QUALITY ASSURANCE FOR THE DEEPEST IMMERSED TUBE TUNNEL: MARMARAY PROJECT

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Abstract

The Marmaray Bosphorus Crossing Project, the deepest immersed tube tunnel in the world, is presented as an important example of record-breaking mega projects in Turkey, started in 2004. The main parts of the Marmara project are an immersed tunnel of 1.38 km, a TBM tunnel with a total length of 18.72 km as a twin-bore tunnel, and a NATM tunnel of 250 m. The immersed tunnel is composed of 11 elements that are 15.3 m wide, 8.6 m high and a maximum of 135 m long. The immersion depth will be a maximum of 60 m.

Durability is one of the parameters of serviceability of the structure and therefore during the design stage all parameters were evaluated together in order to check compliance with the service life time requirement which was targeted for the overall project. The composition of the concrete mixture was optimized by pre-testings to resist the relevant exposure conditions that impact concrete's durability, including early age cracking, alkali silica reactivity, sulfate resistance, freeze-thaw and corrosion. Methods to be applied during construction for ensuring durability requirements is another step of the studies such as quality control system for constituent materials, hardening and hardened concrete properties, curing of concrete and methodology for repairs.

1. INTRODUCTION

The Consultancy Contract of the project was signed in December 2001 and following preparation of the contract and the requirements, construction physically commenced in August 2004. Marmaray Project consists of three parts: i) Railway Bosphorus Tube Crossing, Tunnel and Station Construction (BC1), ii) Gebze-Haydarpaşa, Sirkeci-Halkali Commuter Rail Upgrading: Civil, Electrical and Mechanical Systems (CR1), and iii) Rolling Stock Production (CR2).

In order to provide a structural service life of a minimum of 100 years without major maintenance, the specifications for concrete in the Marmara Project include certain requirements regarding materials, mixture design, and the fresh, hardening and hardened properties of the concrete. A series of performance-based pre-tests are the basis for decisions on deciding on the concrete mixtures for design and construction (Tasdemir and Akkaya, 2007).

Due to the following factors, special precautions both in the design and construction stage are required in this project.

- the geographical location the Bosphorus Railway Tube Crossing Project;

- the currents – there are two-layered currents of up to 6 knot strength in the Istanbul Strait;
- navigation – with its local and international marine traffic the Istanbul Strait is one of the busiest sea channels in the world.
- ground conditions – there are different ground layers ranging from very soft ground to very hard rock, and in some parts a the risk of liquefaction;
- seismic conditions – the Project alignment is in average at a 16 km distance to the North Anatolian Fault line. There is an expectation that with 65% probability there will be an earthquake of 7.5 scale in the region within the next 30 years.

2. PRODUCTION OF TUNNEL ELEMENTS

The length of the immersed tunnel on the seabed is 1.387 metres. This tunnel which forms a vital link over the Istanbul Strait, stretches between Eminonu district on the European side and Uskudar district on the Asian side. It consists of 11 immersed tube elements that have two compartments through which two railway lines will cross. The tube elements are 8.75 metres high and 15.5 metres wide. Eight of the elements are 135 metres long each, two of them are 98.5 metres long each and one of the elements is 110 metres in length. Before the elements are placed onto the sea bed, a trapeze shaped channel is dug. Any contaminated material that is excavated, is taken to a Confined Disposal Facility (CDF) and sealed off.

In the Transport Ministry's facilities at Tuzla, in two dry docks built for the Project, first the steel structure and base part of the tube element is constructed and the element is moved up to a pier for the construction of the upper part. Once the production of the tube element at the pier is completed, it is taken to Buyukada where the preparations for the immersion take place. A trial immersion is carried out, and taking into consideration suitable weather and current conditions, the tube element is floated to its location in the alignment in the Istanbul Strait and placed into the channel which was previously dredged and layed out with foundation material. The immersed element is placed in line with the previous tube element, connected to it and the connection point sealed off against water. Then the foundation concrete in completed and lock filling applied to avoid any horizontal movement to either side. Once the last tube element is placed, cover concrete is applied to the connection point of the immersed tunnel with the bored tunnel, and the tunnel is covered up with backfill. Where the cover above the tunnel is less than 4 metres high, rock blocks are placed as protection against sinking ships, and protective layers are formed along the whole of the tunnel as a protection against ships anchors. Later this tunnel is connected to the tunnels excavated by the Tunnel Boring Machines (TBM), with seismic joints at the connection points that provide earthquakes resistance (Erdogdu and Lykke, 2008; Akkaya and Demir, 2010).

