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New guidance for the use of concrete in maritime engineering

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NEW GUIDANCE FOR THE USE OF CONCRETE IN MARITIME ENGINEERING

by

by S. Dupray[1][2] , K. Gamst[3] and B. Wood-Ballard[4]

ABSTRACT

This paper presents an overview of project that aims to deliver an up-to-date, self-supported and decision aiding guidance on the use of concrete for design / construction / repair and maintenance of maritime structures. Some of the key findings relevant to navigation structures are detailed.

1. INTRODUCTION

Concrete has been extensively used as one the main material to construct navigation structures and the various structures associated to navigation, because it is versatile material, durable and widely available. Despite the long history of capital investment in concrete maritime structures, it is generally recognised that there are gaps in technical guidance documents available on the use of concrete for such structures. In particular, the need for consolidated guidance has been identified in the United Kingdom and France : joint action was needed to provide comprehensive guidance in particular considering key codes in Europe have appeared e.g. Eurocodes (in particular Eurocode 2) and standards on concrete (in particular EN 206) and concrete constituents (in particular EN197). The paper presents highlights on key conclusions from a collaborative project between UK and France.

The project aimed at providing a holistic view on the subject, at summarizing good practice (Allen 1998, Concrete Society 1986, CETMEF 2008) and at transferring findings from recent researches into the day-to-day practice. The objectives of the research is to guide asset managers, designers and contractors on how to deliver concrete structures that are durable over their design life, to make an optimum selection from concrete materials and concrete construction options. For example the guidance provides guidance on how to avoid the risks of corrosion, how to deal with long design lives (typically greater than 50 years) and how to address the risk of attrition . It focuses on maritime and estuarine port structures ; although not focused on inland navigation structures, some of the findings may also be relevant. Generalities on concrete and concrete constituents, detailed concrete mix design procedures and detailed calculation of hydraulic conditions and loads are avoided but key references are identified.

2. APPROACHES TO MARITIME CONCRETE

2.1 Holistic approach

The ‘ideal concrete’ does not exist and there is no ‘off the shelve’ concrete for a project: an optimum balance between factors and constraints of the project for design, construction, operation and maintenance should be achieved. This could be achieved by accounting for various aspects including fitness for purpose, ease of action, safety, environmental aspects, cost aspects, durability and strength.

Hence the approach to concrete material and concrete structures should encompass asset management, understanding of deterioration agents and environmental forcing, design for durability and for loads, concrete technologies, construction technologies, specific testing, construction and quality control as well as monitoring / maintenance and repair. Other holistic considerations that are important include service life requirement, programming, health and safety, risks, whole life costs, environmental considerations including sustainability and architectural issues. Title

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2.2 Structure specific approach

To provide a rational approach to structures, they have been grouped into families that display comparable functions and service exposures. For each group or family, information is given on structural forms, possible construction methods, key durability issues and key design issues. The relevant structures are to be found amongst some of the families that are solid vertical and battered walls, block works walls (such as quays), wave walls, crown walls, concrete armour units, caissons, revetments, piled concrete structures (such as jetties) and others structures (such as navigation towers, slipways, locks) … Some examples are given in Figure 1. Coastal works is also a family within the project.


Crown wall on rubble mound breakwater (CETMEF)


Concrete armour unit (CLI)


Blockwork wall (Halcrow)


Jetty (Halcrow)


Maritime lock (Grand Port Maritime du Havre)


Caissons (SAIPEM)

Figure 1: example of concrete structure relevant to navigation

3. DEGRADATION OF MARITIME CONCRETE

3.1 Overview of degradations and their effects

All maritime structures are exposed to aggressive environmental agents and other factors, including :

- Seawater (with active components such as sulphate, chloride, dissolved CO2),
- Moving waters (including tides, waves and currents),

- Climate and climate change,
- Abrasion induced by moving waters, sediments, propeller jets, and operations,
- Impact induced by sediments or water alone,
- Toe scour and erosion,
- Unexpected incompatibility between concrete constituents, and
- Other factors such as collision, spillage, biological attack (Dhir 2002, Toutlemonde 2007).

