Specification and Production of Durable Reinforced Concrete

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A durability design method that has been used to quantify the requirements for reinforced concrete is described. It specifies the data required and decisions that need to be taken to achieve the specified performance. Codes and standards currently used for design are insufficient to ensure the long-term durability of structures in aggressive environments. Specific environmental data are a prerequisite for the modeling processes used to predict the performance of different mix designs. Selecting suitable materials is vital to ensure that performance is achieved and may necessitate that the concrete producer adopt more stringent performance requirements than those demanded by the specification. Mix design trials must consider the performance aspects of the specification and particular site characteristics. In extremely severe environments, concrete alone may not be sufficient to ensure durability performance, and additional protective measures may be necessary.

Quantitative analysis based on the measurement of physical properties has been used in the structural design of reinforced concrete for many years. Durability design, however, has been largely empirical, based on standards and codes that have been modified only in response to increasing numbers of structural failures (*1*). Although this approach may be satisfactory for conventional structures in normal environments, it is inappropriate for major structures in unusually severe environments.

To determine the likely mechanisms of deterioration, quantitative design of reinforced concrete for durability must be based on (a) the assessment of the design life requirements of the structure and (b) the thorough characterization of internal and external environments to which it will be subjected.

With the ever increasing costs of construction, the required durability of structures (i.e., the time before an item fails or requires unacceptable expenditure on maintenance to sustain performance) is also increasing. The current British Standard (BS) for structural concrete, BS 8110 (*2*), has an implicit design life of 60 years. Highway structures designed in accordance with the U.K. Department of Transport specification (*3*) have an expected life of 120 years, and recent examples of structures in North America are required to be durable for 100 years.

To quantify local concentrations of acidic gases and depassivating ions, and so forth, reliable environmental data can only be obtained from systematic site investigation. The risk of attack can then be characterized for each structural element. It is essential not to ignore or underestimate the synergism of deteriorating factors, for example, the release of bound chlorides by the carbonation of the cement paste.

The properties of the concrete constituents should be considered in terms of their individual performance and their collective effects on the structure. For example, cement with a high alkali content and a reactive aggregate may, individually, perform adequately as concreting materials; however, the combination of the two may prove disastrous. The thermal behavior of the concrete and the possible incompatibility of the components can also have a major influence on the overall durability of a structure.

Predictions of the time to structural damage can be made by modeling different concrete mix designs with varying proportions of mix constituents, total porosity, depth of cover and so forth. Thus the properties required to limit the ingress of these aggressive substances into concrete can be evaluated and the likely long-term performance of the structure more accurately predicted.

In extremely aggressive environments, the use of concrete alone may not be sufficient to ensure that the required design life is achieved. In such cases it is necessary to enhance the durability of the concrete and any embedded steel reinforcement by influencing the factors that control the rate of deterioration. The design and use of very low-permeability, high-resistivity concrete limit the magnitude of corrosion currents that can pass between adjacent bars. Experimental work (*4*) has shown that the application of nonconductive coatings to either the concrete or the reinforcement provides a physical barrier to aggressive species. The use of coated reinforcement can also limit the size and distribution of active sites, with corrosion only able to initiate at imperfections.

The approach described in this paper was developed over many years from specifying and testing high-quality concrete. It establishes the specific requirements for structures in particular environments. It does not provide general requirements for all structures because this may result in (a) over-specification in benign environments, which would be costly for the contractor, or (b) underspecification in aggressive environments, which could be very expensive for the structure owner. The strategy described here was adopted for the design and specification of concrete on major projects around the world, including the Channel Tunnel (U.K.), Storebaelt Tunnel (Denmark), St. Clair River Tunnel (U.S.-Canada), and the Lantau Fixed Crossing (Hong Kong).

DETERIORATION OF REINFORCED CONCRETE

Most reinforced concrete around the world performs adequately and gives few problems. A few structures have deteriorated as a result of either the action of aggressive components from the external environment or incompatibility of the particular mix constituents. Problems can arise as a result of incomplete or inaccurate site investigation, poor design, badly specified concrete, poor workmanship, and a range of other factors. The mechanisms of deterioration are primarily chemico-physical (i.e., a chemical reaction with the formation of products greater in volume than the reactants producing physical effects, such as cracking and spalling) and occur in three discrete stages, as shown in Figure 1 (*5*).