3. REQUIREMENTS FOR DURABILITY

The durability of concrete is one of its most important properties because it is essential that concrete should be capable of withstanding the conditions for which it has been designed throughout the life of a structure. Lack of durability can be caused by external agents arising from the environment or by internal agents within the concrete. Causes can be categorized as physical, mechanical and chemical. Physical causes arise from the action of frost and from differences between the thermal properties of aggregate and of the cement paste, while mechanical causes are associated mainly with abrasion and physical load conditions. Chemical causes are attacks by sulphates, acids, sea water and also by chlorides which include electrochemical corrosion of steel reinforcement (Akkaya and Demir, 2010).

3.1 Summary of Requirements

For the bored tunnel, durability was analyzed for the carbonation of concrete and the attack of chloride ion in consideration of the design life of 100 years. A cover of 25 mm or above is considered for resistance to carbonation. The chloride ion content in water is extremely small, thus the influence on the tunnel lining is considered to be small. Therefore, a concrete cover of 70 mm is used from the strait part to the above mentioned boring hole location. The typical cross sections of the Bored and Immerse Tunnels are shown in Figure 1 (Tasdemir and Akkaya, 2007; Erdogdu and Lykke, 2008)

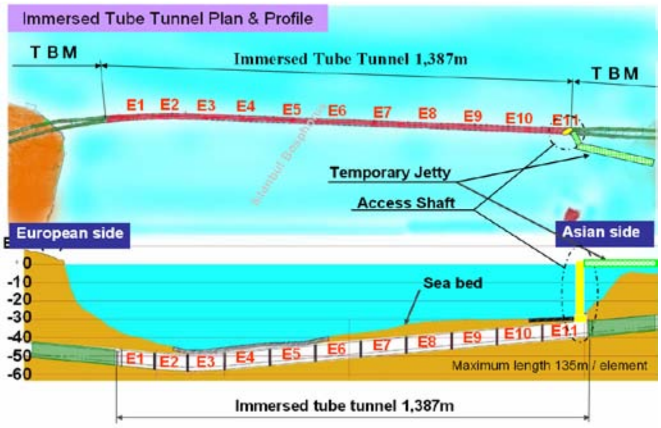


Figure 1.Typical cross sections of the Bored and Immerse Tunnels

For the Immersed Tunnel (IMT), reinforced structure is enclosed in a steel membrane and waterproofing sheet and isolated from the aggressive environment. The condition of exposure for the immersed tunnel can be classified as frequently wetted condition, designated as XC2, with the structure totally submerged in seawater. For this exposure condition, the nominal cover required by standard is 50 mm. Although there is an isolation of concrete with a layer of steel membrane and waterproofing sheet, 70 mm minimum cover is appropriate for severe environmental exposure conditions in case the external face of the member should have the waterproofing membrane fail and exposes the concrete structure to seawater seepage. Additionally, steel membrane is protected against corrosion by cathodic protection (Erdogdu and Lykke, 2008).

3.2 Design of Concrete

Inspection, testing and quality plans constitute a system for controlling the requirements related to concrete. Materials and methods should be based on proven and well known technology. Properties of concrete, constituent materials and production methods play an important role in this strategy. The specification prescribes some limits on certain aspects of material properties to ensure the quality, and at the same time, leaves as much freedom as possible in the choice of concrete mixture design to ensure performance.

