Mehta and Aitcin (1990) proposed a simplified mixture proportioning procedure that is applicable for normal weight concrete with compressive strength values of between 65 and 120 MPa. The method is suitable for coarse aggregates having a maximum size of between 10 and 15 mm and slump values of between 200 and 250 mm. It assumes that non-air-entrained HPC has an entrapped air volume of 2%, which can be increased to 5 to 6% when the concrete is air-entrained. The optimum volume of aggregate is suggested to be 65% of the volume of HPC. The steps of this procedure are as follows (Aitcin 1998):

(1) Strength determination: A table lists five grades of concrete with average 28-day compressive strength ranging from 65 to 120 MPa.

(2) Water content: The maximum size of the coarse aggregate and slump values are not considered here for selecting the water content since only 10 to 15 mm maximum size are considered and because the desire slump (200 to 250 mm) can be achieved by controlling the dosage of superplasticizer. The water content is specified for different strength levels.

(3) Selection of the binder: The volume of the binding paste is assumed to be 35% of the total concrete volume. The volumes of the air content (entrapped or entrained) and mixing water subtracted from the total volume of the cement paste to calculate the remaining volume of the binder. The binder is then assumed to be one of the following three combinations: (a) 100% Portland cement to be used when absolutely necessary; (b) 75% Portland cement and 25% fly ash or blast-furnace slag by volume; and (c) 75% Portland cement, 15% fly ash, and 10% silica fume by volume. A table lists the volume of each fraction of binder for each strength grade.

(4) Selection of aggregate content: The total aggregate volume is equal to 65% of the concrete volume. For strength grades A, B, C, D and E the volume ratios of fine to coarse aggregates are suggested to be 2.00: 3.00, 1.95: 3.05, 1.90: 3.10, 1.85: 3.15 and 1.80: 3.20, respectively.

(5) Batch weight calculation: The weights per unit volume of concrete can be calculated using the volume fractions of the concrete and the specific gravity values of each of the concrete constituents. A table lists the calculated mixture proportions of each concrete type and strength grade suggested in this method.

(6) Superplasticizer content: For the first trial mixture, the use of a total of 1% superplasticizer solid content of binder is suggested. The mass and volume of a superplasticizer solution are then calculated taking into account the percentage of solids in the solution and the specific gravity of the superplasticizer.

(7) Moisture adjustment: The volume of the water included in the superplasticizer is calculated and subtracted from the amount of initial mixing water. Similarly, the mass of aggregate and water are adjusted for moisture conditions and the amount of mixing water adjusted accordingly.

(8) Adjustment of trial batch: Because of the many assumptions made in selecting a mixture proportioning, usually the first trial mixture will have to be modified to meet the desired workability and strength criteria. The aggregate type, proportions of sand to aggregate, type and dosage of superplasticizer, type and combination of supplementary cementitious materials, and the air content of the concrete can be adjusted in a series of trial batches to optimise the mixture proportioning.

The limitations of this method are stated ahead. First, it is applicable for concrete compressive strength ranging from 65 MPa to 120 MPa. Second, it considers maximum size of coarse aggregates (MSA) in the ranges of 10 mm to 15 mm only. Third, it gives mix proportions for using 25% fly ash or 15% fly ash and 10% silica fume in addition to cement as binders. Moreover, because of the many assumptions made in this method, it requires many trial batches to get the mix with the desired performance.

4.3.4 Aitcin Method

Professor Aitcin (1998) developed a mix design method for HPC. The limitations of the previously discussed methods are overcome in this method. Alves et al. (2003) made a comparative study of four methods for design of high-strength concrete. In that study, it was proved that Aitcin method (1998) is the one that represents the lowest cement consumption per cubic metre of concrete. In the same study, it was also proved that Aitcin's method appeared to give the lowest unit cost of concrete from 80 MPa onwards compressive strength range. This method is the latest and systematic method in the high performance concrete mix design domain. Therefore, this method has been selected as the mix design procedure for the present study. The method is explained in the following sections.

The method itself is very simple: it follows the same approach as ACI 211.1 Standard Practice for Selecting Proportions for Normal, Heavy-weight and Mass Concrete (ACI Committee 211 1991). It is a combination of empirical results and mathematical calculations based on the *absolute volume method*. The water contributed by superplasticizer is considered as part of the mixing water. A flow chart of this method is presented in Figure 4.1. A sample calculation of mix proportions using this method is presented in Appendix B.

The procedure is initiated by selecting five different mix characteristics or materials proportions in the following sequence (Aitcin 1998):

Step 1 – the Water-Binder (W/B) ratio;
Step 2 – the water content;
Step 3 - the superplasticizer dosage;
Step 4 – the coarse aggregate content;
Step 5 – the entrapped air content (assumed value).

(1) Step 1. Water-Binder ratio: The suggested water-binder ratio can be found from Figure 4.2 for a given 28-day compressive strength (measured on 100 x 200 mm faced cylinders). Owing to variations in the strength efficiency of different supplementary cementitious materials, the curve in Figure 4.2 shows a broad range of water-binder ratio values for a given strength. If the efficiency of the different supplementary cementitious materials is not known from prior experience, the average curve can be used to give an initial estimate of the mix proportions.

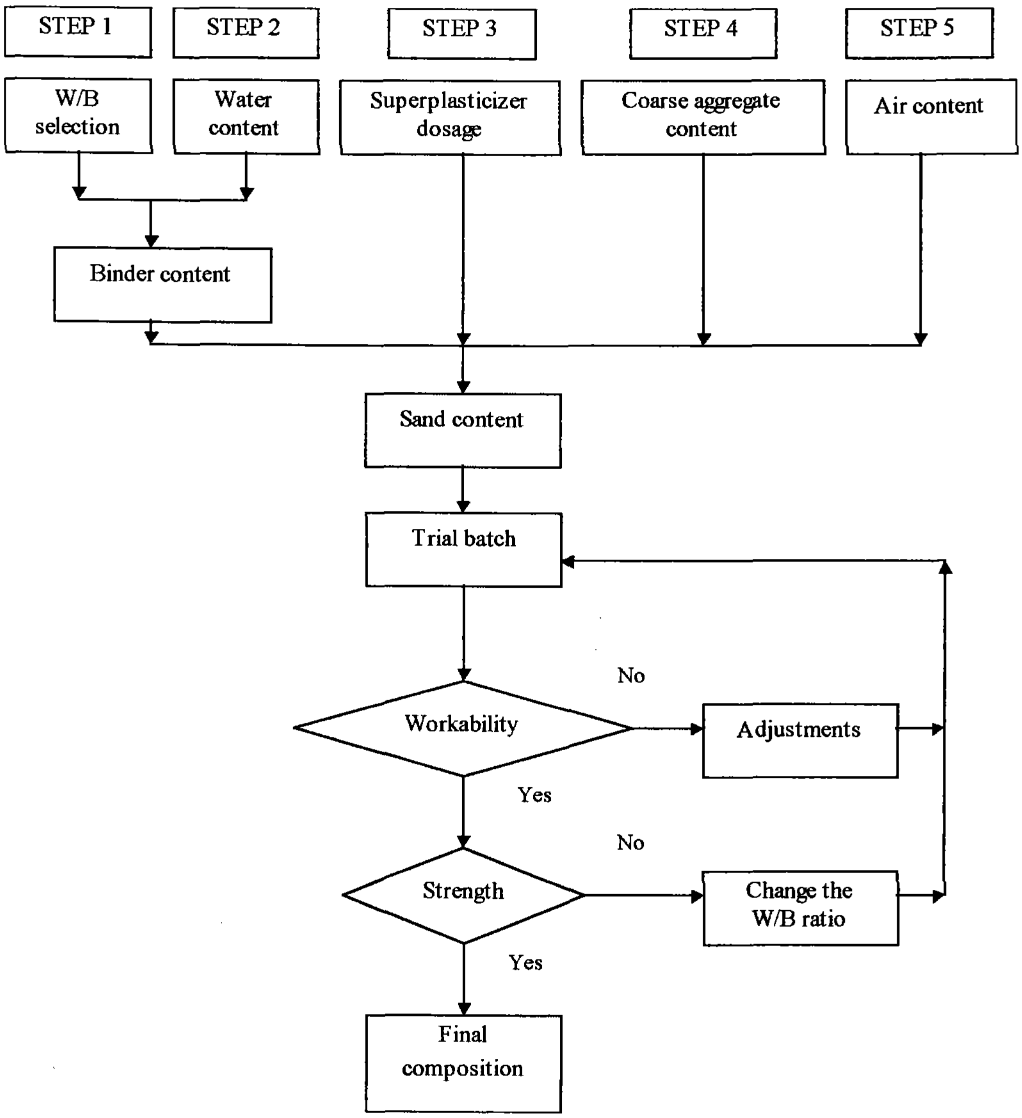


FIGURE 4.1 Flow chart of Aitcin mix design method

Source: Aitcin 1998

(2) Step 2. Water content: One difficulty when designing HPC mixtures is to determine the amount of water to be used to achieve a HPC with a 200 mm slump 1 hour after batching because the workability of the mix is controlled by several factors: the amount of initial water, the 'reactivity of the cement', the amount of superplasticizer, and its degree of compatibility with the particular cement. Therefore, a 200 mm slump concrete can be achieved when batching the concrete with a low water dosage and a high superplasticizer dosage or with a higher water dosage and a lower superplasticizer dosage. From an economical point of view there is no great difference between the two options, but from a rheological point of view the difference can be significant, depending on the rheological 'reactivity of the cement' and the efficiency of the superplasticizer. Owing to differences in fineness, phase composition, phase reactivity, composition and solubility of the calcium sulphate of the cements, the minimum amount of water required to achieve HPC with a 200 mm slump varies to a large extent. If the amount of mixing water selected is very low, the mix can rapidly become sticky and as a high amount of superplasticizer has to be used to achieve this high slump, some retardation can be expected.

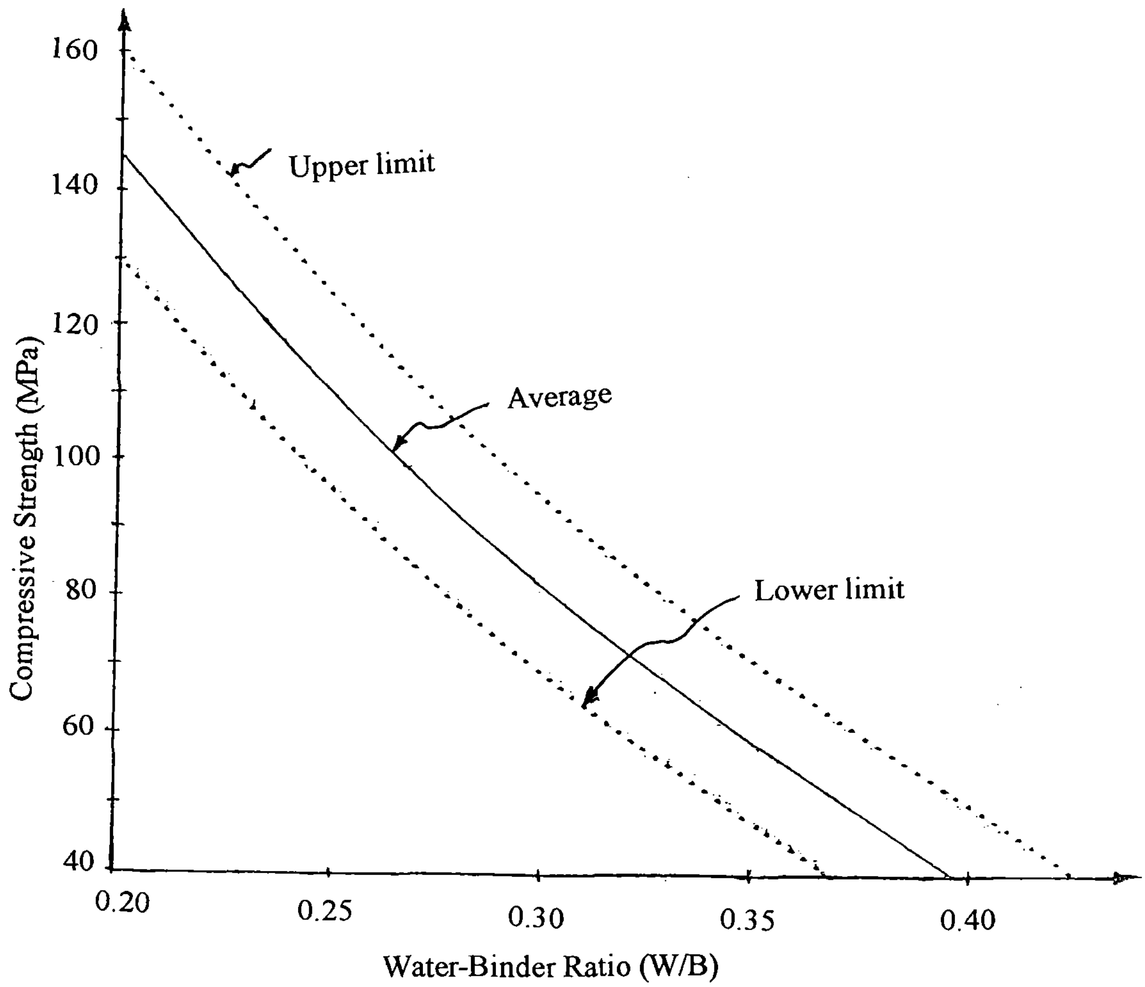


FIGURE 4.2 Proposed W/B vs. compressive strength relationship

Source: Aitcin 1998

The best way to find the best combination of mixing water and superplasticizer dosage is by carrying out a factorial design experiment (Rougeron & Aitcin 1994), but this method is not always practical, therefore a simplified approach based on the concept of the saturation point is given by Aitcin (1998) as shown in Figure 4.3. To design a very safe mix, 5 l/m^3 of water can be added to the values presented in Figure 4.3. If the saturation point of the superplasticizer is not known, it is suggested starting with water content of 145 l/m^3.

Saturation Point of Superplasticizer (%)	0.6	0.8	1.0	1.2	1.4
Water Dosage (l/m^3)	120 to 125	125 to 135	135 to 145	145 to 155	155 to 165

FIGURE 4.3 Determination of minimum water dosage

Source: Aitcin 1998

(3) Step 3. Superplasticizer dosage: The superplasticizer dosage can be deduced from the dosage at the saturation point. If the saturation point is not known, it is suggested starting with a trial dosage of 1.0%.

(4) Step 4. Coarse aggregate content: The coarse aggregate content can be found from Figure 4.4 as a function of the typical particle shape. If there is any doubt about the shape of the coarse aggregate or if its shape is not known, a content of 1000 kg/m^3 of the coarse aggregate can be used to start with.

(5) Step 5. Air content: For HPC that are to be used in non-freezing environments, theoretically there is no need for entrained air, so the only air that will be present in the mix is entrapped air, the volume of which depends partly on the mix proportions. However, in order to improve concrete handling, placeability and finishability, Aitcin (1998) strongly suggested the use of some amount of entrained air.

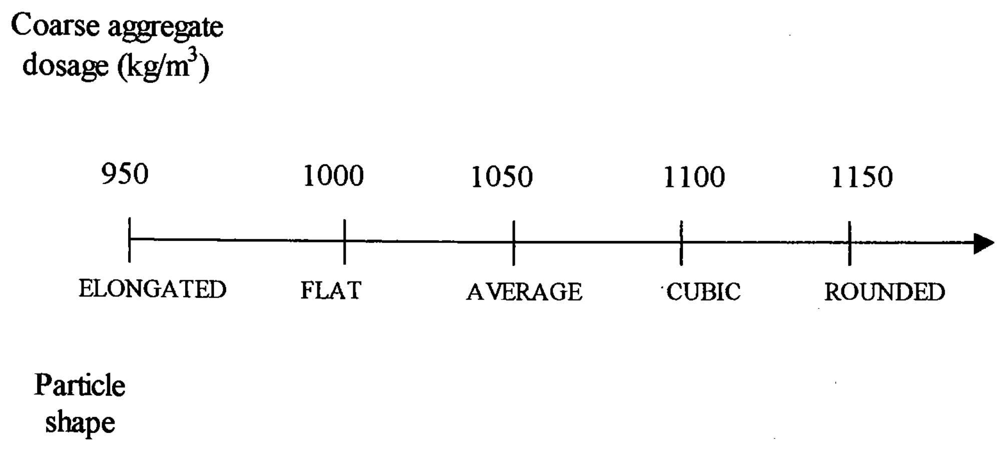


FIGURE 4.4 Coarse aggregate content

Source: Aitcin 1998

When making HPC with very low water-binder ratios, it has been observed that not every cement-superplasticizer combination entraps the same amount of air. Moreover, some concrete mixers tend to entrap more air than others. From experience it has been found that it is difficult to achieve less than 1% entrapped air and that in the worst case the entrapped air contents can be as high as 3%. Therefore, Aitcin (1998) suggested using 1.5% as an initial estimate of entrapped air content, and then adjusting it on the basis of the result obtained from the trial mix.

4.4 ONE CUBIC METRE SSD (SATURATED-SURFACE-DRY) COMPOSITION

When a satisfactory HPC mix having the right consistency (initial and final slump) has been obtained after different adjustments, it is necessary to go back to the composition of 1 m^3 of concrete in SSD condition. The mass of the mixing water added in the mixer is known, but the actual water present in the mixture is not, because the aggregates are not likely to be in their SSD state and some water is 'hidden' in the liquid superplasticizer; therefore, the water-binder ratio of the mix is not known. Thus it is necessary to calculate the so-called *'water corrections'* to be able to know a precise amount of water present in the mixture. This is done according to a simple flow chart presented in Figure 4.5.

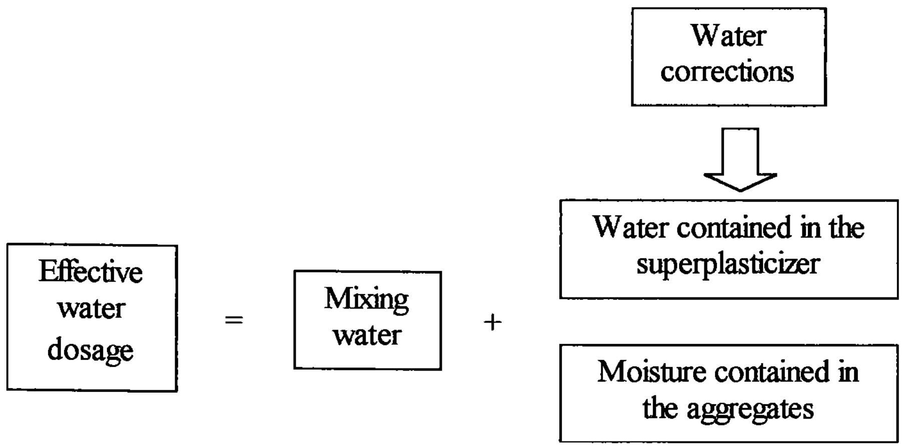


FIGURE 4.5 Calculation of the effective water dosage of a trial batch

Source: Aitcin 1998

As the air content is known as a percentage of the mix volume, it is necessary to calculate the volume in litres of each ingredient in order to know the volume of concrete made in the trial batch. The total of these volumes is computed. The actual volume of the mix is then computed, taking into account the measured air content of the concrete of the trial batch.

The trial batch represents a certain fraction of a cubic metre; thus in order to calculate the composition of 1 m^3 of this concrete it is necessary to calculate how many times this trial batch is contained in 1 m^3 or 1000 litre of concrete. One thousand (1000) is divided by the volume of the trial batch and this value is a factor called f. The different masses of materials used to make the trial batch will be multiplied by f in order to get the composition of 1 m^3 of concrete (SSD condition). The unit mass of the concrete is calculated by adding the masses of all ingredients. Then the total amount of supplementary cementitious materials used and the water-binder ratio are calculated. A sample calculation for this is presented in Appendix B.

4.5 BATCH COMPOSITION

When HPC is to be batched, the proportions obtained from the trial mix or given by the laboratory are always for SSD aggregate conditions. As the aggregates contained in the bins at the batching plant are not usually under SSD conditions, the amount of mixing water has to be adjusted. The content of water added by the superplasticizer also has to be subtracted from the mixing water content.

The mass of water added to the mix by the superplasticizer is calculated. The mass of wet coarse aggregate, M, to be weighed is equal to $M_{SSD}\ (1 + w_h)$; where, M_{SSD} is the mass of coarse aggregate in SSD condition, and w_h is the water content of aggregate. The mass of water to be added or subtracted to water content is computed. The same is done for the fine aggregate. The values computed are added or subtracted to the water content in order to calculate the mass of mixing water necessary to make 1 m^3 of the desired concrete from the aggregates that are in the bins.

Now, the masses of the different materials needed to make, say, X m^3 of concrete can be calculated by multiplying by X all the values calculated earlier. A sample calculation of batch composition is presented in Appendix B.

4.6 MIX PERFORMANCE ADJUSTMENT

In the present state of the art, the successful fabrication of HPC depends on a combination of empirical rules derived from experience, laboratory work and observation. It can thus be said that the proposed method is a transition between an art and a science (Aitcin 1998).

Applying, step by step, the materials selection criteria and the mix design method proposed by Aitcin (1998) should help one to find the best, or at least the most acceptable locally available materials and to select their proportions in order to make the best (or close to the best) HPC in terms of rheology, strength and economy that can be made from the materials available in a given area to meet the expectations of the designer. However, improvements to this method could always be made (Aitcin 1998).

An important factor in the mix design of HPC, much more than in the case of ordinary concrete mixes, is the selection of materials. A blind application of the proposed mix design method (or of any other method) does not guarantee success because, in HPC, all concrete ingredients work at, or near, their critical limits. Any HPC has a weak link within it, and when it is tested, failure always initiates at this weakest link and then propagates through the stronger parts. The key to success in designing HPC mix is to find materials in which the weakest link is as strong as required to meet the performance requirements, while the stronger parts are not so strong that they lead to an unnecessary expenditure.

The mix design method proposed by Aitcin (1998) is based on experience gained through the years. Like all mix design methods, it should be used only as a guide (Aitcin 1998). In general, the calculated proportions should provide a mix having almost the desired characteristics. However, if the cement is not suitable, if the aggregates are not strong enough, if the superplasticizer is not efficient enough, if the selected cement/superplasticizer combination is not fully compatible or if some other unexpected factors intervene, the concrete may not reach the desired level of performance. On the other hand, with careful observation of the rheology, the surface failure and some other critical characteristics, it should generally not be too difficult to find out why the concrete did not achieve the design performance level that was desired. Some associated mix performance problems and their solutions for mix performance adjustment are discussed below (Aitcin 1997b, 1998; Safiuddin 1998):

(1) When the desired compressive strength is not obtained and the fracture surface shows a number of intragranular fractures, the aggregates can be blamed and a stronger aggregate has to be found.

(2) If the fracture surface shows considerable debonding between the coarse aggregate and the hydrated cement paste, the coarse aggregate used has a

too smooth surface or is simply too dirty. Therefore, a coarse aggregate with a rougher and cleaner surface must be used.

(3) If the fracture surface passes almost entirely through the hydrated cement paste around the aggregates, stronger concrete can be made with the same aggregates by lowering further the water-binder ratio.

(4) If the compressive strength does not increase when the water-binder ratio decreases, this indicates that the aggregate strength or binder-aggregate bonding controls the failure rather than the water-binder ratio, and so stronger concrete may be possible to get with the same cement or binder but using stronger aggregate.

(5) If the concrete does not have the desired slump, the superplasticizer dosage is not high enough and must be increased, or else, the water dosage has to be increased as well as the cement or binder content in order to keep the same water-binder ratio.

(6) If the concrete experiences a rapid slump loss, the cement is perhaps more reactive than expected and the water dosage has to be increased, or the superplasticizer is particularly inefficient with the selected cement so that its dosage has to be increased or another brand of superplasticizer has to be used.

(7) If the workability of the mix is inadequate, a poor shape or gradation of the coarse aggregate or the incompatibility of the particular cement-superplasticizer combination can be blamed for. In the first case, the amount of coarse aggregate has to be decreased and in the second case, either the cement or the superplasticizer or both should be changed.

(8) Excessively high slump can result in weak concrete because of phase segregation that develops just behind the forms. So, the quality of concrete may become critical if the slump of concrete increases. As a result, structures made of high slump HPC could present a weak surface vulnerable to external aggressive agents. In order to compensate this

situation, all high slump concretes would have to contain some anti-segregation admixture.

(9) The so-called wall-effect is greatly increased when the slump increases. The use of permeable form seems to be an option very often used in Japan to deviate wall-effect (Katayama & Kabayashi 1991).

(10) When different supplementary cementitious materials are used to produce HPC, segregation of the fine particles of the cementitious part may occur, particularly when the fine particles of the different supplementary cementitious materials have different specific gravities. This is possibly due to the excessive vibration applied at some particular places, which creates a kind of segregation within the concrete resulting in a concentration of fine particles. So, evenly distributed proper vibration could solve this problem.

4.7 SUMMARY

The various methods of mix selection may seem simple and, indeed, they do not involve any complex calculations. However, a successful implementation of the selection requires experience, coupled with knowledge of the influence of various factors upon the properties of concrete; this knowledge must be based on an understanding of the behaviour of concrete. When these three desiderata - experience, knowledge, and understanding - are all present, the first trial mix is likely to be approximately satisfactory, and can be rapidly and successfully adjusted so as to achieve a mix with the desired properties. It is not enough to select a suitable concrete; it is also necessary to ensure a proper execution of all the operations involved in concreting. Such execution requires skill backed by appropriate knowledge at the execution level. Competently used, concrete is a very successful construction material but, in the literal sense of the word, concrete is not foolproof (Neville 1995). An expert system can help a non-expert user to make intelligent decision regarding these issues. The next chapter presents a concise review on the history and application of artificial intelligent and expert system. That chapter also examines literatures on the various considerations that must be dealt with in order to ensure a sound and systematic environment for expert system development.

CHAPTER V

EXPERT SYSTEMS

5.1 INTRODUCTION

Expert systems are generally considered to be a branch of artificial intelligence with a knowledge base. These systems can function as "experts" to make higher-level decisions based on varying performance levels (Basri 1999). By definition, an expert system is a computer program designed to model the problem-solving ability of a human expert (Durkin 1994). It has also been described as a new software technology that permits the formalization and representation of knowledge as well as expertise. An expert system is able to give recommendations at a level comparable to, or above, an expert. Expert systems are most useful when the knowledge is based on heuristics. It is designed to work in a narrow area, similar to the focus of an expert, such as medical diagnosis, computer configuration and work personnel scheduling (Winston 1992; Durkin 1994). Many agree that the expert systems area has advanced furthest and achieved the most success in applying artificial intelligence methods to real-world problems (Kaetzel & Clifton 1995). A successful expert system is one that mimics the way an expert would apply his problem-solving abilities in making a recommendation or drawing a conclusion, with a high degree of accuracy.

Expert systems are the result of many years of attempting to simulate or reproduce intelligent problem-solving behaviour in a computer program. The development of expert systems, which are also known as knowledge-based systems, has been among the most active research areas in artificial intelligence during the last few decades. Developing intelligent computer systems began in the sixties but it was in the early seventies that the first successful expert system began to appear. Example of these are MYCIN that was developed at Stanford University for medical diagnosis and to identify drug therapies for treating pulmonary bacteria, and DENDRAL for determining the structure of complex molecules from mass spectrograms. At first, expert systems were primarily of academic interest, with little attention being given to their practical applications (Clifton et al. 1985). The usefulness of expert systems in solving difficult practical problems, however, has become recognized and their development is being pursued in many fields. For example, expert systems have been developed to give recommendations in such areas as medical diagnosis (Shortliffe 1976), molecular structure identification (Buchanan & Feigenbaum 1978), mineral exploration (Duda et al. 1979), computer configuration (Dermott 1980), structural analysis (Bennett & Englemore 1979), agriculture (Acuna et al. 1997), waste management (Basri 1994, 2000; Basri 1999; Basri & Stentiford 1995) and so on. With so much experience gained with these systems, the advancement of artificial intelligent is set to dominate the civil engineering community. The basic activities of expert systems can be grouped into the categories shown in Table 5.1. The general distinctions between expert systems and conventional programs are illustrated in Table 5.2.

5.2 REASONS FOR USING AN EXPERT SYSTEM

The goals sought by expert system builders include helping human experts, assimilating the knowledge and experience of several human experts, training new experts and providing requisite expertise to projects that cannot afford scarce expertise on site (Martin & Oxman 1988). Castillo and Alvarez (1991) summarised the following reasons for using an expert system:

- Non-expert personnel can solve problems that require some expertise.
- Attainment of more reliable and quick solutions.
- Cost reduction.
- Elimination of uncomfortable and monotonous operations.
- Lack of human experts.
- Wider access to knowledge.

TABLE 5.1 Types of Problems Solved by Expert Systems

Category	**Problem Addressed**
Control	Governing system behaviour to meet specifications
Design	Configuring objects under constraints
Diagnosis	Inferring system malfunctions from observation
Instruction	Diagnosing, debugging and repairing student behaviour
Interpretation	Inferring situation description from data
Monitoring	Comparing observations to expectations
Planning	Designing actions
Prediction	Inferring likely consequences of given situations
Prescription	Recommending solution to system malfunction
Selection	Identifying best choice from a list of possibilities
Simulation	Modelling the interaction between system components

Source: Durkin 1994

TABLE 5.2 General Distinctions Between Expert Systems and Conventional Programs

Expert System	**Conventional Program**
Makes decisions	Calculates results
Based on reasoning	Based on algorithm
Conducive to change	More difficult to change
Can handle uncertainty	Cannot handle uncertainty
Can work with partial information, inconsistencies, partial belief	Requires complete information
Can provide explanations of results	Gives results without explanation
Symbolic reasoning	Numerical calculations
Primarily declarative	Primarily procedural
Control and knowledge separated	Control and knowledge interlaced

Source: Kaetzel & Clifton 1995

The first factor provides many advantages, not only because problems can be solved without participation of human experts, but also important savings and improvements are made and the number of people with access to knowledge increases. Another remarkable contribution of expert systems is the increment in reliability that can be achieved, due to the reliability associated with computer operations and sometimes to the joint participation of groups of experts, which is possible with expert systems. In addition to the above reasons, the use of expert systems is especially recommended for the following conditions (Shams 2001):

- Human experts are expensive and difficult to find.
- Knowledge improvement is needed and when there is a lack of knowledge among all those who need it.
- Knowledge is difficult to acquire and is based on rules that can only be learnt through experience.
- Available information is poor, partial and incomplete or when problems are incompletely defined.
- When the problem is subject to rapidly changing legal rules and codes.

5.3 EXPERT SYSTEM ARCHITECTURE

The components of an expert system are shown in Figure 5.1. There are three core components that make up the expert system architecture, they are:

- The ***knowledge base*** in an expert system contains facts (data) and rules (or other representations) that use these facts as the basis for decision-making, which represents expertise in the particular domain.
- The ***inference engine*** makes inferences by deciding which rules are satisfied by facts, prioritises the satisfied rules and executes the rules with the highest priority. Inference engines contain an interpreter and a scheduler. An

interpreter decides how to apply the rules to infer new knowledge and a scheduler decides the order in which the rules should be applied.

- The ***working memory*** is a global database of facts used by the rules. It holds all information that represents the current state of the problem at hand.

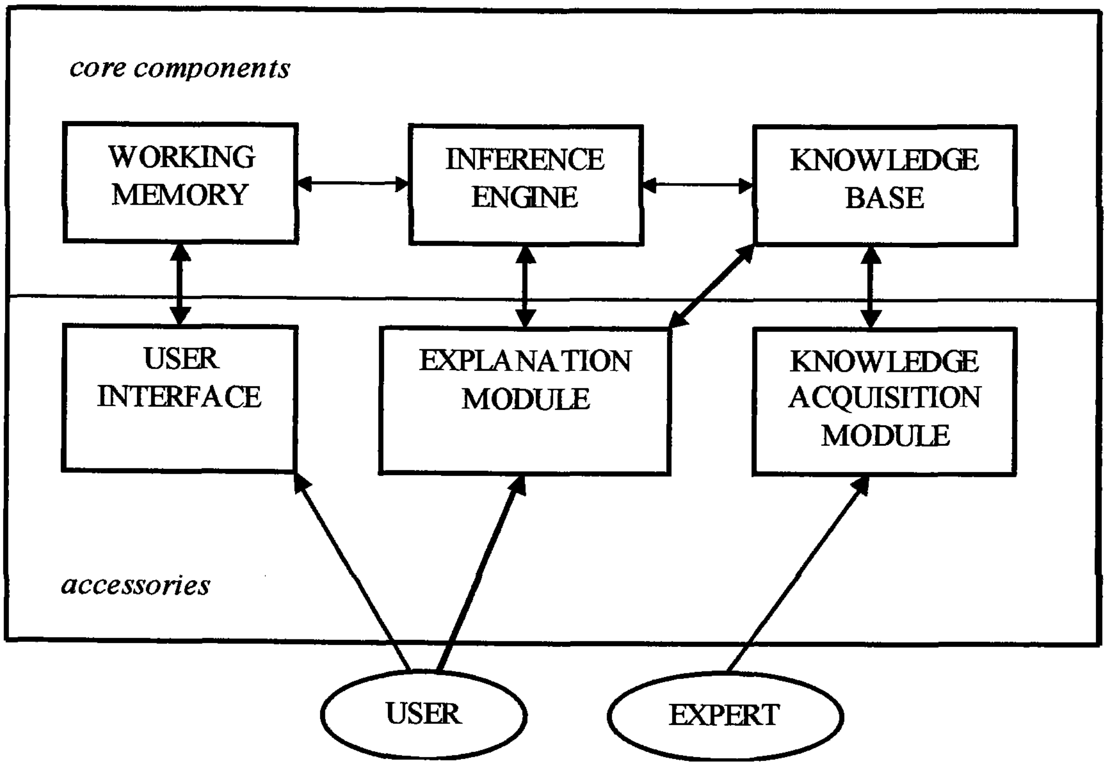


FIGURE 5.1 Components of an expert system

Source: Basri 1994

The separation of these components has provided great flexibility in the application of these systems to different problem domains. This structure also makes the system more understandable to the user and easier to modify. It is of utmost importance to know how the system uses its knowledge because an expert system must have both the appropriate knowledge and the means to use the knowledge effectively.

In addition to the three core components, the following support facilities are an integral part of an expert system (Basri 1999):

- ***User interface*** allows the user to monitor the system performance, gives information, requests explanations or controls problem solving strategies;
- ***Knowledge acquisition module*** aids the process of knowledge elicitation from the expert and codifies it into the knowledge base; and
- ***Explanation module*** allows the system, when requested or programmed, to explain its reasoning and the problem-solving process to the user.

5.4 KEY PARTICIPANTS IN EXPERT SYSTEM DEVELOPMENT

The main players in expert system development are the *domain expert*, the *knowledge engineer*, the *expert-system-building tool*, and the *user*. Figure 5.2 shows the program and key players in expert system development.

User: The term user refers to the *end-user*, the person for whom the expert system is developed. The user may be a tool builder debugging the expert-system-building language, a knowledge engineer refining the existing knowledge in the system, a domain expert adding new knowledge to the system, an end-user relying on the system for advice, or a member of the clerical staff adding data to the system. Identifying the intended users of the expert system leads to a clear idea of the focus of the output and its level of sophistication.

Knowledge engineer: The knowledge engineer is a person, usually with a background in computer science and artificial intelligence, who knows how to build expert systems. Often the task performed by a knowledge engineer is similar to that carried out by system analysts on conventional information systems which include analysing information flow, determining program structure, working with experts to obtain information, and performing design functions. Figure 5.3 indicates various tasks of a knowledge engineer.

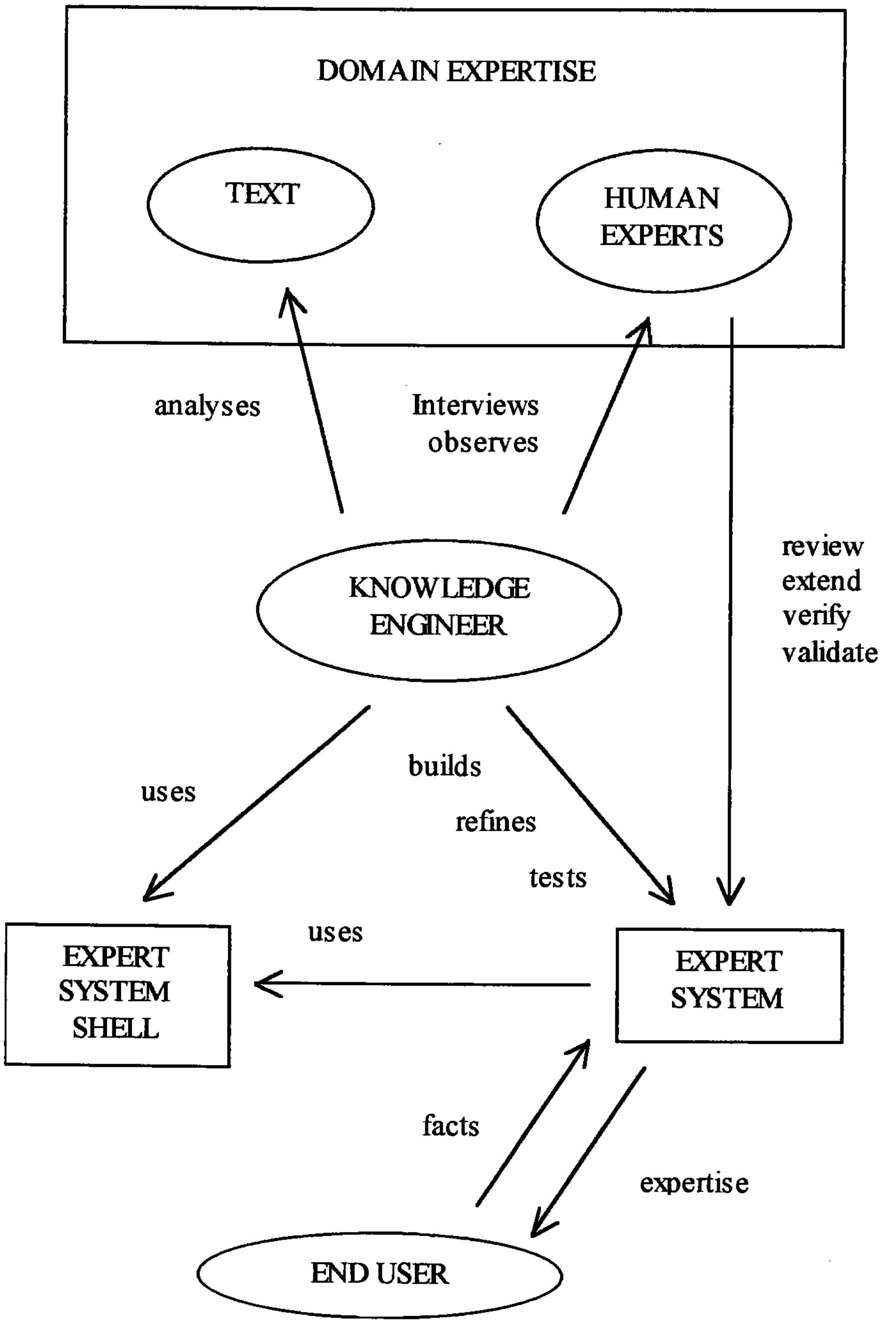


FIGURE 5.2 Programs and players in expert system development

Source: Basri & Stentiford 1995

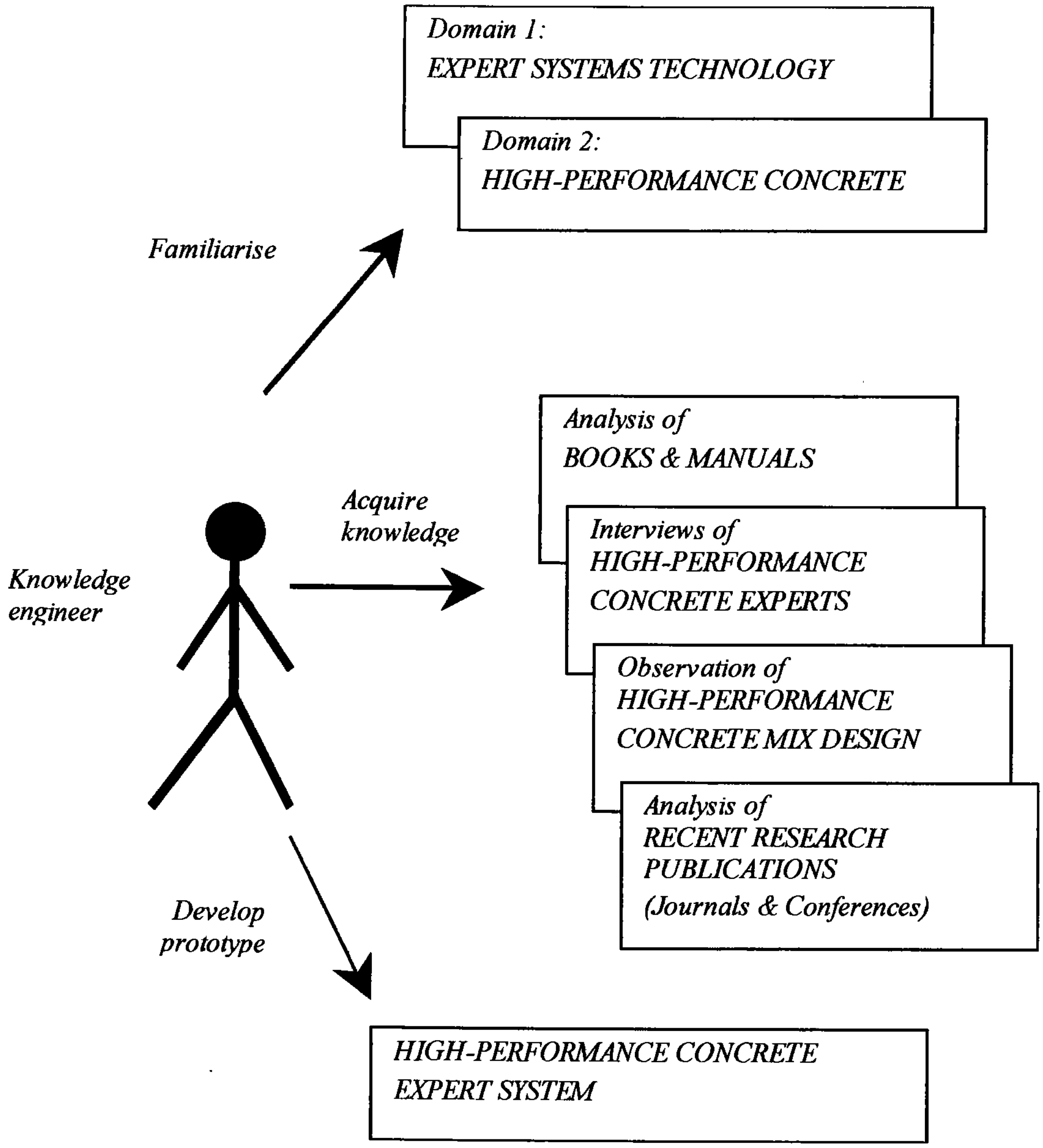


FIGURE 5.3 The tasks of a knowledge engineer

Familiarization with expert system technology can be accomplished by means of:

- reviewing the evolution and architecture of an expert system as applied in an engineering area;

- reviewing the methodologies and techniques of expert system development based on the experiences and guidelines documented by previous expert system developers;
- reviewing other expert system prototypes on related subjects;
- reviewing the built-in capabilities of expert system shells by going through the software documentation and tutorial facilities.

Domain Expert: The domain or area expert is an articulate, knowledgeable person with a reputation for producing good solutions to problems in a particular field. The expert uses tricks and shortcuts to make the search for a solution efficiently, and the expert system models these problem-solving strategies. A person's ability to serve as a domain expert will depend on characteristics such as the ability to explain important knowledge or heuristics, be introspective, be patient, and communicate effectively.

There are broad categories of expertise sources to be identified and selected from: textbooks and manuals written by experts and related professional institutions; experts involved in the domain; and research papers from journals and conferences. The advantages of multiple sources of expertise are as follows: bias towards a single view will be avoided; conflicting views manifested by several different experts provide a genuine picture of the uncertainty of the subject matter or indicate that further research is required; the knowledge engineer will not be bound or handicapped by availability constraints of any one source of expertise; and completeness of knowledge will be readily achieved.

5.5 EXPERT SYSTEMS IN CIVIL ENGINEERING

Since late 1970s, concentrated research on expert system applications in civil engineering has begun (Adeli 1988; Kostem & Maher 1986). Many expert systems have been developed in application areas including structural engineering, environmental engineering, geotechnical engineering, transportation engineering, water resources engineering and construction engineering. The expert systems listed in Table 5.3 are some examples of prototype expert systems during the early ages of expert systems in civil engineering (Adeli 1988; Bai 1992; Kostem & Maher 1986).

TABLE 5.3 Some Examples of Prototype Expert Systems in Civil Engineering

System Name	Year	Developer	Subject
SACON	1979	Bennett & Englemore	Finite Element Structural Analysis
HRS	1982	MITRE Co.	Hazardous Waste Management
BTEXPERT	1984	H. Adeli	Optimum Design of Bridge Trusses
HI-RISE	1984	M. L. Maher	Preliminary Structural Design of High Rise Buildings
SITECHAR	1985	Rehak	Interpretation of Geotechnical Site Data
HOWSAFE	1986	Ray Levitt	Diagnosis of Construction Safety
FLOOD ADVISOR	1986	Fayegh & Russell	Flood Design Expert System
CONE	1986	Mullarkey	Interpretation of Cone Penetrometer Data
RAISON-MICRO	1986	Swayne & Fraser	Acid Rain Data Analysis
EARTHMOVIN G E.S.P.	1990	N. L. Baker	Selection of Earthmoving Equipment
CRANE RISE	1991	S. E. Mohler	Tower Crane Selection for High Rise Buildings

Just as programming languages offered the civil engineer convenient aids in complex analyses and design, expert system technology has the potential to program reasoning applications and the conceptual aspects of the design process (Basri 1994). Table 5.4 shows how the development of computer science applications has benefited the civil engineering domain.

TABLE 5.4 Computer Science Applications in Civil Engineering

Serial Number	Computer Science Technology	Civil Engineering Applications
1	Programming languages	Computer aids in engineering analysis and design
2	Software engineering	Information presentation and sharing
3	Artificial intelligence and expert system	Reasoning applications and design heuristics

In engineering design, an engineer often faces a situation where the inflow of information becomes too great for effective comprehension and judgement. He then tends to choose, in the presence of these myriad of complex and sometimes confounding alternatives, an approach which is most familiar or simply nearest (physically) to him. Unfortunately this chosen design method may not be the most appropriate. This is one major area of application where expert systems can be useful (Basri 1994).

Other examples include pre- or post-processing for complex software, fault diagnosis, performance prediction and monitoring, characterisation and selection, laboratory analyses and operational guides. Already many prototypes have been developed for these applications (Adeli & Hung 1989; Celik et al. 1989; Miles & Moore 1989; Payne 1989; Shiraishi et al. 1989; Thompson et al. 1989; Wu 1997).

Leading researchers (Alim & Munro 1987; Carra & Cossu 1990) have predicted that expert systems will have a tremendous impact on the productivity of the civil engineering profession. The following list gives a few of the predictions for the future of expert systems in the field of civil engineering (Basri 1994).

(1) Expert systems will be in common integration with computational packages (Alim & Munro 1987; Cameron 1989; Levitt 1987) and computer-aided designs (Alim & Munro 1987). Adeli and Balasubramanyam (1988) reported the first expert system to integrate with mathematical optimisation.

(2) Knowledge bases will become less trivial and more general-purpose. Fenves (1989), and Burgoyne and Jayasinghe (1991) suggested that in the early formative years, expert systems may have been "oversold" such that many address trivial civil engineering problems.

(3) Expert systems with automated learning modules will become common.

(4) Multiple expert systems will "talk" to each other via "blackboards". DESTINY is one early example (Sriram 1986).

