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Concrete mixes for durable marine structures

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The marine environment provides a severe test of the durability of reinforced concrete structures. Predictions of durability need to consider the complex interactions between environment, materials and structure that affect long-term performance of marine structures. An empirical chloride prediction model has been developed for chloride ingress into marine concretes. The prediction model was formulated from the relationship between early-age chloride conductivity test results and medium-term and long-term observations of the performance of concrete in different marine environments. This paper presents some of the practical results of this approach in terms of design limits and mix design recommendations. Design guidance is given such that a matrix of factors may be optimised, including water/binder ratio, binder type, cover depth, environment, and construction practice, in order to produce durable marine concrete structures. Preferred concrete mixes for marine applications are also given, showing the advantage of concrete containing supplementary cementitious materials. However, good material selection and design are not sufficient to ensure durability, and recommendations are made for a system of performance specifications to ensure durable marine structures.

INTRODUCTION

The marine environment provides a severe test of the durability of reinforced concrete structures due to chloride-induced corrosion of reinforcement. Corrosion may occur fairly rapidly and is invariably expensive to repair. Several South African research papers have been published in recent years on the deterioration of reinforced concrete structures in marine environments, methods of predicting chloride ingress and suitable methods of repair (Strohmeier & Alexander 1996; Mackechnie & Alexander 1997; Alexander & Scott 1999). Information is therefore available to designers, specifiers and contractors to ensure that durable marine concrete structures can be constructed.

Concrete mix design for marine applications is no longer a 'black box' topic requiring mere rules of thumb. It is now possible to undertake rational design of concrete mixes based on performance data of South African materials under actual marine exposure conditions. Research has produced a rational prediction model that allows chloride ingress rates to be estimated for various concrete types in different marine exposure environments.

Design of durable concrete mixes is multifaceted, incorporating cognisance of the environment, selection of suitable binders and mix ratios, corresponding minimum cover depths, allowance for construction factors such as curing, and appropriate concrete grade for structural purposes. All of these factors need to be 'matrixed' into a final solution that is both economical and practical. Equally important is the need for site verification and quality control of construction to ensure that the design specifications are satisfied. This requires a scheme that involves

actual measurement of concrete and cover properties in new structures, coupled with suitable measures to handle non-compliance (Alexander 2003).

This paper provides useful design information for practitioners at the preliminary design stage. It also covers aspects of site assessment of concrete for achievement of durability during the construction stage. The approach adopted is to

- provide a classification of environmental aggressiveness by means of suitable marine exposure categories
- use an existing chloride prediction model to estimate the likely performance of reinforced concrete structures in marine environments
- present the results generated from the model in a form readily usable by design engineers, that is, in terms of appropriate concrete cover, w/b ratio, binder types and concrete grade
- relate predicted performance to a measurable parameter, the chloride conductivity index, which can be used to assist in specifying and controlling the quality of concrete structures

DESIGNING FOR DURABILITY IN THE MARINE ENVIRONMENT

Chloride-induced corrosion of reinforcing steel is the major form of deterioration of marine concrete structures. Potential durability may therefore be defined in terms of resistance of the cover concrete to chloride ingress, that is, the protection provided to the reinforcement. When designing for durability, a number of important factors need to be considered.

Table 1 Marine exposure categories for South African conditions

Marine exposure category (after BS 8110 and SABS 0100-2)	Marine tidal and splash zones	Marine spray zones
Extreme	Exposed to sea water, heavy wave action	Not applicable
Very severe	Exposed to sea water, sheltered location	Within 500 m of shore in an exposed location
Severe	Not applicable	Near shore (> 500 m) in an exposed location
Moderate	Not applicable	Anywhere else within 30 km of the coast