Accredited laboratory is required for testing of materials and concrete. Marmaray Laboratory is established at Istanbul Technical University for testing aggregates, fresh, hardening and hardened concrete properties (Akkaya and Tasdemir, 2009)

For ensuring durability of concrete, mix design has been optimized for a max. free water/cement ratio of 0.4, min. cement content of 375 kg/m^3, strength class of C40, min. nominal cover of 70 mm (external faces), 32 mm (internal faces), and a max crack width of 0.2 mm (except early-age cracking).

CEM I and CEM III/B of 42.5 and 52.5 types are specified in the specification. When CEM I is used, addition of up to 15% of fly ash and 5% of microsilica is allowed. The efficiency factors, for the calculation of cementitious content and w/c ratio, are given as 0.3 and 2 for fly ash and microsilica, respectively. Use of fly ash and microsilica is not allowed with CEM III/B type of cement. These precautions are taken to control the heat of hydration of concrete, although no upper limit is specified. The contents of alkali and C_3A in the cement are also limited to prevent aggressive reactions with amorphous silica and sulphates. Cement, fly ash and microsilica contents are 285, 50 and 15 kg/m3, respectively. The maximum water-to-cementitious ratio of the concrete mixture is 0.38.

In order to achieve a well grading, natural sand (0-2mm), crushed sand (0-4mm), No.I (4-16) and No.II (16-22) coarse crushed limestone aggregates are used.

The total alkali content and chloride content of the concrete are calculated from the constituent materials. The slump of concrete is declared as 18-22 cm to ensure workability. A polycarboxylate based superplasticizer and air entraining agent is used to ensure high workability, stability and segregation resistance. Air-entrainment is required for the structures exposed to freeze-thaw. The quality of entrained air is measured by the stability in fresh state; dispersion, size, shape and volume of air bubbles in the hardened state. Besides measuring air content by pressure-methods, air structure is examined by ASTM C457.

3.3 Pre-testing of Concrete

A comprehensive pre-test program was developed and executed. A part of the pre-testing was full scale trial casting (FSTC) executed under realistic circumstances. FSTC was not allowed to start until the pre-testing of the concrete mix was completed and should be done using the proposed construction methods and equipment performed by operators and staff would be involved in the execution of the concreting works (Erdogdu and Lykke, 2008; Lykke, 2005)

All tests of constituent materials according to related standards were performed and certified as Inspection Section. Aggregates were tested for particle size distribution, density, water absorption properties, alkali, chloride, methylene blue and drying shrinkage. Special attention was paid for mineralogical structure and reactive minerals in the aggregates. After defining the reactive minerals with thin section analysis, short term and long term alkali-silica length expansion tests were performed. As well as 14 days long (80^{o}C NaOH, ASTM C1260) test, 6 months long (50^{o}C NaCl, TI-B 52) and 12 months long (38^{o}C humid conditions, CAN A23.2-14A) tests were also performed. Expansion above the limit criteria were investigated by microscopy to ensure that the expansions were due to alkali-silica gel formation (Akkaya and Demir, 2010).

After selecting the materials with appropriate quality, performance properties of concrete have to be defined in both fresh and hardened states. The importance of specifying fresh concrete properties is important for insitu performance of concrete. Fresh Concrete properties such as consistency, density, temperature, air-content, bleeding, slump retention and setting time are declared by the contractor. Strength class is determined by sampling of fresh concrete prior to casting concrete in formworks. 150 mm diameter, h=300 mm cylinders are kept under humidity conditions at 20^{o}C for 28 days.

Hardening concrete was tested for determining the early age properties and calculation of cracking risk by simulation programs. At 0.5, 1, 2, 3, 7, 14, 28. days, the development of compressive and split tension, loading and unloading E modulus, thermal expansion coefficient, adiabatic heat development, autogeneous shrinkage and creep of concrete were measured according to TI-B 101, 102 and 103.

Hardened concrete tests such as compressive strength, density, air content, chloride diffusion, petrography were performed. The permeability of concrete is determined by accelerated tests (ASTM C1202 and NT-BUILD 443). The permeability class and chloride diffusion coefficient are determined. Performance of resistance to freeze-thaw cycles is tested by salt-scaling test (EN 12390-9) and critical dilation test (ASTM C671). The in-situ quality of concrete is examined by thin sections and plane sections (DS 423.39-45). Concrete composition, paste homogeneity, micro-cracks and degree of compaction, bond between aggregates and paste, joints and internal stability are evaluated.

