97

Technical Note

CONCRETE STRUCTURES IN MARINE AND OTHER SALINE ENVIRONMENTS

INTRODUCTION

The purpose of this Technical Note is to highlight various technical requirements which are considered fundamental to the construction of good quality concrete structures in marine and other saline environments. Reinforced concrete structures situated in marine environments (Fig. 1) such as the ocean tidal and splash zones are subject to very aggressive deteriorating actions. The concrete itself is the primary defensive media and requires a high level of protective measures to deliver adequate durability for the life of the concrete structure. The need to design, specify and construct durable concrete structures has been in the forefront of concrete technology and worldwide attention at least over the past 15 years. Attention to durability of concrete has been the result of a growing number of durability - related problems in concrete structures, the main one being the corrosion of steel reinforcement. The number of reinforced concrete structures exposed to particular environmental conditions, undergoing serious deterioration has been steadily increasing in recent years, due mainly to material failures and inadequate design, construction and maintenance practices. The strength of concrete alone is no longer considered as the property which can guarantee long lasting structures. It is now recognised that a dense and impermeable concrete can best ensure long-term durability in harsh marine exposure conditions.

The increased attention to the durability of concrete structures has also led to the progressive development of a durability based VicRoads structural concrete specification Section 610[1]. Furthermore, in recognition of these developments a multi-stage durability protection strategy has been developed which incorporates a number of measures against the possible ingress of chlorides in aggressive marine and other saline environments with specific emphasis on the long term durability of concrete structures in order to ensure a minimum 100 years service life. A number of specific requirements representing the latest advances in concrete technology and high performance concrete are included in this strategy[2,3].

DURABILITY STRATEGY

The overall durability strategy developed for the construction of bridges and other concrete structures in marine and other saline environments[2,3] must be underpinned by strict specification requirements with durability enhancing parameters. These include improved high performance Supplementary Cementitious Materials (SCMs) concretes with lower water/cementitious material (W/C) ratio to offer adequate chemical and dimensional stability. These SCMs concretes are used in conjunction with improved construction practices and procedures for compaction, curing and cracking control. In addition, a range of other requirements included in specifications should address various controls of source materials, chemical admixtures, and the impermeability of concrete. Such performance requirements are normally tailored to suit local environments and materials. To this end the quality assurance and documentation requirements must provide for better control of the whole construction operation, including the vital interaction between the various technical and practical processes which have the potential to compromise the overall intent of the durability strategy. This should allow the identification and elimination of quality problems as early as possible, thus maintaining the integrity of the specification. In recognition that the durability of a structure may diminish over the years whilst exposed to harsh conditions, this multi-stage protection approach is intended to ensure that sufficient redundancy exists to ensure the long term serviceability of the structure. It should be noted that the concrete durability section of AS 5100 (Bridge Design)[4] is wholly based on Section 5 of the AUSTROADS 1992 document whose technology pre-dates the advances in concrete durability made over the past 20 years and is therefore inadequate for the design and construction of new structures for marine and other aggressive environments.

Protective Measures

Special protective measures which can form part of a multi-stage approach to durability should include:

- The use of concrete containing SCMs[5,6,7] (i.e. silica fume, fly ash, slag) at the correct replacement levels;
- Protection of all materials against chloride contamination prior to concrete placement;
- Use of a combination of water adding curing techniques;
- Total isolation of all exposed in-situ concrete surfaces against the ingress of chlorides during the curing period;
- Electrical continuity of the steel reinforcement;
- Limitations to drying shrinkage and soluble salts, alkali-aggregate reactivity (AAR) and temperature

differentials across a concrete element;

- Application of protective coatings in the form of silane impregnation, decorative/anti-carbonation, anti-graffiti coatings and water tolerant epoxies in tidal zones;
- Proper quality control including permeability testing in terms of VPV during mandatory trial mixes as well as during the construction period;
- Use of cathodic prevention[8] as part of the protection strategy (Fig.2); and
- As part of a long term monitoring program, mild steel and carbon macrocell/galvanic current corrosion monitoring probes could be installed in a concrete member such as a pier column prior to placement of the concrete (Fig.1).