5.6 EXPERT SYSTEMS IN CONCRETE TECHNOLOGY

Expert system technology, a spin-off the artificial intelligence (AI) research, offers a new way of solving various problems related to concrete technology. Their application has been applied successfully to the design of structures and structural components, distress identification and diagnostics of the failure of structures and materials, repair and rehabilitation and in project planning.

The application of expert systems to the concrete technology has been most successful in areas where an expert's judgement and experience are important in decision making for repetitive tasks. Thus, 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). Many reviews and symposia proceedings have been published that survey expert systems applications for the concrete technology (Adeli 1988; Allwood & Stewart 1985; IABSE 1989; Kim et el. 1986; Maher 1987; Malasri et al. 1990; Seren 1988). The volume of published literature attests to the perceived importance of expert systems to concrete technology. Now it is time to reflect on these experiences and assess their impact on real-world problem solving. Growth in the application of the technology will occur due to the existence of efficient development tools and reduced development time. Also, recent successes in the business community will influence the acceptance of the technology for engineering applications.

Mohon (1990) listed 37 expert systems applications in the fields of construction management and engineering. The various characteristics of these 37 state-of-the-art expert systems can be summarized as follows:

(1) **Developer institutions:** Most of the expert systems were developed in academic institutions. Of the 37 expert systems listed, 22 were affiliated with universities, eight with research institutions and only seven with the construction industry. Although this trend is expected for an emerging technology, it delays the field testing and marketing of potentially successful expert systems. It is very likely that several of the expert systems developed at universities will never be fully operational.

(2) **Knowledge sources:** For many of the expert systems listed, the sources of knowledge encoded were not explicitly defined in the literature. It was roughly estimated that about 40% of the expert systems extracted knowledge from experts and the remaining ones from books and journals.

(3) **Hardware:** Twenty-four of the 37 expert systems listed were developed on the IBM PC class of microcomputers, and ten were developed on LISP machines and the rest three were developed on other types of hardware. The trend was away from LISP machines and toward advanced PCs and workstations.

(4) **Software:** Eighteen of the 37 expert systems used commercial expert system shells; seven were developed on expert system environments like KEE, ART, KNWOELDGECRAFT, and OPS5; seven were implemented in AI programming languages (four in PROLOG and three in LISP); and five were developed in other proprietary languages/environments which indicated the popularity of expert system shells.

(5) **Knowledge representation:** Rule-based knowledge representation was the most popular scheme, used in 19 of the reported systems.

Mohon (1990) predicted the following trends for future expert systems in concrete construction:

(1) The next few years will see several small expert systems and company-proprietary expert system routinely used within the industry. A good number of these expert systems will be capable of interfacing with graphics, database management programs and algorithmic programs; and

(2) The expert system building process will consolidate and document construction knowledge currently dispersed among many individuals, journals and books. This consolidation of domain knowledge will give rise to the building of larger expert systems, which will have frame-based-knowledge representation with graphic input and output, will be integrated with several external programs and have a blackboard architecture. Furthermore, most of them will be implemented in more efficient languages like "C" and will run on UNIX-operated workstations.

5.7 EXPERT SYSTEMS IN CONCRETE MIX DESIGN

Expert systems have characteristic attributes of combining factual knowledge with judgment, are able to handle incomplete and uncertain data and can communicate with their users in the natural language. As a result they have a special appeal for the concrete technology especially for concrete mix design. In spite of this appeal, there are currently very few operational expert systems in the field of concrete mix design. Successes in using expert systems technology to develop practical applications for the concrete mix design are relatively few, compared with advances in computer aided design, real-time control and data analysis. One reason for this may be a lack of awareness by the industry as to what expert systems currently exist, what their capabilities are and who their developers are. Another reason for this may be the constraints in acquiring knowledge about concrete technology.

The following sections discuss the result of a survey of the existing prototype and operational expert systems that have been developed for the purpose of concrete mix design. The discussion includes those that are representative of the areas of the concrete mix design and that have received the greatest attention from expert system developers. A majority of the expert systems developed so far for concrete mix design are available on microcomputers, have the rule-based knowledge-representation scheme and are implemented using commercial expert system shells.

(a) COMIX (Smith 1987)

COMIX is a rule and frame based expert system that gives recommendations on the design of normal weight concrete mixes. It was developed to provide expert knowledge to concrete technologists, design engineers and consultants. The mix design is based on the New Zealand concrete code "Specification for Concrete Construction". The system relates the type of structure to the consistency and the placement method. The system recommends a water-cement ratio from a specified strength and calculates the amount of cement. The volumes of coarse aggregate and sand are finally calculated and the masses of the components of the concrete mix are calculated and displayed. The system was developed at the Central Laboratories in New Zealand.

(b) Concrete Mix Designer (Malasri & Maldonado 1988)

Malasri and Maldonado (1988) developed a prototype rule-based expert system, which was named "Concrete Mix Designer". The system provides the proportion of the trial mix of concrete. It was developed using the Personal Consultant Plus expert system shell in the Department of Civil and Architectural Engineering of the University of Miami. Computer programs were also written in Basic to provide question and answer capability. The system is useful especially for engineering students as well as practicing engineers. The main limitation of the system is that it was developed only for normal weight concrete with strength ranging from 17 MPa (2500 psi) to 35 MPa (5000 psi) without the provision of using any admixture.

(c) EXMIX (Akhras & Foo 1994)

EXMIX is a rule-based goal-driven knowledge-based system for the proportioning of normal concrete mixtures. It is capable of selecting proportions of mixing water, cement and aggregates, with consideration being given to the effects of air-entraining admixtures and moisture conditions of aggregates. The system is basically divided into eight blocks or groups. EXMIX was developed using an expert system shell called Level 5. It was developed in accordance with CSA A23.1-M90 (Canadian Standards Association 1990) and ACI 211.1-89 (ACI Committee 211 1989). It also conforms to building code ACI 318-89 (ACI Committee 318 1989) with respect to concrete quality requirements. A user's manual has been prepared for the current version of EXMIX. On a trial basis, both the program and the manual have been sent to two community colleges in Canada for educational purposes.

(d) Expert System for Concrete Mix Design (Bai & Amirkhanian 1994)

Bai and Amirkhanian (1994) developed a rule-based expert system to assist the user in concrete mix design, including the necessary adjustments to the design. The system can handle mix designs for normal-weight concrete, heavyweight concrete and lightweight concrete. Besides workability, consistency, strength, durability and density, the expert system considers other criteria such as admixtures, transportation, and air temperature that affect the concrete mix design. The expert system development package for this project was EXSYS Professional, a ruled-based expert system shell. The concrete mix design that is determined by the expert system is presented on a spreadsheet (i.e., QUATTRO PRO). The knowledge incorporated into the expert system is taken from technical literature (e.g., ACI manuals, ASTM standards, etc.), interviews with experts and a survey of several experts. The system was developed at the Department of Civil Engineering of Clemson University of the USA. It was tested on three projects. The system's selection of concrete proportions compared favourably with the experts' selections.

All these developed expert systems can handle only ordinary concrete and most of them do not consider criteria such as use of admixtures, which affect the concrete proportions. Also, most of them have no function to diagnose the performance failure of the trial mix and to make the necessary adjustments to the mix. Most of these systems are rule-based systems, work using DOS operating system and do not consider the cost of concrete mix selected. Most importantly, they do not consider the criteria of mix design for high performance concrete such as use of superplasticizer, silica fume, ground granulated blast furnace slag (GGBS), fly ash and so on. Therefore, these systems cannot be used for mix design of high performance concrete.

5.8 EXPERT SYSTEMS FOR DURABLE CONCRETE

Expert system technology has also been applied to the selection of ingredients of durable concrete. DURCON (Clifton et al. 1985; Clifton & Kaetzel 1988; Clifton & Oltikar 1987; Kaetzel & Clifton 1988) and HWYCON (Kaetzel et al. 1993) are two expert systems that give recommendation on the selection of concrete constituents for durable concrete as explained in the following sections.

(a) DURCON (Clifton et al. 1985)

An expert system prototype called DURCON was developed by Clifton et al. (1985). The purpose of developing DURCON was to demonstrate the application of expert system to improve the process of selecting constituents for durable concrete. Four major deterioration problems were covered by DURCON: freezing and thawing, corrosion of reinforcing steel, sulfate attack and alkali-aggregate reactions. The knowledge of DURCON was acquired from the American Concrete Institute 'Guide to Durable Concrete' (ACI Committee 201 1977) and from ACI Committee 201 members. The knowledge was divided into four sub-systems, each representing an area of durability. DURCON was developed originally in the conventional programming languages of Fortran and Pascal. It was later converted to the Insight expert system shell and in 1988 upgraded to the Level5 PC shell. DURCON was designed to run on an IBM PC/XT/AT using the DOS operating system. The system has been distributed to ACI constituents for critique. An ACI 201 task group is currently revising the system to include new knowledge from the revised ACI 201 guide.

(e) HWYCON (Kaetzel et al. 1993)

The Highway Concrete (HWYCON) expert system was designed to assist highway department personnel involved in diagnostics, selection of materials, and repair and rehabilitation activities to make better decisions about concrete structures. HWYCON's Concrete Materials (CONMAT) component of the knowledge base gives recommendations on the selection of materials for the design of durable concrete in corrosive, sulfate, freeze-thaw and alkali-aggregate reactive environments. CONMAT was intended for use by concrete specifiers. The HWYCON knowledge base was developed using knowledge from multiple sources: expert team; published literature; field distress guides; ACI guides; ASTM and AASHTO guides; and results from Strategic Highway Research Program (SHRP). Its knowledge base includes digitised photographs, drawings, facts, and rules-of-thumb, explanatory information and tables. The user answers questions about the structure and its environment to get recommendation. Visual information helps the user to identify distresses and answer questions better. The system was developed using the Level5 Object expert system shell program. It was designed to run on desktop and also on portable computers for field use. It is an operational expert system being used by US state, local government and city transportation departments. Three thousand copies of the system have been distributed.

However, these systems were developed on the basis of earlier editions of the guide and do not include knowledge from the recent editions. Both of these systems consider only four major durability issues. They do not consider exposure conditions such as acid, carbonation, abrasion and seawater that are also causes of durability problems of concrete. Thus the knowledge bases of these systems regarding durability of concrete are not considered as complete sources of knowledge for the domain.

5.9 EXPERT SYSTEM AS A TOOL FOR MAKING HIGH PERFORMANCE CONCRETE

Concrete mix design involves complicated issues, and the correct ways to perform this can be achieved with expert advice and experience (Bai & Amirkhanian 1994). Mix design of HPC (high performance concrete) is more complicated because HPC includes new materials like superplasticizers and supplementary cementitious materials (e.g., silica fume, fly ash, fillers etc.). Traditionally, experienced civil engineers, largely based on their experiential knowledge, do the job of mix design. However, experts are not always available, nor do they always have the time to consult all possible references, review available data and so on. Some companies do not have personnel with the experience to make the necessary decisions regarding concrete mix design. The conventional computer programs are useful only in manipulating the numerical data and providing mathematical reasoning for the final selection. They lack the intuition reasoning based on heuristic knowledge such as experience and rules of thumb (Foo & Akhras 1993). It is believed that the problem of making HPC can be alleviated if the engineer can be augmented with an expert system for affirming his judgment.

The nature of mix design and durability aspects of high performance concrete readily lends itself to applications involving knowledge-based expert systems. These are multidisciplinary areas whose problems may require specialized expertise in such diverse fields as engineering, chemistry, mathematics, statistics, geology and economics. The mechanics of mix design and durability aspects for high performance concrete are often too complex to be modelled using traditional methods thus forcing design engineers to rely more on experience and intuition. Since individual engineers will not always be well versed in all of these areas, expert systems can serve as valuable support tools to supply solution-directed knowledge in unfamiliar areas.

Expert system technology is particularly suitable for making high performance concrete for the reasons set out below.

- Expert systems make extensive use of approximate methods or heuristics, experience, and "rule-of-thumb". Expert systems use heuristics because of the tasks these systems undertake such as a combination of possibilities, limitations on time to make a decision, uncertainty/unreliability of information, cost of gathering information, incompleteness or too much data, inconsistency, ill-defined concepts and weak inference.

- The multidisciplinary nature of domain of high performance concrete expertise including that of engineers, mathematicians, statisticians, chemists, geologists and economics etc.

- The scarcity of human experts.

- The minimal need of rigorous mathematical analysis and modelling.

In identifying the problems that lend themselves to solutions using expert systems, it is often useful to try to determine whether the following characteristics apply (Hushon 1990): the situation occurs often and is complex; the knowledge of experts is required (higher reasoning); the situation is dynamic with uncertainty involved; and there is a need to achieve a consistency of response. These are often the cases for making high performance concrete. In addition, expert system technology is especially suitable for making high performance concrete for the following reasons:

- There are a variety of inexpensive, off-the-shelf expert system development packages that makes the technology available to a wide range of potential expert system developers. They can become the knowledge engineers themselves because the expert system shells dramatically expand the talent pool of people able to work creatively on a vast array of potential applications.

- Expert system technology can now run on microcomputers that commonly exist all over the world.

- A substantial number of applications of relatively small, simple expert systems can make a useful contribution for making high performance concrete since many of the everyday problems and solutions of high performance concrete may not be as complex as thought to be.

5.10 EXPERT SYSTEM DEVELOPMENT

The process of expert system development or, knowledge engineering, is the extraction, articulation and computerization of knowledge. It can be viewed as five highly interdependent and overlapping phases (Dym 1987; Terry 1991; Waterman 1986): (1) *task analysis*, (2) *knowledge acquisition*, (3) *prototype development*, (4) *expansion and refinement*, and (5) *verification and validation*. Although the phases of expert system building can be distinguished, there is actually no simple way to describe the order in which they take place (Basri 1999). Task analysis normally does happen first and testing last, but at any time during system development the knowledge engineer may engage in any other aspects of the process. Figure 5.4 is a flow chart showing the steps in building an expert system.

5.10.1 Task Analysis

Knowledge engineering process begins with the analysis of the domain tasks. Task analysis is a methodology tool that can be used to describe the functions a human expert performs in solving the problems and to determine the relation of each task to the overall job (Basri 1999; Durkin 1994). There are no established rules for the completion of the task analysis, which implies that the function may determine the form. The results of the analysis are used to determine the subsequent strategy, methodology and techniques employed for prototype development. The knowledge engineer and domain experts determine the important features of the problem. These include identifying the problem itself (e.g., type and scope), the participants in the development process (e.g., additional experts), the required resources (e.g., time and computing facilities), and the goals and objectives of building the expert system (Waterman 1986).

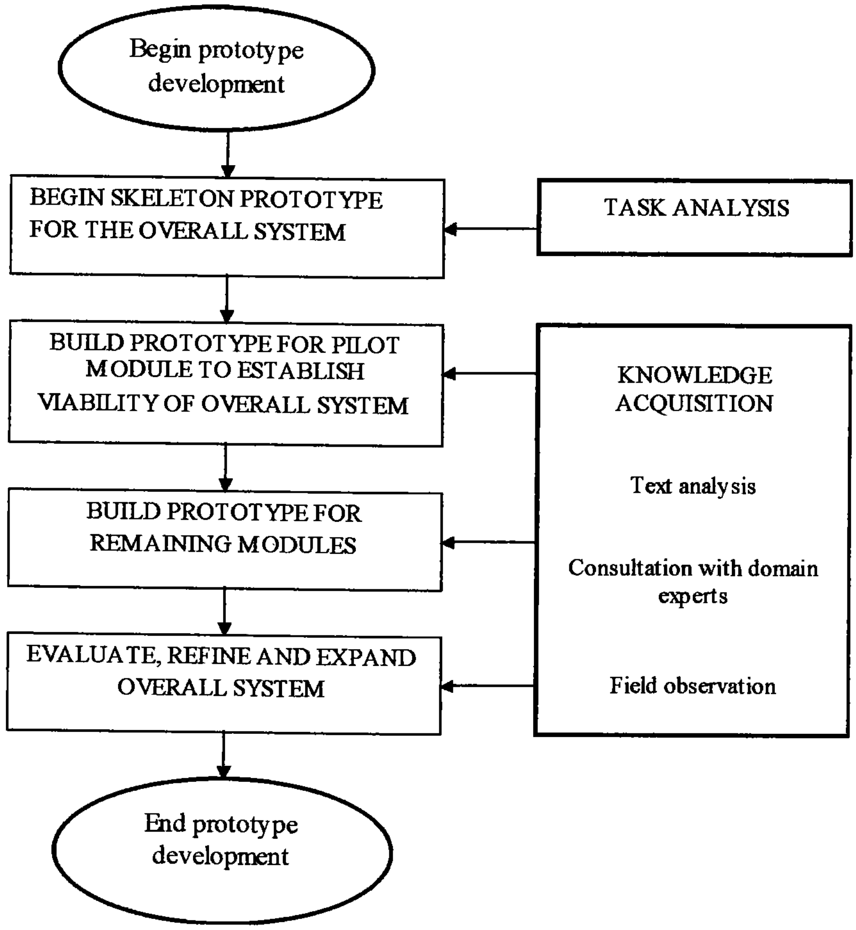


FIGURE 5.4 Expert system development process

Source: Basri 1999

The developer must determine that the problem is well suited to the use of expert system technologies and the problem has not already been solved to the satisfaction of the client by other types of conventional programming such as modelling, decision support or databases. Expert system development projects must be reasonably scoped to avoid failure in tackling an overly complex problem. It is important that the expert must be available and the problem must be capable of being solved by conventional means since it does not make sense to attempt to solve the problem if the answer is unknown. The problem should have recognized boundaries, which means that there should not be an infinite set of solutions. The investment in an expert system application must produce a payoff either in terms of improved productivity, improved designs or measurable profits (Basri 1999; Durkin 1994; Waterman 1986).

Task analysis involves expressing the key concepts and relations in some formal way, usually within a framework suggested by an expert system building language. It requires the knowledge engineer to map the recognized concepts, subtasks, relations, and other information into formal representation mechanisms. Thus, the knowledge engineer should have some idea about appropriate tools for the problem by the time the prototype begins. The results of the analysis are used to determine the subsequent strategy, methodology and techniques employed for the prototype development (Basri 1999).

5.10.2 The Knowledge Acquisition Process

The knowledge acquisition stage is considered as the most important, difficult, and time-consuming phase of expert system development (Basri 1994; Basri 1999; Basri & Stentiford 1995; Cohn et al. 1988; Durkin 1994; Prerau 1987; Waterman 1986). It is defined as the transformation of problem solving expertise from some knowledge source to a program (Buchanan et al. 1983). The main processes involved are problem definition, implementation and refinement. The knowledge acquisition process is sometimes referred to as knowledge elicitation or extraction. It is defined as the process of transferring problem-solving expertise from a knowledge source (e.g. human experts or documents) and transforming it into some convenient form of subsequent representation as a computer-compatible base (Basri 1999; Durkin 1994).

There is no formal methodology applicable for methods of knowledge acquisition. It is important to carefully check on factors such as: familiarity of the knowledge engineer with the domain; availability of human experts and expert literature; personality of human experts; management environment and financial constraints.

The task of a knowledge engineer is to extract, articulate and computerize knowledge (Durkin 1994). This requires a demanding range of skills for effective knowledge manipulation from an average engineer. Knowledge in an expert system may originate from many sources, such as textbooks, reports, databases, case studies, empirical data and personal experience, but the dominant one in today's expert system is expert literature. The characteristics of an ideal human expert are: his skills must be acquired from complex experience, he must have a special way of working with tacit knowledge and he must be regarded as an expert by his peers. The common methods of knowledge acquisition are set out below (Basri 1999).

- **Text analysis:** The knowledge engineer locates relevant books, technical papers and other documents, examines their contents, and extracts knowledge and expertise from them.

- **On-site observation:** The knowledge engineer watches the expert solving real problems on the job, acting as a passive observer without interfering.

- **Problem discussion:** The knowledge engineer picks up representative problems and informally discusses them with the experts to explore the kinds of data, knowledge and procedures needed to solve specific problems. The main objective is to determine how the expert organizes knowledge about each problem, represent concepts, hypotheses and handles inconsistent, inaccurate and imprecise knowledge and data relating to the problem.

- **Structured interview analysis:** This method is suitable for knowledge engineers who are already familiar with the domain. The aim is to elicit knowledge in depth, structured and definitive manner from the expert. The subject matter of interview can take several formats.

- **Inductive machine learning:** A computer system designed to extract knowledge by examination of a sufficiently large and diverse set of initial conditions and the resulting decisions made by an expert. The system will induce a general rule that covers all domain cases from sample cases. This is a new field that is still being actively researched.

However, there are also major problems to be acknowledged in the knowledge acquisition process which are mainly due to: lack of knowledge traceability; redundancy of knowledge; escalation of man-hours and costs; diversion from the domain; knowledge at the wrong level; lack of appropriate documentation and disgruntled experts (McGraw & Harbison-Briggs 1989).

5.10.3 Prototype Development

At this stage, the knowledge engineer turns the knowledge into a working computer program. Constructing a program requires content (from domain knowledge made explicit during formalization which is the data structure, inference rules and control strategies), form (specified by the language chosen for system development) and integration (involves combining and reorganizing various pieces of knowledge to eliminate global mismatch between data structures and rules or control specifications) (Basri 1999).

The first prototype should proceed rapidly because one of the reasons for implementing the initial prototype is to check the effectiveness of the design decisions made during the earlier phases of development. Many researchers (Basri 1994; Basri 1999; Basri & Stentiford 1995; Hart 1986; Johnson et al. 1987; McGraw & Harbison-Briggs 1989; Trimble 1989) recommended the rapid prototyping approach where knowledge acquisition is integrated with the development of the prototype. The first prototype development is often the interesting subset of the task chosen to demonstrate the credibility of the whole project. For an encouragement and as a focusing device, rapid prototype development may be based solely on texts. The time scale for the development of a typical prototype varies according to the nature of the problem. There are three conditions under which rapid prototyping can be successful in developing solutions to knowledge-intensive problems, they are: the problem should be sufficiently small that one person can understand and encode the problem directly; the system is experimental and will not require maintenance or modification and a tool should be available for developing the prototype (Basri 1999).

One of the major steps in prototype development is knowledge representation. The methods of knowledge representation are described in Section 5.11.

5.10.4 Expansion and Refinement

Expansion and refinement involves evaluating the performance and utility of the prototype program and revising it as necessary. It involves checking for mistakes in knowledge acquisition to ensure that the knowledge base correctly reflects that of the experts', and to establish that the system performs with an acceptable level of accuracy, user-friendliness, and overall usefulness. It is reviewed repeatedly until a sufficiently satisfactory prototype is achieved (Basri 1999; Durkin 1994; McGraw & Harbison-Briggs 1989; Waterman 1986).

5.10.5 Verification and Validation

A suitable verification and validation process is carried out using conventional techniques for software verification and validation, an expert system verification tool, or qualitative techniques (Basri 1999; Stunder 1990).

5.11 KNOWLEDGE REPRESENTATION

Knowledge representation is the method used to represent knowledge for use in an expert system (Basri 1994; Reichgelt 1990). A notation is needed to allow a knowledge engineer to represent knowledge about the problem domain. It must also be possible to build a mechanism that can draw inferences from the knowledge so represented, in order to make decisions and solve problems. A language in which knowledge can be formally described is needed. The language should have a well-defined syntax governing what expressions are allowed in the language and a well-defined semantics governing what the expressions mean (Basri 1999).

According to Firebaugh (1988), the key difference between knowledge representation in expert systems and conventional databases in the procedural programs is the nature of the knowledge. Databases traditionally represent simple numbers, strings or arrays, but in expert system development, there is the need to represent complex information. Three techniques that have been shown to be effective for knowledge representation in expert systems are production rules, frames, and semantic nets. The practical choice of representation techniques depends on the capabilities of the expert system tools used (programming language, toolkit or shell).

Jackson (1986) identified three criteria with which to judge knowledge representation languages.

- **Logical adequacy:** The language should allow the knowledge engineer to say what he wants to say about the problem domain.
- **Heuristic power:** It must be possible to draw useful inferences from knowledge represented in the language in order to solve problems. There is often a trade off between the expressiveness of the language and the ease of its use.
- **Notation convenience:** It should be straightforward to express knowledge in the language and the expression so represented should be easy to read and understand.

5.11.1 Production Rules

Production systems based on the use of production rules for manipulating strings of symbols were studied in the 1940's; later variants of these systems were used (Basri 1999). MYCIN and other early expert systems proved that the most successful technique was proven to be production rules (sometimes termed inference systems or rule-based systems). In fact, most expert system architectures and shells are based on this technique. The success of this technique is due to its simplicity and ability to represent expertise in an intuitive and expressive manner. It is knowledge-intensive and the discrete nature of individual rules enhances modularity and modifiability (Basri 1994). A rule-based system consists of the following elements (Basri 1999).

- **Working memory**: This element represents the knowledge that the system has gathered about the current problem instance. The information in working memory comes from the user and the inferences made so far. It is up to the person writing the rules to ensure that the format used to add items to the working memory is the same as that expected by the rules, which are trying to match items. Facts can be stored in working memory in many different ways. Commonly object-attribute-value triples are used, where the triple (A, B, C) means, "The B of A is C", e.g. (Cement, Specific gravity, 3.14) means, "The specific gravity of cement is 3.14".

- **Rule base:** It is a set of rules and instructions consisting of a triggering pattern. When the triggering pattern matches elements in the working memory, the instruction may be carried out. The result of acting on the instructions is a change in the working memory. A production rule resembles a simple sentence. It consists of a condition part, IF (sometimes termed as condition, premise, or antecedent) on the left hand side, and an action part, THEN (sometimes termed as consequence or conclusion) on the right hand side. If the condition of the rule is satisfied by the working memory, the rule becomes applicable and will be fired or executed by the inference engine.

- **Interpreter:** The interpreter controls the firing order, resolves conflicts if more than one rule is applicable, and repeatedly applies rules to the working memory until a goal state is reached. The interpreter repeats cycles through the following steps: (i) retrieval - finds all rules whose triggering patterns match the working memory; (ii) selection - chooses a rule from a set of matching rules (or the conflict set); and (iii) execution - executes the selected rule instructions.

There are two main control strategies in which rules can be used in a rule-based system; one is called *forward chaining* (or data-driven inference) and the other is called *backward chaining* (or goal directed inference).

Forward chaining: The forward chaining control strategy is a straightforward implementation of the select-execute cycle. The triggering pattern is the LHS (Left hand side) of the rule. On the other hand, the RHS (Right hand side) of the rules commonly: add a fact to working memory; remove a fact from working memory; display a fact; or ask the user for information (and add it to working memory). The interpretation of a rule ***If X then Y*** in forward chaining is "if we know X then we can deduce Y". The user usually supplies a goal, and the algorithm terminates when the goal has been reached, i.e. there is a fact in working memory that satisfies the goal or no more facts can be deduced, whether or not the goal is satisfied. Alternatively, the goal may be defined in the rules.

Backward chaining: Working memory contains two kinds of items that are things to know and things to find out. It starts with what it wants to prove, and executes rules that are relevant to establishing it. The triggering pattern is the RHS of a rule and must be matched against the current goal (or a thing to find out). The interpretation of a rule ***If X then Y*** in backward chaining is "if we want to find out if Y is true then we should try to find out if X is true". The user supplies a goal: a statement whose true value is to be established, or an object-attribute pair whose value is to be found. Backward chaining recursively matches the RHS of rules in the rule base against the current goal as follows: (i) the user supplies the goal, (ii) if unknown this becomes the current goal, (iii) match goal against RHS of rules (in rule base), (iv) LHS of matching rule is either TRUE: execute RHS, FALSE: remove rule and find another matching rule, or UNKNOWN: either ask the user or make this the LHS current goal (recursion). The algorithm terminates either because it has succeeded in satisfying the goal or because it has failed after trying all the rules, which have the goal in the conclusion (RHS) without being able to satisfy the goal.

Some disadvantages of production rules are: (i) opacity of inference engine processes, (ii) operational inefficiency (too many rules may be required to perform a disproportionately minor task), and (iii) inability to learn automatically (Basri 1994).

5.11.2 Frames

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 (Basri 1994; Basri 1999). In a frame system, the concept at each node is defined by a collection of attributes (e.g. name, colour, and size) and values of those attributes (e.g. John, black, and big), where the attributes are called slots. Each slot can have procedures (arbitrary pieces of computer code) attached to it, which are executed when the information in the slot (the values of the attribute) is changed. Collections of related frames may be linked to form frame systems. A frame is a network of nodes and relations organized in hierarchical structure, which is very suitable for declarative types of knowledge. Transformation between various frames may be triggered depending on information contained in the slots and through inheritance of attributes (top-down in the hierarchical structure). A number of different objects can share the same frame, thus avoiding duplicative representation. Frame systems are useful for problem domain where expectations about the form and the content of the data play an important role in problem solving, such as understanding visual scenes or understanding speech. They are also appropriate for more complex and richer representations of knowledge. However, they are more difficult to develop compared to production rules.

5.11.3 Semantic Nets

A semantic net is a collection of nodes representing objects, concepts, events or situations, which are linked together (in no systematic manner) by arcs representing relationships between nodes (Basri 1994; Basri 1999). Arcs can be defined in a variety of ways depending on the kind of knowledge being represented. Relationships are of primary importance in semantic nets because they provide the basic structure for organizing knowledge. The main difference with frames is that there exists no particular hierarchical structure within the semantic net. It is the oldest and most general of the three knowledge representation methods. Figure 5.5 shows an example of a semantic net representing knowledge of pozzolans.

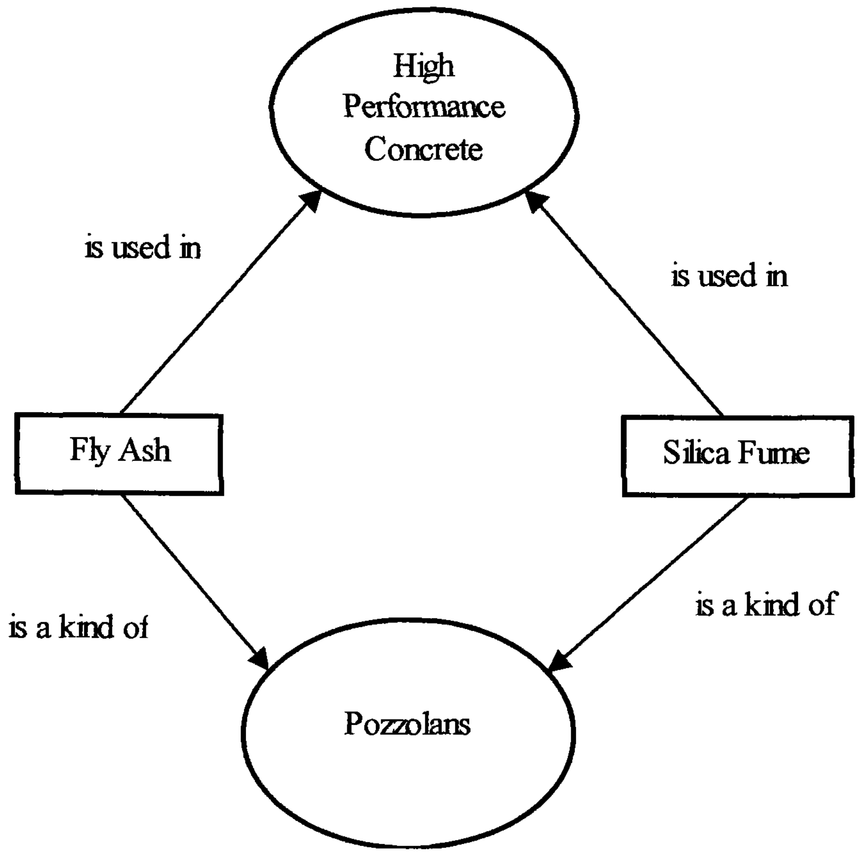


FIGURE 5.5 An example of semantic net

5.11.4 Object-Oriented Modelling

The object-oriented paradigm has been around since the early 1970s, but only became widely utilized and acclaimed recently with the advent of cheap-but-powerful computers (Basri 1999). The object-oriented design methodology is well suited to a program, which describes complex objects and the relationships between them. This method uses a special organization consisting of fundamental programming items called objects that present entities capable of exhibiting behaviour and communicating with each other via messages. When an object receives a message, it consults its database and rules to decide what action to take. The rules may be stored in directly with the object or in a higher-level object somewhere in the network hierarchy. Interactions, relations and procedures that are central to conventional programming, become secondary considerations in object-oriented programming.

The object-oriented model approaches problems by thinking about the world as set of entities or objects that relate, communicate or interact with each other. Frames and semantic nets represent knowledge based on object entities (Basri 1994; Basri 1999). Each object has distinct object-oriented approach in design and programming. While conventional structured programming is unable to satisfactorily handle heuristics and non-monotonic aspects of design, the object-oriented approach is generally more flexible and adaptable, and there is mounting evidence in the literature that it has the potential to provide solutions to these problems (Biedermann & Grierson 1993).

Booch (1991) defined object-oriented programming as "a method of implementation in which programs are organized as cooperative collections of objects, each of which represents an instance of some class, and whose classes are all members of a hierarchy of classes united via inheritance relationships". He further specified four major elements that constitute an object model (Basri 1994):

a) abstraction (of essential characteristics from the real world);
b) encapsulation (or hiding of all complexities/details within object);
c) modularity; and
d) hierarchy.

Object-oriented design requires no special language features; it can be done in FORTRAN, BASIC, C and so on. A common example of an object-oriented application is the Microsoft Windows software (as compared to DOS) used for operating systems in personal computers. Windows is simpler to, but requires much more memory and speed than DOS.

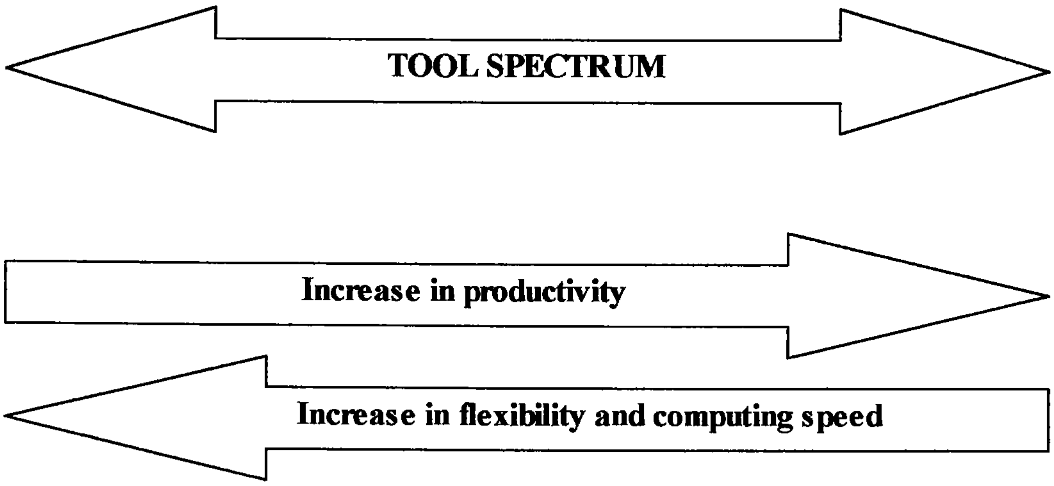
5.12 EXPERT SYSTEM BUILDING TOOLS

As with other building processes the construction of an expert system can be made considerably easier and more cost-effective through the use of tools. Tools can assist in many different areas such as knowledge acquisition, system construction, validation and testing (Basri 1999). Expert system tools are still very much in the development stages. Tools have not been designed with specific problems in mind. Expert system tools range from high-level programming languages to low-level expert system shells. Figure 5.6 illustrates the spectrum of knowledge engineering tools, their characteristics and examples.

On the left end of the spectrum are standard high-level programming languages, which are able to provide the expert system with flexibility and computing speed (Basri 1994; Basri 1999). They do not provide the knowledge engineer with a single prefabricated inference engine. Instead they offer a large set of tools from which the knowledge engineer is able to design and build a customized system suitable for the intended application. While this can lead to a more appropriate and sophisticated system, it demands the skill of experienced programmers and takes a longer time for development. At the other end of the spectrum are the expert system shells that are commercially available at relatively lower prices. With a built-in inference engine, the shell provides convenience and saves time for the expert system developer who has to just add the knowledge base. This will provide an optimum strategy for a system developer who is relatively new to artificial intelligence field with limited time available. However, some expert system developers prefer the conventional high-level languages because shells have lost their freedom and flexibility due to the imposed standard data structure format. In some instances the knowledge representation is even awkward.

Expert system shells are essentially abstractions of one or more application programs. The first expert system shell was introduced in 1972 when the pioneering expert system MYCIN was stripped off its knowledge base to become purely an inference engine, EMYCIN (Basri 1994; Basri 1999; Durkin 1994; Waterman 1986). Since then, expert system shells have proliferated and progressed rapidly, triggering a new era in expert systems development where novices in artificial intelligence can easily be trained to become knowledge engineers.

Conventional Programming Language e.g., Pascal, C, Basic, Fortran	**General Purpose Programming Language** e.g., PROLOG, LISP, LOOPS, OPS5	**Expert System Environment and Toolkit** e.g., ART, S.1, KEE, KES, TIMM, Knowledge Craft	**Expert System Shell** e.g., Kappa-PC, Xi Plus, PC Easy, Savoir



Characteristics	**Conventional Programming Language**	**Expert System Shell**
Control by	Statement order	Inference engine
Control and data	Implicit integration	Explicit separation
Control strength	Strong	Weak
Solution by	Algorithm	Rules and inference
Solution search	Small and none	Large
Problem solving	Algorithm is correct	Rules
Input	Assumed correct	Incomplete, incorrect
Unexpected input	Difficult to deal with	Very responsive
Output	Always correct	Varies with problem
Explanation	None	Usually
Applications	Numeric, file and text	Symbolic reasoning
Execution	Generally sequential	Opportunistic rules
Program design	Structured design	Little or no structure
Modifiability	Difficult	Reasonable
Expansion	Done in major jumps	Incremental

FIGURE 5.6 Spectrum of knowledge engineering systems

Source: Basri 1999

In between the languages and tools is the environment provided for the system builder. It is a collection of programming tools available to the system builder to facilitate the production of quality software, which includes editors, debuggers, system libraries, file and database managers and a variety of graphic support routines.

It is quite difficult to keep up with the latest developments since expert system shells are constantly being upgraded (Mullarkey 1987). Van Koppen (1988) suggested that a good quick start could be achieved in expert systems development by initially using shells and subsequently changing over to another more suitable tool if necessary. Thus, even with experience, it is impossible to be certain in advance that a given task is feasible for expert system application using a particular shell. Expert system developers must select the system most appropriate for the resources available such as time, money, personnel and hardware against the nature (level of complexity) of the particular task at hand (Basri 1999). Other factors that should be taken into account are the availability of tool support facilities, maintenance aspects, and reliability of the chosen tool. The shell should be proven, well-supported and well-reviewed rather than brand new even though new ones often offer more powerful features. The ideal tool for civil engineering application should have the following characteristics (Basri 1994):

a) varied knowledge representation techniques;
b) varied inferencing strategies; and
c) good interface facilities with external programs and systems.

Notwithstanding the above, Palmer and Mar (1988) concluded from experience that the real deciding factor in the practical choice of shells is not its inherent technical capability to solve problems, but rather the less "academic" aspects of quality of documentation and tutorials, reliability of after-sales services, price and length of its learning curve.

5.13 LIMITATIONS OF EXPERT SYSTEMS

Expert systems are still in the fairly early stages of development as compared to other artificial intelligent research (Basri 1999; Durkin 1994; Waterman 1986). Although expert systems hold considerable promise for concrete technologists, the user community should always bear in mind that expert systems technology still have shortcomings such as (Fenves 1989): (i) knowledge acquisition is a difficult process; (ii) current concepts and tools are based on diagnostic/interpretative domains only, and hence are not very suitable for generative/formative design methodologies; and (iii) the feasible scope for the domain is still too narrow.

It is important to recognize the difficulties in building an expert system in advance so that management and all those potentially involve in the system development are reminded to proceed with caution. According to Beerel (1987), several other difficulties encountered in developing an expert system are due to lack of resources. This might be in the form of competent personnel, appropriate software tools and/or organizational capital. The problem is further aggravated by the time required for building a system. An expert system development process takes a relatively long time starting from the conceptualisation stage to its delivery, which depends on the complexity of the problem and the number of people assigned to the application team. Another shortcoming is that the unrealistic expectations of the user make the end product appear to be ineffective.

Choosing a suitable tool for building an expert system is another expected problem. Identifying a meaningful application, defining the problem scope and selecting the appropriate tool for building expert system are the most difficult decisions that need to be made. If the software tool chosen is not appropriate for the task, the end result is destined to be less than effective. Sometimes reasons for choosing the wrong tool are that it is the cheapest or it is the most efficient and suitable for the existing hardware or the knowledge engineer is most familiar with a particular tool.

Furthermore, various problems always arise during planning and developing the expert system project. Hence, management awareness and willingness in tackling various problems will greatly improve the chances of successful system development. It is also important to bear in mind that the expert system needs to be maintained in much the same way as experts themselves need to keep abreast of their field. The system will lose its power once the knowledge it holds is outdated.

5.14 SUMMARY

In this chapter, a concise review on the history and application of artificial intelligence and expert system is presented. Expert systems in civil engineering areas are also discussed. Several developed expert systems related to concrete mix design and durability are presented. The various considerations that must be dealt with in order to ensure a sound and systematic environment for expert system development are also presented. Chapter VI explains the techniques developed and employed, particularly in the knowledge acquisition and programming stages, during the development of the HPCA (High Performance Concrete Advisor) prototype. A detailed explanation of knowledge acquisition is also presented there.

CHAPTER VI

EXPERT SYSTEM DEVELOPMENT FOR THE PROTOTYPE

6.1 INTRODUCTION

An outline of knowledge engineering for the development of expert system was reviewed in Chapter V. This chapter reports the various stages in building an expert system prototype named HPCA (High Performance Concrete Advisor), which was developed for proportioning of high performance concrete mixes and for giving recommendations on mix performance adjustment and various durability aspects of high performance concrete. From the research experience, it was found that the knowledge acquisition process is the most difficult and time-consuming part of expert system development phase. The major steps involved were the extraction of expertise, its articulation into a format that could be easily understood and programming into computer code. Knowledge acquisition began from the task analysis stage and extended into the final stages of the prototype development. The prototype was used as a demonstration to improve the confidence of the knowledge engineer and other parties. It will always be subjected to additional knowledge acquisition in order to ensure that its knowledge is up-to-date.

6.2 THE KNOWLEDGE ENGINEER

The key players in the HPCA expert system development were the knowledge engineer and the sources of expertise (see Figure 5.2). Given the *engineering* nature of the high performance concrete domain, the *Engineering Expert Systems Approach* as advocated by Simonovic and Savic (1989) was appropriately adopted. In this approach, an engineer of the domain who has mastery of expert systems technology was to become the knowledge engineer. The author assumed this challenging role – one that demanded the best all round qualities of a person (Section 5.10) as well as an acceptable degree of basic training in the fields of expert systems and high performance concrete mix design and its durability aspects. A graphical representation of this role was shown in Figure 5.3 (Chapter V).

6.3 DOMAIN ACQUAINTANCE

It is important for a knowledge engineer to gain a good understanding of the domain to enhance the building of the prototype with respect to its feasibility and evaluation (Basri 1999). The first and foremost step for the knowledge engineer is to gain the knowledge engineering skill. This task is done by becoming familiar with the essential components of expert systems technology as well as gaining a good grasp of concrete technology, specifically with respect to mix design, mix performance adjustment, cost estimation and durability aspects of high performance concrete. This assignment was accomplished by undertaking the following steps:

(i) reviewing the methodologies and techniques of expert system development from textbooks, documented manuals and guidelines on related field;

(ii) understanding the concept of concrete mix design, mix performance adjustment, cost estimation and becoming familiar with the durability aspects of high performance concrete;

(iii) reviewing the evolution and architecture of expert systems as applied in the science and engineering fields, in particular with respect to concrete technology;

(iv) reviewing some expert system prototypes developed by other expert system developers on various topics related to concrete mix design and durability;

(v) becoming familiar with expert system shell (i.e., Kappa-PC) by using the software documentation and tutorial facilities; and

(vi) interacting with other knowledge engineers who were in the process of building similar prototypes.

6.4 SOURCES FOR THE KNOWLEDGE BASE

The knowledge was extracted from multiple sources of expertise in the field of concrete technology. It is advantageous to use multiple sources in order to arrive at an acceptable agreement on procedures and ideas. The advantages of multiple sources are that no bias is shown towards one single view; there is less reliance on a single domain expert for knowledge elicitation; and the conflicting views gained represent the real situation in the field that often require further research (Basri 1994; Basri 1999).

6.4.1 Textbooks and Manuals

A pre-requisite for the knowledge acquisition process was to gain basic knowledge through detailed text analysis of textbooks and manuals. This acquired knowledge was used as the core knowledge for the development of the initial prototype modules. This phase was mainly to achieve understanding of the domain's prevailing concepts and viewpoints. Text analysis is a technique that involves consulting public domain knowledge recorded in published material (Basri 1999). It was used as the first choice technique, being the least time consuming and the least expensive compared to the others. The principal textbooks and manuals referred to in the knowledge acquisition process were as follows:

1. Aitcin, P.-C. 1998. *High-performance concrete*. London: E & FN Spon.

2. ACI Committee 201. 1995. Guide to Durable Concrete. *ACI Manual of Concrete Practice: Part 1* (ACI 201.2R-92). Detroit: American Concrete Institute.

3. ACI Committee 211. 1991. *Standard practice for selecting proportions for normal, heavyweight, and mass concrete* (ACI 211.1-91). Detroit: American Concrete Institute.

4. ACI Committee 211. 1993. *Guide for selecting proportions for high strength concrete with Portland cement and fly ash* (ACI 211.4R-93). Detroit: American Concrete Institute.

5. ACI Committee 363. 1995. *State-of-the-art report on high-strength concrete* (ACI 363R-92). Detroit: American Concrete Institute.

6. Nawy, E.G. 1996. *Fundamentals of high strength high performance concrete*. London: Longman Group Limited.

7. Neville, A.M. 1995. *Properties of concrete*. 4th ed. Essex: Longman Group Limited.

8. Safiuddin, M. 1998. Influence of different curing methods on the mechanical properties and durability of high performance concrete exposed to medium temperature. M. Sc. Thesis. Universiti Kebangsaan Malaysia.

9. Malier, Y. (ed.). 1992. *High performance concrete: from material to structure*. London: E & FN SPON.

10. Shah, S.P. & Ahmad, S.H. (eds.). 1994. *High performance concrete and applications.* London: Edward Arnold.

11. Shetty, M.S. 1993. *Concrete technology*. New Delhi: S. Chand & Company Ltd.

12. Day, K.W. 1999. *Concrete mix design, quality control and specification*. 2nd Edition. London: E & FN SPON.

13. Zain, M.F.M. 1995. The study on the physical properties of surface layer concrete under the influence of medium temperature environment. Ph. D. Thesis. Kyushu University, Japan.

14. Mehta, P.K. 1991. *Concrete in the marine environment.* New York: Elsevier Science Publishers Ltd.

The textbooks and manuals contained a great variety of knowledge on concrete mix design and durability for both the normal and high performance concrete. Aitcin (1998), Safiuddin (1998), Nawy (1996), Shah and Ahmad (1994), and Malier (1992) specialized in the theory and practical aspects of high performance concrete. The remaining publications covered various topics on mix design, mix performance adjustment and durability of concrete. Most of the texts and manuals were written by the USA experts, one was written by expert from the United Kingdom, one from Canada, one from France, one from Australia, one from India, one from Japan and one from Malaysia. These provided a wide variety of information and experiences of many people working in high performance concrete, including mix design and durability, from various parts of the world. Using a range of textual sources was an advantage in ensuring that most of the considerations and common problems encountered within the domain were covered by the text analysis exercise.

