INDUSTRY/FRD COLLABORATIVE RESEARCH PROGRAMME: ACHIEVING DURABLE AND ECONOMIC CONCRETE CONSTRUCTION IN THE SOUTH AFRICAN CONTEXT

SERIES OF RESEARCH MONOGRAPHS

The work reported in this monograph, and others in the series, has arisen chiefly from a research programme into how to achieve durable and economic concrete construction in the South African context. The present programme has been in operation since 1997, and continues the good work achieved in a previous programme under the Foundation for Research Development. The programme is a joint collaborative effort between research students and staff at the Universities of Cape Town and the Witwatersrand. The work of the research students, in particular, is acknowledged. The monographs are essentially compilations of research papers and reports that have emanated from the programme over the past several years.

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M G Alexander, (UCT); Y Ballim (Wits), J R Mackechnie (UCT), March 1999

See inside back cover for a list of monographs in this series

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RESEARCH MONOGRAPH NO. 2

Guide to the use of durability indexes for achieving durability in concrete structures

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Reference 16 was also used extensively in compiling this monograph, and the Concrete Society of Southern Africa is thanked for permission to use this paper.

INTRODUCTION

The durability performance of construction materials has long been a concern for engineers. Only in recent years however has the actual deterioration been accurately quantified and the extent of the problem been recognized. Durability may be defined as the ability of a material or structure to withstand the service conditions for which it was designed over a prolonged period without significant deterioration. Concrete has generally been regarded as having chemical and dimensional stability in most environments thereby possessing inherently durable characteristics. This perception is also associated with reinforced concrete structures which are expected to be relatively maintenance-free during their service life. These assumptions must be questioned given the weight of evidence of premature deterioration of concrete structures. Many modern concrete structures need substantial repairs and maintenance during their service life with the resultant costs to the economy reaching 3 – 5% of GNP in some countries.[1]

Neville[2] suggests that reasons for the widespread lack of durability include poor understanding of deterioration processes by designers, inadequate acceptance criteria of concrete on site, and changes in cement properties and construction practices.

There is an increasing awareness that concrete is a complex composite material, that environmental and service conditions vary widely and that deterioration mechanisms interact dynamically with material and structural influences. Deterioration of concrete begins almost immediately after casting as the hardened properties are influenced by phenomena which occur at an early stage, such as plastic cracking, bleeding, segregation and thermal effects. In the hardened state, concrete may be affected by a variety of internal and external factors which cause damage by physical and/or chemical mechanisms. Deterioration is often associated with ingress of aggressive agents from the exterior such that the near-surface concrete quality largely controls durability. The interaction between the various material and environmental elements influencing durability is shown in Figure 1.

The bulk of durability problems concerns the corrosion of reinforcing steel rather than deterioration of the concrete fabric itself. The problem is then cast in terms of the adequacy of the protection to steel offered by the concrete cover layer, which is subjected to the action of aggressive agents such as chloride ions or agents of acidification arising from the surrounding environment.

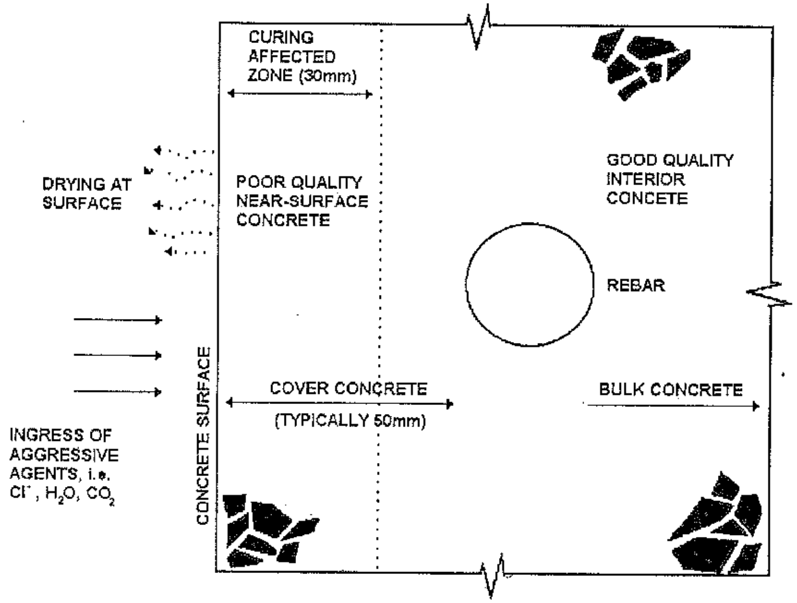

Figure 1: Schematic diagram of concrete protection of reinforcement

Modern design and construction practice has led to improvements such as the use of more consistent quality cement, higher allowable stresses, faster concrete casting and setting times and greater variety of binder types and admixtures. Whilst these advances have improved concrete productivity, they have made concrete more sensitive to abuse that has contributed to the premature deterioration of modern concrete structures. The increasing number of concrete structures exhibiting unacceptable levels of deterioration has resulted in more stringent specifications for concrete construction. Unfortunately the durability performance of concrete structures has not always shown a corresponding improvement despite these specifications. This appears to be due to a lack of understanding of what is required to ensure durability as well as inadequate means of enforcing or guaranteeing compliance with specifications during construction.

Most national codes and specifications are of the 'recipe' type, setting limits on w/c ratios, cement contents, cover, etc., but without really addressing the issue of achieving adequate quality of the concrete cover. Furthermore, it is difficult, if not impossible, to ensure compliance with these specifications on site, since they generally comprise difficult-to-measure aspects of construction. (The one notable exception is, of course, checking concrete cover to steel. Many have expressed the opinion that enforcing this one simple expedient would cure 90% of current durability problems!) It is clear that current durability specifications are not very effective.

As in other countries, durability problems in South Africa derive from inadequate attention to durability with regard to both design and construction. Coupled with a relatively harsh environment in many parts of the country, this has resulted in extensive deterioration of concrete. In response to the current situation, a concerted research effort has been mounted in South Africa to provide practical solutions to the problem of concrete durability. This research has led to the development of a durability index approach that seeks to characterize the potential durability of new concrete.

This monograph is intended to outline the philosophy of the durability index approach, to review the current index tests, and to indicate how the approach may used in practice. It is hoped that it will stimulate debate on how best to move forward in achieving better durability in concrete construction.

PHILOSOPHY OF THE DURABILITY INDEX APPROACH

A plethora of durability tests have been developed to measure fluid transport rates by various mechanisms through concrete. Sophisticated equipment, complex monitoring and lengthy testing periods are generally required to accurately model these mechanisms. While such techniques provide useful research information, they have limited practical value for site concrete given the rigorous constraints of the test methods. In response to the need for more practical durability tests, the philosophy of durability index testing of concrete was formulated, and is outlined below.

Improved durability will not be achieved unless some relevant durability parameter(s) can be unambiguously measured. This is where the crux of the problem lies. The issue is compounded by the fact that concrete is highly complex, changes with time, and is affected by a multitude of processes. However, engineers have grappled with this successfully in the past in respect of, for example, concrete strength, by adopting a simple quality control test -- the cube or cylinder compression test. The test itself bears little resemblance to the conditions existing in a real structure. Nevertheless, experience has permitted the correlation of the results of the compression test with structural performance, so that structures may be designed for different levels of stress. In essence, the test can be thought of as an 'index' test, which characterises the intrinsic potential of the material to resist applied stresses. By experience, this 'index' has come to be associated with acceptable performance, and has generally worked very well.