TYPES OF ENVIRONMENTAL AGGRESSIVENESS

Three distinct exposure zones consistent with corresponding potential corrosion zones have been identified within a marine environment. For design purposes these exposure zones can be categorised in terms of the exposure classifications given in AS 5100[4] (i.e. B2, C etc). The exposure zones consistent with appropriate concrete mix designs, concrete grades, VPV values, and concrete cover to the steel reinforcement are defined as follows:

a) **Atmospheric zone** – subject to salt-spray wind and weathering by the sun. Depending on the height of the structure, pier crossheads and superstructure usually fall into this category with an exposure classification of either B2 or C. Nevertheless, for low level structures both beams and crossheads should be classified as exposure classification C in order to ensure that they are designed and constructed with a greater protective capability against the ingress of moisture and waterborne chlorides. Above deck components such as parapets must also be classified as exposure classification C.

b) **Tidal/splash zone** – subject to tidal water rich, in chloride, and greatly influenced by the wetting and drying processes which promotes ingress of water, waterborne chloride ions, and diffusion of oxygen (i.e. exposure classification C). Columns/piles, crossheads, pile caps and bored piles exposed to tidal conditions fall into this category. Piles should also be classified as such for additional protective capability.

c) **Submerged zone** – where piles are underwater or are completely saturated, thus severely restricting the supply of oxygen, which is vital for corrosion initiation and subsequent propagation.

The required concrete grades and mix design parameters for the various concrete components and typical exposure classifications are listed in Table 1.

Table 1: Exposure Classifications [1,4] & Concrete Mix Design Parameters for Marine Environment

Concrete Members	Exposure Classification	Concrete Grade/ W/C Ratio (Max)
Piles Pile Caps Columns Crossheads	C	VR450#/50-0.40 (50 MPa)
Deck slab Approach slab Abutments Fender walls Wing walls Above Deck (Parapets etc)	B2 B2 B2 B2 B2 C	VR400#/40-0.45 (40 MPa) # : Min. cementitious content (Kg)
Beams	C	VR450#/50-0.40 (50 MPa)

CONCRETE MIX DESIGN, CEMENTITIOUS TYPES

Concrete grades and mix proportions should comply with the requirements of Section 610. It is considered that the use of SCMs[5,6,7] such as silica fume, or combinations with fly ash or slag would be most appropriate. A 10% silica fume replacement as shown in Table 2 is proposed to provide adequate long-term impermeability with appropriate chemical admixtures for all structural components especially pile caps, piers and beams. Other possible combinations at medium replacement levels are shown in Table 2 for piles, deck slabs, approach slabs, fender walls and wing walls. Higher replacement levels as shown in Table 2 could be used although expert advice should be sought and consideration should be given to their lower early strength development, longer formwork removal times, lifting strengths and release of prestress. In particular early stripping of formwork with no subsequent protection (or isolation) of such concretes in marine environments, would render them susceptible to chloride ingress at a very early age as the initial VPV would be fairly high. Silica fume concrete would give the best VPV results, followed by fly ash and then slag[5]. The triple blends would provide comparable results. The various combinations shown in Table 2 have been used very successfully for VicRoads projects (Fig.1) including Patterson River Bridge, North Arm Bridge at Lakes Entrance, and Grey River Bridge on Great Ocean Road.

Table 2: Typical Proportioning of Cementitious Materials for Structures in Marine Environment

Recommended Proportioning of Cementitious Material (% mass) in concrete mixes	Structural Concrete Members
• 90% GP/ 10% SF#	Preferred for all concrete members
• 90% GP/10% SF; or • a triple blend combination of SF and FA (75% GP /17% FA/8% SF); or • S and FA (68% GP/24% S/8% FA); or • S and SF with GP (68% GP/24% S /8% SF)	Piles, deck slabs, approach slabs, fender walls, wing walls # GP Portland Cement (GP); Silica Fume (SF); Fly Ash (FA); Slag (S)
• Higher replacement levels of: » at least 30% FA ; or » 30%GP/60%S/10%SF or » 65% S /35% GP	Piles, Pile caps, columns
• May use 20% - 25% FA	Beams

Silica fume concrete (10% silica fume/ 90% GP cement) offers a superior strength development at early ages compared to the higher replacement levels required for either slag or fly ash[5]. This is an advantage with regards to expediting the construction process in terms of formwork removal and avoiding the exposure to the aggressive environment of high VPV concrete (i.e. high slag or fly ash concretes) at an early age. It should also be noted that both silica fume and fly ash are available in biodegradable bags, which can dissolve in the concrete during mixing. It may also be possible for bulk fly ash and slag or in combination to be supplied.

CONCRETE COVER TO STEEL REINFORCEMENT

Based on the principle of construction with good quality high performance SCMs concrete and quality control with VPV, concrete covers consistent with AS 5100 should be adopted. The depth of cover of high quality concrete is a fundamental parameter for the durability of reinforced concrete structures. Both the amount of cover and the quality of the concrete within such cover are the dominant influences in regards to the protective capacity of a given concrete to the ingress of aggressive agents such as water and waterborne chloride ions. Apart from the chemical protection afforded to the steel reinforcement through the highly alkaline environment, the impermeable concrete cover reduces the electrical resistivity and therefore any potential corrosion currents.