6.4.2 Research Publications

Expertise drawn from research publications in journals and conference proceedings represented a recent and more specialized data source within the domain to improve the strength, workability and durability performances of concrete. Hence such expertise was acquired as "desirable additions" to the knowledge base during the *refine and expand* phase of prototype development. The core journals consulted were:

1. ACI Materials Journal (published by American Concrete Institute).
2. Journal of Materials in Civil Engineering (published by ASCE).
3. Cement and Concrete Research (published by Elsevier Science)
4. Cement, Concrete and Aggregates (published by ASTM).
5. Cement and Concrete Composites (published by Elsevier Science).
6. Journal of Construction Engineering and Management (published by ASCE).

7. Journal of Computing in Civil Engineering (published by ASCE).
8. Concrete International (published by American Concrete Institute).
9. Materials and Structures (published by RILEM).
10. Magazine of Concrete Research (published by Thomas Telford Publishers).
11. Concrete (Published by the Concrete Society of UK)

The information gained was evaluated and when conflicting views arose, they were rationalized at this stage. The relevant rules and facts were then extracted, and later codified as part of the core knowledge base. There were some aspects of the textbooks that were too general or outdated to be of practical use. For example, authors of various textbooks and manuals were not in agreement regarding strength requirement for high performance concrete. However, in these cases the data was compensated for by other information from other textual sources. Generally, some aspects that were not dealt satisfactorily in one source were covered in others.

6.4.3 Consultation with Domain Experts

The knowledge from domain experts was obtained through communication with the experts. This interaction consisted of a series of systematic consultations, extended over a period of a few months. The domain experts were selected from experienced high performance concrete practitioners from Malaysia and Indonesia (see Appendix C). The experts were chosen from individuals who: (i) were currently practicing, (ii) had sufficient knowledge and experience, (iii) had available time, (iv) possessed good communication skills, (v) were willing participants, and (vi) were acknowledged as experts by their peers.

Due to financial and time constraints, most of the consultations with the domain experts were done informally and conversation was not taped. The first consultation with domain a expert was important for rapport building between the knowledge engineer and the expert. It had an introductory function to identify the domain, motivate the expert, clarify roles and build general confidence. The subject of discussion was rather open and unspecific with the objective of building an appreciation of expert systems technology and convincing them of the importance of their expertise. The initial topics discussed were the introduction to artificial intelligence and expert systems; the background and objective of the project; the role of the domain expert in the knowledge acquisition process; and the demonstration of a pilot module prototype.

The next stage for the knowledge engineer was to outline specific goals and questions for the knowledge acquisition session. The knowledge engineer picked a set of representative problems and informally discussed them with the experts. The goal was to determine how the expert organized knowledge about each problem, represented concepts and hypotheses, and handled inconsistent, inaccurate, or imprecise knowledge and data relating to the problem. The information gathered was used to clarify or extend information received via other techniques.

The experts were asked to describe a typical problem for each category of answer that could arise. This helped the knowledge engineer to define a prototypical problem for each category of answer to select a strategy or basic approach to solving a given problem. This exercise also suggested ways to organize knowledge hierarchically in the expert system. During the discussion, the experts often introduced new terms, concepts and relations. When this happened, the knowledge engineer asked the expert to define these new factors and relate them to the existing body of concepts and relations, which required redefining or combining with existing concepts in the evolving knowledge base. Once the knowledge engineer had formulated some specialized rules relating to particular problems, the rules were then revised to make them as general as possible without compromising their ability to produce a solution in the context of the original problems.

The last stage to complete the knowledge acquisition process was on-site observation method, which was done in Malaysia on high performance concrete mix design and adjustment projects (see Appendix C). The knowledge engineer relied on watching the expert solve a realistic problem rather than describing the process. The knowledge engineer did not interrupt the expert with questions or comments during the problem solving to avoid influencing the expert's problem-solving approach.

Instead, the transcript of the session was analysed later to clarify the fact with the expert's help. This process avoided missing important tacit aspects that experts sometimes take for granted.

6.5 TASK ANALYSIS

The foremost step for task analysis was to ensure that the domain under consideration was suited to the application of expert system technology. The domain of mix design and durability aspects of high performance concrete is characterized by many features that make it appropriate and relevant for this purpose. Currently, high performance concrete is seen as an emerging concept that can provide construction industries with an effective means of producing durable concrete structures. Mix design and adjustment of high performance concrete as well as durability aspects are specialized fields of study for many engineers, but they prefer to leave the job to others who are especially trained and experienced in its practice.

The knowledge necessary for making high performance concrete is multidisciplinary, thus making it desirable to harness a wide variety of expertise into a unified, easily accessible and understandable form. In the mix design and adjustment of high performance concrete considering durability aspects where such expertise is scarce, this need is even greater. Finally, the design process should not be too time-consuming or complex, since it is mostly based on sound mathematics and heuristics as well as basic engineering principles.

As mentioned earlier, the important characteristic of an expert system is that it should have a clearly defined scope. For the design of high performance concrete mix and its adjustment, it was limited only to the first trial batch, batch composition for a project, conversion from field composition to SSD composition and vice versa, cost estimation, and recommendation on mix performance adjustment. It also included recommendation on various durability aspects. However, it is claimed that these stages often determine the overall cost effectiveness and performance of a concrete construction project.

Having established the suitability of the domain for expert systems application, the next step was to plan a methodology for identifying the component tasks of the domain and the subtasks that made up each of them. Figure 6.1 shows the conceptual flow diagram of task analysis methodology. One way to approach the task analysis was to classify the tasks according to types of human behaviour. This allowed the knowledge engineer to study the major functions currently performed by human experts and to identify those that could be emulated by the expert system. Additionally, this structure allowed the knowledge engineer to identify important information that the human expert used in making decisions.

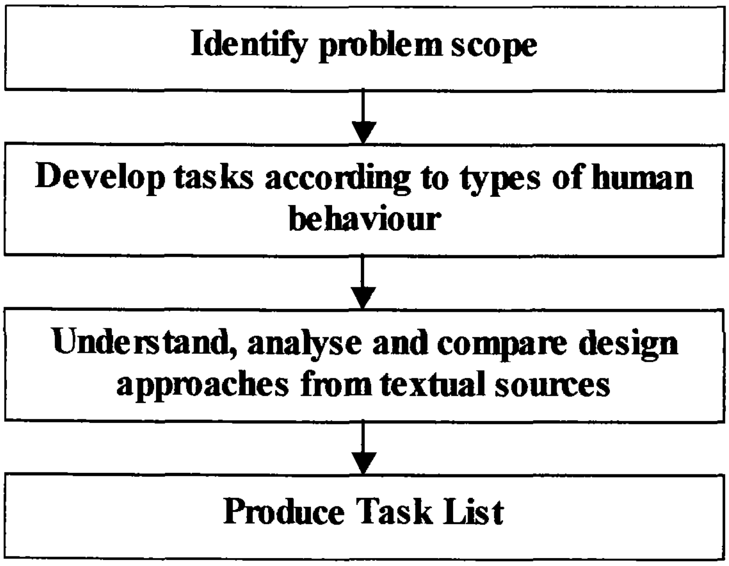


FIGURE 6.1 Task analysis methodology

Source: Basri 1999

The task selection process began by becoming familiar with, understanding, analysing and comparing the design approaches adopted from textual sources. They were selected from various approaches endorsed by domain experts before formulating the final task lists. Devising a set of acceptable behavioural classifications and task verbs enabled the knowledge engineer, other than those who originated the analysis, to study and use the information within the analysis diagram. In addition, such documents became part of the overall documentation system and later could be used to support the system prototype development.

The primary determinants of the final form of task analysis included variables such as the purpose of the task analysis, the desired detail within the task analysis and the existing information of a similar nature. The types of subtasks within each task were then identified by analysing the contents of the relevant topics in each of the textual sources. Varying degrees of emphasis were given to each of the texts on each of the component task topics. In considering the required amount of detail, the knowledge engineer recognized that the expanded task analyses could be very time-consuming, might require extensive observation of the human expert, and could require assistance from an engineer. Any differences in emphasis and priorities were noted, the reasons identified, and finally, the most appropriate version was adopted.

6.5.1 Formalization of Tasks

The design, adjustment and cost estimation of a mix for high performance concrete as well as recommendations on durability aspects consist of many distinct tasks. Each of these tasks formed the basis for the development of knowledge base modules that made up the components of the system. The proposed tasks and their integral subtasks are shown below:

Task 1	**Mix Design**
Subtasks:	Design first trial batch
	Design trial batch for laboratory
	Calculate one cubic metre SSD composition
	Calculate batch composition.

Task 2	**Mix Performance Adjustment**
Subtasks:	Diagnose causes for strength failure and advise accordingly
	Diagnose causes for workability failure and advise accordingly
	Diagnose causes for durability failure and advise accordingly.

Task 3	**Cost Estimation**
Subtasks:	Calculate cost of a given mix.
	Calculate cost of batch composition.

Task 4 **Durability**

Subtasks: Advise on corrosion resistance

Advise on alkali-aggregate reactivity potential

Advise on sulfate attack

Advise on seawater exposure

Advise on acid attack

Advise on carbonation

Advise on abrasion resistance

Advise on freeze-thaw resistance.

There were several other tasks related to the domain but they were not included in the system development as knowledge base modules for various reasons. These tasks are listed in the following paragraphs:

1. *Mixing and placing of concrete:* This task has already been established by another expert system developer. It is a wide knowledge base module on its own which demands consideration of various aspects of expert system development.

2. *Crack diagnosis of concrete structure:* This task also has been established by another expert system developer. Furthermore, it requires a substantial input of time and effort.

3. *Predicting service life of a concrete structure:* This task has already been established by another expert system developer. It is also a wide knowledge base module on its own demanding substantial efforts.

4. *Commercialisation of the system:* Knowledge base is not applicable for this task because it is characterized by divergent requirements and needs of university governing authority and construction company.

6.6 PROTOTYPE DEVELOPMENT

6.6.1 Modular Development Approach

The domain of mix design and durability aspects of high performance concrete was approached from a modular perspective. The task analysis exercise (described in section 6.5.1) first identified and separated out the component tasks of high performance concrete. Even though some inter-dependency did exist between each of these component tasks, they were dealt with as separate entities for the development of distinct knowledge modules, with each knowledge module solving a specific problem aspect within the domain.

Such a modular approach facilitated the development of the HPCA (High Performance Concrete Advisor) expert system by providing simplicity and ease of knowledge organisation. The knowledge extracted during the acquisition process was grouped together into modules. This allowed for pruning and trimming of the inference net using simple questions at the beginning of each module consultation. This approach also helped in avoiding the various problems of rule overcrowding as reported by Schreiner and Chard (1990). The modular approach also enabled the building process to be suitably phased to match the available resources (time, manpower, finance, etc) during the various development stages. The various phases of the HPCA prototype development were shown in part of Figure 5.4 (Chapter V).

6.6.2 Incremental Rapid Prototyping Method

The modular approach suggested that the *incremental rapid prototyping* methodology as described by Hart (1986) should be followed. The first prototype was one of many would-be prototype modules that eventually constituted the whole expert system. In *rapid prototyping*, knowledge acquisition is integrated with prototype building (Basri 1994). It is widely advocated and especially suitable when the development tool allows easy expert system development, as was the case for the tool used in the HPCA development.

A pilot prototype was first built rapidly to solve one of the domain tasks with the objective of exploring the feasibility of the whole project. The task of designing the first trial batch was selected for this purpose because its knowledge was relatively easy to deal with, being fairly straightforward and abundantly available in most textbooks and manuals. Following Trimble's (1987) recommendation, the prototype was developed based on data acquired during the domain familiarisation stage (which included an initial text analysis from the textual sources shown in section 6.4.1). The process was repeated for the other modules incrementally.

6.7 SELECTION OF A BUILDING TOOL FOR THE PROTOTYPE

The range of expert system building tools and their selection criteria were mentioned in detail earlier in Section 5.12. It was suggested that the development process of an expert system could be made considerably easier and more cost-effective through the use of tools that could be selected from high-level programming languages to low-level expert system shells.

An expert system shell was preferred for the development of the prototype over other types of building tools since it offered the advantages of ease of manipulation and increased productivity. Without the necessity for any new or special knowledge representation or inferencing technique, most commercial shells could adequately cater for the needs of the chosen domain. Many knowledge engineers (Acuna et al. 1997; Basri 1994; Basri 1999; Basri 2000; Jamil 2003; Recio et al. 1999; Sapuan et al. 2002; Shaked & Warszawski 1995) explained the features and advantages of Kappa-PC shell (IntelliCorp Inc. 1997) and selected it as their expert system building tool. Considering their explanation, Kappa-PC shell was chosen as the building tool for the present prototype. Moreover, Kappa-PC shell was chosen because of its proven reliability. 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.

The selected expert system shell, Kappa-PC, runs on Microsoft Windows, which has true “windowing’ capabilities. The main advantage of Windows applications is their use of graphic packages, popular data files and conventional programming languages to interface with the user, making human-computer interaction more natural and easier.

Another advantage of Kappa-PC is that it can integrate well the *object-oriented programming* and *rules,* which allows knowledge representation using hybrid technique. The object-oriented programming is used to represent the behaviour of individual objects, while rules are used to represent IF-THEN reasoning, which may or may not relate to individual object.

6.8 KAPPA-PC FEATURES

Kappa-PC provides the developer with the flexibility and power required in supporting complex applications. It allows the knowledge engineer to develop prototype using hybrid knowledge representation technique. The major elements of Kappa-PC are set out in the following paragraphs (Basri 1994; Basri 1999; IntelliCorp 1997).

(i) True object-oriented development

Object-oriented programming provides a natural way of representing real-world entities that have the ability to act on their own. It also allows the developer to create objects that are intuitive representations of the real-world counterparts. For example high performance concrete is an entity or object, made up of various ingredients, i.e. water, binder, aggregates, and admixtures. It has fresh and hardened states. It has properties like workability, strength and durability. Such realistic representations allow Kappa-PC applications to represent knowledge clearly. Its objects provide powerful modelling of real world solutions, increased development productivity, simplified maintenance, and a strong foundation for future application expansion.

Object-oriented programming using Kappa-PC enhances the modularity of the prototype by organizing the knowledge bases into object modules and object hierarchies. When an application is composed of relatively independent modules, a change in one module can be made without having to make corresponding changes elsewhere.

(ii) Interactive graphical development

Kappa-PC has the following tools as unique windows or editors in the development system:

- The **Object Browser** is the primary editor for describing and managing application objects. It allows viewing and modification of the objects and their relationships in the application. The graphical view of the object hierarchy in an Object Browser window is shown in the next chapter (Chapter VII).

- The **Session Window** is the main interface for the end-users of a Kappa-PC application, i.e. either to accept input from the users or to display the output of the application. It allows users to efficiently create user-friendly, dynamic application interfaces. Kappa-PC supports multiple overlapping session windows. Each window is a Kappa-PC object that is easily customisable (colour, menus, position, background actions, etc.). Examples of various Session Windows are shown in Chapter VII.

- The **KAL (Kappa-PC Application Language) Interpreter** window provides an interface for the system developer to write a program, permitting access to more than 300 functions and other user-defined functions, classes, instances, rule and goals within KAL. In addition, KAL Interpreter window allows: access to codify development in an interpreted format; extensive help commands to shorten the learning curve; syntax checker for increased productivity; cut and paste between interpreter and other tools; execution of external programs; and saving work sessions as an ASCII file.

- The **KAL Code Debugger** allows the efficient debugging of KAL code.

- The **Find/Replace Utility** allows for "local and global", "find" and "replace" text that appears anywhere in the knowledge base.

- The **Edit Tool** window provides high-level browsing of application components and easy access to knowledge editors for rule processing. The system developer could create, examine, modify, delete and rename any knowledge items through this window.

(iii) Powerful, high-level application development language

The Kappa-PC Application Language (KAL) is a powerful, integrated, high-level language for rapidly defining, building, testing and refining applications without stopping to compile and link. KAL compiles to efficient ANSI C code for manipulating application objects, mathematical functions, strings, lists, logic, files, control blocks, windows, popup menus, input forms, application graphics, interfaces and system access.

(iv) Integrated graphic interface libraries

The dynamic graphic interface libraries can be accessed through the Session Window editor, which include the following features:

- graphics are represented as objects which make maintenance easier;
- active images which accept interactive input from the end-user;
- capabilities for drawing two dimensional images;
- links to bitmap or metafile graphics;
- single and multiple value menus;
- mouse position detection and tracking;
- specific font and colour control for individual images; and

- the system developer specified colours, fonts, titles, scroll bars, borders, mouse left and right click actions, positions, size, and keyboard mapping.

(v) Intelligent links to popular software

Kappa-PC intelligent links to popular software help preserve current software investments while adding additional functionality to existing applications. They allow dynamic interaction and simplify data access. Among the advantages of Kappa-PC are its ability to interface with databases, spreadsheets, graphics, CAD packages, conventional programming languages and ASCII files.

(vi) Expert system tools (Rule-based reasoning)

Kappa-PC rules broaden the scope of possible applications by allowing developers to incorporate judgment and experience and to take a consistent solution approach across an entire organization.

6.9 KNOWLEDGE REPRESENTATION IN KAPPA-PC

In the Kappa-PC system, the components of the domain are represented by structures or entities called *objects*. Objects can either be *classes* or *instances* within classes that can represent concrete things or tangible concepts. Each object possesses *slots*, or sets of attributes that define the state of the object, and *methods* or sets of procedures/rules that describe the objects behaviour. *Methods* are invoked to objects by means of messages. Messages are the primary way in which objects communicate and interact with each other. The examples for *classes, instances, slots* and *methods* are demonstrated in the next section (Section 6.9.1).

In Kappa-PC's object-oriented system, classes of objects are arranged as a hierarchy of modular objects with top-down inheritance of slots and methods. Each object is an abstraction of real-world system components, and encapsulates or hides its attributes and behaviour from other objects. Abstraction, encapsulation, modularity and hierarchy constitute the four fundamental features of a truly object oriented model (Booch 1991).

6.9.1 Representing the Domain with Classes, Instances and Slots

A representation of the domain can be created using a model-based system. In this case the domain is mix design and durability aspect of high performance concrete. The various aspects of high performance concrete mix design and durability are represented using *classes, instances* and *slots*.

Classes, subclasses, and instances are objects representing entities (physical or conceptual) of the knowledge domain. A *class* is a collection or a group of particular *instances*. A *subclass* is a class that is part of or a subset of another class; it is below a class in hierarchy. On the other hand, *ancestor* and *descendant* describe indirect relationships between classes, subclasses and instances. The hierarchy in Figure 6.2 shows that *Cement* and *Pozzolanas* are the descendants of the *Binders* class and vice versa *Binders* is the ancestor of *Cement* and *Pozzolanas*.

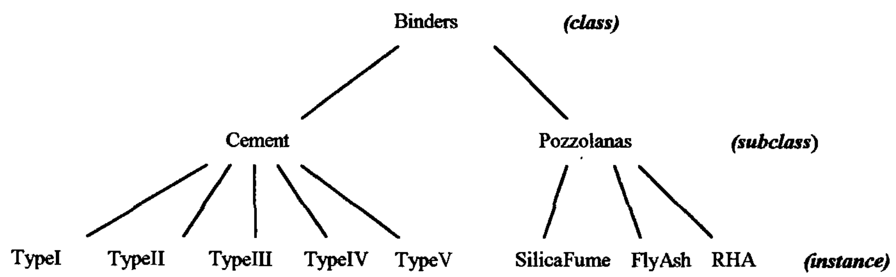


FIGURE 6.2 Hierarchy of the *Binders* class

In order to tailor an object so that it represents all the important properties of the real object, a number of *slots* could be given. *Slots* can be thought of as descriptions of a particular object. They add detail structure, list attributes or properties which can be single or multiple-valued, textual strings or numeric, or even Boolean. Slot values can be pre-defined, restricted to a range or set of pre-specified possible values, user-defined or determined from user consultations with the system. For example the slots of the instance *Silica Fume* (Figure 6.2) includes, among others, content in percent, specific gravity and content in kg/m^3. Table 6.1 shows these slots and the corresponding slot values.

TABLE 6.1 Description of an Instance Using Slots

Instance: SilicaFume, Parent Class: Pozzolanas		
Slot Name	**Slot Value**	**Comment**
ContentPercent	10.00	User defined value
SpecificGravity	2.20	User defined value
ContentKgPerM3	51.60	System derived value

6.9.2 Representing Processes with Methods, Functions and Rules

In Kappa-PC, the processes of the domain are represented in three different ways using *methods, functions* and *rules*. The first approach involves enhancing objects so that they represent the behaviour of the things to which they correspond. The behaviour of a slot is specified by creating *methods*. *Methods* are written in KAL (Kappa-PC Application Language) and stored within the object. For example, the *TestResult* instance of the *MixPerforAdj* class receives slot values from the user and stores the values in the *PerformanceCriteria, StrengthPerformance,* and *WorkabilityPerformance* slots. When the user requests for recommendation, the inference engine uses these slot values to search for possible recommendation about the performance failure. The recommendation function uses a method named *InvalidCombination* defined in the *MixPerforAdj* class. If the performance criteria and performance value do not match, then the method posts a message informing the user that there is an error in data input involving invalid combination of data.

The next approach to representing processes involves *functions*. *Functions* are also written in KAL and can either be user-defined or built-in the system. Kappa-PC provides a library of over 300 functions that allow for the manipulation of its knowledge base. These functions range from simple numeric operators such as "+", to logic functions such as *Let*, and complex functions such as *PostInputForm* and *ForwardChain*.

The third approach involves using *rules* to represent the relationship between causes and effects which specifies the conditions under which a particular action or inference can occur. Furthermore, *rules* can specify complex relationships between the components of a system. The syntax for *methods, functions* and *rules* is identical; therefore, the same syntax can be used to add an object, to write a method or to create a rule. Below is an example of a rule written for the *Sulfate Attack* submodule of the knowledge base:

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 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. 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.

6.9.3 Inheritance of Slots and Methods

Inheritance is an important feature of Kappa-PC knowledge bases. Objects can have their own slots, inherit slots from ancestors, or share slots and communicate with each other using methods. Slots, slot values and methods are inherited top-down within the hierarchy of objects. Hence, the general properties need to be specified only once, in the slot of the appropriate class. Similarly, methods common to members of a class need only be defined once in that class. For example, *InitialContent* method was defined only once in the *Ingredients* class. Consequently all the descendant classes, subclasses and instances inherit this method.

The main advantage of inheritance is the ease and efficiency of creating and maintaining knowledge objects. The general properties and behaviour can be stored in one class object, which are applicable to all of its descendants automatically. It can also be used to express a relationship between a class and its subclass. Another advantage of inheritance is conceptual clarity. The similarities (and differences) among objects are readily apparent because similar objects share the same parents. To find out what makes a group of object similar, one only needs to look at their common parent. This clarity makes understanding a knowledge base easier (Basri 1994; Basri 1999).

6.9.4 The Rule System

In Kappa-PC, rules are equipped with an inference engine, which is a special program for managing rules and applying them as appropriate. Inference refers to the process of applying production rules to a particular situation in order to produce conclusions relevant to that situation (Basri 1994; Basri 1999). There are two types of rule-based reasoning, i.e. forward chaining (or event-driven reasoning) and backward chaining (or goal-directed reasoning). The forward and backward chaining control strategies were explained in detail in Section 5.11.1.

An Example of Rule Inferencing:

Rule inferencing can be illustrated by an observation of two simplified, typical forward chaining rules (written in English) taken from one of the modules in the prototype, i.e. the *Mix Performance Adjustment* module as shown below. When the user commences consultation for getting recommendation, then the inference engine scans its knowledge base and uses its intelligence to give recommendations based on the information about the performance failure and test results supplied by the user.

Rule 1:

IF	*strength performance of the designed mix is inadequate*
	And *strength test result indicates intragranular fracture,*
THEN	*strength performance of the mix can be improved using stronger coarse aggregates.*

Rule 2:

IF	*strength performance of the designed mix is inadequate*
	And *strength test result indicates that fracture surface passes through hydrated cement paste,*
THEN	*strength performance of the mix can be improved using lower water-binder ratio.*

It is assumed that the user has only these two rules to work with. It is also assumed that, for the user's case, the strength performance of the mix is inadequate. Given this, what would happen if the value of the strength test result slot were set to "*intragranular fracture*"?

To initiate forward chaining, the user asserts a new fact. In this case, the user would assert that the strength test result indicates "*intragranular fracture*". As a result, Kappa-PC's inference engine discovers that a premise of a rule matches this new fact. It goes on to check the other premise (i.e. whether strength performance of the mix is inadequate or not). Once the other relevant slot value of the premises is verified, the first rule applies, and the recommendation is given as stated ahead: *strength performance of the mix can be improved using stronger coarse aggregates*. The inference engine, in this case, has forward chained from a new fact through rules to give recommendation. This recommendation is displayed in a transcript image for the user. The user can view the explanation for the reasoning process and the knowledge base items that were utilised to arrive at that recommendation.

6.10 SUMMARY

The techniques developed and employed, particularly in the knowledge acquisition and programming stages, during the development of the HPCA (High Performance Concrete Advisor) prototype are explained in this chapter. A detailed explanation of knowledge acquisition is given. There are three stages in the knowledge acquisition process, which include collecting knowledge from the literature, interviewing experts, and field observation. The findings from this research are also discussed. Chapter VII describes the HPCA system architecture, its various modules, their characteristics and utilization guidelines.

CHAPTER VII

SYSTEM ARCHITECTURE

7.1 INTRODUCTION

The implementation of knowledge acquisition and prototype building for the HPCA (High Performance Concrete Advisor) has been described in Chapter VI. This chapter reports the system architecture of the finished product, detailing the HPCA prototype components and its operational mechanisms. The chapter begins with a description of the object-oriented model of the domain, the HPCA's general architecture, its object hierarchy, attributes and behaviour. The various components of the HPCA, i.e. the main design modules (four) and accessory facilities (data input, advice, and explanation), are then outlined. Finally, the characteristics of the HPCA user-interface are described.

7.2 OBJECT-ORIENTED MODEL FOR THE HPCA DOMAIN

The object-oriented approach for the HPCA domain involves the development of a model based around object entities, both physical and conceptual. The attributes of these domain objects are defined as object slots, whose values as a whole represent the current state of the problem at hand. The interactions between, instructions to, and processes of the objects, which as a whole represent the design and recommendation procedures, are codified in the form of methods, functions, rules and messages. This object-oriented model for the HPCA domain is further described in the following sections.

7.2.1 General Architecture

The general architecture of the HPCA can be related back to that of a generic expert system (Figure 5.1). With the adoption of an object-oriented development tool, the nature of each system component becomes to some extent more varied. The characteristics of the basic system components, i.e. the **knowledge base**, **working memory**, and **knowledge manager**, are still retained. Figure 7.1 shows the basic components of the HPCA system.

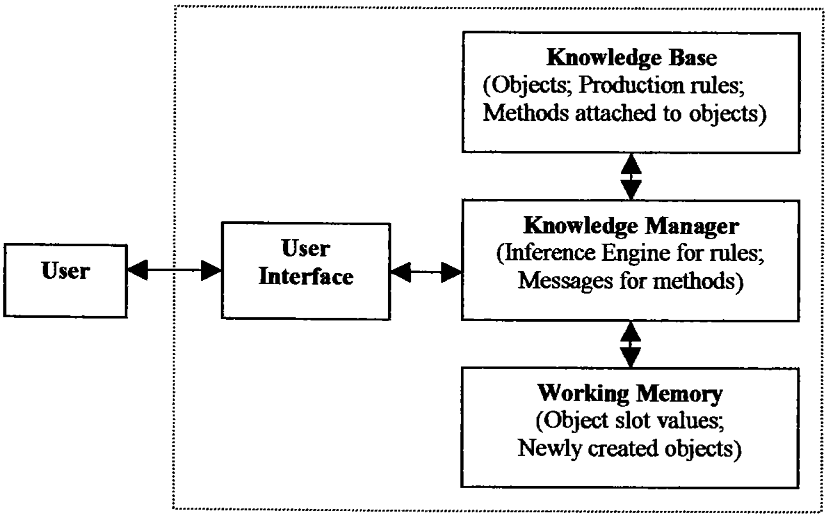


FIGURE 7.1 Basic system components of the High Performance Concrete Advisor (HPCA)

The *knowledge base* of the HPCA represents expertise in the domain of high performance concrete. The expertise have been acquired and codified in the form of production rules, object entities in a specified hierarchy, and the various methods attached to the objects.

The function of the *knowledge manager* is carried out by the rule inference mechanism, and in addition, the messages and monitors that activate the methods. According to Basri (1994), the term *knowledge manager* is more appropriate than *inference engine* because the latter gives the impression that it is restricted to rule inferencing only. The *knowledge manager* manipulates information in the working memory, utilising the knowledge base to produce new information for the working memory.

Initial and derived information representing the current state of consultation, is registered in the *working memory* in the form of slot values, newly created objects, and newly created slots.

7.2.2 Object Representation of the HPCA

The Object Browser window in Figure 7.2 represents the top-level hierarchy in the object model developed for the HPCA domain. The class HPCA represents the overall prototype that is comprised of two major subclasses, *DesignModules* and *AccessoryModules*. The subclasses of these two objects constitute the component modules of the prototype.

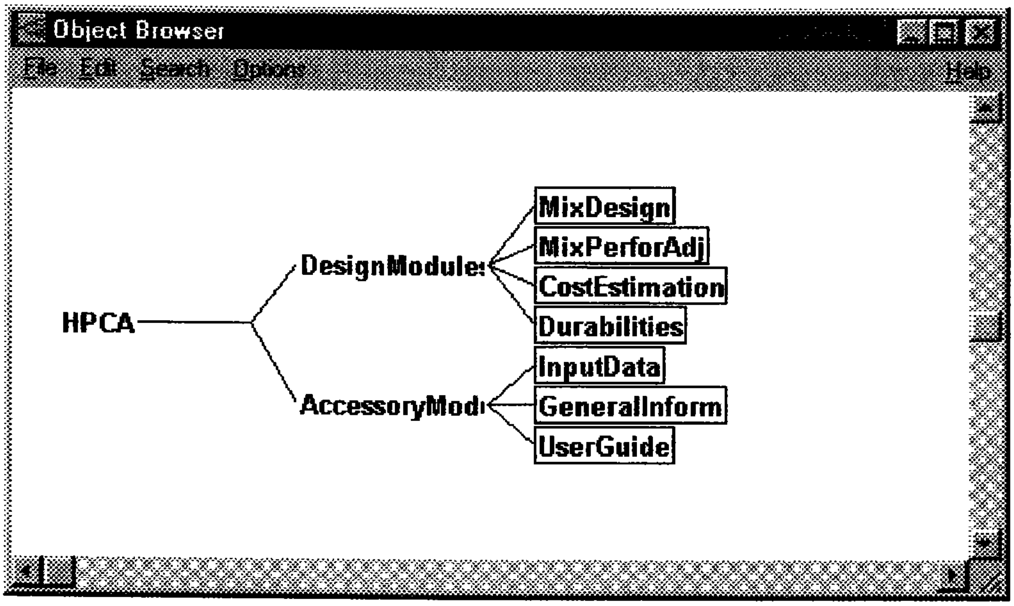


FIGURE 7.2 Top-level object hierarchy of the HPCA

The module names in Figure 7.2 are boxed to indicate that their subclasses are not shown. Further description of these modules is given in Sections 7.3, 7.4 and 7.5. The object hierarchy of the *DesignModules* class is shown in Figure 7.3.

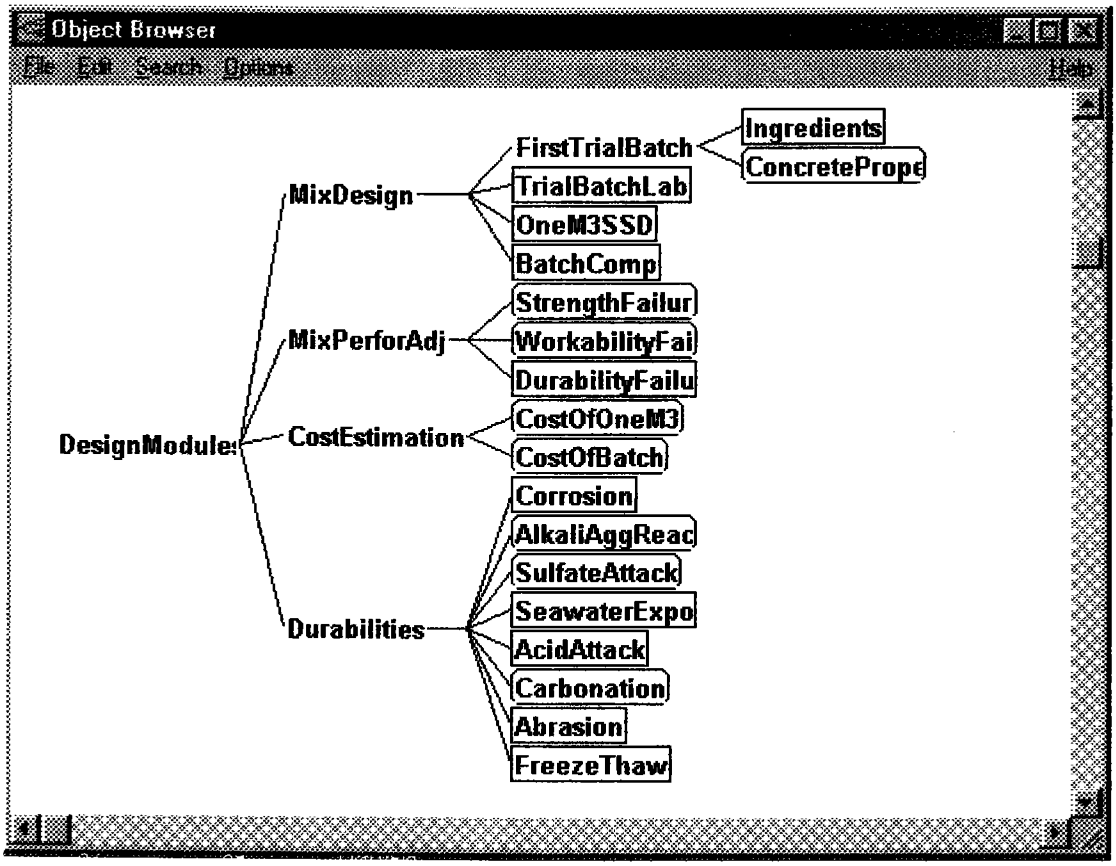


FIGURE 7.3 Object hierarchies of the Design Modules of the HPCA

As an illustration of a typical object representation in the HPCA domain, the hierarchy of the *Ingredients* class that is a descendant of the *FirstTrialBatch* class (see Figure 7.3) is shown in Figure 7.4. *Water* is a physical object entity that represents an ingredient of concrete. It contains the slots: (i) *Content*, which indicates initial content of water obtained from saturation point of superplasticizer; (ii) *ContentKgPerM3*, which indicates water content in one cubic metre of concrete mix; (iii) *ContentFieldAdjustment*, which indicates the amount of water after adjusting for water contributed by moisture conditions of aggregates and water contained in liquid superplasticizer; (iv) *ContentLabTrial*, which indicates the amount of water required for laboratory testing of a trial mix; and (v) *ContentOneM3SSD*, which indicates the amount of water required for one cubic metre of concrete mix for SSD (Saturated-and-Surface-Dry) conditions of aggregates. These slots are inherited from the parent class *Ingredients*.

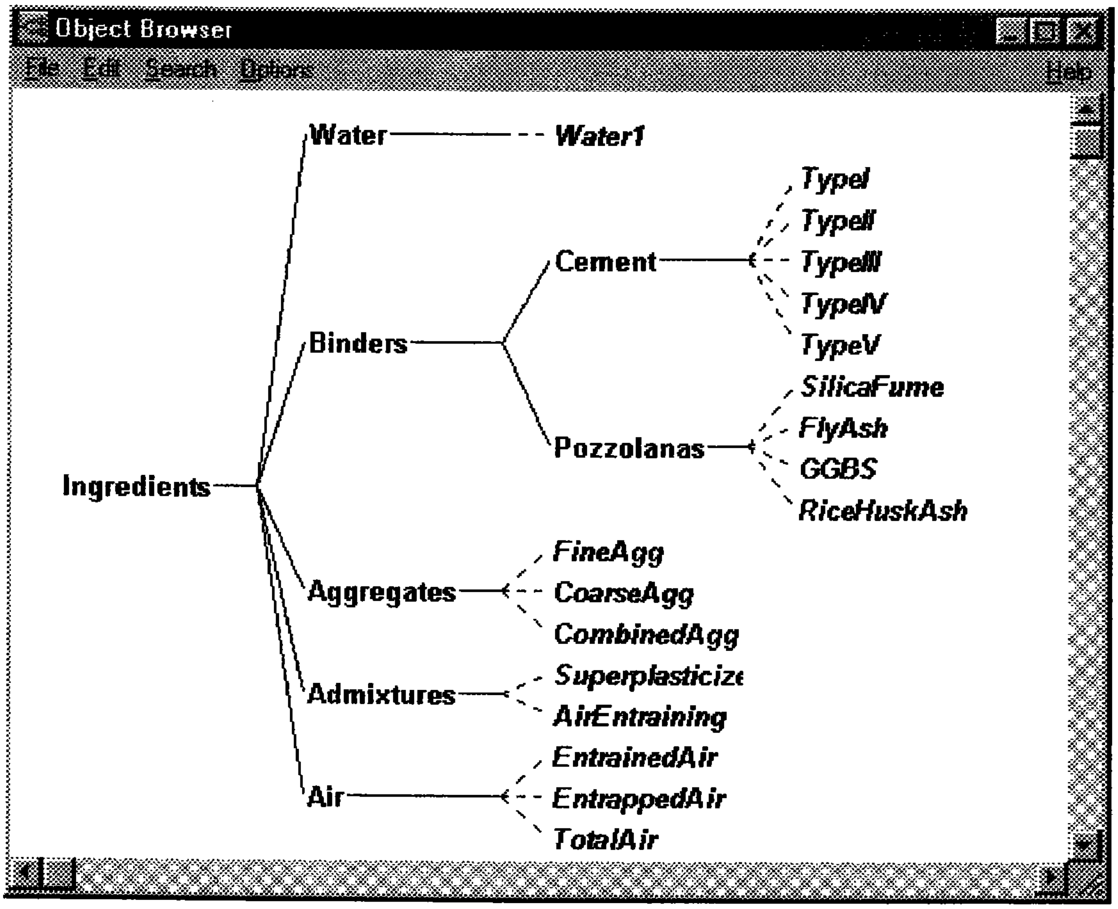


FIGURE 7.4 Object hierarchy of Ingredients class

The objects under the *Binders* class represent the actual physical binding components that are required for high performance concrete production. These components are further divided into two classes, i.e. *Cement* and *Pozzolanas*. The objects contain slots that describe their properties. An example of slots of *SilicaFume* object, which is an instance of *Pozzolanas* class, was shown in Table 6.1 (Chapter VI).

The *Aggregates* class contains objects that represent the various types of aggregates that contribute solid volume to concrete namely *FineAgg, CoarseAgg* and *CombinedAgg*. Their slots, inherited from the *Ingredients* class, include *Content, ContentKgPerM3, ContentFieldAdjustment, ContentOneM3SSD* and *ContentLabTrial*. In addition, they have other slots inherited from the *Aggregates* class, namely *AggAbsorption, FieldMoisture, MoistureContent, FinenessMod,* etc. The *CoarseAgg* instance has two other slots of its own i.e., *MaxSizeOfAgg* and *ShapeOfAgg*. The values of these slots are input by the user or calculated during the mix design process and stored as a database from which the properties of different aggregates are known.

The *Admixtures* class represents different chemical admixtures used in concrete production to achieve specific performance. It has two instances namely *Superplasticizer* and *AirEntraining*. The *Air* class contains three instances namely *EntrappedAir*, *EntrainedAir* and *TotalAir*. Their slots are also inherited from the *Ingredients* class. In addition, the *Air* class has one new slot named *ContentPercent* that is inherited by its instances.

7.2.3 Design Processes in the HPCA

The mechanisms of the design process are modelled by the methods attached to the objects. These methods contain programmed procedures that vary according to the approach employed to design a particular item. For example, the method *WatBindRatio* for high performance concrete mix design, may, depending on the approach desired, take the form of a rigorous mathematical analysis to find the optimum water-binder ratio for achieving the desired strength performance. Alternatively, it may involve simply assigning a default value for achieving a specific durability performance. In the case of the HPCA, the water-binder ratio for achieving strength performance suggested by Aitcin (1998) as a logarithmic curve was incorporated in the *WatBindRatio* method for the *WaterBinderRatio* slot of the *FreshConcrete* object. This approach allows for a great deal of flexibility for the system designer where in the future, methods for design may be improved, modified or totally changed.

Object interaction is achieved by means of sending messages, either from other objects or from the user interface. For example, pressing the *Composition* button in the interface window of the laboratory trial batch sends a message that triggers the execution of the *Composition* method for the *ConcreteProperties* object.

Object-to-object interaction is achieved using slot monitors, which trigger messages to activate methods automatically in other objects whenever change in value is detected in the monitored slots. For example, whenever the value of the *ConcCompStr* slot (of the *HardConcrete* object) changes, it will activate the execution of the *WatBindRatio* method (of the *FreshConcrete* object), which recalculates the water-binder ratio of the concrete mix to achieve desired compressive strength.

The object-oriented approach as illustrated above, where objects (classes and instances) are intrinsically linked with attributes (slots) and behaviour (methods), provides a means of managing system complexity as well as allowing for easier expansion, modification and refinement.

7.2.4 Modelling Design Heuristics in the HPCA

The object-oriented model also provides a means for representing design heuristics that are often identifiable for certain parameters. For example, the required water content in kg/m^3 (kilogram per cubic metre) of high performance concrete mix can be heuristically determined by a linear relation to the saturation point of superplasticizer used, i.e. for every percent of saturation point of superplasticizer, fifty times saturation point plus ninety kilogram of water per cubic metre of concrete is required for a high performance concrete mix (Aitcin 1998). This simple relationship can be represented by a linear equation defined in the *WaterDosage* method of the *Ingredients* class.

Heuristics can also be represented in the form of default values. For example, the air content in percent of a non-air-entrained high performance concrete mix is determined from experience and not by any rigorous modelling. Thus a value of 1.5% as heuristically recommended by one of the textual sources (Aitcin 1998) is specified as the default value for the *ContentPercent* slot of the *EntrappedAir* object. The user may also override this value by entering the actual data for his case.

Methods can make use of rules that represent heuristic knowledge. For example, the amount of coarse aggregate in a concrete mix in kg/m^3 (kilogram per cubic metre) can be related to shape of coarse aggregate heuristically. If the shape of aggregate is *elongated*, then the coarse aggregate content of the mix will be 950 kg/m^3. On the other hand, if the shape of aggregate is *rounded* then coarse aggregate content will be 1150 kg/m^3 (Aitcin 1998). In between the two shapes, other shapes are considered by the system, such as *average*, *average and cubic*, *cubic*, and *cubic and rounded*. The above heuristic reasoning is reflected in the rules invoked for determining coarse aggregate content. Table 7.1 is an example of a set of rules used to determine the coarse aggregate content of high performance concrete mix. A few functions, methods and rules in KAL format are included in Appendix D.

TABLE 7.1 The Set of Rules for Coarse Aggregate Content of HPC Mix

Antecedent (IF part)	**Consequent (THEN part)**
Shape of coarse aggregate is *elongated*	Coarse aggregate Content = 950 kg/m^3
Shape of coarse aggregate is *elongated and flat*	Coarse aggregate Content = 975 kg/m^3
Shape of coarse aggregate is *flat*	Coarse aggregate Content = 1000 kg/m^3
Shape of coarse aggregate is *flat and average*	Coarse aggregate Content = 1025 kg/m^3
Shape of coarse aggregate is *average*	Coarse aggregate Content = 1050 kg/m^3
Shape of coarse aggregate is *average and cubic*	Coarse aggregate Content = 1075 kg/m^3
Shape of coarse aggregate is *cubic*	Coarse aggregate Content = 1100 kg/m^3
Shape of coarse aggregate is *cubic and rounded*	Coarse aggregate Content = 1125 kg/m^3
Shape of coarse aggregate is *rounded*	Coarse aggregate Content = 1150 kg/m^3

7.3 KNOWLEDGE BASE MODULES OF THE HPCA

The HPCA knowledge base is made up of four modules, each dealing with a specific task of the high performance concrete domain. They are:

(i) mix design,
(ii) mix performance adjustment,
(iii) cost estimation, and
(iv) durability.

A description of each of the above modules is given in the following subsections. The modules are generally independent of each other despite some degree of information interchange. Even though some of them are more extensive than others, module size is not necessarily indicative of their relative importance. Figure 7.5 shows the HPCA Main Screen from which the design modules can be accessed with the help of appropriate buttons.

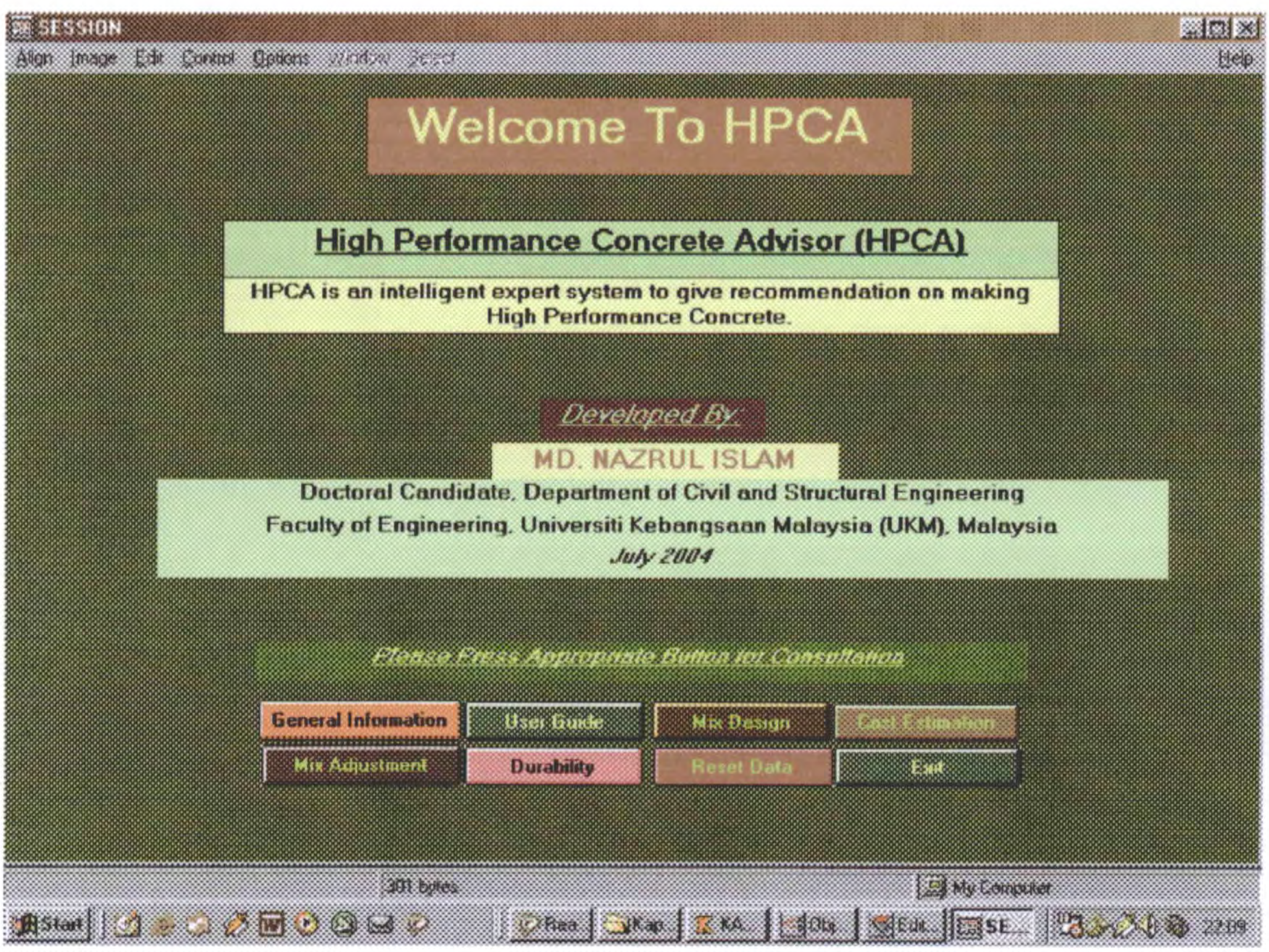


FIGURE 7.5 The HPCA main window from which the modules are accessed

The Main Screen also has *User Guide* and *General Information* buttons to access advice on how to proceed and other essential information relating to the HPCA system (i.e., overview of the system) and the essentials of high performance concrete mix design and durability aspects. Figures 7.6 to 7.21 show the windows through which users access the design modules.

