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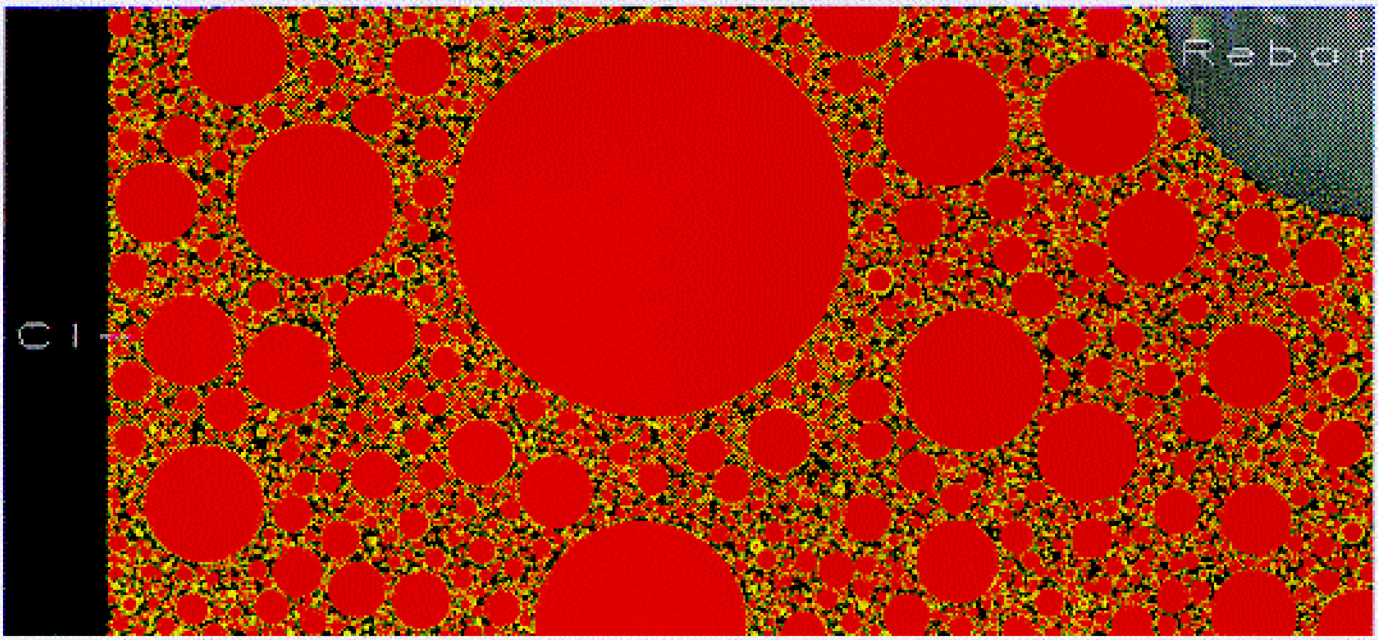

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United States Department of Commerce
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National Institute of Standards and Technology
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COMPUTERIZED INTEGRATED KNOWLEDGE BASE SYSTEM FOR HIGH-PERFORMANCE CONCRETE: AN OVERVIEW

James R. Clifton, Dale P. Bentz, and Lawrence J. Kaetzel

ABSTRACT

A Computerized Integrated Knowledge Based System (CIKS) is a computerized intelligent system of integrated knowledge base systems providing the knowledge for solving problems of a range of complexities. Knowledge bases which can be incorporated into a CIKS include databases, mathematical and simulation models, AI systems, guides, handbooks, and standards and codes. Along with these knowledge bases, a comprehensive CIKS will include ways to obtain knowledge from distributed knowledge sources using Remote Database Access (RDA) and Agent technologies.

The development of a CIKS involves the following major steps: (1) defining the purpose of the system and who are the intended users; (2) identifying and developing the architecture for the system; (3) developing an information model; (4) developing a prototype system; and (5) establishing methods for the maintenance of the system. The reliability of a CIKS will depend on the quality of the knowledge it contains. The needs for the establishment of a validation process for knowledge bases and for the complete CIKS system are discussed.

Four examples of the application of CIKS technology applicable to high-performance concrete (HPC) are described to illustrate the diversity of the technology. Also, an operational, prototype CIKS which predicts the service life of reinforced concrete, which is susceptible to corrosion induced by an external source of chlorides, is presented.

KEYWORDS: Building technology; concrete, databases; expert systems; high-performance concrete; intelligent agents; knowledge bases; models; neural networks; remote database access.

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1 INTRODUCTION

Advances in the computer representation and electronic exchange of knowledge is facilitating the conversion of concrete knowledge from printed media to electronic media. Data bases, knowledge based (high-level reasoning or expert) systems, mathematical models, and guides such as the ACI Manual of Concrete Practice have been placed on computer diskettes and CD-ROM discs. Simulation models are now downloadable from Internet homepages [1]. Civil engineering World Wide Web (WWW) sites are now located on the Internet [2]. While most of these WWW sites describe the projects of various organizations or commercial products, in the future they will contain more factual materials information, e.g., in databases. These developments are impressive and are forming the basis for decision making Computerized Integrated Knowledge Base Systems (CIKS) for high-performance concrete (HPC), which eventually could develop into a National CIKS Network.

The knowledge base of a CIKS can range from a set of databases of commercial construction materials and their properties, with intelligent search capabilities, to a system consisting of multi-forms of distributed knowledge bases such as is being developed for HPC by NIST. This system is intended to demonstrate the integration of coalesced knowledge in the form of expert systems, mathematical models, databases, guidelines, and standards. If fully developed, by partnership with the concrete community, the system would be able to provide information, guidance, and recommendations on the selection, design, processing, and quality control testing and inspection of HPC. The process would begin with the design of a structure and covering the in-between processes leading to the commissioning of a structure. Then, as the technology on HPC advances, the system could be further developed to cover the complete life-cycle of HPC in structures and would have the potential to become the most authoritative information and problem solver for HPC.

This report is intended to present an overview of the features, components, development, and applications of CIKS. Also, a prototype CIKS developed for predicting the service life of reinforced concrete subject to corrosion induced by external chloride ions is presented. While a CIKS for HPC is the focus of this report, the overview is applicable to other High-Performance Construction Materials and Systems (HPCMS). The HPC research at NIST is making a significant contribution to the CIKS and products from the research are noted.

2. PRINCIPLES OF CIKS

2.1. What is a CIKS?

For the purpose of this report, a CIKS is defined as a computerized intelligent system of integrated knowledge base systems providing the knowledge needed for solving problems of a wide range of complexities. A CIKS can be more than an Artificial Intelligence (AI) knowledge system or an expert system that solves problems using an internal knowledge base, which is most often a combination of heuristic and empirical knowledge. A CIKS can be developed to solve problems that necessitate the use of a wide spectrum of knowledge ranging from heuristics to fundamental knowledge and factual data that is contained in either local or globally distributed knowledge bases. The term "knowledge base" is used herein to denote any entity that contains knowledge, including databases, mathematical and simulation models, expert systems, guides, and standards and codes. Some typical knowledge bases are listed in Table 1 with examples of possible contents. Integration means that knowledge and data flows seamlessly (automatically) across interfaces, i.e., from one knowledge base to another and through a Graphical User Interface to the user. In a completely integrated system, the system obtains all the necessary information on the specific problem (application), during an interactive session with the user, and the recommendations or conclusions are seamlessly presented to the user.

2.2 Desired Features of a CIKS.

Some of the desired features of a CIKS for HPC are enumerated:

(1) Fully integrated architecture which provides seamless (automatic) transfer across interfaces of knowledge systems.
(2) Open system, in which execution is independent of computer platform and software system.
(3) Interactive, with a Graphical User Interface (GUI)
(4) Capable of knowledge and data acquisition from distributed knowledge systems
(5) Easily assimilates new knowledge
(6) The integrity of the knowledge is validated

3. APPROACH IN DEVELOPING CIKS.

The development of a CIKS involve several major steps as outlined in the following.

(1). Purpose. Defining the purpose of the system, identifying what problems will be addressed, and determining who are the intended users are the first major steps in developing a CIKS . Numerous knowledge based systems have never become operational, or if operational, little used, because of the lack of defining the purpose of the system or the knowledge needs of potential users. It is crucial that the user groups be identified during the early stages of development.

(2). Architecture. Identifying or developing an architecture for the system and the media for distribution is becoming an easier task with the rapid advancements in information technology. For example, the architecture of Distributed Artificial Intelligence (DAI) knowledge systems is rapidly evolving [3] which should facilitate transforming the concept of CIKS with distributed knowledge sources into reality. An architecture for a CIKS to facilitate mixture proportioning, operating over the Internet, is illustrated in Figure 1. This architecture is used in the prototype CIKS discussed in Section 6 of this report. A conceptual design which shows the flow of information and the decision making path in a CIKS for designing HPC, based on service life requirements, is shown in Figure 2. In principle, the knowledge bases for the CIKS could be distributed on computer diskettes and CD-ROMS discs . However, we envision that when the various CIKS's for HPC are developed they will be made accessible through the Internet.

(3). Information Model. Development of an information model, requires identification of what knowledge will be included and how it will be presented, exchanged, and used or interpreted. This has been a major area of research in the field of information engineering, especially with regard to the application of CASE (Computer-Aided Software Engineering) [4] software. The knowledge of the CIKS will likely exist in data bases, computer models, standards for test methods, and AI systems. The knowledge in a knowledge base should be formatted and represented according to available information technology standards.

(4). Prototype Development. Develop a prototype system which is tested by potential users. Make recommended changes and have the system re-tested, which could involve several cycles before an operational system is produced.

(5). System Maintenance. Establish methods for the maintenance of the system. Producing an operational CIKS is an iterative process and a continuing effort during the life of the system. If new knowledge is not periodically incorporated into a CIKS, it could rapidly become obsolete.

4. COMPONENTS

Knowledge bases and other system components which are likely to be included in CIKS developed in the near future for HPC are described in this section. Also, some barriers to their use in an operational CIKS are discussed.

4.1 Agents.

Agents are likely to become necessary components of systems involving a large number of distributed knowledge bases. A limited number of distributed databases, as is the present case for HPC, may be effectively queried using Remote Data Access (RDA) technology which is described later. The development of agent technology is an area of very active research by AI researchers, commercial database developers, and by Internet software developers. Palsey and Roddis have discussed the use of agents in the process of designing steel buildings [5].