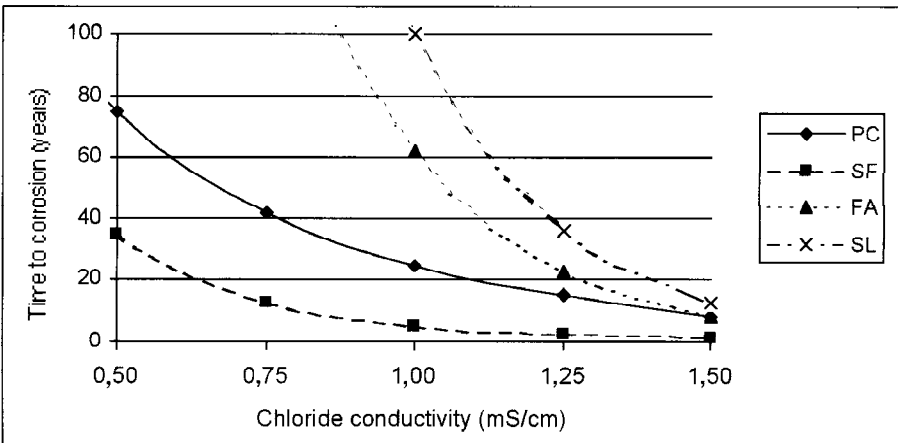


Figure 1 Durability predictions for extreme marine exposure (cover depth of 50 mm)

Severity of exposure

The severity of marine exposure varies considerably depending on local climatic conditions, location relative to the sea, and service function. The current SA code of practice SABS 0100-2 (SABS 1992) provides limited guidance about exposure conditions, without being specific concerning the different marine zones in which structures may exist. The wide variations of exposure in the spray zone are not adequately defined. This is particularly problematic since most marine concrete structures are located in the spray zone. A more comprehensive and rational system of defining the severity of marine exposure is shown in table 1 (Mackechnie 2001; British Standards Institute 1985; SABS 1992).

Design life

The selection of a design life for a structure generally implies that this is the useful service life before major repairs or obsolescence occurs. The high capital cost of reinforced concrete structures means that relatively long service lives are required, typically 50 years or more. Selection of short design lives (ie less than 30 years) for temporary installations may become problematic as many of these structures become permanent installations and cannot be replaced (eg Saldanha Ore Jetty). Bridge structures and strategic installations generally require design lives of over 100 years.

Binder type

The type of binder used in concrete has a major influence on durability, since the material affects the rate at which chlorides move through the concrete cover. Current codes of practice largely ignore the role of different binder types in controlling chloride resistance and mainly rely on the grade of the concrete and minimum binder contents as indicators of performance (SABS, 1992). While chloride resistance of concrete does improve with increasing concrete grade, far better resistance can be achieved using concrete containing supplementary cementitious materials such as ground granulated slag (SL), fly ash (FA) and silica fume (SF). Accepted replacement levels for these materials are 50 % for slag, 30 % for fly ash and 8-10 % for silica fume.

Site practice

Poor site practice, particularly with regard to placing, compacting and curing of concrete may negate the benefits of good design and material selection. Active moist curing is known to improve the near-surface properties of concrete while poor placing and compaction allows immediate short-circuits to the reinforcement (Ballim 1993). Unfortunately many of these construction activities are not easy to specify and monitor on site. Until suitable methods have been implemented to guarantee compliance on site, these

crucial activities are not likely to be given the attention they deserve.

Cover to reinforcing steel

The durability of reinforced concrete is greatly enhanced if adequate cover is provided to the reinforcement. Cover to reinforcement for marine concrete structures should ideally be between 50 and 70 mm, depending on the concrete binder type and grade. Low cover depths are risky even when using high-quality concrete, since defects such as cracks and voids may provide a low resistance path to the steel. Cover depths of 75 mm and greater should be used with caution because of the potential of cracking at the concrete surface.

BACKGROUND TO THE CHLORIDE PREDICTION MODEL

The chloride prediction model was based on the empirical relationship between early-age concrete properties and medium-term (three years) performance data from marine exposure stations (Mackechnie 1996). Chloride resistance of concrete was measured using a simple and rapid chloride conductivity test (Streicher & Alexander 1995). Predictions are based on correlations between 28-day chloride conductivity results and medium-term chloride diffusion coefficients measured after marine exposure. Further marine exposure testing has been undertaken since the development of the model, specifically with regard to silica fume and slag concrete (Mackechnie & Alexander 2002 *et al*, Magee *et al* 2002).

