Doha New Orbital Highway Contract 3

Concrete durability challenges and design strategy

by Ioannis P. Sfikas, Leo D. McKibbins, and George Daoutis

The 195 km (121 mile) New Orbital Highway (NOH) is a project owned by Ashghal, the State of Qatar's public works authority, built to connect the northern and southern parts of the country. The new highway will allow the movement of heavy vehicles from the center of the capital, Doha, to the outer areas by linking the Mesaieed Industrial City with Al Khor in the north and the new Hamad Port to the south. It will provide improved accessibility through several grade-separated interchanges along its alignment, and it is a vital component of Qatar's preparation for the 2022 FIFA World Cup. Thus, the project will provide enhanced safety as well as economic and urban development benefits (Fig. 1).

Contract 3 (NOH3) is the largest of four contracts on this project. The associated work stretches from the existing Mesaieed interchange to Salwa Road, southwest of Doha. The scope of the work for NOH3 includes the design and construction of about 55 km (34 miles) of freeway and side roads, five interchanges, and several service structures, including underpasses, culverts, retaining walls, pump stations, substations, drainage structures, tanks, and gantries (Fig. 2).

As part of a design-and-build joint venture formed by Leighton Contracting and Al Jaber Engineering, Mott MacDonald Ltd. was retained as the contractor's consultant. A core project management team in Mott MacDonald's Qatar office coordinated the design, which involved, at its peak, mobilizing 200 staff from 15 of its offices in 10 countries. The project work for the contract started in 2014, with most major components now completed and delivered. Full completion is expected in 2019.

Durability Design Package

As part of the detailed design, a specialist materials team at Mott MacDonald in London, United Kingdom, prepared a project-wide durability assessment report on concrete

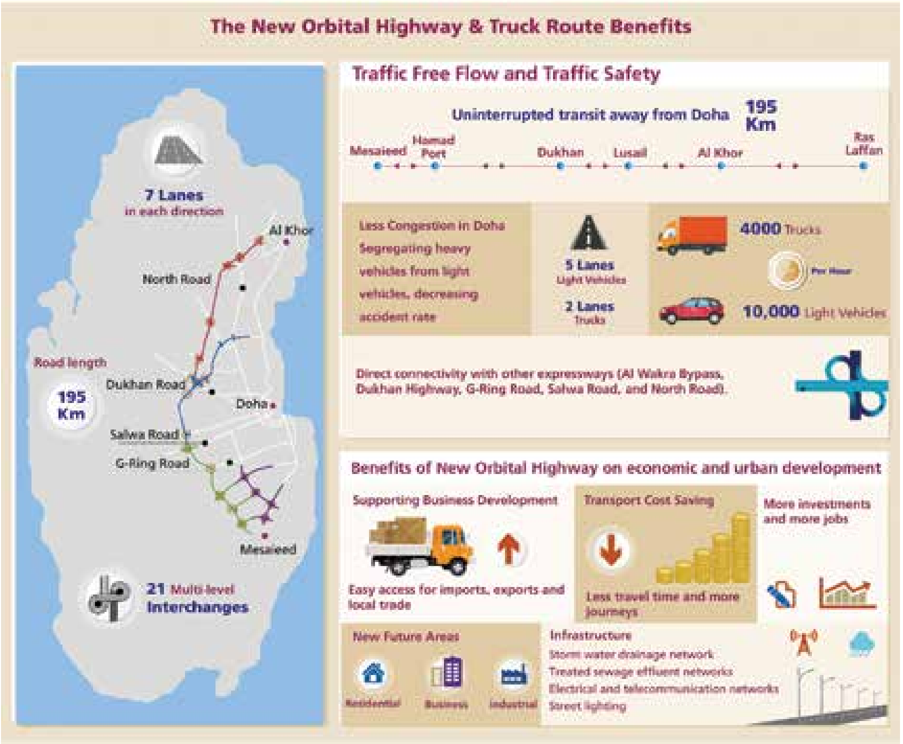

Fig. 1: The New Orbital Highway and Truck Route Benefits *(figure courtesy of Ashghal, State of Qatar public works authority)*

materials and structures. The aim of this was to identify risks to durability and propose mitigation measures to ensure resistance of the concrete to deterioration over the client's required service life of 120 years. This involved factoring in the aggressive exposure environment typically encountered in Qatar and the characteristics of the reinforced concrete structures. Where possible, the materials and construction specifications were rationalized to enhance quality assurance and control. Ancillary components and materials were also reviewed during the design and construction stages. However, in this article, we focus only on concrete materials and their durability.