4.1.1 General Description In general terms, intelligent agents are software programs that carry out some set of operations for a user or another program with some level of independence or autonomy, while attempting to fulfill the user's goals or desires [6]. Another, but more precisely stated, definition is "An autonomous agent is a system situated in and part of an environment that senses that environment and acts on it, over time, in pursuit of its own agenda and so as to effect what it senses in the future" [7]. According to this definition, ordinary programs are not agents. Some attempt has been

Table 1. Typical Knowledge Bases and Examples of Contents

Form of Knowledge Base	Examples of Possible Contents
Databases	Data for aggregates, concrete constituents, mix proportions, concrete properties
Models	Simulation models of transport properties, service life models, mix design models
Expert systems	Durability of HPC, processing of HPC, quality control, diagnostics of distresses
Neural systems	Prediction of properties of HPC, analysis of images, diagnostics
Videos	Tutorials on testing, processing, inspection
Guidelines	Curing of HPC, strength testing
Test methods	Tests for transport properties, mechanical properties, durability, quality control
Handbooks	Properties and compositions of HPC constituents
Books and reports	Electronic monograph on cement and concrete modeling, reports on HPC research

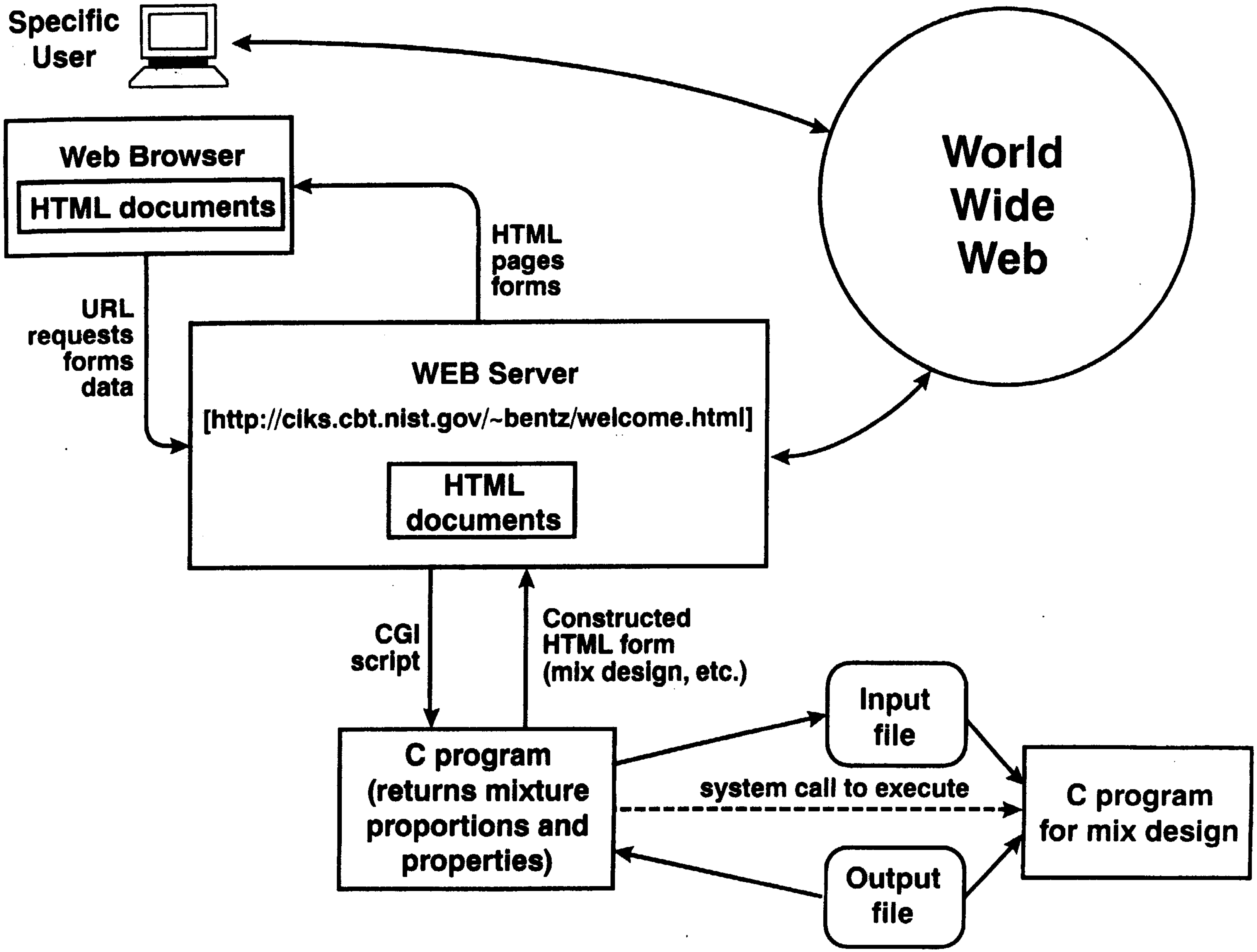


Figure 1. Architecture of CIKS operating over the Internet.

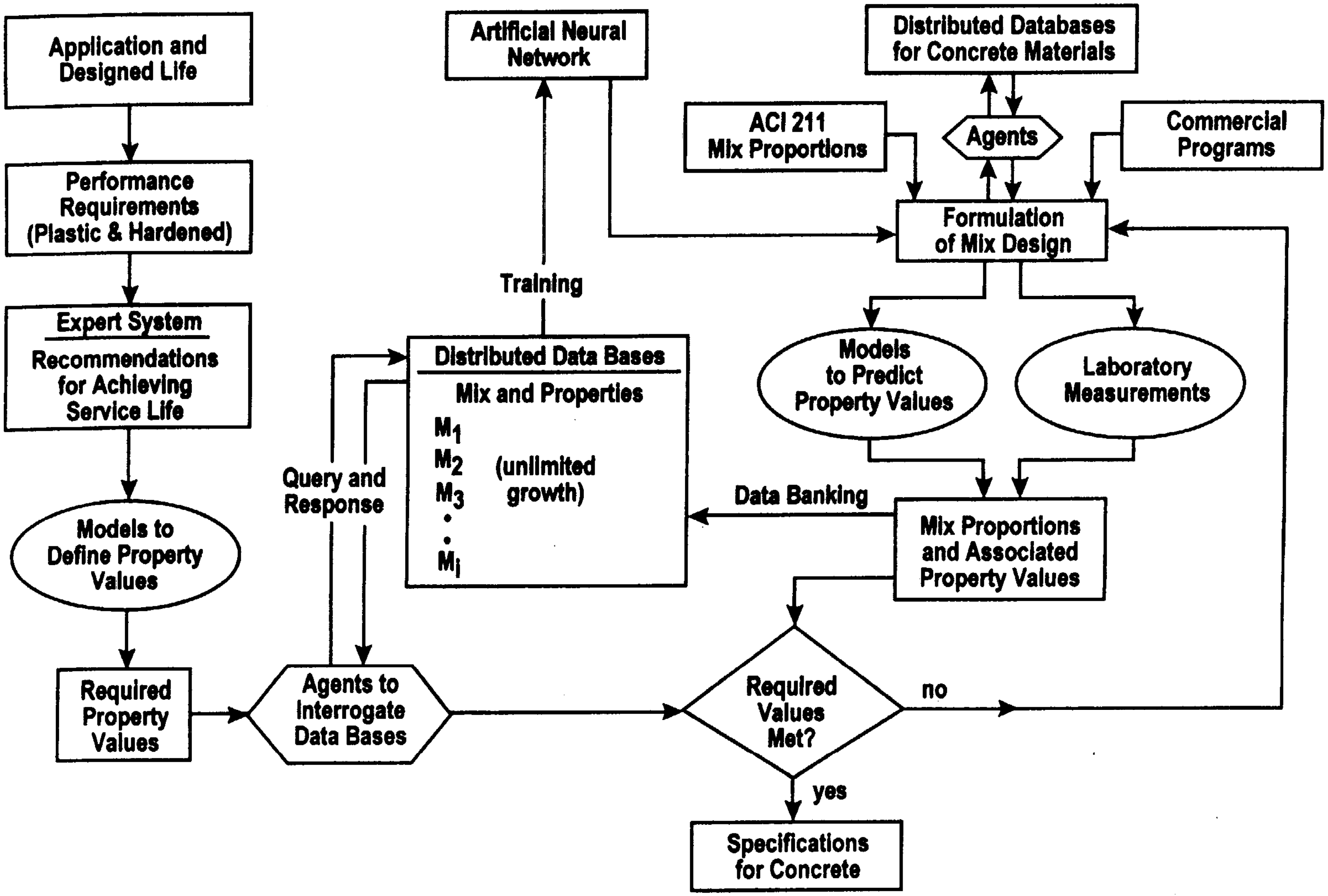


Figure 2. Conceptual CIKS for designing mixes for HPC, based on service life requirements.

made to classify some agents as being intelligent but essentially all agents exhibit "intelligence", only differing in the level of intelligence [8].

4.1.2 Properties of Agents. A preliminary set of properties of agents is given in Table 2 which provides an insight to their capabilities [6].

A taxonomy of agent functions based on a review of the status of agent technology is as follows [3]:

- Information filtering. Agents can filter incoming electronic mail and news. Depending on their complexity, they can examine structured aspects of text, looking for predictable fields, and then search for matches with the user's preferences. In their more complex form, these agents can use statistical word matching, natural language analysis, and AI knowledge-based techniques for dealing with unstructured text and other data types.

- Information search and retrieval. These agents go beyond filtering agents in that they can navigate networks to find the information which needs searching. In such cases, a search of information sources (knowledge bases) is necessary. They make the concept of using numerous distributed knowledge bases in a CIKS possible.

- Scheduling. Agents can function as active schedulers, presenting their masters with (either a person or a superior agent) information about availability for meetings or other events. Such agents could be subagents in a multi-agent CIKS.

- Workflow. Agents can be assigned the responsibility of automatically taking appropriate action on routine work tasks, e.g., agent in a parallel processor system used by a CIKS.

- Tutors. Agents can be incorporated into software to determine how a user is working and then make suggestions to improve productivity. Such agents can be very simple hint givers that correct obvious mistakes, or they can be very sophisticated teaching tools, e.g., they can be superior to training manuals. Conceivably, such an agent could be used to assist a user in the operation of a CIKS.

- Guides. Guides can help users to navigate through content in multimedia or multi-knowledge base environments, e.g., to locate appropriate models in a large multi-dimensional set of knowledge bases.

4.1.3 Specification for Agent-Communication Language. A specification for agent-communication language is under development based on Knowledge Query and Manipulation Language (KQML). KQML is a language and protocol for exchanging information and knowledge [9]. The application of KQML to agent technology provides both a message format and a protocol for run-time knowledge sharing between agents.

Table 2. Properties of Agents

Property	Meaning
reactive	responds in a timely fashion to changes in the environment
autonomous	exercises control over its own actions
goal-oriented	does not simply act in response to the environment
continuous	is a continuous running process
communicative	communicates with other agents, possibly with people
learning	changes it behavior based on its previous experience
mobile	able to transport from one machine to another
flexible	actions are not scripted
character	believable personality and emotional state

KQML would also support development of a security architecture for agent communication language.