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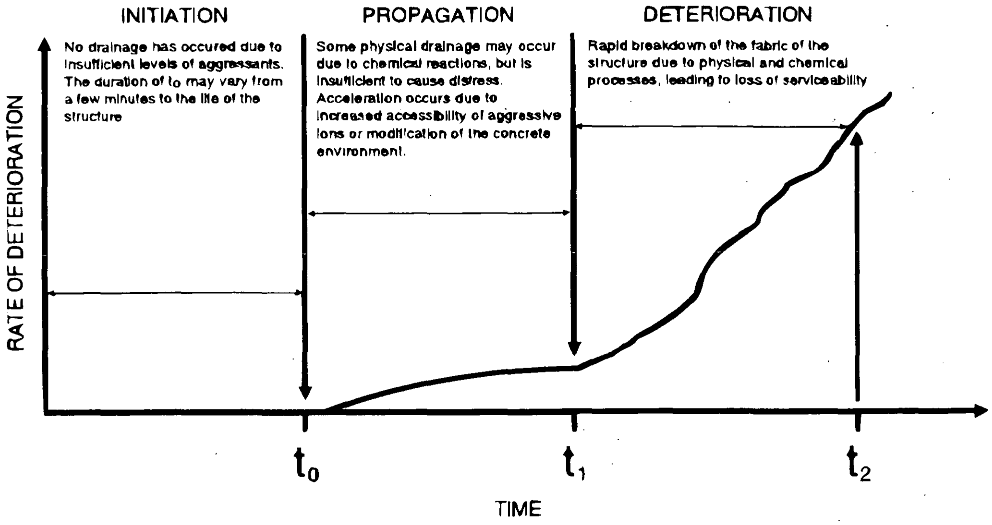


FIGURE 1 General model of the chemico-physical deterioration of concrete.

- Stage 1: Initiation (t_0)—Concentration of aggressive species is insufficient to initiate any chemical reactions, or the chemical reaction is occurring slowly. No physical damage has occurred. The duration of t_0 may vary from a few minutes to the design life of the structure.
- Stage 2: Propagation (t_1)—Chemical reactions begin or are continuing. Some physical damage may occur, but it is insufficient to cause distress. Acceleration of the deterioration process usually occurs during this stage because of increased accessibility of aggressive ions or modification of the concrete environment.
- Stage 3: Deterioration (t_2)—Breakdown of the fabric of the structure is rapid. The combined effects of the physical and chemical processes are of sufficient severity that the structure is no longer serviceable (failure occurs), and major remedial work or, in extreme cases, demolition is required.

Deterioration may occur as a result of a number of mechanisms on which a large body of literature already exists (*6,7*). These mechanisms include

- Corrosion of reinforcement because of chloride ions, carbonation, and change in the rebar environment (e.g., impinging cracks);
- Sulfate attack of concrete;
- Soft water or acid attack of concrete;
- Alkali aggregate reaction (AAR);
- Other aggregate quality problems, such as popouts, abrasion resistance, and D-cracking;
- Thermal incompatibility of concrete components;
- Shrinkage; and
- Frost damage.

The factors must be considered during design and specification(*8*).

SPECIFICATION OF CONCRETE

Current Methods of Design and Specification for Durability

The design and specification of most structural concrete is carried out in accordance with codified recommendations based on past experience and accepted good practice at the time of writing. Therefore innovative techniques and materials can only be incorporated after relatively long periods and as experience of their successful application increases.

The requirements for a durable concrete mix design, primarily in terms of strength, are detailed and many other properties that influence durability are ignored in works by the British Standards Institution (*2,9*). Water to cement (w-c) ratio, minimum cement content, and depth of cover to reinforcement are defined for concrete in relation to various grades of environmental exposure from mild to extreme. The inability of this system always to work satisfactorily, particularly in severe environments, is demonstrated by the number of structures that fail within their design life.

Fundamental questions concerning rates of deterioration in a given environment, such as the rate of penetration of aggressive species, cannot be predicted using this approach. It is therefore not possible to reliably estimate the duration of each stage of deterioration and hence obtain the likely maintenance-free life of the structure.

The properties of individual components are often covered by their own standards, which occasionally conflict with codes for the specification of concrete. For example, BS 12:Ordinary Portland Cement (*10*) allows concrete to contain up to 0.1 percent Cl^- by mass, while BS 8110 states that for prestressed concrete, the maximum allowable Cl^- concentration is 0.1 percent by mass of cement. This makes compliance with the specification difficult, or impossible, to achieve.

By specifying fixed levels of aggressive ions that may be incorporated in the concrete, it is possible for the initiation stage in the deterioration process to be completely eliminated. For example, the level of acid-soluble chloride necessary to initiate the corrosion of reinforcement in OPC concrete is widely regarded as being 0.4 percent (by mass of cement), yet this is specified as the maximum allowable level in accordance with BS 8110. American Concrete Institute (ACI) codes (*11*) permit only 0.2 percent acid-soluble chloride in conventional reinforced concrete, thus extending the duration of the initiation period and increasing the time to first damage of the structure.

