DESIGN OF CONCRETE FOR HIGH PERFORMANCE STRUCTURES

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SUMMARY

Concrete production methods and material compositions have changed radically during the last few decades. This change has partly been driven by a globally recognized crisis in concrete durability and partly by the need to justify the large investments in e.g. the infrastructure of the industrialized world by predictions of very long service lives of the structures. These predictions have been based on apparently consistent modelling of deterioration mechanisms supported by assessment of material properties through laboratory testing of advanced concretes. Based on observations of recently constructed major civil engineering structures it seems probable that this approach has not been successful. As a consequence it may be expected that requirements to Quality Assurance and Quality Control may be considerably strengthened by the parties, which are engaged in the funding of these structures, and that requirements for more predictable and robust concretes will emerge. It may be foreseen that material requirements which are primarily related to the construction process will, in future, be given enhanced attention in the process of designing concretes for high performance structures.

1. INTRODUCTION

1.1. General Concept of High Performance Concrete

From its first use concrete has always had to comply with a variety of criteria. It must be workable enough to be able to be cast into forms and be strong enough to carry the applied loads. Frequently, the criteria place conflicting demands on concrete, e.g. addition of water increases workability but decreases strength. In the past designers, primarily, have been interested in strength. However, as the ability to produce High Strength Concrete (HSC) has become more widespread, designers have realized that the specification of high strength alone is seldom sufficient to give them all the qualities they may be seeking. Thus, the concept of High Performance Concrete (HPC) has developed. It has, as yet, no universally agreed meaning, though Aitcin, Mehta, Neville a.o. [1, 2] suggested criteria of low permeability and high dimensional stability.

For the purpose of clarifying the scope of the present paper the following definition has been chosen:

'HPC is the term for a concrete which in its application in the structure meets multiple performance criteria which are significantly more stringent than those required for normal structural concrete ' [3].

1 Professor, h.c., Technical University of Denmark 1988-2000, Managing Director, Dansk Beton Teknik A/S and DBT Engineering A/S, Consultant of Öyak Beton
This definition of HPC is well in accordance with the ACI terms:

**Definition:**

*High-performance concrete – concrete meeting special combinations of performance and uniformity requirements that cannot always be achieved routinely using conventional constituents and normal mixing, placing and curing practices.*

**Commentary:**

*A high performance concrete is a concrete, in which certain characteristics are developed for a particular application and environment.*

Examples of characteristics that may be considered vital for such particular application are:

- Ease of placement
- Compaction without segregation
- Early age strength
- Long-term mechanical properties
- Permeability
- Density
- Heat of hydration
- Toughness
- Volume stability
- Long life in severe environments

Because many characteristics of high-performance concrete are interrelated, a change in one usually results in changes in one or more of the other characteristics. Consequently, if several characteristics have to be taken into account in producing a concrete for the intended application, each of these characteristics must be clearly specified in the contract documents.

Modern HPC materials are often designed for a service lifetime of the structures exceeding 100 years.

The basis of the design approach is apparently consistent modelling of deterioration mechanisms supported by assessment of material properties obtained through testing of laboratory produced samples of advanced concrete compositions.

Based on observations of recently constructed major civil engineering structures it seems very probable that this approach has not been successful.

Lack of performance may be found to relate to one or more of the following deterioration mechanisms:

- structural failure;
- alkali aggregate reactions;
- detrimental chemical reactions of the cementitious binder;
- freeze-thaw;
- corrosion of steel reinforcement.

Whereas it maybe claimed that the design and construction requirements to counteract the first two of these causes of deterioration are rather simple and well-known, the chemical reaction (e.g. Delayed Ettringite Formation), the freeze-thaw deterioration and first of all the deterioration of reinforced structures, resulting from corrosion of the steel reinforcement are worldwide problems and the cost of repairs is substantial.

The fact that the mechanisms leading to deterioration as described above are believed to be reasonably well understood and scientifically explained supports the common
practice of dealing with the problems through prescriptive specifications for the composition of concrete only.

Such specifications are to a large extent based on empirical rules obtained in the concrete laboratories and on diffusion and sorption theories which may be proven valid under these conditions (laboratory) but fail to satisfy in the real world of structures.