4.2 Remote Database Access.

Remote Database Access (RDA) is an ISO standard that represents a generic model for accessing data from distributed SQL compliant relational databases [10]. It also has been adopted as an American National Standard by ANSI and as a Federal Information Processing Standard (FIPS) for the U.S. Federal Government. The standards consists of two parts:

Part 1	Generic RDA	ANSI/ISO/IEC 9579-1:1993
Part 2	SQL Specialization	ANSI/ISO/IEC 9579-2:1993

The standards provide protocols for establishing remote connections between a database client and a database server. The client uses an application program while the server is interfacing to a process that controls data transfers to and from databases. The purpose of RDA is to permit the interconnection of database applications across heterogeneous environments. It promotes the establishment of an open system. The function of RDA in a client-server system linked through the Internet is illustrated in Figure 3.

RDA is not an agent since the databases must be previously identified, e.g., in a database client and a database server. However, an agent could be used to identify appropriate databases, as shown in Figure 2, and a RDA interface established.

4.3 AI Knowledge Base Systems

4.3.1 Description. AI Knowledge Base Systems (KBS), also known as expert systems, attempt to capture the knowledge and reasoning of human experts. They essentially consist of two elements, knowledge bases and inference (logic) systems. The knowledge base contains concepts and relationships between the concepts, about which the system needs to know. The inference system , often in the form of rules, simulate the way that an expert(s) makes inferences about the subject. The principles and applications of KBS to concrete were discussed by Clifton and Oltikar [11] and Clifton and Kaetzel [12]. The state-of-the-art of the expert system for construction materials was recently reviewed by Kaetzel and Clifton [13].

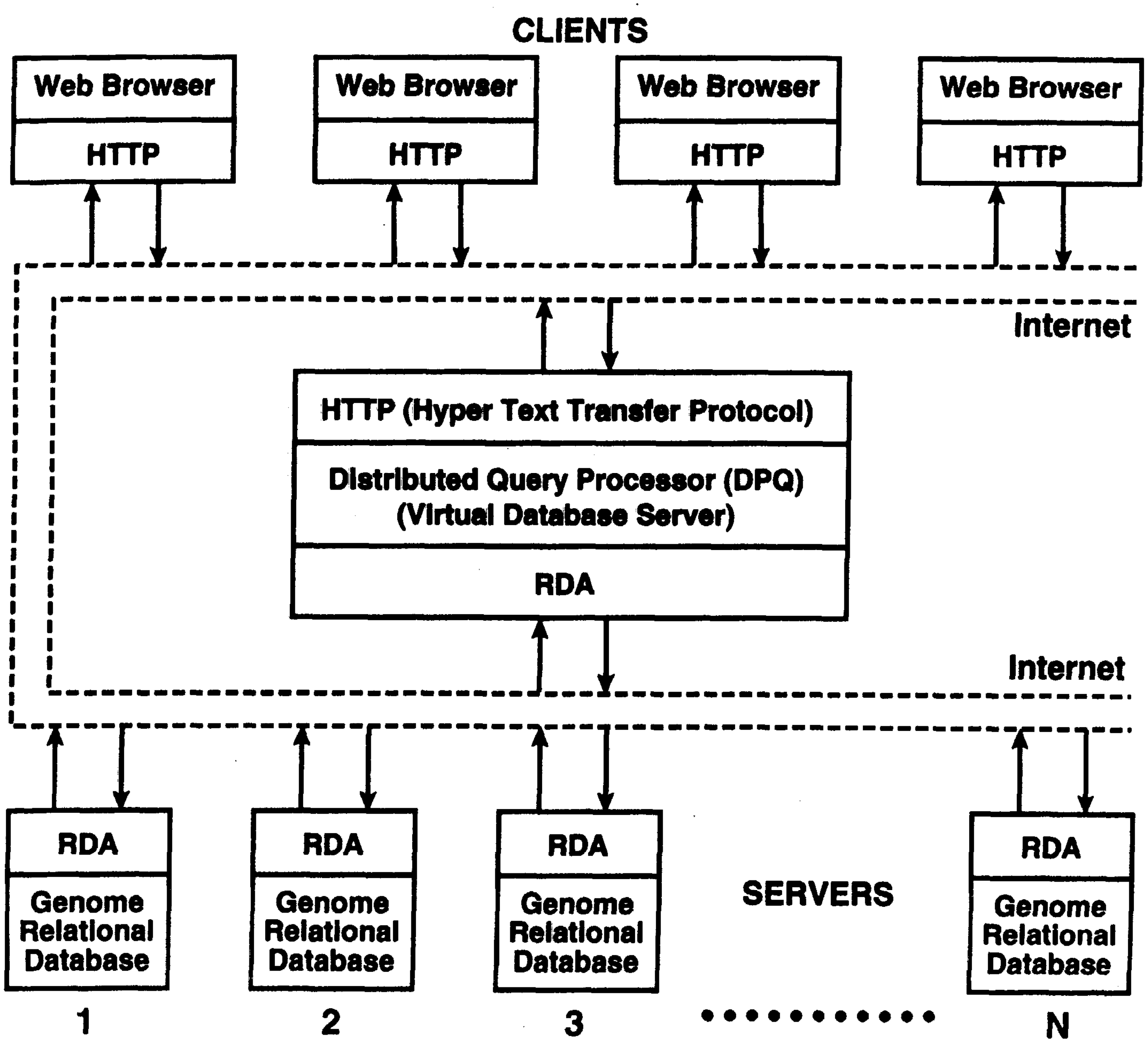
4.3.2 Application Domains. KBS are applicable to certain types of problems which potentially could exist in any HPC. Some of the major categories are discussed in the following [3].

- Diagnosis: Diagnostic systems were among the first KBS developed. An example is HWYCON [14] which assists highway inspectors in identifying the causes of distresses in highway concrete pavements and bridges. Other applications include interpreting the information from sensors to produce estimates of impending or existing failures in mechanical equipment and provide instructions for making repairs.

- Selection: Selection systems can form a basis for selecting cost effective or more durable HPC for specific applications. Also, they can provide information on the proper use of construction tools and equipment.

- Scheduling/processing planning: Scheduling systems may have application in strategic planning or simulation in construction. The KBS is likely to contain a model of the construction process.

- Monitoring/control system KBS that continuously monitor and, in some cases, control complex processes usually can effectively handle a large amounts of input data and respond to routine situations. For example, systems could be used in monitoring the structural condition of structures containing HPC.



[illegible] using Remote Database Access (RDA) [10]

- Information filtering/retrieval systems. KBS can be developed to serve as an agent to search for information, either for filtering (e.g., electronic mail) or for examining and retrieving information.

- Computer-aided design. Computer-aided design systems, based on KBS technology, have enabled engineers and architects to develop customized models of plants, factories, and any other engineered system or structure.

4.3.3. Needed KBS for HPC. Needed KBS for HPC have been described in a Civil Engineering Research Foundation (CERF) technical report [15] and are as follows:

- Aid in the preliminary materials selection and proportioning in designing HPC.
- Provide guidance on the curing of HPC.
- Provide guidance on the selection and use of methods for assessing condition of HPC in a structure.
- Provide guidance in selection of materials and procedures for repairing damaged or deteriorated concrete.
- Provide guidance for making service life predictions of HPC.

Some other opportunities for KBS include the following:

- Identifying QC problems and solutions for fresh HPC.
- Interpreting non-destructive tests of fresh and mature HPC.
- Resolving problems with processing plastic HPC.

4.3.3 Standards for KBS. Historically, the KBS field has had few standards for development or inter-operation of KBS. At present, no commonly accepted standard appears to exist for KBS [3]. An example of a KBS-related standards attempt is KQML (Knowledge Query and Manipulation Language), which is part of the ARPA Knowledge Sharing Effort program. It can be used as a high-level communication interface for KBS, facilitating communications between KBS and other programs that understand each other's content. However, if the entities have different knowledge representations, such as data formats, further tools are necessary to permit inter-operation. Such a tool is the Knowledge Interchange Format (KIF), which is a computer language for the exchange of knowledge between disparate programs [16]. Outside of a single relatively small KBS vendor, the KBS-industry community in the U.S. has made no serious efforts toward establishing standards. In addition to standards for development and inter-operation of KBS's, a standard practice for evaluating the reliability of KBS is needed.

4.4 Artificial Neural Networks

In Figure 2, an artificial neural network is shown for assisting in designing concrete mixes, which is trained using the data from the distributed database on concrete mixes.

As the name implies, neural networks are considered to model the functioning of neurons in the human brain [17]. At the best, they are simplistic models of human intelligence and thus other names have been introduced for neural networks including adaptive systems, parallel distributed processing models, and self-organizing systems.

A brief description of neural networks follows. For more detailed information many books give an overview such as references 17 and 18. Neural networks use networks of simple but highly interconnected neurons with weighted connectors which process inputs to give desired outputs. The connected elements can consist of either single or multiple layers. A 3-layer network is presented in Figure 4. Similar to regression equations, the elements have "weighed" connections, which are adjustable. Several models have been developed by which the weighed connections are adjusted by training with actual data. In general neural networks appear to yield better statistical fits than regression analysis, while being capable of working with incomplete or unreliable data. Neural networks excel at relatively low-level, data-rich tasks such as image processing [3]. Neural networks appear to have great potential for determining the effects of different variables on the performance of concrete. However, they are basically empirical and do not provide information on the reason for the observed effects. While commercial shells are available for developing neural networks, applicable standards have not been established.

Some applications of neural networks to concrete have included the prediction of thickening times of oil field cements [19], prediction of shear strength of concrete beams [20], evaluation of deteriorating concrete structures [21], and the interpretation of impact echo test results [22]. At present the effectiveness of a neural network in designing concrete mixes (see Figure 2) needs further study. With the large body of data available on mix design the application of neural networks deserves additional exploration

4.5 Databases

4.5.1 Database Applications. Databases will be an important component of CIKS for HPC as well as for other HPCMS. Examples of information which may be contained in databases for HPC include the following:

- Composition and physical properties of concrete making materials
- Properties of HPC such as transport properties, mechanical properties, fire performance, and durability vs. mix design
- Rheological properties and consolidation characteristics of HPC mixtures
- Performance data from research, laboratory and field studies
- Pictures of distresses in concrete materials and structures
- Representational images such as graphs of relationships and the results of models
- Standards and guidelines
- Bibliographic information

