MARMARAY PROJECT: PHILOSOPHY BEHIND THE CONCRETE REQUIREMENTS FOR MARMARAY BASED ON EXPERIENCE FROM THE OERESUND TUNNEL, DENMARK

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SUMMARY

The process and principles of ensuring the end product quality of concrete as construction material in Mega-Projects like the Bosphorus Commuter Rail Crossing connecting two continents and the Oeresund tunnel project connecting Denmark and Sweden can in many aspects be compared to ensuring the quality of the best menu to be served in the best restaurants of the best hotels on the Globe. There is no room for failure and the quality is the product of how well you can control a number of interrelated activities to be performed by professionals. The Chief Cook must base the planning on extensive experience and the desires of the costumers (the Employer’s Requirements), he must ensure access to the best raw materials he will need for his menu (the Constituent Materials), he will have to check the quality and consistency of raw materials before cooking (pre-testing of constituents), he will need the best recipe for the meal (concrete mix design recipe), he will need to test the recipe (pre-testing of mix design), he will need to arrange a small scale test panel for testing of the fresh meal and the feedback comments after the meal has been served have to be collected for potential corrections (laboratory testing of the concrete mix design, fresh concrete properties, hardening and hardened concrete) and finally he will need to test the kitchen’s full-scale capacity to produce the meal for a big audience in the same quality as the test panel was given (the production line quality and capacity and the full-scale trial castings). A prudent Cook performs all these tests successfully before he dares to serve the menu for the first time in front of all the customers of these world class hotels (all pre-testing of concrete must be successfully finalized before the first concrete is used in the Permanent Works of Mega-Projects). A professional restaurant will also ensure that the surroundings and the environment offered during the meal will support and strengthen the impression that this meal was absolute sublime and amongst the best in the world (curing and temperature control during hardening of the concrete). The cook will do this in order to ensure that his own reputation will stay high and in order to ensure costumer satisfaction in the future (to ensure full end-product quality and a 100 years lifetime of the concrete structures). The cook will also be aware that failure in just one phase of these interlinked activities will inevitably lead to dissatisfaction of his costumers. These analogies have been the underlying principles in developing the strategies and the requirements to concrete on the Bosphorus Project and the Oeresund Project.

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1. INTRODUCTION

Scandinavia is one of the regions where engineers and authorities have had to realize that concrete does not last for ever. In the 60's and 70's the opinion was that concrete is a material where lifetime evaluations is simply not a topic worth discussing. Engineers as well as authorities were wrong. For example, in Denmark, some 1500 highway bridges were constructed in this period as part of the major motorway systems. Most of these bridges had to be refurbished or renewed in the late 90's simply because the condition of these bridges and the damages due to frost, Alkali-Silica Reactions, chloride penetration and other inherent problems were so severe that it was estimated that the safety of the bridges were at stake.

Since the early 60's a number of major infra structure projects were realized as well. The Limfjord tunnel in Jutland was the first major immersed tunnel constructed in Denmark, and later the Guldborgsund immersed tunnel followed. Other major bridge structures were under way in the same period. Gradually it was realized by engineers and authorities that there was a need to start looking much more carefully into the mechanisms that will actually spoil the concrete if not taken care of during construction.

The Faroe Bridge, the Vejlefjord Bridge and other major bridges are examples of structures where the quality of the concrete was in focus. However, it was early realized that all the different parameters of importance for the durability of concrete often were in internal conflict with each other. The knowledge about these things were combined in an effort by all experts in the first Mega Project initiated in Denmark in 1987, the Great Belt Link between two major islands in Denmark, Sealand and Fyn. A systematic approach was adopted on this project in order to establish a comprehensive set of requirements to concrete that would ensure a lifetime of the concrete of not less than 100 years in a very severe environment.

However, during realization of this project, it was documented how difficult it is to combine the knowledge from the laboratories of what is right and what is wrong with the reality at Site. The end product of the Great Belt link has a very high quality, but it is also a well known fact that there were many disputes between the Employer and the Contractor under way, and many details related to the specifications had to be re-evaluated and modified. Most of the problems related to these discussions were linked to the requirements of what appeared to be very low water/cement ratios.