All of the above should be taken into account during the design to ensure appropriate performance during construction, operation and maintenance. However, this is not sufficient. Actually – and less obviously – maritime concrete structures are also prone to specific internal degradation mechanisms that are associated with the forms of construction :

- The use of slender elements requires reinforcement to resist the severity of service/hydraulic loads, which is consequently exposed to the corrosion risks associated with the maritime environment ;
- Awkward shape are sometime used to optimize the structures mass performance but, in turn, plastic settlement of concrete and associated weakness may become a significant risk ;
- An alternative is to use large and/or bulky (sometime non reinforced) elements, which in turn may lead to significant temperature increase in the concrete during setting (greater than 65℃) resulting in delayed ettringite formation (DEF) and internal sulphate attacks that may alter concrete strength without signs at early stage ;
- High temperatures may lead to thermal cracking in particular if large thermal gradient exists ;
- High density concrete is a means to increasing hydraulic stability, e.g. of concrete armour units. Durability and volume stability of heavy aggregates should be studied to avoid deteriorations in service ;
- Structures are often build in stages which may lead to friction shrinkage cracks when fresh concrete is cast in long sections over hardened concrete, e.g. when casting (or recasting) a capping beam on top of a quay.

If not correctly accounted for during design and construction, these may results in negative effects on the concrete and its reinforcement that are summarized in Table 1.

3.2 Rational approach to aggressiveness

In Eurocode 2, a rational approach to assessing/designing for several of the external agents is given. Standard classes of exposure are given depending on the exposure, the location and the position of the structure or part of it, including:

- XF for freeze and thaw ;
- XA for chemical attack, e.g. induced by ground ;
- XM for attrition.

Other classes of exposure are specifically associated with corrosion:

- XS for corrosion induced by seawater attack on reinforcement ;
- XC for corrosion induced by CO2 and carbonation ;
- XD for corrosion induced by other sources of sulphate.

Other exposure classes have also been developed in specific European countries such as XH exposure classes for Delayed Ettringite Formation (LCPC 2007) or ACEC for aggressiveness of the chemical environment (BRE 2005).

These classes of exposure allow standard selection of concrete constituents (nature and quantities) and reinforcement cover for a 50 year design life (and in some instance for a 100 year design life).

Table 1 gives a more detailed inventory of deterioration agents and their associated effects.

Overview of agents		Overview of effects	
External agents	**Internal agents**	**On reinforcement**	**On concrete**
Ambient temperature Traffic Solar exposure Fire and chemical spillages Tide Wave action Current action Ice action Berthing/mooring forces Off-loading forces Impact Atmospheric CO2 Seawater (capillary rise/evaporation) Seawater (diffusion) Seawater (pressure head) Biological Ground sulphates Abrasion	Temperature (internal) Chloride content (internal) Sulphates (internal) Alkalis (internal) Unstable constituents	Rebar corrosion Expansion Section loss Strength loss	Sulphate attack Alkali-aggregate reaction Leaching Cracking Expansion Spalling Scaling Section loss Strength loss Water tightness loss

Table 1: Overview of agents acting on concrete and/or reinforcement at element and/or structure scale, and associated effects

4. CONCRETE DESIGN

4.1 Concrete technologies

The various risks identified earlier can be met by selecting the most appropriate concrete constituents and quantities, the most appropriate concrete fabrication and placing techniques, which is discussed below.

The designer can specify / adjust the reinforcement type (none, steel, fiber, others), the source of concrete (ready-mix supplier or in-situ mixer), the place of casting (in situ, precast or a combination of both using precast elements as permanent formwork for the cast in situ concrete), the type of placing of in situ concrete (e.g. underwater, sprayed, jumpformed, slipformed etc). The designer can also specify the concrete constituents / properties / performance such the concrete density, strength, porosity and permeability. Hence, the designer can select the most appropriate option to facilitate construction of the various parts of the structure, allowing for the best construction quality, and in fine the best durability.