Durability Assessment and Design Strategy

The methodology for the assessment of durability and the associated durability design principles for the project included:

- Identification of the main structural components for each structure (Table 1), including a review of the construction method and materials proposed to be used;
- Identification and development of the durability design criteria (Table 2) based on a review of the contractor's and owner's requirements and supporting design standards, national and international guidelines and codes, and best practice for similar structural types;
- Classification of exposure of all structural components (or groups of similar components) based on a review of the in-service conditions, including geology, soil, and aggressivity of groundwater;
- Identification of potential deterioration mechanisms and evaluation of potential mitigation strategies, given local resources and capabilities (Table 3);
- Service-life design, using deterministic and probabilistic durability modeling tools, to reduce the risk of deterioration to a tolerable level;
- Establishment of primary measures for enhancing the intrinsic durability and concrete quality of the structures:
  - The elimination of vulnerable construction details, such as complex sections or highly congested reinforcement;
  - The specification of concrete mixtures, for both precast and cast-in-place structural elements, that are highly resistant to deterioration mechanisms by specifying suitable limiting values for concrete mixture design and performance;
  - The selection of suitable materials and techniques to simplify placement and allow for effective compaction; and
  - The specification of appropriate nominal cover depths, comprising the minimum depth for durability plus a reasonable allowance for deviation in practice.
- Recommendations for workmanship, fabrication, and curing techniques to ensure production of a high-quality, dense, impermeable concrete;
- Recommendations for secondary protection measures where appropriate, including surface coatings, corrosion inhibitors, and measures to facilitate the later installation of a cathodic protection system if required; and
- Where necessary, recommendations for monitoring the condition of critical elements, allowing mitigation measures to be implemented if premature deterioration is observed or an extension of the service life is required.

Fig. 2: Typical structures of the New Orbital Highway Contract 3 project

Key Challenges and Approach to Ensuring Durability

Due to its location, size, and significance, the design of the NOH3 project was confronted with a range of challenges.

Local conditions

Structures in Qatar are subject to very aggressive conditions.[1-3] High ambient temperature, high and variable relative humidity, generally high levels of chloride and sulfate in soils and groundwater, and wind-blown sand and marine sprays present significant challenges for ensuring the durability of structures. Therefore, each structural component (or groups of similar components) on the project had to be separately classified in terms of its exposure. Three classification systems were used: the European Norm BS EN 206-1,[4] as modified by National Annexes BS 8500-1 and BS 8500-2 and BRE SD1[5-7]; Concrete Society 163[1]; and QCS 2010.[8]

Factors considered in the assessment of exposure conditions included:

- Environmental conditions, both general and regional as well as local climatic conditions of individual

Table 1:
Major structural components for new NOH3 structures

Type of new structures	Principal structural components
Main bridges	Pier foundation/pad footings, piers to main span, abutments, bridge spans/ post-tensioned box girders, approach slab, wingwalls, parapet upstands
Ramp flyovers (ramp bridges)	Pier foundation/pad footings, piers to main span, abutment, bridge spans/ post-tensioned box girders, approach slab, wingwalls, parapet upstands
Truck underpasses	Base slab/foundation, roof slab, approach slab, barriers, wingwalls
Qatar Petroleum pipe protection structures	Strip footing/foundation, arch structure, wingwalls/headwalls, central ventilation shaft