It is this idea of 'indexing' of the material that needs to be applied to the achievement of adequate concrete durability. What is required is a means of characterising the quality of the cover or surface layer, using parameters that influence the deterioration processes acting on the concrete. The use of strength parameters is not sufficient for this, since these merely measure the overall bulk response of the material to stress. It is the surface layer that is most affected by curing initially, and subsequently by external deterioration processes. These processes are linked with transport mechanisms, such as gaseous and ionic diffusion, water absorption, etc. Thus a series of index tests is needed to cover the broad range of durability problems, each index test being linked to a transport mechanism relevant to that particular process.

Ultimately, the usefulness of index tests will be assessed only by reference to actual durability performance of structures built using the indexes for quality control purposes. This is a long-term undertaking. A framework for durability studies is therefore necessary, incorporating early-age material indexing, direct durability testing, and observations of long-term durability performance.[3]

Material Indexing. This requires quantifiable physical or engineering parameters to characterise the concrete at early ages. Such indexes (e.g. permeability, water sorptivity), must be sensitive to important material, processing, and environmental factors such as cement type, water:binder ratio, type and degree of curing etc. The purpose of material indexing is to provide a reproducible engineering measure of microstructure and properties of importance to concrete durability at a relatively early age (eg. 28 days). The material indexes allow the material to be placed in an overall matrix of possible material values, these values depending on the important factors given above. Thus, it should be possible to produce concretes of similar durability by a number of different routes : additional curing, lower w/c ratio, choice of a different cement or extender, etc.

Direct Durability Testing. This should comprise a suite of tests suited to a range of durability problems. Such tests would embrace accelerated as well as long-term evaluations. The need for accelerated testing is obvious in view of the long time periods involved in concrete deterioration. Nevertheless, it is usually necessary to also undertake long-term testing, since mechanisms dominant in accelerated tests may be different from those in the normal environment. Observations of long-term structural behaviour are also necessary in order to provide a quantifiable estimate of durability performance.

Two other major issues exist with direct durability testing:

- The definition of a suitable measure of deterioration, and a threshold or limiting value of deterioration (e.g. should the extent of sulphate attack be characterised by measuring expansion, mass loss, change in strength and stiffness, etc?)
- A lack of standard test methods, which prevents useful comparisons between reported results and hampers understanding of mechanisms.

Correlations are required between indexes and durability results, and between these two and actual structural performance, such that the index tests can ultimately be used as follows:

- as a means of controlling a particular property of concrete, or the quality of a particular zone of a concrete element, for example the surface layer. (This control would typically be reflected by a suitable construction specification, in which limits to index values at 28 days would be specified.)
- as a means of assessing the quality of construction for compliance with a set of criteria
- as a basis for fair payment for the achievement of concrete quality
- as a means of predicting the performance of concrete in the design environment, on an empirical basis.

Index properties fulfil the requirements of a measurable property that can be specified.

In essence, durability should be viewed as a 'property' that needs to be paid for, just as strength is at present. This is consistent with the idea of concrete as an engineered material, in which the requisite properties are provided by intelligent design. Each desired property needs to be specified, and appropriately paid for. This is not to imply that the cost of concrete structures is likely to dramatically escalate due to such payment for durability. Life-cycle costing almost always proves that paying for durability initially is an investment that is best in the long run.

A strong argument can therefore be put forward for having an item in the Bill of Quantities to pay for durability. This may cover various approaches to achieving durability such as curing, material selection, mix proportions, coatings and sealants, etc.

This item in the Bill would represent a resource to ensure adequate durability. For example, if curing is the desired means of achieving a durable cover concrete, and measurement of a suitable index on the finished concrete shows that curing has not been properly carried out, then savings on the particular payment item can be redirected to provide another measure such as a suitable coating or sealant in order to ensure cover quality.

The criteria for suitable index tests require, inter alia, that the tests:

- be site- or laboratory-applicable (site-applicable could involve retrieval of small core specimens from site for laboratory testing)
- be linked to important fluid and ionic transport mechanisms and have a reasonable theoretical basis
- be quickly and easily performed with minimum demands on operator skill
- have sufficiently low statistical variability
- involve a minimum of specimen preparation, with uniform preconditioning to ensure standardized testing
- be conducted at relatively early-age (typically 28 days).

DURABILITY INDEX TESTS

Three durability index tests have been developed to characterize concrete according to transport mechanisms; oxygen permeability for permeation, water sorptivity for absorption and chloride conductivity for diffusion. The development, results and applications of these tests

are discussed briefly below. More details about the philosophy and testing procedure of durability index tests are given in companion monographs in the series.[4,5]

a) Oxygen permeability test

Permeation describes the process of movement of fluids through the pore structure under an externally applied pressure whilst the pores are saturated with the particular fluid. Permeability is therefore a measure of the capacity for concrete to transfer fluids by permeation. The permeability of concrete is dependent on the concrete microstructure, the moisture condition of the material and the characteristics of the permeating fluid.

Permeability test methods which have been developed for concrete include throughflow, inflow and falling-head types, while permeating fluids are either gases or liquids. Throughflow permeability tests attempt to determine the Darcy coefficient of permeability by measuring pressure gradient or flow rate through concrete under a sustained pressure head. Measuring permeability intrinsically is slow and often impractical for dense concretes. More empirical inflow permeability tests were therefore developed that measure the depth or amount of fluid penetration after a period of applied pressure. Falling-head permeameters apply an initial pressure to concrete and allow the pressure to decay as permeation proceeds. This approach allows for ease of testing while maintaining a high level of accuracy since pressure may be reliably monitored with time.

The falling-head gas permeameter developed at the University of the Witwatersrand by Ballim is shown in Figure 2.[6] The permeability of oven-dried concrete core samples to oxygen gas is determined by measuring the pressure decay with time (from the initial value of 100 kPa). The pressure decay curve measured either directly from gauges or using data logging from transducers is converted to a linear relationship by plotting the logarithm of the ratio of pressure heads versus time.