7.3.1 Mix Design Module

The interface window of the *Mix Design* module is shown in Figure 7.6. The objective of this module is to proportion high performance concrete mixes. It consists of four submodules, namely (a) *First Trial Batch*, (b) *Trial Batch for Laboratory*, (c) *One Cubic Metre SSD Composition*, and (d) *Batch Composition*.

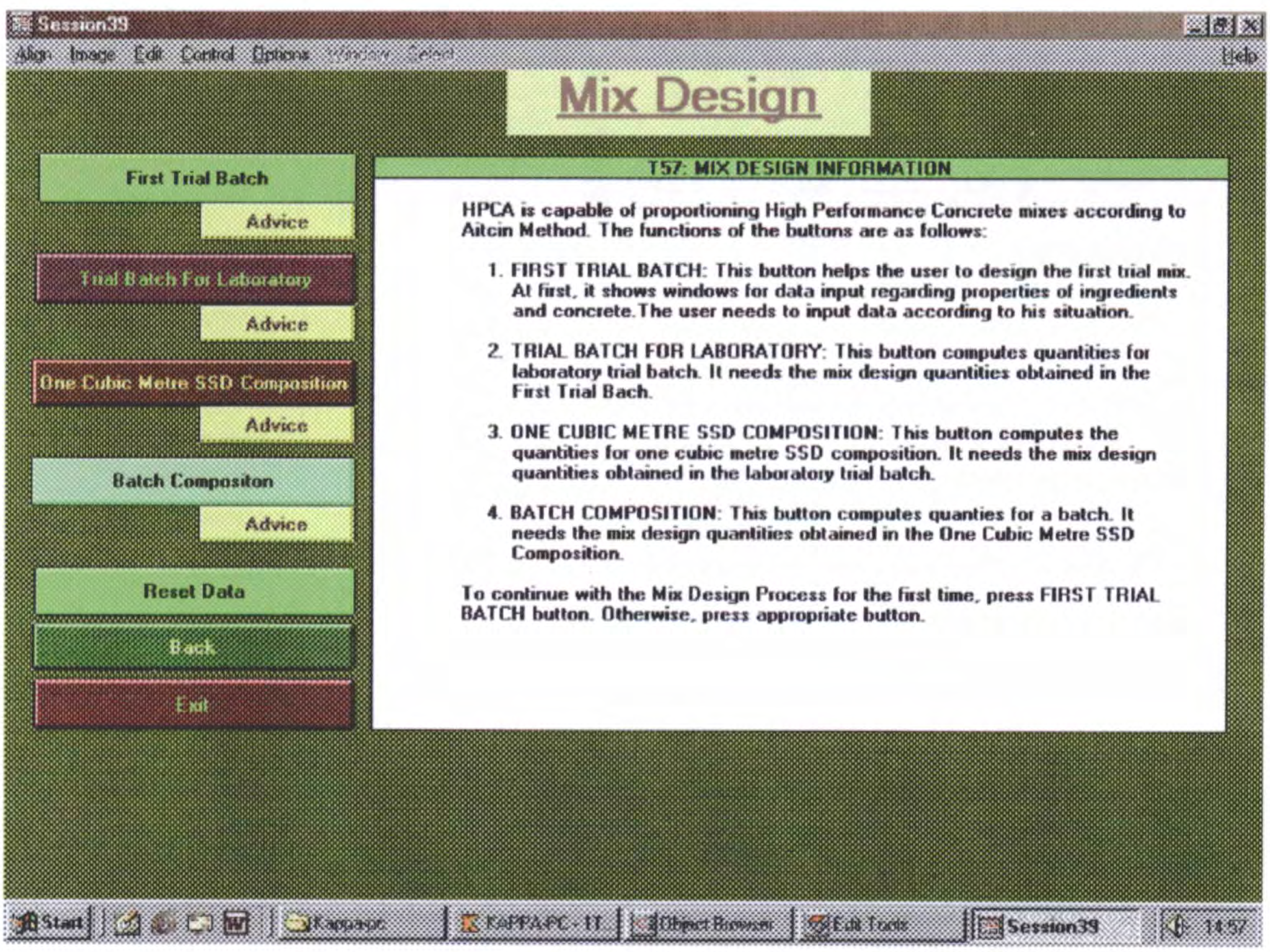


FIGURE 7.6 Interface window for the Mix Design module

(a) First Trial Batch Submodule

The *First Trial Batch* submodule is accessed through the *First Trial Batch* button of Figure 7.6. This submodule computes the proportion of concrete mix according to the data supplied by the user. It gives composition for one cubic metre of concrete for field conditions of aggregates. It is usually expected that the user will first consult with this submodule for mix design purpose. During consultation, the system asks for information regarding required concrete properties as well as properties of the concrete making ingredients. After data input, the system displays the data for checking and correction. The system prompts for mix design when the user presses the appropriate button. Figure 7.7 shows the First Trial Batch Composition window. It displays the composition of one cubic metre of concrete and some of the related data.

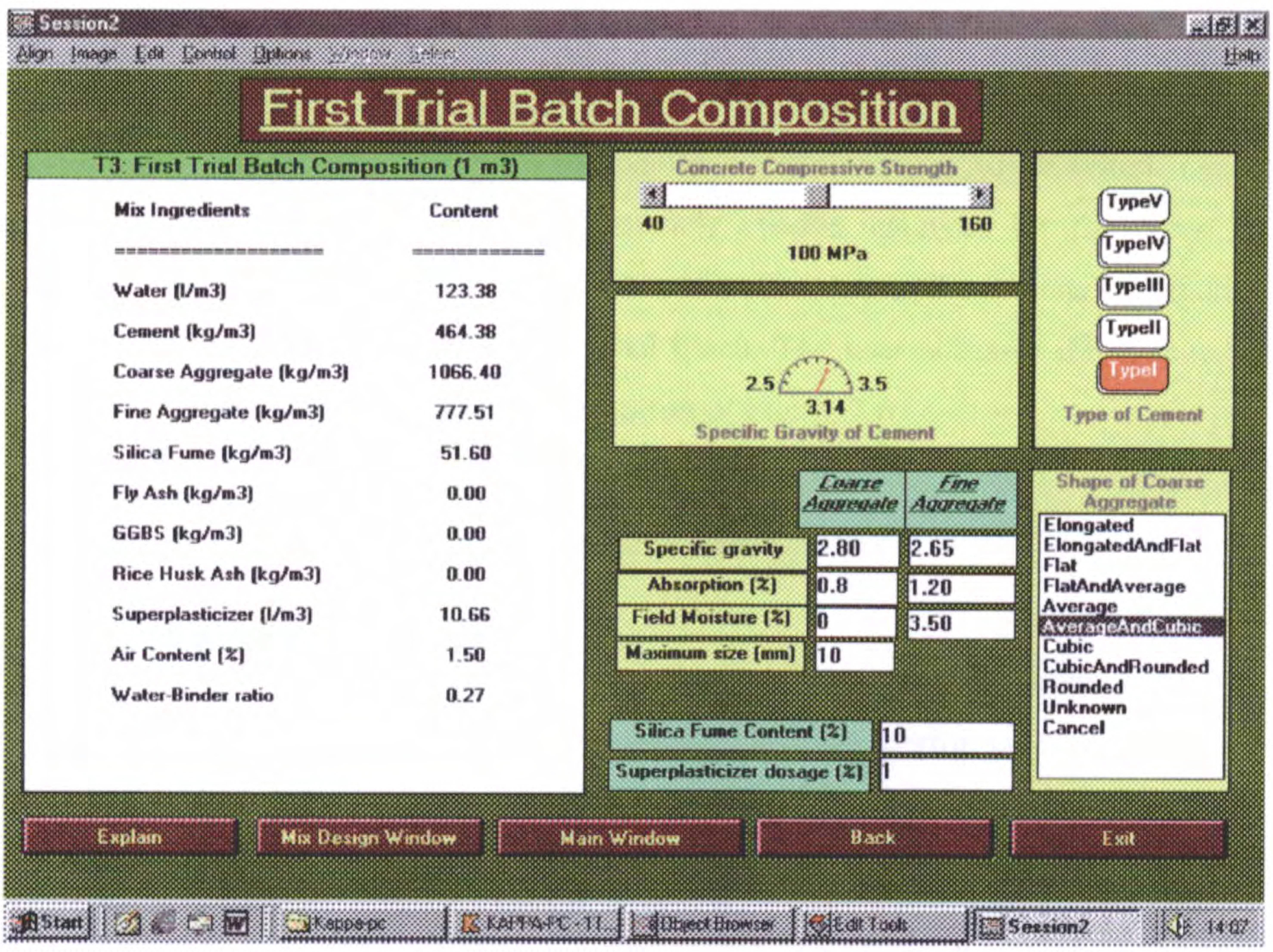


FIGURE 7.7 Window for the First Trial Batch Composition

This submodule computes the mix design values i.e., quantities of the ingredients. This is achieved by activating a function. The calculation uses data for cement, aggregates, supplementary cementitious materials, admixtures etc. and is based on mix design method for high performance concrete proposed by Aitcin (1998). Alternatively a different method for mix design can be adopted by the HPCA later, if desired. As the aggregates to be used are not likely to be in the SSD conditions, and as the superplasticizer will bring some water to the mix, the system makes water corrections taking into account the appropriate sign convention.

(b) Trial Batch For Laboratory Submodule

The *Trial Batch for Laboratory* submodule helps in computing the quantities of ingredients for making concrete samples for laboratory testing. This will give the user opportunity to test the mix design results in a laboratory for the desired performance requirements for small quantities of proportioned ingredients. This module requires data of the *First Trial Batch* and specifications of the samples to be tested. During collecting data from the user, it automatically creates instances for the types and number of samples. Then it asks for details of each sample from which it calculates quantities of ingredients for laboratory trial batch. The user accesses this submodule through the *Trial Batch For Laboratory* button of Figure 7.6.

(c) One Cubic Metre SSD Composition Submodule

It is necessary to compute the composition of one cubic metre of concrete in the SSD conditions of aggregates after getting a satisfactory high performance concrete mix having the right consistency (initial and final slump) (Aitcin 1998). This submodule performs the necessary calculation for the user. The aggregates are not likely to be in their SSD conditions and some water is "hidden" in the liquid superplasticizer. Therefore, the water-binder ratio of the mix is unknown at this stage. Thus it is necessary to calculate the so-called "water corrections" to be able to know precisely the actual amount of water present in the mixture proportioned. In order to make all these calculations systematically, a method is used by a function attached to the button named *One Cubic Metre SSD Composition* (see Figure 7.6). Thus, the *One Cubic Metre SSD Composition* submodule calculates proportions of one cubic metre of concrete for SSD conditions of aggregates.

(d) Batch Composition Submodule

The proportions obtained from the trial mixer or given by the laboratory are always for SSD aggregate conditions (Aitcin 1998). On the other hand, the batch composition is always for the field conditions of aggregates. As the aggregates contained in the bins at the batching plant are not usually in SSD conditions, the amount of mixing water needs to be adjusted in order to compute the batch composition from the trial mix composition. Superplasticizer brings some water in the mix that also needs to be subtracted from the mixing water content. The *Batch Composition* submodule performs this task if requested by the user. *Batch Composition* button (Figure 7.6) will activate a function to calculate the amount of batch quantities for the field conditions of aggregates. In order to perform this task, the submodule needs the quantities of the *One Cubic Metre SSD Composition* as calculated by the previous submodule and the expected batch size.

7.3.2 Mix Performance Adjustment Module

The *Mix Performance Adjustment* module helps in adjusting the mix after laboratory testing. It analyses test results and gives recommendations on the adjustment of ingredients in order to achieve the desired concrete performance. The interface window of this module is shown in Figure 7.8.

Incorporating the knowledge that experts use in diagnosis, the *Mix Performance Adjustment* module diagnoses possible causes of performance failure and recommends remedial measures to be undertaken. The *Quantitative Advice* button (Figure 7.8) of this module gives specific quantitative recommendations on achieving various performances of high performance concrete mix.

The system considers three criteria for judging the performance of a mix i.e., strength, workability and durability. If a mix fails in strength performance, then the system asks about the indication of test results regarding any of the following to find out the possible causes of performance failure: (i) fracture pattern, (ii) bond failure pattern, (iii) passage of fracture surface, and (iv) effect of water-binder ratio. On the other hand, if the workability performance is inadequate then the system wants to know which workability performance of the following is inadequate: (i) rapid slump loss, (ii) low slump, or (iii) inadequate workability. After collecting these data, the system produces recommendation in order to achieve the desired performance. The system also displays the explanation of the recommendation in a transcript image as shown in Figure 7.8.

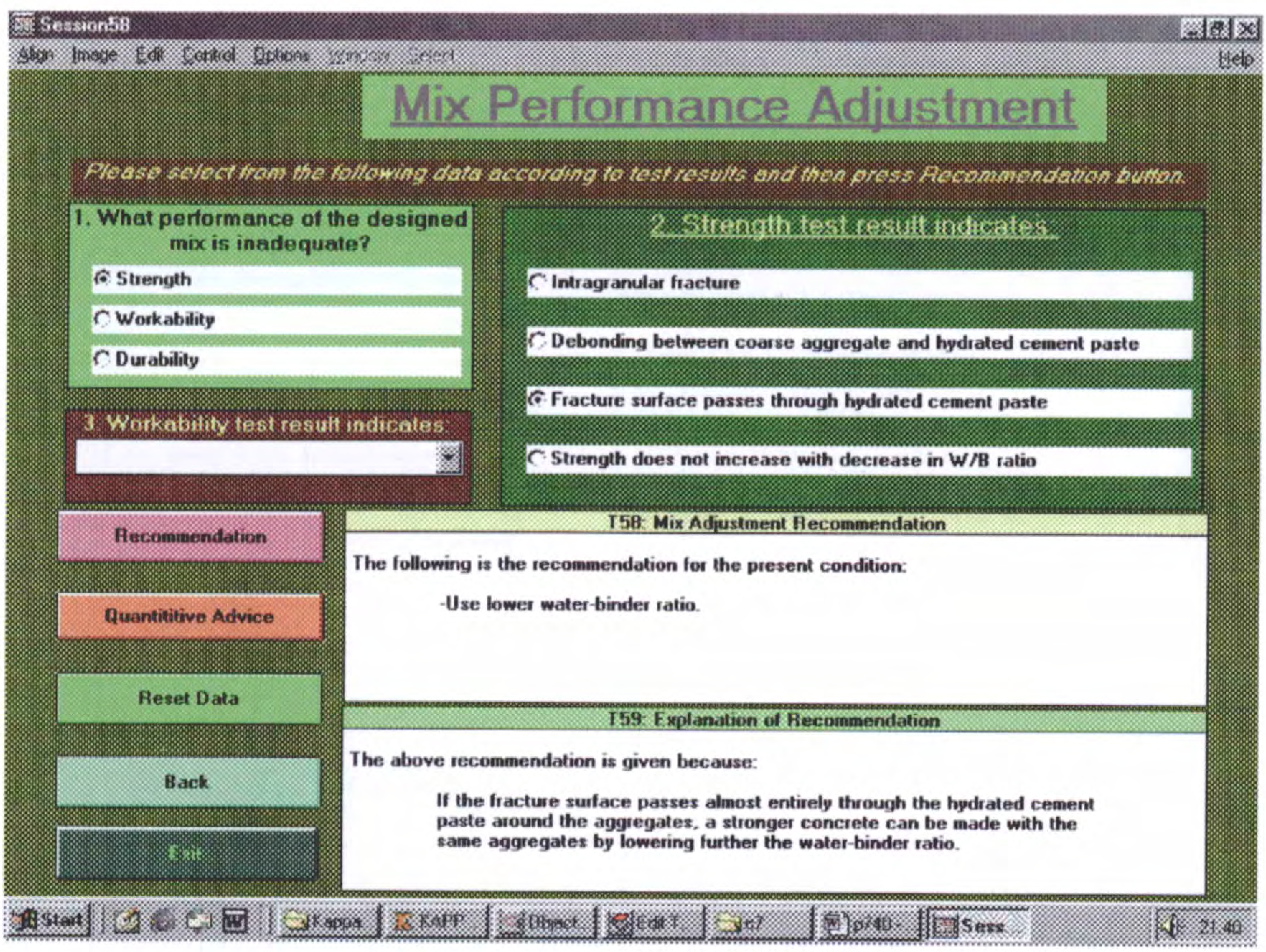


FIGURE 7.8 Main interface window of the Mix Performance Adjustment module

7.3.3 Cost Estimation Module

If the cost estimation is felt to be necessary, it can be carried out using the *Cost Estimation* module shown in Figure 7.9. The first step is to input unit cost of the proportioned ingredients. A transcript image in the *Cost Estimation* interface window (Figure 7.9) helps the user by displaying information about the ranges of unit cost of concrete ingredients. Although these values vary in different parts of the world as well as in the same region of a country, this information will help the user in getting an idea about the approximate unit cost of individual ingredients. After inputting the unit cost of ingredients, the user gets the total cost of the concrete mix for one cubic metre and for a particular batch composition by pressing appropriate buttons.

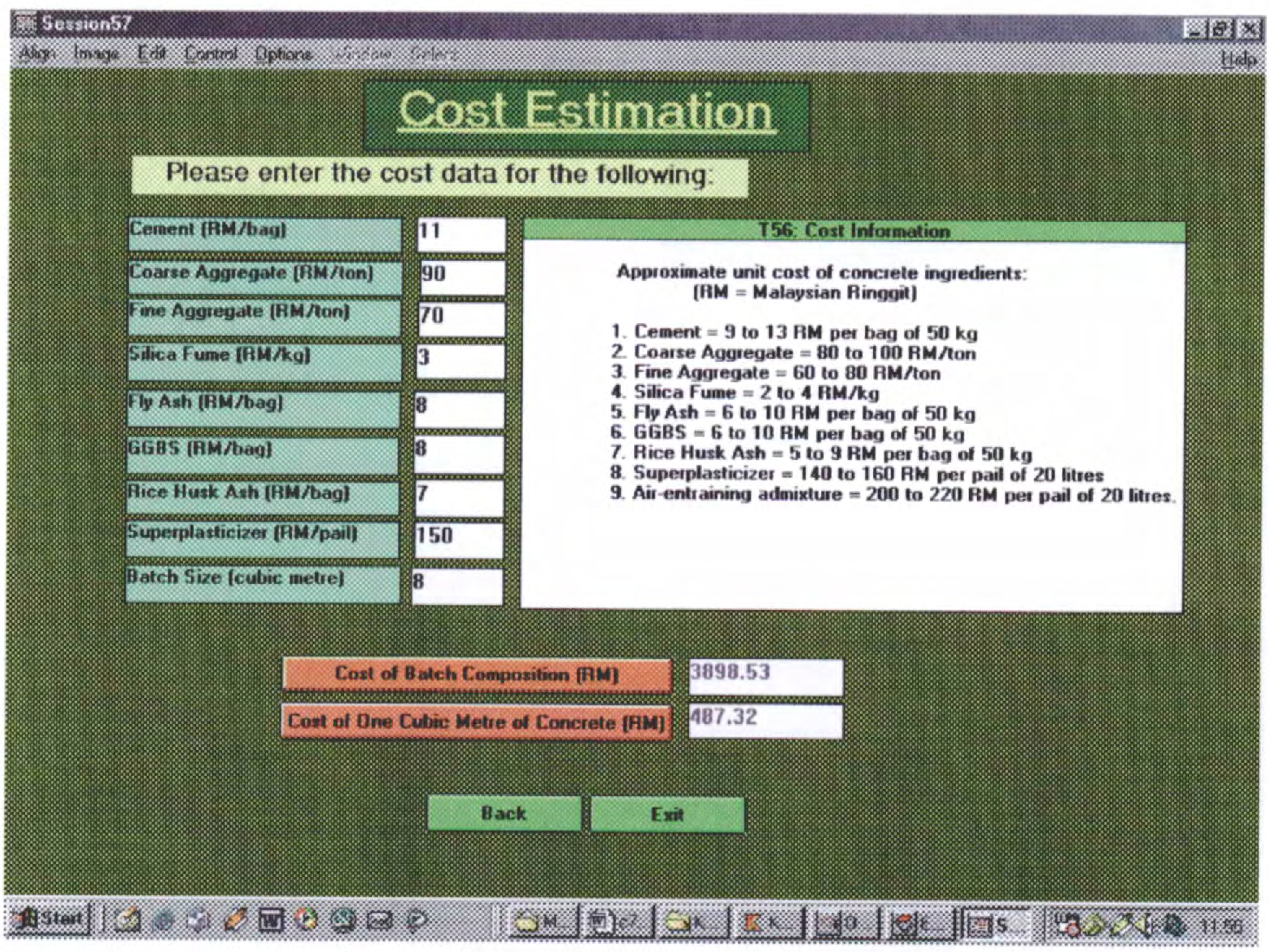


FIGURE 7.9 Interface window for Cost Estimation module

7.3.4 Durability Module

The main interface window of the *Durability* module is shown in Figure 7.10. The objective of this module is to give recommendations on the durability issues of high performance concrete. The recommendations have major cost and technical implications, and as such the knowledge content of the module that lead to the conclusions are very important and require careful consideration during mix design, mix performance adjustment and construction stages. The knowledge base contains knowledge mainly in the form of production rules, which are involved whenever the relevant button is pressed.

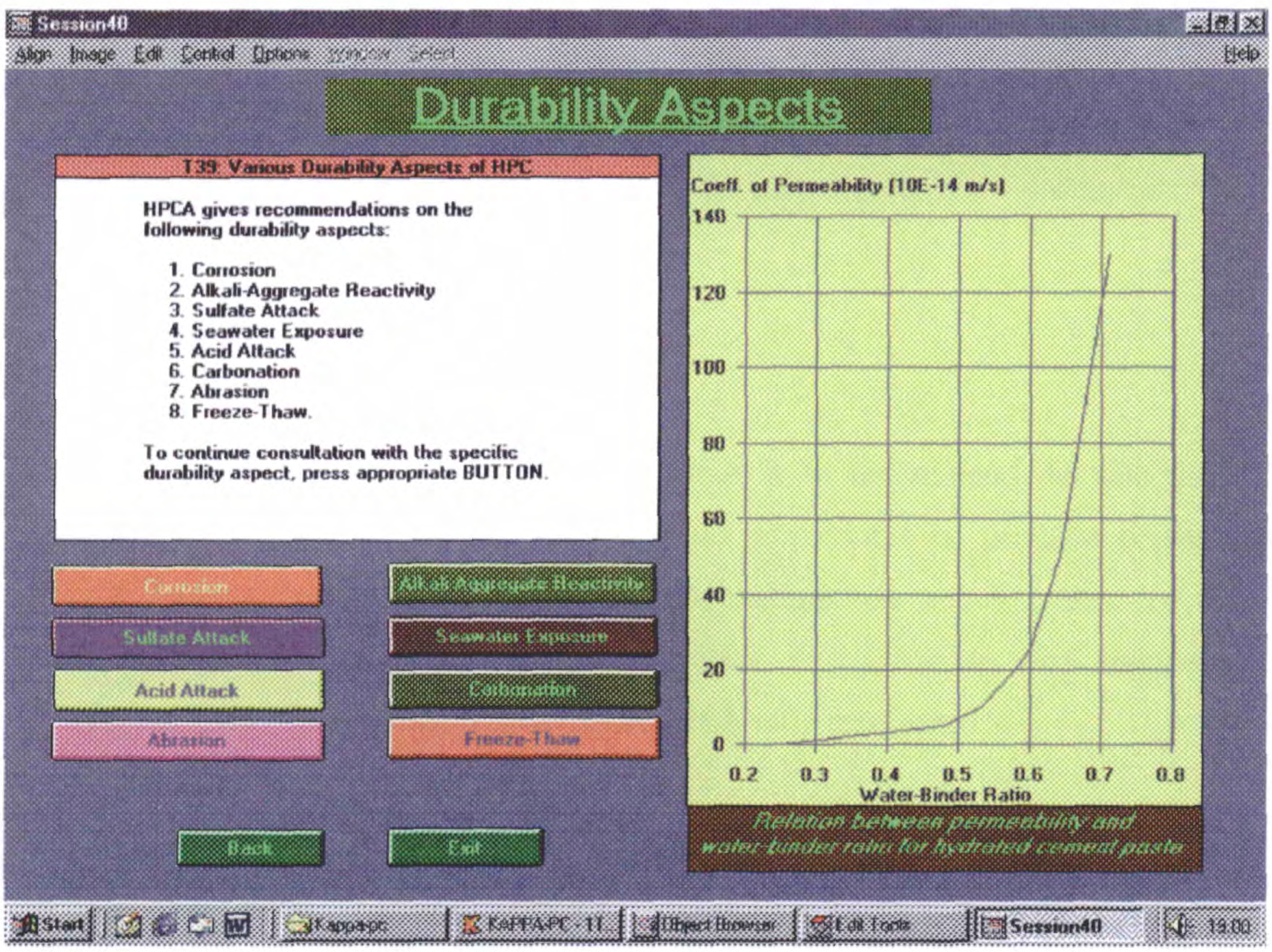


FIGURE 7.10 Interface window of the Durability module from which eight submodules are accessed

The permeability of concrete is the major cause of external chemical attack and hence affects the durability of concrete. The interface window shows the relationship between permeability and water-binder ratio for hydrated cement paste. It can be seen that a reduction of water-binder ratio from, say, 0.7 to 0.3 lowers the coefficient of permeability by 3 orders of magnitude.

The following eight concrete durability problems are considered by the system for high durability performance of concrete (Figure 7.10) and these submodules are described in the subsequent sections.

(a) Corrosion
(b) Alkali-Aggregate Reactivity
(c) Sulfate Attack
(d) Seawater Attack
(e) Acid Attack
(f) Carbonation
(g) Abrasion
(h) Freeze-thaw.

(a) Corrosion Submodule

The objective of the corrosion submodule is to recommend the selection of concrete ingredients and other concrete making procedures to produce corrosion-resistant durable concrete. It gives recommendations on requirements for high performance concrete to be resistant to corrosion of reinforcing steel induced by chloride ion. Other factors inducing corrosion are briefly mentioned.

The control flowchart for the *Corrosion* submodule is shown in Figure 7.11. The flowchart shows that the concrete environment is broadly divided into two categories: indoor and outdoor. Both types are further divided into subcategories as shown in the figure. This flow diagram is used to develop objects and rules for the knowledge base.

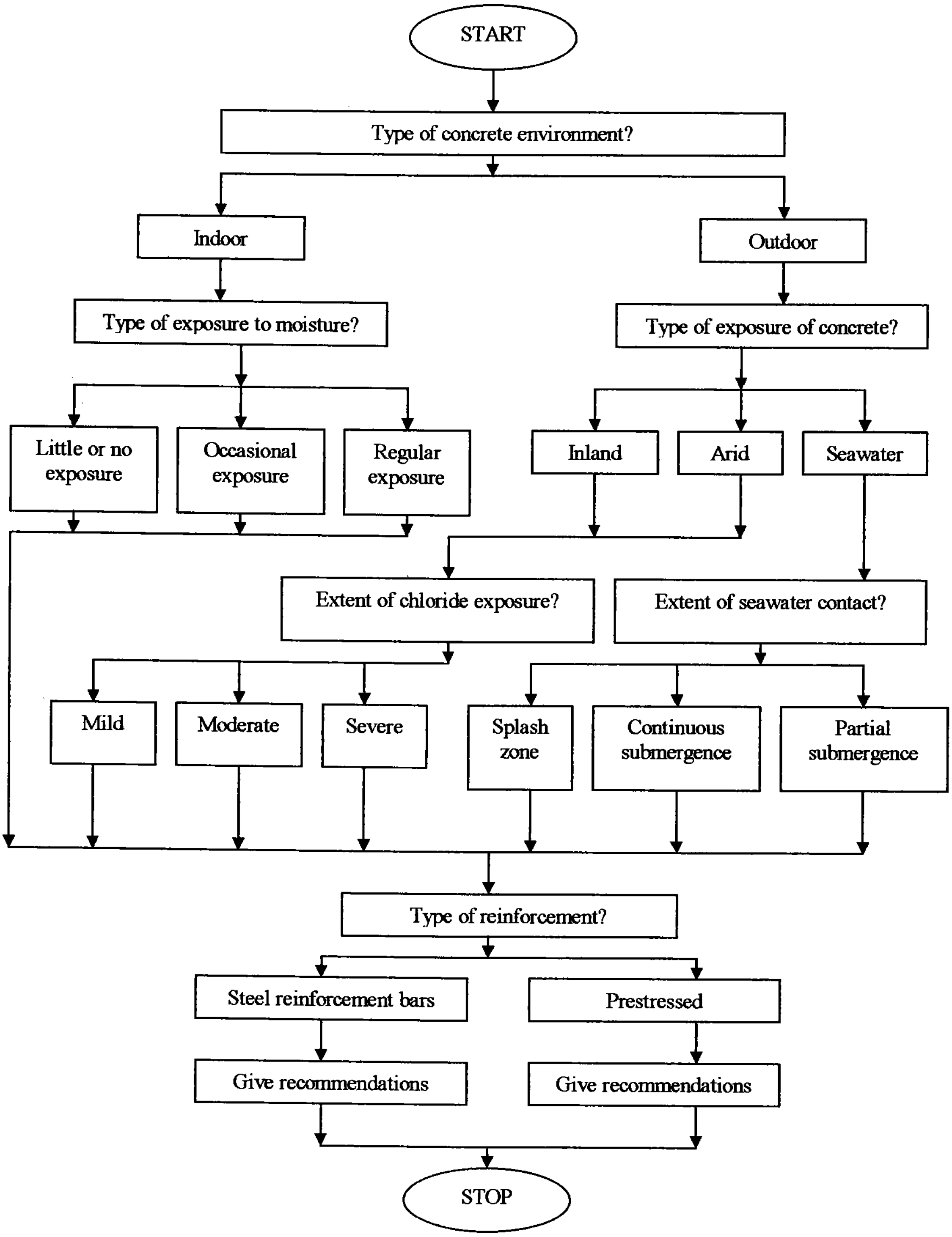


FIGURE 7.11 Control flowchart of the Corrosion submodule

This submodule is accessed through the *Corrosion* button of Figure 7.10. Figure 7.12 shows the interface window of this submodule. The initial transcript image shows the preliminary information about corrosion. It also describes briefly the functions of the buttons of the corrosion interface window. The *Occurrence* button explains the general situation where corrosion might be a problem. On the other hand, *Mechanism* button describes corrosion mechanism. The interface window shows the diagrammatic representation of damage induced by corrosion i.e., cracking, spalling, and delamination. The products of corrosion occupy a volume several times larger than the original steel so that their formation results in cracking, spalling or in delamination of concrete. These facilities encourage the user to be aware of the potential corrosion situation and train the inexperienced user about corrosion problem.

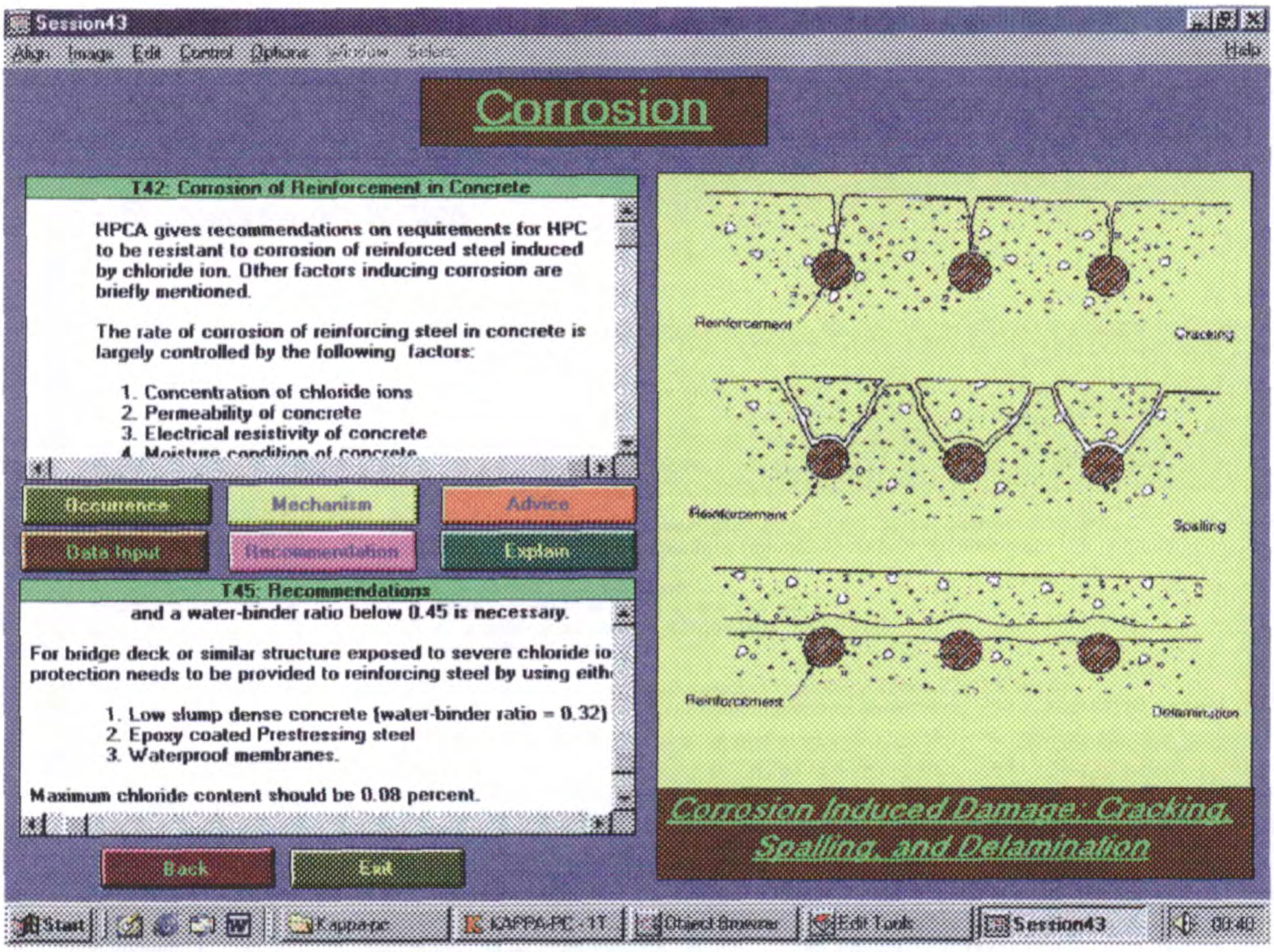


FIGURE 7.12 Main interface window of the Corrosion submodule

(b) Alkali-Aggregate Reactivity Submodule

This submodule gives recommendations on requirements for high performance concrete to be resistant to alkali-aggregate reactivity. It states that the magnitude of expansive reactions depends on the specific aggregate, the alkali content of the cement and concrete, availability of extraneous alkalis (i.e., seawater) and availability of water as shown in Figure 7.13. The interface window (Figure 7.13) also shows diagrammatically typical cracks in a vertical wall and in a pavement in order to demonstrate the potential problem due to alkali-aggregate reactions.

The consultation starts after pressing *Data Input* button (Figure 7.13). The system asks the user for required information such as field and lab performance of aggregates to be used, whether aggregates meet the mandatory requirements or not, and type of aggregates (carbonaceous or siliceous). If the petrographic examination of aggregates indicates to be potentially reactive, the system recommends that laboratory testing of the aggregates should be performed. If the aggregate passes the minimum requirements in laboratory testing, then the system confirms that the aggregate is suitable for concrete production.

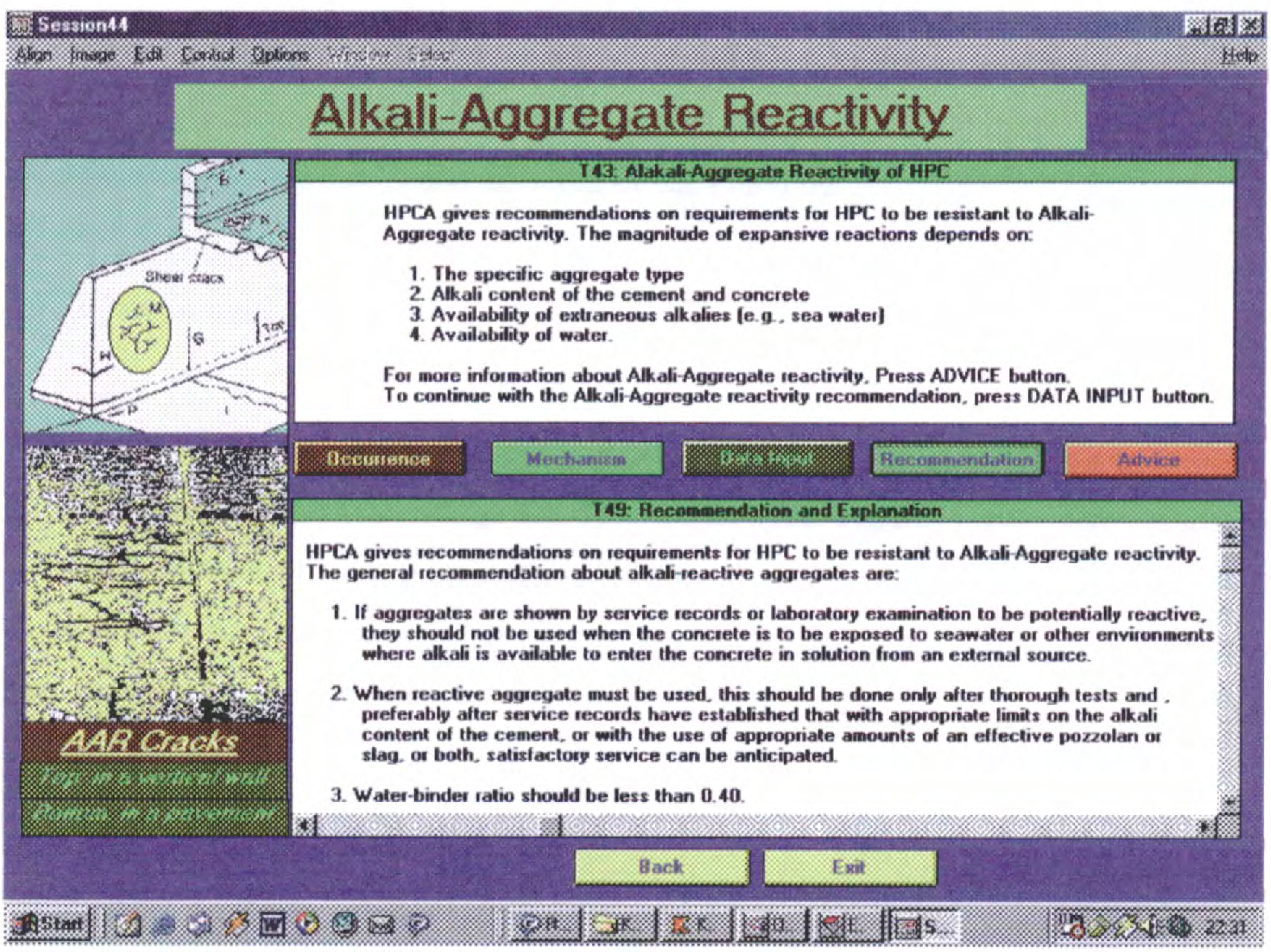


FIGURE 7.13 Interface window for Alkali-Aggregate Reactivity submodule

The system also recommends on the procedures that can be employed for minimizing the effects of alkali-carbonate rock reaction which include:

- avoiding reactive rocks by selective quarrying;
- diluting with non-reactive aggregates, or using a smaller nominal maximum size; and
- using very low-alkali cement (less than 0.6% Na_2O equivalent). This will prevent harmful expansion in most cases. However, in pavements where NaCl is used as a de-icing chemical, this cannot be taken as certain.

The system also states that avoiding reactive rocks by selective quarrying is the safest and usually the most economical procedure to minimize alkali-carbonate reactions. It should be noted that pozzolans serve only as diluents and are not effective in mitigating alkali-carbonate reactions. The *Advice* button of the interface displays the possible causes of alkali-aggregate reactivity and their solutions. It also briefly discusses the relative merits and demerits of each method.

(c) Sulfate Attack Submodule

If it is expected that the concrete will be exposed to sulfate environment, then the consultation can be done using this submodule (see Figure 7.14). 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. An *Advice* button is also available in order to access information in case of need during the consultation process.

The reactions of sulfates with hardened cement paste are also displayed in the interface window (Figure 7.14). It describes the reactions that are associated with the sulfate attack. The *Occurrence* button shows the general situation where sulfate attack may be a problem. The *Mechanism* button opens a text file in a transcript image describing the sulfate attack mechanism. The control flowchart of this submodule is shown in Figure 7.15.

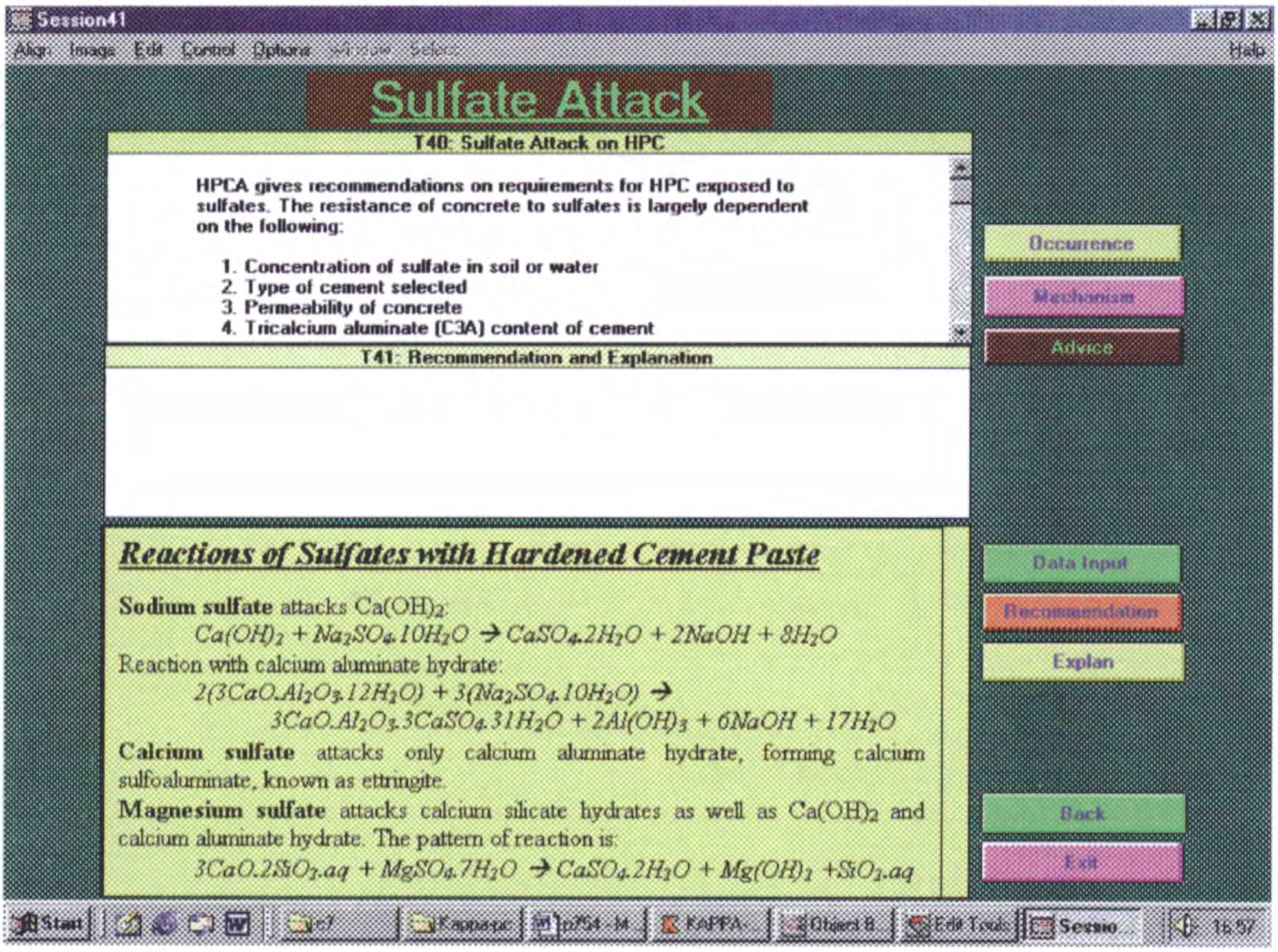


FIGURE 7.14 Interface window of the Sulfate Attack submodule

The recommendation is obtained by pressing *Recommendation* button after completion of data selection. 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 HPCA recommendations also include required curing practices, presence of other materials such as calcium chloride and use of available field performance information of existing concrete structures. After getting recommendations, the user may ask for explanation about the recommendation by pressing on the *Explain* button. Data and recommendations for a typical session are shown in the next chapter (see Table 8.13 and Table 8.14). The recommendations for this submodule are based on heuristic knowledge acquired from textual sources. The future extension of this submodule may include the addition of photographs showing the sulfate attack problem of the existing structure and corresponding recommendation from experts for solving the problem.

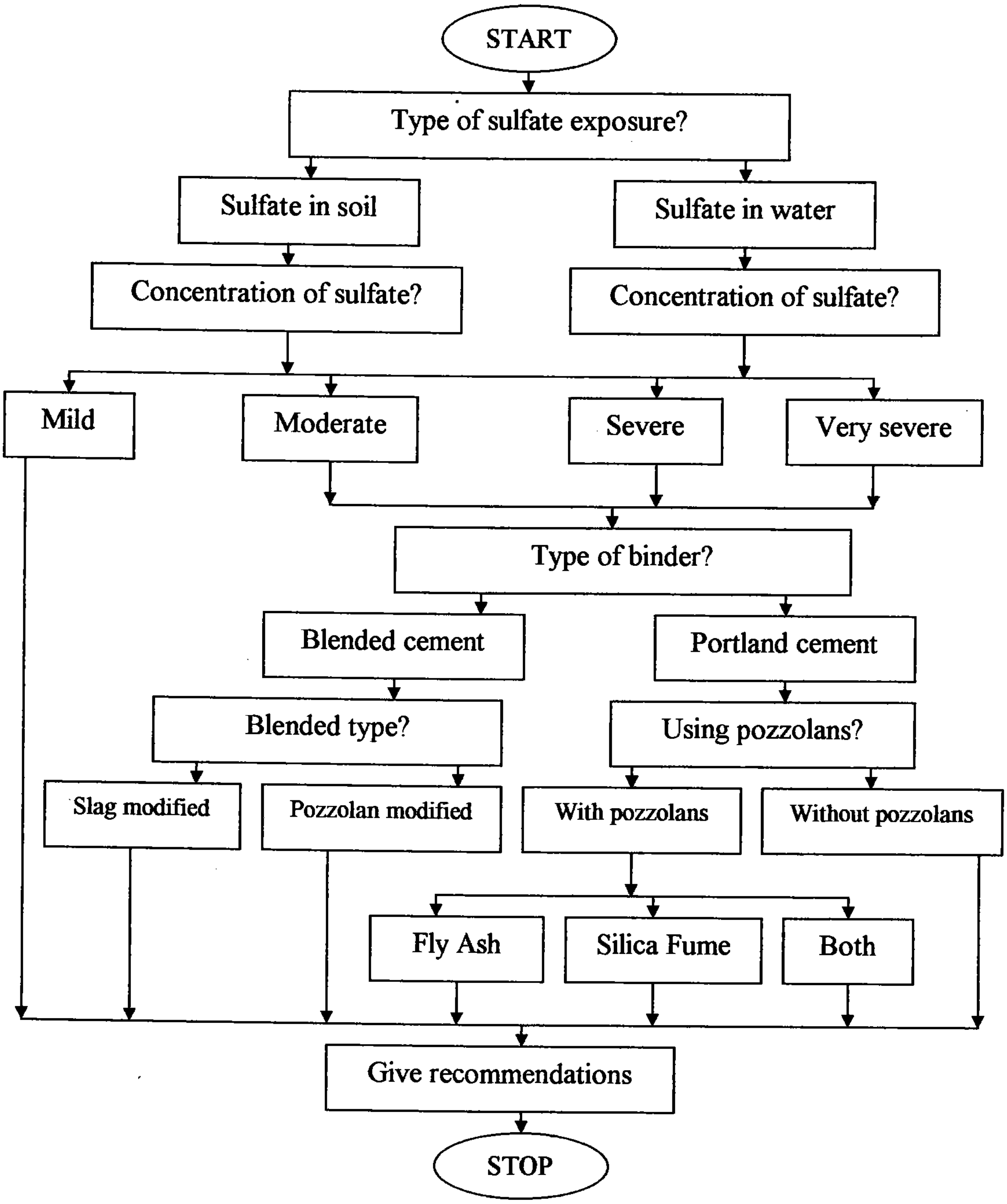


FIGURE 7.15 Control flowchart of the Sulfate Attack submodule

(d) Seawater Exposure Submodule

The objective of this submodule is to give recommendations on making concrete to be resistant to seawater exposure. Figure 7.16 shows the seawater consultation window. The recommendations are based on rules, which consider factors such as climatic condition near the structure, depth of water and rate of evaporation, and foundations below the saline groundwater level. The data selected by the user during a particular session are displayed in the interface window for checking and confirmation.