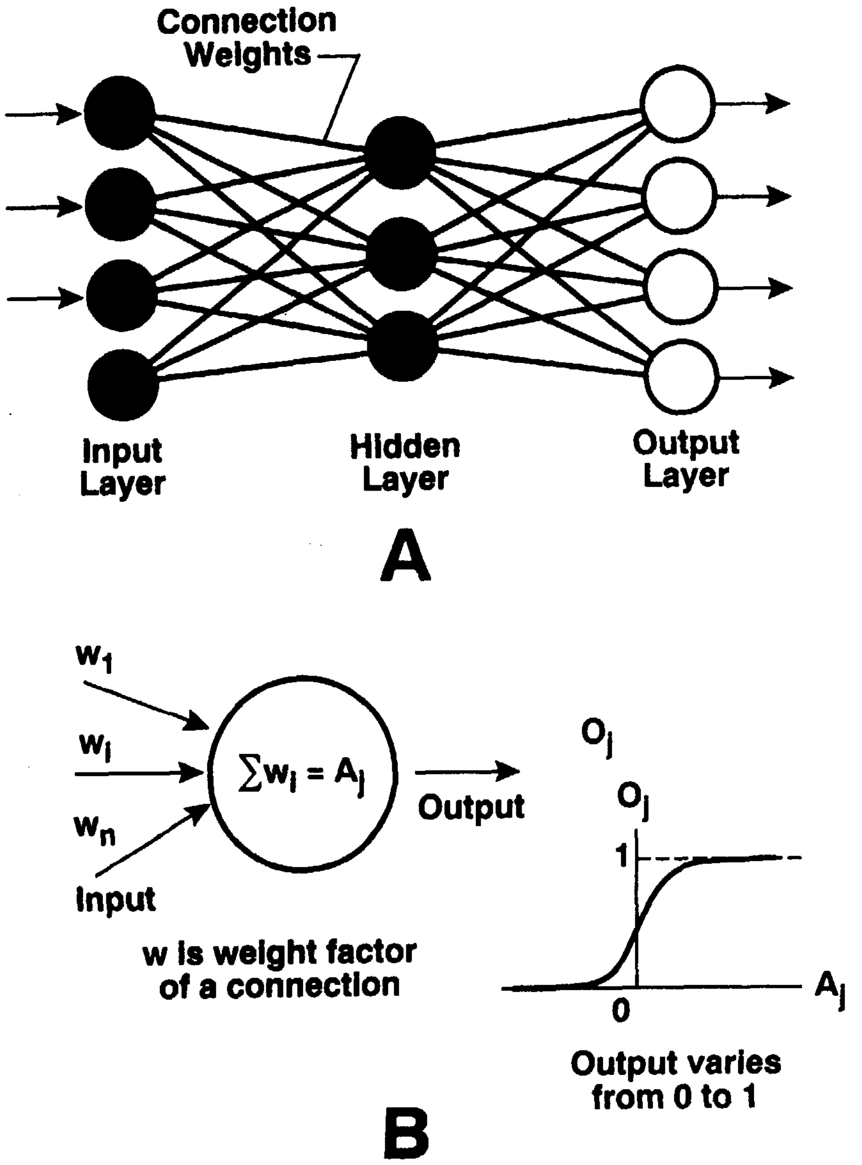


Figure 4. Artificial neural network. A. A 3-layer neural network with connections. B. Connections weights W_n, and output O_j.

Westbrook, Kaufman, and Cverna recently reviewed [23] the state-of-the-art of electronic access to numerical scientific and engineering databases. Several types of applications were discussed: fundamental research, material selection, component design, process selection and control, material identification and equivalency, expert systems, and education.

4.5.2 Database Development. Approaches for developing databases are described in many publications and, therefore, only some of the major aspects are covered herein. One of the many excellent sources of information on database technology is that by Date [24]. Also, the process of developing scientific and engineering databases in science and engineering and their application has been described by Rumble and Smith [25]. According to Rumble [26], two of the major aspects of the database development process are the development of a data dictionary and the database schema [27]:

> *Data Dictionary.* A data dictionary is essentially a guide for the information in a database and has features similar to those found in a language dictionary. In the data dictionary, one can find a description, the origin, and the usage of each specific piece of data presented in the database. It also provides additional information describing the relationship of a given piece of data to all other pieces of data including the format that best fits the data, such as numeric, alphanumeric, data, or customized. The data dictionary is a framework on which the database is built.
>
> *Database Schema.* A schema is a perspective, a way of seeing the information in a database. Three widely accepted schema are called conceptual, physical, and external or subschema. The conceptual schema is the complete, logical view of the entire datebase including the data dictionary along with the data existence requirements and constraints. The physical schema is basically the viewpoint of the computer's operating system and includes descriptions of database file characteristics. The external or subschema is the user's, and often a program's view of the database.

4.5.3 Standards for Databases, Formats, and Quality of Data. An important aspect of database technology which needs to be considered in developing databases for CIKS is the standardization of formats and the quality and reliability of the data. ASTM Committee E49 has pioneered the development of material database formats and guidelines. The committee's goal is to promote and develop standard classifications, guides, practices, and terminology for building, processing, and exchanging information among computerized material and chemical property databases. Database formats for materials used in construction covered by ASTM E49 or other ASTM committees include metals, ceramics, composites, concrete, fibers and polymers [28]. Standards developed by Committee E49 applicable to databases of HPCMS are listed in Table 3. Knowledge of the quality of data values will often be critical to the use of a database

Table 3. Standards Pertinent to HPCMS Developed by ASTM Committee E-49

DESIGNATION	TITLE
E 1308	Identification of Polymers (Excludes Thermoset Elastomers) in Computerized Material Property Databases
E 1313	Development of Standard Data Records for Computerization of Material Property Data
E 1314	Structuring Terminological Records Relating to Computerized Test Reporting and Materials Designation Formats
E 1338	Identification of Metals and Alloys in Computerized Material Property Databases
E 1339	Identification of Aluminum Alloys in Parts in Computerized Material Property Databases
E 1443	Terminology Relating to Building and Accessing Material and Chemical Databases
E 1484	Formatting and Use of Material and Chemical Property and Database Quality Indicators
E 1485	Development of Material and Chemical Property Database Descriptions

and in the database development some form of quality indicators should be included. According to ASTM E 1484 [29], the following quality indicators are recommended.

- *Source of data.* Indication of the type of publication or document from which the data was taken.

- *Statistical basis of data.* Provides a measure of the degree to which data can be compared to other data.

- *Material development/production status.* Indicates if material is being commercially produced, is experimental, or no longer in production.

- *Validation status.* Indicates if the data were generated by a standard test method, or the data were validated by a recognized and competent method, or if the data was not validated.

- *Evaluation status.* Indicates if the data were evaluated by an expert value or individual to determine reasonableness and fit to theory or expectations.

- *Certification status.* Indicates if the tests were certified by an expert body or an individual to determine their applicability or appropriateness to a specific application.

- *Completeness of materials information.* Indicates the completeness of information relative to description of its composition and properties, condition, and processing.

- *Completeness of procedure description.* Indicates whether the data was obtained from a standard test procedure, taken from service experience, or the test procedures were not documented.

- *Database support.* Indicates the level of support and maintenance for the database.

Field values for the indicators given in Table 1 of ASTM E 1482 . For example, the field values for the "Source of data" are:

U - Unpublished report
J - Journal publication
H - Handbook publication
G - Government report
P - Producer brochure
S - Source unknown

In another scheme of data quality [23] three classifications are used: (1) Limited Use Data; (2) Qualified Data; and (3) Highly Qualified Data (Table 4). In applying the criteria to existing databases, it was found that most databases did not even meet the criterion for "limited use." The topics of data quality and database reliability are further discussed by Kaufman [30] and Barrett [31].

Building on the work of ASTM E 49, ACI Committee 126 (Database Formats for Concrete Materials Properties) is developing formats to be used in reporting and storing data on the composition and properties of cements, aggregates, chemical admixtures, mineral admixtures, information on the processing of concrete, and data on the properties and performance of concrete. The guide for chemical admixtures has been published. Formats are being developed for concrete materials property data with their relationship represented in Table 5 [26]. The guide consists of the following four data segments representing categories of information necessary for the identification of a chemical admixture and for recording its properties and performance in concrete:

- Constituent identification
- Chemical and physical characteristics
- Manufacture recommendations
- Admixtures performance in concrete

Table 4 Suggested Data Quality Standards [23].

Limited Use Data

- Data are traceable to an individual, organization, or reference.
- After an independent review, an identifiable authority approved the digitized version for inclusion in the database.
- Basis of data is identified.
  a. experimental measurements
  b. derived data
  c. estimated data
- Type of data is indicated
  a. original point values
  b. analyzed data
    1. standard fit - specify fit and data
    2. fit unknown

Qualified Data

- Number of measurements and data sets stated.
- Nominal confidence limited estimated.
- Traceable materials specification assures reproducibility.
- Testing methods are specified and conform to a standard
- Data are traceable to a testing/data - generating organization or individual.

Highly Qualified Data

- High confidence limits determined (i.e., 0.99, 0.95, n).
- Perform minimum number of individual measurements.
  a. from minimum number of sample lots
  b. from multiple suppliers (if appropriate)
- Data determined for each variable that significantly affects property
- Independent testing performed (other than from the producer and preferably by several leading laboratories
- A second, independent evaluation (evaluator identified)
- Producer(s) identified

TABLE 5. DATA ELEMENTS FOR THE DEFINITION OF CHEMICAL ADMIXTURES FOR CONCRETE [26]

Constituent Designation Data Segment			
Number[a]	Name	Type[b]	Format
3001.xx	Constituent Class	Essential	Alphanumeric String
3002.xx	Constituent Common name	Essential	Alphanumeric String
3003.xx	Constituent Producer Name	Essential	Alphanumeric String
3004.xx	Constituent Producer Plant Location	Essential	Alphanumeric String
3005.xx	Constituent Producer's Identification Number	Essential	Alphanumeric String
3006.xx	Constituent Standards Organization	Desirable	Alphanumeric String
3007.xx	Constituent Specification Number	Desirable	Alphanumeric String
3008.xx	Constituent Specification Version	Desirable	Alphanumeric String
3009.xx	Constituent Specification Designation	Desirable	Alphanumeric String
3010.xx	Constituent Notes	Desirable	Alphanumeric String

a) Data Element numbers are a functional part of the guide
b) All data elements are considered desirable. Reporting of essential data elements is strongly recommended

The data elements for the definition of chemical admixtures are presented in Table 6 and are typical of those for the other data segments as well as those for other concrete materials property data sets.

4.5.4. Database Languages. In recognition of the need for standardization, a standard database language "Structural Query Language" (SQL) has been promulgated. There are two versions which are identical except for the introductory portion and references to other standards. They are available from ANSI as:

- ISO/IEC 9075:1992, "Information Technology-Database Languages-SQL"
- ANSI X3.135-1992, "Database Language SQL."

The ANSI standard has been adopted [32] as the U.S. Federal Information Processing Standard for Database Language SQL (FIP SQL). However, due to the lack of strict

TABLE 6. DATA ELEMENTS [26]

Chemical and Physical Characteristics Data Segment [c]

3011.xx	Chemical Name	Essential	Alphanumeric String
3012.xx	Percent by Mass	Essential	Floating Point
3013	Total Solid	Essential	Floating Point
3014	Total Solid Units (customary units)	Desirable	Alphanumeric String
3015	Total Solid Units (SI units)	Essential	Alphanumeric String
3016	Customary to SI conversion factor	Desirable	Floating Point
3017	pH	Desirable	Floating Point
3018	Density	Desirable	Floating Point
3019	Density (Customary Units)	Desirable	Alphanumeric String
3020	Density (SI units)	Essential	Alphanumeric String
3021	Customary to SI Units Conversion Factor	Desirable	Floating Point
3022	Comments	Desirable	Alphanumeric String

c) repeat the data elements for this data segment as many time as necessary.

conformance testing requirements different dialects of SQL are appearing which are not completely compatible, which is of great concern in establishing networks of distributed databases [33].