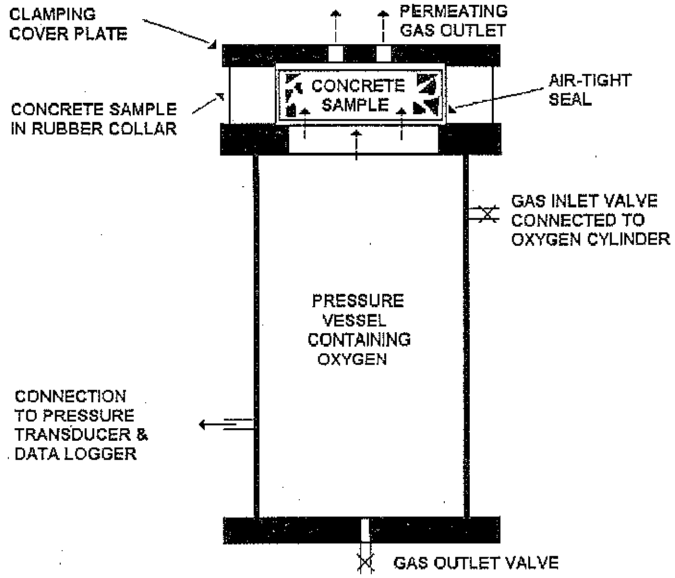

Figure 2: Oxygen permeability apparatus

From the slope of the straight line produced by this plot, the coefficient of permeability may be determined as follows (see Appendix A):

$$k = \frac{\omega V g d}{R A \theta t} \cdot \ln \frac{P_0}{P} \quad \text{.......} (1)$$

where
k – coefficient of permeability (m/s)
ω – molecular mass of permeating gas (kg/mol)
V – volume of the pressure cylinder (m^3)
g – acceleration due to gravity (m/s^2)
d – sample thickness (m)
R – universal gas constant (Nm/K mol)
A – cross-sectional area of specimen (m^2)
θ – absolute temperature (K)
t – time (s)
P_0 - pressure at start of test (kPa)
P – pressure at time t (kPa)

The coefficient of permeability is an unwieldy exponential number and it was therefore simplified by defining the permeability index (OPI) as the negative logarithm of the coefficient of permeability, i.e.

$$OPI = -\log_{10} k \quad \text{.......} (2)$$

Typical experimental plots from the oxygen permeability test are shown in Figure 3 for Grade 40 OPC concrete tested at 28 days.[7] Figure 4 shows OPI results for 3 different grades of OPC concrete. Oxygen permeability results may be used to characterize young concrete for influences such as concrete grade, binder type, initial curing and construction effects such as compaction. Oxygen permeability may also be used at later ages to assess the deterioration of concrete but careful interpretation is required when assessing results.

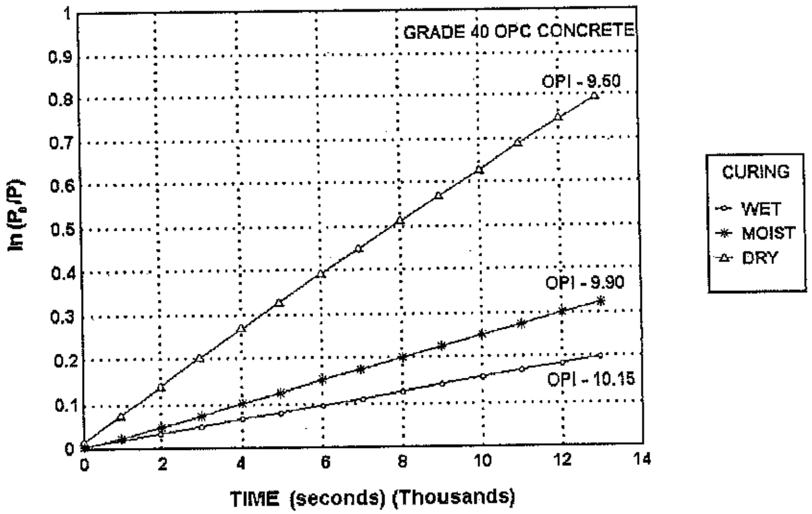

Figure 3: Typical oxygen permeability results

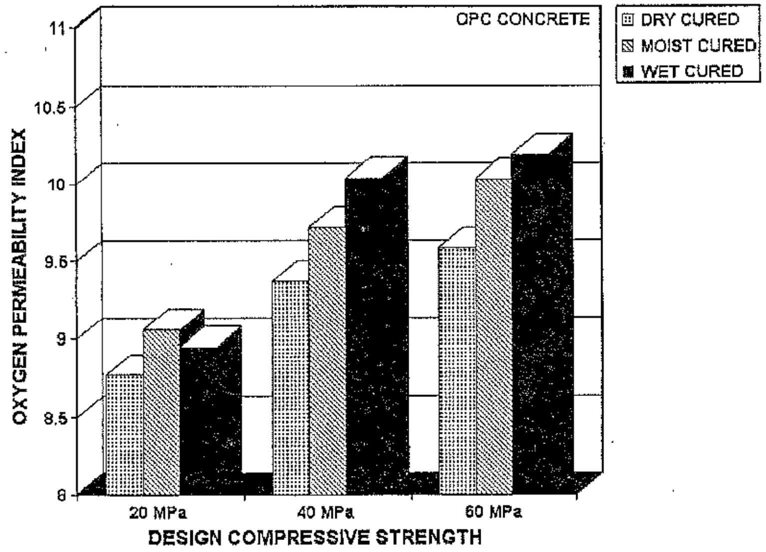

Figure 4: Oxygen permeability index for OPC concretes with varying degrees of moist curing

b) Water sorptivity test

Absorption is the process whereby fluid is drawn into a porous, unsaturated material under the action of capillary forces. The capillary suction is dependent on the pore geometry and the saturation level of concrete. Water absorption caused by wetting and drying at the concrete surface is an important transport mechanism near the surface but becomes less significant with depth. The rate of movement of a wetting front through a porous material under the action of capillary forces is defined as sorptivity.

Several general absorption tests have been developed for concrete in which concrete is immersed in water and the total mass of water absorbed is used as a measure of the absorption of the material. These tests merely measure the porosity of the concrete but cannot quantify the rate of absorption and do not distinguish between surface and bulk effects. Essentially such tests measure porosity which may not be sensitive to the transport mechanisms influencing concrete durability.

A modified version of Kelham's sorptivity test was chosen as a compromise between acccuracy and ease of use.[8,9] Concrete samples (usually cores 68 mm diameter, 25 mm thick) are initially preconditioned at 50°C to ensure uniformly low moisture contents at the start of the test. The circular edges of the core are sealed with either epoxy or tape to ensure uni-directional absorption. The concrete specimens are then exposed to a few millimetres of water with the test surface facing downwards as shown in Figure 5. At regular time intervals, the specimens are removed from the water and the mass of water absorbed is determined using an electronic balance. Measurements are stopped before saturation is reached and the concrete is then vacuum-saturated in water to determine the effective porosity.

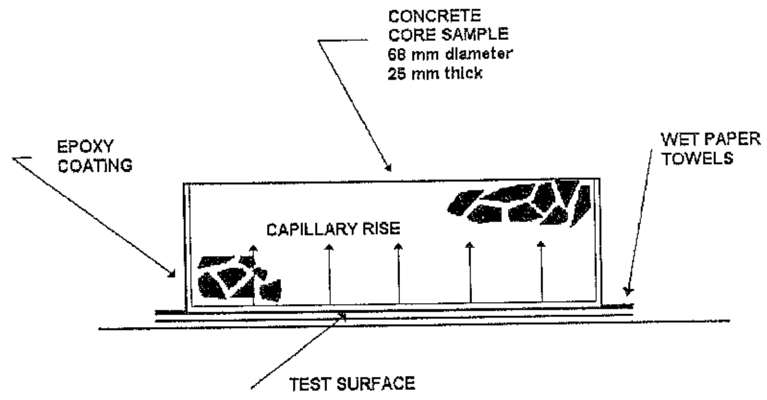

Figure 5: Water sorptivity test

A linear relationship is observed when the mass of water absorbed is plotted against the square root of time. The sorptivity, S of the concrete is determined from the slope of the straight line produced (see Appendix B), such that:

$$S = \frac{\Delta M_t}{t^{1/2}} \cdot \frac{d}{M_{sat}-M_0} \quad \text{..} (3)$$

where
ΔM_t – change of mass with respect to the dry mass (g)
M_{sat} – saturated mass of concrete (g)
M_0 – dry mass of concrete (g)
d – sample thickness (mm)
t – period of absorption (hr)

The sorptivity test is able to characterize concrete for much the same influences as the permeability test but with emphasis more on near-surface effects such as curing. Typical experimental data are shown in Figure 6.[7] (Note that the early (1 min) rapid increase in mass is omitted in the calculations.)