The next Mega-Project - the tunnel and bridge constructions between Denmark and Sweden - was approved in 1992, and naturally all the experiences from the Great Belt link were brought into this project as well. It was very early realized by the top-management, that an overhaul of the existing knowledge was a prudent activity to plan and conduct, and therefore a work group and a steering committee was formed including some of the most experienced experts and hands-on senior engineers and professors. The aim of the work was to prepare a master concrete specification according to the agreed strategy and then to use this master as basis for the tender documents for the Tunnel, the Bridge and other structures on the Öresund Project.
The author of this paper had the honor of being the chairman of the steering committee conducting this overhaul, and the experiences from these studies and the following construction works has formed the basis for the Employer's Requirements on the Marmaray Project. The reason behind this decision by DLH is that the knowledge compiled for the Öresund Project from Japan, United States, Europe and Scandinavia can still today be considered to be "State of the Art" when it comes to practical requirements fit for the purpose related to ensuring quality of concrete on such Mega-Projects as the Marmaray Bosphorus Crossing Project. This paper will guide the reader through some main issues of these requirements.

2. THE STRATEGY FOR CONCRETE PRODUCTION

The Employer, DLH, has decided to define and control the concrete quality of the Marmaray Project. The quality is defined by the requirements to production of concrete (Materials) including mix design and the requirements to the execution including curing (Workmanship). The quality must be controlled by requirements to inspection, testing and documentation as a part of a quality system in accordance with ISO 9000/2000. The requirements shall be based on well-known technology and they shall secure a service life of not less than 100 years.

The service life is defined as the period within which full function is maintained. Reinforcement corrosion is not allowed to start within the 100 years service life. The structures shall be prepared for cathodic protection, but the service life shall be obtained without taking the cathodic protection into account. Well-known technology is defined as technology well-tried with positive results under similar environmental conditions.

The strategy is enforced by the preparation of a comprehensive concrete specification as a part of the tender documents. The Employer wants an open competition between contractors, but it shall be ensured that the contractors do not compete on quality.

The specification shall leave as much freedom as possible to the contractors in the choice of concrete mix design, but thorough attention shall be given to the risk of failing to obtain the defined quality.
Tunnel elements are normally exposed to extreme conditions, and the resistance of the concrete due to the environment must be an inherent quality. The picture is from the Øresund Tunnel Project.

2.1. Summary of the Requirements

The material-part of the specification requires first class constituents. High-grade Portland cement, blast furnace cement, silica fume and fly-ash are allowed. Aggregates are required as high-grade and non Alkali-Silica-Reactive. European standards or similar for constituents are used whenever possible.

The requirement to the mix design is primarily a water-cement ratio w/c of maximum 0.40 or 0.45 (depending on the environmental action on the structural elements), which in combination with requirements to the cover of typical 50 or 75 mm (based on the Contractors calculations regarding fit for purpose) will ensure the durability. The quality must be assured and documented by requirements to Quality Systems and Conformity Procedures.

In the workmanship-part of the specification the prime requirement is planning - partly formulated by requirements to Quality Control Procedures and partly by requiring a comprehensive program of pre-testing and trial castings. Great effort is taken to secure the Quality of the concrete during the casting and curing operations. Early-age cracking is limited by requiring a low risk of cracking evaluated by stress-calculations based on early-age properties of the concrete.
2.2. Testing and Ensuring Conformity

The only 100% safe way to be absolutely sure that a 100 years lifetime was obtained is to wait 100 years and check the structures. Such methods are absurd to use in real life situations. The philosophy has therefore been to identify each parameter of importance for ensuring this lifetime, to find the most reliable test methods directly focusing on this parameter and then test the preferred concrete mix type in accordance with these test methods.

However, this approach has some inherent problems related to time constraints. Many of these reliable tests take quite some time (up to one year) to perform, and therefore such tests are not convenient during production testing. In many cases, it is possible to find a relationship between the slower but reliable long term tests and some other quite accelerated but not as reliable tests for the same property, and the principles have been that where this is possible, such correlation must be done during pre-testing in order to get early indications if new inspection sections differ from the old inspection sections during production. Traceability “upstream” for constituents has been required to be 90% or higher, and traceability “downstream” of constituents and concrete mix is required to be 100%.