The use of inappropriate standards for the design of structures has also led to problems of concrete durability. In the United Kingdom, the use of BS 8007 (*12*) to limit crack widths in structures designed to retain aqueous liquids has frequently been specified for the design of structures that retain aggressive liquids, although the standard clearly states that it is not applicable for use with such fluids.

Although there are clearly problems associated with the use of codes and standards, this approach works reasonably well for everyday, nonaggressive environments. Where structures of major importance are to be exposed to severe environments, a different approach must be adopted based on the detailed classification of the environment and the fundamental properties of the structural materials.

Characterisation of Service Environment

Current British Standards classify the service environment of the concrete into five groups based on exposure to moisture, chloride, and frost action. This type of approach, classifying environments on moisture content and exposure to deicing salts, seawater, and chemical attack, with or without freezing is followed elsewhere (*13*). However, none of these parameters is quantified in terms of concentration or number of cycles of action. Quantification of environmental parameters is essential if durability design is to be successful. The classification of environments for acid and sulfate attack by the U.K. Building Research Establishment (BRE) (*7*) partly satisfies this requirement in that five classes and two subclasses are defined with relation to the concentrations of aggressive anions and cations present in the soil or groundwater. ACI (*14*) also follows this type of approach by specifying for exposure classes related to sulfate concentration and recommends suitable cement types for use in them.

This type of approach should also be followed to classify environments for other potential mechanisms of deterioration. Rigorous site investigation must be undertaken to collect the necessary specific data on groundwater compositions and other environmental factors, for example:

- Ionic concentrations in the ground, groundwater, and atmosphere;
- pH of groundwater, hydrostatic pressure, and any rate of flow data;
- Temperature variation, including numbers of freezing cycles;
- Relative humidity variation;
- Rainfall; and
- Presence of organic compounds.

These factors will vary from site to site. For example, the principal durability considerations for the Channel Tunnel were sea water strength chloride ion concentrations [approximately 18,000 mg/l (ppm)] and a maximum hydrostatic pressure of 2 bar (equivalent to 20 m of water). The initial investigations for the St. Clair River Tunnel indicated the possibility of very high concentrations of chloride ions in the strata adjacent to the tunnel, up to 175,000 mg/l (ppm) were reported. The Tsing Ma suspension bridge (Lantau Fixed Crossing) was to operate in warm saline conditions, 19,000 mg/l (ppm), with temperature varying from 7°C to 35°C (see Figure 2) and to have a number of large concrete pours. Also of importance is the orientation of a particular structure on a site and the influence of design in the inadvertent formation of corrosive microenvironments where, for example, high concentrations of aggressive ions accumulate.

The internal environment likely to occur within the structure when it is in service also affects the durability of the concrete. For example, the concrete lining of a tunnel may be cool and water saturated at the extrados and hot and dry (e.g., Channel tunnel, 40°C, 25 percent RH) at the intrados. The concrete should be designed to accommodate both of these environments. The behavior of concrete in structures with environments similar to those expected (particularly the internal environment) should be examined to obtain basic performance data.

Factors That Affect Concrete Durability

Concrete can be thought of as a four-component system consisting of aggregate, cement paste, void space (porosity), and pore solution that fully or partially fills the void space. The durability of good-

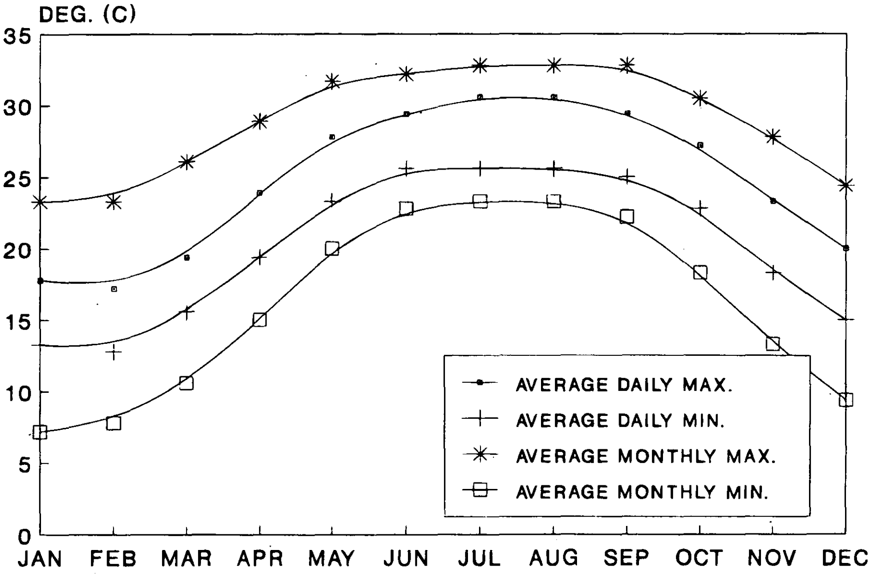


FIGURE 2 Climatic data for Hong Kong.

quality concrete is dominated by the paste fraction, pore solutions, and void space, with the aggregate remaining largely inert. The physical structure of the cement paste consists of a complex interlocking network of crystalline and gel phase material with spaces (pores) within and between them. The pore solution is primarily an alkaline solution with a pH generally of more than 12.4. It is this alkalinity that provides the means by which steel reinforcement is protected through the stabilization of a passive oxide film on the metal surface.