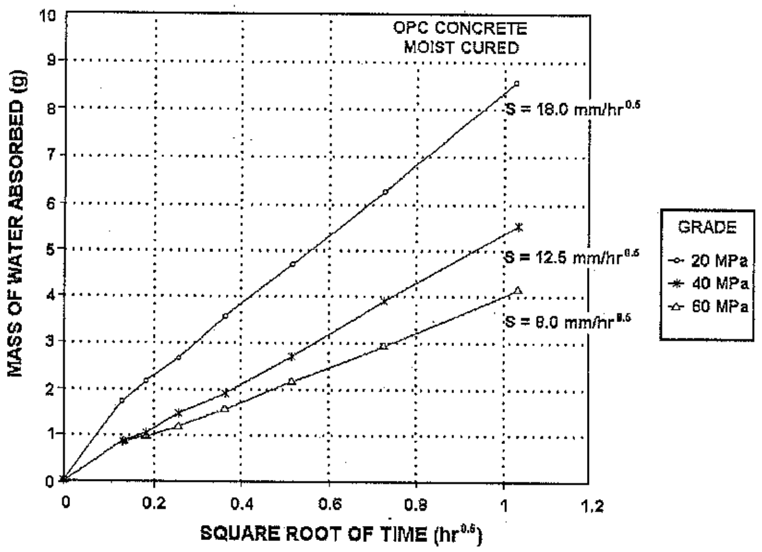

Figure 6: Water sorptivity results

Figure 7 shows water sorptivity indexes for three different grades of OPC concrete.

The degree of initial curing affects the quality of the concrete near-surface which in turn influences the sorptivity of the material. Sorptivity testing is best done on young concretes as older concretes may be contaminated with salts or be carbonated which alters the absorption of water into the pore structure.

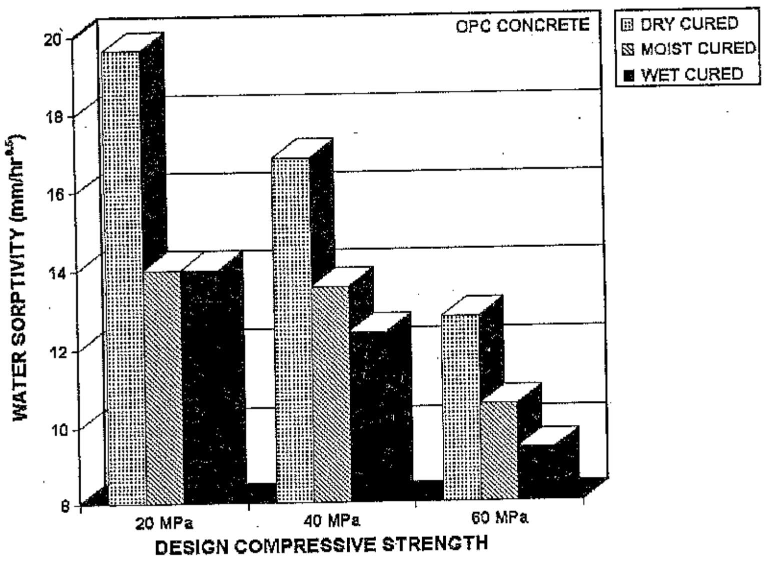

Figure 7: Water sorptivity indexes for OPC concretes with varying degrees of moist curing

c) Chloride conductivity test

Diffusion is the process by which liquid, gas or ions move through a porous material under the action of a concentration gradient. Diffusion occurs in partially or fully saturated concrete and is an important internal transport mechanism for most concrete structures exposed to salts. High surface salt concentrations are initially developed by absorption, and the salt migrates by diffusion towards the low concentrations of the internal material. Diffusion rates are dependent on temperature, moisture content of concrete, type of diffusant and the inherent diffusibility of the material. Diffusion into concrete is complicated by chemical interactions, partially saturated conditions, defects such as cracks and voids and electrochemical effects due to steel corrosion and stray currents. In the marine environment, diffusion of chloride ions is of particular importance due to the depassivating effect of chlorides on embedded steel which ultimately may lead to corrosion.

Intrinsic diffusion tests, where concrete is exposed to high and low concentrations of the diffusing species on opposite faces, have been successfully used to measure the coefficient of diffusion. Diffusion is a slow process, even when using high concentration gradients and these tests may take several months to reach equilibrium. Accelerated diffusion tests using an applied potential difference have therefore been developed to obtain more rapid results in the laboratory. A fundamental weakness of some of these rapid chloride migration tests is that the increased ionic flux is caused by both diffusion and conduction and some tests lack a sound theoretical basis.

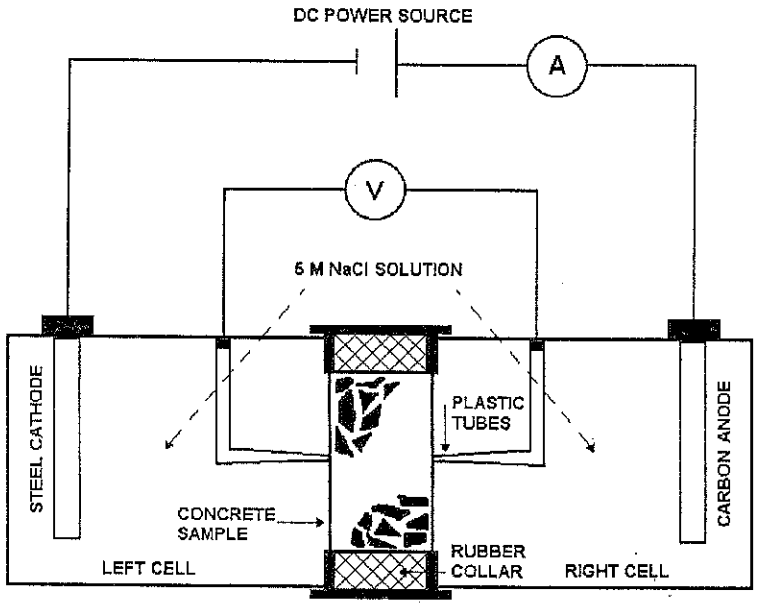

Figure 8: Chloride conductivity apparatus

Streicher has developed a rapid chloride conductivity test at UCT where the ionic flux occurs by conduction due to a 10V potential difference.[10] The apparatus, shown in Figure 8, consists of a two cell conduction rig in which concrete core samples are exposed on either face to 5M NaCl solution. The core samples are preconditioned before testing to standardize the pore water solution (oven-dried at 50 °C followed by 24 hours vacuum saturation in a 5M NaCl solution). The movement of chlorides is accelerated by applying a 10V potential difference and the chloride conductivity determined by measuring the current flowing through the concrete specimen. The apparatus allows for rapid testing

(virtually instantaneous readings) under controlled laboratory conditions.

