Concrete technology and durability design
COWI and concrete

COWI – the company
COWI is internationally recognised as a major consultant in several areas from energy and waste to economics, but in particular known for its leading position in major bridge, road, airport, marine structures and tunnel projects throughout the world. Concrete is a key material for these modern structures and COWI has therefore created a strong concrete design and research environment within the company to provide specialist services in this area.

Concrete – the material
The structural design, suitable specifications for the concrete and the reinforcement, the placing and the proper curing are all important parameters to achieve the desired results.

COWI’s concrete technology expertise covers standards and specifications both in Europe and internationally. Suitable specifications can be prepared to ensure that the customer receives the concrete solution that is optimal for the intended service life requirements and the exposure conditions.

COWI participates in R&D networks and projects with universities, government institutions as well as private partners in several countries. COWI’s concrete technologists and designers participate in national and international standard organisations, through CEN-groups, Danish and European standardisation work, FIB model codes, RILEM, etc. They are often invited speakers or keynote lecturers at international conferences on concrete technology and this is reflected in the large number of COWI publications and references in the concrete field.

COWI seeks to include innovative ideas as part of large and small projects in order to create value for their customers through savings to provide durable and sustainable solutions.

Concrete technology and durability design
• Durability and service life design
• Specifications and construction monitoring
• Materials technology
• Special design solutions
# Durability and Service Life Design

**COWI's Durability Design Services**
- Assistance in defining the owner's service life requirement, e.g. end of design life, level of reliability and frequency of maintenance.
- Elaboration and evaluation of different durability design options including appropriate structural detailing.
- Assessment of macro and micro exposure conditions.
- Modelling of deterioration mechanisms for materials and environmental actions.
- Service life modelling and design using the DuraCrete approach.
- Development of appropriate specifications for materials through durability modelling.
- Conversion of specifications to concrete mix designs and compliance testing.
- Back analysis of service life upon completion of construction.
- Quality assurance programmes.
- Life cycle costing.
- The Birth Certificate.

## Probabilistic Service Life Design

Nowadays, civil engineering structures, such as bridges, tunnels, marine structures and other infrastructure projects, are designed for a service life of 100, 120 or even 200 years. This surpasses the assumed design service life of most codes and standards substantially.

The operational approach to design for durability is to define durability as a service life requirement. In this way, the non-factual and rather subjective concept of ‘durability’ is transformed into a factual requirement of a number of years during which the structure performs satisfactorily without unforeseen high costs for maintenance. In this way, the time factor is introduced as a design parameter. Service life design based on these functional requirements is carried out in a similar way to the load and resistance factor design concept used for structural design.

COWI’s leading position within durability design is based on more than 40 years of worldwide experience in design, operation and maintenance of reinforced concrete structures.

COWI, spearheading the international development of rational service life designs, provides a modern fully probabilistic design methodology for durable concrete structures, i.e. the DuraCrete approach. COWI implements this state-of-the-art approach in new designs and in the re-evaluation of existing structures. It has been adopted by national authorities and individual clients all over the world as well as by international associations, e.g. fib.

The DuraCrete approach can effectively combat chloride and carbonation induced reinforcement corrosion. All uncertainties regarding environmental exposure, material properties and deterioration are taken into account.

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**Service Life Design Flow Chart**

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**Table: Design Flow Chart**

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<tr>
<th>Assumptions</th>
<th>Terms of definitions</th>
<th>Other administrative provisions</th>
<th>Principles of service life</th>
<th>Design criteria</th>
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**Design/Verifications**
- Probabilistic models:
  - Resistances
  - Load/exposure
  - Geometry
- Design values:
  - Characteristic values
  - Partial safety factors
  - Combination factors
- Limit states
- Design equations
- Design provisions
- Exposure classes
- Exposure classes
- Project specification for material selection and execution
- Inspection/monitoring plan
- Quality plan for execution (optional)
- Inspection of execution
- Maintenance
- Condition control during service life

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In case of non-conformity with the performance criteria, the structure becomes either obsolete or subject to a redesign.
**Life cycle costing**

Life cycle cost optimisation, e.g. formulated as an optimisation of the net present value of a structure, has become an integral part of COWI’s service life design philosophy. Without this, a rational evaluation of future costs in a comparable manner to rate alternative solutions, preferably as a life cycle costing (LCC), the service life design will not be possible. This is mainly because any serious savings in future maintenance costs will not be adequately considered to compensate for any increased initial construction costs, although such future savings may be very substantial. COWI’s LCC services include:

- Recognition of potential savings in whole-life costs through built-in durability, e.g. selective use of stainless steel
- Evaluation of life-cycle costing and cost options

**The Birth Certificate**

A valuable means to increase the knowledge of the expected performance and service life is to establish a baseline study of the finally achieved quality of the in-situ structure. This could conveniently be done and reported as part of the handing-over of the structure from the contractor to the owner. Therefore, COWI has established the concept of the Birth Certificate, which includes a first forecast of the service life based on factual data, e.g. the actual cover thicknesses and the actual chloride diffusion coefficients, from the existing structure. At later inspections this data can be updated and used to revise the expected residual service life resulting in an ever-increasing accuracy of the remaining service life forecast. This powerful decision tool provides the owner with valuable information on future maintenance and repair needs.
Specifications and construction monitoring

Specifications
COWI has many years experience in assisting both clients and contractors in the preparation and/or review of specifications for major international projects, including immersed and bored tunnels, all types of bridges, marine structures, airports and infrastructure schemes all over the world. Irrespective of the type of contract COWI can provide specialist assistance to fulfil particular needs.

COWI’s expertise is based on a thorough understanding of the relevant international standards complemented by an extensive knowledge of concrete and materials technology in combination with experience in a multiplicity of construction techniques. Consequently, COWI has the ability to interpret any special demands, be they structural, environmental or financial, in order to provide specific requirements for particular parts of a project.

Quality assurance and construction monitoring
In order for a concrete structure to function as foreseen by the design, the construction process must be controlled by a suitably framed quality assurance (QA) scheme.

COWI has the knowledge to establish suitable QA schemes in line with the preparation of project specifications. In addition, COWI has experienced concrete specialists, who can review/audit construction materials, mix designs, functional requirements, method statements and inspection and test plans, etc., against specified requirements and project objectives.

Consequently, the same personnel have the ability to assess the acceptability of non-conformances if and when they arise and the suitability of associated corrective actions, remedial works, etc., to ensure that the project objectives are met.
Architectural finishes

Architectural finishes is another area of importance as the achievement of an acceptable surface finish to the concrete is often in conflict with the durability requirements of a structure. This is particularly important where prestigious and/or innovative structures are exposed to harsh environments, e.g. the Middle East.

COWI has special experience and interest in this area and can advice on appropriate solutions to achieve the overall architectural objectives of the project.

Curing technology

In order to secure the long term durability of a concrete structure a well thought-out curing programme should be specified and the curing properly monitored during construction.

COWI’s main areas of curing technology expertise include:

- Control of early age cracking due to thermal movements, early shrinkage, creep and settlements
- Evaporation control to avoid the damaging effects of drying out which can lead to cracking and reduction in surface quality
- Hot weather concreting, particularly relevant to the Middle East and other high temperature environments
- Cold weather concreting to ensure early protection from damage due to freezing conditions
- Limitation of maximum temperature to avoid the deterioration effect of delayed ettringite formation (DEF)

Most of the above curing conditions are interconnected and cannot be considered in isolation.

COWI has experienced personnel and specialist tools, e.g. 2/3-D finite element method (FEM) programmes for temperature and stress simulation to design appropriate integrated curing systems and/or review proposed systems against specified requirements.
COWI’s concrete and materials specialists have broad international experience from almost every region around the world and from almost every type of civil engineering structure.

COWI’s concrete and materials group has more than 40 years experience in materials and concrete investigation methods, durability and technology and contribute regularly to national and international conferences, books and magazines on concrete and reinforcement, from the design stage up to and including the as-built phase.

Activities include all kinds of material and construction topics, ranging from petrography and scanning electron microscopy at nanometre level to large scale tunnelling, bridge and pavement construction.

COWI has an in-house, ISO 9001 certified concrete laboratory specialised in concrete investigations from chemical analyses and petrography to destructive as well as non-destructive methods.

With funding from the World Bank and DANIDA, COWI has presented innovative solutions in road construction with the use of alternative binders and/or marginal aggregates in road stabilisation. Besides providing passable roads all year round in third world regions, such solutions are also environmentally friendly with regard to preservation of aggregate resources as well as limiting CO₂ emissions.

Concrete microstructure
COWI’s specialists have been involved in many investigations concerning concrete durability and deterioration of various kinds of concrete structures worldwide; especially with several references from the Middle East known for its harsh climate.