Casting of 1 m^3 concrete at the production plant enables measurement of temperature rise, concrete surface quality check and fresh concrete properties. Full scale trial casting is performed to observe the findings of the simulation program. Both designed concrete and production methods are tested in full scale trials. Properties of fresh concrete at the batching plant, at the construction site and after pumping are tested and correlated. Besides workability (slump and flow tests), density, temperature and air content, slump life of concrete on site are also determined. Development of heat of hydration is measured and monitored by thermocouples. Post-cooling is pretested. Quality of formworks and pumping, efficiency of vibration and workmanship are evaluated.

Crack widths are measured and compared with the limit values. Formwork, insulation and workmanship quality, vibration and compaction, and curing methods are also tested during the full scale trials. Properties of fresh concrete after mixing, before pumping and after pumping are measured for correlation. Core samples taken after hardening of concrete enables for testing freeze-thaw resistance, paste homogeneity, internal stability, chloride permeability, strength and unit weight testing of the in-situ concrete.

Water-to-cement ratio of the insitu concrete can be approximated according to the reference thin sections prepared at the laboratory by using same materials. Cracking, capillary porosity and carbonation depth are measured by the thin sections of in-situ concrete. Dispersion of cement and other binding materials such as fly ash and silica fume are observed by microscopy. Properties of air entrainment such as, air content, specific surface of voids and spacing factor of air pores are measured on cut and polished concrete cross sections.

The risk of delayed ettringite formation is tested by curing concrete at the highest temperature expected, calculated from the simulation program. Decrease in strength or increase in permeability of concrete indicated the damage occurred due to high temperature exposure during early ages. Permeability of concrete is measured by rapid electrical methods (ASTM C1202) and chloride diffusion methods (NT BUILD 443).

Workmanship, methods and materials used during repair works are also presented. The pull-off test determines the quality of adherence between the repair mortar and the substrate concrete. Necessary preparations should be made at the interface for ensuring high bonding strength. Repair mortar thin section reveal the mixing and homogeneity of the mortar, porosity at the interface and shrinkage cracks in the mortar. The depth of epoxy injection can also be measured by the plane section of the cores. The viscosity of the injected epoxy and the pressure applied during injection are two important parameters to determine during these trials (Akkaya and Demir, 2010).

Concrete covers are used, as they are superior to plastic ones due to thermal compliance with the surrounding concrete, and provide better bonding. Their stiffness guarantees the distance required for protection of the steel reinforcement (Akkaya and Demir, 2010).

All surface of the newly cast concrete is protected against evaporation. The protection is established after completion of compaction and surface treatment is applied to prevent cracking due to plastic shrinkage. The protection against evaporation is maintained until a minimum degree of hydration of 90% has been reached at the concrete surface, except for internal formed surfaces in tunnel items where the requirement for 90% degree of hydration may be replaced by a requirement to reach 96 maturity hours. The degree of hydration in the concrete surface is determined from measurements of the temperature at a depth of a maximum 10 mm, except for construction joints where a maximum depth of 20 mm is allowed. For concrete surfaces cast against formwork, an acceptable evaporation protection to leave the formwork in place (Erdogdu and Lykke, 2008).

3.3 Crack Control at Early Ages

To ensure durability for long service life, the risk of early age cracking is defined and limited. Hardening concrete properties, approximate specific heat capacity and heat conductivity properties were used as an input of the database of an 2-D FEM based computer simulation software. Cracking risk is calculated by the ratio of tensile stress at early ages to the tensile strength of concrete. The tensile stress is calculated by the measurement of autogeneous shrinkage, basic creep and thermal deformations. The measured early age shrinkage, creep and thermal strains are multiplied by the unloading modulus of elasticity to calculate the tensile stress. The tensile strength is calculated by 0,9 x split tensile strength at respective ages. The measured material properties, structural restrains (geometry of the structural members, specific heat capacity and heat conductivity of the ground, casting sequence) and casting schedule (formwork/insulation properties, time of formwork removal, curing, post cooling, environmental temperature and humidity) are given as an input to the simulation program. Cracking risk is limited to 0,7 and 1,0 for water retaining members and all other members, respectively. Cracking risk under different scenarios are calculated based on seasonal changes and construction method requirements. For each type of structural element and all water-retaining structures planned risk of early-age cracking are determined through temperature and stress analysis. If cracking occurs, cracks are injected in case they exceed the design crack widths (Erdogdu and Lykke, 2008).