The bulk of the concrete acts as a physical barrier to the ingress of aggressive ions from the external environment. Ions can migrate into concrete by a number of mechanisms (*15*), such as

- Permeation under a pressure gradient,
- Diffusion across a chemical gradient in both the liquid and gaseous states,
- Capillary suction (sorption), and
- Wetting and drying cycles.

Ionic movement through solids is extremely slow; hence the factors that influence the rate of transport are concerned with the void space within the paste matrix. The paste density, (i.e., quantity of hydrates per unit volume) determines the porosity, permeability, pore size distribution, and pore tortuosity. All of these factors influence the rate of migration, as does the degree of water saturation of the concrete. Gaseous aggressants migrate more slowly through the liquid phase in water-filled pores than in the gaseous state through open pores.

The rate of migration of ions through concrete can be described by appropriate coefficients that depend on the physical properties of the paste and that can be used to model the ingress processes. The composition of the paste and pore fluid influences the rate and extent of deleterious chemical reactions by limiting the quantities of reactants or adjusting the reaction conditions, or both, such that some reactions are not thermodynamically favorable.

The final feature that determines durability is the strength of the concrete, particularly its tensile strength. The higher the tensile strength of the concrete the more resistant it will be to the stresses generated by the deleterious reactions.

Modeling Concrete Behavior

Figure 3 shows the stages that must be undertaken when modeling concrete to arrive at a rational basis for specification. The design life requirement of the structure must be clearly established so that the time period over which the model must be run can be established.

The site investigation will provide the basic starting data to quantify the external environment and identify the mechanisms of deterioration that are likely to occur. Initial parameters for the concrete can then be selected, including quantities of mix constituents, w-c ratio, and appropriate coefficients of diffusion, permeability, and so forth. The physical dimensions of the element concerned are also important. The model can then be run to establish the performance of the particular mix in relation to the site environment. By varying the concrete parameters, it is possible to establish the minimum requirements of the concrete to achieve the required durability.

One example of this type of approach is the CHLORPEN program, which models the ingress of chloride ions into concrete and evaluates the time to initiation of corrosion. The principal factors that affect the rate of penetration of chloride ions into concrete are the coefficients of diffusion, permeability, and the rate of evaporation from an exposed internal face. The processes described by Fick and D'Arcey's laws are mathematically modeled in a series of incremental time steps into the concrete, which is divided into a number of lamina of fixed material properties. A typical plot of the output based on a simple diffusion process is shown in Figure 4.

Where chlorides originate from deicing salts, the number of applications and quantity of chloride applied during each freezing cycle are also important. On particularly sensitive structures, where chloride-based deicers have been prohibited, the extent of carryover from the use of chloride deicers must also be considered. On a U.K. submarine tunnel road deck, chloride concentrations of up to 26,000 mg/l (ppm) have been recorded at distances of 2 km (1.2 mi) from the boundary of chloride deicer use after each application.

Initiation of corrosion is assumed to occur when the level of chloride reaches 0.4 percent by mass of cement. From the output data for a design life of 120 years before initiation occurs, two options become apparent: (a) the depth of cover can be specified for a concrete with a fixed diffusion coefficient or (b) the diffusion coefficient of the concrete can be specified for a fixed depth of cover. In the St. Clair River Tunnel, the cover to the extrados reinforcement was fixed; therefore the diffusion coefficient was specified to achieve the maximum resistance to chloride penetration. A value of 600×10^{-15} m^2/s was selected as being achievable in production. Measured values from trial mix designs of less than 350×10^{-15} m^2/s were reported.

Once the durability of the concrete has been determined, the materials selection process to achieve the desired properties can begin. It is important to establish the behavior of the proposed mix (particularly its thermal properties) to minimize the likelihood of early thermal cracking and to establish the curing regime and stripping times of formwork. Modeling can also be used to establish the likely thermal behavior of concrete mixes with respect to boundary conditions (Figure 5). This shows the effect of varying the boundary conditions (formwork type and period before striking) on the thermal behaviour of a 70 percent ggbs mix proposed for use in the cable anchorage of a suspension bridge. Where boundary conditions are fixed (e.g., concrete cast against the ground) the effects of varying the mix design can be simulated.

