DURABILITY AND THE IMPACT OF THE EXECUTION PROCESS ON THE USEFUL SERVICE LIFE OF CONCRETE STRUCTURES

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SUMMARY

The quality of the concrete as achieved in the finished structures is highly sensitive to the execution process. The more efforts put into refining the concrete the more sensitivity becomes the concrete to the execution process. The designer's obligation is to adopt design criteria for the concrete properties which can be achieved realistically on the individual site. He must respect the locally available materials and recognise the true competence and experience of the available local workforce. The first few hours, days and weeks of the life of a structure are decisive for the length of its useful service life.

INTERACTION OF DESIGN AND EXECUTION

Already at the design stage possible means of construction shall be considered and fixed, as this will influence the durability design.

It is important that this interaction between the foreseen execution and the provision to provide durable structures is identified at an early stage of the design in order to optimise the design and prepare the structure for easy inspection and maintenance.

The challenge of structural concrete

Designing with structural concrete poses some unique challenges. The consequences are not fully recognised in every-day design. These are:

1. The quality and the performance of the concrete are only assumed at the design stage, but govern the full design and the specifications.

2. The true concrete quality and its performance characteristics are determined through the actual execution and after-treatment processes. Hence, the very short period of time during construction and initial hardening, represents the most important period of time during which the required durability performance of the finished structure shall be ensured.

3. If durability performance of the finished structure turns out to be sub-standard, this is most often not apparent nor detectable until some time has passed, due to the nature of the deterioration of concrete structures exposed to an aggressive environment, Figure 1. The time passed before premature deterioration becomes apparent may often be longer than the contracted liability period of the contractor and the designer, but very much shorter than the service life expected by the owner.

Such potential difference between design assumptions and really achieved qualities does not exist for other structural materials like structural steel.

Deterioration of concrete structures depends on the aggressive substance from the surrounding environment is transported to the concrete surface and then moves into the outer concrete layer and when a sufficient concentration has been achieved then either destroys the concrete, or moves further inwards towards the reinforcement and causes corrosion of the reinforcement.

Figure 1: Consequences of undetected reinforcement corrosion of a parking deck due to de-icing salt brought in by the vehicles. The deck below was also fully occupied by vehicles!

Therefore, it is evident that the quality of the outer concrete layer exposed to the aggressive environment becomes the one most important quality determining parameter, Figure 2 [1].

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Concrete denseness and the size of the concrete cover on the reinforcement are generally assumed to provide the corrosion protection needed.

Figure 2: Importance of the penetrability of the outer concrete layer, and the thickness of the cover on the reinforcement to protect the structure against ingress of aggressive substance and deterioration of concrete and reinforcement.

The above challenge highlights also a fundamental difference whether a design is made with structural concrete or with structural steel. In the latter case the visual detection of beginning corrosion is usually possible at a very early stage. This is not the case for concrete structures, particularly when suffering reinforcement corrosion, Figure 3.

Figure 3: The famous Golden Gate Bridge, a steel suspension bridge seen from the harbour of San Francisco, USA. However, the view is dominated by the reinforced concrete wall suffering extensive and unsightly corrosion damage.

THE EXECUTION STAGE

The execution stage constitutes the most vital step in achieving the required quality of concrete structures. From a durability point of view the essential part of the execution process is to ensure the correct concrete quality and thickness of the concrete cover - it is as simple as that!

The following two issues relate to the resistance of the concrete cover to ingress of aggressive substance from the environment:

- The compaction, in order to ensure uniform, dense and strong covers.
- The type and duration of curing, i.e. controlling moisture levels and temperature differences in order to limit or avoid early age cracking.

In addition, the following two recent developments are expected to obtain considerable influence on the quality and service life of future exposed structures:

- Permeability controlled formwork liners (PFL).
- Self compacting concrete (SCC).

Means of providing the required thickness of the concrete cover with spacers is an integral, but often neglected part of ensuring durable structures.

Because the execution phase itself has dominating influence on the final quality and performance of the structure the on site supervision and quality control is an essential part of the construction process.

Prestressing and prestressed concrete structures pose specific execution problems not dealt with in this paper.