Concrete design and selection of the concrete constituents are important steps to fulfill the client needs. The designer has to identify and take into account the constraints of the site and the possible construction methods that would be envisaged to adapt the properties of both the fresh and hardened concrete to the project needs.

In Europe, most of the concrete constituents, including cement and additions, various sizes of aggregates, admixtures, and fibres are subject to unified Euro-standards (such as EN 197 for cements) in substitution for previously used national standards. Maritime concrete constituents should be selected with reference to availability, cost, environmental aspects, risk of alkali aggregate reaction, etc. In addition, risks of deterioration are key drivers in the maritime environment, in particular:

- Cement should be able to resist attack from seawater (by having a limited C3A content or by complying to NF P 15317 in France) (Boutouil et al 1999),
- Some cements/additives can offer improved durability,
- Some cements/additives with lower heat of hydration can reduce the risk of DEF/ETC,
- Sulphate resisting cements display a better resistance to DEF,
- High quality aggregates can result in concrete that is resistant to the abrasive forces of water / sediment,
- Fibres can improve concrete strength and resistance to abrasion,
- High density aggregates can result in higher density concrete, and
- Admixtures (used in small quantities) can improve the properties of concrete in the fresh and hardened state, and are possible ways to enhance both concrete workability and durability.

4.2 Design for loads

The mix design will benefit from empirical mix design relations but will require laboratory trials to confirm concrete performance during both the construction phase and in service, in particular for special concreting techniques such as underwater placing, spraying, slip-forming etc. Full scale trials (including trial pour or pumping trials) will at times be required as well as pilots or mock-ups for larger sites.

Concrete design includes both design for loading and design for durability. Design for loading has many things in common with design of other civil engineering concrete structures, although the determination of the loading condition and internal stress may be challenging when the structure is exposed to wave impact loadings. Physical modelling may be the route required to refine loading conditions that would otherwise be determined using empirical relations. For other elements, such as concrete armour units, the actual forces on / stress within the individual elements have historically not been required during the structural design nor were such data readily available (Davidson and Magoon 1990). In such scenarios, concrete design has been based on field or laboratory trials and experiences of the unit inventor or licensee.

4.3 Design for durability

Concrete generally offers a high durability ; nevertheless, the duration over which it should display a good performance without specific repair or maintenance activity, ie. the ‘design life’, should be defined and agreed upon as an input data to the design process. At least two routes are available for the design of concrete for durability, depending on the design life.

For the design life of 50 years, concrete design can be carried out by using standard recommendations of EN206 and complementary standards. Mix design tables are available that allow to select concrete mix characteristics for the various classes of exposure to environmental agents. This includes the type of cement, the water to cement ratio, the concrete grade, the concrete dosage, the air content. Some national complementary standards may include the cement class, water absorption, class of compaction, class of consistence or further details on proportions of additions (e.g. British standard BS 8500 or French standard NF EN 206). The details for the minimum cover required for durability reinforcement are given by EN 1992 and may be detailed or adapted for various concrete qualities and grades in national complementary standards.