Modeling is a powerful predictive tool, but there are limitations. Some processes are almost impossible to model because of a lack of basic data on the nature of the process or the high variability in behavior. A good example is AAR, where a number of different processes operate simultaneously and are sensitive to the chemical and physical environment. In such cases it is necessary to rely on codified rules to minimize the risk (*16*).

MIX DESIGN

When designing the concrete, the contractor who is to produce the concrete must initially consider the detailed requirements of the specification and the site to simultaneously satisfy all the specification requirements, including the durability and structural properties. A program of trial mixes that clearly identifies principal performance criteria to be evaluated, particularly in areas where onerous or unusual requirements occur, must be undertaken. After the important parameters that must be achieved have been established, an assessment of the particular site requirements, the local materials available, and alternative reserve supplies should be made.

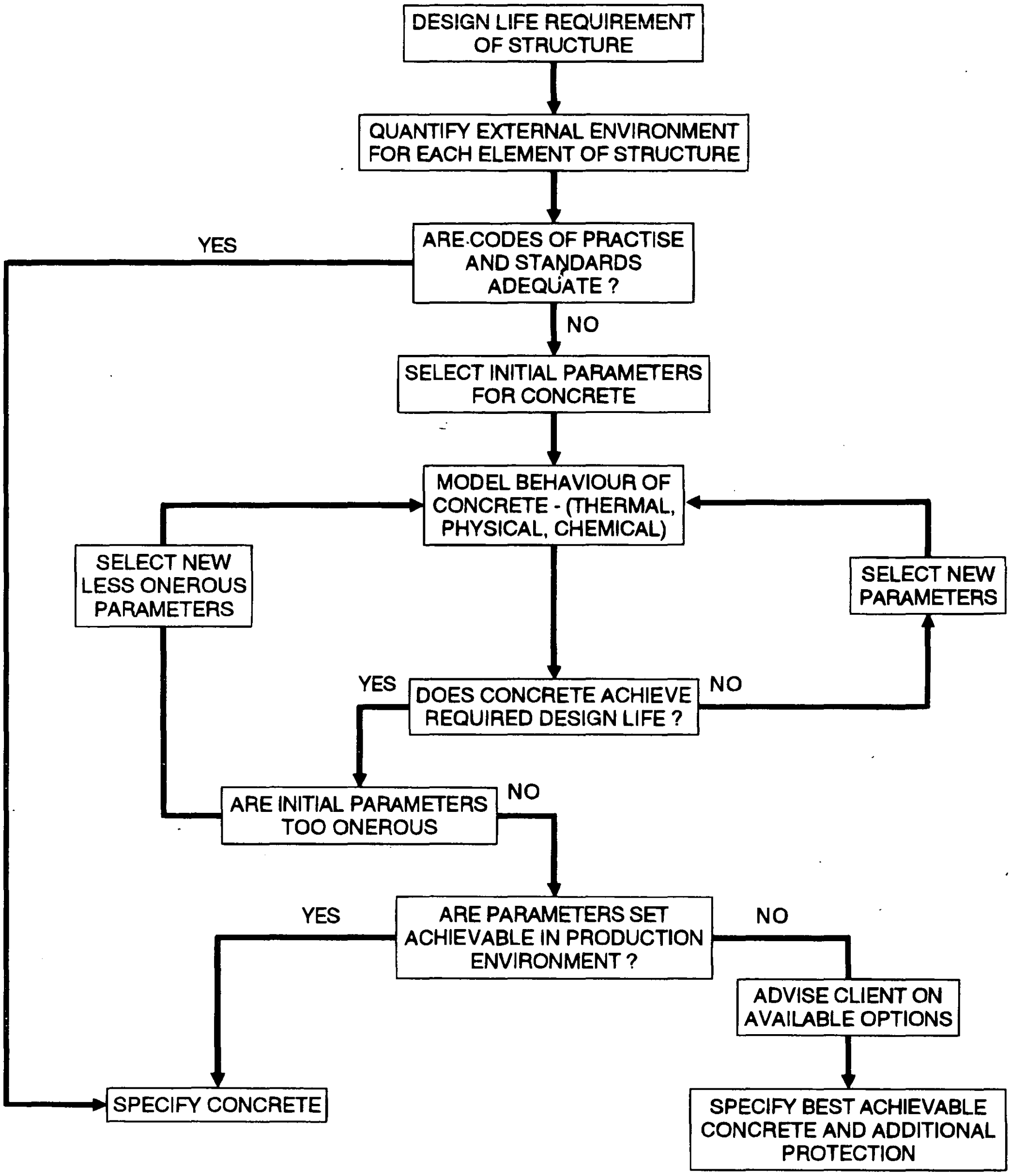


FIGURE 3 Flowchart of the modeling process leading to the specification of concrete.