The conformity procedure to be used has been adjusted to suit each situation and this traceability requirement in order for the Contractor to prepare smooth production of stable quality concrete.

3. TECHNICAL NOTES

Based on the state of the art of concrete technology and experience from similar major concrete constructional works, a number of subjects were identified which were to be evaluated before the final requirements could be formulated. For each of these subjects a technical note was prepared. Each technical note comprises a statement of the art of the subject concerned and a critical analysis of previously formulated requirements. All technical notes include a conclusion containing the recommended set of requirements.

The technical notes define the uncertainty in the formulation of the requirements, for example by making a division into three groups: Well established requirements (e.g. compressive strength), requirements accepted by convention (e.g. scaled material from freeze/thaw testing) and requirements that are not well founded (e.g. micro cracks). It is a necessary acknowledgement that a specification may consist of requirements from all three groups.

Technical notes were prepared about the following subjects:
- Frost Resistance
- Temperature and Stress Requirements
- Protection against evaporation
- Conformity Procedures
- Comparison of Concrete Requirements and Properties for other Structures
- Chloride Penetration in Concrete
• Alkali-Silica Reactions
• Blast furnace Cement
• Casting Methods
• Crack Investigation
• Fire Resistance

In the following a short discussion based on the essence of some of these notes is given:

3.1. Technical Note on Frost Resistance

The two major frost destruction mechanisms existing are: Internal damage mainly caused by freezing of pore water and water in aggregate and salt scaling concentrated to the surface of the concrete. Different parameters such as freezable water, environmental factors, the air pore structure and the air content in hardened and fresh concrete are described and their influence on the frost resistance is evaluated.

Requirements to frost resistance are in many countries stated by requirements to the air void structure and the specific surface area. Based on these studies it was decided that the Employer's Requirements must include two freeze-test methods based on salt scaling and critical dilation testing together with a high frequency of testing the air content in fresh concrete and random checking of air void structure in hardened concrete.

3.2. Technical Note on Temperature and Stress Requirements

For durability reasons and for water tightness purposes structural members must be well protected against penetration of water, chlorides and other aggressive chemicals which means that cracks must be avoided. Formation of cracks can take place already during the hardening process, and an evaluation of the risk of crack formation incorporates a stress analysis. In stress analyses of hardening concrete structures, the load consists of differences in thermal strains, arising from the heat of hydration. Also the mechanical properties of the concrete changes during the hardening process. Consequently, the analysis has to take such effects into account as well.

A sensitivity analysis was carried out and it was shown that the static boundary condition, creep, shrinkage and thermal expansion have a significant effect on the cracking risk. The sensitivity analysis also illustrates that although the tensile stresses are caused by temperature differences, the stresses depend on restraints and concrete properties to such an extent that temperature differences alone can not give a reliable measure of the cracking risk. Therefore, more sophisticated methods combining these effects in the calculations have been required.

3.3. Technical Note on Protection against Evaporation

To be able to control this important part of the concrete works in practice, information from measurements on the hardening concrete must be used, especially the adiabatic heat development and the maturity concept. It is assumed that the adiabatic heat development is
an indirect measure of the reaction between water and cement, the hydration process, and consequently the degree of hydration can be defined as the actual heat Q divided by the maximum possible heat Q_{max}. To avoid plastic shrinkage protection against drying out shall be established before a certain amount of water has evaporated from the concrete. The duration of the protection shall ensure a required degree of hydration in all parts of a structure. The requirements to ensure these effects have been given directly in the Contract.

3.4. Technical Note on Conformity Procedure

This note discusses aspects of conformity procedures, i.e. the sampling plans and conformity criteria which are used to document that the requirements are fulfilled. Among the treated aspects are the normal European practice, advantages and disadvantages of inspection by variables (figures) and attributes (conforming/non-conforming), the real life problems using conformity procedures and the methods to secure the required statistical protection.