4.5.5. Distributed Databases. "Distributed database" can have different meanings such as a system which is distributed geographically; a system which is distributed architecturally, comprised of systems with different architectures and access methods; or a system composed of different databases all running on the same platform [33]. In the present report, the definition of distributed databases given by Date [34] is used, which proposes than an ideal distributed database will have the following 12 attributes:

- Local autonomy. All the data are owned and managed locally
- No reliance on a central site. No site has directorship over another. Each site has its own data directory security.
- Continuous operation. Remote sites are available to the overall system continuously.

- Location independence. Data are retrieved without any reference to the physical location of the distributed database.

- Fragmentation independence. Logically related information can be stored at different physical locations.

- Replication independence. The ability of a database to create copies of a master database at remote sites.

- Distributed query processing. The ability to execute a query against more than one database. With some types of databases (relational databases), data items can be queried from widely distributed databases in a single distributed query.

- Distributed transaction management (update processing). The ability of a system to manage an update, an insert, or a delete to multiple databases from a single query.

- Hardware independence. The ability of a query to query and update information regardless of the hardware platform on which the data reside.

- Operating system independence. Fulfilling a query is not dependent on the operating system.

- Network independence. The use of distributed databases should not be controlled by network protocols.

- Database independence. Ability to retrieve and update information from different databases and database architectures.

If more information is desired on the attributes of distributed databases, Burleson [33] gives a more detailed description.

The development of an "ideal" distributed database system will be a very challenging task [33]. For example, a single architecture system, with the role of the query access manager defined, is shown with SQL dialects in Figure 5A. Although SQL is supposed to be standardized, each implementation of SQL by a vendor will likely contain added features and extensions. Therefore, any queries that rely upon these new features may not be successful in a distributed multi-vendor architecture. Established guidelines for use by database developers will be necessary to promote and document database compliance to specific standards. The development of a distributed multi-architecture database system becomes more complex. Such a distributed database is shown in Figure 5B. In this case, the query manager (RDA) needs to have the ability to decompose the subqueries into the appropriate access languages.

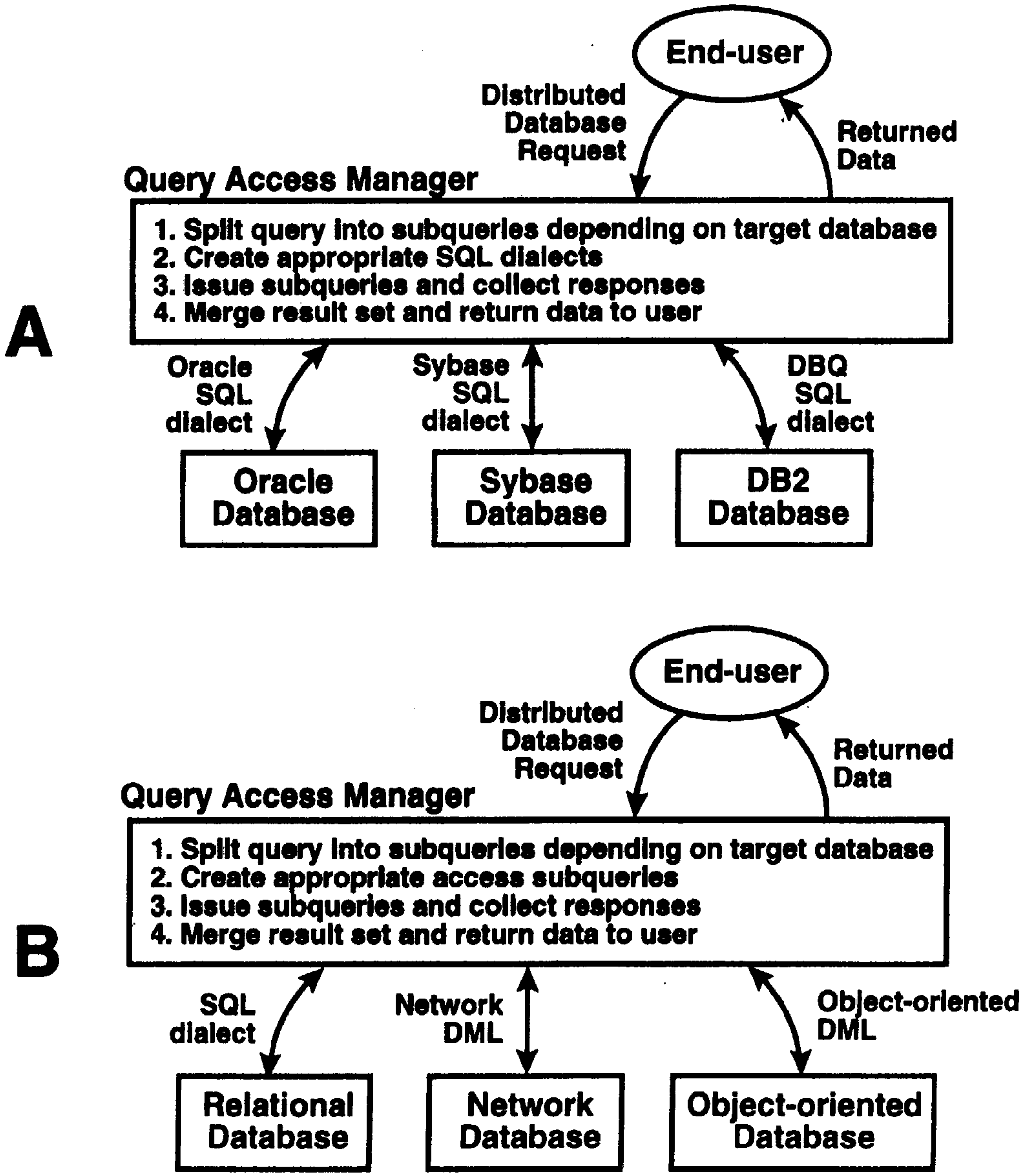


Figure 5. Distribute database queries. A. Single-architecture queries. B. Multi-architecture queries [33].

4.5.6. Integration of Databases and AI Systems

Brodie [35] predicted that information systems of the future will not be simply based on distributed database technology but rather on intelligent interoperability which will involve the incorporation of artificial intelligence techniques and natural language processing. The ways that artificial intelligence and databases can be integrated and the concept of distributed artificial intelligence realized were further discussed by Bell and Grimson [36]. They propose that the integration can be achieved in three ways:

1. Enhanced expert system
2. Intelligent database
3. Intersystem communication

In the enhanced expert system approach, the expert system is augmented with data management functions or is interfaced to a dedicated general purpose database management system. In the intelligent database approach, a deductive database management system is embedded in the expert system. In the third approach, both the expert system and database coexist and communicate with each other. Control may reside with either system or in an independent system.

If the control resides with the expert system, it would have the capability of selecting from a matrix of distributed knowledge bases those germane to a specific problem. In addition, it would control the retrieval, flow, and interpretation of data and knowledge, and transform them into conclusions and recommendations and present them to the user. A CIKS which is controlled by such an expert system would have a problem-solving ability limited only by our level of fundamental knowledge of HPC and our ability to represent that knowledge, and thus have infinite growth potential.

4.6 Computational Models.

4.6.1. Applications of Computational Models. Computational models are anticipated to be an integral component of many, if not all, of the CIKS which will be developed by NIST for HPC. Computational models are being developed in the NIST program on HPC many of which will be included in the CIKS for HPC. The kind of models which will be integrated into the CIKS include those providing data and information on:

- Mix proportions of HPC to produce desired properties or service lives.
- Rheological models that will aid in the design of HPC mixtures.
- Transport properties, e.g., chloride ion diffusivity.
- Durability of HPC, including alkali-aggregate reactivity, sulfate attack, and fire resistance
- Data to be used in the service life design and life cycle cost analysis of HPC structures.
- Data to be used in predicting the remaining safe life of in-service HPC structures.
- Creep and drying shrinkage characteristics of HPC.
- Values of other materials properties needed for the design of HPC structures.

This modeling can be called, in general, the computational materials science of concrete.

4.6.2. Documentation and Validation of Models. Of the different knowledge base systems which are proposed to be integrated into a CIKS, mathematical models are probably the least documented element and most likely to be of questionable reliability, possibly often providing data classified as "Limited Use Data" (Table 4). Two reasons for these deficiencies are the lack of standards for documentation and for validation. To overcome these deficiencies, NIST established a Cementitous Materials Modeling Laboratory [37]. Documentation of the models developed within the laboratory should include descriptions, in detail, of the conceptual model; derivations and assumptions made in transforming the model from its conceptual form into a mathematical representation; the computer program flow; the computer program's source code; and examples of its operation and outputs. Also, procedures for downloading the computer program and operating instructions should be given.

Some form of validation of computational models of cementitious based materials should be required before their results are used in design or in other critical decision-making processes. The need for validation is especially crucial for models of virtual materials, which are becoming more prevalent as applications of fundamental material science are advancing the scope and complexity of computational modeling of construction materials. The authors recommend that a classification scheme be established for judging the quality of data from models similar to that in Table 4 for data from databases.

4.7 Concrete Standards and Guidelines.

Existing standard test methods and guides for conventional concrete, and in some cases non-standard methods, may of necessity be used in developing the early versions of CIKS for HPC. In the recent workshop on Standards for Cement and Concrete [38], it was recommended that the applicability of existing standard test methods and practices to HPC should be assessed, and if necessary new standards developed. The NIST program on HPC is taking an active role in the modification and development of new test methods and practices in such areas as characterizing the material properties and durability. For example, recommendations on the practice of measuring the compressive strength of high-strength concrete have been prepared [39]. Also, test methods are being evaluated for measuring the chloride ion diffusivity of HPC with the goal of developing standard test methods.

Although ASTM Standards and ACI Guides are disseminated in the form of CD/ROMS, they are not represented in an intelligent electronic form which would facilitate their integration into a CIKS. Wright has [37] recommended that computer aids, equivalent to a "shell" for the development of expert systems, should be used in the formulation and representation of standards in electronic forms which are complete in their coverage of the intended scope, consistent and unambiguous in their logic, and correct in the evaluation of the pertinent product or service. DURCON [40] is an expert system which is based upon the knowledge base in the ACI Guide on Durable Concrete [41]. It demonstrated how the pertinent knowledge can be extracted from a guide and represented in a concise, logical, and intelligent electronic knowledge system.

4.8 Multimedia Technology

Multimedia includes such media as full-motion video (including animation), sound, text, images, graphics, and knowledge bases. With the possible exception of videos, these media are easily integrated into a CIKS functioning on the Internet. For example, the methodology of integrating images and graphics has been demonstrated in the development of HWYCON [14]. Depending on their running time, the integration of videos into a CIKS accessible on the Internet may not be feasible, at least not until substantially larger transmission bandwidths are available to CIKS users and at a reasonable cost. Until then, the most efficient means of distributing large videos appears to be by the use of CD/ROMS.