The procedure for constructing the prediction model was as follows:

- Concrete was characterised at 28 days using the chloride conductivity test, which has the advantage of being rapid and simple to perform while having a sound theoretical basis.
- Allowance was made for continuing cementing reactions and chloride binding on the basis of binder type. This ensures that predictions are not made on the basis of sometimes misleading early-age properties of concrete.
- Concrete blocks were placed into several marine environments for periods of up to eight years, and rates of chloride ingress monitored periodically.
- Fick's second law of diffusion is used in the model but modified to allow for reducing diffusion coefficients with time.
- The reliability of the prediction model was validated using data from a range of concrete structures in the marine environment.

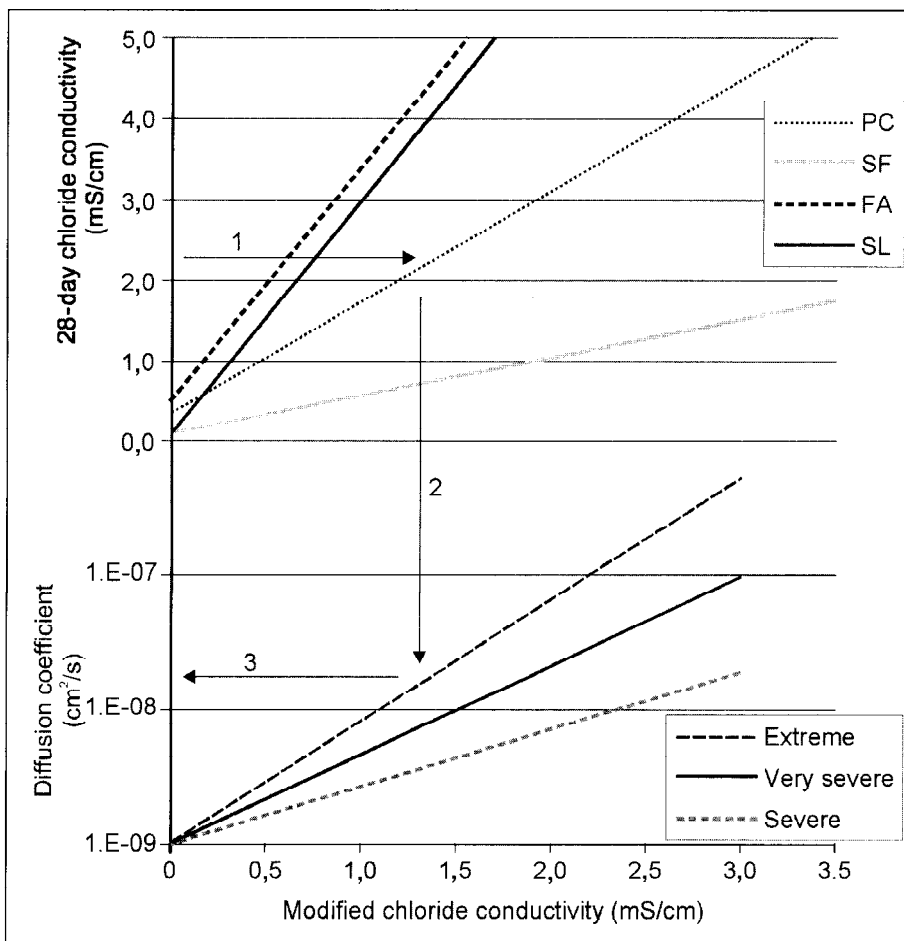


Figure 2 Nomogram of chloride prediction model (Mackechnie 2001)