The chloride conductivity of concrete may be defined as follows (see Appendix C):

$$\sigma = \frac{i\,t}{VA} \quad \text{.......................................} \quad (4)$$

where σ – chloride conductivity (mS/cm)
i – current (mA)
V – voltage (V)
t – specimen thickness (cm)
A – cross-sectional area (cm^2)

Chloride conductivity decreases with the addition of fly ash, slag, and silica fume in concrete, extended moist curing and increasing grade of concrete. While the test is sensitive to construction and material effects that are known to influence durability, results are specifically related to chloride ingress into concrete. Figure 9 shows typical results measured at 28 days.[7]

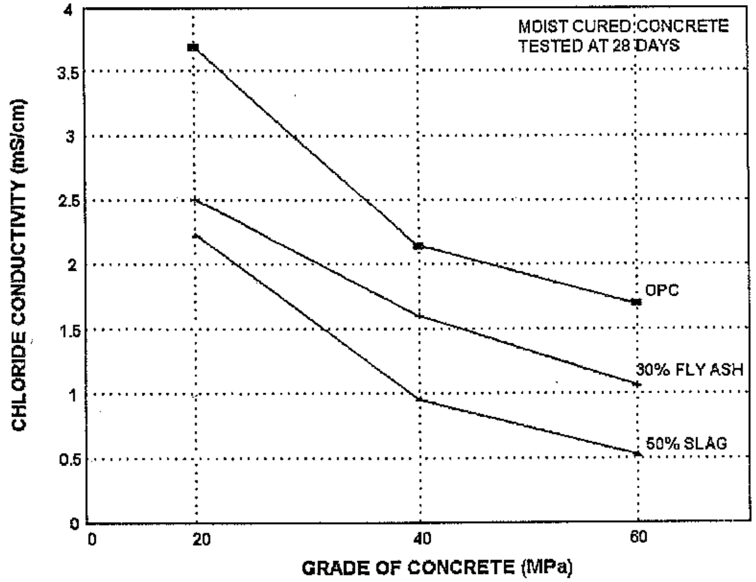

Figure 9: Chloride conductivity results

USE OF DURABILITY INDEX TESTS

A suite of three durability index tests – oxygen permeability, water sorptivity and chloride conductivity – have been shown to be sensitive to the important material, environmental and constructional factors known to influence concrete durability. The index tests may be used in the following applications:

a) Quality control of site concrete

The sensitivity of the index tests to material and constructional effects makes them suitable tools for site quality control. Since the different tests measure distinct transport mechanisms, their suitability depends on the property being considered. Permeability is best suited for assessing compaction since it is particularly sensitive to changes in the coarse pore fraction; sorptivity is sensitive to surface phenomena such as the effects of curing, while chloride conductivity provides good characterization of marine concretes.

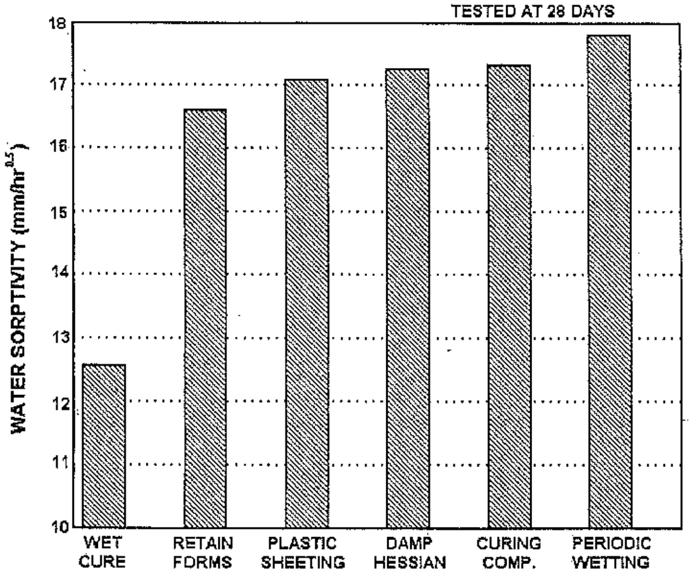

Figure 10: Sorptivity versus initial curing

The sensitivity of sorptivity testing to curing is illustrated from a laboratory study where concrete panels were exposed to a variety of curing systems.[11] The concrete panels, of grade 40 OPC concrete, were initially cured in a variety of ways for seven days before being exposed to dry summer conditions until 28 days. Control concrete cured in water for 28 days had significantly lower sorptivity than any of the other curing systems as shown in Figure 10.

b) Concrete mix optimization for durability

Durability index testing may be used to optimize materials and construction processes where specific performance criteria are required. At the design stage the influence of a range of parameters such as materials and construction sytems may be evaluated in terms of their impact on concrete durability. A cost-effective solution to ensuring durability may in this way be assessed using a rational testing strategy.

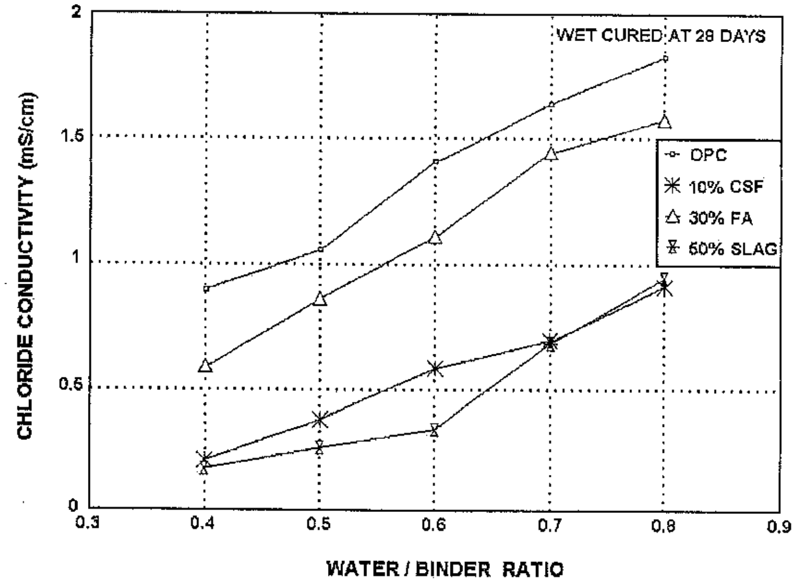

Figure 11: Chloride conductivity versus water/binder ratio

When designing reinforced concrete structures in the marine environment, the chloride resistance is critical for durability. The effect of various binder systems on the chloride resistance of concrete can be rapidly assessed using the chloride conductivity test. Figure 11 shows chloride conductivity results for a range of concrete types plotted against water: binder ratio.[12]

For mix design purposes, it is necessary to be able to choose appropriate proportions and materials to satisfy required index values. Figures 12, 13 and 14 provide guides for such selections, for the three durability index values and concretes based on OPC, or blends of OPC with FA (30%), GGBS (50%) or CSF (10%). These figures should help to provide first estimates for design and it will usually be necessary to check by conducting laboratory or site trials with actual mixes.