The application of multimedia technology to construction has been discussed by Aminmansour [42]. One of the most promising application of multimedia technology is in education. For example, products of the Strategic Highway Research Program [SHRP] include tutorial videos on [43]:

- Quality control of concrete at the construction site.
- Alkali-silica testing.
- Freeze-thaw testing.
- Bridge deck overlays.

5. APPLICATIONS OF CIKS TECHNOLOGY

Four examples of broadly different applications of CIKS technology to construction materials and systems are presented to illustrate the benefits of the technology.

5.1 Service Life Design

The conceptual CIKS shown in Figure 2 denotes a methodology for designing a concrete mix design to obtain a specific service life. First, an expert system and mathematical models are used to define the necessary material properties required by the concrete to give the designed service life. Then distributed databases are searched to determine if existing mix designs can be found which will give the necessary material properties. If such a mix design is found, it is specified. If not, a new mix design must be formulated. Several methods can be used, possibly in combination, to formulate a new mix design that is more likely to give the required property levels. The new mix design can be tested either by models or standard test methods, or their combination. If the new mix design gives the required properties, it is then specified; if not the process of formulating a new mix design is repeated. Note that each new mix designed is "banked" into the database. An operational prototype CIKS that can deal with the service life of reinforced concrete, in which the most probable mode of degradation is chloride-induced corrosion, is described in Section 6.

5.2 Electronic Handbook of HPCMS.

In a recent workshop on CIKS for HPCMS [44], a prevailing opinion was that, in the near future, a likely widespread application of CIKS to HPCMS will be the dissemination of databases on the types, properties, and sources of commercially available construction materials. Development of such databases for HPCMS would increase the awareness of designers and material specifiers of their availability and this in itself would probably stimulate interest in the use of HPCMS. However, linking the databases with models, giving reliable predictions of performance and life cycle costs, and making apparent the technical and economical benefits of HPCMS, are likely to be more effective than stand-alone databases in stimulating the use of HPCMS.

5..3 Data Mining with CIKS

Data mining is currently one of the 90's most intensively researched database technologies. Data mining can be defined as a computer assisted process intended to sift through large sets of data in search of hidden relationships and patterns, and then evaluate them for usefulness [45]. If the claim that knowledge is already available to solve 95% of concrete problems has any merit, data mining would be of tremendous assistance. Assuming that the data are available, data mining would be very useful in developing a historical record of material performance for use in many applications such as validating models, projecting the remaining life of in-service concrete structures, and comparing the performance of competing materials

A major problem with data mining is if the user does not know what to look for, it is unlikely that any significant relationships will be found. To effectively use the information provided by data mining an analyst with expertise and insight to the specific field undoubtedly will be required, a position that a CIKS could fulfill. Inductive reasoning methods could also be applied. Expert systems and neural systems, along with agents, could be developed to assist in searching for significant relationships, which then are tested by appropriate models.

5.4 Educational Application

The educational value of a CIKS is illustrated by describing an electronic monograph which will be accessible through the Internet. An electronic monograph is being prepared by Garboczi and Bentz which, when completed, will be added to the CIKS for HPC. The monograph is based on modeling work related to cement-based materials in the Building Materials Division of NIST. This modeling can be considered to represent the computational materials science of concrete. The purpose of the monograph is to sufficiently cover concepts, approaches, and applications so that graduate students and researchers will be able to understand the principles of modeling from a material science approach, and possibly be encouraged to use modeling in their research. The Table of Contents of the electronic monograph is presented in Table 7. For someone who is knowledgeable about concrete, but new to modeling, it is recommended that they start

Table 7. Table of Contents of Electronic Monograph on Computational Modeling of Concrete

1. Introduction
2. Composites Materials Concepts
3. Percolation Theory
4. Cements
5. Modeling of Cement Hydration and Microstructure Development
6. Mortar and Concrete Microstructure
7. Transport Properties of Mortar and Concrete
8. Modeling the Degradation of Mortar and Concrete

Appendix 1: Summary of Concrete and Concrete Modelling for Non-Cement Materials Researchers
Appendix 2: Manual for Finite Difference Element Program for Digital Images

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with the introduction and work straight through the monograph. For those who are acquainted with modeling but not concrete, an appendix is included to introduce non-concrete researchers to sufficient knowledge on concrete to understand the results of the models.

6. MODEL CIKS FOR CONCRETE

6.1 Description of the CIKS

NIST has developed a model CIKS [46] based on the general architecture shown in Figure 1. The system has been developed as a series of hypertext markup language (HTML) pages and forms which can be accessed over the World Wide Web. It includes numeric and literature databases, concrete mixture proportioning for ordinary and high-strength concretes, simulation and service life models, and guidance on analyzing experimental results. Forms are utilized to submit input to the computer program:

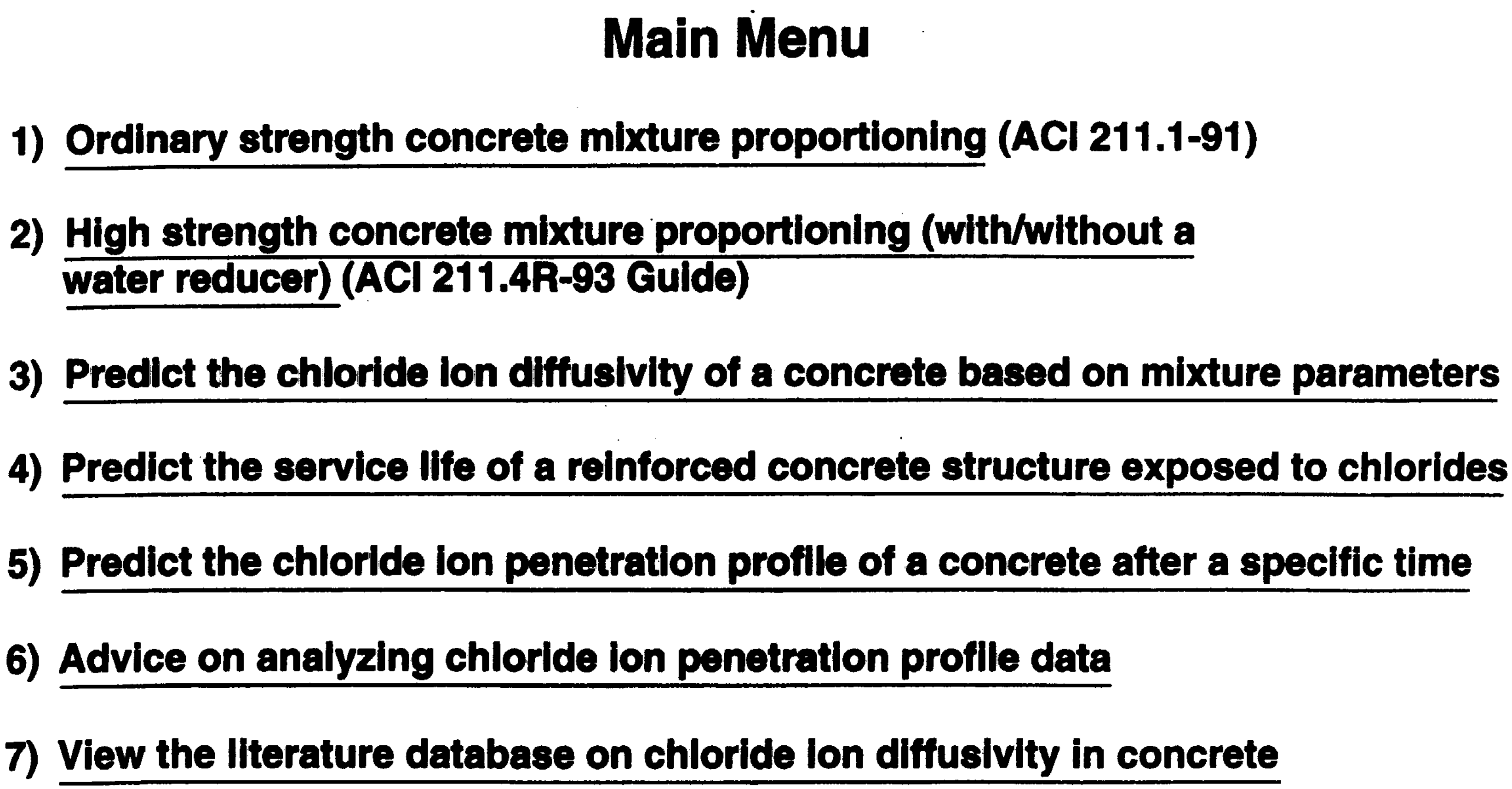
(1) mixture proportioning of ordinary and high-strength concrete;
(2) estimating the chloride ion diffusion coefficient of a concrete as a function of mixture proportions;
(3) predicting the service life of reinforced concrete exposed to an external source of chloride ions; and
(4) simulating the concentration profile of a concrete exposed to an external source of chloride ions.

6.2 Example of a Session.

The steps in designing a concrete and predicting its service life are outlined in the following. A more detailed explanation of the system's basis and operation is given in reference no. 46. The main menu viewed upon accessing the system is shown in Figure 6. The first step in obtaining a concrete with a desired service life is selecting the concrete materials and designing the mix proportions. The current ACI guidelines for ordinary concrete [47] and for high-strength concrete [48] are computerized and they form the basis for designing the concrete mix proportions. The user fills in the forms shown in Figure 7 for proportioning an ordinary strength concrete. Then a mix design is proposed to the user, along with the predicted chloride ion diffusivity (D) (Figure 8). The prediction of chloride ion diffusivity is based on a model developed at NIST [49]. The next step involves predicting the service life of the reinforced concrete based on the assumption that the initiation period (time for threshold concentration of chloride ions to accumulate at the depth of reinforcement) is the rate controlling step. The time for the threshold of chloride ions to reach the reinforcement is modeled using Fick's second law of diffusion [50, 51]. In addition to knowing the value of D, the depth of concrete cover over the reinforcement, and the concentration of chloride ions at the concrete surface, must be known. Using the values given in example 1 of a bridge deck, from the report by Weyers and Cady [51], the service life predictions for the ordinary concrete and a higher strength concrete are given in Table 8.

6.3 Future Developments of the Model CIKS

It is anticipated that in the future, the system will be extended to include other degradation processes such as alkali-aggregate reactivity, frost attack, leaching, and sulfate attack, forming a basis for designing HPC from a service life approach. This extension will likely involve adapting a computer model which integrates corrosion of reinforcement, sulfate attack, and leaching of concrete, which was developed for predicting the service life of underground vaults for disposal of low-level radioactive waste [52]. Recommendations for preventing damage from frost attack and alkali-aggregate expansive reactions will be provided as performed by HWYCON [14].