Compaction of concrete

Adequate compaction of the concrete in the cover may be difficult to achieve due to the limited space and the need for the cover concrete to be moved through the outer layer of reinforcement. This movement of the concrete may cause “sieving” of the concrete if the spacing of the reinforcing bars is small or the concrete is stiff. When designing the reinforcement layout the realistic ability to compact the concrete on site shall be respected. Figure 4 illustrates a situation where this has not been achieved.

The compaction by vibrators shall be achieved through vibrating the concrete inside the reinforcement cage. Experience has shown that vibrating directly in the cover concrete may lead to inferior compaction of the concrete, e.g. by leaving porous traces from the vibrator. The problem requires particular attention in the case of
dense high performance concretes with mineral admixtures due to the tixotropy of such low water/cement ratio concretes with high amounts of plasticizer and superplasticizer.

Figure 4: Example of reinforcement detailing which does not respect the need for reliable casting and compaction of concrete. Particularly the quality of the concrete cover, the “skin”, is in danger.

The use of external form vibrators to compact the concrete, and in particular the cover concrete, is also a questionable procedure. The reason being, that the entrapped air voids in the concrete tend to move towards the location of the vibrator and accumulate to form porous concrete. With correct use of poker vibrators such air bubbles are extracted from the concrete when slowly lifting the vibrator head out of the concrete.

Curing

Curing of the concrete is part of the hardening process, which ensures an optimal development of the fresh, newly cast concrete into a strong, impermeable and durable hardened concrete in the cover zone free from plastic shrinkage and thermal cracks. During this initial stage of the life of the concrete, it is necessary to:

1. Use an appropriate hardening process. Casting must be planned such that the required strength at the time of form stripping is achieved.

2. Ensure against damage from drying. Premature drying-out of the concrete surface should be avoided, as this may lead to large plastic shrinkage cracks as seen on Figure 5.

3. Ensure against damage through early freezing. The concrete must not freeze until a required minimum degree of hardening has been achieved.

4. Ensure against damage from thermal stresses. Differential movements due to thermal differences across the section or across a construction joint between hardened and newly cast concrete should not lead to cracks.

Figure 5: Plastic shrinkage cracks on bridge deck.

The increased sensitivity to too early drying out of some types of cement and concrete (composite and blended cements; chemical and mineral admixtures) has accentuated the need to develop simple and rational heat and moisture curing procedures. Several comprehensive tools are now available to design the appropriate types of moisture and heat curing.

According to experience with Ordinary Portland Cement concrete, it is recommended to stay within the following limits for temperature stresses:

- A maximum of 20 °C temperature difference over the cross-section during cooling after stripping
- A maximum of 10 - 15 °C difference across construction joints and for structures with greatly varying cross-sectional dimensions.

Concretes with very low water/cement ratio, such as high performance concrete, may be particularly sensitive to heat and temperature control during the hardening process, and values for
temperature differences should be lower - and at times considerably lower - than indicated for Ordinary Portland cement concrete above.

The heat balance to be controlled is sensitive to changes in the selected level of insulation. In practice it is often necessary to decide at short notice whether to strip formwork or whether possible additional or reduced insulation of a hardening cross-section has to be made.

In short, good curing is needed to profit from a good concrete mix. Bad curing destroys an otherwise good concrete mix. And good curing cannot compensate for a bad concrete mix. All efforts to ensure an optimal heat and moisture curing may be in vain, if the initial quality of the concrete mix is inferior.

In practice temperature profiles can be calculated, and the whole curing process can be designed prior to casting the concrete. PFL results in some of the excess water in the surface concrete layer being temporarily absorbed by the liner thus reducing the water/cement ratio. When then hardening takes place the hydrating cement in this layer would need some additional water for optimised hardening, and this water is then readily available in the liner. Hence, an optimal moist or water curing takes place in this outer layer, and an improved density of the cover is obtained.

The liner leaves a characteristic tissue like pattern on the surface of the concrete and requires therefore that care shall be taken when placing the liner on the formwork. Particular care shall be taken with the flexible tissue type liner as they tend to fold during casting and compaction if not correctly fixed to the form. Such folds and all physical means of fixing the liner to the formwork will be permanently visible on the future concrete surface. Therefore, the aesthetical issue of visible surfaces shall be carefully considered.