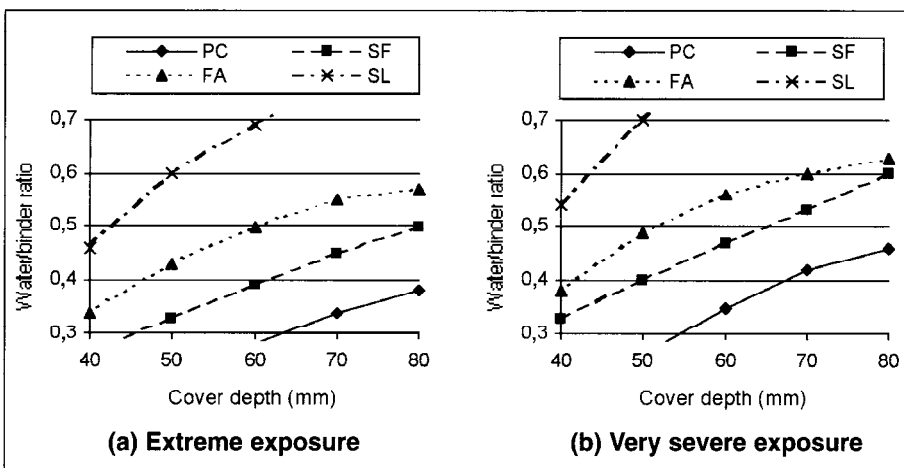


Figure 3 Cover and water/binder ratio limits for 50 years' service

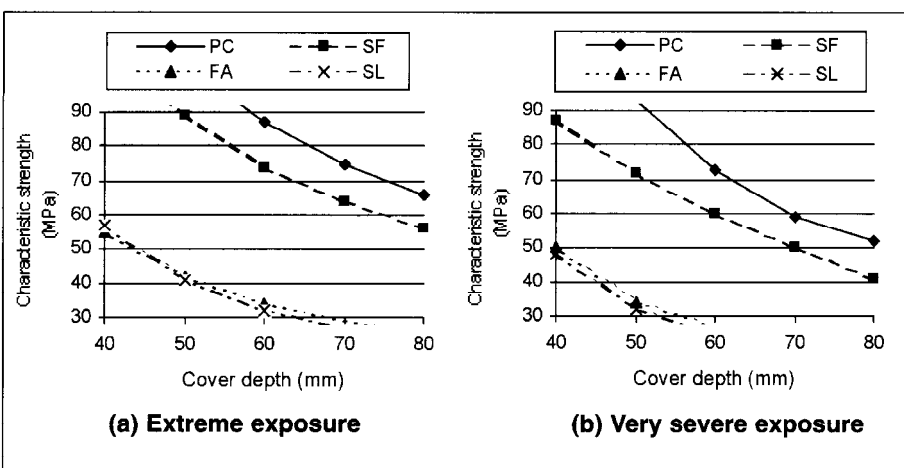


Figure 4 Cover and strength requirements for 50 years' service

The prediction model was constructed in such a way that chloride conductivity values measured at 28 days could be used to predict long-term performance in terms of resistance to chloride ingress. Typical outcomes from the prediction model are shown in figure 1 for different concretes (PC = 100 % Portland cement, SF = 10 % silica fume, FA = 30 % fly ash and SL = 50 % slag). SF concrete appears to perform poorly, but this is misleading as the material often achieves very low chloride conductivity values at 28 days, because of the highly reactive nature of silica fume.

Figure 2 shows a graphical nomogram of the chloride prediction model. The nomogram gives the relationship between 28-day chloride conductivity values and 50-year chloride diffusion coefficients for concrete made with different binder types exposed to various marine exposure conditions. Allowance is made therefore for different rates of maturity, continuing cementing reactions, and the effect of chloride binding by major binder types.

DESIGN OF DURABLE MARINE CONCRETE MIXES

This section outlines the design of concrete mixes that potentially should provide satisfactory durability in marine environments. The procedure is based on the use of the chloride prediction model to limit chlorides at the depth of the reinforcement to values unlikely to cause corrosion at the end of the design life of the structure.