Contractors are requested to follow the strengthened/conventional specifications in the construction of most modern concrete structures, i.e.,
- to prove through laboratory pre-testing that low w/c-ratios and satisfying air void structures in the concretes will prevent frost damage;
- to prove through laboratory pre-testing that migration of chlorides into the concrete may be controlled by low values of the chloride diffusion coefficient.
- to prove, through a representative trial casting, that properties in full scale are comparable with the laboratory findings.

This QA approach does, however, not take into consideration that a full scale production is carried out within a certain range of material properties, time and equipment performance.

2. CLASSIFICATION OF CONCRETE STRUCTURES

If the global concrete production is divided into groups according to the severity of the exposure it may be assumed that such division can be presented as follows:

1. 90% of all concrete will never be exposed to an environment, which is likely to cause any type of deterioration. Environment in this context means those chemical, physical and mechanical actions to which the concrete is exposed and which result in effects that are not considered as loads in structural design. [4]

2. 9% of all concretes will be exposed to environmental conditions which may affect the durability but where the design of lifetime and structural performance do not require any special high performance strategy introduced in the material design, i.e. traditional structural concretes of good quality.

3. 1% of all concretes may be characterized as High Performance Concrete where special requirements cannot be fulfilled by the concretes of type 2, e.g. lifetime exceeding 100 years, compressive strength exceeding 100 MPa etc.

It is obvious that structures representing these different conditions do not require the same engineering skill neither in terms of construction suitability of the concrete nor in regard to Quality Assurance and Quality Control.

Present technologies and procedures in these fields have proven adequate for both type 1 and type 2 structures.

It is, however, the opinion of the author that the technology at present does not lend itself to a fully controlled construction process in the field of High Performance Concrete Structures and that a large portion of these structures as a direct consequence will not meet the High Performance targets which are set.
3. ASSESSMENT OF PREVAILING FLAWS IN PRESENT STATE-OF-THE-ART CONCRETE STRUCTURES

3.1 Introduction

During production of a structure the concrete material is exposed to impacts from transportation, placing and consolidation. At the same time the concrete itself undergoes changes due to the curing process of the binder and possible chemical reactions between the cement reaction products and the admixtures. It is not unusual that the perfect, well performing concrete from the laboratory specimens cannot be recognized when samples taken in the structures are analysed. The difference could be in the microstructure, in the air void structure or in the macroscopical appearance of the concrete. It is obvious that something happens during construction, which differs significantly from the regime of the laboratory.

The loss of air content and the degradation of the spacing factor due to pumping and vibration are well known phenomena. Still it, frequently, appears that air void structures in high performance concretes are inadequate.

On casting the concrete it is essential to introduce the compaction energy needed for making the concrete/cement paste flow. This assures both a dense packing and an adequate internal bonding between constituents of the concrete. However, it is of utmost importance that the amount of energy is restricted in order to retain a stable structure of the concrete and thus prevent the constituents from segregating. A given concrete composition may not achieve the needed flow without at the same time causing segregation. Other concrete compositions may give rise to segregations, e.g. internal bleeding at even the slightest action.

The mix design and the age from time of mixing, define the flow and compaction characteristics of a concrete and are, indeed, related to the problems described in the following. Furthermore, the flow characteristics are dependent also on the homogeneity of the concrete at the time of use. Even greater changes in the quality of concrete may appear when concrete that has lost its true plasticity is exposed to vibration or disturbance from mechanical impacts during early hardening exposing semi-plastic behaviour.

In the following these mechanisms will be discussed in more detail and the typical flaws in the structures constructed with low slump and moderate to high slump concretes will be described.

3.2 Low Slump Concretes

In concrete pavements insufficient compaction energy most often results in an open structure of the concrete, i.e. air inclusions of irregular shape, 2-30 mm in diameter. Also the cement paste may contain openings between the cement grains, 0.1-0.5 mm wide, due to lack of flow and hence lack of paste compaction. The bonding between cement paste and aggregate contains defects of both orders of size, i.e. 0.1-30 mm. These compaction defects result in lowered density, lower strength and eventually susceptibility to environmental and structural load impacts.