COWI’s materials and concrete specialists are recognised in their separate fields as independent experts to perform investigations and evaluations of new or deteriorated concrete and whenever a technical dispute may arise. This also includes expert witness assistance in cases which may end up in court. Design topics and expert knowledge on materials and standards from all over the world are also part of COWI’s knowledge base.
Deterioration mechanisms
COWI's main fields of expertise in materials technology include evaluation of concrete concerning:

- Surface attack
- Chloride ingress and risk of corrosion
- Surface carbonation
- Detection of causes of cracking
- Determination of concrete composition including water-cement ratio, type and content of cement as well as aggregate, use of air entrainment, addition of fly ash, blast furnace slag, silica fume, etc.
- Sulphate and seawater attack, delayed ettringite formation (DEF) and thaumasite formation
- Soft water leaching, carbonic acid and aggressive CO₂ attack
- Alkali-silica reactions (ASR) and residual reactivity and expansion potential. Experience with local aggregate types and test methods
- Freeze-thaw durability, evaluation of quality of entrained air void systems

Such evaluations, alone or combined with other advanced investigations, can solve almost any case of premature concrete deterioration. Investigations of concrete exposed to chlorides can include determination of chloride profiles and determination of the chloride diffusion coefficient to quantify the future risk of reinforcement corrosion.

Modelling of the residual service lifetime by the DuraCrete approach or other models is based on reliable results obtained from advanced laboratory investigations.

Innovative, environmentally friendly and low-cost road construction methods using blast furnace slag or local pozzolans for stabilisation of secondary or marginal aggregate resources, Tanzania
**Special design solutions**

COWI’s durability and concrete specialists have a broad international experience in tailored, special concrete and reinforcement design solutions.

Selected special design solutions offered by COWI include, but are not limited to the following:
- High performance concrete
- Self-compacting concrete
- Steel fibre reinforced concrete
- Polypropylene fibre concrete
- Green concrete
- Membranes
- Diaphragm walls and secant piles
- Corrosion resistant reinforcement

**High performance concrete**
The continuous demand for increased strength and improved durability of concrete structures has led to the development of HPC. This development had three main objectives:
- Protect the reinforcement against corrosion
- Resist deterioration of the concrete itself
- Provide adequate high strength to fulfil the structural requirements

HPCs for normal type structures usually have a high cementitious binder content, a low water-cement ratio and higher contents of plasticiser and superplasticiser. Such concrete can be used for bridges, tunnels, marine works, offshore structures and high rise buildings, where the strength requirements usually remain within a range of 50-80 MPa. A drawback of HPC is that the more refined the concrete mixes become, the higher is the sensitivity in relation to the actual handling during execution.

HPC sets high demands on competence and experience; competence and experience that COWI can offer.

**Self-compacting concrete**
A concrete mix, where the placing and compaction has minimal dependency on the available workmanship on site, improves the true quality of the concrete in the final structure. This has been the main driving force in recent years’ development of self-compacting concrete (SCC). With the aid of a range of chemical admixtures and optimal grading of the aggregates, concrete with a low water-cement ratio can be made to flow through complicated form geometry and around complex reinforcement without segregation. The form can be filled and a uniform compaction without honeycombs can be achieved, also in the cover zone of the concrete. SCC exerts an increased pressure (at times close to the hydrostatic pressure) on the formwork.

COWI’s concrete specialists provide expert knowledge on both mix design and execution including formwork design for SCC.
Steel fibre reinforced concrete
For many applications steel fibre reinforced concrete (SFRC) is a very suitable solution for structural members, which are not highly loaded in flexure or tension. Besides advantages in terms of construction and cost, SFRC grants structural benefits and superior durability properties compared to conventional reinforced concrete. The capacity of the fibres to reduce crack width and deflection is often more important than the increase in tensile strength of the concrete. Furthermore, the addition of fibres enables bearing capacities after cracking and allows stress redistribution, which makes the otherwise quasi-brittle behaviour of the concrete more ductile.

COWI has manifold experience and expert knowledge in all phases of the design and the execution of SFRC structures.

Polypropylene fibre concrete
The provision of an adequate level of fire protection is particularly important for tunnels as has been witnessed by the Great Belt and Channel Tunnel experience, but it can also be relevant to other structures where the evacuation of personnel and emergency services should be protected.

With regard to concrete structures the addition of a relatively small amount of polypropylene fibres (PPF) to the concrete during the mixing process can provide considerable improvement in the fire resistance of the finished structure. A recent innovation has been to add PPF to shotcrete to improve the fire resistance of existing structures and unstable rock formations.