SPECIFICATION REQUIREMENTS

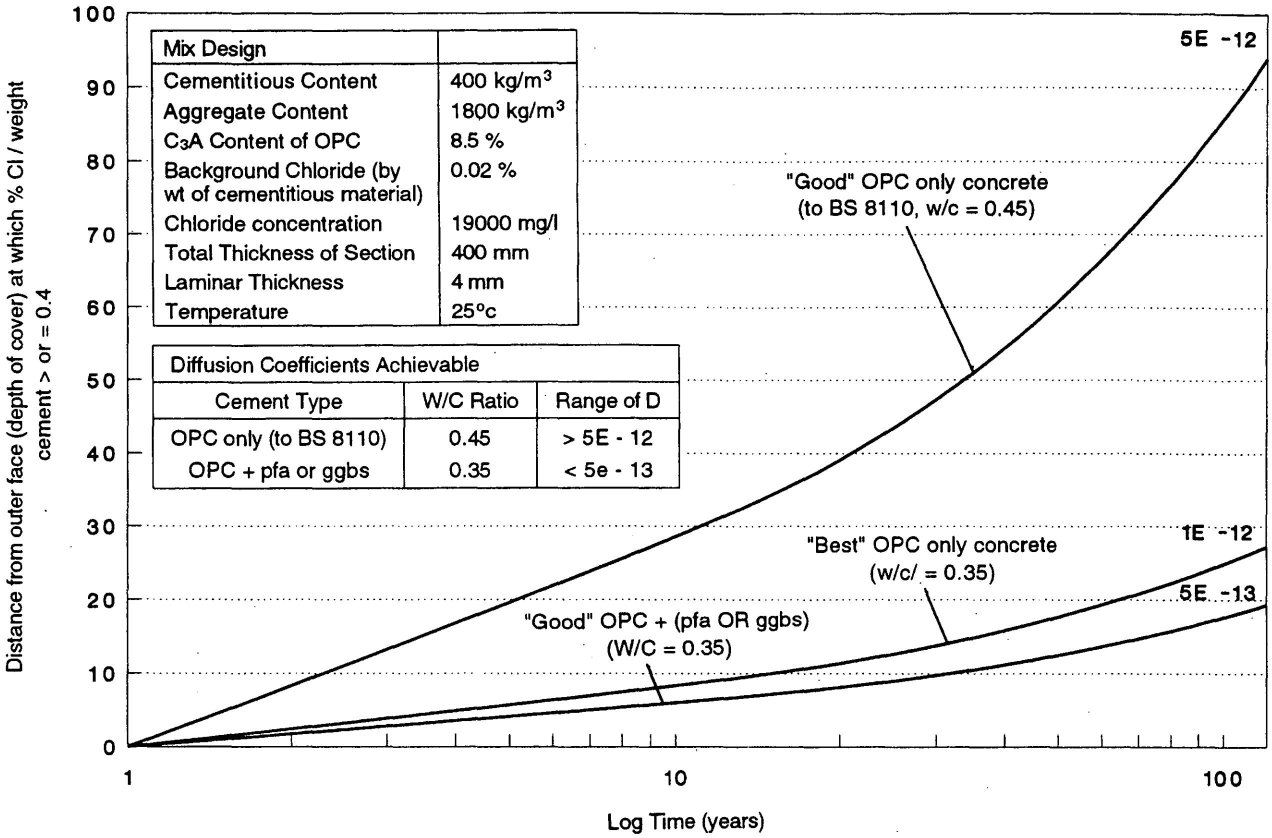
The specification should be studied to identify all the requirements that must be met and those likely to be the most difficult to achieve. The study should distinguish between compliance tests (to achieve specified values) and reference tests (where data on particular properties are required, but no minimum values must be achieved).

Time and resource implications of the testing specified, particularly where the contractor is unfamiliar with the test methods specified or long-term data are required, must be considered and a suitable program for conducting the testing developed. Some durability tests (e.g., diffusion resistance) may require extended test periods [3 to 4 months in some cases (*15*)]. It is essential that this be recognized and sufficient time allowed for all the testing to be completed and the results evaluated before construction begins.

SITE REQUIREMENTS

With the examination of the specification requirements, the individual site requirements need to be identified, particularly the types and volumes of concrete required, the earliest date by which each mix design is needed, and any special requirements of the mix for construction (e.g., pumping or placing characteristics.)