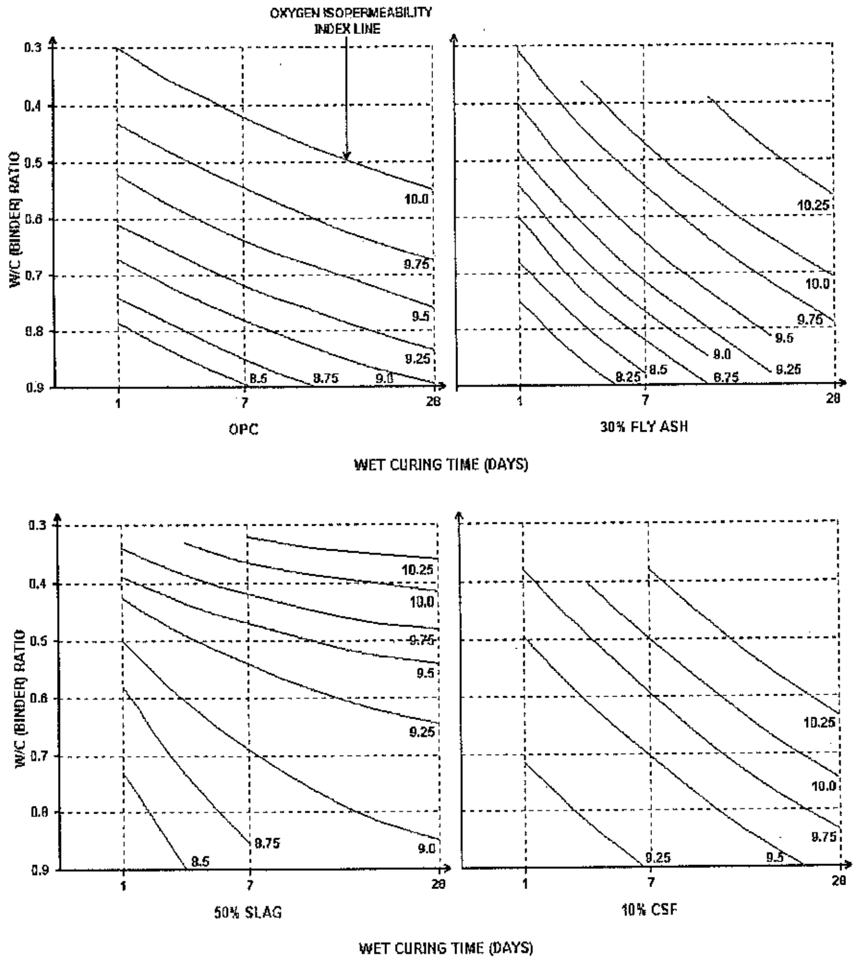

Figure 12: Isopermeability curves for concretes of different cement types

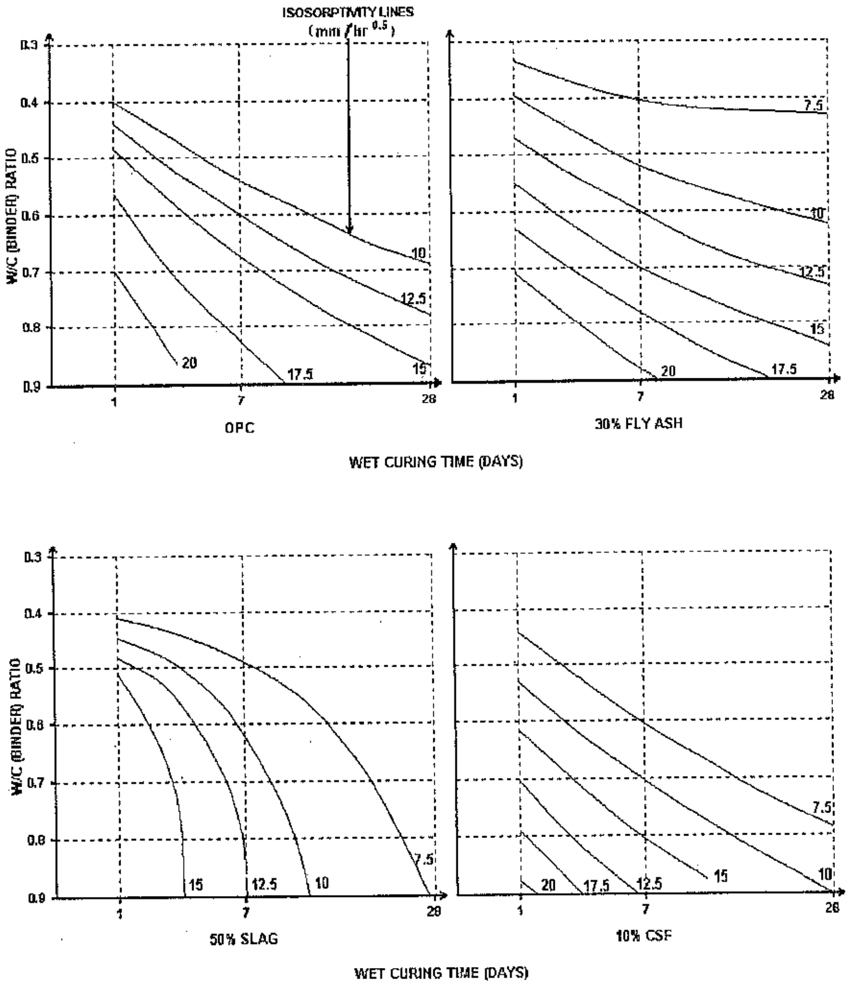

Figure 13: Isosorptivity curves for concretes of different cement types

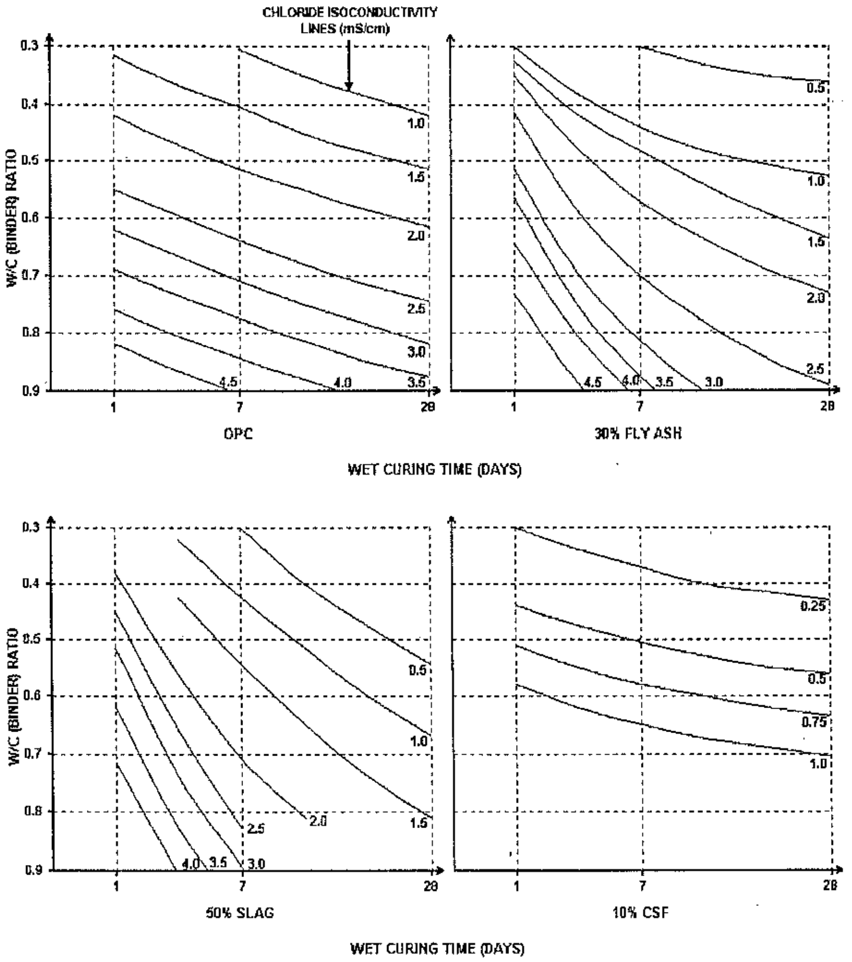

Figure 14: Isoconductivity curves for concretes of different cement types

c) Performance-based specifications

From controlled laboratory studies and site data, a matrix of durability index parameters is being developed that could be used to produce a set of acceptance and rejection criteria for performance-based specifications. The approach needs to be refined and launched on an incremental basis but could have major benefits for all parties involved in construction. The current prescriptive approach to durability specifications is not only vague and sometimes inappropriate but it is often inflexible. Performance-based specifications allow contractors more leeway in deciding how best to achieve the durability requirements while still having sufficient control to ensure satisfactory compliance. Suggested ranges for durability classification of concretes for the three index tests, based on site and laboratory data, are shown in Table 1.

Table 1: Suggested ranges for durability classification using index values

Durability class	*OPI (log scale)*	*Sorptivity (mm/√h)*	*Conductivity (mS/cm)*
Excellent	>10	<6	<0,75
Good	9,5 – 10	6 – 10	0,75 – 1,50
Poor	9,0 – 9,5	10 – 15	1,50 – 2,50
Very poor	<9,0	>15	>2,50

d) Predictions of long-term performance

Service life predictions of reinforced concrete structures are affected by a large number of variables that prevent precise estimates of durability performance. The durability prospects of concrete structures can be improved by having a broad framework that allows for a system of rational designs, practical specifications and means of ensuring satisfactory compliance with specifications on site. Since durability index tests are based on transport mechanisms associated with deterioration, it is not surprising that these indexes are able to be used for durability predictions. Correlations between oxygen permeability and carbonation depth have been found to be good and are shown in Figure 15.[12]

Correlations between 28 day chloride conductivity results and diffusion coefficients after several years marine exposure have also been shown to be good over a wide range of concretes as shown in Figure 16.[12] Some of the variability observed may be ascribed to the fact that the results represent three separate studies where concrete specimens of differing sizes were exposed to three different marine sites in the Cape Peninsula.

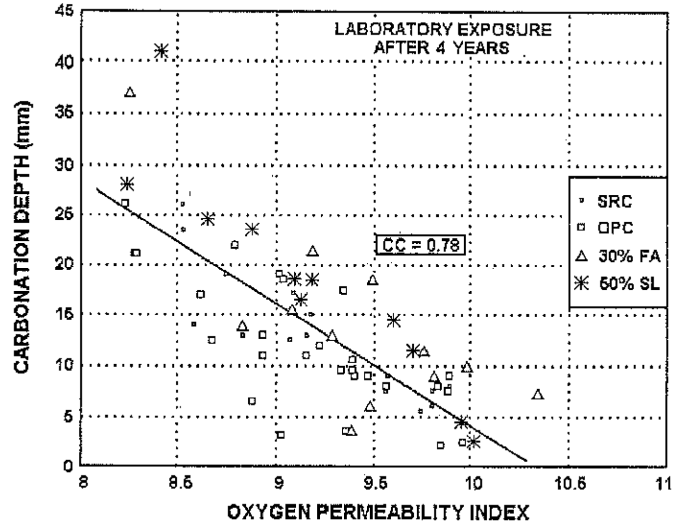