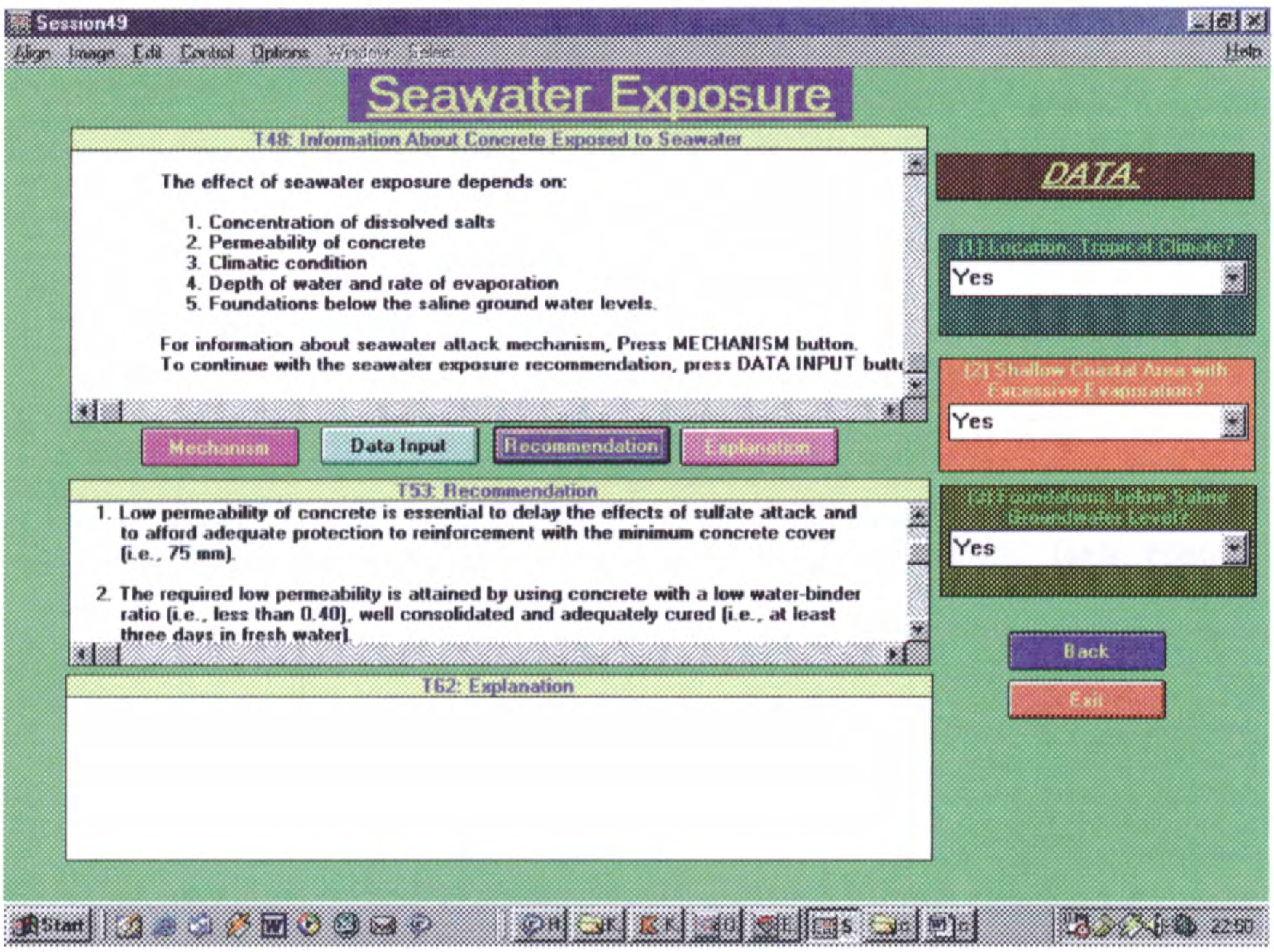


FIGURE 7.16 Main interface window for Seawater Exposure submodule

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 cracks in concrete in order to prevent the 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.

(e) Acid Attack Submodule

This submodule 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 acid attack on concrete arising from these sources are summarized in Table 7.2. The interface window of this submodule is shown in Figure 7.17.

TABLE 7.2 Sources and Ways of Acid Attack on Concrete

Sources 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 that 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 that 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.

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.

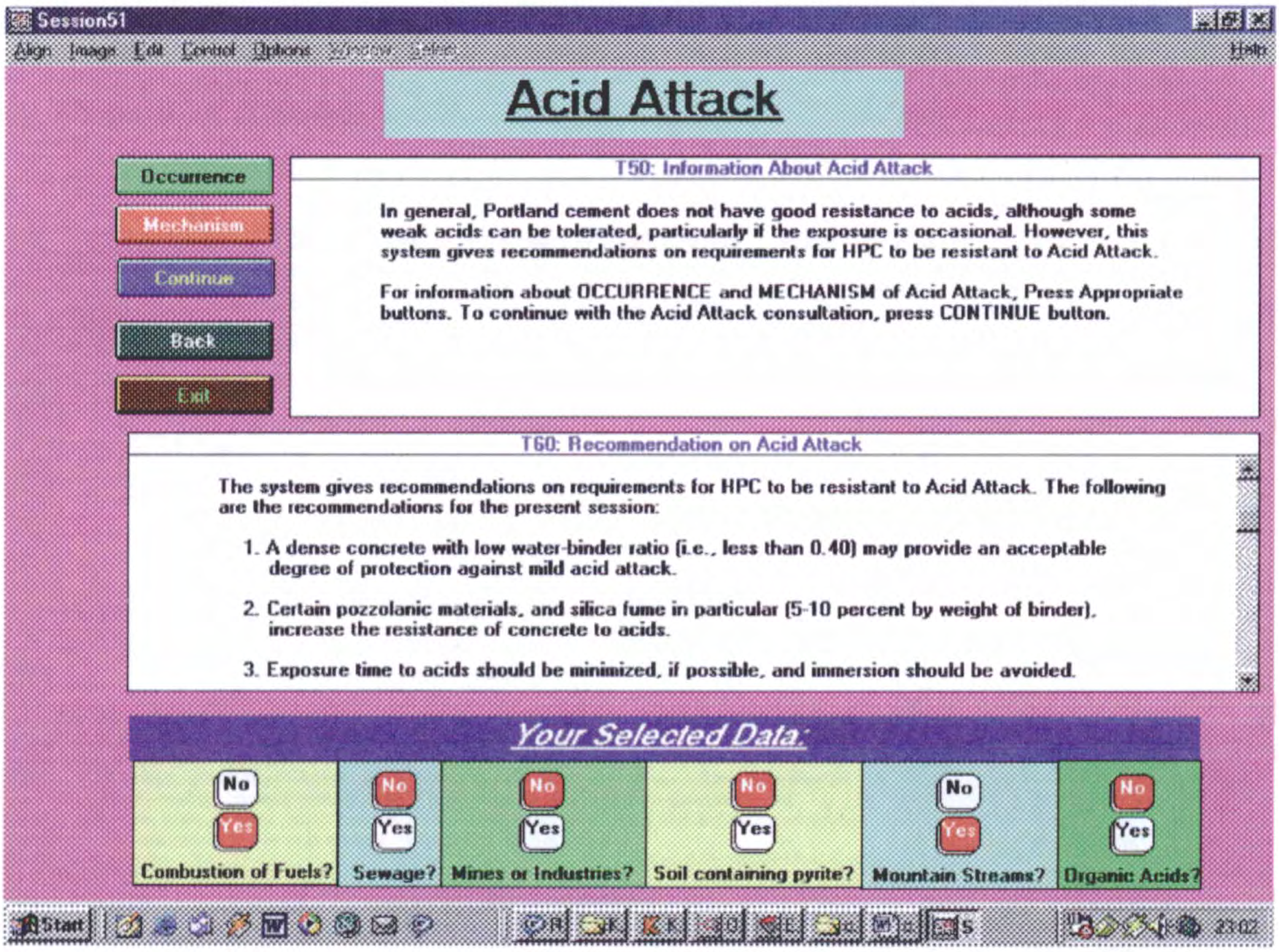


FIGURE 7.17 Main interface window of the Acid Attack submodule

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, if possible, and immersion should be avoided. It states that no hydraulic-cement concrete, regardless of its composition, will long withstand water of high acid concentration. In such cases, the HPCA recommends the use of an appropriate protective-barrier system or treatment.

(f) Carbonation Submodule

The main interface window of this submodule is shown in Figure 7.18. The objective of this submodule is to assist the user in producing concrete for carbonation environment. The relative humidity of the environment, temperature, permeability of concrete and concentration of carbon dioxide are the major factors that control carbonation of concrete.

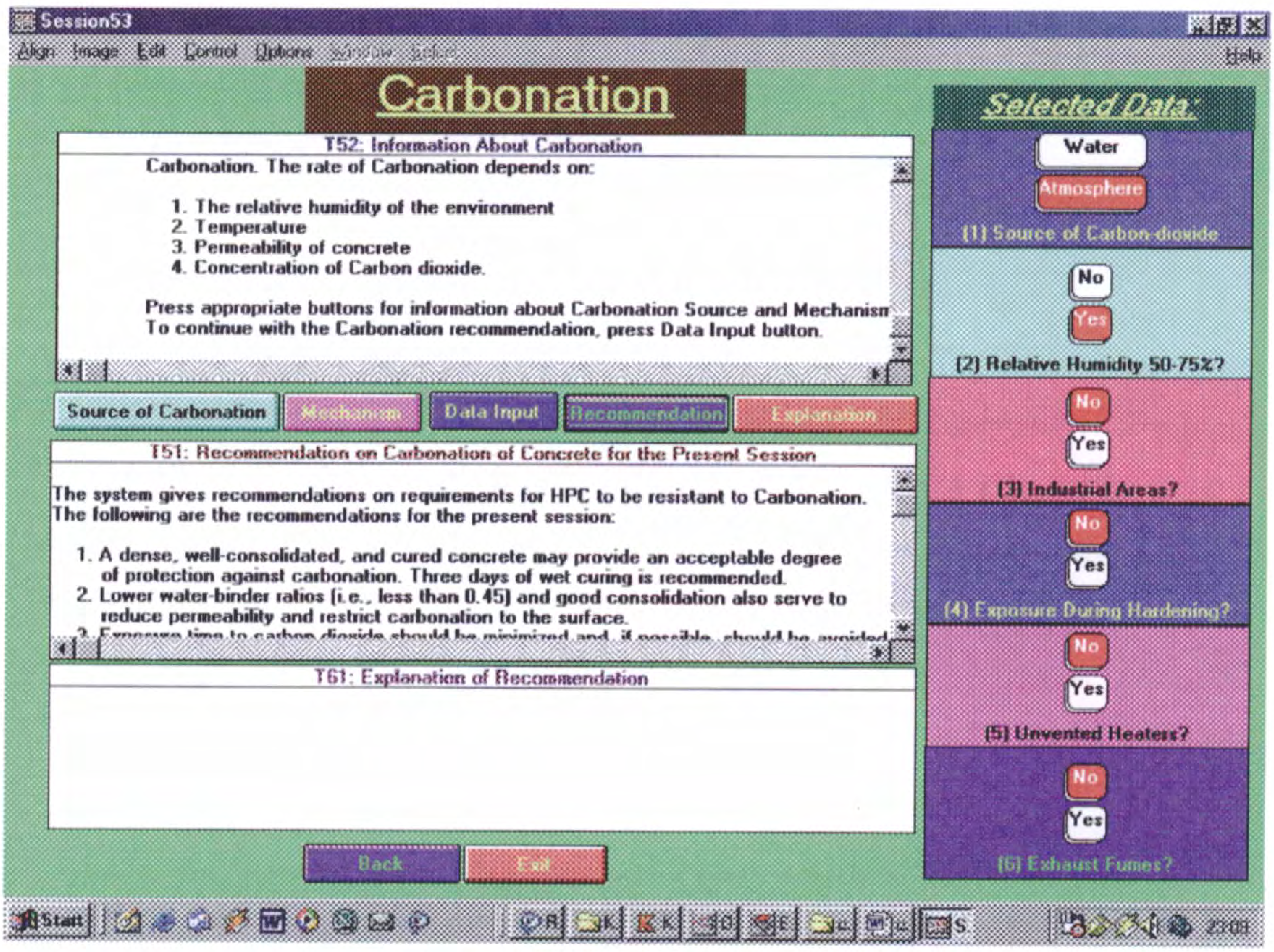


FIGURE 7.18 Main interface window of the Carbonation submodule

The system states that the sources of carbon dioxide can be either atmosphere or water carrying 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, and dusting, 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 minimised and, if possible, should be avoided. It emphasises that good quality concrete is essential to prevent initiation of carbonation.

(g) Abrasion Submodule

Figure 7.19 shows the interface window for this submodule. The submodule informs the user that the magnitude of abrasion is influenced by compressive strength of concrete especially at the surface, aggregate-to-paste bond strength, hardness of the aggregates, quality of the aggregates at the surface region, curing, and the use of the concrete surface. The influence of water-binder ratio on the abrasion loss of concrete in Steel Ball Test is shown as a line plot in the interface window (Figure 7.19). This line plot shows that reducing the water-binder ratio is a major step in preventing abrasion loss of concrete.

The *Advice* button (Figure 7.19) opens a text file that describes the sources of abrasion problem. It states that abrasion of floors and pavements may result from production operations, or foot or vehicular traffic, abrasion resistance is therefore of concern in industrial floors. Wind and waterborne particles can also abrade concrete surfaces. There are instances where abrasion is of little concern structurally, yet there may be a dusting problem that can be quite objectionable in some kinds of services. The button also explains the limitations of the system. For example, it states that abrasion (erosion) of concrete in hydraulic structures is discussed only briefly in this system. The system also informs the user that the erosion problem is treated in detail in ACI 210R.

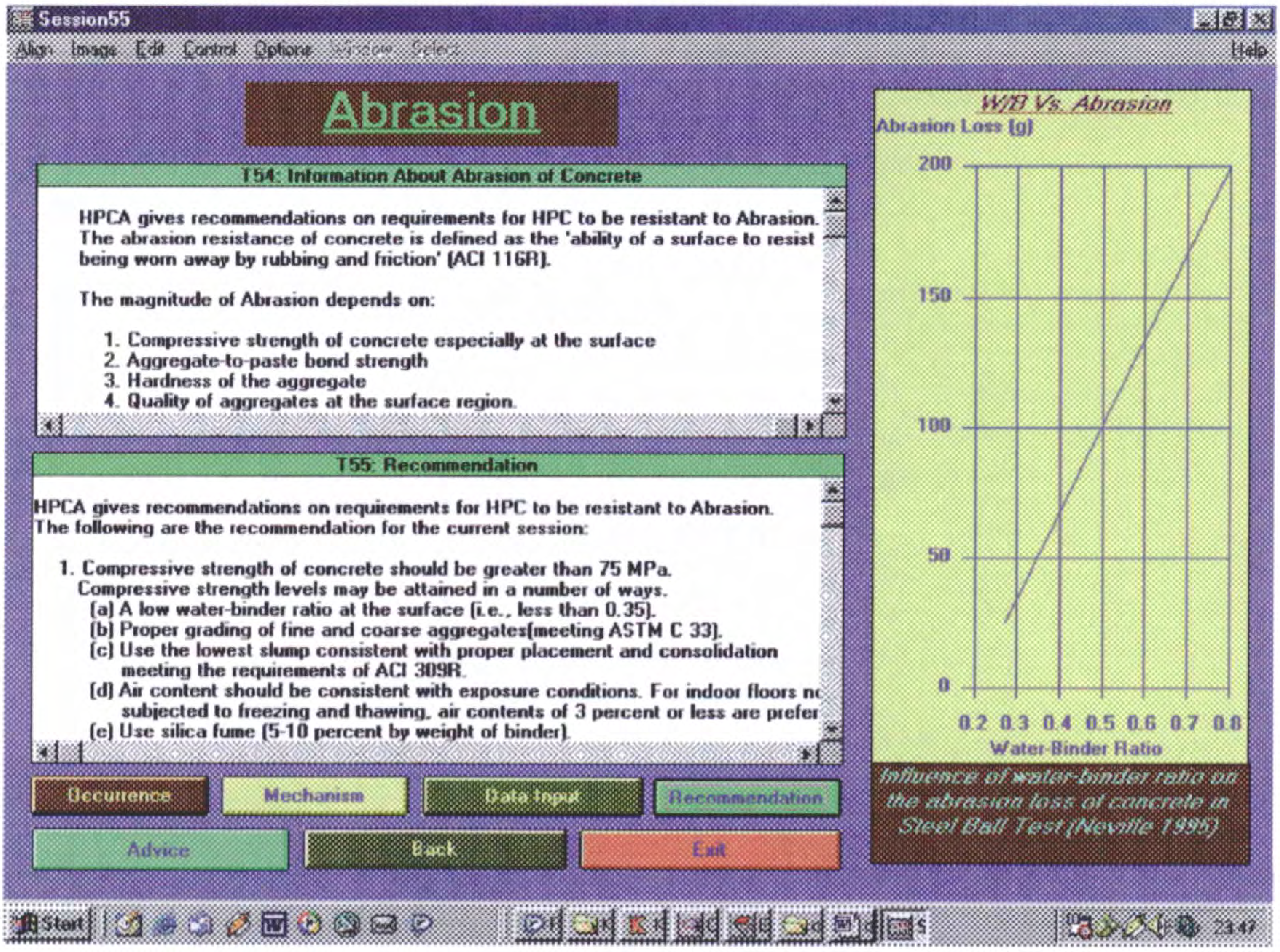


FIGURE 7.19 Interface window for Abrasion submodule

Before producing recommendations, the system considers factors such as types of floor, usual expected traffic, and types of topping. A typical data input form of the *Abrasion* submodule is shown in Figure 7.20.

The system suggests that appropriate concrete strength should be chosen for abrasion resistance. The compressive strength levels may be attained in a number of ways such as by ensuring low water-binder ratio at the surface, by ensuring proper grading of fine and coarse aggregates (meeting ASTM C33), and by using the lowest slump consistent with proper placement and consolidation requirements. The system also suggests the air content of concrete consistent with exposure conditions. It also recommends on issues like finishing techniques for base and topping, curing practices, use of special aggregates, and use of vacuum dewatering method to remove water from concrete immediately after placing. Use of special dry shakes and toppings, and use of two-course floors are among other recommendations given by the system. Its recommendations include special consideration such as mesh reinforcing, bonded breaker on old concrete surface and minimum thickness requirement for the floor, where appropriate, in order to make it abrasion resistant.

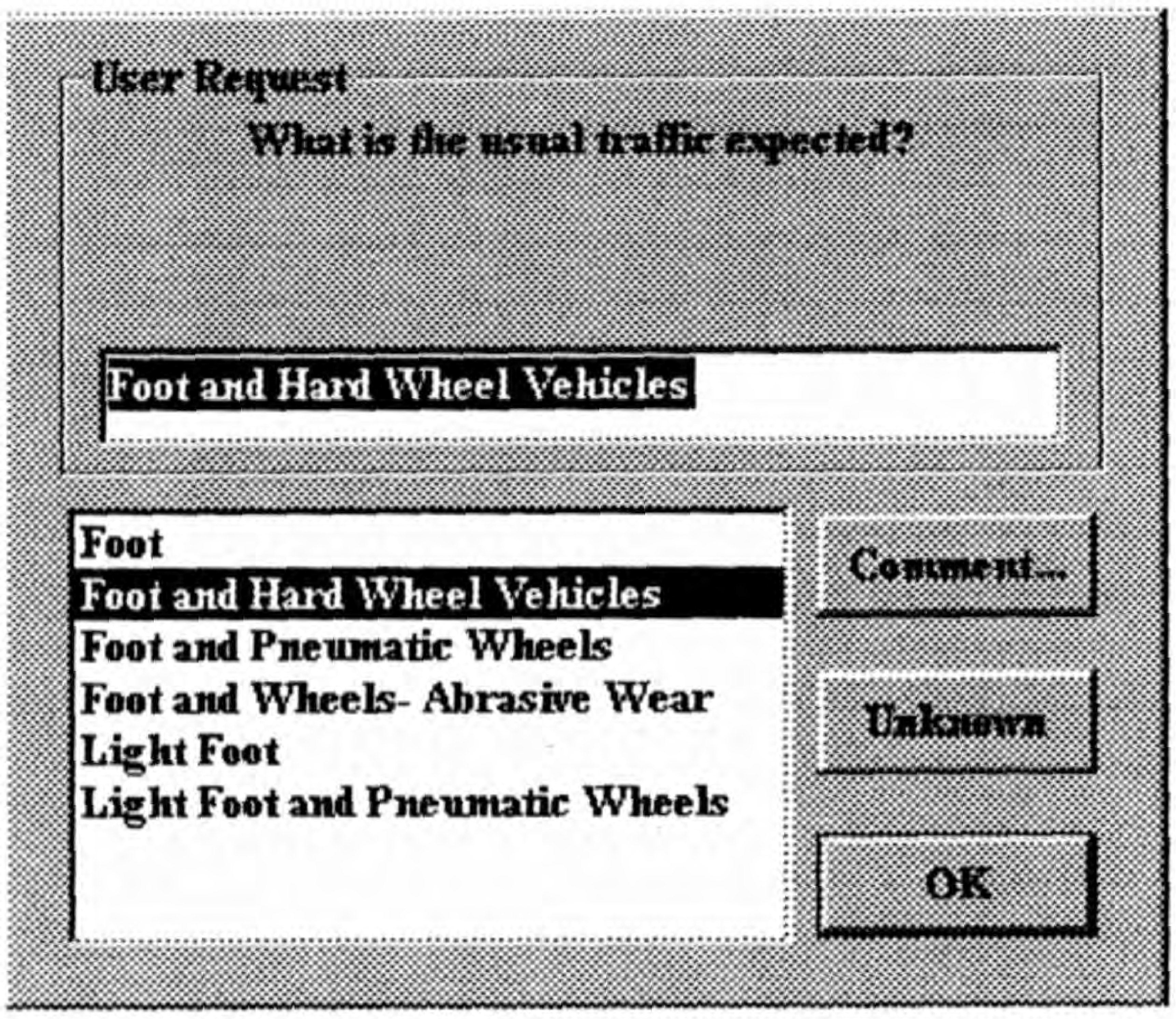


FIGURE 7.20 A typical data input form of the Abrasion submodule

(h) Freeze-thaw Submodule

Freezing-and-thawing is not a major problem for concrete structures in Malaysia. However, this submodule is included to give the system a sense of completeness with respect to durability aspects. The objective of this submodule is to make freeze-thaw resistant high performance concrete. The main interface window of this submodule is shown in Figure 7.21.

In the beginning of the consultation, the system informs that the resistance of concrete to freeze-thaw cycles depends on the following factors (Figure 7.21): water-binder ratio; type of structure; exposure conditions; aggregate properties; and entrained air. This submodule needs the following information in order to produce recommendation: anticipated exposure conditions (dry, moderate, or severe); types of hydraulic cement to be used (blended or ordinary Portland cement); concrete sections description (thin or normal); aggregate acceptance criteria (experience or ASTM C33); and nominal size of aggregate to be used (9.5, 12.5, 19, or 37.5 mm).

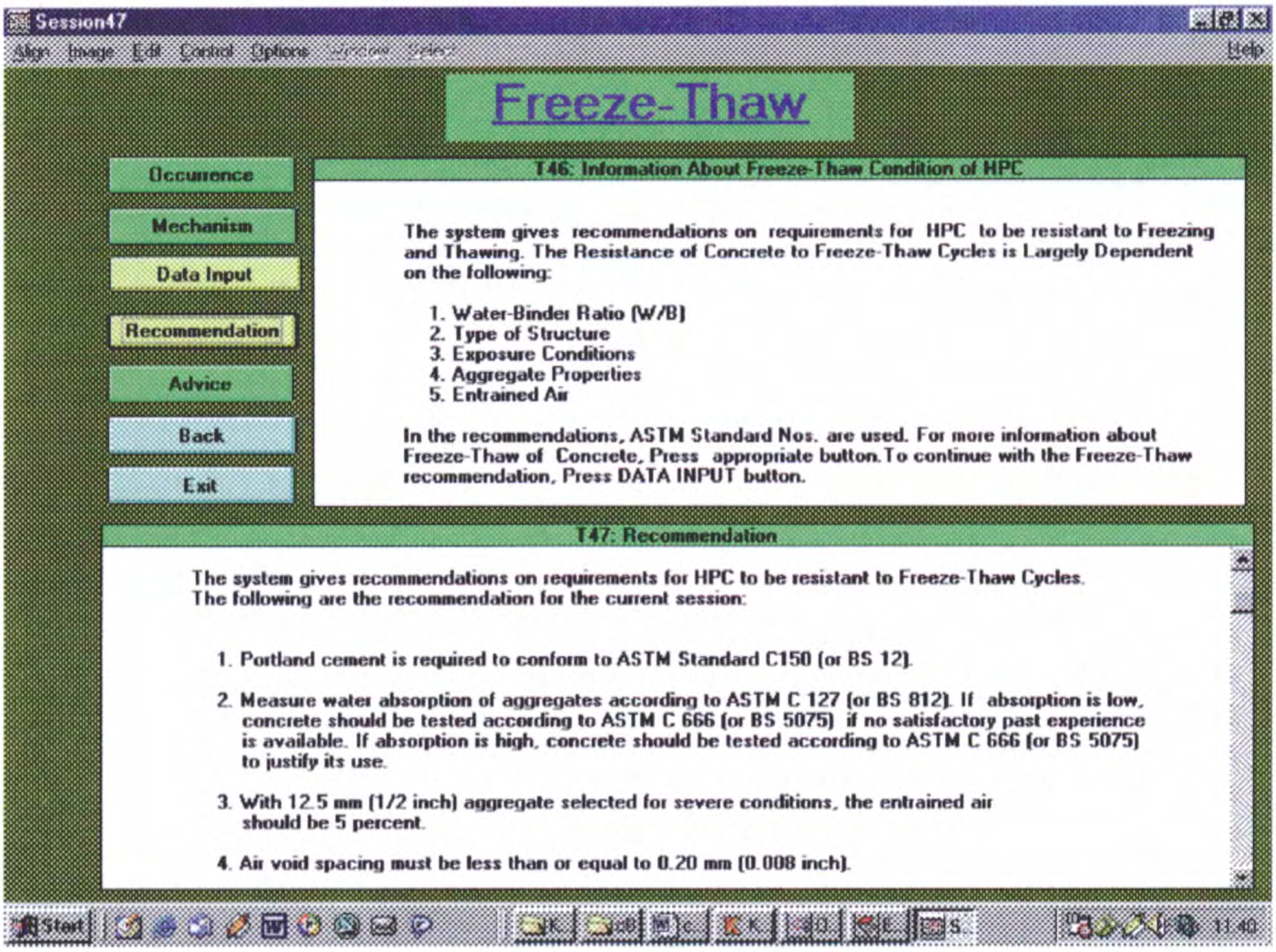


FIGURE 7.21 Main interface window of the Freeze-Thaw submodule

After collecting data from the user, this submodule searches its knowledge base and gives recommendations on the following issues:

- use of type of cement and corresponding ASTM Standards;
- use of pozzolans and GGBS (ground granulated blast furnace slag), and corresponding ASTM Standards;
- service records for acceptability of aggregates;
- compressive strength requirements while curing and before exposure to severe conditions; and

- standards for air entraining admixtures, chemical admixtures, admixtures for flowing concrete and guidelines for the use of admixtures.

7.4 ACCESSORY FACILITIES

Apart from the main user interface (which will be described latter in Section 7.5), several accessory facilities are available in the HPCA with the general objective of enhancing the performance of the consultation process. They are further described in the following sections.

7.4.1 Data Input Facility

The objective of the *Data Input* facility is to facilitate the entry of data for required concrete properties and properties of available concrete ingredients. The data also includes the exposure conditions of concrete and costs of ingredients. Data required for consultation with a specific knowledge module has been incorporated with the corresponding knowledge module. This facilitates the avoidance of irrelevant data input for a specific knowledge module and enhances the performance of the system. Even though input data can be entered at any stage during consultation, it is usually more convenient for the user, especially with respect to collecting and preparing information, to devote a one-time consultation session for data input of the modules and submodules that are expected to be consulted. It can be quite awkward if the user is forced to search for say, the solid content or saturation point of the superplasticizer from the dealer, in the middle of a mix design consultation. Nevertheless, the HPCA is still able to identify the occasional information gap and accommodate late data entry by means of automatic user prompts.

Data entry is divided into several categories, i.e. mix design data, trial batch data, data for one cubic metre SSD composition, data for batch composition, durability data for each durability submodule, cost data and mix performance adjustment data. Data is entered by using mainly *User Request* forms, which are customised forms designed for entering value for a single slot. These forms help to enter values for only one slot at a time but with more explanatory comments and better display of allowable or possible values as well as comments about the data. A typical *User Request* form for data input during the consultation with the *Mix Design* module is shown in Figure 7.22. It shows the limits of the value of input parameter. If the user is not sure about the value of the parameter, he can press on the *Comment...* button for getting help about the usual range of the values of the parameter as shown in Figure 7.23. This figure also shows the sources of the information.

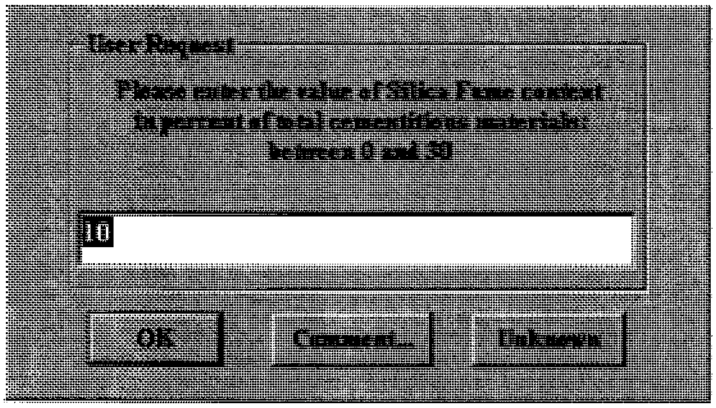


FIGURE 7.22 Typical *User Request* form for data input in the Mix Design module

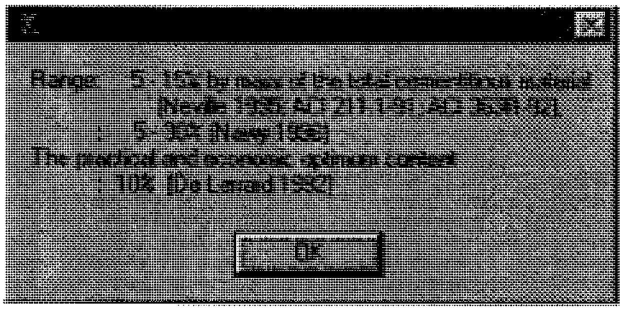


FIGURE 7.23 Advice regarding the question after pressing "*Comment...*" button of Figure 7.22

Other type of form used is *Multiple Input Form*. An example of *Multiple Input Form* is shown in Figure 7.24, which allows data entry of many slots at a time. Some interface windows also display some of the important information that has been entered or computed automatically upon entry of other information (for example, see Figure 7.18). Such a display keeps the user up-to-date of the important properties of concrete and its ingredients, expected exposure condition, and desired performance requirement of concrete.

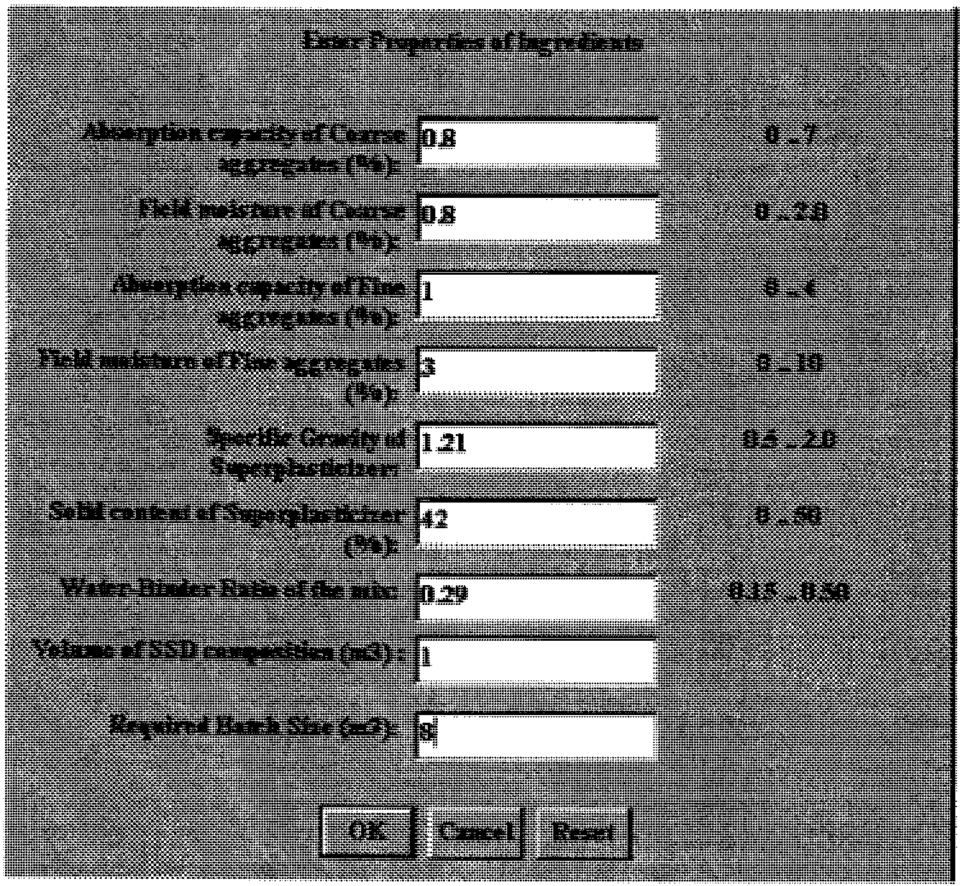


FIGURE 7.24 A *multiple input form* allows data entry of many slots at a time

7.4.2 Advice Facility

The advice facility forms a very important part of the HPCA system. Its general objective is to assist the user in the efficient utilisation of the HPCA. This is achieved by advising the user on the operational steps of the HPCA (how and why), and on the fundamentals of mix design and durability aspects of high performance concrete. In most of the HPCA interface windows, advice buttons guide the user along the consultation process, enabling access to pre-prepared files, which contain text describing the requested subject matter. The various HPCA advice buttons perform the following functions.

1. *Provide general user friendliness.* With the advice facility constantly at the user's disposal, the user becomes more comfortable consulting the system since the user consistently understands the reasons, methods, the expected results and implications of the design and recommendation processes.

2. *Inform the user about the limitations of the system.* The HPCA has its limitations as well, about which the user is kept informed by the advice facility. For example, the *Advice* button in the *Abrasion* interface window (Figure 7.19) explains the limitation of that submodule. It states that abrasion (erosion) of concrete in hydraulic structures is discussed only briefly in this system. The system also informs the user that the erosion problem is treated in detail in ACI 210R. Moreover, the *Durability* module gives recommendations on binder types, curing and finishing practices according to the ASTM, ACI or AASHTO standards. The information regarding these limitations is available to the user through the *Advice* buttons in the interface windows for various submodules of the durability module.

3. *Enlighten the user about the next design step.* Due to the flexibility in determining the flow of consultation, the HPCA user may need to be advised on the most appropriate sequence of design steps. The *Advice* button as well as *Introductory Transcript Image* in the beginning of consultation with most of the knowledge modules provide this facility (for example, see Figure 7.6).

4. *Give brief help for each task as required by the user.* Each design step normally has an *Advice* button attached to it. This aids the user in responding more efficiently to the prompts of the design procedure. Examples of *Advice* buttons can be found in most of the HPCA windows (see Figures 7.6 and 7.19).

5. *Advise the user of alternative solutions to a problem*. The advantages and disadvantages of each alternative solution must be made clear to the user so that he can interact with the HPCA with greater wisdom. For example, the interface window for *Alkali-Aggregate Reactivity* submodule (Figure 7.13) has an *Advice* button that opens a text file on the methods of avoiding alkali-aggregate reactivity problems. It will explain to the user the arguments for and against the alternative methods of preventing alkali-carbonate rock reaction as stated ahead: (i) by avoiding reactive aggregates that produce deleterious expansion, (ii) by using cement with low alkali contents, and (iii) by using mineral admixtures. He will then be able to have a better understanding of the recommendations of the system and the explanations for it.

7.4.3 Explanation Facility

One of the distinguishing characteristics of an expert system, such as the HPCA, is the transparency of its reasoning processes and knowledge base. This advantage is available to the user through *Explanation* windows that display the rules that have been used by the inference mechanism, thus explaining the reasons for arriving at a particular recommendation. Explanation windows can be lengthy and can be manipulated by normal scrolling bars. Two examples of this facility are: (i) window for *Explanation for Recommendations* in the *Mix Performance Adjustment* interface window (Figure 7.8), and (ii) *Explain* button for explanation of selecting amount of coarse aggregate in the *First Trial Batch Composition* window (Figure 7.7). These explanation facilities of the system facilitate verification and validation of results and also make it suitable for educational purposes.

7.4.4 General Information and User Guide Modules

Figure 7.25 shows the interface window of the *General Information* module. The interface window of the *User Guide* module is shown in Figure 7.26. The general objective of these modules is to assist the user in the efficient utilisation of the HPCA prototype. The user is advised by the system on the fundamentals of high performance concrete, the approaches of making high performance concrete and durability aspects through these modules.

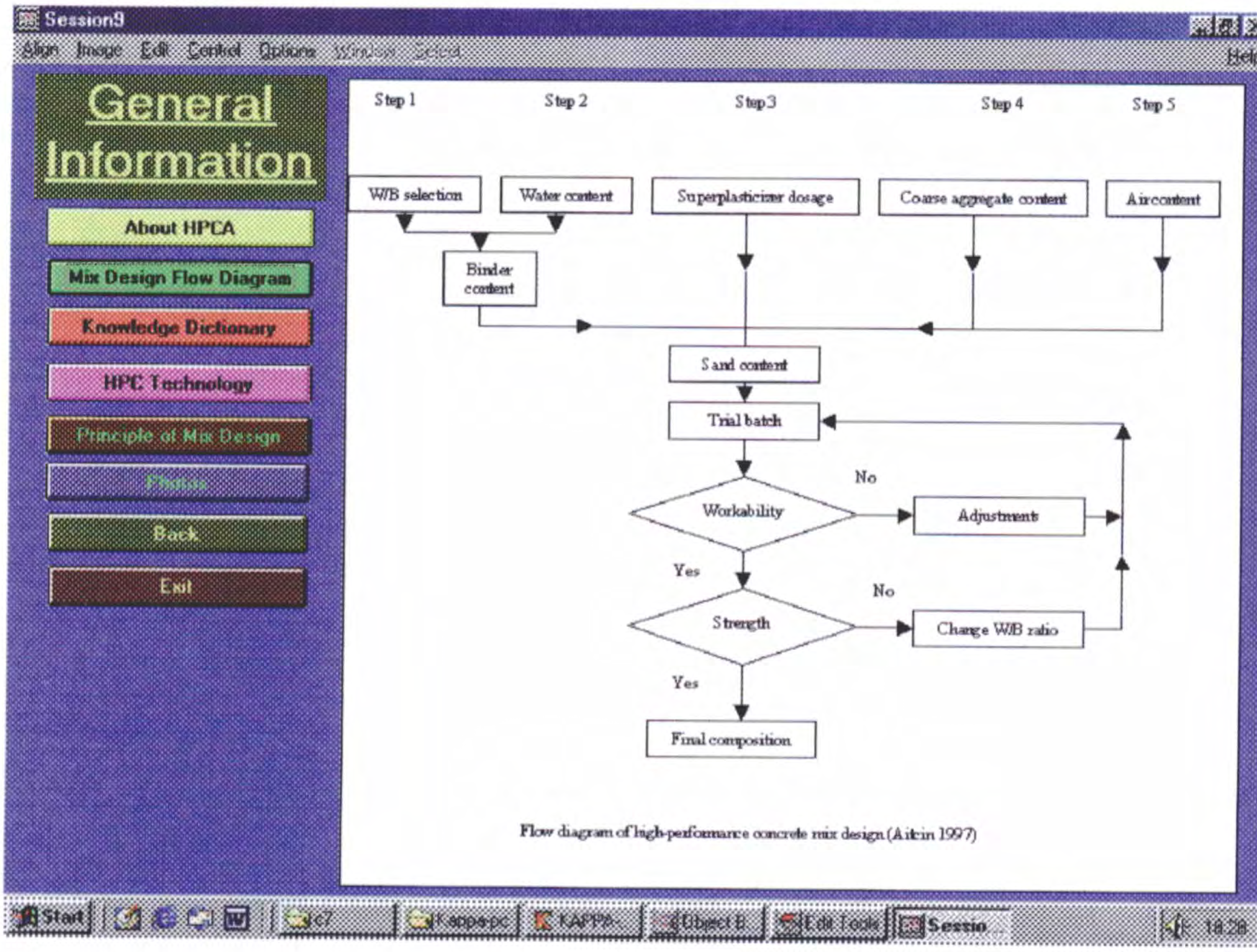


FIGURE 7.25 The interface window of the General Information module of the HPCA

A knowledge dictionary is also available to assist the user with unfamiliar technical terms. Having common ground in terminology among the experts and engineers in a field is very important in order to make sure that using the expert system efficiently is not hampered by inaccurate definitions or different interpretations. It was, therefore, essential to establish a knowledge dictionary as a tool to collect definitions and concepts in a common reference. The idea of establishing knowledge dictionary is a new development in expert system. The concept of a knowledge dictionary relevant to knowledge base is similar to data dictionary pertinent to databases (Abideen et al. 1999). The dictionary is stored in the system as a database related to the expert system. This dictionary is also useful as an educational feature. As a matter of fact it is considered as the backbone of the educational part. The dictionary of the present system includes: basic definitions of concrete mix design, high performance concrete and expert system; type of tests for evaluation of fresh and hardened concrete; and statistical measures used in assessment of concrete mix design.

In addition, a general conceptual flow diagram of high performance concrete mix design (see Figure 7.25) and various photographs showing the durability aspects are also accessible to enable the user to have a clear idea of the scenario.

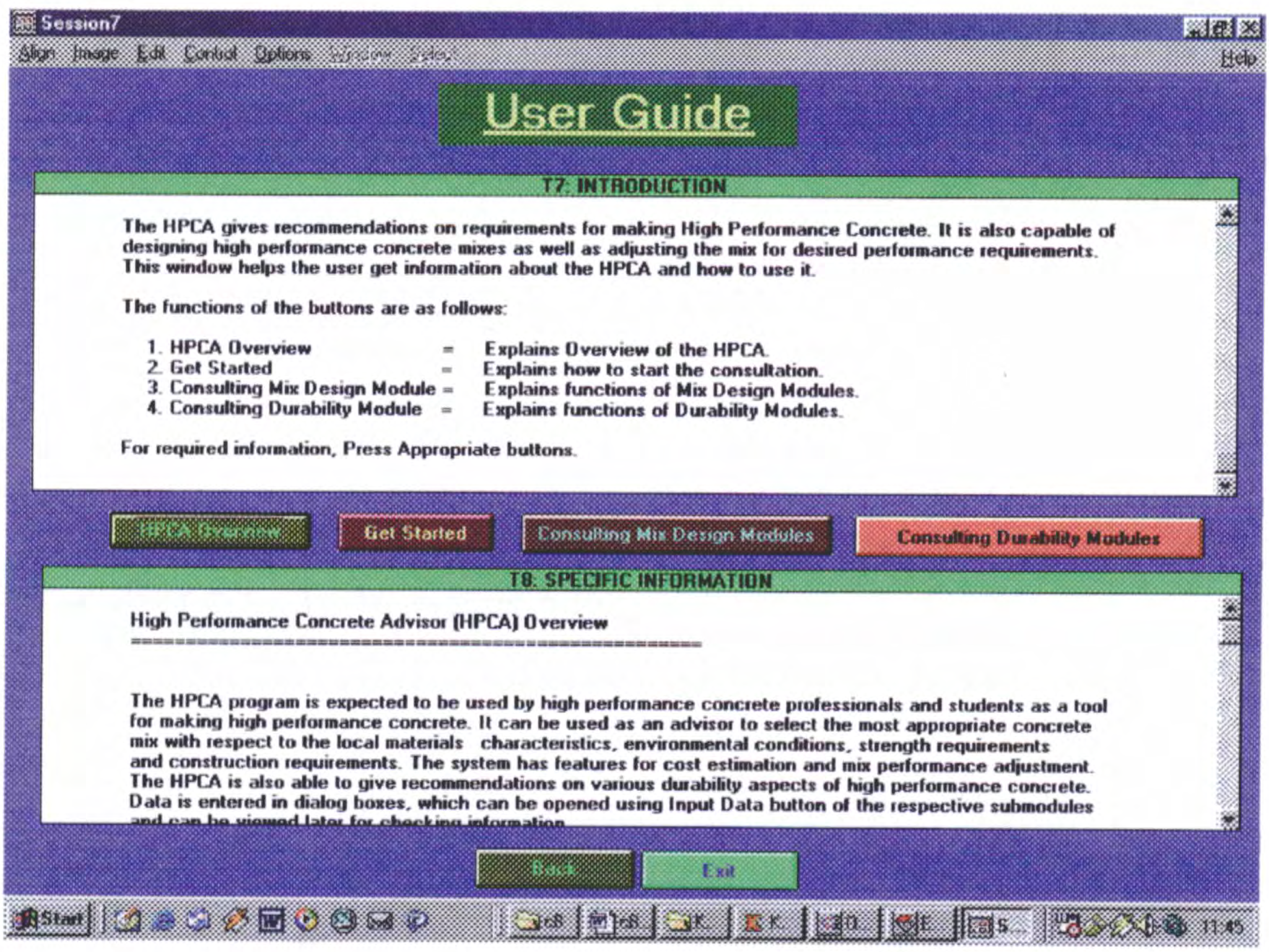


FIGURE 7.26 User Guide interface window

The *User Guide* module (Figure 7.26) provides a user-friendly environment whereby the various guidelines and advice facility are available to the user. The user should make himself familiar with the system and comfortable in consulting it by referring to this *User Guide* facility. A summary of the *User Guide* is presented in Appendix E as a user manual.