PFL can improve the quality of the outer part of the concrete cover, but cannot compensate for local bad compaction and honeycombs. However, the new developments within self-compacting concrete could be a realistic solution to this problem, and thus a combination of PFL with SCC would have a valuable synergy effect in improving the durability of concrete structures.

Self-compacting concrete (SCC)

The need for durable concrete in an aggressive environment leads automatically to concrete with optimised mix composition and a low water/cement ratio. Such concrete is difficult to compact and the risk of honeycombs, particularly in the cover concrete, increases. In addition, the quality and efficiency of compaction is extremely dependent on the individual person handling the vibrator.

Hence, the better the concrete mix is, from a durability point of view, the greater becomes the risk of having inferior or bad execution leading to reduced quality in the final structure. This inconsistency is due to the dominating influence of the execution process on the final quality and performance of the structure regardless of the good quality of the initial concrete mix.

The development of a concrete mix where the placing and compaction has minimal dependence on the available workmanship on site would therefore improve the true quality of the concrete in the final structure. This has been a main driving force in recent year's development of SCC. With the aid of a range of chemical admixtures and optimal grading of the aggregates concrete with low water/cement ratio can be made to flow through complicated form geometry and around complex reinforcement layout, without segregation. The form can be filled and a uniform compaction without honeycombs can be achieved, also in the cover zone of the concrete, with no or only minimal additional contribution to the compaction and levelling of the concrete from the workforce on site.

The flowing concrete will exert an increased pressure on the form, which shall be taken carefully into account when designing the formwork. The form pressure may at times be close to the hydrostatic pressure, but with the concrete density of 2.4!

In addition, SCC will "escape" through any hole or slot in the formwork, see Figure 6, so the formwork for SCC shall be tight.

The use of SCC is also an environmentally friendly technology as the noise level from
vibrators is nearly eliminated and the concrete workers need only minimal work with the vibrators, with all the adverse effects vibrating concrete has on the body, such as "white fingers".

Figure 6: Self Compacting Concrete, SCC. Left: uniformly filling the form by pouring the concrete into one end of the form. Suddenly the concrete stopped rising in the form. Right: The reason being that a small slot in the form let the SCC flow out of the form! Conclusion: Formwork for SCC shall be (water-) tight, and also stronger than usual to resist the increased form pressure.

The main current drawback with this technology is the sensitivity of such concrete to the precise dosing, mixing and transporting of the concrete and the dependence on the weather conditions while casting the concrete. Under adverse conditions the ability to flow may suddenly be lost. In addition, the increased cost of such concrete is noticeable, and the demand for expertise and experience is moved nearly fully to the mixing plant.

Spacers

The minimum concrete cover specified for a design is usually the value used to design the expected service life based on assumptions regarding the penetration of de-passivating and corrosive substance to the reinforcement. Therefore this minimum value shall be ensured in the final structure by taking the relevant tolerances into account in the selection of type, dimension and spacing of spacers.

Spacers shall be designed according to $c_{\text{rem}}$ and not to comply only with $c_{\text{min}}$. This fact is often overlooked in practice!

The spacing of spacers shall be adequate to ensure the required cover considering the dimensions, i.e. stiffness, of the reinforcement and the fresh concrete pressure on the reinforcement, which can be expected during casting and compaction of the concrete.

When controlling concrete cover after placing and hardening of the concrete the measured values may not be less than $c_{\text{min}}$.

In aggressive environments spacer material should preferably have good adhesion to the concrete. The spacer geometry and fastening shall ensure good and stable positioning on the reinforcement. Spacers with geometry and fixing as shown on Figure 7 should not be acceptable.

Figure 7: Small concrete spacers with large spacing of spacers. Such spacers are not adequate to ensure a reliable concrete cover, as shown on

The reason why such tiny spacers as shown on Figure 7 should not be acceptable is clearly illustrated on from the same structure.

Figure 8: The small concrete spacers shown on Figure 7 have no stability and cannot be fixed adequately. In view of the importance of achieving the correct concrete cover, this situation is not acceptable.

The concrete cover in aggressive environments shall usually be minimum 50 mm according to several codes and standards. However, the special aggressive conditions like in tidal and splash zones would lead to larger covers in the above-water zone. Values of 75 mm have become normal for long life marine structures (100-120 years service life), and even larger values are considered sometimes.