Design limits and assumptions

Recommendations are produced subject to the following limitations and assumptions:

- design life of 50 years (time to corrosion activation)
- corrosion threshold of 0,4 % total chloride by mass of binder
- concrete largely crack-free and defect-free
- Western Cape aggregates and exposure conditions

The following parameters and general conditions were used in the analyses:

- curing: concrete moist-cured for three days
- concrete grade: 30-90 Mpa
- cover to reinforcement: 40-80 mm
- marine exposure categories: extreme and very severe (see table 1)
- binder types: PC = 100 % CEM I, SF = 10 % silica fume, FA = 30 % fly ash, SL = 50 % corex slag

While this paper presents results based on the above assumptions, clearly other conditions can be allowed for in specific

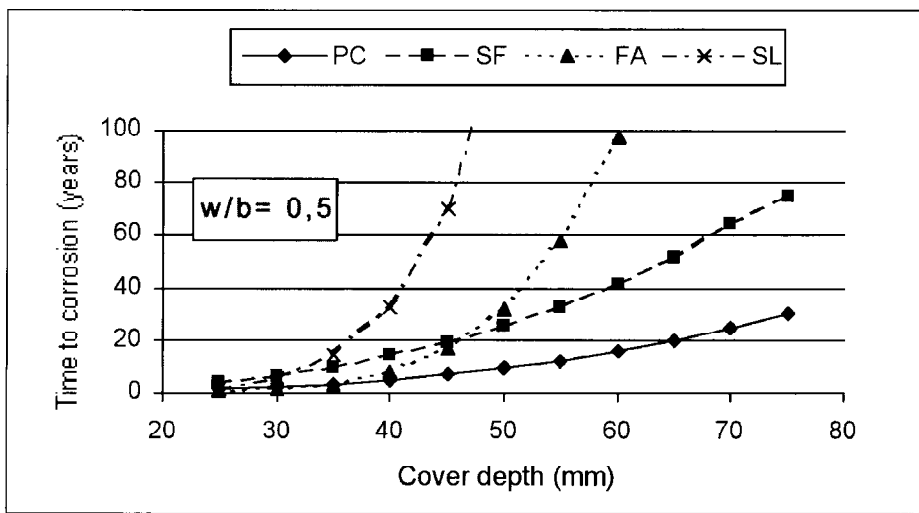


Figure 5 Time to corrosion activation in very severe marine environment

Table 2 Preferred mix proportions for 50-year service life under (a) extreme and (b) very severe exposure

(a) Extreme exposure

Concrete binder type	Cover depth (mm)	28-day CC # (mS/cm)	w/b ratio	Concrete grade (MPa)	Required proportions (kg/m ³)				
					CEM I	Extender	Coarse aggregate	Fine aggregate	Water
PC	75	1,38	0,36	70	485	-	1 100	685	175
PC-SF	60	0,39	0,41	70	405	45	1 100	670	185
PC-FA	50	1,24	0,42	45	265	115	1 100	780	160
PC-SL	50	1,45	0,60	40	150	150	1 100	830	175

(b) Very severe exposure

Concrete binder type	Cover depth (mm)	28-day CC # (mS/cm)	w/b ratio	Concrete grade (MPa)	Required proportions (kg/m ³)				
					CEM I	Extender	Coarse aggregate	Fine aggregate	Water
PC	75	1,64	0,44	55	400	-	1 100	755	175
PC-SF	60	0,49	0,48	60	345	40	1 100	730	185
PC-FA	50	1,42	0,48	(35)*	250	110	1 100	800	160
PC-SL	50	1,80	0,69	(35)*	140	140	1 100	840	175

28-day chloride conductivity values are based on three days moist-curing, and are the expected values that would be obtained.

* Although table 2 indicates that concrete grades of less than 40 MPa may be adequate for FA and SL concrete under very severe exposure conditions, it is generally recommended that a minimum grade of 40 MPa be used for all concretes under these conditions.

cases by use of the prediction model, for instance a design life other than 50 years.