As such it is important to comply with strict criteria of ensuring the accuracy of the concrete cover to the steel reinforcement. Issues that should be addressed include high standard of workmanship, construction practices and procedures, design detailing and correct use of spacers. Spacers must be in sufficient numbers and correctly positioned to stop potential rotational or lateral movements of the reinforcement cage. The specified minimum cover to tie wire must be achieved. Performance testing of cover should involve direct inspection and random measurements of all concrete components prior to the placement of concrete, and actual checking of cover in the hardened concrete with a cover meter after removal of formwork. It is proposed that calibrated cover meter measurements be undertaken and recorded on randomly selected grids on faces of concrete piers, beams and the top surface of concrete deck slab at predetermined frequencies.

PROTECTION OF STEEL REINFORCEMENT

All reinforcement and embedded metallic fixtures of site-cast concrete should be protected against chloride contamination during the construction period. All reinforcement should be cleaned with water complying with the specification prior to casting the concrete to ensure that salt deposits are removed.

CURING

The period of curing for all cast-in-place concrete must be not less than 14 days. It is considered that various combinations of water adding techniques, retention of formwork in place and polyethylene plastic (in combination with wet hessian) should be utilised as necessary to provide effective curing to the exposed surfaces of concrete of the various cast-in-place components. Curing compounds must not be used for these works. The use of an aliphatic-alcohol based evaporative retarding compound (to prevent early evaporation of moisture) must be a mandatory requirement for the construction of all concrete components including the concrete deck and slabs and must be applied after initial screeding in accordance with the requirements of Section 610. In order to prevent the ingress of chlorides into site-cast concrete in its early days, formwork should be kept in place for the minimum time required before removal. Immediately following the removal of formwork, and for the remainder of the curing period, polyethylene sheet (in combination with continuously wet hessian) or similar means should be used to protect the surfaces of concrete being cured against ingress of chlorides from salt water or sea spray during its early maturing and strength developing period.

ELECTRICAL CONTINUITY OF REINFORCEMENT

All non-prestressed reinforcement should be made electrically continuous (and checked as such) to allow for future application of a cathodic protection/prevention system if required.

USE OF PROTECTIVE COATINGS

It is considered that the application of protective coatings to all exposed concrete surfaces during construction can be a very effective and integral part of an overall multi-stage protection approach. This will ensure that the various concrete components will not be exposed to the aggressive environment of chlorides for at least 20 years. Even if recoating is not undertaken any chloride ingress will subsequently be countered by the impermeable non-absorptive high performance SCMs concrete, particularly if VPV testing is used as a quality control tool. If coated at construction, the durability of the good quality concrete will further improve during the first 20 years, when the concrete has further opportunity to cure, facilitate further hydration of cementitious materials and further enhance its strength gain and penetrability. A dual protective coating system comprising pure silane (95% active) or solid silane (as per Section 686[9]) together with an anticarbonation coating on to all exposed surfaces such as piers, exposed piles, all surfaces of all beams, exposed areas of decks, abutments and bridge barriers, will provide an effective protective barrier. A water tolerant epoxy coating can be applied on any exposed pile caps and other tidal areas. The application of such coatings say 14 to 28 days after casting of concrete will prevent any ingress of chlorides into the concrete during the early maturing days of its life.

CONTROL OF TEMPERATURE DIFFERENTIALS

In order to prevent excessive temperature differentials (between core and surface of concrete) a limit of 20oC across any element should be achieved. This is to minimise the build up of excessive thermal stresses leading to early-age thermal cracking of the hardening concrete. This coupled with potential shrinkage cracking and other restraining effects could result in more severe cracking of concrete components. In general, early-age thermal cracking occurs within 1 to 7 days of casting concrete. For massive sections, such cracking can take several weeks to develop. Improved curing regimes and the use of thermal blankets can help to minimise large temperature differentials within a concrete element.

ONGOING REMEDIAL AND MAINTENANCE ISSUES

The aim is to design and construct a concrete structure which will deliver a 100 year service life with minimal maintenance requirements – that is some regular inspection and maintenance which is part of a good management system. The structure design should include an effective drainage system capable of being cleaned, to ensure that any water leakage comes into contact with as little concrete as possible. Drip lines should be designed where necessary to protect areas from leakage and contamination. Joints where necessary should be reliable and watertight across the full width of the deck, including kerbs. A brief maintenance manual for the concrete structure could be prepared describing what maintenance may be needed, the expected frequencies, and how access can be achieved.

MONITORING REQUIREMENTS

Macrocell/galvanic current corrosion monitoring probes (i.e. corrosion monitoring ladders at Patterson River Bridge[2,3]) can be installed at various locations either upstream or downstream of columns at the most appropriate height locations (Fig. 1). These can be procured from Australian suppliers and can be remotely monitored via modem.