Main Menu

1) Ordinary strength concrete mixture proportioning (ACI 211.1-91)

2) High strength concrete mixture proportioning (with/without a water reducer) (ACI 211.4R-93 Guide)

3) Predict the chloride ion diffusivity of a concrete based on mixture parameters

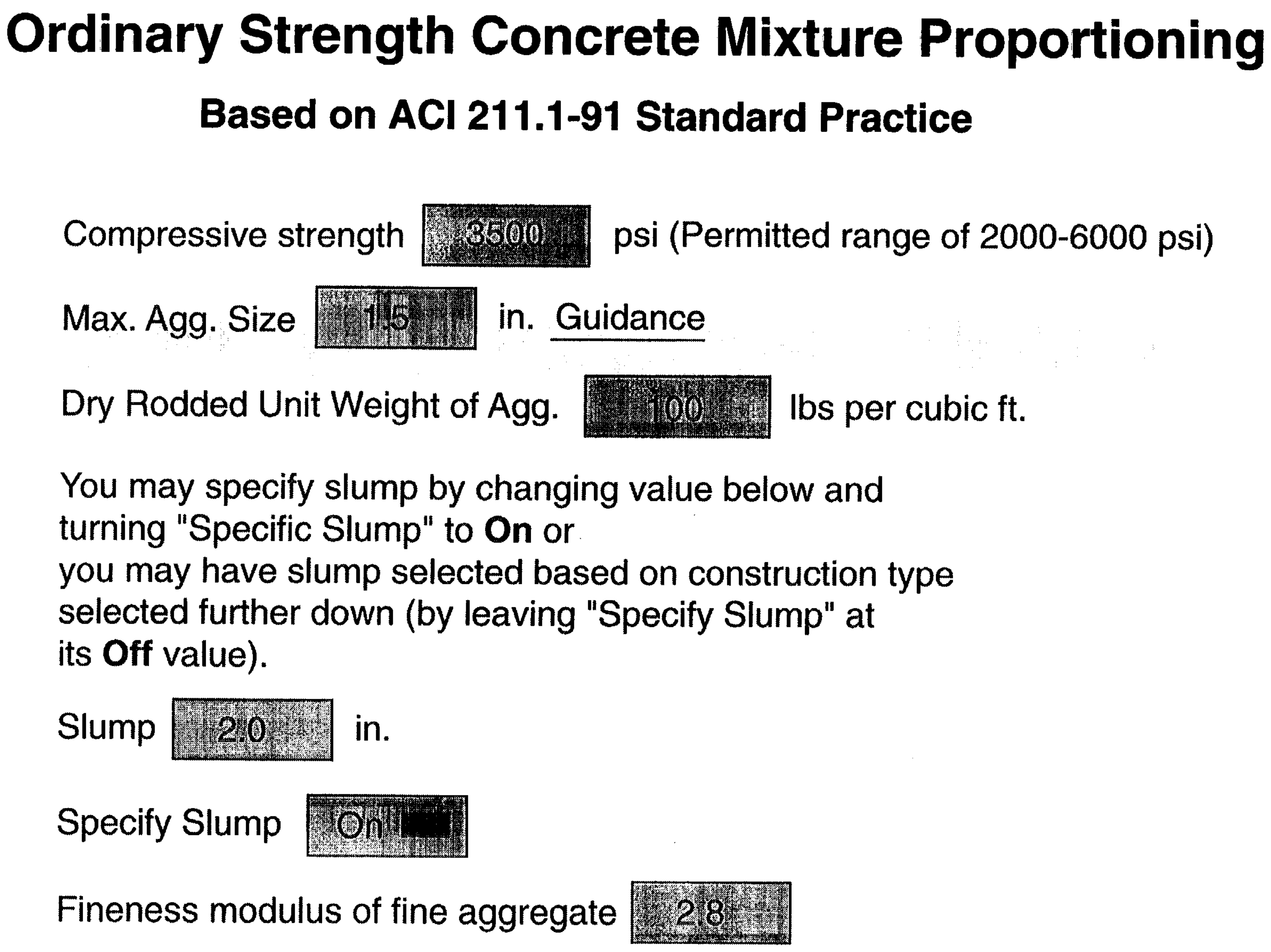
4) Predict the service life of a reinforced concrete structure exposed to chlorides

5) Predict the chloride ion penetration profile of a concrete after a specific time

6) Advice on analyzing chloride ion penetration profile data

7) View the literature database on chloride ion diffusivity in concrete

Figure 6. Main menu of Model CIKS for Concrete [46]. Reproduction of monitor screen.



Ordinary Strength Concrete Mixture Proportioning

Based on ACI 211.1-91 Standard Practice

Compressive strength 3500 psi (Permitted range of 2000-6000 psi)

Max. Agg. Size 1.5 in. Guidance

Dry Rodded Unit Weight of Agg. 100 lbs per cubic ft.

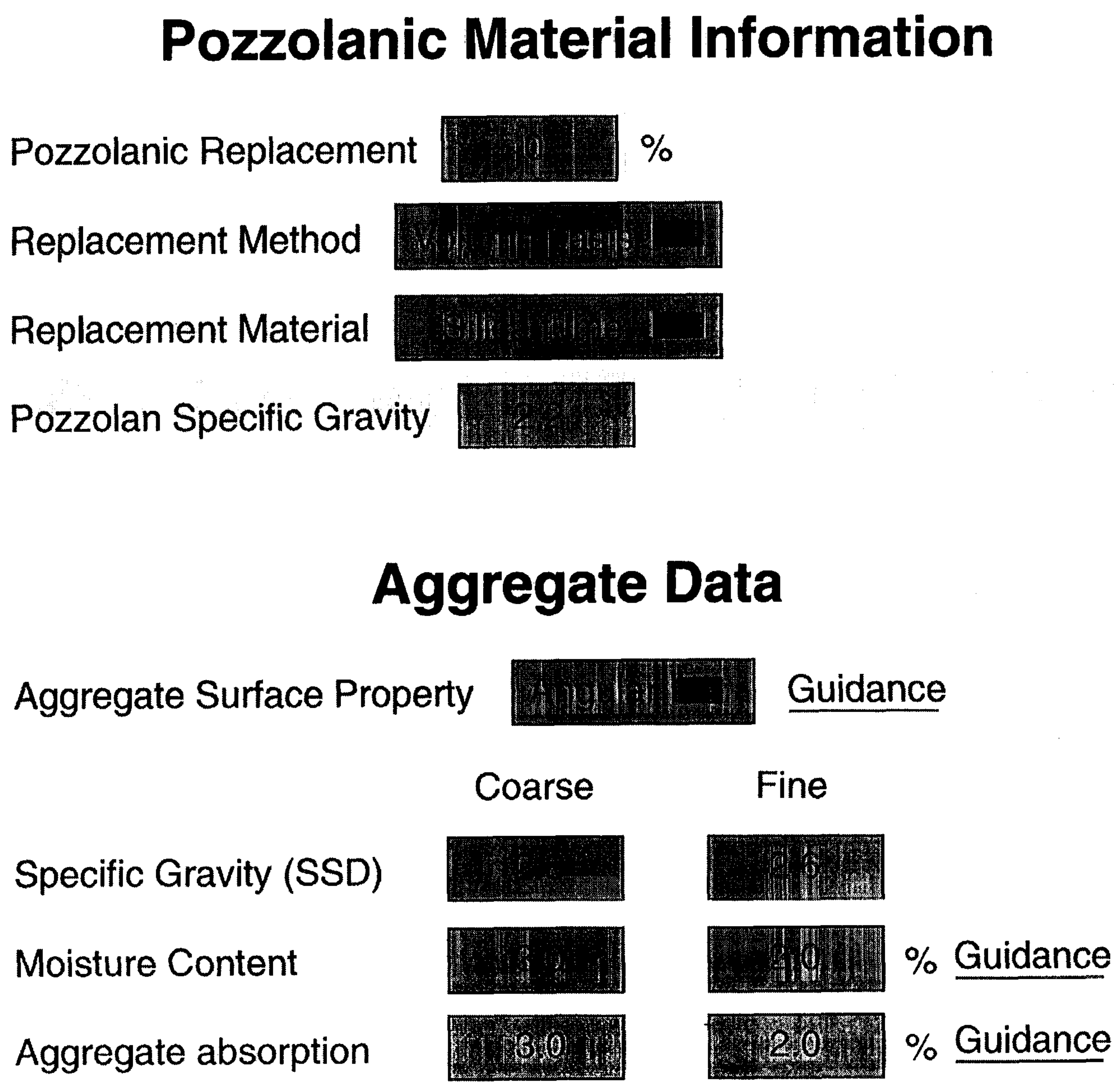
You may specify slump by changing value below and
turning "Specific Slump" to **On** or
you may have slump selected based on construction type
selected further down (by leaving "Specify Slump" at
its **Off** value).

Slump 2.0 in.

Specify Slump On

Fineness modulus of fine aggregate 2.8

Figure 7A. Data needed to be inputted to the Model CIKS for Concrete [46]. Properties of concrete. Reproduction of monitor screen.