Design recommendations

Cover depths and maximum water/binder ratios for reinforced concrete structures in marine environments are shown in figure 3. Examination of the results shows that high grades of PC and SF concretes are required to provide adequate protection to embedded reinforcement. In contrast, only moderate grades and covers are required for FA and SL concretes, which have both economic and practical advantages.

Concrete is typically specified in terms of characteristic strength or grade in South Africa rather than referring to water/binder ratio. Figure 4 shows the limitations of grade and cover to achieve satisfactory durability in extreme and very severe marine environments. The advantages of using supplementary cementitious materials such as fly ash, slag and silica fume are obvious from these results.

The durability of reinforced concrete structures exposed to marine environments may be compromised by inadequate control over cover to reinforcement. The nature of chloride diffusion

profiles in concrete means that a shortfall in cover causes an exponential reduction in the time to corrosion activation. While some variability of cover is inevitable during construction, some absolute minimum value must be ensured for durability. Figure 5 shows the dramatic effect that changing cover depths have on the predicted time to corrosion activation for different concretes, all with water/binder ratios of 0,5 exposed to very severe marine conditions. It should be noted that reinforcement at cover depths less than 30 mm are extremely difficult to protect, even when using high-performance concrete.

The use of fly ash or slag in concrete may provide increased chloride resistance, but these materials do require special attention during construction, particularly with respect to curing. Poor near-surface quality due to lack of moist-curing may significantly reduce the chloride resistance of fly ash or slag concrete. This is particularly important when low covers are specified (ie in some precast elements with cover depths of less than 30 mm).

Preferred concrete mixes

The choice of concrete materials used in marine applications will be dictated by economic, logistic and technical factors. Preferred concrete mixes for reinforced concrete structures under extreme and very severe exposure conditions are given in tables 2a and 2b. Assumptions were that all the mixes were sufficient for structural purposes, a standard service life of 50 years was required, and that all mixes were well proportioned with good-quality aggregates (eg low water demand) and appropriate plasticising admixtures.

In concrete mix and structural design for marine conditions there is a trade-off between cover and concrete quality: generally higher covers allow less stringent concrete requirements. Decisions in this regard will generally be made on the basis of practicality and economics.

PC concrete

PC concretes have poor resistance to chloride ingress and should only be used with high cover depths to reinforcement. Cover depths of 75 mm were therefore selected that still required high-grade PC concrete for protection (ie grade 60 and above). High binder contents of these mixes will also require that non-alkali reactive aggregates be used. Additional problems may also arise from cracking due to the large cover and high exotherms resulting from the high cement contents.

SF concrete

Replacement of cement with 10 % silica fume will produce a higher-strength concrete with a refined pore structure. The concrete will have a higher water demand