Due to the effect of environmental and internal temperature on the concrete properties, maturity concept is employed in the calculation of early age cracking risk. Activation energy is calculated based on the slopes, calculated from the early age compressive strength vs. maturity relationship, evaluated at 5^{o}C, 15 ^{o}C, 20 ^{o}C, 25 ^{o}C and 35 ^{o}C curing temperatures.

Based on stress analysis, limiting temperature differences for each structural element are established corresponding to the following two limits;

(a) For structural items that are restrained by neighboring elements, a maximum temperature difference between the mean temperature of the newly cast element and the mean temperature of previously cast items (D_{ext}) should be defined (Table 1).

(b) For all structural elements, a maximum temperature difference between the mean temperature of the element and the temperature of the element (D_{int}) should be defined.

The maximum temperature of the concrete is 50^{o}C in the central part of bottom slabs. If higher than 50^{o}C special consideration of Delayed Ettringite Formation (DEF) must be given. A graphical comparison to the requirements is possible. Graphs showing the temperature developments is available on site for execution of the temperature control and other actions related to the temperature and maturity development, e.g. stripping of formwork (Erdogdu and Lykke, 2008).

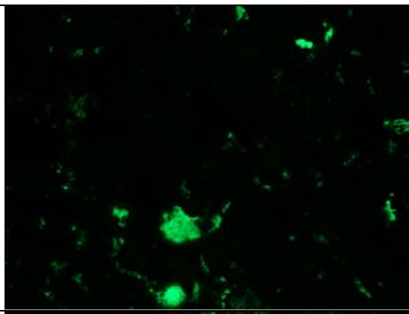
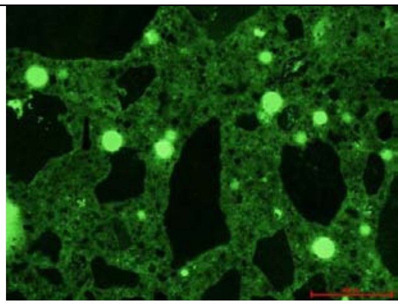
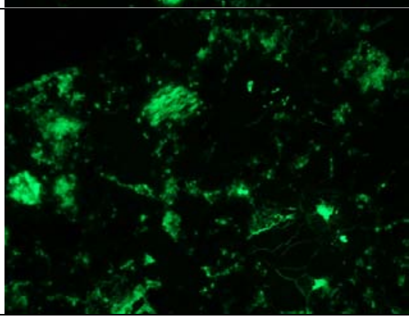
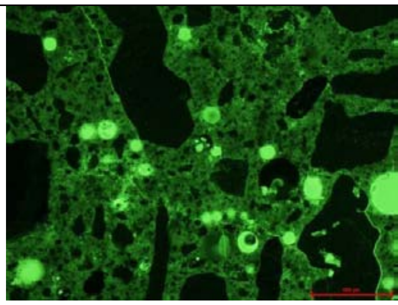
Table 1. Overview of Parameters Related to Early-Age Cracking.