7.4.5 Occurrence and Mechanism Facilities in Durability Module

The *Occurrence* buttons in the interface windows for various durability submodules show the general situation where specific durability aspect may be a problem. The *Mechanism* buttons open text files in transcript images describing the concrete deterioration mechanism. These text files describe the reactions that are associated with the specific durability aspects. With the help of these accessory facilities, the user becomes familiar with the potential durability problem in his situation and feels confident in dealing with the durability problem. On the other hand, the inexperienced users get trained about the durability problems and their implications through consultation with these facilities.

For example, the *Occurrence* button in the interface window of the *Corrosion* submodule (Figure 7.12) explains the general situation of corrosion and conditions that accelerate corrosion. After consulting the sources of corrosion problem using this button, the user will be aware about his situation whether it will be subjected to corrosion or not. The *Mechanism* button in the same window opens a text file in transcript image describing the electrochemical process of corrosion. Facilities like information about occurrence and mechanism of durability problems are some of the improvements of the HPCA over other existing systems in the durable concrete domain.

7.5 USER INTERFACE

7.5.1 Overview of User Interface Development

The user interface stands between the HPCA expert system and its user. Its function is to facilitate communication between them by transforming responses from the user into a format that is understandable to the HPCA, and vice-versa. A good user interface protects the user from the system's complexities and still encourages effective information transfer (Basri 1994). The role of the user interface within expert system architecture was illustrated in Figure 5.1.

The ideal user interface should be based on a full-scale study and formulation of the *user model*, i.e., a conceptual representation of the user's thought processes in solving the problem (Basri 1994). This task was beyond the scope of this study and is recommended as possible further work on the HPCA. The development of the user interface for the HPCA was instead aimed at meeting the more obvious cognitive needs of the potential end-user. It attempts as best as possible to provide a user-friendly interactive environment, where the user is always kept informed of the *why*'s and *how*'s of each design step, and is made aware of his responsibility and other implications upon every decision he makes. The advice facility (described in Section 7.4.2), explain buttons, transcript images, comment buttons and the various interface components that have built-in user friendliness (described in Section 7.5.3), are major contributors in enhancing the performance of the HPCA user interface.

7.5.2 Typical End-Users of the HPCA

The end-users of the HPCA are potentially drawn from two groups, i.e., (i) technical personnel in government organisations, and (ii) design engineers in consultancy organisations. Government authorities (or other local authorities) are commonly the responsible agencies for the planning, design and construction of high performance concrete structures. This task is however only a small part of their wide-ranging responsibilities, hence it is very seldom that they employ specialist engineers for mix design and mix performance adjustment considering the various durability aspects of high performance concrete (barring the few exceptionally large projects). The engineer entrusted with the task of producing high performance concrete is normally the ordinary civil engineer with general engineering experience and training. The development of the HPCA user interface takes into consideration the typical characteristics of this group.

The second potential user group for the HPCA is engineering consultants who have been commissioned to undertake the design and construction of high performance concrete structures. Project initiators, including government authorities, may not have at their disposal sufficient technical design personnel thus necessitating such design and construction works to be contracted out to consultancy organisations. Consultant engineers specialising in high performance concrete mix design and consideration in various durability aspects are not easily available, especially if the design has to consider the peculiarities of specific durability performance requirements. The design job will normally be passed on to the typical design engineer. He will normally have general experience in civil engineering works, perhaps with broad specialisation in structural or construction engineering projects. Such an engineer will require a suitable user interface to utilise the HPCA efficiently.

The two user groups described above have the following common characteristics that are relevant considerations to the development of the HPCA user interface:

1. they have some knowledge and experience in general engineering design and construction;
2. they have some knowledge and experience, but not in-depth, of high performance concrete as a construction material option;
3. they have little knowledge but no experience of mix design and adjustment of high performance concrete which accounts for specific performance requirements;
4. they are reasonably familiar with computer, but restricted to routine applications such as word processing;
5. they have little or no knowledge of expert systems technology; and
6. they have little time to spare for self-education and training for new skills.

7.5.3 Windows as User Interface for the HPCA

The HPCA interfaces with the user through windows. The HPCA main interface window, shown in Figure 7.5, is the first that is presented to the user. It contains the main menu in the form of buttons, which in turn opens the windows for (i) mix design, mix performance adjustment, cost estimation and durability modules, and (ii) user guide on how to proceed, general information about concrete mix design, high performance concrete, expert system and the HPCA itself. Each of these windows has buttons that open other windows representing submodules or specific tasks. Several windows may be opened at any given time.

The windows are in themselves objects within the Kappa-PC environment. All Kappa-PC windows follow standard Microsoft Windows procedures for opening, closing, maximising, scrolling, etc. Thus a computer user who is already familiar with Microsoft Windows will have little difficulty in adapting to the HPCA user interface. Each HPCA interface window contains a customized set of components (described in the next section i.e., Section 7.5.4) that facilitate communication with the end-user.

7.5.4 Components of the User Interface

The HPCA user interface was designed to provide some flexibility of interaction to the user, and yet shield him from the more complicated aspects of the system. Many of the components of the user interface display information about the state of the application for the end-user; most of these also allow the user to input or alter information as well. Other components are prompts for the user to provide some form of response. Menus or response options are used whenever possible to enhance interactive efficiency. When the possible range of responses are displayed as a menu, the user will be able to recognise a correct choice better than recalling that choice solely from memory.

Each of these interface components are themselves Kappa-PC objects that possess slots and methods. The descriptions and examples of these components are given below.

(a) Buttons

A button is a rectangular image which, when clicked with the mouse, calls a function that has been associated with it. This function call typically starts a chain of actions, such as sending a message to a method, displaying other images or running the rule inference mechanism. Buttons allow rapid interaction, yet they provide the end-user with some degree of control over how the HPCA runs without being tied down to a rigid pre-determined set of interactions. They are the most widely used interface component in the HPCA and are found in all the HPCA windows (for example, see Figures 7.5 to 7.26).

(b) Text and Edit Images

Text images display static pieces of text or text files. They are useful for posting titles or labels in windows to improve clarity of the functions for the window and its components. The title *High Performance Concrete Advisor* in the main interface window (see Figure 7.5) is an example of a text image in the HPCA.

The edit image allows the monitoring of slot values while an application is running. It is restricted to single-valued slots. The edit image has a box into which the user can type a new slot value or overwrite an old one. The boxes for costs of ingredients such as *Cement (RM/bag), Coarse aggregate (RM/ton)* etc. in the interface window for *Cost Estimation* (see Figure 7.9) are examples of edit images in the HPCA.

(c) Monitor and Change Boxes

There are several types of box images that enable the HPCA user to monitor, enter or change values of different types of slots with the range of possible values displayed. They are single-list boxes for single-valued slots, multiple-list boxes for multiple-valued slots, check boxes for single-valued textual slots; all of which do not allow entry of new values outside the allowable list. The combo box is a standard Microsoft Windows image that combines the editing capability of an edit box with the display capability of a single-list box. Examples of some of the above types of boxes can be found in the windows of various modules in the HPCA (for example, see Figures 7.8 and 7.16).

(d) Transcript Windows

A transcript window is used to output a text for display to the user at any time while running an application. The user can use scrolling facilities if the text is lengthy, for example, if it is sourced from a descriptive text file. The window *Mix Design Information* in the interface window for *Mix Design* module (see Figure 7.6) is an example of a transcript window in the HPCA.

(e) Graphics

The HPCA can communicate graphics using bitmap and drawing images. A bitmap image allows display of pre-stored pictures of any size on the screen. It, however, requires massive computer memory. For example, *Mix Design Flow Diagram* in the interface window for the *General Information* module (Figure 7.25) shows the flow diagram of mix design of high performance concrete. A drawing image is a customised drawing produced using built-in functions of Kappa-PC that can draw lines, text, circles, etc.

(f) State Boxes

A state box image monitors textual parameters while an application is running. It is attached to a slot that has value type *text* and an *Allowable Values* value limit. The state box vertically displays ellipses containing each possible value. The ellipse representing the actual value is highlighted. Every time the value of the slot changes, so does the highlighted portion of the box. The box for *Source of Carbon-dioxide* in the interface window for *Carbonation* submodule (see Figure 7.18) is an example of a state box image in the HPCA.

(g) Line Plots

A line plot image allows the graphical display of up to six pairs of x-y vectors containing numerical values. The line plot displays each x-y vector pair as a curve with a different line style and colour. It displays scales for the x- and y-axes and legends for each plot. The interface window for *Durability* module (see Figure 7.10) contains an example of line plots in the HPCA displaying the variation of permeability of hardened cement paste with water-binder ratio.

(h) Sliders

The slider image monitors a numerical value attached to a slot and allows it to be changed while an application is running. The slot value must be of the type *number* and its minimum and maximum values specified. Every time the value of the slot changes, the box on the horizontal bar moves to indicate the new value. This box can be moved using the mouse if the user wants to change its value. The slider *Compressive Strength* in the window for *First Trial Batch Composition* (Figure 7.7) is an example of a slider image in the HPCA.

(i) Dialog Windows

The HPCA can interact with the user using pop-up dialog windows. A variety of option menus, multiple input forms, multiple selection list boxes, and message boxes are available for display as windows upon instruction. The windows pop-up in the middle of the screen and require the immediate attention of the user. Some examples are available in Figures 7.20, 7.22, 7.23 and 7.24. They have been described in Section 7.4.1.

7.6 SUMMARY

The system architecture of the finished product, detailing the HPCA prototype components and its operational mechanisms is reported in this chapter. In the beginning, the object-oriented model of the domain is described. The HPCA's general architecture, its object hierarchy, attributes and behaviour are also included. The various components of the HPCA, i.e. the main design modules (four) and accessory facilities (data input, advice, and explanation), are then outlined. Finally, the characteristics of the HPCA user-interface are described. The evaluation and testing of the HPCA prototype is described in the next chapter.

CHAPTER VIII

EVALUATION AND TESTING OF THE EXPERT SYSTEM PROTOTYPE

8.1 INTRODUCTION

The prototype testing is the process of evaluating the performance and utility of the prototype program and revising it as necessary. It also involves checking for mistakes in knowledge acquisition to ensure that the knowledge base correctly reflects that of the experts' to establish that the system performs with an acceptable level of accuracy, user-friendliness, and overall usefulness. Testing the prototype also involves looking at the ease of handling the user interface and understanding the explanatory text (Basri 1999).

The evaluation of expert systems has only been considered recently and, therefore, there is currently no formal universal approach for assessing a prototype performance (Berrais 1992). A formal external evaluation that involves end-users and domain experts may require substantial effort and resources. Many prototypes were tested based on case studies, and the results were analyzed internally by the system developers themselves (Mahmoud 1989; Berrais 1992). Expert system development involves continuous processes of modifications, improvements and testing of prototypes. According to Basri (1999), this is an advantage of an expert system in that the knowledge can be continually improved and updated.

It should be recognized that HPCA (High Performance Concrete Advisor) is only a research prototype; hence, the expert system must be refined and tested further before it can be released for commercial use. This is because users in the field not only demand more than high-quality performance but also want the system to be fast, reliable, easy to use, easy to understand, and very forgiving when they make mistakes. Consequently, it needs extensive field-testing before it is ready for widespread commercial use.

The performance of the HPCA was evaluated internally by the system developer based on text analysis, advice from domain experts and the developer's own knowledge and experience. Several case studies were performed for testing and result validation for some of the modules of the HPCA. These case studies were some means of evaluation of performance of the HPCA in proportioning concrete mixes and in giving recommendations on durability aspects of high performance concrete. The purpose of these case studies was to give some measure of the accuracy of its knowledge base. Finally, the user-friendliness of its user interface was evaluated.

8.2 CASE STUDY FOR MIX DESIGN OF HIGH PERFORMANCE CONCRETE

The objective of this case study was to evaluate the performance of the HPCA consultation process and results when it was applied to a high performance concrete mix. The case study was carried out on an example mix design of high performance concrete from a classical textbook (Aitcin 1998). The results of the design of the HPCA were compared with those reported in the textbook. This example was selected for comparison because the author of this textbook is considered as one of the few experts in the domain of high performance concrete all over the world. Furthermore, if any designer is entrusted with the mix design of a high performance concrete project, he will normally consult a typical textual source such as this particular one.

At first, the user looked at each knowledge base in turn from the main screen (Figure 7.5). If the user needed information about the program procedure, he pressed the *General Information* or the *User Guide* button during the consultation process, which provided the introduction and description on how to proceed with the program. The consultation process started off after clicking on *Mix Design* button on the main screen. This opened the interface window for the *Mix Design* module (Figure 7.6).

From that window, the user learned about the functions of the buttons regarding mix design submodules and got advice about each design step or submodule by pressing on appropriate *Advice* button. The user then pressed on the *First Trial Batch* button to get the first trial batch for his situation and started to input data. After the completion of data input, the user pressed on appropriate buttons to view the mix design and specifications recommended by the system. The summary of data, consultation and explanation of results of each submodule of the mix design module as well as mix performance adjustment module are described in the following sections. The data and sample calculation of the mix design case study are included in Appendix B. A comparison of mix design values with experimental results is presented in Appendix F. Comparison among mix design values obtained using the HPCA and those obtained using another expert system developed by Jamil (2003) is presented in Appendix G.

8.2.1 First Trial Batch

This section illustrates an example test run of the HPCA for getting the *First Trial Batch* composition. Data that might be typical for mix design of high performance concrete would include several elements as shown in Table 8.1. This table also includes the data of the present example. In this example, a 100 MPa concrete mix was designed with Type I Portland cement, a naphthalene-type superplasticizer, a dolomitic limestone, a siliceous natural sand and silica fume.

Table 8.2 shows the final mix design values after moisture adjustment as proportioned by the HPCA. The water contributed by the superplasticizer was also considered as part of the mixing water. Mix design comparison between the results of the expert (Aitcin 1998) and those of the HPCA is also shown in Table 8.2. The results indicated that the differences between the two mix designs were not critical. It may be relevant to mention here that, for a particular mix design, there are always several answers which can satisfy the requirements of the specification (Bai & Amirkhanian 1994). Thus the concrete proportions selected by the system were accurate enough for the first trial batching. The developed system is, therefore, capable of proportioning the first trial batch of high performance concrete mix with acceptable accuracy.

TABLE 8.1 Data Required and the Corresponding Values for the First Trial Batch

Item	Requested Information	Data for the Sample Example
Strength of Concrete	Compressive strength at 28 days in MPa	100
Binder Materials	Cement and Pozzolans or Cement only	Cement and Pozzolans
Cement	Type	Type I
	Specific gravity	3.14
Silica Fume	Content in percent (by weight) of total cementitious materials	10
	Specific gravity	2.20
Coarse Aggregate	Maximum size in mm	10
	Dry-rodded density (kg/m^3)	2480
	Shape	Average and Cubic
	Specific gravity (SSD)	2.80
	Absorption capacity in percent	0.80
	Field moisture in percent	0.00
Fine Aggregate	Specific gravity (SSD)	2.65
	Absorption capacity in percent	1.20
	Field moisture in percent	3.50
Superplasticizer	Solid dosage at saturation point in percent	1.00
	Solid content in percent	40
	Specific gravity	1.21
Air Content	Content in percent	1.50

TABLE 8.2 Mix Design Comparison Between the Results of the Expert and those of the HPCA for the First Trial Batch

Item	Expert	HPCA
Water-Binder Ratio	0.27	0.27
Water (l/m^3)	124.00	123.38
Cement (kg/m^3)	470.00	464.38
Silica Fume (kg/m^3)	50.00	51.60
Coarse Aggregate (kg/m^3)	1066.00	1066.40
Fine Aggregate (kg/m^3)	772.00	777.51
Superplasticizer (l/m^3)	10.70	10.66
Air Content (percent)	1.50	1.50

8.2.2 Trial Batch for Laboratory

The calculated mixture proportions should be checked by means of trial batches prepared and tested for the intended performance requirements (Aitcin 1998). These tests and observation on the designed mix are usually performed in the laboratory by using a small portion of the designed mix i.e., by laboratory trial batch. For the purpose of validation of the system, data for an example laboratory testing is described in the following section.

It was assumed that the following specimens were needed to test the performance of the concrete mix in the laboratory: three 100 x 200 mm cylinders for tests at 1, 7, 28 and 91 days in compression (total number of samples = 12); three 150 x 300 mm cylinders for tests at 28 days in compression; three 150 x 300 mm cylinders for tests for elastic modulus at 28 days; three 100 x 100 x 400 mm beams for test for modulus of rupture at 7 and 28 days, plus one spare for a total of seven. A slump test, an air content test and a unit mass test would be done on the fresh concrete. Except for the air content test, the concrete used for these tests would be recovered. Knowing that an air test needs 15 kilogram, the amount of concrete to make this trial batch was calculated assuming 10% extra materials to compensate for losses. The results computed by the system and those of the expert are compared in Table 8.3. The comparison indicated that the proportions selected by the HPCA were close enough to the proportions selected by the expert. Thus the present system can be used for the calculation of laboratory trial mix of high performance concrete with acceptable accuracy.

TABLE 8.3 Comparison of Results for Laboratory Trial Batch

Item	**Expert**	**HPCA**
Water-Binder Ratio	0.27	0.27
Mixing Water (litre)	11.53	11.49
Cement (kg)	43.70	43.26
Silica Fume (kg)	4.70	4.81
Coarse Aggregate (kg)	99.10	99.33
Fine Aggregate (kg)	71.80	72.42
Superplasticizer (litre)	0.99	0.99
Air Content (percent)	1.50	1.50

8.2.3 One Cubic Metre SSD Composition

This submodule can be used to compute proportion of concrete ingredients for one cubic metre of concrete for SSD conditions of aggregates using the data of laboratory trial batch. It can also be used for conversion of concrete composition from field conditions of aggregates to SSD conditions of aggregates. During the computation, it takes into account the moisture conditions of aggregates in the bins as well as water hidden in liquid superplasticizer. The data and results of this calculation for the sample example are presented in the following sections.

It was supposed that a trial batch with an adequate consistency and adequate initial and final slumps was made using the quantities of materials shown in Table 8.4. The air content of this trial batch was 1.5%. The materials used to make this trial batch had the properties shown in Table 8.5.

TABLE 8.4 Quantities of Materials for Trial Batch

Water (litre)	**Cement (kg)**	**Fly ash (kg)**	**Aggregate (kg)**		**Superplasticizer (litre)**
			Coarse	**Fine**	
12	45	5	100	70	0.9

Source: Aitcin 1998

TABLE 8.5 Properties of Materials Used in Trial Batch

Aggregate	**Specific gravity (SSD)**	**Absorption capacity (%)**	**Field moisture (%)**
Coarse	2.75	1.0	0
Fine	2.65	1.0	3.9

Source: Aitcin 1998

The fly ash used had a specific gravity of 2.50. The superplasticizer was naphthalene-based with a specific gravity of about 1.21 and a solid content of 42%. It was required to compute one cubic metre composition of this concrete for the SSD conditions of aggregates (Aitcin 1998). The results are compared in Table 8.6 and show good agreement between the results of the HPCA and those of the expert. These results served as the means of verification of the accuracy of knowledge base of the developed system.

TABLE 8.6 Comparison of Results for One Cubic Metre SSD Composition

Item	Expert	HPCA
Water-Binder Ratio	0.27	0.27
Water (l/m^3)	144.88	144.61
Cement (kg/m^3)	478.35	478.70
Fly Ash (kg/m^3)	53.15	53.19
Coarse Aggregate (kg/m^3)	1073.63	1074.51
Fine Aggregate (kg/m^3)	722.84	723.65
Superplasticizer (l/m^3)	9.57	9.57
Air Content (percent)	1.50	1.50

8.2.4 Batch Composition

This submodule computes the batch composition for a concrete plant for field conditions of aggregates. The system collects the following data from the user in order to compute batch composition: one cubic metre SSD composition, the moisture conditions of aggregates in the field, and the expected batch size. It was assumed, for example, that a concrete batch plant was to produce 8 m^3 of high performance concrete on the basis of the SSD composition shown in Table 8.7.

TABLE 8.7 Concrete Mix for One Cubic Metre SSD Composition

W/C	Water (litre)	Cement (kg)	Aggregate (kg)		Superplasticizer	
			Coarse	Fine	Liquid (litre)	Solid (kg)
0.29	130	450	1050	750	8	4

Source: Aitcin 1998

The aggregates having the following water contents were in the bins: coarse aggregate with field moisture of 0.8% and absorption capacity of 0.8%; fine aggregate with field moisture of 3.0% and absorption capacity of 1.0%. The superplasticizer was a naphthalene type containing 42% solids and having a specific gravity of 1.21. The user input these data by pressing appropriate buttons of the *Batch Composition* interface window. After the completion of data input, the user got the results of the batch composition for the field conditions of aggregates stated above. The results are compared in Table 8.8. Again, it can be seen that the results of the HPCA compared well with those of the expert. This gave a positive indication of the accuracy of the knowledge base of the HPCA.

TABLE 8.8 Comparison of Results for Batch Composition

Item	**Expert**	**HPCA**
Water-Binder Ratio	0.29	0.29
Mixing Water (litre)	872	875
Cement (kg)	3600	3600
Coarse Aggregate (kg)	8400	8400
Fine Aggregate (kg)	6120	6120
Superplasticizer (litre)	64	64

8.2.5 Mix Performance Adjustment

This module analyses the possible causes of performance failure of a high performance concrete mix and recommends on the remedial measures to be taken in order to achieve the desired performance. These features are demonstrated in this portion of the case study. The interface window of this module is shown in Figure 7.8.

In this case study, the user selected data from the interface window (Figure 7.8). The user selected that the strength performance of the mix was not achieved in the testing of the first trial batch. The user noticed that the fracture surface of the test specimen passed through hydrated cement paste. The user was also interested in getting quantitative recommendations. These selected data together with the data options displayed by the system are shown in Table 8.9.

TABLE 8.9 Questions and the User's Selection for an Example Session with Mix Performance Adjustment Module

Question Asked by the System	Options to Select	User's Selection
(1) What performance of the designed mix is inadequate?	(a) Strength (b) Workability (c) Durability	(a) Strength
(2) What does the strength test result indicate?	(a) Intragranular fracture (b) Debonding between coarse aggregate and hydrated cement paste (c) Fracture surface passes through hydrated cement paste (d) Strength does not increase with water-binder ratio	(c) Fracture surface passes through hydrated cement paste
(3) Do you need quantitative recommendation?	(a) Yes (b) No	(a) Yes

After selecting those data, the user pressed on the recommendation button. As a consequence, the HPCA inferenced through its knowledge base and produced the recommendation shown in Table 8.10. The system recommended that water-binder ratio of the mix should be reduced in order to improve its strength performance. Because if the fracture surface passes entirely through hydrated cement paste around the aggregates, then a stronger concrete can be made with the same aggregate by lowering further the water-binder ratio (Aitcin 1998). The system also explained this in the second transcript image of the interface window (see Figure 7.8). The system also recommended that increasing the 28-day compressive strength of concrete by 1 MPa necessitate the addition of approximately 9 kg/m^3 of extra cement to the mix. In order to maintain the yield, the system recommended appropriate reduction of fine aggregate content. The system recommended use of superplasticizer because its use can reduce water demand by 12 to 25% with a corresponding increase in compressive strength. These recommendations and explanation were similar to those of the experts (Aitcin 1998; Bai & Amirkhanian 1994). Thus the performances of the prototype to diagnose mix performance failure and to give corresponding recommendation are considered to be satisfactory.

TABLE 8.10 Recommendations of Mix Performance Adjustment Module for Data of Table 8.9

Recommendations of Mix Performance Adjustment Module
The following is a list of the recommendations concerning mix performance adjustment for this session: (1) Use lower water-binder ratio. Because if the fracture surface passes almost entirely through the hydrated cement paste around the aggregates, a stronger concrete can be made with the same aggregates by lowering further the water-binder ratio. (2) Increasing the 28-day compressive strength of a concrete mix by 1 MPa requires the addition of approximately 9 kg/m^3 of extra cement to the mix. (3) Adjustment should be made in fine aggregate weight as necessary to maintain required total effective displaced volume. (4) The yield can be maintained by an appropriate reduction of fine aggregate content. (5) Superplasticizer can reduce the water demand by almost 12-25% with a corresponding increase in compressive strength. Therefore, its use is recommended.

8.2.6 Cost Estimation

Cost estimation of a designed mix can be carried out using the *Cost Estimation* module. The first step was to input unit cost of the proportioned ingredients and the batch size. A transcript image in the *Cost Estimation* interface window (Figure 7.9) helped the user by displaying information about the ranges of unit cost of concrete ingredients. Although these values vary in different parts of the world as well as in the same region of a country, this information helped the user in getting an idea about the approximate unit cost of individual ingredients. After inputting the unit cost of ingredients, the user got the total cost of mix for one cubic metre of concrete and for a particular batch composition by pressing appropriate buttons. The input data together with the estimated costs are shown in Table 8.11. The table shows that the values estimated by the HPCA were very close to those of the expert (last two columns of Table 8.11). It can be seen that the differences between costs estimated by the expert and the HPCA are very insignificant. Therefore, the performance of the prototype to estimate costs of one cubic metre and batch composition of designed mix is considered to be satisfactory.

TABLE 8.11 Data and Results for Evaluation of the Cost Estimation Module

Item	Trial Batch Composition (Table 8.2)	Unit Cost (Malaysian Ringgit)	Cost of 1 m^3 (Malaysian Ringgit)	Cost of 8 m^3 (Malaysian Ringgit)
(1) Cement	464.38 (kg)	11 (per 50 kg)		
(2) Coarse aggregate	1066.40 (kg)	90 (per 1000 kg)	487.31 (Expert)	3898.49 (Expert)
(3) Fine aggregate	777.51 (kg)	70 (per 1000 kg)	487.32 (HPCA)	3898.53 (HPCA)
(4) Silica Fume	51.60 (kg)	3 (per kg)		
(5) Super-plasticizer	10.66 (litres)	150 (per 20 litres)		

8.3 CASE STUDY FOR DURABILITY

This module gives recommendation on durability aspects of high performance concrete. The knowledge base mainly contains knowledge in the form of production rules, which are invoked whenever the relevant button is pressed. The system gives recommendation on the following durability aspects: (a) Corrosion, (b) Alkali-Aggregate Reactivity, (c) Sulfate Attack, (d) Seawater Exposure, (e) Acid Attack, (f) Carbonation, (g) Abrasion, and (h) Freeze-thaw. At first, the user pressed on the *Durability* button of the main interface window of the HPCA (Figure 7.5). As a result, the interface window for durability module (Figure 7.10) appeared. The user read the instruction in the transcript image of the interface window. The user was convinced by observing the bitmap image in the interface window that water-binder ratio is the major factor in order to reduce the permeability of concrete, which is the principal cause of concrete deterioration. The user then went through various submodules of the durability module by pressing on appropriate buttons. The following sections describe case studies for these durability aspects.

8.3.1 Corrosion

Figure 7.12 showed the main interface window of the *Corrosion* submodule of the *Durability* module. This interface window was accessed through *Corrosion* button of the interface window for the *Durability* module (Figure 7.10). The interface window for corrosion gave preliminary information about factors that affect corrosion of reinforcement in concrete and displayed several buttons to facilitate the consultation process. It also explained, schematically, the three major aspects of deterioration of concrete by corrosion of reinforcement i.e., cracking, spalling and delamination.

The user then clicked on the *Data Input* button (Figure 7.12) and selected data appropriate for his concrete condition. Table 8.12 shows the data required by this submodule for a particular consultation session and the corresponding response of the user. One of the features of the system is that the data input is self-consistent. For example, if the user selects outdoor environment, then the system further asks whether the outdoor exposure is inland, arid or seawater.

TABLE 8.12 Required Information and the User's Selection for a Particular Session of the Corrosion Submodule

Requested Information	**User's Selection**
(1) Concrete environment: Indoor Outdoor	Outdoor
(2) Climate or exposure of concrete: Arid Inland exposure to wet environment Seawater	Seawater
(3) Extent of seawater contact: Continuous submergence Partial submergence Splash zone	Continuous submergence
(4) Type of reinforcement steel: Prestressed Steel reinforcement bars	Prestressed

After getting the input data from the user, the *Corrosion* submodule of the HPCA produced recommendations by comparing these data with the knowledge contained in its knowledge base. A typical output screen of recommendation for the input data of Table 8.12 is shown in Table 8.13. The recommendations included, among others, water-binder ratio, cover requirements, drainage requirements, workmanship requirements, slump requirements and maximum chloride contents, like other expert systems in the domain. Moreover, the recommendation included a note, which indicated that the use of high quality concrete, adequate cover over steel, and good design are prerequisites if corrosion is to be minimized. These are some of the improvements of the HPCA over other existing systems (Clifton & Oltikar 1987; Kaetzel et al. 1993) available in the corrosion-resistant concrete domain.

After getting recommendations, the user might ask for explanation by pressing on the *Explain* button. The explanation facility of the system facilitated verification and validation of results and also made it suitable for educational purposes. The output information or recommendation, like input information, was also self-consistent. For example, if the type of reinforcement was prestressed, then the system recommended that the maximum chloride content should be 0.08% by mass of cement as shown in Table 8.13.

TABLE 8.13 Recommendations of the Corrosion Submodule (Based on Data Given in Table 8.12)

Recommendations For Making Corrosion-Resistant Concrete
The following is a list of the recommendations concerning Corrosion of concrete for this session: Good Workmanship is extremely important. Well-graded aggregates should be used. Seven days of uninterrupted moist or membrane curing is recommended. Avoid contact between different metals in the concrete to prevent stray current. Be cautious of protruding metals. A 75 mm (3-inch) cover and water-binder ratio below 0.40 or a 90 mm (3.5 inch) cover and a water-binder ratio below 0.45 are necessary. Any means of decreasing the permeability of concrete, such as by the use of superplasticizers, pozzolans such as silica fume, will prolong the onset of corrosion. For bridge deck or similar structure exposed to severe chloride ion environment, additional protection needs to be provided to reinforcing steel by using either or combination of: 1. Low slump dense concrete (water-binder ratio = 0.32) 2. Epoxy coated Prestressing steel 3. Waterproof membranes. Maximum chloride content should be 0.08% by mass of cement. Note: Portland cement concrete can provide excellent corrosion protection to embedded steel. When corrosion occurs, costs of repairs can be exceedingly high. The use of high quality concrete, adequate cover over the steel, and good design are prerequisites if corrosion is to be minimized.

8.3.2 Alkali-Aggregate Reactivity

This submodule gives recommendations on requirements for high performance concrete to be resistant to alkali-aggregate reactivity. The main interface window of this submodule was shown in Figure 7.13. In the beginning of the consultation, it stated through the first transcript image that the magnitude of expansive reactions depended on specific aggregate, alkali content of cement and concrete, availability of extraneous alkalis (i.e., seawater) and availability of water. The user also got some idea about typical cracks due to alkali-aggregate reactions in a vertical wall and in a pavement by observing the bitmap image in the interface window. The bitmap image also indicated that the typical crack pattern of alkali-aggregate reaction is "map crack".

The user started data input by pressing *Data Input* button. The system asked the user for required information about field and lab performances of aggregates to be used. When the user selected that there were problems with aggregates, the system wanted to know whether aggregates met the mandatory requirements or not. The user confirmed the system that the aggregates met mandatory requirements. The next question of the system was about the type of aggregates. The user's choice was *siliceous*. Then the system posted a message recommending the user for *Siliceous Petrographic Examination* of the aggregates. The user informed the system that the result of the *Petrographic Examination* of the aggregates indicated to be *Reactive*. Then the system asked the user of his preferred method of preventing the alkali-aggregate reactivity. After the user had selected *Pozzolan or Slag,* the system displayed three options for this choice. The user confirmed the system that he preferred silica fume as a pozzolan to prevent harmful reaction. This was the last data for the present consultation. The complete set of data for the present consultation is shown in Table 8.14. After completing the data input, the user pressed the *Recommendation* button. As a result, the system displayed the recommendations for the present session as shown in Table 8.15.

TABLE 8.14 Data Options and the User's Selection for an Example Session with Alkali-Aggregate Reactivity Submodule

Question Asked by the System	Options to Select	User's Selection
(1) What do you think about the aggregate lab and field performance?	(a) Problems (b) Unblemished	(a) Problems
(2) Does the aggregate meet the mandatory requirements?	(a) Yes (b) No	(a) Yes
(3) What is the type of aggregate?	(a) Carbonaceous (b) Siliceous	(b) Siliceous
(4) What does the Petrographic Examination of the aggregate indicate?	(a) Cement Reactive (b) Reactive (c) Unreactive	(b) Reactive
(5) Which of the following preventive measures do you prefer?	(a) Low-Alkali Cement (b) Pozzolan or Slag	(b) Pozzolan or Slag
(6) Which of the following admixture do you prefer?	(a) Fly Ash (b) Silica Fume (c) Slag	(b) Silica Fume

In addition to the recommendations of Table 8.15, the *Advice* button displayed the possible causes of alkali-aggregate reactivity and the corresponding solutions. It also displayed the relative merits and demerits of each method of preventing harmful alkali-aggregate reaction briefly. To the user's judgement, the recommendations of this module for the present session are fairly comprehensive and satisfactory.

8.3.3 Sulfate Attack

The main interface window of the sulfate attack submodule of the HPCA was shown in Figure 7.14 (Chapter VII). The interface window showed preliminary information about sulfate attack and eight buttons including those of accessory facilities for smooth flow of consultation. The interface window also displayed the reactions that are associated with the sulfate attack.

TABLE 8.15 Recommendations of the Alkali-Aggregate Reactivity Submodule for the Input Data of Table 8.14

Recommendation for Alkali-Aggregate Reactivity Problem
HPCA gives recommendations on requirements for HPC to be resistant to Alkali-Aggregate reactivity. The recommendation about alkali-reactive aggregates are: 1. If aggregates are shown by service records or laboratory examination to be potentially reactive, they should not be used when the concrete is to be exposed to seawater or other environments where alkali is available to enter the concrete in solution from an external source. 2. When reactive aggregate must be used, this should be done only after thorough tests and preferably after service records have established that with appropriate limits on the alkali content of the cement, or with the use of appropriate amounts of an effective pozzolan or slag, or both, satisfactory service can be anticipated. 3. Water-binder ratio should be less than 0.4. 4. In cases where alkali from the environment is not involved and there are no nonreactive materials available economically, reactive materials may be used provided the following safeguards are provided: a) Silica Fume should meet the requirements of ASTM C 618. b) Silica Fume (5-10%) should be tested in accordance with ASTM C 441 to determine their effectiveness. c) Mortar-Bar Expansion should be less than 0.02% at 14 days.

The user first pressed on the *Occurrence* button. It displayed the general situation where sulfate attack might be a problem. The *Mechanism* button opened a text file in a transcript image describing the sulfate attack mechanism. These accessory facilities encouraged the user to have a clear idea about the basics of sulfate attack of concrete. It also trained the user about possible sulfate attack problem. The accessory facilities such as information about occurrence and mechanism of sulfate attack and reactions associated with this attack are some of the improvements of the HPCA over other existing systems (Clifton & Oltikar 1987; Kaetzel et al. 1993) in the sulfate-resisting concrete domain.

Table 8.16 shows the data required by the system for a particular consultation session and the corresponding response of the user. In this case study, the user selected the following data: type of environment was soil; content of sulfate ions was in the range of 0.20-2.00% (severe sulfate exposure); and binder was Portland cement with pozzolan. These data constituted the key information for the user's situation. One of the features of this submodule, like other submodules, is that the data input are self-consistent. For example, if the user selected blended cement as binder, then the system further asked whether blended cement was pozzolan modified or slag modified.

TABLE 8.16 Data Required by the Sulfate Attack Submodule and Corresponding Response of the User for an Example Session

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

After getting the input data from the user, the *Sulfate Attack* submodule of the HPCA produced recommendations in a transcript image by comparing these data with the knowledge contained in its knowledge base. The method of making recommendations was very similar to the way a human expert would handle the problem. The recommendations for the input data of Table 8.16 are shown in Table

8.17. The recommendations included, 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 recommendations of the HPCA also included required curing practices, use of other materials such as calcium chloride and use of available field performance of concrete. Moreover, the recommendation included a note which indicated that the recommendations were conservative and were intended to ensure longer service life of concrete and so on. These are some of the improvements of the HPCA over the other existing systems (e.g., DURCON, HWYCON) available in the sulfate-resisting concrete domain.

TABLE 8.17 Recommendations of Sulfate Attack Submodule for Data of Table 8.16

Recommendations for Making Sulfate-Resistant Concrete

The following is a list of the recommendations concerning sulfate attack of concrete for this session:

(1) The maximum water-binder ratio should be 0.45. (For lightweight concrete, 28-day compressive strength should be greater than 30 MPa).

(2) Portland cement should be Type V (ASTM C150) or sulfate resisting cement (BS 4027).

(3) Pozzolan should be either Fly Ash (ASTM C618 or BS 6610) or Silica Fume (AASHTO M307-90 or BS 6610).

(4) The hardened concrete should contain 2 to 3% entrained air (More may be necessary if freeze-thaw problem 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.

(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 ensure long service life of concrete. Less stringent requirements are appropriate when justified by local experience or for shorter desired service life.

After getting recommendations, the user might ask for explanation about the recommendation by pressing on the *Explain* button. The explanation facility of the system facilitated verification and validation of results and also made it suitable for educating the user. The output information or recommendations, like input information, were also self-consistent. For example, if a moderate, severe or very severe exposure condition was selected, then the system recommended the use of air-content in percent as shown in recommendation number 4 of Table 8.17.

8.3.4 Seawater Exposure

The aim of this submodule is to give recommendations in order to make durable high performance concrete to seawater exposure. This submodule, like any other expert system, requires some key information for giving recommendation for a particular situation similar to a domain expert. Therefore, the first step in a consultation process with this submodule was to collect and analyse the required basic data. It was important that accurate information was acquired to obtain durable concrete to seawater exposure.

The user needed to press *Data Input* button of the main interface window of this submodule (Figure 7.16) to start data input. Like other submodules of the system, this submodule also has buttons for mechanism, transcript image for showing preliminary information and consultation steps. The user input data by selecting from a list of slot values displayed by the system after pressing *Data Input* button similar to other submodules. In addition, the data could also be selected from the combo box images displayed on the right portion of the main interface window for this submodule (Figure 7.16). The selected data were displayed by the system in these combo boxes for verification. The questions asked and options to select as well as user's selection for present session are shown in Table 8.18.

After the completion of data input, the user needed to press on *Recommendation* button for getting recommendation. The text containing recommendations and a detailed explanation given by the system were displayed in separate transcript images under the titles *Recommendation* and *Explanation*, respectively, after selecting appropriate buttons (see Figure 7.16).

TABLE 8.18 The System's Prompt and the User's Response for an Example Session with Seawater Submodule

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

The following is a list of recommendations displayed by the system for the input data of Table 8.18:

(i) 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 (i.e., 75 mm).

(ii) The required low permeability is attained by using concrete with a low water-binder ratio (i.e., less than 0.4), well consolidation and adequately cured (i.e., at least three days in fresh water).

(iii) 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. Moreover satisfactory performance of concrete containing GGBS in marine environment has been described in literature.

(iv) Joints should be designed and constructed properly to assure that cracking is minimized to prevent the exposure of reinforcement. Additionally, concrete should reach a maturity equivalent of not less than 35 MPa (5000 psi) at 28 days when fully exposed to seawater.

(v) 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.

(vi) 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.

These recommendations for the input data of Table 8.18 were considered to be satisfactory by the user. After getting recommendation, the user could also ask for explanation about the recommendation by pressing on *Explanation* button.

8.3.5 Acid Attack

The main interface window of this submodule was shown in Figure 7.17. The window displayed five buttons, two transcript images and six state box images. The purpose of the buttons is to help the user in the consultation process. The *Occurrence* and *Mechanism* buttons opened text files describing the sources and mechanism of acid attack on concrete, respectively. The first transcript image gave preliminary information about acid attack and guided the user about consultation steps. The second transcript image displayed recommendation of a consultation session. The state boxes displayed data selected by the user.

Typical example of a session on acid attack is described below. The user selected data from a list of slot values displayed by the system. The user informed the system that there was possibility of products of combustion of fuels that contained sulfurous gases in contact with concrete. The user also informed the system that concrete would be in contact with mountain streams containing carbon dioxide or hydrogen sulfide, or both. These data together with the other required information are shown in Table 8.19. The user could verify data in the state box images displayed by the system (Figure 7.17). These state box images made the system transparent of its consultation process to the user.

TABLE 8.19 Data Required and User's Selection for an Example Session with Acid Attack Submodule

Data Required	Options to Select	User's Selection
Products of combustion of fuels that contain sulfurous gases	Yes / No	Yes
Collection of sewage on concrete	Yes / No	No
Water draining from mines or industries	Yes / No	No
Peat soil, clay soil or Alum shale that contain iron sulfide (pyrite)	Yes / No	No
Mountain streams that contain CO_2 or H_2S, or both	Yes / No	Yes
Organic acids from farm silage, or from manufacturing or processing industries such as breweries, dairies, canneries and wood-pulp mills	Yes / No	No

The system gave recommendation based on data selected by the user. The recommendation for the data of Table 8.19 is shown in Table 8.20.

TABLE 8.20 Recommendations of Acid Attack Submodule for the Data of Table 8.19

Recommendation for Acid Attack Problem
The system gives recommendations on requirements for HPC to be resistant to Acid Attack. The following are the recommendations for the present session: 1. A dense concrete with low water-binder ratio (i.e., less than 0.4) may provide an acceptable degree of protection against mild acid attack. 2. Certain pozzolanic materials, and silica fume in particular (5-10% by weight of binder), increase the resistance of concrete to acids. 3. Exposure time to acids should be minimized, if possible, and immersion should be avoided. 4. No hydraulic-cement concrete, regardless of its composition, will long withstand water of high acid concentration (pH of 3 or lower). In such cases, an appropriate protective-barrier system or treatment must be used (See ACI 515.1R).

The recommendation included obtaining dense concrete with low water-binder ratio, using pozzolans such as silica fume, and minimizing exposure time to acids. The system also stated that no hydraulic cement concrete, regardless of its composition, would long withstand water of high acid concentration (pH of 3 or lower). In such cases, an appropriate protective-barrier system or treatment must be used. These recommendations, for the data of Table 8.19, were considered satisfactory by the knowledge engineer.

8.3.6 Carbonation

The main interface window of the carbonation submodule of the HPCA was shown in Figure 7.18 (Chapter VII). The interface window displayed three transcript images, seven buttons and six state box images. The first transcript image displayed the preliminary information about carbonation of concrete. The user first pressed on the *Source of Carbonation* button. As a result, the general sources from where carbonation problem of concrete might arise were displayed. The text regarding carbonation mechanism was displayed in a transcript image when the user pressed on the *Mechanism* button. Table 8.21 shows the data required by the system for a particular consultation session and the corresponding response of the user. In this case study, the user stated that, for his concrete environment, the source of carbon dioxide was atmosphere and the relative humidity of the environment was between 50 to 75%.

After the completion of data input, the user needed to click on *Recommendation* button for getting recommendation. The recommendations for the data of Table 8.21 were displayed by the system in a transcript image. The recommendations are shown in Table 8.22. The recommendations included that a dense, well-consolidated, and well-cured concrete may provide an acceptable degree of protection against carbonation. Lower water-binder ratio serves to reduce permeability and restricts carbonation to the surface. Good quality concrete is essential to prevent initiation of carbonation.

TABLE 8.21 The System's Prompt and the User's Response for an Example Session with Carbonation Submodule

Question Asked by the System	Options to Select	User's Selection
What is the source of CO_2?	Atmosphere Water	Atmosphere
Is the relative humidity of environment between 50 and 75%?	Yes / No	Yes
Is concrete structure located near industrial areas with higher concentration of CO_2?	Yes / No	No
Will concrete be exposed to CO_2 during hardening process?	Yes / No	No
Will unvented heaters be used during hardening process?	Yes / No	No
Is there any possibility of exposure of concrete to exhaust fumes from equipment or other sources?	Yes / No	No

TABLE 8.22 Recommendations of Carbonation Submodule for the Data of Table 8.21

Recommendation for Carbonation Problem
The system gives recommendations on requirements for HPC to be resistant to Carbonation. The following are the recommendation for the current session: 1. A dense, well-consolidated, and well-cured concrete may provide an acceptable degree of protection against carbonation. Three days of wet curing is recommended. 2. Lower water-binder ratio (i.e., less than 0.45) and good consolidation also serve to reduce permeability and restrict carbonation to the surface. 3. Exposure time to carbon dioxide should be minimized and, if possible, should be avoided. 4. Good quality concrete is essential to prevent initiation of carbonation. 5. Compressive strength of concrete should be greater than 30 MPa. 6. Concrete cover over steel reinforcement should be at least 70 mm for 25 MPa concrete and 30 mm for 50 MPa concrete.

These recommendations are similar to those of the ACI guide (ACI Committee 201 1995) for making durable concrete in carbon dioxide exposure. After getting recommendation, the user also got explanation about the recommendation by pressing *Explanation* button.

8.3.7 Abrasion

Figure 7.19 showed the interface window for this submodule. The first transcript image of the window defined the abrasion resistance of concrete as the "ability of a surface to resist being worn away by rubbing and friction" (ACI Committee 116 1995). It also informed the user that the magnitude of abrasion depended on compressive strength of concrete especially at the surface, aggregate-to-paste bond strength, hardness of the aggregates, quality of the aggregates at the surface region, curing, and use of the concrete surface.

The *Advice* button (Figure 7.19) opened a text file that described the sources of abrasion problem. It stated that abrasion of floors and pavements might result from production operations, or foot or vehicular traffic, abrasion resistance was therefore of concern in industrial floors. Wind and waterborne particles can also abrade concrete surfaces. There are instances where abrasion is of little concern structurally, yet there may be a dusting problem that can be quite objectionable in some kinds of service e.g., floors in hospital. The button also explained the limitations of the submodule. For example, it stated that abrasion (erosion) of concrete in hydraulic structures was discussed only briefly in this system. The system also informed the user for his future reference that the erosion problem was treated in detail in ACI 210R (ACI Committee 210 1994). On the other hand, by observing the line plot image on the interface window, the user got clear idea about the effect of water-binder ratio on the abrasion loss of concrete.

A sample user request form for data input was shown in Figure 7.20 (Chapter VII). This type of user request form helped the user in avoiding input errors. The input form of the user interface included *Comment* button (see Figure 7.20) to explain importance/effect of the input data on the abrasion resistance of concrete. This button also helped to expand the meaning of a question. During data input, the user selected the following data for his situation: type of floor was two-course, expected usual traffic was foot and hard wheel vehicles, and type of topping was unbonded. These data are shown in Table 8.23.

TABLE 8.23 Data Required and User's Selection for an Example Session with Abrasion Submodule

Data Required	Options to Select	User's Selection
Type of floor	Single course Two course	Two course
Usual expected traffic	Foot Foot and Hard Wheel Vehicles Foot and Pneumatic Wheels Foot and Wheels – Abrasive Wear Light foot Light Foot and Pneumatic Wheels	Foot and Hard Wheel Vehicles
Type of topping	Bonded Unbonded	Unbonded

The recommendations produced by the system for the data of Table 8.23 are shown in Table 8.24. The recommendations were similar to those of the expert committee report (ACI Committee 201 1995) and were considered to be satisfactory.

8.3.8 Freeze-Thaw

As mentioned earlier, freeze-thaw is not a major problem for the concrete structures in Malaysia. However, this submodule is included to give the system a sense of completeness. This submodule also made the system suitable for use as an advisor in colder region beyond the boundary of Malaysia.