COWI has considerable experience in this area to provide assistance with the following:
- Concrete and shotcrete mix designs
- Fixing systems for shotcrete
- Fire testing
- Acceptance criteria

Green concrete
Green concrete is a synonym for resource-saving concrete. Use of green concrete reduces the environmental impact of concrete structures with regard to energy consumption, waste water and CO2 emissions. Green concrete can be less expensive to produce, because waste products can be used as a partial substitute for cement, landfill taxes can be avoided and the energy consumption in production can be lowered.

COWI’s concrete specialists have been involved in related R&D projects and are experienced in specifying green concrete.
Membranes
The application of membranes for concrete structures can be twofold: either to achieve a watertight concrete structure or to act as a protective barrier in case of concrete attack, e.g. high sulphate concentrations in soil/groundwater.

COWI has specialist experience and can support clients and contractors with selecting the most appropriate membrane type depending on the aggressivity of the environment, the geometric conditions of the structure and the construction procedure.

Diaphragm walls and secant piles
Historically, diaphragm walls and secant piles have been used with success in relatively benign environments. However, in more hostile or aggressive environments, e.g. in the Middle East, and with extended service life expectancy, special measures are necessary to secure the required durability of the structure. COWI has specialist experience in this area and can support clients and contractors by providing innovative durability design solutions, as special reinforcement solutions and/or concrete mix-design requirements to mitigate the effects of chloride induced reinforcement corrosion.

Corrosion resistant reinforcement
The implementation of corrosion resistant steel reinforcement is the simplest and most effective method to eliminate the risk of reinforcement corrosion. This method does not only solve the corrosion problem in an infallible way even in the most corrosive chloride environments, but it also leaves the site activities nearly unchanged. The selective use of stainless steel reinforcement in zones exposed to high chloride concentrations is a highly reliable solution. This solution ensures very long problem-free service life in that part of the structure, provided the concrete itself is made sufficiently resistant to avoid other types of deterioration. Of particular importance is the often overlooked fact, that SSR can be coupled with carbon steel reinforcement without causing galvanic corrosion. Another benefit is the added value, which follows from the possibility of accepting the use of locally available materials even with chloride contamination and the possible lack of special qualifications of the local work force.

COWI has expert knowledge in specifying appropriate reinforcement solutions to attain the required service life in all possible environments.

COWI’s durability specialists can also offer services concerning the assessment of alternative corrosion countermeasures for concrete reinforcement and for the evaluation of corrosion protection of exposed structural steel. This is supported by a continuous cooperation with universities and COWI’s involvement in various related ongoing and future R&D projects.
Tunnel shaft with secant piles and waterproofing membrane, District Heating Tunnel, Copenhagen, Denmark

Photo: Henrik Pyndt Sørensen
During recent years the European Union supported a number of closely related research projects and technical networks of considerable magnitude and with very valuable and directly applicable output in relation to safety, durability and service life design of concrete structures for major infrastructure projects.

COWI is the only consultant in all of the five interrelated projects: DuraCrete, DuraNet, UPTUN, DARTS and FIT.

This has placed COWI in the absolute forefront in the rational service life design and safety assurance of tunnel concrete structures. The results are generally applicable for all types of concrete structures exposed to an aggressive environment and have been implemented in numerous recent and current constructions.

**DuraNet**

The recognised success of the DuraCrete project resulted in the European Commission granting further support for establishing the special international network DuraNet to disseminate the valuable possibilities of applying the DuraCrete service life design methodologies on an international level.

**DARTS**

The objective of DARTS was to develop operational methods and supporting practical tools for the best pro-active decision-making process for choosing, in each individual case, the cost optimal tunnel type and construction procedures.

The dominating innovation of DARTS was the integration of reliability-based structural design, geotechnical issues, service life design based on the DuraCrete methodology, hazard design including risk assessment, environmental aspects, society’s needs, sustainability and economic aspects.

COWI was the key proposer and the project and scientific manager of the DARTS project and acted as appointed coordinator between DARTS and FIT.

**UPTUN**

The UPTUN project main objects were the development of innovative and cost-effective fire-protection technologies for tunnel applications and the development, demonstration and promotion of procedures for rational safety level evaluation. The main output of UPTUN was a set of innovative cost-effective technologies and a risk-based evaluation and upgrading model.

COWI was a member of UPTUN and responsible for one key working party.

**FIT**

The European thematic network FIT is a group of stakeholders focusing on the exchange of knowledge, integration and creation of know-how. FIT has strong links with actual and future European and national research projects.

COWI was a FIT member and leader of two task forces.
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COWI is a leading northern European consulting group. We provide state-of-the-art services within the fields of engineering, environmental science and economics with due consideration for the environment and society. COWI is a leader within its fields because COWI’s 3500 employees are leaders within theirs.