For longer design lives of permanent maritime structures (between 50 to 120 years or even more than 120 years in exceptional situations), EN 206 does not offer direct guidance for concrete design. The designer should use a ‘performance based approach’ to set properties that the concrete should achieve with reference to buildability, structural strength in service and in particular durability. In this situation the designer does not specify concrete constituents and proportions but rather target characteristics and durability indicators to be achieved by the concrete. As an example, durability indicators for the concrete in relation to corrosion of the reinforcement might be porosity, permeability to water and gas, and chloride diffusion rates (AFGC 2004, AFGC 2007). Other specific durability indicators are required for other degradation mechanisms affecting concrete such as the amount of free silica for alkali aggregate reaction (LCPC 1994, BRE 2004), elevated temperatures for delayed ettringite formation (BRE 2001, LCPC 2007) or temperature differences for early thermal cracking (Bamforth, 2007). The values of the durability indicators are generally not readily available and need to be determined by testing, sometime over a sufficient period of time, say several months; this time requirement needs to be taken into account in the programme (Arliguie and Hornain 2007). Durability modelling may also help to refine estimates of the ingress of chloride, carbonation etc over the design life of the structure (Quillin 2001). In addition, durability indicators can be confirmed by regular monitoring of the concrete in the structure in service to refine the estimate of the actual remaining life of the structure (Buenfeld et al 2008).

4.4 Enhancement of durability

Concrete material alone may not achieve the required durability ; enhancement measures are available to extend the concrete design life and can be very useful when exceptional design lives are sought. These enhancement measures comprise of special admixtures, cathodic prevention, coating, barriers but also specific construction techniques such as controlled permeability formwork (Price 2000). Some enhancement techniques can also be used on existing structures as part of maintenance activities.

To address the specific aggressiveness of the maritime environment and specific forms of concrete, adhoc tests / trials are generally required in addition to more conventional tests/trials for durability design; such adhoc tests / trials may also be required during construction and for QA/QC. During the monitoring process of the structure in service, these tests are a way to assess the remaining life of the structure. The tests comprise of testing of seawater and chloride penetration, testing attrition and impact resistance. Specific tests are also available for underwater, slipformed, sprayed concrete as well as trial manufacturing of concrete units.

5. WORKING WITH CONCRETE

5.1 Construction

Construction with concrete in the maritime environment is particularly challenging because some work may need to be carried out underwater. Dry construction windows can be reduced due to tides, concrete may be exposed at early age to water and waves and also delivery of concrete to its location in the works may be difficult. Construction may also need to be carried out while traffic is maintained in access channels, berth or infrastructures. To ensure successful construction of structures, early consideration of all these constraints must be recognized and construction activities in difficult areas should be minimized. Hence, the use of precast concrete is an attractive option in the maritime environment as it allows for some work to be done without contact with seawater. The key construction factors that need to be considered when selecting between cast in situ concrete, precast concrete or a combination of both are the position of the work with reference to water levels, waves and tide, lead time prior to work commencing on site, construction time on site, access and remoteness, space available on site or adjoining the site as well as workmanship and lifting equipments (including their access to site).

Some concreting techniques are particularly adapted to the maritime environment including underwater tremmied concrete, self compacting concrete, horizontal and vertical slipformed concrete and also sprayed concrete. In situ concrete can be used in combination with precast elements that can act as permanent formwork and falsework as these offer increased flexibility and quality. Precast elements – factory manufactured or cast near to the site – may also be used as part of the permanent structure without in situ concrete e.g. in block work walls or armour layers.

Quality control and quality assurance during concrete fabrication and construction are important because of the restriction on inspection (or repair) of the completed works. Such procedures should be adapted to the structure location and position, and to the form of the completed works. They should focus on those aspects critical to quality and durability of the construction.

5.2 Repair and maintenance

Many of the existing structures are aging and some of them are actually historical structures dating back to the XIXth century. They have been build with different materials, techniques than the recent ones and the knowledge of these structure is rarely comprehensive.

Regular inspections and appropriate monitoring should be carried out as part of asset management, which allows optimized investigations, maintenance and repair of the structure. Also, it allows determination and refinement of the remaining life of the structure, in particular when managing for exceptional design lives. The various potential repair activities for maritime concrete, i.e. partial restoration, full restoration, protection and prevention and strengthening largely use concrete as a repair material. Some other specialist techniques / materials are also used for protecting the structure, protecting its concrete and preventing it from further deterioration. A multi-scale approach is essential as these activities can (and sometimes should) take place at both the material scale as well as the structure scale. After selective removal of the degraded component or deteriorated concrete, common methods of repair are replacement of the concrete / element, in-situ recasting, spraying concrete, and placement of concrete bags.