The spacer material shall have good bond to the concrete and shall have similar hygro-thermal deformation characteristics as concrete.

In this respect plastic spacers are not compatible with the surrounding concrete, in the sense that they have no direct adhesion and that they have
different temperature coefficients (factor ten) than concrete, and furthermore age under exposure to air, sun and marine environment, see Figure 9 and Figure 10. In aggressive environments high quality concrete spacers shall be the preferred option and it is important to ensure that the spacers are of the same high quality as required for the structural concrete itself. Hence, high quality concrete spacers with reliable fixing, as shown on Figure 11 shall be used in exposed areas.

Figure 9: A concrete box girder bridge built about 20 years ago. A view of the underside of the box 22m above the sea is shown on Figure 10.

Figure 10: A systematic set of spalled concrete is clearly visible of the underside of the box girder of Figure 9, as seen to the left. The reason is documented on the close-up to the right: The use of plastic spacers. Plastic spacers are not compatible with concrete and should not be used in highly corrosive environments.

High performance concrete (HPC)

The continuous demand for increased strength and improved durability and performance of concrete structures has led to the development of HPC. This development has had three main objectives in mind:

1. Protect the reinforcement against corrosion; in particular provide protection against ingress of chlorides by creating dense impermeable concrete in the cover zone with very low penetrability of aggressive ions such as chlorides, sulphates and CO$_2$.

2. Resist deterioration of the concrete itself when exposed to the aggressiveness of the environment such as sulphates, seawater and other chemical attacks, as well as resist freeze/thaw attack.

3. Provide adequately high strength to fit the structural requirements.

This development has been very successful in many respects. HPC products have met very complex and demanding structural challenges. Nevertheless, specifying HPC for almost any structure is today more the norm than the exception. It may be questioned whether this in practice has led to, or will lead to improved performance of concrete structures.

Figure 11: Solid and reliable type of concrete spacer with reliable fixing, and with strength to resist even very high concrete pressures, and still with no or only marginal imprint on the finished concrete surface.

HPC for normal type structures will usually have a relatively high cementitious binder content (blended cements), a low water/cement ratio, say in the range of 0.35 - 0.40, and a high contents of plasticizer and superplasticizer. Such concrete can conveniently be used for bridges, marine works, offshore structures, high rise buildings etc. where the strength requirements usually remain within the range of say 50 - 80 MPa.

A typical HPC-mix is illustrated in Figure 12.

One drawback has been that these more refined concrete mixes become more sensitive towards the actual handling during execution.

Workmanship

The increased sensitivity of HPC compared to normal concrete relates to the mixing, transport, placing, compaction and curing processes. HPC
requires an experienced and competent workforce and high quality workmanship to achieve the potential benefits, but this is not always available on site.

Figure 12: A typical mix for a HPC with a maximum water-binder ratio of 0.35. A three-powder binder combination is used, comprising OPC, flyash and silica fume. Such a mix is extremely sensitive to correct execution and curing. All additives and admixtures have to be mixed into the bulk of the concrete, but mostly only needed in the cover zone - A noticeable waste in all aspects. (Photo: N. Thaulow).

HPC concrete in the "better" end of the strength scale can be very difficult to place and compact, and the risk of honeycombs, particularly in the cover concrete, increases. In addition, the quality and efficiency of compaction is extremely dependent on the individual person handling the vibrator. Hence, the better the concrete mix, from a durability point of view, the greater the risk of having inferior or bad execution leading to reduced quality in the final structure. This fact is seldom respected on site. This inconsistency is due to the dominating influence of the execution process on the final performance of the structure.

To varying degrees these concretes differ from the long-term known types of structural concrete through the following [2]:

- The dosing and mixing become more complicated and sensitive, even with respect to timing and sequence of adding the different ingredients.

- The placing requires special methods and routines as such mixes can be rather tixotropic (cohesive) and sticky.

- Compaction is more demanding as the vibration shall be more intensive and requires more vibration energy.