The site requirements must be carefully linked to the requirements in the specification and the testing program so that sufficient



Mix Design	
Cementitious Content	400 kg/m³
Aggregate Content	1800 kg/m³
C3A Content of OPC	8.5 %
Background Chloride (by wt of cementitious material)	0.02 %
Chloride concentration	19000 mg/l
Total Thickness of Section	400 mm
Laminar Thickness	4 mm
Temperature	25°c

Diffusion Coefficients Achievable

Cement Type	W/C Ratio	Range of D
OPC only (to BS 8110)	0.45	> 5E - 12
OPC + pfa or ggbs	0.35	< 5e - 13

FIGURE 4 Effect of diffusion coefficient (D) on depth of penetration of 0.4 percent Cl^- (by mass of cement) front (example is for concrete immersed in seawater, no external pressure).

time is allowed, before construction begins, to carry out all the necessary testing and reporting and gain approval for the use of the concrete before it is required in the structure.

MATERIALS SELECTION FOR DURABILITY

The component materials must be selected with care to ensure that the required performance level can be achieved and maintained. This necessitates considering the specification and collection of technical data on a wide range of material types and sources. It should be noted that the specification will define only minimum acceptable values and that the performance requirements of the concrete may necessitate the use of materials with superior qualities. It may therefore be necessary for the contractor to impose limits on some materials properties that are tighter than those required by the specification (e.g., the use of a tighter grading curve on aggregates or the selection of admixtures to reduce the effects of retardation.) Selection is also influenced by the availability of the required quantities of each material of the necessary quality at the delivery rates required by the construction program, handling and storage on site, and cost. A short list of materials considered to be suitable can then be established. This list can also be used to determine technical performance.

It is important to optimize the performance of the individual and the materials combinations, particularly when considering their synergistic effects—using cements with a high-lime saturation factor with pozzolanic materials and the effects of aggregate properties, cleanliness, shape, grading, on the development of the cement paste microstructure.

It is possible to produce concretes with a wide range of properties: from what would be considered normal concrete to mixes that, if carefully produced, will offer a high degree of durability. Quality assurance testing of materials throughout the duration of the contract should be undertaken to ensure that the requirements are consistently maintained.

MIX DESIGN TRIALS

Trials are essential to ensure that the specified properties can be achieved in a cost-effective manner. The mix design process must consider the factors that have the most influence over the specified parameters and design a series of trial mixes accordingly. With respect to durability against deterioration because of aggressive species in the environment, these factors are likely to be

- Minimizing voids and cracks (including micro-cracking),
- Ensuring good bond between the aggregate and the cementitious paste,
- Minimizing the porosity of the paste fraction, and
- Minimizing the paste fraction in the concrete (this is likely to be the path for the ingress of aggressive ions as dense aggregate is generally considered to be effectively impermeable).