Table 2:
Key design criteria

Durability design parameter	Applicable criteria	
Service life	120 years	for bridges, underpasses, tunnels, and retaining walls
	50 years	for nonreplaceable elements of expansion joints (metal runners and anchors)
	25 years	for deck dampproofing systems, replaceable elements of expansion joints (elastomeric seals), asphaltic plug joints, cover plates, drainage components
	10 years	for protective coatings to concrete
Serviceability limit state	Steel corrosion, including the corrosion initiation period and 10-year allowance based on the provision of protective coatings that are fully effective in the early period of service life	
Cover depth	Designed as minimum cover to the outer reinforcement (including ties or stirrups), further increased by a fixing tolerance to give a nominal cover	
Permissible maximum surface crack widths	0.25 mm	for aboveground structures that are protected with dampproofing
	0.20 mm	for aboveground structures that remain unprotected (protective coatings and asphalt without dampproofing, for example, are considered unprotected)
	0.20 mm	for belowground structures that are protected with dampproofing
	0.15 mm	for belowground structures that remain unprotected
	0.10 mm	for structures exposed to seawater, seawater spray, or wetting and drying effects

Note: 1 mm = 0.04 in.

Table 3:
Major types of deterioration and adopted mitigation measures

Type of deterioration	Mechanism	Adopted mitigation measures
Internal	Delayed ettringite formation (DEF)	Control of concrete hydration temperatures, limit sulfate content, use of supplementary cementitious materials
	Alkali-aggregate reaction (AAR): alkali-carbonate reaction (ACR) or alkali-silica reaction (ASR)	Avoid use of reactive aggregates, limit expansion for aggregates or aggregate-cementitious materials combinations, limit alkali content
External chemical attack	Sulfate attack	Specify innate resistance to sulfate attack (for example, selection of appropriate cementitious materials, achievement of low permeability), use surface protection measures
	Physical salt attack	Provision of dense, impermeable cover concrete, use surface protection measures
	Acid attack	Establish physical protection by membranes or design for inherent protection (dense, low-permeable concrete)
Steel corrosion	Carbonation-induced and chloride-induced corrosion	Specify concrete durability performance (chloride migration coefficient, carbonation resistance) of mixtures incorporating supplementary cementitious materials, a minimum cover or corrosion-resistant reinforcement
Shrinkage cracking	Thermally induced shrinkage (can increase the risk of cracking)	Control concrete temperatures by using supplementary cementitious materials, lower cement content and/or ice or chilled water to produce concrete, use aggregates with low coefficient of thermal expansion, control locations of joints and restraints where possible
	Autogenous shrinkage (can increase the risk of cracking)	Control mixture design parameters and effectiveness of curing measures applied
	Drying shrinkage	Use high-quality aggregates with low absorption capacity, combined with a low *w/cm*

components, including the effects of solar radiation, ambient air temperature and relative humidity, rainfall, and the risk of airborne chlorides;
- Ground conditions on the planned route, including the nature of the geology and soil and the presence and characteristics of groundwater, in particular where there was exposure to potentially aggressive chlorides and sulfates (for example, in sabkha conditions); and
- The potential impact of climate change on conditions over the 120-year service life.

Workmanship

Workmanship is a major contributory factor in obtaining good quality, durable concrete, particularly where high ambient temperatures and humidity may impair working conditions and give rise to increased risk of construction-related problems. The associated risks were overcome by simplifying construction details during design, proposing materials that improve constructability (such as self-consolidating concrete to enhance fresh properties), specifying appropriate curing regimes for cast-in-place and precast elements, and using a specialized and supervised workforce.

Materials procurement

The use of unsuitable or contaminated materials, such as low-strength cement; aggregates that are sulfate-rich, unsound, or susceptible to alkali-aggregate reaction; and salt contamination of steel surfaces are common causes of deterioration in reinforced concrete. The associated risks were addressed by careful specification and selection of raw materials for concrete and rigorous quality control procedures. Good collaboration between the designer and the contractor throughout the process allowed those deterioration risks to be rapidly identified and efficiently resolved.