TABLE 8.24 Recommendations of Abrasion Submodule for the Data of Table 8.23

Recommendation for Abrasion Problem

HPCA gives recommendations on requirements for HPC to be resistant to abrasion. The following are the recommendations for the current session:

1. Compressive of concrete should be greater than 75 MPa. Compressive strength levels may be attained in a number of ways.
    a) A low water-binder ratio at the surface (i.e., less than 0.35).
    b) Proper grading of fine and coarse aggregates (meeting ASTM C 33).
    c) Use the lowest slump consistent with proper placement and consolidation meeting the requirements of ACI 309R.
    d) Air content should be consistent with exposure conditions. For indoor floors not subjected to freezing and thawing, air contents of less than 3% are preferable.
    e) Use silica fume (5-10% by weight of binder).
2. Use special concrete aggregates (i.e., metallic or granite aggregate).
3. Follow proper finishing procedures (i.e., surface levelled by screeding for base and special power floats with repeated trowelling for topping).
4. Use vacuum dewatering method to remove water from concrete immediately after placing.
5. Use special dry shakes and toppings.
6. Follow proper curing procedures (at least 7 days of wet curing in fresh water).
7. Minimum thickness of floor should be 65 mm (2.5 inch)
8. Use mesh-reinforcing and bonded breaker on old concrete.

The objective of this submodule is to make freeze-thaw resistant high performance concrete. The interface window of this submodule was shown in Figure 7.21. The user started consultation by pressing on the *Data Input* button. In the beginning of the consultation, the system informed that the resistance to freeze-thaw cycles depends on water-binder ratio, type of structure, exposure conditions, aggregate properties and entrained air. The data required for this submodule are shown in Table 8.25. The table also shows the user's selection for the present session.

TABLE 8.25 The System's Prompt and the User's Response for an Example Session with Freeze-Thaw Submodule

Question Asked by the System	Options to Select	User's Selection
(1) Which of the following describes the anticipated exposure condition?	(a) Dry (b) Moderate (c) Severe	(c) Severe
(2) Which type of hydraulic cement is to be used for this application?	(a) Blended Cement (b) Portland Cement	(b) Portland Cement
(3) Which of the following best describes the application?	(a) Normal Section (b) Thin Section	(b) Thin Section
(4) Aggregate selection will be made according to which of the following?	(a) Accepted by Past Experience (b) ASTM C33 (c) Lab Test ASTM C666	(c) Lab Test ASTM C666
(5) Which nominal size of aggregate is to be used in this application?	(a) 9.5 mm (3/8 inch) (b) 12.5 mm (1/2 inch) (c) 19 mm (3/4 inch) (d) 25 mm (1 inch) (e) 37.5 mm (1.5 inch)	(b) 12.5 mm (1/2 inch)

After collecting data from the user, this submodule searched its knowledge base and gave the recommendations shown in Table 8.26. These recommendations for the present data were considered to be satisfactory.

8.4 TESTING AND EVALUATION OF THE HPCA CONSULTATION PROCESS

Generally, the flow of the consultation session between the user and the system was flexible. The user was able to review or update data and recommendations given by the system for an existing situation consulted earlier, or start a new consultation for a new situation. He was also allowed to reset conclusions, repeat certain procedures or rule inferences until satisfactory results and design were attained.

TABLE 8.26 Recommendations of Freeze-Thaw Submodule for Data of Table 8.25

Recommendation for Freeze-Thaw Problem
HPCA gives recommendations on requirements for HPC to be resistant to Freeze-Thaw Cycles. The following are the recommendations for the current session: 1. Portland cement is required to conform to ASTM C150 (or BS 12). 2. Absorption of aggregates should be measured according to ASTM C 127 (or BS 812). If absorption is low (i.e., less than 1%), concrete should be tested according to ASTM C 666 if no satisfactory past experience is available. If absorption is high, concrete must be tested according to ASTM C 666 (or BS 5075) to justify its use. 3. With 12.5 mm (1/2 inch) aggregate selected for severe conditions, the entrained air should be 5%. 4. Air void spacing must be less than or equal to 0.20 mm (0.008 inch). 5. For application using thin sections the recommended water-binder ratio is 0.40. 6. Concrete for severe exposure conditions should have an f_c' of about 3.45 MPa (500 psi) prior to one or two cycles of freezing and thawing while curing (at least 7 days of wet curing in fresh water). It should attain an f_c' of about 27.6 MPa (4000 psi) before exposure to severe conditions. 7. Fly ash and natural pozzolans should conform to ASTM C 618 (BS 6610). Ground granulated blast-furnace slag should conform to ASTM C 989 (or BS 6699). Air entraining admixtures should conform to ASTM C 260 (or BS 5075). Chemical admixtures should conform to ASTM C 494 (or BS 5075). Admixtures for flowing concrete should conform to ASTM C 1017. Detailed guidance on the use of admixtures is available in ACI 212.3R.

Kappa-PC has its own built-in editor, which ensures that the production rules are in the right syntax during the development of the prototype. However, if a conclusion cannot be reached during the execution process, Kappa-PC has the facilities to look at the properties of identifiers and values within the knowledge base checking for wrong inferences, missing values, circular reasoning, conflicting values and unused consequences. This allowed the knowledge engineer to review on screen all the steps that the system went through for a derivation of the conclusions, and pinpointing where the consultation stopped so that the problem could be rectified.

It is important to ensure that all the solutions are available for all the questions asked when the system is being tested. This is because there could be a large number of possible solution routes that can be created from a small number of questions. A systematic way to check that all possible outcomes should be produced is by producing a grid setting out all the possible goals and coding them within the knowledge base (Basri 1999). This procedure was followed during the development of the HPCA to ensure its consistent and enhanced performance.

8.5 USER FRIENDLINESS OF THE SYSTEM INTERFACE

A user-friendly system is one that is easily consulted even by the inexperienced end-user. There should be no need to memorise numerous computer commands and syntax, or to key in long-worded instructions on the keyboard. The system generally should be more understandable, and to some degree, more attractive to users (Basri 1994).

Testing the expert system also involved looking at the user-friendliness of the interface. The system interface was designed to suit the intended end-user with just a basic knowledge or some experience in computers (the user interface was described in detail in Chapter VII). The interface built was considered to be adequate in its design and functioning. It did not present any problem in its functioning during the consultation process. This is because the HPCA interface was built using a standard Microsoft Windows image so that users already familiar with Windows would not have difficulty in adapting to the interface.

The Main Screen of the HPCA, which consists of several buttons with text images, is similar to most application software. It contains a selection of commands in each window for the user to click-on with a mouse. Therefore, the user was only required to perform a minimum amount of work with the keyboard, and very few computer commands and syntax were involved.

The HPCA also provides a teaching facility to aid an inexperienced designer by guiding him through the design steps, viewing a typical system available, explaining the fundamentals of mix design requirements and various issues related to durability aspects of high performance concrete. These facilities are available to the user through *User Guide* and *General Information* buttons as well as through line plot and bitmap images. Furthermore, the user is able to access the *Advice/Explain* facility if he is having difficulty in proceeding at any stage during the consultation.

Some modifications to the interface came about through its use. The modifications included looking at the wording of questions, output forms/recommendations and explain forms. It was important to ensure the clarity of instructions being conveyed. It was also important to ensure that a sufficient depth of knowledge was well forwarded to the intended end-user.

As a working prototype, the current version of the HPCA has a degree of user-friendliness that is acceptable for the intended end-user. However, a user-friendlier interface is important for commercial use. Much refining work could be done on the HPCA to enhance its user-friendliness. For example, system prompts and textual displays could be reworded or rephrased to be more easily understood, questions could be arranged in a more logical manner, advice and explanation facilities could be expanded, and screen formatting and colours could be made more meaningful and attractive. Such refining effort is very time-consuming and may require two to three times the man-time resources needed for basic prototype building (Basri 1994). Prototype refinement to enhance user friendliness could be a commercially initiated future project.

8.6 SUMMARY

The evaluation and testing phases of the prototype development are described in this chapter. Generally, the performances of the modules were comprehensive and satisfactory to the author's judgment, based on his own knowledge and advice from domain experts. The results of the case studies were reported in Sections 8.2 and 8.3, which covered several aspects of the performance of the HPCA. The mix design case study demonstrated that the design values and recommendations of the HPCA compared well with the design values and recommendations reported in a classical textbook. This gave a positive indication of the accuracy of the knowledge base of the HPCA. In the case studies regarding durability aspects, the consultation process of the HPCA and the general quality of its recommendations were scrutinised and considered to be satisfactory. The judgement was made by the knowledge engineer himself based on the ACI Committee reports, textbooks and journals as well as on the knowledge engineers own knowledge and experience. The general quality of the results was examined and each knowledge base was scrutinized. The user-friendliness of the HPCA was then assessed to be satisfactory as a working prototype. As a whole, the preceding evaluation and discussion suggested that the overall performance of the HPCA was satisfactory and acceptable as a working prototype. The next chapter sums up the research by presenting its conclusions and recommendations for future work.

CHAPTER IX

CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK

9.1 CONCLUSIONS

A review of the mix design and durability aspects of high performance concrete literature reveals a growing complexity and challenge for a concrete technologist to decide on the workable, strong and durable concrete that best serve the present and future needs of a particular structure. With the development of global computer technology, expert systems become potentially beneficial to the engineering design, especially in the domain of high performance concrete. The goals for developing an expert system include helping individual human experts, assimilating the knowledge and experience of several human experts, training new experts and providing requisite expertise to projects that cannot afford scarce expertise on site.

Furthermore, the nature of concrete technology readily lends itself to applications involving knowledge-based expert systems which are multidisciplinary areas whose problems may require specialized expertise in such diverse fields as engineering, chemistry, mathematics, geology, statistics and economics. The process of mix design of high performance concrete and considerations regarding its durability aspects are often too complex to be modelled using traditional methods, thus, forcing design engineers to rely more on experience and intuition. Since individual engineers will not always be well versed in all of these areas, expert systems can serve as valuable support tools to supply solution-directed knowledge in unfamiliar subjects.

As a means of demonstrating the validity of the suggested knowledge-based system, a working prototype named HPCA (High Performance Concrete Advisor) was developed to assist with the mix design and durability aspects of high performance concrete, which adopted an object-oriented approach. The prototype was designed to identify the activities and decisions required to make workable, strong and durable concrete. The system contains components related to mix design as stated ahead: first trial batch; laboratory trial batch; one cubic metre SSD composition; batch composition; performance failure diagnosis and corresponding recommendation; and cost estimation. It also contains following components related to concrete durability: corrosion; alkali-aggregate reactivity; sulfate attack; seawater exposure; acid attack; carbonation; abrasion; and freeze-thaw.

The following general conclusions can be drawn from this research work:

(i) The application of an expert system for mix design and durability aspects of high performance concrete is feasible.

(ii) Expert system development requires careful considerations.

(iii) The extent of knowledge required for the expert system is available from a variety of expertise sources.

(iv) The HPCA prototype building process successfully adopted the hybrid knowledge representation technique (i.e., object-oriented approach and production rules).

(v) The domain of mix design and durability aspects of high performance concrete was realistically modelled using expert system technology.

(vi) The best approach to designing a high performance concrete mix is to use proportions previously established for similar concrete using the same materials. Where such prior information is limited or unavailable, the developed expert system can be used to assist the user in selecting concrete mix proportions.

(vii) Wherever possible, rules-of-thumb and past experience should be used for mix design, mix performance adjustment and durability aspects of high performance concrete. If information regarding these issues is limited or unavailable, the developed expert system can be used to help the user make intelligent decisions.

(viii) The system can be utilized as an educational tool.

The general conclusions stated above are described in further detail in the following sections. With these conclusions, it is considered that the research objectives set out in Section 1.3 have been adequately addressed.

9.1.1 Potential Benefits of Expert Systems in Making High Performance Concrete

Expert system technology provides a new opportunity for harnessing the scarce and often scattered pieces of valuable knowledge and experience in the high performance concrete domain. The experience of the HPCA development and endeavours in other branches of engineering to utilise this new computing technology have shown that high performance concrete expertise in various forms has the potential to be encoded into expert systems. The multi-disciplinary nature of its science, coupled with recent advances in computing technology, provides a very opportune situation for expert systems to play a significant role in enhancing the performances of the concrete structures. Practitioners and researchers involved in high performance concrete should at least begin to familiarise themselves with expert system technology in order not to miss out many benefits that expert system technology can offer.

9.1.2 Expert Systems for Mix Design and Durability Aspects of High Performance Concrete

Expert system technology is particularly suitable for the mix design and durability aspects of high performance concrete for the following reasons: extensive use of approximate methods or heuristics, experience, and 'rule-of-thumb'; multidisciplinary nature of domain expertise ranging from engineers, mathematicians, geologists, chemists, statisticians etc.; scarcity of human experts especially in high performance concrete; and minimal need of rigorous mathematical analysis and modelling. Thus, expert systems technology provides an opportunity for harnessing the scarce and scattered pieces of valuable knowledge and experience in the domain of mix design and durability aspects of high performance concrete.

More specifically an expert system application is particularly suitable as a useful tool for making high performance concrete for some other reasons. There are a variety of inexpensive, off-the-shelf expert system development packages, which bring the technology to a wide audience of potential expert system developers. They could become the knowledge engineers because the expert system shells dramatically expand the talent pool of people able to work creatively on a vast array of potential applications. Furthermore, expert system technology can now run on the existing large and increasing number of microcomputer machines that are available all over the world. In addition to that, a substantial number of applications on relatively small and simple expert system can make a useful contribution to the mix design and durability aspects of high performance concrete. Because many problems and solutions of the mix design and durability issues of high performance concrete may not be as complex as they seem to be. Moreover, there are at present many useful applications of expert systems in use in some of the aspects of the concrete technology. Hence, the potential of expert system to capture expertise regarding mix design and durability issues of high performance concrete may be of far greater use.

9.1.3 Considerations in Expert System Development

The essential elements of expert system development require careful considerations to ensure success. The experience of researchers in building prototype expert systems (including the experience in developing the HPCA) provides valuable guidelines for prospective expert system developers. However, these researchers were by no means unanimous in reporting their recommendations due to variations in their professional background and in the nature of their domains. After reviewing their experiences, the following guidelines are considered appropriate and, thus, recommended for developing expert systems, particularly in the high performance concrete domain.

(i) The rapid prototyping method, where a small pilot prototype precedes the main expert system development, is preferred over delaying all prototype building until after completion of the entire knowledge acquisition process.

(ii) A knowledge engineer who has a reasonable degree of mastery of both expert system technology and the domain expertise is more effective over a "pure" knowledge engineer who has no training or background in the domain.

(iii) Expertise of mix design and durability aspects of high performance concrete is likely to be acquired from many sources, i.e. high performance concrete experts, consulting and construction engineers, books, manuals and research literature.

(iv) The most practical and economical method for knowledge acquisition is text analysis, the results of which can be supported and confirmed by other more elaborate methods.

(v) Expert system shells provide the most practical and cost effective platform for developing prototypes compared to programming languages and toolkit environments.

(vi) Hybrid knowledge representation technique is the best approach in representing knowledge compared to adopting frames or production rules alone.

9.1.4 Conclusions from the HPCA Knowledge Acquisition Process

The most important and difficult part of the HPCA expert system development was the knowledge acquisition process. The "Engineering Expert Systems Approach" was adopted, where the author assumed the role of knowledge engineer and had to be initially trained in the basics of expert system technology as well as in the domain of high performance concrete. The knowledge acquisition process for the HPCA utilised several techniques with expertise drawn from a variety of sources.

The principal conclusions derived from the knowledge acquisition process are:

(i) expertise acquired from text analysis of textbooks and manuals was appropriate for use in developing the core knowledge base for the basic prototype system;

(ii) expertise acquired from text analysis of research publications, interviews with domain experts, and observations of high performance concrete mix design was appropriate for use in the subsequent refinement and expansion of the basic prototype;

(iii) multiple sources of expertise provided many advantages which increased the effectiveness of the knowledge acquisition process;

(iv) the knowledge acquisition techniques were chosen based on the circumstances of each individual situation (the selected techniques for the HPCA were text analysis of public domain knowledge, unstructured interviews with practising domain experts and observation of high performance concrete mix design);

(v) the interest and enthusiasm of domain experts needed to be developed by means of initial familiarisation sessions and sustained by regular briefings; and

(vi) an analysis of the domain tasks based on the design approaches adopted by many textual sources was useful in formulating the subsequent strategy, methodology and techniques employed for prototype development.

The above conclusions are unique to the development of the HPCA. Other expert system developers employ different approaches (as reported in literature) since there is as yet no prescriptive methodology which is universally accepted. The knowledge acquisition experience for the HPCA presented valuable lessons for other prospective expert system developers.

9.1.5 Conclusions from the HPCA Prototype Building Experience

The HPCA prototype was built based on a modular approach following the incremental rapid prototyping methodology. The main conclusions that can be deduced from the prototype building experience are described below.

(i) The modular approach facilitated the development of the HPCA prototype by providing simplicity and ease of knowledge organisation. It also enabled the building process to be suitably phased to match the available resources during the various development stages.

(ii) The adopted incremental rapid prototyping methodology allowed the system developer to attain a gradual and simultaneous experience in both the knowledge acquisition and prototype building processes. With a better and wider understanding of both processes, good strategic decisions could be made early, such as the choice of the building tool for the expert system and the techniques for knowledge acquisition.

(iii) State-of-the-art shell (i.e., Kappa-PC) made the incremental rapid prototyping methodology more convenient to implement. The efficiency and user-friendliness of this powerful tool allowed prototype to be quickly built and easily upgraded or modified using hybrid knowledge representation technique.

(iv) In building the HPCA prototype, choosing an object-oriented shell (i.e., Kappa-PC) having better knowledge representation techniques was shown to be a feasible decision due to the shorter learning curve.

(v) Hybrid knowledge representation technique using Kappa-PC presented many advantages. The use of the object-oriented paradigm in combination with production rules for the HPCA prototype development provided a powerful and efficient means of representing domain knowledge, increased development productivity, simplified prototype maintenance and flexibility in modification procedures.

9.1.6 An Evaluation of the HPCA for the Mix Design and Durability Aspects of High Performance Concrete

The product of the research was the HPCA prototype, which is made up of several modules that addressed major domain tasks of mix design and durability issues of high performance concrete. As a working prototype, the current version of the HPCA has a degree of user-friendliness that is acceptable for the intended end-user. However, a user-friendlier interface is important for commercial use. Within window-based interfaces of the HPCA, the user communicates with the system mainly by mouse clicking on screen objects (e.g., buttons), which minimizes unfamiliarity with keyboard manipulation.

The overall performance of the HPCA in dealing with the intended scope of work was then evaluated to be satisfactory. The general conclusion derived from the working prototype is that the domain of mix design and durability issues of high performance concrete can be successfully modelled using the expert systems technology. The expert system has been shown to be an important tool in harnessing scarce and scattered knowledge, which in many cases has taken a long time to be built. Furthermore, the HPCA prototype will assist the less-experienced designers by making expertise more accessible and understandable. The utilization of the prototype capability as an educational tool and teaching aid for the inexperienced designer is very valuable. In addition to that, the HPCA could significantly influence design decisions by taking into account various durability characteristics of high performance concrete.

9.2 RECOMMENDATIONS FOR FURTHER WORK

The experienced gained and the prototype produced from the research have thrown light on other possible areas where more work could be done to improve, expand or complement the scope presently covered by the HPCA. The areas recommended for further research work are described in the following subsections.

9.2.1 Improvement of the Knowledge Base

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 knowledge base in an expert system is a continuously changing entity, which requires continuous improvement and expansion. The quality of a knowledge base is as good as the sources of expertise themselves (Basri 1994). All expert systems, the HPCA included, cannot claim completeness in their knowledge bases; they are always subject to updating, upgrading, modification, correction and addition. The existing knowledge base for the HPCA can thus 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) improving existing mix design methods and durability performance criteria using other pozzolanic materials (e.g., metakaolin) and new breed of superplasticizer (e.g., hyperplasticizers);

(iii) using alternative mix design methods if they are proven to yield more meaningful results; and

(iv) adding further functional capabilities such as mix design of flowing concrete (i.e., self-compacting concrete), lightweight concrete, mass concrete and use of fibres in concrete etc.

9.2.2 Development of Additional Modules

Additional expert system modules that were identified earlier could be combined with the present prototype, for example, mixing and placing procedures, predicting service life, and repair as well as maintenance aspects of high performance concrete structures. A module is needed to expand the developed system so that it will be able to handle other problems, such as slump loss due to pumping concrete, which can affect the concrete mix design. These modules were excluded in this research because of time and other resources limitations. Limitations of time and other resources have confined the scope of the research to the tasks described in Section 6.5.1.

The development of modules for the tasks mentioned above demand significant allocation of resources and require a lot of expertise input from experts. They will complement the functions of the existing modules and are thus recommended as possible future research work.

9.2.3 Refinement of the User Interface

The user interface of the HPCA needs major refining work to enhance its user-friendliness if it is to be used commercially. For example, system prompts and textual displays could be reworded or rephrased to be more easily understood, questions could be arranged in a more logical manner, and screen formatting and colours could be made more meaningful and attractive.

The current HPCA user interface was aimed at meeting the more obvious cognitive needs of the potential end-user. While this was adequate for a working prototype, the ideal user interface should be based on a full-scale study and formulation of the user model, i.e. a conceptual representation of the user's thought processes in solving the problem. The interface can also be improved by allowing a great number of users to use the system and collecting their feedback and criticism. This task was beyond the scope of this project and is recommended as possible further work on the HPCA.

9.2.4 Upgrading of Advice Facilities

The advice facilities of the HPCA are based on pre-prepared text files, which provide explanations on the requested topics. The advice and explanation facilities may be upgraded by improving the quality and comprehensiveness of these text files to enhance its user-friendliness. The files for advice on how to use the HPCA can be refined by studying the behavioural patterns of users during actual case-study consultations. The files advising the user on the essentials of mix design of high performance concrete can be expanded by consulting relevant topics from various textual sources.

Graphics can also be included as part of the advice facilities. Furthermore, additional figures for each mix design operation may convey a more effective message to the user. For example, descriptions for mix performance evaluation methods (i.e., slump test, flow test, statistical methods etc.) can be more effectively conveyed to the user using bitmap images instead of words. The incorporation of graphics however requires massive computer memory.

9.2.5 Modification of System Architecture

The HPCA architecture in its present form did not consider measures, which could optimise the use of computer memory. Although it may be satisfactory as a working prototype, it is desirable that the HPCA architecture be restructured into a more memory-efficient system to avoid the occasional operational instability (system crashes) and to improve response times.

9.2.6 Other Future Work

The HPCA can be viewed as potential part of a more encompassing group of expert systems addressing the wider aspects of mix design and durability issues of high performance concrete. Other expert systems could be developed for the following aspects:

(i) analysis of causes of concrete cracking;

(ii) selection of options for repair and maintenance of distressed concrete;

(iii) conceptual design of intrinsic materials related problems such as plastic shrinkage and thermal cracking of concrete; and

(iv) complex statistical software for related analysis and design.

The different expert systems could cooperate with each other using an interfacing technique known as the blackboard. The blackboard concept is based on the idea of "experts sitting around a blackboard" which attempts to co-ordinate the activities of a number of different knowledge sources by providing a global database between them (Bundy 1986). It would be advantageous to have an optimum group of people as a team to speed up the development time. With diverse subject areas of high performance concrete, the team would be able to produce a more powerful expert system prototype within the time and specification restraints of a commercial market.

Another possible area of research is the incorporation of case-based reasoning (also known as transformational analogy) into the HPCA. In case-based reasoning, the results of actual case studies are preserved and collectively used as a basis for the design of new concrete mixes or giving recommendations on durability aspects, i.e. design decisions can be made based purely on precedence, and not on any logical reasoning. There should be a wide variety of domain experts to be consulted for the development of a well-functioning expert system prototype. However, this requires a great deal of time and preparation, which could become the constraint factor that should be acknowledged in developing an expert system.

From the author's experience of using Kappa-PC, choosing an appropriate shell to suit a particular problem at hand is not an easy task. The use of a more recent expert system shell with better capabilities of interfacing with other applications such as JAVA^{tm}, which could be accessed via Internet, could be worthwhile to be looked into.

The prototype could be incorporated as part of an integrated knowledge-based system for high performance concrete technology. As the technology of high performance concrete advances, the system could be further developed to cover the complete life cycle of high performance concrete in structures and would have the potential to contain the most authoritative information and to become the universal problem solver for high performance concrete.

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APPENDIX A

GLOSSARY

Agenda: An internal task list generated by the inference engine, which controls the inferencing process.

Aggregate absorption (w_{abs}): The amount of water absorbed in the aggregate when it is in the SSD (saturated and surface dry) state. This absorption is expressed as a percentage of the mass of the dry aggregate.

Artificial intelligence: A field of study in computer science that pursues the goal of making a computer reason in the same manner as humans.

Attribute: A property of an object. For example, cement has the attributes of 'specific gravity' and 'fineness'.

Backward chaining: A method of reasoning that is goal driven. It proceeds from a given goal to be evaluated by examining other rules, which lead to it.

Blackboard: An expert system design where several independent expert systems share information in a common working memory.

Class: It is the description of a set of nearly identical objects that share common attributes and behaviour (term used in object-oriented programming).

Context: Memory that holds all information, either inputted or derived, which represents the current state of the problem handled by the expert system. (Also known as *working memory*, *global memory* or *database*).

Database: Memory that holds all information, either inputted or derived, which represents the current state of the problem handled by the expert system. (Also known as *working memory*, *global memory* or *context*).

Design or specified compressive strength (f_c'): It is the strength of concrete that has been taken into account by the designer in his/her calculation.

Demon: A rule that automatically fires when its conditions become true.

Development environment: A software that provides a suitable environment for the development of the application programmes including expert systems.

Development tool: A software that aids for the development of application programmes including expert systems.

Domain: The area of problem solving expertise.

Domain expert: A human expert who contributes his/her expertise for expert system development.

Expertise: Symbolic information used by a domain expert to solve problems. (Also known as *knowledge*).

Expert system: A computer programme that emulates a human expert. Conventionally, it is comprised of an *inference engine*, which manipulates *expertise* in a *knowledge base*, and stores newly derived information in *database*.

Forward chaining: A method of reasoning that is data driven. It proceeds from a known item and uses all related rules to find the implications of that item.

Frame: A technique of knowledge representation where the knowledge domain is viewed in the form of objects, or classes of objects that contain slots for all kinds of information about them.

Global database: Memory that holds all information, either inputted or derived, which represents the current state of the problem handled by the expert system. (Also known as *working memory*, *database* or *context*).

Incremental rapid prototyping: Rapid prototyping where the first prototype is one of the many modular prototypes, which eventually make up the whole expert system.

Inference engine: The part of an expert system that manipulates information from the user and the expertise in the knowledge base to generate expert advice and information.

Inference mechanism: The workings of the inference engine.

Instance: A specific object that is a member of a class (term used in object-oriented programming).

Knowledge: Symbolic information used by a domain expert to solve problems. (Also known as *expertise*).

Knowledge acquisition: The process of extracting and articulating knowledge from sources of expertise.

Knowledge base: A collection of knowledge items representing expertise in a particular domain. Contains rules, facts, data, beliefs, assumptions, and procedures needed for problem solution.

Knowledge domain: An area of problem-solving expertise.

Knowledge engineer: The individual who develops the expert system. He/she extracts knowledge from expertise sources, then articulates and computerizes it.

Knowledge engineering: The process of extracting, articulating and computerizing knowledge.

Knowledge representation: A means of organizing knowledge into a format that can be systematically computerized. The most common techniques are production rules, frames and semantic nets.

Modular approach: An approach where the domain is broken down into limited segments that perform complete functions and are, therefore, understandable in themselves. This greatly facilitates development and verification of complex systems.

Moisture content (w_h): The difference between the total water content of an aggregate (w_{tot}) and its water content in the SSD state (w_{abs}) is called the moisture content of the aggregate.

Object: A discrete entity possessing attributes and behaviour. An object is a variable in object-oriented programming.

Object-oriented: Object-orientation involves thinking about the world as a set of entities or objects that are related to and communicate with one another. It is a level of computer abstraction beyond that of procedures and data. (Used as, *object-oriented programming, object-oriented design, object-oriented approach*).

Pozzolan: It is a natural or artificial material containing silica in reactive form. It is a siliceous or siliceous and aluminous material, which in itself possesses little or no cementitious value, but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperature to form compounds possessing cementitious properties.

Production rule: A technique of knowledge representation resembling ordinary written text. It consists of a "condition" part, IF (known as antecedent), followed by a "consequent" part, THEN.

Rapid prototyping: The rapid building of an expert system in order to understand the problem at hand. Prototype building commences immediately when some knowledge is acquired.

Required average compressive strength (f_{cr}'): It is the average compressive strength of concrete required to meet the acceptance criteria. Its value depends on the design or specified value as well as on the level of control that is actually achieved in the field and the acceptance criteria.

Rule: Also used to mean production rule.

Rule-based reasoning: The technique of obtaining conclusion in which knowledge is represented as a set of rules.

Saturated and surface dry (SSD) aggregate: In this state of aggregate, there is no free or surface moisture on the aggregate, but all voids within the aggregates are filled with water. The SSD state of coarse aggregate is obtained by soaking the aggregate in water for 24 hours and then removing the surface water from it. For the fine aggregate, the SSD state is obtained when a small truncated sand cone no longer holds together owing to the capillary forces between the wet sand particles.

Saturation point of superplasticizer: This is the dosage of superplasticizer at which, in the experimental conditions used for the measurement of the flow time, any increase in the dosage of the superplasticizer has no effect on the rheology of the grout.

Semantic net: A technique of knowledge representation using a collection of nodes to represent objects, concepts, or situations, which are linked together (in no systematic manner) by lines of relationships/interactions.

Shell: A computer software used to develop an expert system with a built-in inference engine. It can also be considered as an expert system with an empty knowledge base.

Specific gravity (SSD): The specific gravity of an aggregate in the SSD state is called the SSD specific gravity. The SSD specific gravity of aggregate is obtained by dividing the mass of SSD aggregate by the difference between the mass of SSD aggregate and the weight of aggregate in water. For Portland cement or any supplementary cementitious material, the specific gravity is equal to the mass of the dry material divided by its dry density.

Structured interview: An interview where the knowledge engineer outlines specific sample goals and questions.

Sub-task: A sub-component of work that is part of getting a task done.

Superplasticizer dosage: It can be given in litres of commercial solution per cubic metre of concrete. This is the best way to express it at the batching plant. But in the scientific papers or in a book, it is always better to give the superplasticizer dosage as the amount of solids it contains expressed as a percentage of the mass of cement.

Supplementary cementitious material content: If the supplementary cementitious material is incorporated at a concrete plant, separately from Portland cement, then the term *'content'* is only related to the mass of Portland cement that is used to make the concrete. When the supplementary cementitious material is added at the cement plant, its content is related to the mass of the blended cement and not only to the cement content.

Task: A component of work that is a part of getting the job done by the whole system.

Task analysis: A rigorous qualitative analysis of the nature of problem to be addressed by the expert system.

Text analysis: A rigorous analysis of the contents of a textual source in order to extract knowledge or expertise for use in an expert system.

Unstructured interview: An interview with no specific sample goal or question. The domain expert is allowed to freely talk on any matter that he deems relevant.

Water-binder ratio: It is usually defined as the ratio of the weight of water to the weight of cement or cement plus cementitious additive in the concrete mix.

Water content (w_{tot}): The water content of an aggregate is defined as the amount of evaporable water divided by the dry mass of the aggregate and is expressed as a percentage. To measure it, it is only necessary to place a certain amount of wet aggregate in an oven at 105 ^{0}C and to weight it when it has a constant mass.

Water reducer and air-entraining agent dosages: These dosages can be expressed in terms of litres of the commercial solution per cubic metre of concrete. These can also be expressed in millilitres of commercial solution per 100 kg of cement, the usual way of expressing those in North America.

Working memory: Memory that holds all information, either inputted or derived, which represents the current state of the problem handled by the expert system. (Also known as *database, global memory*, or *context*).

APPENDIX B

SAMPLE CALCULATION OF HIGH PERFROMANCE CONCRETE MIX DESIGN

B.1 FIRST TRIAL BATCH

Suppose that a 100 MPa concrete has to be made with: a Type I Portland cement; a naphthalene-type superplasticizer with a total solids content of 40% and specific gravity of 1.21; a dolomitic limestone having D_{max} = 10 mm, G_{SSD} = 2.80, w_{abs} = 0.8% and w_{tot} = 0%, and the shape of the particles can be described as between average and cubic; a siliceous natural sand having G_{SSD} = 2.65, w_{abs} = 1.2% and w_{tot} = 3.5%; silica fume at 10% replacement (of total cementitious material) is to be used; its specific gravity is 2.20; the dosage of solids superplasticizer at the saturation point is 1.0%.

Calculation:

Water-binder ratio = 0.27 (From Figure 4.2 of Chapter IV for 100 MPa concrete).
Water content = 140 l/m^3 (From Figure 4.3 for 1% saturation point)
Binder content =140/0.27 = 518.5 kg/m^3 $\approx$ 520 kg/m^3 (say).
Silica fume content = 10% of 520 = 52 kg $\approx$ 50 kg (say).
Cement content = 520 – 50 = 470 kg/m^3.
Coarse aggregate content = 1075 kg/m^3 (From Figure 4.4).
Entrapped air content = 1.5% (assume).

Mass of solids in superplasticizer, M_{sol} = 520 x (1/100) = 5.2 kg $\approx$ 5.0 kg (say).
Volume of superplasticizer, V_{liq} = 5.2/[(40/100) x 1.21] = 10.74 l/m^3 $\approx$ 10.7 l/m^3.
Water in superplasticizer, V_w = 10.74 x 1.21 x (100 – 40)/100 = 7.8 l/m^3 $\approx$ 8.0 l/m^3.
Volume of solids in the superplasticizer, V_{sol} = 10.74 – 7.80 = 2.94 l/m^3 $\approx$ 3.0 l/m^3.

Volume of cement = 470/3.14 = 149.7 l/m^3 $\approx$ 150 l/m^3 (say).
Volume of silica fume = 50/2.2 = 22.7 l/m^3 $\approx$ 23 l/m^3 (say).

Volume of coarse aggregate = 1075/2.80 =383.9 l/m^3 ≈ 384 l/m^3 (say).

Volume of entrapped air = 1.5 x 10 =15 l/m^3.

Volume of sand = 1000 – (140 + 150 + 23 + 384 + 15 + 3) = 285 l/m^3.

Mass of sand (SSD) = 285x 2.65 = 755 kg/m^3.

Unit mass of this concrete = 140 + 470 + 50 + 1075 + 755 + 5 = 2495 kg/m^3.

Mass of dry coarse aggregate = 1075 [1- (0.8/100)] = 1066 kg.

Absorption by coarse aggregate = 1075 – 1066 = 9 kg of water.

Excess water in fine aggregate = 755 (1 + 2.3 / 100) - 755 = 772 –755 = 17 l/m^3.

Volume of mixing water to be measured = 140 + 9 - 17 - 8 = 124 l/m^3.

This gives the final composition of 1 m^3 of concrete.

B.2 LABORATORY TRIAL BATCH

Suppose that the following specimens are needed to test the concrete mix in the laboratory:

- 3 100 x 200 mm cylinders for tests at 1, 7, 28 and 91 days in compression (total number of samples = 12);
- 3 150 x 300 mm cylinders for tests at 28 days in compression;
- 3 150 x 300 cylinders for tests for elastic modulus at 28 days;
- 3 100 x 100 x 400 mm beams for test for modulus of rupture at 7 and 28 days, plus one spare for a total of 7.
- A slump test, an air content test and a unit mass test will be done on the fresh concrete. Except for the air content test, the concrete used for these tests will be recovered. An air test needs 15 kg of concrete.

The amount of concrete to make this trial batch needs to be calculated.

Calculation:

Mass of concrete for the test specimens = 12 x 5 + 6 x 15 + 15 x 3 + 1 x 15 = 210 kg.

Assuming 10% loss, total mass of concrete required = 1.10 x 210 = 231 kg.

Multiplying factor, *f* = 231/2495 = 0.093. (Unit mass of concrete = 2495 kg/m^3).

Mixing water = 124 x 0.093 = 11.53 say 11.5 litre.

Cement = 470 x 0.093 = 43.7 kg.

Silica fume = 50 x 0.093 = 4.7 kg.

Coarse aggregate = 1066 x 0.093 = 99.1 kg, say 99 kg.

Fine aggregate = 772 x 0.093 = 71.80 kg, say 72 kg

Superplasticizer = 10.7 x 0.093 = 0.995 litre, say 1 litre.

B.3 TRIAL BATCH PROPORTIONS TO 1 M³ SSD COMPOSITION

Suppose that a trial batch with an adequate consistency and adequate initial and final slumps was made using the quantities of materials as stated ahead: water = 12 litre, cement = 45 kg, fly ash = 5 kg, coarse aggregate = 100 kg, fine aggregate = 70 kg, superplasticizer = 0.9 litre. The air content of this trial batch was 1.5%. The materials used to make this trial batch had the following properties: for coarse aggregate G_{SSD} = 2.75, w_{abs} = 1.0%, w_{tot} = 0%, and for fine aggregate G_{SSD} = 2.65, w_{abs} =1.0%, w_{tot} = 3.9%. The fly ash used had a specific gravity of 2.50. The superplasticizer was naphthalene-based with a specific gravity, G_{sup}, of about 1.21 and a solid content of 42%. What is the composition of 1 m³ of this concrete?

Calculation:

Mass of coarse aggregate (SSD) = 100 / (1 + (- 1 / 100)) = 101 kg

Mass of fine aggregate (SSD) = (70 / (1 + 2.9 / 100)) = 68 kg.

Water absorbed by the coarse aggregate = 101 – 100 = 1 kg

Water added to the mix by the fine aggregate = 70 – 68 = 2 kg.

Water contained in the superplasticizer = (0.9 x 1.21 x ((100 – 42) / 100)) = 0.63 litre.

Water correction = –1.0 + 2.0 + 0.63 = + 1.63.

Volume of effective water in the mix = 12 + 1.63 = 13.63 litre.

Volume of cement = 45/3.14 = 14.33 litre.

Volume of fly ash = 5/2.5 = 2.0 litre.

Volume of coarse aggregate = 101/2.75 = 36.73 litre.

Volume of fine aggregate = 68/2.65 = 25.66 litre.

Volume of solids in the superplasticizer = 0.9[1-1.21 x (100 – 42)/100] = 0.27 litre.

Total volume = 13.63 + 14.33 +2.0 + 36.73 + 25.66 + 0.27 = 92.62 litre.

Actual volume of concrete in this trial batch = 92.62/(1-1.5/100) = 94.03 litre.

Multiplying factor = 1000/94.03 =10.63.

The composition of 1 m^3 of concrete for SSD conditions of aggregates is:

Water = 13.63 x 10.63 = 144.88, say 145 l/m^3

Cement = 45 x 10.63 = 478.35 kg, say 480 kg/m^3

Fly ash = 5 x 10.63 = 53.15, say 53 kg/m^3

Coarse aggregate = 101 x 10.63 = 1073.63, say 1075 kg/m^3

Fine aggregate = 68 x 10.63 = 722.84, say 725 kg/m^3

Superplasticizer = 0.9 x 10.63 = 9.567 l, say 9.6 l/m^3.

Mass of the solids of superplasticizer = 9.6 x 1.21 x 0.42 = 4.88 kg/m^3, say 5 kg/m^3.

Unit mass of this concrete = 145 + 480 + 53 + 1085 + 725 + 5 = 2483 kg/m^3.

The binder mass is: 480 + 53 = 533 kg.

The actual water-binder ratio is: 145/533 = 0.27.

B.4 BATCH COMPOSITION

A concrete batch plant is to produce 8 m^3 of HPC on the basis of the SSD composition as stated ahead: w/c = 0.29, water = 130 litre, cement = 450 kg, coarse aggregate = 1050 kg, fine aggregate = 750 kg, superplasticizer = 8 litre (with solid content of 4 kg). The water content of the aggregates in the bins are: coarse aggregate w_{tot} = 0.8%, w_{abs} = 0.8%, and fine aggregate w_{tot} = 3.0%, w_{abs} = 1.0%. The superplasticizer is a naphthalene superplasticizer containing 42% solids and having a specific gravity of 1.21. What are the masses of materials that must be weighed to make 8 m^3 of concrete?

Calculation:

Mass of the solids contained in the superplasticizer, M_{sol} = 8 x 1.21 x 0.42 = 4.06 kg.

Unit mass of this concrete = 130 + 450 + 4 + 1050 + 750 = 2384 kg.

Water in superplasticizer, V_w = 8 x 1.21 x (100 – 42)/100 = 5.61 litres, say 6 litres.

Mass of water included in the wet sand = 750 (1 + 2/100) – 750 = 15 kg.

Mass of mixing water to be measured = 130 –6 – 15 = 109 kg.

Batch composition for 8 m^3 of concrete:

Water = 109 x 8 = 872 litres.

Cement = 450 x 8 = 3600 kg.

Coarse aggregate = 1050 x 8 = 8400 kg.

Fine aggregate = (750 + 15) x 8 = 6120 kg.

Superplasticizer = (8 x 8) litres or (8 x 1.21 x 8) kg = 64 litres or 77 kg.

Concrete load = 872 + 77 + 3600 + 8400 + 6120 = 19 069 kg.

APPENDIX C

LIST OF EXPERTS AND VISITED SITES

C.1 LIST OF EXPERTS

The following experts were consulted for the purpose of knowledge acquisition at various stages of this study.

1. **Dr. Muhammad Fauzi Mohd. Zain**, Associate Professor, Department of Civil and Structural Engineering, Faculty of Engineering, Universiti Kebangsaan Malaysia.
2. **Prof. Ir. Dr. Hassan Basri**, Department of Civil and Structural Engineering, Faculty of Engineering, Universiti Kebangsaan Malaysia.
3. **Mr. Hashem Al-Mattarneh**, Lecturer, Department of Civil Engineering, UiTM, Malaysia.
4. **Dr. Ir. Ade Ilham**, Indonesia.
5. **Mrs. Maslina Jamil**, PhD Student, Department of Civil and Structural Engineering, Faculty of Engineering, Universiti Kebangsaan Malaysia.
6. **Mr. Faisal Mahmud**, Kuala Lumpur, Malaysia.

C.2 LIST OF VISITED SITES

The following sites were visited for the purpose of knowledge acquisition regarding mix design and adjustment of high performance concrete.

1. KLCC Convention Centre construction site, Kuala Lumpur (Date: 21-04-2004).
2. Petronas Twin Tower, Kuala Lumpur City Centre (KLCC), Kuala Lumpur (Date: 16-07-2003, 26-05-2004).
3. Concrete Laboratory, Department of Civil and Structural Engineering, Faculty of Engineering, Universiti Kebangsaan Malaysia (Throughout this study).