Insufficient compaction seen in a less serious situation results in volumes of entrapped air of size 3-20 mm. In this context the concrete does flow but the content of entrapped air
may cause a reduction of the compressive strength of the concrete. If the effective compaction of the pavement varies across the slab, the resulting concrete height may vary; especially in air-entrained concrete the surface may be seen to rise to a varied degree after the passage of the extrusion plate of the paver, thus indicating differences in air content across the slab. Similar phenomena will occur if the air content in the concrete varies from batch to batch.

Excessive compaction may give a low content of coarse aggregate in the top 10-20 mm in concrete pavements. If the concrete is air entrained, the air void structures may be of reduced quality and content due to excessive compaction, e.g. from the poker vibrators dragged through the concrete. The air content can, thus, be changed from e.g. 8% to 1% through the full concrete slab thickness at the positions of the poker vibrators. In roller compacted pavements the compaction may result in bonding failures with widths of 0.02-0.2 mm along the coarse aggregate. This is caused by the rotation action of the aggregate during the heavy compaction in the very 'dry' concrete used.

3.3. Moderate and High Slump Concretes

Moderate and high slump concretes are used in various structures such as walls, columns, pylons, decks etc. The compaction equipment used is most often poker vibrators, functioning at high frequencies. For moderate and high slump concretes insufficient compaction mainly involves the formation of bodies of entrapped air at surfaces being cast against formwork. The defects are most often a cosmetic problem but may be of importance in respect to protection of reinforcement if the general thickness of the cover layer is diminished or in cases where the under-compaction results in honeycombs.

The compaction around the rebars and the general bonding between concrete and rebars may be of low quality if the concrete is insufficiently compacted. The defects are seen as irregular cavities along the rebars with a length of 3-50 mm dependent on e.g. degree of compaction. Porous construction joints may be expected to pose problems to service lifetime in reinforced structures as well.

The compaction of medium and high slump concretes by use of poker vibrators is often extended beyond the limit necessary for the proper consolidation of the concrete material and result in segregation of the concrete causing:

- settling of coarse aggregates,
- micro bleeding in the paste,
- porosities at grains and densified paste between grains,
- larger bleeding structures, i.e. porous areas of local very high w/c-ratio,
- porous bands with high w/c-ratio along rebars.

The segregations involve settling of coarse aggregates leading to increased paste content in the stone-depleted region. The content of coarse aggregate may vary from 20 vol.% in the depleted upper zone to 60 vol.% in the enriched lower zone. The upper depleted zone has an increased content of paste and will, thus, have increased shrinkage on hydration and tendency to crack formation. Such cracks may form map patterns and will typically be 0.01-0.5 mm wide, appearing perpendicular to the surface.

Micro bleeding in the paste due to excessive vibration will cause the water to be pressed out of the paste and placed along sand grains and stones. Consequently, the paste between the sand grains will be densified due to closer spacing of cement grains. The
hardened paste may achieve local differences in capillary porosity corresponding to differences in equivalent w/c-ratio of 0.20-0.30.

With intensified vibration the internal structure of the concrete will form larger, highly porous volumes below stones due to bleeding. These volumes equal the size of the coarse aggregates in a layer of 0.5-2.0 mm thickness. The porous volumes may well form partly interconnecting bands in the concrete.

Large, interconnecting porous volumes may be formed along and below horizontally placed rebars and surrounding the vertical rebars. The cement paste may be highly porous - corresponding to a w/c-ratio of e.g. 0.60 - in a distance of 5-20 mm from the rebars. Especially, when the vibrators are placed on the reinforcement during vibration, defects like these may develop.

In air entrained concretes the air void system may be ruined by excessive poker vibration forming an inhomogeneous air void system where the single air voids clump into agglomerates that may collapse into air inclusions. These may in turn be vibrated out of the concrete. Eventually, the air content of the concrete will be lowered.

Due to demands for low permeability and high strength it has become general practice to specify low capillary porosity of the cement paste. This is achieved by lowering the w/c-ratio, by adding silica fume or other pozzolants. These approaches demand the use of superplasticisers.

It is believed that the amounts of superplasticiser used for High Performance Concrete with high slump are directly involved in the formation of several types of defects, e.g. low quality air void systems and lack of cement hydration.