Sustainability

Sustainability in construction is one of the most important aspects and key drivers of design for big infrastructure projects.[9] The introduction of relatively high levels of supplementary cementitious materials was promoted to enhance durability but also to minimize carbon emissions from cement production. Local material resources were evaluated and used when appropriate, supporting the local economy and reducing transportation requirements.

Existing structures

As part of the design, there were plans to upgrade two existing bridges and include them on the new highway route. To support their integration into the new highway scheme, Mott MacDonald engineers undertook a condition and durability assessment exercise. This included visual inspections, a geometric survey, and intrusive and nondestructive tests (Fig. 3(a)). The findings were evaluated to verify the construction and materials details shown on the original construction drawings. A design solution was then developed for the upgrade of the existing bridges and their integration with the new bridges (Fig. 3(b)).[10]

Confidence in design

The involvement of specialist multidisciplinary engineers with both global and local experience helped to ensure that durability was considered and successfully integrated into the design as it developed. The design was completed in compliance with the national construction standards QCS 2010 and specifications by Ashghal,[8] which consider local conditions and characteristics and set minimum requirements for cover depths and concrete performance (strength, resistance to water absorption and penetration, and chloride permeability and migration). Where beneficial, these were augmented with refinements from elsewhere (such as the ACI guidelines, Eurocodes, British standards, and the UK Concrete Society's technical recommendations). This helped to more effectively embody and communicate the important aspects of the durability design and influence the construction stage. Following a rigorous checking and review process and in continual collaboration with Ashghal—especially where coordinated design and construction decisions had to be taken—a robust durability strategy was established and applied.

Fig. 3: Existing bridges were integrated into the project: (a) condition survey; and (b) schematic of widening scheme

Service-Life Design Modeling

Apart from the recommended mitigation measures to resist deterioration summarized in Table 3, three types of durability modeling tools were used as part of the design process. Modeling required an informed selection of project-specific input parameters related to local exposure conditions, construction sequence and materials, and processes selection. The output is sensitive to most of the input values, which need to be selected carefully. Good understanding of the likely in-service project conditions was aided by knowledge and experience gained from similar projects, and strong analytical skills were critical to identify and analyze all available relevant information, make informed selections, and minimize uncertainty. The materials specialists in the design team had significant experience with Middle East infrastructure projects and an in-house database of materials performance allowed statistical analyses to support the confident selection of durability modeling parameters.[11]

Chloride-induced corrosion modeling

The initiation period for chloride-induced reinforcement corrosion was modeled using a deterministic approach based on Fick's law of diffusion, with the assumption that this is the dominant mechanism of chloride ingress into a structure. The model takes account of the early resistance of concrete to chloride diffusion and gradual enhancement during the hydration period. For a specific concrete mixture, based on assumed values for the surface chloride concentration and the chloride threshold for reinforcing bar corrosion initiation, the required minimum cover depth to reinforcement can be estimated to ensure that the reinforcement will not start corroding within the desired service life.

Various options were modeled for different mixtures, incorporating types and quantities of supplementary cementitious materials, for precast and cast-in-place concrete structures. Modeling supported the specification of "triple blend" mixtures to produce concrete with sufficiently low chloride diffusion coefficient values, necessary to provide good intrinsic durability over a 120-year service life in these very aggressive conditions.

With a minimum cementitious materials content of 380 kg/m^3 (640 lb/yd^3), these mixtures were specified to incorporate either slag cement (35 to 42% of total binder for precast and 65% of total binder for cast-in-place structures) or fly ash (20 to 30% of total binder for precast and 30% of total binder for cast-in-place structures). They also include silica fume (5 to 7.5% of total binder) and a low maximum water-cementitious materials ratio (*w/cm*) of 0.35. A maximum chloride migration coefficient was specified to vary, depending on the cement blend used, between 1.75 and 2.0×10^{-12} m^2/s for precast elements and between 2.0 and 3.0×10^{-12} m^2/s for cast-in-place elements. To allow the development of such low chloride diffusion values, it was recommended that the compliance age for testing was extended beyond the typical 28-day period used for compressive strength testing to 56 or 91 days.