MAXIMUM CRACK WIDTH

Under normal exposure or favourable service conditions (i.e. dry conditions); crack widths of less than 0.3 mm on the concrete surface do not pose any threat of corrosion of the steel reinforcement. In highly aggressive or corrosive environments however, the safe limit is considered to be 0.2 mm or less. In the most severe exposures (alternate wetting and drying) or in structures designed to retain or exclude liquids, the safe limit is considered to be 0.1 mm. In the case of bridge decks, cracks tend to grow in length and width due to the influence of the traffic and impact loading and therefore, even cracks of the order of 0.1 mm to 0.2 mm may become significant for the long-term durability. Sometimes under favourable conditions, cracks, which do not exceed 0.2 mm, may seal by the process of autogenously healing (i.e. deposition of calcium carbonate). The crack width for exposure classification C[1,4] should be limited to 0.1 mm and for exposure classification B2 to 0.15 mm in accordance with the requirements of Section 610. In addition, the acceptable crack width at the concrete surface of pre-cast pre-stressed concrete elements should not exceed 0.1 mm. Consideration should be given to appropriate remedial measures during construction if these crack widths are exceeded in accordance with the requirements of Section 610 and Section 687[10].

OTHER PROTECTION MEASURES

Other protection measures may include the use of corrosion inhibiting admixtures; controlled permeability formwork for columns; reinforcement coatings and selective use of stainless steel such as in the tidal/splash zone area of columns. Novel protection measures such as fibre reinforced polymer (FRP) bars and prestressing tendons, permanent formwork, permanent cladding, and deck enclosure systems are not considered appropriate at this stage.

CATHODIC PREVENTION

Cathodic prevention[8] could be considered as part of the overall durability strategy (Fig.2). Cathodic prevention is the name given to cathodic protection of new structures that could become contaminated with chlorides in the future. Cathodic protection and prevention is a most appropriate protective and preventative measure for all non-prestressed concrete components, particularly the concrete piers and submerged foundations. A new structure will only be exposed to significant chloride ion levels in the future. Cathodic prevention works to establish an electric field, which opposes the chloride ion movement towards the steel reinforcement. This is achieved by inserting into the new concrete member an anode which is connected to the positive output of a D.C. power supply and the reinforcing steel is connected to the negative output, in the same manner as a regular cathodic protection arrangement. Installation of cathodic prevention at construction would represent a fraction of the cost of full cathodic protection installed in the future.

QUALITY CONTROL TESTING

Further to the requirements of Section 610, in addition to compressive strength testing, quality control testing during construction should include VPV testing of cylinders for the prequalification of concrete mixes and the associated curing regimes, and as a quality control tool to ensure compliance in cast-in-place work, including sprayed concrete and the manufacture of precast concrete products at the same sampling frequency as compressive strength. The VPV method should also be used for testing concrete cores extracted from the in-situ structural components as required.

REFERENCES

1. *VicRoads Standard Specification (2005), Section 610 "Structural Concrete".*
2. *Andrews-Phaedonos, F. (1997), "Durable concrete construction – Patterson River Bridge, Nepean Highway, Melbourne, Victoria". AustRoads Bridge Conference 1997, Volume 1, pp. 353-364.*
3. *Andrews-Phaedonos, F., Shayan, A., Xu., A (2003) "Durable Concrete Construction– Performance Monitoring of Patterson River Bridge, Nepean Highway, Melbourne – 8 Years On". Concrete Institute of Australia Conference, Brisbane, Queensland.*
4. *AS 5100 (2006), Bridge Design (Australian Standard)*
5. *Andrews-Phaedonos, F. (1996) "Establishing the Durability Performance of Structural Concrete", VicRoads, Melbourne, Australia, January.*
6. *Andrews-Phaedonos, F. (1997) "Recommended Durability Classifications for Structural Concrete Based on the Measurement of VPV", CANMET, Durability of Concrete Conference, Sydney.*
7. *Andrews-Phaedonos, F. (2000), "Volume of Permeable Voids (VPV) - Ensuring the Durability Performance of Structural Concrete". AustRoads Bridge Conference 2000, Adelaide, South Australia.*
8. *Ackland, B. (2006) "Cathodic Prevention and Cathodic Protection of Steel in Concrete", Australasian Corrosion Association Conference, CAP-06, Paper 064.*
9. *VicRoads Standard Specification (2000), Section 686 "Coating of Concrete".*
10. *VicRoads Standard Specification (2001), Section 687 "Repair of Concrete Cracks".*

CONTACT

For further information on concrete structures in marine and other saline environments please contact:

Fred Andrews-Phaedonos *Phone: (03) 9881 8939*
Email *fred.andrews-phaedonos@roads.vic.gov.au*
Mobile *0419 597 277*

Techncical Consulting Facsimile *(03) 9881 8900*

Fig. 1 Bridge in marine environment (L). Location of Macrocell/galvanic current corrosion monitoring probes within column at various levels (R)

Fig. 2[8] Installation of an anode into new concrete member as part of cathodic prevention