A crucial parameter for highly plasticised concretes is the pronounced rate of loss of workability experienced in the fresh concrete. The extensive use of plasticisers, which is a part of the modern HPC concept, leads to an incompatibility between 'flowability' of the paste and the setting time. Actually, many concretes show a geotechnical (soil mechanical) behaviour in the most critical part of its curing life, i.e. from say 1 hour after casting when all flow properties are lost until 10 hours when the paste gains some strength (setting). Any impact on these concretes when true plasticity is lost will introduce plastic defects unlikely to heal. Such impacts may be introduced in several ways:

- On revibrating earlier placed, already settled 'crunchy' layers of concrete in order to secure well compacted joints. The defects comprise plastic cracks in the paste and along the aggregate 0.01-0.1 mm wide and paste separations involving locally reduced hydration of cement grains.
- In slipformed walls, if the speed of formwork lifting exceeds the capability of the placed concrete to sustain itself. The defects introduced may be paste separations and plastic, mainly surface, parallel cracks 0.01-0.2 mm wide. The cracks may be concentrated in the outer parts of the wall.
- If the concrete is cast on a sloping bottom form or in bottom plates without top formwork if cast in one with walls.
- By direct impact on formwork or rebars

Similar plastic defects may arise also in concretes of conventional design at early formwork collapse or if formwork is stripped too early. The plastic cracks will in such cases be wider and more widespread.

Above are described some types of flaws which are frequently appearing in modern
high performance structures, e.g. in high strength concrete pavements, major bridges or tunnels, high rise buildings and off-shore platform structures.

The non-conformance in relation to expectations may be summarized as follows:
- Reduced air content
- Increased spacing factor
- Macro segregation
- Inhomogeneous cement paste with interconnecting porosities
- Systematic (oriented) plastic cracking in the microstructure
- Severe debonding to reinforcement.

Of these deficiencies only the non-conformance of the air void structure is generally identified and accepted as problematic in regard to durability. The other types of flaws are not described in international literature and are often considered to be without significant impact on the durability. Recent research does, however, indicate that properties like freeze-thaw resistance and chloride permeability may be reduced by as much as an order of magnitude in samples where such phenomena appear compared to expectations based on testing of laboratory produced samples.

4. COMMON CONSTRUCTION PRACTICE

4.1. Concrete Compositions

The above-mentioned deficiencies in some modern HPC structures may to a great extent be caused by the fact that it is not yet possible to define exact performance requirements in regard to durability. It is, indeed, in itself impossible to prove the relevance of durability requirements, which shall assure a service life of more than 100 years.

As a consequence most designers have chosen a prescriptive requirements approach, which certainly is prohibitive to both a more classified simplicity, and an advanced approach in concrete design.

As an example it could be mentioned that at the Great Belt Link project in Denmark, the specified chemically active materials were Portland cement, fly ash and micro silica. In addition, a requirement for a maximum of 135 kg/m³ of water leads to extensive use of chemical admixtures to enable the contractor to control the rheological properties of the concrete. The content of micro silica specified as min. 5%/max. 8% of the powder, the content of fly ash as min. 10% of the powder. The maximum content of mineral additions 25% of the powder. Specification for the Portland clinker cement content: min. 300 kg/m³.

In other recent HPC projects various ternary blended cementitious materials have been prescribed and limitations to the amount of free water are frequently met. Such requirements, which are interdependent to a degree probably never seen before, do not give the contractors much freedom of choice. The composition is already given. But the sole responsibility for the quality of the concrete is at the same time placed on the contractor.

This situation is not viable and specifications for future contracts should not be expressed in this way.
4.2. Placing and Compaction

Modern concrete structures are usually characterized by high volume of obstacles and high concrete lifting. Heavy steel reinforcement, ducts for post-tensioning strands and cooling/heating pipes all create a rather congested space in which the concrete shall be placed and consolidated; often by unskilled labourers who cannot see what is happening in the darkness of the moulds.

The contractor does, however, often choose a concrete with a high workability or expressed in the most common way: with a high slump. If deviation from planned concreting schedule or other delays does not occur, this method may prevent severe honeycombing, large blowholes in the formed surfaces and reasonably tight construction joints.