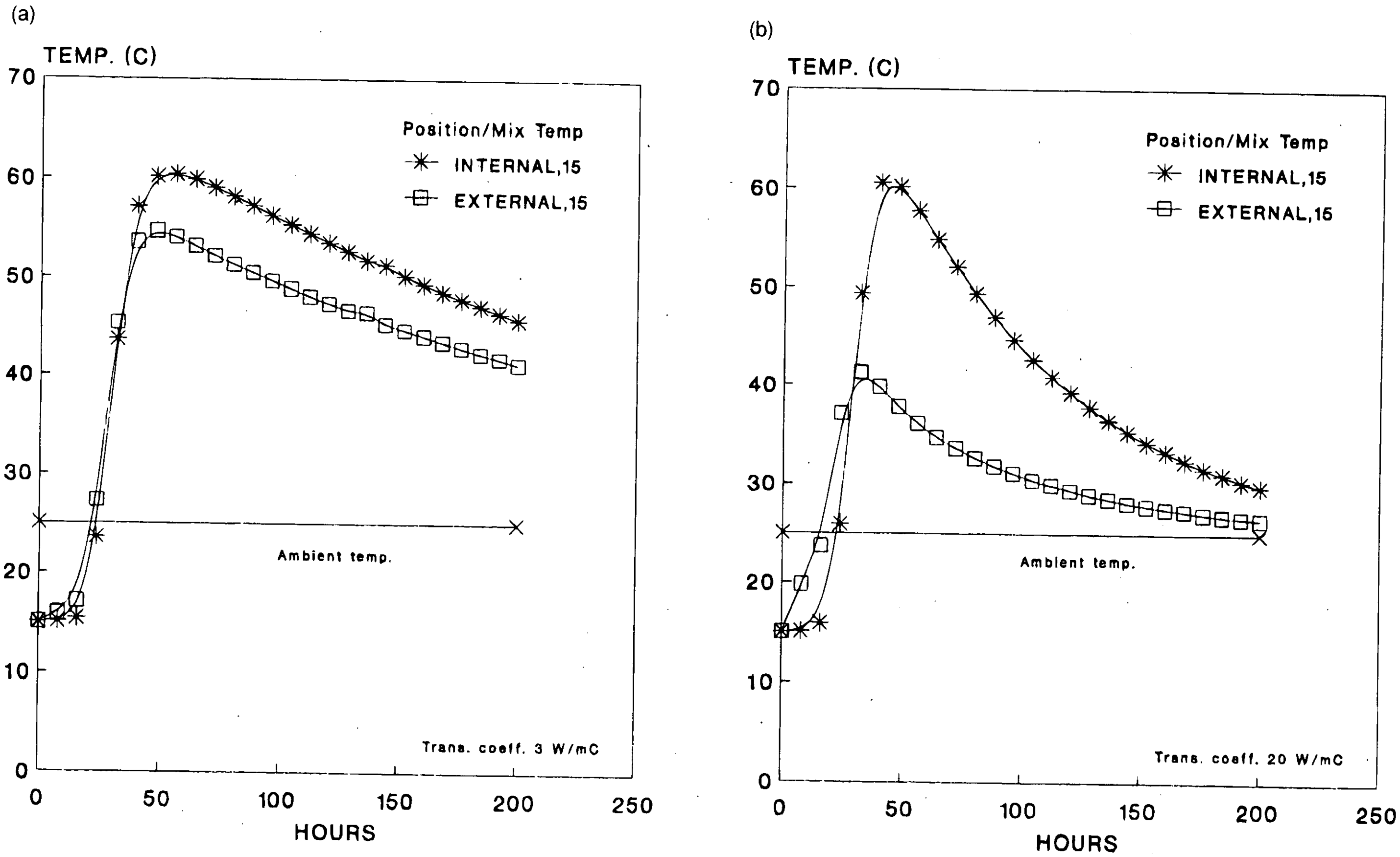


FIGURE 5 Modeling of thermal behavior of the interior and surface of concrete [examples are for a mix with a cementitious content of 400 kg/m^3, 70 percent ggbs with (*a*) extended period before striking shutters and (*b*) early striking of shutters].

The mix design should therefore adopt constituent materials and practices consistent with achieving these requirements. The use of cement replacement materials or pozzolans—such as fly ash, ground granulated blast-furnace slag (ggbs), or micro-silica—results in densification of the cement paste and modification of the long-term pore size distribution, and provides long-term hydration characteristics (*17*). The water-to-cementitious ratio adopted should be as low as practicable to minimize the porosity of the paste (but sufficiently high to prevent self-desiccation). The use of admixtures, such as plasticizers and superplasticizers, is beneficial in enabling high-workability mixes to be produced while retaining low water-to-cementitious ratios. However, other side effects, such as retardation of setting, must also be considered. The selective processing of constituent materials can improve properties that hinder workability and increase water demand, particularly aggregate shape and grading. Workability is important in the overall durability of an element by ensuring that uniform good compaction can be achieved, especially where complicated reinforcement cages are to be used.

Materials that improve some aspects of durability performance may increase the risk of deterioration from others, such as the use of pozzolanic materials to reduce porosity, and may reduce the scaling resistance of concrete exposed to deicing salts. It is important that all the results of the durability testing be considered holistically to select the most appropriate mix design for the particular application.

ADDITIONAL PROTECTIVE MEASURES

There are particularly severe environments where concrete alone will not be sufficiently durable to achieve the required design life. In such the cases, additional protective measures will need to be specified. Many systems are becoming available to improve the durability of reinforced concrete structures, including the following:

- Thermosetting and thermoplastic coatings to reinforcement;
- Coatings to the surface of the concrete;
- Admixtures to modify the structure of the cement paste, improving its resistance to the ingress of aggressive ions;
- Admixtures that modify the corrosion processes;
- Modification of the external environment, such as by cladding; and
- Cathodic protection.

These techniques all have advantages and disadvantages in service and may not be universally applicable. Specialist advice must always be sought before implementing the measures.

CONCLUSIONS

The approach described has been used to specify concrete for long-term durability on major projects around the world. By using this method it is possible to predict with a high degree of accuracy the likely behavior of different concrete mix designs in a wide range of aggressive environments. It is also possible to predict the thermal behavior of the concrete during mixing, pouring, and setting. A rational basis for the durability requirements can be established, and concrete of the appropriate standard and properties can be specified. Appropriate materials and testing to verify performance can then be selected and investigated. Testing the structure while in service may also be undertaken to verify the predictions of long-term performance. Where concrete alone will not be sufficiently durable, additional protective measures may be specified; however, these measures should not be routinely used without specialist advice.

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