- The denseness of the concrete, when correctly placed and compacted, minimises bleeding, and the available water is so limited, that protection against evaporation shall be introduced promptly following levelling and trowelling of horizontal surfaces exposed to drying, in order to avoid plastic shrinkage cracking. Normal curing compounds are usually not sufficiently effective.

- The high content of cementitious material will most often generate more heat than normal concrete, thus increasing the risk of thermal cracking. However, this depends on the cementitious material used in the individual cases, where e.g. slag cement has reduced risk of thermal cracking due to a slow rate of hydration.

- The autogenous, or chemical shrinkage, is more pronounced due to the low water/cement ratio, and this sets much stronger demands on controlling the temperature differences in hardening concrete if thermal cracking shall be avoided. The limiting temperature differences generally accepted may have to be halved, and in extreme cases reduced to 1/3 for HPC to avoid unacceptable thermal cracking.

- HPC requires air entrainment to be frost resistant according to the generally adopted (rather severe) freeze-thaw tests. However, such mixes with high contents of superplasticizer are usually difficult to air entrain, and the air may easily disappear during the compaction due to the increased vibration energy needed. Hence, HPC may be more sensitive to freeze-thaw actions, i.e. less frost resistant than normal type structural concrete.

The sensitive elements of HPC listed above are not necessarily valid for all types and uses of such concretes. It is however necessary to have these potential problems in mind when designing structures based on the application of HPC, taking the realistically available competence of the local workforce into account when making the selections.

One new issue has evolved during the last few years, which may influence the broad - but not always successful - application of HPC. This is related to the increased availability and competitiveness of non-corrodible reinforcement bars to avoid reinforcement corrosion in heavily chloride containing environments [1]. The non-corrodible reinforcement bars are made from either glass, aramid or carbon fibres, or...
galvanised reinforcement, epoxy coated reinforcement or - as described in detail in [1]; stainless steel reinforcement.

The best long-term service record using stainless steel reinforcement in a highly corrosive environment is illustrated in Figure 13.

**Figure 13**: The 2.2 km long pier into the Gulf of Mexico at Progreso, built 65 years ago and in full operation today carrying heavy container lorries back and forth from a new container terminal built further out at sea. The piers are reinforced with stainless steel reinforcement as described in [1].

SUPERVISION VERSUS QUALITY ASSURANCE AND QUALITY CONTROL

A quality assurance procedure (QA) shall be followed, in order to document the real quality obtained in the structure through the actual construction process. This shall also include a factual documentation of durability related parameters obtained, based on selected tests being made on the finished structure and included in the Birth Certificate as part of the future Operation and Maintenance Manual to be handed over to the owner.

The main value of a quality assurance system enforced on the site operations is to motivate the Contractors workers to exert their true skills when doing their professional work. Bad quality is not produced wilfully but is the result of a lack of awareness of what is good and what is not good, and a lack of knowledge by the people on site. Hence, a formalised system provides one part of a motivating factor in improving quality and workmanship.

On site guidance and supervision by competent personnel is another important part of quality improving measures to improve quality. Finally, quality control (QC) and the physical on site supervision is a further quality enhancing measure, which shall be adapted to the real nature and possibilities of the construction industry.

HANDING-OVER SITUATION: "BIRTH CERTIFICATE"

In order to document the fulfilment of the design specifications, and verify the subsequent performance, the Quality Assurance documentation for design and execution should be enlarged to include information gathered during the operation and use of the structure. Developing an "Operation and Maintenance Manual" specific for each structure can do this. This Manual should be prepared by the Designer and shall include all information from the structural design and the construction being relevant for the future inspections and maintenance. This Operation and Maintenance Manual shall also include recommendations regarding type and frequency of future inspections and should highlight possible sensitive or critical parts of the structure which are assumed beforehand to need particular attention during use.

When the structure is handed over to the Owner, the initial Operation and Maintenance Manual will constitute a "Birth Certificate" of the structure, [3]. Information from future inspections and all other relevant events such as accidental impacts are then filled in as they occur. Depending on the nature and contents of such future information the type, frequency and selected special areas of concern shall be revised or updated by the Owner following his needs at that time.

The Birth Certificate will be the base line study for the future operation and maintenance manual. This is thus a precondition for incorporating the period of use into the overall "cradle-to-grave" design and re-design of concrete structures.

**REFERENCES**