The concrete is usually pumped in place; discontinuous pump operations and high pumping pressures, e.g. exceeding 150 bars are commonly experienced.

Vibration is carried out with internal poker vibrators with diameter ranging from 50 mm to 120 mm. Frequencies of vibration are in the range of 100 Hz to 250 Hz.

It is rarely seen that concrete in general is vibrated too little; Over vibration does not show by sight in the structure.

However, this strive for good looking surfaces and smooth concrete without honeycombs is one of the major causes for the deficiencies in durability performance. Such evidence is expected to materialize in many structures long before their 100 years birthday.

Over the years international journals have documented an increasing concern in regard to the quality of hyper sensitive concretes, i.e. concretes with rapidly changing rheological properties, particularly when exposed to rough pumping and extensive over vibration.

Researchers in Japan were the first to recognize the quality risks related with the new generation of concretes placed in complicated civil engineering structures, maintaining requirements of conventional appearance of the concrete surfaces (1993). The idea of Self-Compacting Concrete was borne.

The concern of the Japanese researchers was soon shared by their colleagues in the rest of the world.

When concrete is pumped under high pressure at least two changes may appear to the 'good' concrete of the laboratory:

i) The entrained air void structure will be partly or even completely absorbed in the water of the paste due to the pressure. When pressure is normalized at the placing of concrete this air will be released again but usually not with the same high specific surface.

ii) When concrete with an instable composition of the paste phase is exposed to differential pressures such as those appearing during pumping of concrete the paste will segregate;

Water will (pressure) bleed in an internal segregation process and the solid particles of the paste will agglomerate.

This is a phenomenon that is also experienced by the injection industry, e.g. grouting ducts and injection of soils.

Mathematical/physical models for the micro stability of cementitious pastes
exposed to differential pressures are at present under development. Until results of this research are available, experience by contractors, best available technology or "trial and error" seem to be the only way to meet the challenge of micro instability.

When concrete is compacted this process is influenced by the previous handling;

The air void structure, which, due to the high pressure pumping has changed characteristics towards larger bubbles, will be driven out of the concrete by vibration.

The disintegration of the paste will result in a much reduced workability and, consequently, to increased vibration efforts. Under normal conditions these changes will not be observed as all trial castings or test sections have been carried out under the same conditions.

If the rheology of the concrete is changed, however, for instance due to a delay in concrete supply, a short break-down in the concrete pump or other impacts on the concreting, it may have severe consequences:

Pumping pressure must be increased to handle the stiffer concrete. Internal segregation will prevail and all air voids will certainly be destroyed.

The result is a sudden change in concrete quality which will be noticed by the labourers during concreting and, indeed, by everyone when the forms are stripped.

What is seldom observed is the internal damage, which most HPC structures expose due to this harsh treatment.

5. CONCLUSIONS AND RECOMMENDATIONS

In the above sections of this paper a number of risk elements in production of modern HPC has been identified.

These may be summarized as follows:

- Concrete is designed and specified for durability of laboratory-produced specimens. In place concrete may have significantly different properties;
- Reliable models for prediction of +100 years' lifetime are not yet available;
- Most specifications apply a prescriptive approach;
- Concrete is often damaged already during pumping due to degradation of the air void structure and internal segregation of the paste;
- Most concretes are not compacted to obtain durability but rather to achieve a nice surface, free of blowholes;
- Internal damage does often appear due to impacts on the concrete during the dormant period.

These problems seem only to be overcome if construction in future will be governed by well-defined performance criteria linked to reliable test methods or verification procedures. The construction industry will then be given the freedom to implement the industrial know-how and the incentive to research in the fields of material science and construction technology. It is believed that future concrete structures necessarily will be characterized by the following:

- Durability of the concretes based on
  * Design of micro stability
  * Stability of air void structures.
- Application of concretes with good flow and filling capacity exposing high resistance towards macro segregation;
- Self-Compacting behaviour of the concrete, which will prevent damage to the properties of the concrete due to unskilful use of vibration.
- Long Life Structures, exposed to an aggressive environment will probably be constructed with a non-corrosive reinforcement.

REFERENCES

[4] Classification of environmental conditions and limiting values of compositions and properties for normal reinforced concrete EN206, Eurocode