Pozzolanic Material Information

Pozzolanic Replacement [illegible] %

Replacement Method Volume Basis

Replacement Material Silica fume

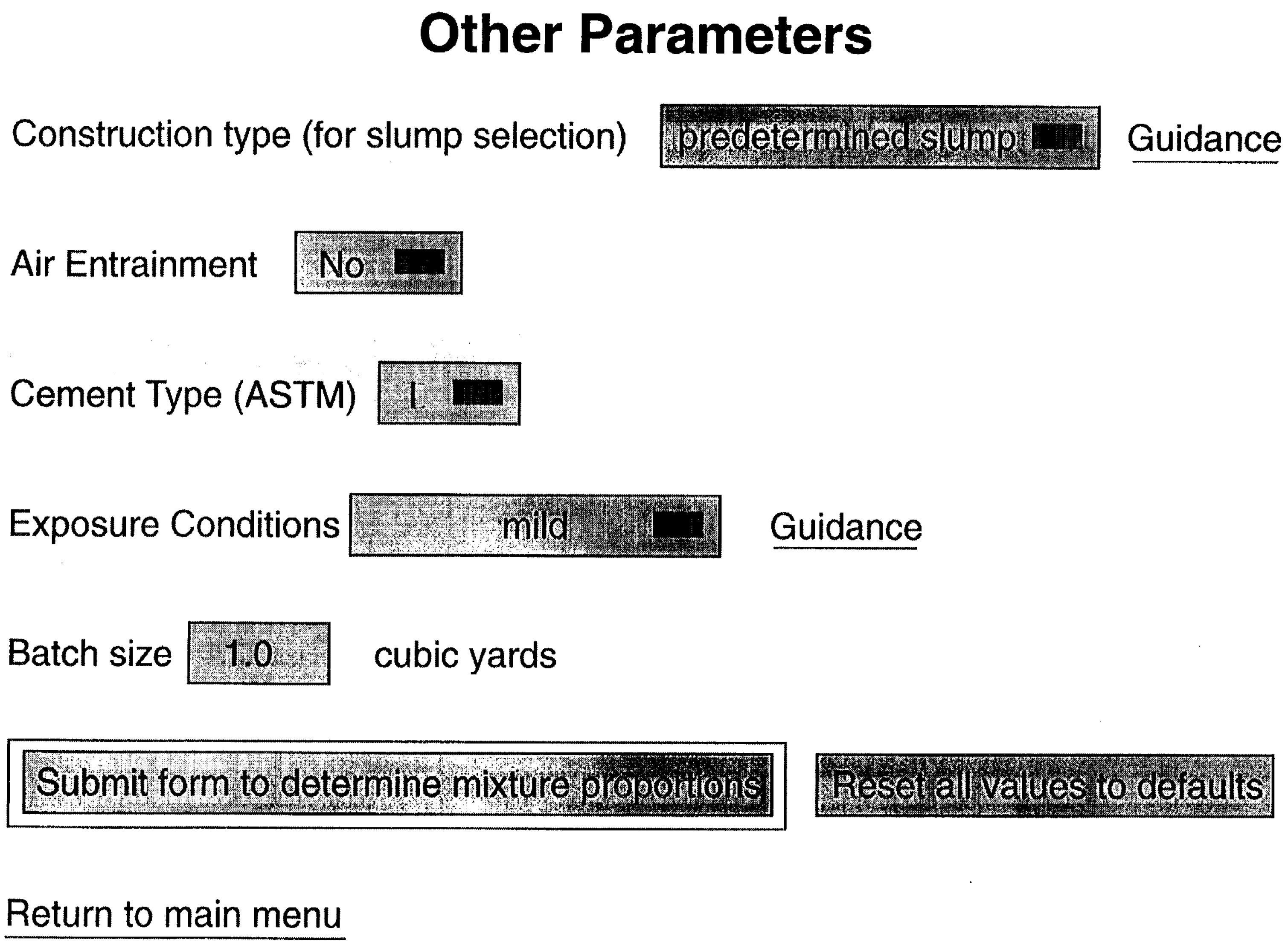
Pozzolan Specific Gravity [illegible]

Aggregate Data

Aggregate Surface Property Angular Guidance

	Coarse	Fine	
Specific Gravity (SSD)	[illegible]	2.6	
Moisture Content	[illegible]	4.0	% Guidance
Aggregate absorption	3.0	2.0	% Guidance

Figure 7B. Data needed to be inputted to the Model CIKS for Concrete [46]. Pozzolanic material information and aggregate data. Reproduction of monitor screen.



Other Parameters

Construction type (for slump selection) predetermined slump

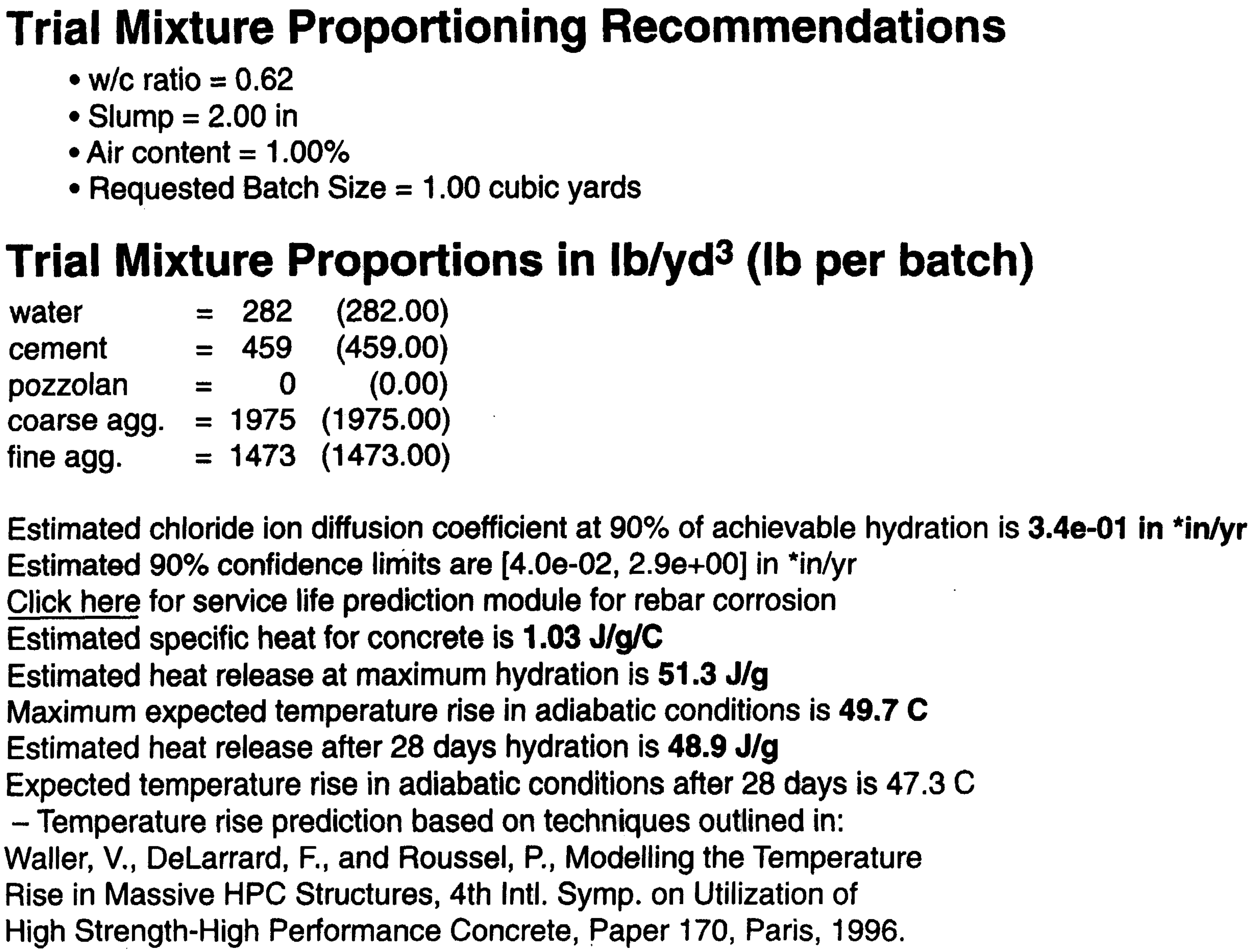
Air Entrainment No

Cement Type (ASTM) I

Exposure Conditions mild

Batch size 1.0 cubic yards

Figure 7C. Data needed to be inputted to the Model CIKS for Concrete [46].
Other parameters. Reproduction of monitor screen.



Trial Mixture Proportioning Recommendations

- w/c ratio = 0.62
- Slump = 2.00 in
- Air content = 1.00%
- Requested Batch Size = 1.00 cubic yards

Trial Mixture Proportions in lb/yd^3 (lb per batch)

water = 282 (282.00)
cement = 459 (459.00)
pozzolan = 0 (0.00)
coarse agg. = 1975 (1975.00)
fine agg. = 1473 (1473.00)

Estimated chloride ion diffusion coefficient at 90% of achievable hydration is **3.4e-01 in *in/yr**
Estimated 90% confidence limits are [4.0e-02, 2.9e+00] in *in/yr
Click here for service life prediction module for rebar corrosion
Estimated specific heat for concrete is **1.03 J/g/C**
Estimated heat release at maximum hydration is **51.3 J/g**
Maximum expected temperature rise in adiabatic conditions is **49.7 C**
Estimated heat release after 28 days hydration is **48.9 J/g**
Expected temperature rise in adiabatic conditions after 28 days is 47.3 C
– Temperature rise prediction based on techniques outlined in:
Waller, V., DeLarrard, F., and Roussel, P., Modelling the Temperature Rise in Massive HPC Structures, 4th Intl. Symp. on Utilization of High Strength-High Performance Concrete, Paper 170, Paris, 1996.

Figure 8. Trial mixture proportioning recommendations from model CIKS for Concrete. Reproduction of monitor screen.

Table 8. Mixture Proportions and Properties for Ordinary and High-Strength Concretes

Compressive strength	24.1 MPa (3500 psi)	48.2 MPa (7000 psi)
w/c	0.62	0.31
Air Content	1.0%	1.5%
Cement	272 kg/m^3	597 kg/m^3
Water	167 kg/m^3	185 kg/m^3
Fine Aggregate	874 kg/m^3	470 kg/m^3
Coarse Aggregate	1172 kg/m^3	1201 kg/m^3
D x 10^{-12}m^2/s	7.0	0.9
Estimated Service Life	3.8 years	29.2 years

7. SUMMARY

The concept, development, and applications of a Computerized Integrated Knowledge Base System (CIKS) for high-performance concrete (HPC) are discussed in this report. CIKS is defined as a computerized intelligent system of integrated knowledge base systems providing the knowledge for solving problems of a range of complexities. Knowledge bases which can be incorporated into a CIKS include databases, mathematical and simulation models, AI systems, guides, handbooks, and standards and codes. Along with these knowledge bases, a comprehensive CIKS will include ways to obtain knowledge from distributed knowledge sources using Remote Database Access (RDA) and Agent technologies. In a completely integrated system, the system obtains all the necessary information on the specific problem (application), during an interactive session with the user, and the recommendations or conclusions are seamlessly presented to the user.

The development of a CIKS involves the following major steps: (1) defining the purpose of the system and who are the intended users; (2) identifying and developing the architecture fir the system; (3) developing an information model; (4) developing a prototype system; and (5) establishing methods for the system maintenance and for determining the reliability of the CIKS. The reliability of a CIKS will depend on the quality of the knowledge it contains. In general, with the exception of databases, little attention has been given to validate knowledge bases, and to assign quality indicators to them. In addition to knowledge bases, a standard validation and quality rating system needs to established for any CIKS used for critical decision-making purposes.

Four examples of the application of CIKS Technology applicable to HPC were described which illustrate the diversity of the technology. (1) A process for designing a concrete mix to obtain a specific service life for reinforced concrete exposed to chloride ions. A model CIKS is presented in which this application is realized. (2) An electronic handbook for dissemination of databases on the types, properties, and sources of commercially available construction materials. (3) The mining of data in databases in search of hidden relationships and patterns which could provide a historical record of material performance for use such as validating models, predicting the remaining life of in-service concrete structures, and comparing the performance of competing materials. (4) An educational application consisting of an electronic monograph describing the computational modeling of the performance of HPC. The purpose of the monograph is to cover concepts, approaches, and applications sufficiently so that graduate students and other researchers will be able to understand the principles of modeling from a material science approach.

From a greater perspective, if the CIKS for HPC is fully developed, it will be able to provide information, guidance, and recommendations on the selection, design, processing, and quality control testing and inspection of HPC: beginning with the design of a structure and covering the in-between processes leading into the commissioning of a structure. As the technology of HPC advances, the system could be further developed to cover the complete life-cycle of HPC in structures and would have the potential to contain the most authoritative information and to become the universal problem solver for HPC.

8. ACKNOWLEDGEMENTS.

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