APPENDIX D

SAMPLE FUNCTIONS, METHODS AND RULES

```
/*******************************************************/
/**          ALL FUNCTIONS ARE SAVED BELOW            **/
/*******************************************************/

        /*************************************
         ****  FUNCTION: Input11
         *************************************/
MakeFunction( Input11, [],
{
 AskValue(CoarseAgg:MaxSizeOfAgg);
 AskValue(CoarseAgg:UnitWeight);
 AskValue(CoarseAgg:ShapeOfAgg);
 AskValue(CoarseAgg:SpecificGravity);
 AskValue(CoarseAgg:AggAbsorption);
 AskValue(CoarseAgg:FieldMoisture);
    FineAggInformation();
 ForAll[x|KSession] HideWindow(x);
 MaximizeWindow(Session21);
} );

        /*************************************
         ****  FUNCTION: MoreSilica
         *************************************/
MakeFunction( MoreSilica, [],
{
ClearTranscriptImage(Transcript25);
DisplayFile(Transcript25,Silica.txt);
} );

        /*************************************
         ****  FUNCTION: CementInformation
         *************************************/
MakeFunction( CementInformation, [],
{
If(Binders:Type#="Cement And Pozzolanas")
Then{
     ClearTranscriptImage(Transcript15);
     DisplayText(Transcript15,FormatValue("\n\t%s\n\t%s\t","For the next
steps, the following information", "is required about Cement:"));
     DisplayText(Transcript15,FormatValue("\n\n\t%s", "    1. Type of
Cement"));
     DisplayText(Transcript15,FormatValue("\n\t%s", "    2. Specific Gravity
of Cement"));
     DisplayText(Transcript15,FormatValue("\n\n\t%s", "For information about
Cement, click More Information button."));
     DisplayText(Transcript15,FormatValue("\n\t%s", "To continue with the
input data, press Input button."));
     ForAll[x|KSession] HideWindow(x);
     MaximizeWindow(Session16);
     }
Else{
      ClearTranscriptImage(Transcript16);
      DisplayText(Transcript16,FormatValue("\n\t%s\n\t%s\t","For the next
steps, the following information","is required about Cement:"));
      DisplayText(Transcript16,FormatValue("\n\n\t%s", "1. Type of Cement"));
```

```
        DisplayText(Transcript16,FormatValue("\n\t%s", "2. Specific Gravity of
Cement"));
        DisplayText(Transcript16,FormatValue("\n\n\t%s", "For information about
Cement, click More Information button."));
        DisplayText(Transcript16,FormatValue("\n\t%s", "To continue with the
input data, press Input button."));
        ForAll[x|KSession] HideWindow(x);
        MaximizeWindow(Session17);
        };
} );

         /************************************
          ****  FUNCTION: BackSESSION
          ************************************/
MakeFunction( BackSESSION, [],
{
 ForAll [x|KSession] HideWindow(x);
 MaximizeWindow(SESSION);
} );

         /************************************
          ****  FUNCTION: ContinueAlkaliAgg
          ************************************/
MakeFunction( ContinueAlkaliAgg, [],
{
AskValue(AlkaliAggReac:AggLabFieldPerformance);
If(AlkaliAggReac:AggLabFieldPerformance#=Unblemished)
Then{
          ClearTranscriptImage(Transcript49);
          Assert(AlkaliAggReac:AggLabFieldPerformance);
          ForwardChain();
     }
Else{
          AskValue(AlkaliAggReac:AggMeetMandatoryReq);
          If(AlkaliAggReac:AggMeetMandatoryReq#=Yes)
          Then{
                    AskValue(AlkaliAggReac:AggType);
                         If(AlkaliAggReac:AggType#=Siliceous)
                         Then{
                         PostMessage("Agg type is Siliceous. Siliceous
                         Petrographic Examination is recommended.");
AskValue(AlkaliAggReac:SiliceousPetroResults);
If(AlkaliAggReac:SiliceousPetroResults#=Reactive)
Then{
AskValue(AlkaliAggReac:PreventionMethod);
If(AlkaliAggReac:PreventionMethod#="Low-Alkali Cement")
Then AskValue(AlkaliAggReac:ExternalSourceExposure)
Else AskValue(AlkaliAggReac:AdmixtureType);
    };
}
Else{
PostMessage("Agg type is Carbonate. Carbonate Petrographic Examination is
recommended.");
AskValue(AlkaliAggReac:CarbonatePetroResults);
If(AlkaliAggReac:CarbonatePetroResults#="Potentially Reactive")
Then{
PostMessage("Petrographic examination indicates that aggregate is potentially
reactive.Therefore, Lab testing is recommended.");
AskValue(AlkaliAggReac:CarbonateLabResults);
     };
     };};

          ClearTranscriptImage(Transcript49);
          Assert(AlkaliAggReac:AggMeetMandatoryReq);
          ForwardChain();
     };
} );
```

```
        /*************************************
         ****  FUNCTION: FlowDiagram
         *************************************/
MakeFunction( FlowDiagram, [],
{
HideImage(Transcript29);
ShowImage(Bitmap1);
} );

        /*************************************
         ****  FUNCTION: ExitAll
         *************************************/
MakeFunction( ExitAll, [],
{
    ForAll[x|KSession]
    HideWindow(x);
} );

        /*************************************
         ****  FUNCTION: DesignBeforeAdjustment
         *************************************/
MakeFunction( DesignBeforeAdjustment, [],
{
BinderContentCalculation();
SendMessage(Superplasticizer,MassVolumeSuper);
SendMessage(FineAgg,FineAggContent,VolumeSolid);
SendMessage(HardConcrete,ComputeUnitWeight,MassSolid);
SendMessage(FreshConcrete,Composition,Design1,Content,Transcript1, Session1);
} );

        /*************************************
         ****  FUNCTION: ResetResult
         *************************************/
MakeFunction( ResetResult, [],
{
    ResetValue(Cement:Content);
    ResetValue(Cement:ContentFieldAdjustment);
    ForAll[x|Pozzolanas]     ResetValue(x:Content);
    ForAll[x|Pozzolanas]     ResetValue(x:ContentFieldAdjustment);
    ResetValue(CoarseAgg:Content);
    ResetValue(CoarseAgg:ContentFieldAdjustment);
    ResetValue(FineAgg:Content);
    ResetValue(FineAgg:ContentFieldAdjustment);
    ResetValue(Superplasticizer:Content);
    ResetValue(Superplasticizer:ContentFieldAdjustment);
    ResetValue(FreshConcrete:WaterBinderRatio);
} );

        /*************************************
         ****  FUNCTION: ExplainCoarseAgg
         *************************************/
MakeFunction( ExplainCoarseAgg, [],
Explain(CoarseAgg:ContentFieldAdjustment) );

        /*************************************
         ****  FUNCTION: LabTrialData
         *************************************/
MakeFunction( LabTrialData, [],
{
SendMessage(ConcreteTests,SpecimenTypes);
SetValue(ConcreteTests:TotalVolume,0);
EnumSubClasses(ConcreteTests,x,
     {
         SendMessage(x,CreateTestSpecimen);
         SendMessage(x,InputSpecimenInfo);
         SetValue(x:TotalVolume,0);
```

```
            ForAll[y|x] SendMessage(y,SpecimenVolume);
        ConcreteTests:TotalVolume+=x:TotalVolume;
    });
ConcreteTests:TotalVolume=1.10*ConcreteTests:TotalVolume;
ConcreteTests:MultiplyingFactor=ConcreteTests:TotalVolume;
PostMessage("Data input is complete. Press COMPOSITION button to see Lab
Trial Composition.");
} );

        /************************************
         ****  FUNCTION: FieldToSSDComposition
         ************************************/
MakeFunction( FieldToSSDComposition, [],
{
SendMessage(CoarseAgg,AggMoistureAdjustment2);
SendMessage(FineAgg,AggMoistureAdjustment2);
Superplasticizer:VolumeOfWater=((1-Superplasticizer:SolidContentPercent/100)
*Superplasticizer:ContentFieldAdjustment)*Superplasticizer:SpecificGravity;
SendMessage(Water1,WaterCorrection2);

Water1:VolumeSolid=Water1:MassSolid;
CoarseAgg:VolumeSolid=CoarseAgg:MassSolid/CoarseAgg:SpecificGravity;
FineAgg:VolumeSolid=FineAgg:MassSolid/FineAgg:SpecificGravity;
Superplasticizer:VolumeSolid=Superplasticizer:ContentFieldAdjustment-
Superplasticizer:VolumeOfWater;
Cement:VolumeSolid=Cement:ContentFieldAdjustment/Cement:SpecificGravity;
ForAll[x|Pozzolanas]{x:VolumeSolid=x:ContentFieldAdjustment/x:SpecificGravity
;};

FreshConcrete:SSDVolume=Sum(Water1:VolumeSolid, Cement:VolumeSolid,
SilicaFume:VolumeSolid, FlyAsh:VolumeSolid, GGBS:VolumeSolid,
RiceHuskAsh:VolumeSolid, CoarseAgg:VolumeSolid, FineAgg:VolumeSolid,
Superplasticizer:VolumeSolid);
FreshConcrete:SSDVolume=FreshConcrete:SSDVolume/(1-
TotalAir:ContentPercent/100);

ConcreteTests:MultiplyingFactor=1000/FreshConcrete:SSDVolume;
        PostMessage("ConcreteTests:MultiplyingFactor= ",
ConcreteTests:MultiplyingFactor);

SendMessage(Water1,CompositionConversion,ContentOneM3SSD,MassSolid);
SendMessage(CoarseAgg,CompositionConversion,ContentOneM3SSD,MassSolid);
SendMessage(FineAgg,CompositionConversion,ContentOneM3SSD,MassSolid);
SendMessage(Cement, CompositionConversion, ContentOneM3SSD,
ContentFieldAdjustment);
ForAll [x|Pozzolanas]
SendMessage(x,CompositionConversion,ContentOneM3SSD,ContentFieldAdjustment);
SendMessage(Superplasticizer, CompositionConversion, ContentOneM3SSD,
ContentFieldAdjustment);
PostMessage("Please see the composition for SSD (One M3) in the transcript
image.");

SendMessage(FreshConcrete, Composition, Design5, ContentOneM3SSD,
Transcript5, Session4);

Superplasticizer:MassSolid=Superplasticizer:ContentOneM3SSD
*(Superplasticizer:SolidContentPercent/100)*Superplasticizer:SpecificGravity;
HardConcrete:UnitWeight=Sum(Water1:ContentOneM3SSD, Cement:ContentOneM3SSD,
SilicaFume:ContentOneM3SSD, FlyAsh:ContentOneM3SSD, GGBS:ContentOneM3SSD,
RiceHuskAsh:ContentOneM3SSD, CoarseAgg:ContentOneM3SSD,
FineAgg:ContentOneM3SSD, Superplasticizer:MassSolid);
Binders:Content=Cement:ContentOneM3SSD + SilicaFume:ContentOneM3SSD +
FlyAsh:ContentOneM3SSD + GGBS:ContentOneM3SSD + RiceHuskAsh:ContentOneM3SSD;
FreshConcrete:WaterBinderRatio=Water1:ContentOneM3SSD/Binders:Content;
} );
```

```
        /************************************
         ****  FUNCTION: ContinueSulfate
         *************************************/
MakeFunction( ContinueSulfate, [],
{
ClearTranscriptImage(Transcript41);
AskValue(SulfateAttack:TypeOfEnvironment);
If(SulfateAttack:TypeOfEnvironment#=Water)
    Then AskValue(SulfateInWater:ContentSulfateIons)
Else AskValue(SulfateInSoil:ContentSulfateIons);
    If((SulfateAttack:TypeOfEnvironment#=Water) And
(SulfateInWater:ContentSulfateIons#="Less than 150 ppm"))
        Or ((SulfateAttack:TypeOfEnvironment#=Soil) And
(SulfateInSoil:ContentSulfateIons#="0 to 0.01 percent"))
    Then { PostMessage("Data input is complete. Press Recommendation button
for Recommendation.");
          }
    Else{If((SulfateAttack:TypeOfEnvironment#=Water) And
(SulfateInWater:ContentSulfateIons#="More than 10000 ppm"))
       Or ((SulfateAttack:TypeOfEnvironment#=Soil) And
(SulfateInSoil:ContentSulfateIons#="More than 2.00 percent"))
       Then AskValue(SulfateAttack:SevereAdmixture)
       Else
             {
            AskValue(SulfateAttack:CementType);
             If(SulfateAttack:CementType#="Portland Cement")
                Then AskValue(SulfateAttack:UsePozzolanAdmixture)
              Else AskValue(SulfateAttack:TypeBlendedCement);
                };
PostMessage("Data input is complete. Press Recommendation button for
Recommendation.");
        };
} );

        /************************************
         ****  FUNCTION: ContinueAbrasionRecom
         *************************************/
MakeFunction( ContinueAbrasionRecom, [],
{
ClearTranscriptImage(Transcript55);
Assert(Abrasion:FloorType);
ForwardChain();
} );


/********************************************************/
/**          ALL CLASSES ARE SAVED BELOW              **/
/********************************************************/

        /************************************
         ****  CLASS: Ingredients
         *************************************/
MakeClass( Ingredients, FirstTrialBatch );

/************** METHOD: InitialContent   **************/
MakeMethod( Ingredients, InitialContent, [],
If(Self:ContentPercent==0)
Then Self:ContentFieldAdjustment=0 );

/************** METHOD: WaterDosage   **************/
MakeMethod( Ingredients, WaterDosage, [],
{
Water1:ContentKgPerM3=50*Superplasticizer:SaturationPoint+90;
Water1:VolumeSolid=Water1:ContentKgPerM3;
Water1:MassSolid=Water1:ContentKgPerM3;
Water1:Content=Water1:MassSolid;
} );
```

```
        /************************************
         ****  CLASS: Water
         ************************************/
MakeClass( Water, Ingredients );

/************** METHOD: WaterCorrection   **************/
MakeMethod( Water, WaterCorrection, [],
{
Self:CorrectedWater=Self:MassSolid - (CoarseAgg:WaterInAgg +
FineAgg:WaterInAgg + Superplasticizer:VolumeOfWater);
Self:ContentFieldAdjustment=Self:CorrectedWater;
} );

        /************************************
         ****  CLASS: Binders
         ************************************/
MakeClass( Binders, Ingredients );

/************** METHOD: PozzolanContent   **************/
MakeMethod( Binders, PozzolanContent, [],
{
Self:ContentKgPerM3=Self:ContentPercent/100*Binders:ContentKgPerM3;
Self:VolumeSolid=Self:ContentKgPerM3/Self:SpecificGravity;
Self:MassSolid=Self:ContentKgPerM3;
Self:Content=Self:MassSolid;
Self:ContentFieldAdjustment=Self:Content;
} );

        /************************************
         ****  CLASS: Aggregates
         ************************************/
MakeClass( Aggregates, Ingredients );

/************** METHOD: CoarseAggContent   **************/
MakeMethod( Aggregates, CoarseAggContent, [],
{
Assert(Self:ShapeOfAgg);
ForwardChain();
Self:MassSolid=Self:ContentKgPerM3;
Self:Content=Self:MassSolid;
} );

/************** METHOD: FineAggContent   **************/
MakeMethod( Aggregates, FineAggContent, [x ],
{
SendMessage(Cement, VolumeCalculation);
SendMessage(SilicaFume, VolumeCalculation);
SendMessage(FlyAsh, VolumeCalculation);
SendMessage(GGBS, VolumeCalculation);
SendMessage(RiceHuskAsh, VolumeCalculation);
SendMessage(CoarseAgg, VolumeCalculation);
Self:x=1000-Sum(Cement:x, SilicaFume:x, FlyAsh:x, GGBS:x, RiceHuskAsh:x,
CoarseAgg:x,Superplasticizer:x, Water1:x,TotalAir:x);
Self:MassSolid=Self:x*Self:SpecificGravity;
Self:Content=Self:MassSolid;
} );

        /************************************
         ****  CLASS: Admixtures
         ************************************/
MakeClass( Admixtures, Ingredients );

/************** METHOD: MassVolumeSuper   **************/
MakeMethod( Admixtures, MassVolumeSuper, [],
{
```

```
Self:MassSolid=Binders:ContentKgPerM3*Self:ContentPercent/100;
Self:VolumeLiquid=Self:MassSolid / Self:SolidContentPercent * 100 /
Self:SpecificGravity;
Self:Content=Self:VolumeLiquid;
Self:ContentFieldAdjustment=Self:Content;
Self:VolumeOfWater=Self:VolumeLiquid*Self:SpecificGravity*(100-
Self:SolidContentPercent)/100;
Self:VolumeSolid=Self:VolumeLiquid-Self:VolumeOfWater;
} );

        /*************************************
         ****  CLASS: ConcreteProperties
         *************************************/
MakeClass( ConcreteProperties, FirstTrialBatch );

/************** METHOD: Composition   **************/
MakeMethod( ConcreteProperties, Composition, [x y z w ],
{
OpenWriteFile(x.wri);
WriteLine(FormatValue("\n\t%s\t\t%s","Mix Ingredients"  ,"        Content"));
WriteLine(FormatValue("\n\t%s", "=========          ==========="));
WriteLine(FormatValue("\n\t%s\t\t%15.2f","Water (l/m3)",Water1:y));
WriteLine(FormatValue("\n\t%s\t\t%15.2f","Cement (kg/m3)",Cement:y));
WriteLine(FormatValue("\n\t%s\t%15.2f","Coarse Aggregate (kg/m3)",
CoarseAgg:y));
WriteLine(FormatValue("\n\t%s\t%15.2f","Fine Aggregate (kg/m3)", FineAgg:y));
WriteLine(FormatValue("\n\t%s\t%15.2f","Silica Fume (kg/m3)", SilicaFume:y));
WriteLine(FormatValue("\n\t%s\t\t%15.2f","Fly Ash (kg/m3)", FlyAsh:y));
WriteLine(FormatValue("\n\t%s\t\t%15.2f","GGBS (kg/m3)",GGBS:y));
WriteLine(FormatValue("\n\t%s\t%15.2f","Rice Husk Ash (kg/m3)",
RiceHuskAsh:y));
WriteLine(FormatValue("\n\t%s\t%15.2f","Superplasticizer (l/m3)",
Superplasticizer:y));
WriteLine(FormatValue("\n\t%s\t\t%15.2f","Air Content (%)",
TotalAir:ContentPercent));
WriteLine(FormatValue("\n\t%s\t\t%15.2f","Water-Binder ratio",
FreshConcrete:WaterBinderRatio));
CloseWriteFile();
    ClearTranscriptImage(z);
    DisplayFile(z,x.wri);
ForAll[window|KSession] HideWindow(window);
    MaximizeWindow(w);
} );

/************** METHOD: DataSSDToField1   **************/
MakeMethod( ConcreteProperties, DataSSDToField1, [],
{
PostInputForm([CANCEL],"Enter SSD Compostion",
    Water1, ContentOneM3SSD,"Water content (l/m3): ",
    Cement,ContentOneM3SSD,"Cement content (kg/m3): ",
    SilicaFume,ContentOneM3SSD,"Silica Fume content (kg/m3): ",
    FlyAsh,ContentOneM3SSD,"Fly Ash content (kg/m3): ",
    GGBS,ContentOneM3SSD,"GGBS content (kg/m3): ",
    RiceHuskAsh,ContentOneM3SSD,"Rice Husk Ash content (kg/m3): ",
    CoarseAgg,ContentOneM3SSD,"Coarse Agg content (kg/m3): ",
    FineAgg,ContentOneM3SSD,"Fine Agg content (kg/m3): ",
Superplasticizer,ContentOneM3SSD,"Superplasticizer content (l/m3): ",
TotalAir,ContentPercent,"Air content (%): ");
} );

        /*************************************
         ****  CLASS: ConcreteTests
         *************************************/
MakeClass( ConcreteTests, TrialBatchLab );

/************** METHOD: SpecimenTypes   **************/
MakeMethod( ConcreteTests, SpecimenTypes, [],
```

```
EnumSubClasses(ConcreteTests,x,
    {PostInputForm([CANCEL],"Enter Types of "#x#" to be tested:", x,
TypesOfSpecimen,"Number of "#x#" Types");}) );

/************** METHOD: CreateTestSpecimen   **************/
MakeMethod( ConcreteTests, CreateTestSpecimen, [],
{
ForAll[x|Self] DeleteInstance(x);
For x From 1 To Self:TypesOfSpecimen Do
MakeInstance(Self#Type#x,Self);
} );

/************** METHOD: InputSpecimenInfo   **************/
MakeMethod( ConcreteTests, InputSpecimenInfo, [],
{
ForAll[x|Self]
If Not(IsAKindOf?(x,OtherTests))
Then{
        If IsAKindOf?(x,Cylinder)
        Then{ PostInputForm([CANCEL],"Enter Dimensions and Number of Samples
of "#x,
                x,Width, "Diameter in mm",
                x,Height, "Height in mm",
                x,NumberOfSpecimen, "Number of samples");
            }
        Else{
              PostInputForm([CANCEL],"Enter Dimensions and Number of Samples
of "#x,
                x,Width, "Width in mm",
                x,Height, "Height in mm",
                x,Length,"Length in mm",
                x,NumberOfSpecimen, "Number of samples");
            };
    };
} );

/************** METHOD: SpecimenVolume   **************/
MakeMethod( ConcreteTests, SpecimenVolume, [],
{
If IsAKindOf?(Self,Cube)
Then { Self:TotalVolume=Self:Height*Self:Width*Self:Length
*Self:NumberOfSpecimen/1000/1000/1000;
        Cube:TotalVolume+=Self:TotalVolume;
     };
If IsAKindOf?(Self,Beam)
Then { Self:TotalVolume=Self:Height*Self:Width*Self:Length
*Self:NumberOfSpecimen/1000/1000/1000;
            Beam:TotalVolume+=Self:TotalVolume;
     };
If IsAKindOf?(Self,Cylinder)
Then { Self:TotalVolume=22/7*Self:Width/2*Self:Width/2*Self:Height
*Self:NumberOfSpecimen/1000/1000/1000;
        Cylinder:TotalVolume+=Self:TotalVolume;
     };
If IsAKindOf?(Self,OtherTests)
Then {
       PostInputForm([CANCEL],"Enter the volume of "#Self, Self,
TotalVolume,"Volume required for "#Self#" in cu-m");
                OtherTests:TotalVolume+=Self:TotalVolume;
     };
} );

        /************************************
         ****  CLASS: Carbonation
         ************************************/
MakeClass( Carbonation, Durabilities );
```

```
/************** METHOD: DisplayOfImage   **************/
MakeMethod( Carbonation, DisplayOfImage, [],
{
If(Self:Source#=Water)
Then{    HideImage(StateBox8);
         HideImage(StateBox9);
         HideImage(StateBox10);
         HideImage(StateBox11);
         HideImage(StateBox12);
         HideImage(RadioButtonGroup3);
         HideImage(RadioButtonGroup4);
         ShowImage(StateBox13);
    }
Else{     HideImage(RadioButtonGroup3);
          HideImage(RadioButtonGroup4);
          HideImage(StateBox13);
         ShowImage(StateBox8);
         ShowImage(StateBox9);
         ShowImage(StateBox10);
         ShowImage(StateBox11);
         ShowImage(StateBox12);
    };
} );


/*******************************************************/
/**          ALL RULES ARE SAVED BELOW                **/
/*******************************************************/

       /*************************************
       ****  RULE: CoarseAggDosage1
       *************************************/
MakeRule( CoarseAggDosage1, [],
    CoarseAgg:ShapeOfAgg #= Elongated,
    CoarseAgg:ContentKgPerM3 = 950 );

        /*************************************
         ****  RULE: CoarseAggDosage3
         *************************************/
MakeRule( CoarseAggDosage3, [],
    CoarseAgg:ShapeOfAgg #= Average,
    CoarseAgg:ContentKgPerM3 = 1050 );

        /*************************************
         ****  RULE: CoarseAggDosage10
         *************************************/
MakeRule( CoarseAggDosage10, [],
    CoarseAgg:ShapeOfAgg #= CubicAndRounded,
    CoarseAgg:ContentKgPerM3 = 1125 );

        /*************************************
         **** RULE: CorrosionOutdoorInland1
         *************************************/
MakeRule(CorrosionOutdoorInland1, [],
    {
    Corrosion:ConcreteEnvironment #= Outdoor
And Corrosion:ExposureOfConcrete #= "Inland exposure to wet environment"
And Corrosion:ChlorideExposure #= Severe
And Corrosion:TypeOfReinforcementSteel #= "Steel Reinforcement Bars";},
 {
    DisplayText( Transcript45, FormatValue( "\n   The following is a list of
the recommendations concerning Corrosion of concrete for this session:" ) );
    DisplayText( Transcript45, FormatValue( "\n\n\t - Good Workmanship is
extremely important." ) );
    DisplayText( Transcript45, FormatValue( "\n\t - Low slump, air
entrainment and well graded aggregates should be used." ) );
```

```
    DisplayText( Transcript45, FormatValue( "\n\t - Seven days of
uninterrupted moist or membrane curing is recommended." ) );
    DisplayText( Transcript45, FormatValue( "\n\t - Avoid contact between
different metals in the concrete to prevent stray current." ) );
    DisplayText( Transcript45, FormatValue( "\n\t - Be cautious of protruding
metals." ) );
    DisplayText( Transcript45, FormatValue( "\n\t - Good drainage is
important." ) );
    DisplayText( Transcript45, FormatValue( "\n\t - A 2 inch cover and water-
binder ratio below 0.40 or a 2.5 inch cover" ) );
    DisplayText( Transcript45, FormatValue( "\n\t     and a water-binder
ratio below 0.45 is necessary." ) );
    DisplayText( Transcript45, FormatValue( "\n\n   For bridge deck or
similar structure exposed to severe chloride ion envionment,  additional" )
);
    DisplayText( Transcript45, FormatValue( "\n   protection needs to be
provided to reinforcing steel by using either or combination of:" ) );
    DisplayText( Transcript45, FormatValue( "\n\n\t 1. Low slump dense
concrete (water-binder ratio = 0.32)" ) );
    DisplayText( Transcript45, FormatValue( "\n\t 2. Epoxy coated reinforcing
steel" ) );
    DisplayText( Transcript45, FormatValue( "\n\t 3. Waterproof membranes. "
) );
    DisplayText( Transcript45, FormatValue( "\n\n   Maximum chloride content
should be 0.10 percent." ) );
    } );

        /*************************************
         ****  RULE: SulfateSevere8
         *************************************/
MakeRule( SulfateSevere8, [],
    {
    SulfateAttack:TypeOfEnvironment #= Soil
And SulfateInSoil:ContentSulfateIons #= "0.20 to 2.00 percent"
And SulfateAttack:CementType #="Portland Cement"
And SulfateAttack:UsePozzolanAdmixture #= No;
    },
    {
    DisplayText( Transcript41, FormatValue( "\n   The following is a list of
the recommendations concerning Sulfate Attack of concrete for this session:"
) );
    DisplayText( Transcript41, FormatValue( "\n\n\t 1. The maximum water-
cement ratio should be 0.45" ) );
    DisplayText( Transcript41, FormatValue( "\n\t 2. Portland cement should
be Type V (ASTM C 150) " ) );
    DisplayText( Transcript41, FormatValue( "\n\t 3. The hardened concrete
should contain 2 to 3 percent entrained air (More may be necessary if freeze-
thaw problems could exist). " ) );
    DisplayText( Transcript41, FormatValue( "\n\t 4. Calcium chloride in
concrete reduces its resistance to attack by sulfate and its use should be
prohibited. " ) );
    } );

        /*************************************
         ****  RULE: ReactivityAlkAgg2
         *************************************/
MakeRule( ReactivityAlkAgg2, [],
    {
    AlkaliAggReac:MethodToAvoidReactivity #= "Use non-reactive aggregate"
And AlkaliAggReac:AggServiceRecordAcceptable #= Yes
And AlkaliAggReac:ChangesInQuarry #= No
And AlkaliAggReac:ChangesInAlkaliContent #= No
And AlkaliAggReac:ChangesInExposureCondition #= No
And AlkaliAggReac:DetermineAggReactivity #= Yes
And AlkaliAggReac:TypeOfAgg #= Siliceous
And AlkaliAggReac:CompileReacSilicaRock #= No
And AlkaliAggReac:ReasonRecomTests #= No
```

```
And AlkaliAggReac:Test #= "Petrographic; Mortar-Bar and Chemical Tests"
And AlkaliAggReac:TestReport #= No
And AlkaliAggReac:StrainedQuartz #= No
And AlkaliAggReac:SandGravelProblem #= No
And AlkaliAggReac:ReasonRecomChemTest #= Yes
And AlkaliAggReac:PetrographicTestAnomalous #= No
And AlkaliAggReac:PermittedTestPeriod #= Yes
And AlkaliAggReac:PassTest #= No;
    },
    {
    DisplayText( Transcript45, FormatValue( "\n   Both  laboratory tests
(Mortar-Bar and Chemical Test)  indicate that" ) );
    DisplayText( Transcript45, FormatValue( "\n   the aggregate is reactive.
So, the aggregates should not be used." ) );
    } );

       /************************************
        ****  RULE: AlkaliAggPerformance9
        ************************************/
MakeRule( AlkaliAggPerformance9, [],
    {
    AlkaliAggReac:AggMeetMandatoryReq #= Yes
And AlkaliAggReac:AggType #= Siliceous
And AlkaliAggReac:SiliceousPetroResults #= Reactive
And AlkaliAggReac:PreventionMethod #= "Pozzolan or Slag"
And AlkaliAggReac:AdmixtureType #= Slag;
    },
    {
    AlkAggRecomGeneral(  );
    DisplayText( Transcript49, FormatValue( "\n\n\t\t  (a) Slag should meet
the requirements of ASTM C 989." ) );
    DisplayText( Transcript49, FormatValue( "\n\n\t\t  (b) Usually, well
granulated and ground blast furnace slag will improve the worikability of
concrete." ) );
    DisplayText( Transcript49, FormatValue( "\n\n\t   The aggregate is
siliceous and reactive. Pozzolan or Slag should be used. Slag is preferred."
) );
    } );

       /************************************
        ****  RULE: FreezeThawModerate48
        ************************************/
MakeRule( FreezeThawModerate48, [],
    {
    FreezeThaw:TypeOfCement #= "Blended Cement"
And FreezeThaw:StructuralMemberType #= "Thin Section"
And FreezeThaw:ExposureCondition #= Moderate
And FreezeThaw:AggSelectionCriteria #= "Acceptable By Past Experience"
And FreezeThaw:NominalSizeOfAgg #= "37.5 mm (1.5 inches)";
    },
    {
    DisplayText( Transcript47, FormatValue( "\n\n\t%s", "HPCMIX gives
recommendations on requirements for HPC to be resistant to Freeze-Thaw
Cycles." ) );
    DisplayText( Transcript47, FormatValue( "\n\t%s", "The following are the
recommendation for the current session:" ) );
    DisplayText( Transcript47, FormatValue( "\n\n\n\t%s", "    1. Blended
cement is required to conform to ASTM Standard C595. " ) );
    DisplayText( Transcript47, FormatValue( "\n\n\t%s", "    2. Aggregate is
acceptable if field service records indicate satisfactory performance." ) );
    DisplayText( Transcript47, FormatValue( "\n\n\t%s", "    3. With 37.5 mm
(1.5 inch) aggregate selected for moderate conditions, the entrained air" )
);
    DisplayText( Transcript47, FormatValue( "\n\t%s", " should be4.5 percent.
" ) );
    DisplayText( Transcript47, FormatValue( "\n\n\t%s", "    4. Air void
spacing must be less than or equal to 0.20 mm (0.008 inch). " ) );
```

```
    DisplayText( Transcript47, FormatValue( "\n\n\t%s", "    5. For
application using thin sections the recommended water-cement ratio is 0.45. "
) );
    DisplayText( Transcript47, FormatValue( "\n\n\t%s", "    6. Concrete for
moderate exposure conditions should have a f'c of about 3.45 MPa(500 psi)
prior to  " ) );
    DisplayText( Transcript47, FormatValue( "\n\t%s", " one or two cycles of
freezing and thawing while curing. It should attain a f'c of about 20.7 MPa "
) );
    DisplayText( Transcript47, FormatValue( "\n\t%s", "(3000 psi) before
exposure to moderate conditions. " ) );
    } );

        /************************************
         ****  RULE: Carbonation4
         *************************************/
MakeRule( Carbonation4, [],
    {
    Carbonation:Source #= Water
And Carbonation:AggressiveCO21 #= Yes
And Carbonation:AggressiveCO22 #= Yes
And Carbonation:ExposureDuringHardening #= Yes;
    },
    {
    CarbonationRecom();
    } );

        /************************************
         ****  RULE: Abrasion71
         *************************************/
MakeRule( Abrasion71, [],
    {
    Abrasion:FloorType #= "Two Course"
And Abrasion:Traffic #= "Foot and Hard Wheel Vehicles"
And Abrasion:Topping #= Unbonded;
    },
    {
    AbrasionRecom(  );
    DisplayText( Transcript55, FormatValue( "\n\n Usual Traffic for the
Present Session: Foot and Hard Wheel Vehicles- Abrasive Wear." ) );
    DisplayText( Transcript55, FormatValue( "\n Use of the Floor: Bonded two-
course heavy industrial (Unbonded Topping)." ) );
    DisplayText( Transcript55, FormatValue( "\n Special Consideration: Mesh
reinforcing; bonded breaker on old concrete surface; " ) );
    DisplayText( Transcript55, FormatValue( "\n minimum thickness 64 mm(2.5
inch)." ) );
    DisplayText( Transcript55, FormatValue( "\n Concrete Finishing Technique
(Base):  Surface leveled by screeding." ) );
    DisplayText( Transcript55, FormatValue( "\n Concrete Finishing Technique
(Topping):  Special power floats with repeated steel troweling." ) );
    } );

        /************************************
         ****  RULE: Abrasion9
         *************************************/
MakeRule( Abrasion9, [],
    {
    Abrasion:FloorType #= "Two Course"
And Abrasion:Traffic #= "Light Foot" Or Foot Or "Light Foot and Pneumatic
Wheels" Or "Foot and Pneumatic Wheels" Or "Foot and Wheels- Abrasive Wear";
    },
    {
    DisplayText( Transcript55, FormatValue( "\n\n\n\t This is not a valid
Floor Type." ) );
    } );
```

```
        /************************************
         ****  RULE: MixAdjustmentWorkability2
         ************************************/
MakeRule( MixAdjustmentWorkability2, [],
    {
    TestResult:PerformanceCriteria #= Workability
And TestResult:WorkabilityPerformance #= "Rapid slump loss";
    },
    {
    DisplayText( Transcript58, FormatValue( "\n The following is the
recommendation for the present condition:" ) );
    DisplayText( Transcript58, FormatValue( "\n\n\t 1. Increase water dosage,
OR" ) );
    DisplayText( Transcript58, FormatValue( "\n\t 2. Increase
superplasticizer  dosage, OR" ) );
    DisplayText( Transcript58, FormatValue( "\n\t 3. Use another brand of
superplasticizer." ) );
    DisplayText( Transcript59, FormatValue( "\n The above recommendation is
given because:" ) );
    DisplayText( Transcript59, FormatValue( "\n\n\t If the concrete
experiences a rapid  slump loss, then the cement is perhaps" ) );
    DisplayText( Transcript59, FormatValue( "\n\t more reactive than expected
or the superplasticizer is particularly inefficient" ) );
    DisplayText( Transcript59, FormatValue( "\n\t with the selected cement."
) );
    } );

        /************************************
         ****  RULE: MixAdjustmentWorkStr
         ************************************/
MakeRule( MixAdjustmentWorkStr, [],
    {
    ( TestResult:PerformanceCriteria #= Workability
And TestResult:StrengthPerformance #= "Intragranular fracture"
Or TestResult:StrengthPerformance #= "Debonding between coarse aggregate and
hydrated cement paste"
Or TestResult:StrengthPerformance #= "Fracture surface passes through
hydrated cement paste"
Or TestResult:StrengthPerformance #= "Strength does not increase with
decrease in W/B ratio" )
Or ( TestResult:PerformanceCriteria #= Strength
And TestResult:WorkabilityPerformance #= "Inadequate workability"
Or TestResult:WorkabilityPerformance #= "Low slump"
Or TestResult:WorkabilityPerformance #= "Rapid slump loss" );
    },
    {
    SendMessage( TestResult, InvalidCombination );
    DisplayText( Transcript58, FormatValue( "\n The following is the
recommendation for the present condition:" ) );
    DisplayText( Transcript58, FormatValue( "\n\n\t 1. This is an invalid
combination of performance criteria and test result." ) );
    DisplayText( Transcript58, FormatValue( "\n\t 2. Please press on Reset
Data button to reset selected data, and then" ) );
    DisplayText( Transcript58, FormatValue( "\n\t 3. Select a performance
criteria and corresponding test result." ) );
    DisplayText( Transcript59, FormatValue( "\n The above recommendation is
given because:" ) );
    DisplayText( Transcript59, FormatValue( "\n\n\t 1. You have selected
invalid combination of performance criteria and test result." ) );
    } );
SetRulePriority( MixAdjustmentWorkStr, 10 );
```

APPENDIX E

THE HPCA USER'S MANUAL

An expert system named HPCA for high performance concrete mix design and the necessary adjustments as well as giving recommendations on durability aspects was developed using Kappa-PC expert system shell (version 2.4). To run the HPCA system, the user needs to have a copy of the Kappa-PC software package. An IBM PC or compatible computer, with a minimum of 64 MB RAM is required to run the system. The computer must also have a hard disk drive with room to load 128 MB of information. The windows must be MS Windows 98 or higher for proper functioning of the system.

Before beginning the consultation, it is recommended that the user get idea about the data requirements from tables of Chapter VIII. The tables outline the information that will be requested from the user during consultation with the system.

To begine the consultation, click on the shortcut for the Kappa-PC folder shown in the windows desktop. It will open the Kappa-PC main interface window. Begin the program by clicking on the File menu, Open option, HPCA file name and OK button. Click on the Session icon and choose SESSION from the pop-up window and press OK button. This will open the main interface window for the HPCA. This window shows eight buttons, namely GENERAL INFORMATION, USER GUIDE, MIX DESIGN, COST ESTIMATION, MIX PERFORMANCE ADJUSTMENT, DURABILITY, RESET DATA, and EXIT. Before running the sytem, the user is recommended to click on the RESET DATA button to remove all data from the previous consultation, if any. If the user is the first time user of the HPCA system, it is recommended to consult with the GENERAL INFORMATION and USER GUIDE buttons to get idea about the capability of the system and the best way to get advice and recommendation from a particular module.

The MIX DESIGN button opens main interface window for the mix design consultation. It has four buttons regarding four stages of mix design process i.e., FIRST TRIAL BATCH, TRIAL BATCH FOR LABORATORY, ONE CUBIC METRE SSD COMPOSITION and BATCH COMPOSITION. The functions of these buttons are described in the transcript image of the interface window. Similar buttons and transcript images are also available for the other modules. The user must read the information given in the transcript image of a module before beginning the consultaion with that particular module.

During the consultation, the expert system asks the user various questions. The majority of the questions offer a selection of choices from which the user will select only one choice. Some questions do not provide the user with a choice of selection; in that case, the user must input the answer according to the parameters set in question. Examples of types of questions used in the developed expert system were presented in Chapter VIII.

To end the consultation, click on the FILE menu and select the EXIT command. You will then be asked if you want to save the file. Click on the YES button and the system will automatically save the file and exit the system.

APPENDIX F

VERIFICATION OF THE HPCA USING LABORATORY TESTS

To evaluate the performance of the HPCA (High Performance Concrete Advisor) developed in this study, concrete mixes of 55 MPa compressive strength at 28 days were designed and tested in the laboratory. The data of concrete making ingredients used in the laboratory are shown in Table F.1.

TABLE F.1 Data of Concrete Making Ingredients

Ingredients	**Properties**	**Values**
Cement	Specific gravity	3.15
Silica Fume	Specific gravity	2.20
Fly Ash	Specific gravity	2.26
Coarse Aggregate	Maximum size (mm)	19
	Dry-rodded density (kg/m^3)	1554
	Specific gravity (SSD)	2.62
	Absorption capacity (%)	0.90
	Field moisture (%)	0.20
Fine Aggregate	Specific gravity (SSD)	2.60
	Absorption capacity (%)	1.20
	Field moisture (%)	0.10
Superplasticizer	Solid dosage at saturation point (%)	1.90
	Solid content (%)	40
	Specific gravity	1.21

Four different types of mixes were designed using three types of replacement of cement for the data of Table F.1. The mixes are coded according to their composition. NPC, SF, FA and SFFA concrete refer to normal Portland cement concrete, silica fume concrete, fly ash concrete and silica fume-fly ash concrete respectively. In silica fume concrete, 10% cement was replaced by silica fume. In fly ash concrete, 10% cement was replaced by fly ash. In silica fume-fly ash concrete, silica fume and fly ash both replaced 5% cement. All the replacements were made by weight basis.

The details of various mix proportions are listed in Tables F.2 to F.5. The mixtures were proportioned to have minimum slump of 200 mm and minimum air content of 1.5%. The mix design values are compared with those of expert in Table F.2, F.3, F.4 and F.5. The results show very good agreement among the mix design values of the expert and those of the HPCA.

TABLE F.2 Mix Design Comparison for NPC (Normal Portland Cement) Concrete

Item	**Expert**	**HPCA**
Water-Binder Ratio	0.35	0.35
Water (l/m^3)	191.22	191.54
Cement (kg/m^3)	530.00	530.02
Coarse Aggregate (kg/m^3)	999.00	993.00
Fine Aggregate (kg/m^3)	667.00	673.86
Superplasticizer (l/m^3)	10.51	10.95
Air Content (%)	1.50	1.50

TABLE F.3 Mix Design Comparison for SF (Silica Fume) Concrete

Item	Expert	HPCA
Water-Binder Ratio	0.35	0.35
Water (l/m^3)	190.42	191.34
Cement (kg/m^3)	477.00	477.01
Silica Fume (kg/m^3)	53.00	53.00
Coarse Aggregate (kg/m^3)	993.00	993.00
Fine Aggregate (kg/m^3)	654.00	655.18
Superplasticizer (l/m^3)	12.13	10.95
Air Content (%)	1.50	1.50

TABLE F.4 Mix Design Comparison for FA (Fly Ash) Concrete

Item	Expert	HPCA
Water-Binder Ratio	0.35	0.35
Water (l/m^3)	191.22	191.36
Cement (kg/m^3)	477.00	477.01
Fly Ash (kg/m^3)	53.00	53.00
Coarse Aggregate (kg/m^3)	997.00	993
Fine Aggregate (kg/m^3)	652.00	656.83
Superplasticizer (l/m^3)	11.25	10.95
Air Content (%)	1.50	1.50

TABLE F.5 Mix Design Comparison for SFFA (Silica Fume-Fly Ash) Concrete

Item	Expert	HPCA
Water-Binder Ratio	0.35	0.35
Water (l/m^3)	190.58	191.35
Cement (kg/m^3)	477.00	477.01
Silica Fume (kg/m^3)	26.50	26.50
Fly Ash (kg/m^3)	26.50	26.50
Coarse Aggregate (kg/m^3)	990.50	993
Fine Aggregate (kg/m^3)	662.50	656.00
Superplasticizer (l/m^3)	11.40	10.95
Air Content (%)	1.50	1.50

In order to evaluate the performance of the HPCA further, the designed mixes were prepared and tested in the laboratory. The details of the process of batching, mixing, sampling, moulding, demoulding, curing and test methods are available elsewhere (Safiuddin 1998). Samples of freshly mixed concrete were taken for slump test and air content test. It may be mentioned here that, due to the limitations of time and other resources, only twelve cylinders (100 mm x 200 mm size; three for each mix type) were cast for evaluation of compressive strength. The samples were water cured for 28 days at 20 ^{0}C.

The complete set of test results together with the designed values is presented in Table F.6. Each of the laboratory test result in Table F.6 is the average of three test values. The table shows that slump of all the mixes were above the minimum designed value of 200 mm. The slump values of the laboratory test suggest that the concrete can be transported long distance before placement. Higher slump values are also suitable for concreting in hot weather environment like that of Malaysia. Therefore, the workability of the designed mixes was quite satisfactory.

Table F.6 also shows that the air content of freshly mixed concrete was between 1.9 to 2.3% which is well above the minimum designed value (i.e., 1.5%). The values are also within the range suggested by expert for non-freezing environment like Malaysia, i.e. 1 to 3% (Aitcin 1998). Thus the air content of the freshly mixed high performance concrete was satisfactory. So, the performance of the HPCA in designing high performance concrete mixes in order to obtain properties of fresh concrete was considered to be satisfactory.

TABLE F.6 Comparison of Concrete Properties

Properties	**Mix Type**	**Designed Value**	**Laboratory Test Result**
(1) Slump (mm)	NPC	200	250
	SF	200	250
	FA	200	235
	SFFA	200	240
(2) Air content (%)	NPC	1.50	2.00
	SF	1.50	2.30
	FA	1.50	1.90
	SFFA	1.50	2.10
(3) 28-day compressive strength (MPa)	NPC	55.00	57.20
	SF	55.00	60.50
	FA	55.00	58.64
	SFFA	55.00	58.96

The comparison of compressive strength results is shown in Table F.6. It can be seen that the laboratory test results were well above the design values. No tested cylinder strength was less than 55 MPa (i.e., the design strength). Therefore, the design mixes are quite satisfactory with respect to 28-day compressive strength. On the other hand, laboratory test results were not much higher than the designed strength. The strengths obtained in the laboratory were higher but within 10% of the designed strength. The maximum difference in the designed compressive strength and the laboratory results was only 5.5 MPa. For economic reason, the maximum difference accepted by experts for concrete strength of 35 MPa and above is 10 MPa. Therefore, no adjustment in the designed mix was necessary. Thus the performance of the HPCA in designing high performance concrete mix in order to achieve a specified strength was considered to be satisfactory.

APPENDIX G

MIX DESIGN USING HPC-MIDEC AND HPCA

G.1 MIX DESIGN FOR 100 MPa, 80 MPa AND 60 MPa CONCRETES

To evaluate the performance of the HPCA (High Performance Concrete Advisor) as well as the Aitcin method of mix design used in this study, concrete mixes for compressive strength of 100 MPa, 80 MPa and 60 MPa were designed. The basic data of concrete making ingredients are shown in Table G.1.

TABLE G.1 Basic Data of Concrete Making Ingredients

Ingredients	Properties	Values
Cement	Specific gravity	3.14
Silica Fume	Content (%)	10
	Specific gravity	2.20
Coarse Aggregate	Maximum size (mm)	10
	Dry-rodded density (kg/m^3)	2480
	Shape	Average and Cubic
	Specific gravity (SSD)	2.70
	Absorption capacity (%)	0.80
	Field moisture (%)	0.10
Fine Aggregate	Specific gravity (SSD)	2.65
	Absorption capacity (%)	1.20
	Field moisture (%)	1.00
Superplasticizer	Solid dosage at saturation point (%)	1.00
	Solid content (%)	40
	Specific gravity	1.21
Air Content	Content (%)	1.50

The same concrete mixes were also designed using another expert system named HPC-MiDeC developed using UKM Mix Design method (Jamil 2003). The mix design values are compared in Table G.2, G.3 and G.4.

TABLE G.2 Mix Design Comparison for 100 MPa Concrete

Item	HPC-MiDeC	HPCA
Water-Binder Ratio	0.30	0.27
Water (l/m^3)	133.36	141.23
Cement (kg/m^3)	490.72	464.38
Silica Fume (kg/m^3)	61.98	51.60
Coarse Aggregate (kg/m^3)	1086.85	1067.47
Fine Aggregate (kg/m^3)	629.64	720.90
Superplasticizer (l/m^3)	18.92	10.66
Air Content (%)	1.50	1.50

TABLE G.3 Mix Design Comparison for 80 MPa Concrete

Item	HPC-MiDeC	HPCA
Water-Binder Ratio	0.36	0.30
Water (l/m^3)	153.37	142.07
Cement (kg/m^3)	446.04	419.53
Silica Fume (kg/m^3)	63.39	46.61
Coarse Aggregate (kg/m^3)	1084.05	1067.47
Fine Aggregate (kg/m^3)	655.40	765.42
Superplasticizer (l/m^3)	10.18	9.63
Air Content (%)	1.50	1.50

TABLE G.4 Mix Design Comparison for 60 MPa Concrete

Item	HPC-MiDeC	HPCA
Water-Binder Ratio	0.40	0.34
Water (l/m^3)	173.08	142.93
Cement (kg/m^3)	401.89	373.07
Silica Fume (kg/m^3)	64.16	41.45
Coarse Aggregate (kg/m^3)	1052.27	1067.47
Fine Aggregate (kg/m^3)	691.99	811.53
Superplasticizer (l/m^3)	5.47	8.56
Air Content (%)	1.50	1.50

It can be observed from Table G.2 that, for 100 MPa concrete, the HPC-MiDeC suggests 490.72 kg/m^3 of cement whereas the HPCA suggests 464.38 kg/m^3 of cement. The suggested values for silica fume are 61.98 kg/m^3 and 51.60 kg/m^3 by HPC-MiDeC and HPCA, respectively. As it is well known that the cost of silica fume and cement are more than any other ingredients of concrete, the composition suggested by the HPCA is more economical than that of the HPC-MiDeC. The similar results are also observed for 80 MPa and 60 MPa concretes (Table G.3 and Table G.4). Therefore, the use of the HPCA is recommended for designing more economical mixes of high performance concrete. It can also be observed from Tables G.2, G.3 and G.4 that the silica fume content suggested by HPC-MiDeC increases as the strength of concrete decreases which is very unusual. The problem may be inherent in the UKM Mix Design method based on which HPC-MiDeC was developed. Therefore, it is suggested that the UKM Mix Design method should be further reviewed.

APPENDIX H

LIST OF PUBLISHED PAPERS FROM THIS RESEARCH

(1) **Islam, M.N.**, Al-Mattarneh, H., Zain, M.F.M. & Basri, H.B. 2002a. Towards an expert system for high performance concrete mix design. *Proceedings of the World Conference on Concrete Materials and Structures (WCCMS), Shah Alam, 14-16 May*, pp. 301-309.

(2) **Islam, M.N.**, Al-Mattarneh, H., Zain, M.F.M. & Basri, H.B. 2002b. Expert system and concrete mix design: a review. *Proceedings of the 6th International Conference on Concrete Technology for Developing Countries (6ICCT)*, Amman, 21-24 October, pp. 605-612.

(3) **Islam, M.N.**, Zain, M.F.M. & Basri, H.B. 2002. High performance concrete mix design using intelligent system. *Proceedings of the Malaysian Science and Technology Congress, Symposium A: Physical Science, Engineering and Technology*, Johor Bahru, 19-21 September, pp. 864-871.

(4) **Islam, M.N.**, Zain, M.F.M. & Basri, H.B. 2003a. Development of an expert system for high performance concrete mix design. *Proceedings of the International Conference on Robotics, Vision, Information and Signal Processing (ROVISP)*, Penang, 22-24 January, pp. 448-451.

(5) **Islam, M.N.**, Zain, M.F.M. & Basri, H.B. 2003b. A knowledge based system for durable high performance concrete exposed to carbonation. *Proceedings of the International Conference on Advances in Strategic Technologies (ICAST)*, Kuala Lumpur, 12-14 August, pp. 1173-1178.

(6) **Islam, M.N.**, Zain, M.F.M. & Basri, H.B. 2003c. Development of a knowledge based system for high performance concrete mix design. *Proceedings of the International Conference on Advances in Concrete and Structures (ICACS)*, China, 17-19 September (accepted).

(7) **Islam, M.N.**, Zain, M.F.M. & Basri, H.B. 2003d. 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, 13-15 October, pp. 316-323.

(8) **Islam, M.N.**, Zain, M.F.M. & Basri, H.B. 2003e. Development of an expert system for making corrosion-resistant reinforced and prestressed concrete. *Journal of the Institution of Engineers Malaysia* **64**(3): 20-26.

(9) **Islam, M.N.**, Zain, M.F.M., & Basri, H.B. 2004a. A prototype expert system for making high performance concrete in seawater. *Proceedings of the International Conference on Planning, Design and Construction of*

Hardened and Protective Facilities (HARDFAC), Kuala Lumpur, Malaysia, 14-16 April, pp. 116-126.

(10) **Islam, M.N.**, Zain, M.F.M. & Basri, H.B. 2004b. An intelligent system for making abrasion-resistant high performance concrete. *Proceedings of the Eighth International Conference On Concrete Engineering and Technology (CONCET)*, Kuala Lumpur, Malaysia, 19-21 April, pp. 196-201.

(11) Zain, M.F.M., **Islam, M.N.** & Basri, H.B. 2003. Development of a knowledge based system for durable high performance concrete exposed to acidic environment. *Proceedings of the International Conference on Advances in Strategic Technologies (ICAST)*, Kuala Lumpur, 12-14 August, pp. 1167-1172.

(12) Zain, M.F.M., **Islam, M.N.** & Basri, H.B. 2004. Development of an expert system for making durable high performance concrete by preventing harmful chemical reactions of aggregates. *Proceedings of the Eighth International Conference On Concrete Engineering and Technology (CONCET)*, Kuala Lumpur, Malaysia, 19-21 April, pp. 190-195.

Several other papers are under reviewing process for possible publication in national and international journals.