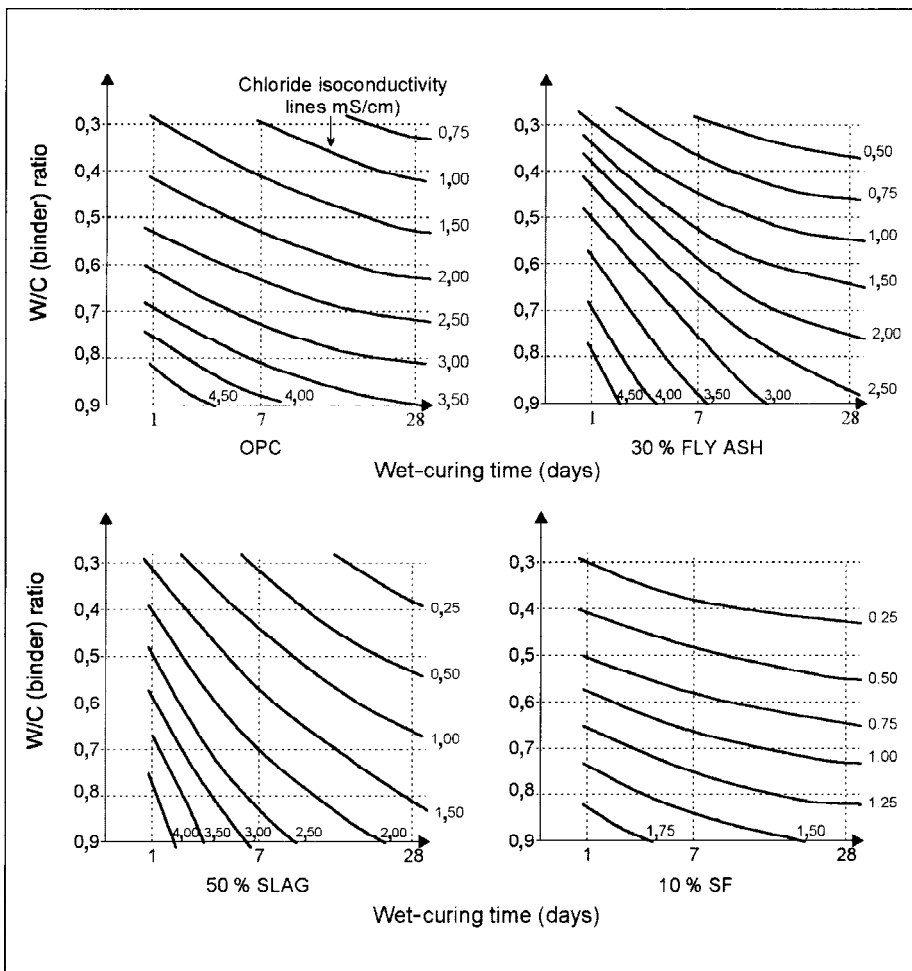


Figure 6 Iso-conductivity charts for PC, SF, FA and SL concrete (Alexander et al 1999)

and super-plasticiser admixtures are required to aid workability and ensure satisfactory dispersion. The improved chloride resistance of SF concrete allows a reduced cover depth to be specified, in this case 60 mm. Relatively high concrete grades are required, but this is easy to achieve with SF concrete.

FA concrete

The excellent chloride resistance of fly ash concrete means that only moderate cover depths are required for durability (ie covers of 50 mm). Fly ash significantly lowers the water demand of concrete even with low levels of water-reducing admixture. While moderately high grades of FA concrete are required, the total binder content is still lower than PC or SF concrete. However, the slower pozzolanic reaction of fly ash means that good curing is essential to produce a dense near-surface quality.

SL concrete

Slag concrete has similar attributes to fly ash concrete with regard to chloride resistance. Only moderate concrete grades and covers are required for SL concrete to provide protection to reinforcement. Cover depth of only 50 mm requires concrete grades of 40 MPa or less. It is therefore possible to provide extra durability and more practical solutions for no addi-

tional capital cost.

It should be noted that chloride resistance alone does not dictate final binder selection and regard should be had for other fresh and hardened concrete properties that affect performance.

The information to produce the mix designs presented above is now available in a series of spreadsheets that can be manipulated to obtain design and prediction data for a variety of concrete types in marine environments. These spreadsheets are available at the web address: <http://www.civil.uct.ac.za/research/materials/index.htm>

CONTROL OF CONCRETE QUALITY ON SITE

The foregoing approach can be used to arrive at suitable design decisions, in terms of materials, mix proportions, concrete grade and cover to reinforcement. These recommendations alone will not guarantee durability, as control of concrete quality on site is just as important as getting the design right. Achievement of durability will ultimately depend on whether concrete of the correct quality and grade is produced on site and properly placed in the structure. Consequently, control of concrete quality on site will involve the following elements:

- conventional monitoring of compressive strength of concrete for compliance with the strength grade specification
- monitoring the quality of concrete at source (eg batch plant or ready-mix plant) from time to time, in respect of maximum chloride conductivity values
- adequate sampling of in situ concrete for chloride conductivity testing (either by coring or other samples)
- monitoring of actual cover depths to reinforcement after concrete has been placed and compacted

The procedure for strength and cover testing of structures is well accepted and specified. Specifying durability-related tests such as chloride conductivity involves a new approach to specifying concrete. Current specifications are based on a prescriptive approach where limits are set on parameters such as water/binder ratio, binder content and strength. It is the considered opinion of the authors that prescriptive specifications on their own are not appropriate or adequate for ensuring durability.