Figure 15: Oxygen permeability index versus carbonation depth

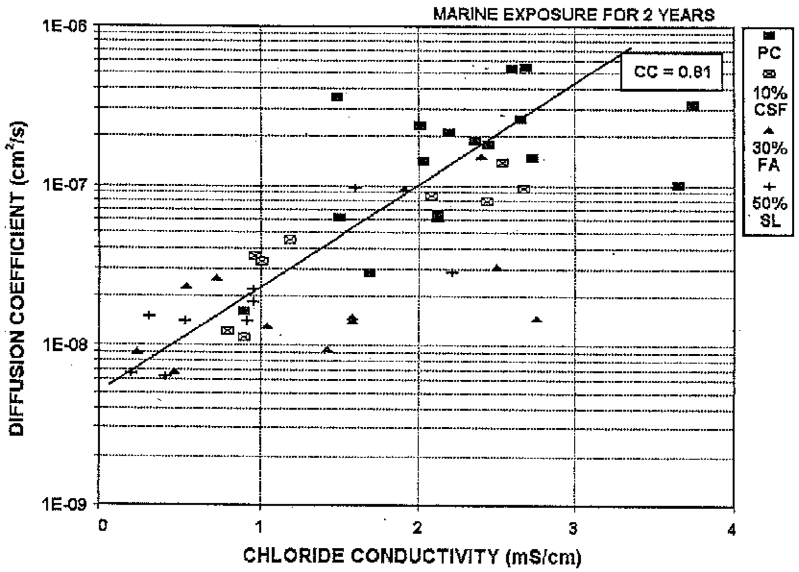

Figure 16: Chloride conductivity versus diffusion coefficient

Durability index tests that measure early-age concrete properties should not be used indiscriminately when making durability predictions. Comparisons between different concretes in particular may be misleading unless long-term effects are considered. Durability predictions should only be made once the relationship between early-age properties and medium or long-term durability performance has been established. Further details about durability predictions for marine concrete structures are given in a companion research monograph in the series.[13]

CLOSURE

A new approach is required to solve the problem of lack of durability in concrete structures. This approach must take a broad view, incorporating a proper definition of the environment, characterisation of the material, and long-term observations of durability performance. By integrating these various aspects, performance specifications can ultimately be produced which require certain durability criteria to be met, while at the same time allowing contractors opportunity to provide innovative and cost-effective solutions.

The durability index approach discussed in this monograph is premised upon the need to provide quantifiable physical and engineering parameters to characterise concrete at relatively early ages. These parameters can be expressed as durability indexes which must be sensitive to the important material, environmental and constructional factors which influence concrete durability. The purpose of such material indexing is to provide a reproducible engineering measure of microstructure, reflecting the transport properties of importance to concrete durability.

Three durability index tests have been proposed: an oxygen permeability index test, a water sorptivity test, and a chloride conductivity test. Each of these measures distinctly different transport properties of the cover layer of concrete. As such they span a range of transport processes which influence concrete durability, i.e. gas permeation, water absorption, and chloride diffusion. The advantages of the tests are that they have a sound theoretical basis, are site- and lab-applicable, are quickly and easily performed, and have sufficiently low statistical variability. The properties of oxygen permeability, water sorptivity, and chloride conductivity are not measured for their own sake, but rather as material indexes i.e. reproducible engineering measures of the ability of the concrete surface layer to resist certain durability-related processes.