6. OUTCOME OF THE RESEARCH

The findings of the research summarised above will be available in 2010 in a CIRIA publication titled ‘Use of concrete in maritime engineering – a guide to good practice’ that will also be available in French by CETMEF early 2011.

The manual will be an integrated, self-supporting document comprising eight technical chapters as shown in Figure 2. It will help the asset manager / designer / contractor to address the key challenges associated with the use of concrete in the maritime environment, in particular:

- Designing for target performance of concrete elements,
- Ensuring durable concrete material which provides appropriate performance during the service life of the structure,
- Providing strength to concrete, while avoiding the corrosion risk associated with conventional uses of reinforcing steel,
- Designing with mass concrete,
- Mitigating chloride-related corrosion of reinforcing steel,
- Delivering concrete which is resistant to attrition,
- Defining the extent to which non-reinforced concrete armour units may be used to structurally respond to hydraulic loads (see Figure 2),
- Carrying out appropriate testing of concrete for the maritime environment – in particular for long term resistance to attrition, resilience to impacts, resistance to chloride attack, including laboratory testing and pilots, and
- Repairing of maritime concrete structures.

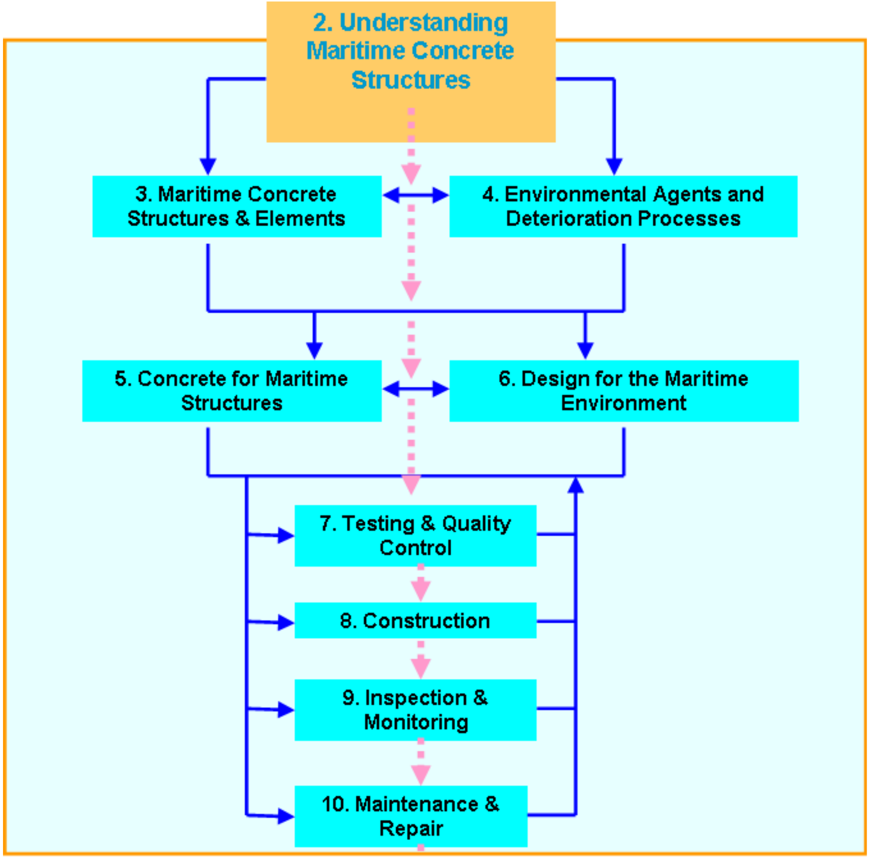

Figure 2: structure of the manual

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