The discussion concludes seven conformity procedures to be used on the Marmaray Project:

- No.1 Product standards, ref. actual product standard No.2 100% inspection
- No.3 Variables, Average Outgoing Conformity Level or in short AOQL
- No.4 Attributes, Acceptable Quality Level or in short AQL, ref. ISO 2859-1 191
- No.5 Attributes LQ ref. ISO 2859-2/101
- No.6 Rolling approval, AOQL
- No.7 Representative samples

Three of the seven conformity procedures are based either on European CEN standards (No.1) or in ISO standards (Nos. 4 and 5). Conformity Procedure No.2, 100% is a procedure which per definition is statistically correct. Conformity procedure No.6, rolling approval, is a procedure which has been designed particularly for these projects.
The Oeresund Tunnel Contractor selected a “safe approach” in controlling the exterior environment in which the casting of the elements was performed. He decided to build a production hall for casting each 22 meter segments of the element in order to avoid and eliminate the effects from low temperatures during winter and the high temperatures during summer. The picture shows the complex hydraulic moveable formwork established to do the concrete casting inside the building in order to control the environment. The Oeresund Tunnel sat a world record in being the biggest immersed tunnel ever constructed. The Marnaray Immersed Tunnel will set another world record in being the deepest immersed tunnel ever constructed.

3.5. Technical Note on Chloride Penetration

The main concrete parameters contributing to the corrosion protection of reinforcement against chloride are the impermeability, the chloride binding and the cover. Increased impermeability or cover increases the lifetime of the structures.

The impermeability of perfect (un-cracked) concrete increases with decreasing w/c-ratios. The importance of these parameters can be illustrated by the fact that a change in w/c ratio of 0.10 can change the permeability with typically a factor between 5 and 10. However, the number of defects in practice (micro and macro cracks) increases with decreasing w/c-ratios, thus leading to a less perfect and less impermeable concrete than what could be expected according to the theoretical values. Selection of max w/c ratios is therefore a matter of getting the right balance. The optimum range seems to be a w/c ratio selected in the range between a little less than 0.40 and up to 0.45. The chloride diffusion model uses values for the coefficient of diffusion (D) and the chloride surface concentration (C). The model can usually be fitted very well to laboratory results as well as chloride profiles obtained from exposed structures. The values for D and C in exposed structures
differ significantly from the accelerated laboratory results. No consistent explanation for those differences can be found in the literature. Fortunately values determined in the laboratory seem to be conservative. The lifetime estimation of the reinforced structure is therefore only a rough estimate of the time before major repairs can be expected. The lifetime model is uncertain, e.g. due to the discrepancy between theory, laboratory and practical values of D and C. The model is, however, the only possibility to give a theoretical evaluation of the consequences of the requirements at the present time and therefore it has been included as a requirement to use this model on the Marmaray Project.

The elements for the Marmaray Project will be constructed in the Tuzla harbor area. The picture shows the steel membranes that will form the primary protection against water ingress. The concrete in itself will be the secondary protection.

3.6. Technical Note on Alkali-Silica Reactions

Alkali Silica Reactions (ASR) have in recent years been considered a severe problem in most countries. As a result methods have been developed which together with experience gathered through the years have made it possible to take the necessary precautions. The ASR is a chemical reaction which takes place in the aggregate particles. When a sufficient number of aggregate particles have reacted the concrete expands and a macroscopic crack pattern may develop in form of map cracking on the surface of the concrete.

Aggregate with reactive silica are of the type porous flint, chert, opal and the slowly reacting aggregate containing so called micro crystalline quartz. The slowly reacting aggregate differ from the typical reacting aggregate and do not respond well to the usual
recognized test methods in the sense that they often pass the tests as innocuous, while causing problems in the actual concrete structures.