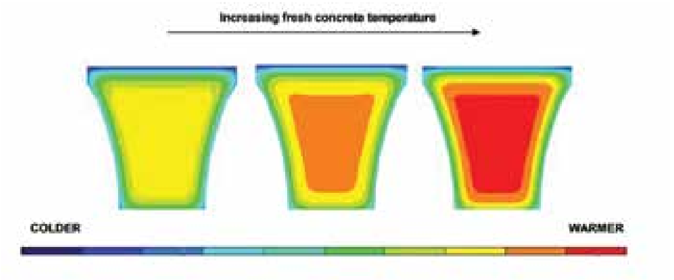

Fig. 4: Temperature contour plots of bridge piers showing effects of increasing fresh concrete temperature

Carbonation-induced corrosion modeling

An in-house tool was used to estimate the risk of corrosion due to carbon dioxide (CO_2) ingress in uncracked concrete, based on a full probabilistic modeling approach as described by the *fib* Model Code for Service Life Design.[12] The methodology is based on a reliability concept and adopts the limit state function suggested by *fib*. The design target is to limit the probability of failure to an acceptable level, which is typically 10% for serviceability. The model includes the carbonation resistance of concrete, and it can provide an estimate of the required cover to limit the associated risk for corrosion under a given set of exposure conditions. For this study, a minimum period of curing between 3 and 14 days was determined for a range of cover depths of between 50 and 60 mm (2 and 2.4 in.) to ensure good quality and sufficient carbonation resistance of the cover concrete. The potential for increased atmospheric CO_2 concentration over the 120-year life of the structures was also taken into consideration.

Thermal analyses

The heat development and the associated risk for delayed ettringite formation due to cement hydration had to be assessed in thick elements. Finite element analysis methods and tools were used to estimate the time-dependent heat distribution across any section geometry.[13] The adiabatic heat curves were developed using models proposed by the UK Guidance for early-age thermal effects in concrete.[14] A parametric study was performed for the maximum developed temperature and the temperature differentials between core and surface for a range of fresh concrete temperatures (Fig. 4). The estimated thermal behavior was then compared against the code provisions, project requirements, and best practice guidance in References 8 and 15; and additional recommendations were made to mitigate the associated risks, in line with standard practice as described in References 16 and 17.

Summary

This article summarizes the actions taken to ensure a 120-year design life for major concrete structures of Qatar's New Orbital Highway Contract 3 project, which is part of the colossal investment program in infrastructure development to prepare for the 2022 FIFA World Cup. The durability aspects of the design were addressed by a specialist materials team of the contractor's consultant, Mott MacDonald Ltd. The UK-based team developed a strategy based on a comprehensive assessment methodology and the application of durability design principles based on experience gained from other major infrastructure projects across the Middle East and elsewhere.

Using advanced deterioration modeling tools and thermal analysis models, minimum requirements for concrete materials and mixture designs were specified to accommodate the very aggressive local environment and ground conditions. These resulted in the specification of "triple blend" cements with target proportions of portland cement, slag cement or fly ash, and silica fume as well as low *w/cm*. In terms of performance, the resistance to chloride migration was one of the most critical design parameters. Additional recommendations for placement techniques, finishing operations, and adequate curing were made aimed at ensuring good mixture quality and superior durability performance of the final product for both precast and cast-in-place concrete elements used in construction.

Consistently promoting collaboration and active communication links between all parties involved in design and construction helped to overcome the inevitable challenges that arose during construction, helping to produce a modern high-capacity highway network that will stand the test of time in these challenging Middle East conditions.

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Selected for reader interest by the editors.

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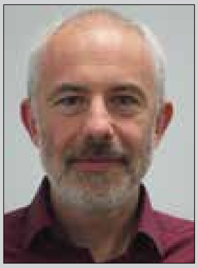

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