It has been shown that the index tests can be used for a number of engineering purposes:

- for quality control of site concrete
- for concrete mix optimisation for durability
- as a basis for performance specifications
- for predictions of long term durability performance.

There is a need to exercise due care in interpreting the results of the index tests, particularly if the samples are retrieved from site concrete. All factors such as the type and nature of the concrete, the likely or actual environment, and possible deterioration must be taken into account. It must also be remembered that the purpose of the approach is to characterise potential durability in terms of relatively early-age properties. It appears that this indexing method of improving concrete durability holds promise for the future.

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APPENDIX A: PERMEABILITY THEORY

The D'Arcy equation for permeation can be expressed as

$$\frac{\partial m}{\partial t} = \frac{-k}{g}\frac{\partial P}{\partial z} \quad \text{.........} \quad (A1)$$

where $\partial m/\partial t$ is the rate of mass flow per unit cross-sectional area
$\partial P/\partial z$ is the pressure gradient in the direction of flow
k is the coefficient of permeability
g is the acceleration due to gravity

For a gas, mass is related to volume V and pressure P by the equation:

$$m = \frac{\omega V P}{R\theta} \quad \text{.........} \quad (A2)$$

where ω is the molecular mass of permeating gas
θ is absolute temperature
R is the universal gas constant

The change in total mass of stored gas in time ∂t is

$$\frac{\partial m}{\partial t} = \frac{\omega V}{R\theta} \cdot \frac{\partial P}{\partial t}$$

For a test specimen of cross-sectional area A, measured normal to the direction of flow, and thickness d; equation (A1) can be rewritten

$$\frac{\partial m}{\partial t} = \frac{k}{g} \cdot \frac{PA}{d}$$

Hence,

$$\frac{\omega V}{R\theta} \cdot \frac{\partial P}{\partial t} = \frac{-k}{g} \cdot \frac{PA}{d}$$

Rearranging,

$$\frac{-\omega V g d}{R\theta k A} \cdot \frac{\partial P}{P} = \partial t$$

Integrating,

$$\frac{-\omega V g d}{R\theta k A} \cdot \ln(P) = t + \text{constant} \quad \text{.........} \quad (A3)$$

At $t = 0$, $P = P_0$, therefore

$$\text{constant} = \frac{\omega V g d}{R\theta k A} \cdot \ln(P_0)$$

Substituting into equation (A3),

$$t = \frac{\omega V g d}{R\theta k A} . \ln \frac{P_0}{P}$$

Rearranging, $$k = \frac{\omega V g d}{R A \theta t} . \ln \frac{P_0}{P} \quad \text{.......... (A4)}$$

APPENDIX B: ABSORPTION THEORY

Using the one dimensional case of water absorption with defined boundary conditions, it is possible to define sorptivity in terms of the extended D'Arcy equation such that

$$i = S\, t^{1/2} \quad \text{.......... (B1)}$$

where i is the cumulative water absorption per unit area
S is sorptivity
t is time

Using equation B1 the change of mass with time after water infiltration can be described by the following equation

$$\Delta M_t = A n \rho_w S t^{1/2} \quad \text{.......... (B2)}$$

where ΔM_t is the change of mass with respect to the dry mass
A is the cross-sectional area
n is the effective porosity of the concrete
ρ_w is the density of water

The effective porosity is determined as follows

$$n = (M_{sat} - M_0)/(A d \rho_w) \quad \text{.......... (B3)}$$

where M_{sat} is the saturated mass of concrete
M_0 is the dry mass of concrete
d is the sample thickness

Substituting into equation (B2),

$$\Delta M_t = \frac{M_{sat} - M_0}{d} . S t^{1/2}$$

Thus $$S = \frac{\Delta M_t}{t^{1/2}} . \frac{d}{M_{sat} - M_0} \quad \text{.......... (B4)}$$

where $\Delta M_t / t^{1/2}$ is the slope of the straight line produced when the mass of water absorbed is plotted against the square root of time.

APPENDIX C: DIFFUSION THEORY

The diffusion process is described by Fick's first law of diffusion for steady state conditions, such that

$$J_x = -D_f \cdot \frac{\partial C}{\partial x} \quad \text{.......} \quad (C1)$$

where J_x is the flux per unit cross-sectional area of the liquid
D_f is the diffusion coefficient
C is the concentration of the liquid

When the liquid is constrained in a pore structure with longer diffusion paths to that of the free liquid phase, a diffusion coefficient D_p may be defined with respect to the pore liquid of the material such that

$$J_x = -D_p \frac{\partial C}{\partial x} \quad \text{.......} \quad (C2)$$

The configuration of the pore structure with longer diffusion paths and localized constrictions produces lower diffusion coefficients, D_p compared to D_f for the free liquid phase. This is due to the constrictivity δ and tortuosity τ of the pore system which effectively restricts diffusion such that

$$D_p = D_f \, \delta / \tau^2 \quad \text{.......} \quad (C3)$$

The flux may be expressed in terms of the medium rather than the liquid to produce the following equations, where < > refers to the medium generally and not the pore liquid.

$$< J_x > = -D_i \frac{\partial C}{\partial x}$$

and $$D_i = D_f \frac{\varepsilon \delta}{\tau^2}$$

where ε is the volume fraction of porosity
D_i is the intrinsic diffusion coefficient

The quantity $\varepsilon\delta/\tau^2$ is a material property that characterizes the pore structure and is referred to as the diffusibility Q of the material.

Diffusibility is an intrinsic material property defined by the concrete pore structure while diffusivity D defines the material resistance to

diffusion being dependent on material properties and the concentration and mobility of diffusing ions.

$$Q = \frac{D}{D_0} = \frac{\sigma}{\sigma_0} \quad \text{.......} \quad (C4)$$

where D is the diffusivity of the ions through the material
D_0 is the diffusivity of the ions in the pore solution
σ is the conductivity of the material
σ_0 is the conductivity of the pore solution

The diffusion of chloride ions through concrete under non-steady state conditions may be described by Fick's second law of diffusion as follows

$$\frac{\partial C}{\partial t} = D_c \frac{\partial^2 C}{\partial x^2} \quad \text{.......} \quad (C5)$$

where D_c is the apparent diffusion coefficient
x is the depth into the material

The partial differential equation C5 may be solved by applying the following boundary conditions and assumptions:

- the surface concentration C_s reaches a constant value almost immediately
- the internal concentration C_x is zero at some point internally
- the diffusivity of the material is constant with depth and time
- the concrete is saturated throughout the diffusion process
- there is no significant interaction between diffusant and concrete

The solution may be written as follows

$$C_x = C_s(1 - \text{erf}\,[x/(2\sqrt{D_c t})]) \quad \text{.......} \quad (C6)$$

where erf is the mathematical error function

Despite the lack of compliance with the above conditions, the error function solution of Fick's Law is widely used. The equation has been found to be useful for characterizing chloride ingress into concrete but may be misleading when used to predict long-term chloride concentrations in concrete.