Performance specifications are based on the premise that it is possible to measure some property of the material related to the performance aspect that is required from the concrete or structure (Alexander 2003). It is then possible to specify actual performance in terms of these properties, and more importantly to monitor and control these properties on the construction site.

Advantages of performance specifications are as follows:

- Actual performance is specified, which helps to ensure that the behaviour of the material/structure is better controlled.
- Acceptance or rejection of construction quality can be assured on site by measurement of suitable parameters.
- If linked to long-term behaviour of the structure, better and more economic construction can be achieved.
- The contractor is given greater latitude in deciding on suitable mixes and materials, and on construction methods, provided the required performance is achieved.

This should lead to more economical construction and provide greater scope for innovation and technology improvements.

Chloride conductivity limits are dictated by durability requirements, material selection and construction practice. Based on analysis of a wide range of South African concrete results, iso-conductivity charts have been developed which show the effect of major parameters on chloride conductivity. Figure 6 shows iso-conductivity charts for different concrete

types. These charts indicate the sensitivity of chloride conductivity to the duration of moist-curing and could therefore be used to adjust design values, should site curing be problematic.

Several preliminary or trial performance specifications for durability are in existence in South Africa (Raath 2001). The chloride conductivity test has also been used in the past to optimise the chloride resistance of concrete mixes before construction of major marine structures, for example Alusaf and Mozal projects (Taylor 2002). Considerable additional work is still required, however, to put a full performance specification approach in place.

Two further tests that assess the near-surface quality of concrete have been found to be good indicators of site construction quality (Ballim 1993; Gouws *et al* 2001; Du Preez & Alexander 2003). These tests are the oxygen permeability and water sorptivity index tests (Alexander *et al* 1999). The oxygen permeability test is sensitive to microstructural defects such as voids and microcracks, and hence to the effectiveness of compaction, while the water sorptivity test is able to characterise the effectiveness of curing. Consequently, an alternative site quality control scheme would be to monitor the mix at source for chloride conductivity (ie to ensure that correct mix ingredients and properties are achieved) and to check the as-built structure for oxygen permeability and water sorptivity (to ensure adequate construction control). The merit of these ideas still requires further development and real-life testing.

CLOSURE

The durability performance of reinforced concrete structures in the marine environment is generally unsatisfactory and needs to be improved. Current approaches of specifying concrete durability are not always satisfactory and may be misleading. The continued reliance on concrete strength as an indicator of potential durability is irrational since factors such as binder type and construction practice have a greater influence on durability performance. A new approach is proposed to ensure the durability of marine concrete structures, using appropriate performance criteria.

The proposed design technique is based on the relationship between early-age concrete characterisation testing and medium-term chloride diffusion coefficients of marine concretes, validated with long-term data from real structures. The technique allows long-term performance of concrete to be predicted on the basis of short-term and medium-term assessments, and does not rely only on early-age properties that have little bearing on durability. Based on this prediction model, durability limits for marine concrete mixes have been developed and preferred concrete mixes outlined. The advantage of using supplementary cementitious materials such as slag, fly ash and silica fume for marine concrete structures is apparent from this approach.

Control of concrete quality on site is essential to ensure the full potential of good designs and material selection. Performance specifications that incorporate the use of chloride conductivity and other durability index testing are proposed to guarantee sufficient chloride resistance and quality of site concrete. The use of this type of approach is also recommended to optimise concrete mixes before construction of major marine projects.

Acknowledgements

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