Experimental work has shown that there seems to exist a concentration of alkalis below which no expansion of the concrete is observed. This limit can be expressed in terms of kg Na₂O-equivalent per m³ concrete, and it has become practice to use this way of specifying the alkali content when reactive or potentially reactive aggregate is to be used in concrete. The sources of alkalis specified to be included in the threshold limit are however not the same in the different countries. According to some references mineral additives as fly ash and ground granulated blast furnace slag may act as sources of alkalis. It is however disputed how much and to what extent the alkalis in these materials are available for ASR. It is generally assumed that addition of constituents like fly ash, ground granulated blast furnace slag and silica fume have a beneficial effect on preventing the expansion of concrete caused by ASR. No cases of damage due to ASR seem to have been reported when slag cement (more than 50% slag) has been used in the concrete. However, results from various research projects have shown that even with mineral additives as ground granulated blast furnace slag, fly ash and silica fume expansion due to ASR can not be mitigated when alkalis from external sources (de-icing salts, sea-water and ground water) are available. The expansion may be delayed only depending on the amount of mineral additives used and the alkali load from the environment.

Close to forty test methods for alkali reactivity are in existence. With special regard to the slowly reacting aggregates it is generally agreed that these tests are unable to detect this kind of aggregates. However, a few accelerated "harsh" tests are able to divide the possible reactive aggregate from the sound aggregate. These tests in combination with petrographic examination of the aggregate seem to offer the best procedure for categorizing and selecting aggregates.

Crushed coarse aggregate and fine aggregate might be screened by the very sever mortar expansion method ("South African method") now ASTM C1266. This is a very aggressive accelerated method that should detect most if not all potentially deleterious aggregates, but it will also reject some aggregate with excellent performance in concrete. It must be emphasized that there is a trade off in limiting the alkali concentration in the concrete in order to mitigate ASR. The reinforcing steel is better protected against chloride induced corrosion at higher alkali hydroxide concentrations. Furthermore the mineral additives require alkali in order to react.

4. TUNNEL ELEMENT PRODUCTION, OERESUND VERSUS MARMARAY

As explained above, the Oeresund Project concrete requirements were developed specifically for Mega-Projects like the Marmaray Project. However, the production methods on the two projects have turned out to have many similarities but also many differences. The similarities are amongst others as follows:
- Concrete is the main construction material for the elements
- The concrete must last and perform well during a 100 years lifetime
- The destructive reactions that may develop in the material are more or less the same.
- The concrete in itself must be water tight.
- The conditions during hardening of the concrete must be controlled within the same limits; limits dictated by the material rather than by the external environment.
  The differences are amongst others:
  - The design and production methods planned are quite different. The Oeresund tunnel was produced “on land” and not flooded before the entire element was finished. The Marmaray tunnel is planned to be cast partly in a shallow area dry dock, and the upper part of the walls and the top slab will be cast in floating position.
  - The castings on the Oeresund was performed in full sections with a length of approximately 22 meters inside a production hall with controlled environment; the castings of the Marmaray IMT is planned to be performed in full 130 meter long sections and the casting environment is not planned to be controlled inside a building but “under open air conditions”.
  - The Oeresund tunnel was a “clean concrete tunnel” without exterior membrane; the Marmaray tunnel will include an exterior steel and PVC membrane.
  - The climate in Turkey is different from the climate in Denmark. Frost problems and exposures are more sever in Denmark than they are in Turkey; but the extreme temperatures during summertime are more sever in Turkey than they are in Denmark.

The challenge for all involved parties will now be to combine all efforts on how to produce sustainable concrete solutions based on all experience from Japan, Turkey, Scandinavia, Europe and United States in order to produce elements for the Marmaray Immersed Tunnel in such a quality that lifetime requirements will be fulfilled to the benefit of all the customers that will use the Bosphorus Crossing Tunnel in many generations to come.

These efforts will be based on the sum of experience existing in the Employer’s organization, in Avrasyaconsult’s organization and the experience of the Contractor’s organization in order to give Turkey what has been required for the Marmaray Project challenge.
The picture shows the magnitude of the construction sites needed for these Mega-Projects. In the upper part of the picture you see the production buildings for casting the concrete on the Oeresund Tunnel Project and the on-Site batching and mixing plants. In the centre part of the picture, you see the “upside-down” dry dock area that allowed the elements to be constructed on land but offered the floating facilities as normal dry-dock constructions do.

The elements on the Oeresund Tunnel were each 176 meter long, a bit less than 40 meter wide and approximately 9 meter deep. The total number of elements was 20. The weight of each element was approximately 57,000 tons. The picture shows one of the elements during flooding of the up-side-down dry dock.