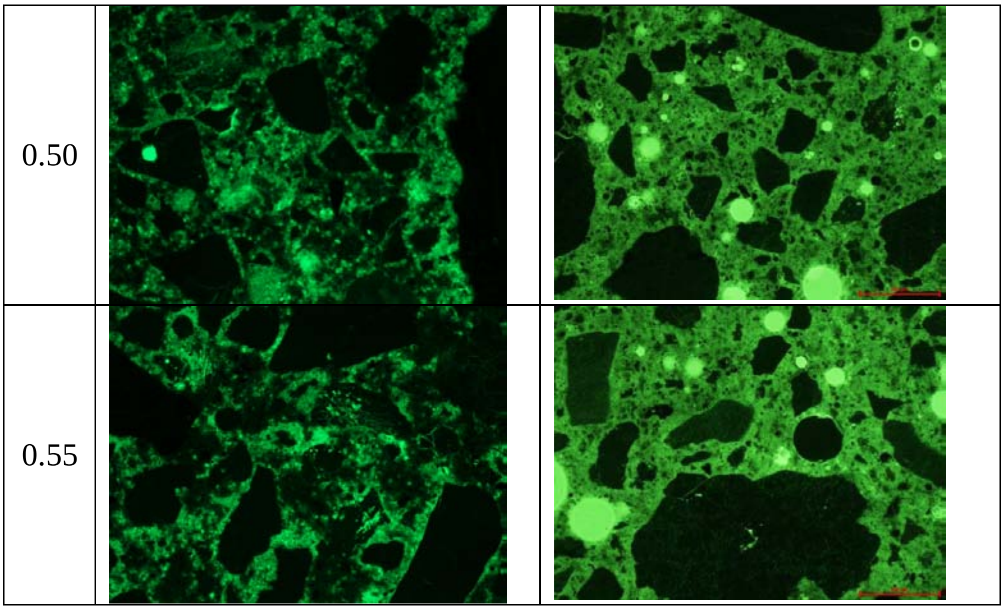
Location/Structure	Max. crack width (mm)	Max. crack risk	Max. D_{ext} (^{o}C)	Max. ΔT_{int} (^{o}C)
Water-retaining parts	0.2	0.70	15	8
Other parts	0.2	1.00	20	12

4. FURTHER EXPERIENCES IN MARMARAY LABORATORY AT ITU

Microstructure investigations and water-to-cement determination of the concrete mixes were performed by thin section analysis. The method is based on vacuum impregnation of concrete core using a fluorescent epoxy. After impregnation with fluorescent epoxy, thin sections are prepared from slices of concrete that are attached to a glass slide, and then ground to a thickness of about 30μm. Under a fluroscence light polarizing microscope, features such as material constituents, carbonation depth, water-cement ratio and paste homogeneity can be observed based on the properties and intensity of light, passing through the concrete thin section. In order to estimate the water-to-cement ratio of a concrete thin section, prepared from a core taken from the structure, a series of reference thin sections were produced at varying w/c ratios. The light intensity of the in-situ concrete thin section is compared to the reference set. It has been observed that the light intensity does not only depend on the water-to-cement ratio, but also the materials used in the mixture design. (Akyuz et al., 2007; Yildirim et al., 2010) Figure 2 presents that the UV-light intensity passing through the concrete is lower for the Mix 1 (with fly ash and silica fume), compared to Mix 2 (only with fly ash).

The alkali-aggregate testing of mortar bars with different methods proved that accelerated ASTM C1260 test results (14 days of NaOH exposure) and TI-B 51 test results (6 months of NaCl exposure) may not be directly correlated. After expansion tests, mortar bars are investigated by thin sections, and reactive aggregates are determined. Figure 3 presents the ASTM C1260 and TI-B 51 expansion test results of a natural sand. Petrographic investigations with UV-light proved that different types of minerals may react under different exposures. The reaction of porous sandstone is observed in ASTM C1260 and reaction of a highly altered porous chert is observed with TI-B 51 (Figure 4). Figure 5 presents the expansion results of a crushed sand from ASTM C1260 test and CAN 14A (12 months of humidity) test. Although CAN 14A expansion presents closer values to the limits, maximum expansion of both tests remain below the limits of expansion. Petrograhical studies proved the reaction of foliated biomicritic limestones which contain disseminated secondary microquartz and recrystallined calcite with CAN 14A (Figure 5).

W/C	Mix 1	Mix 2
0.35		
0.40		



Fgure 2. Effect of water-to-cement ratio and cementitious material content on the UV light intensity under polarising microscope (x50).

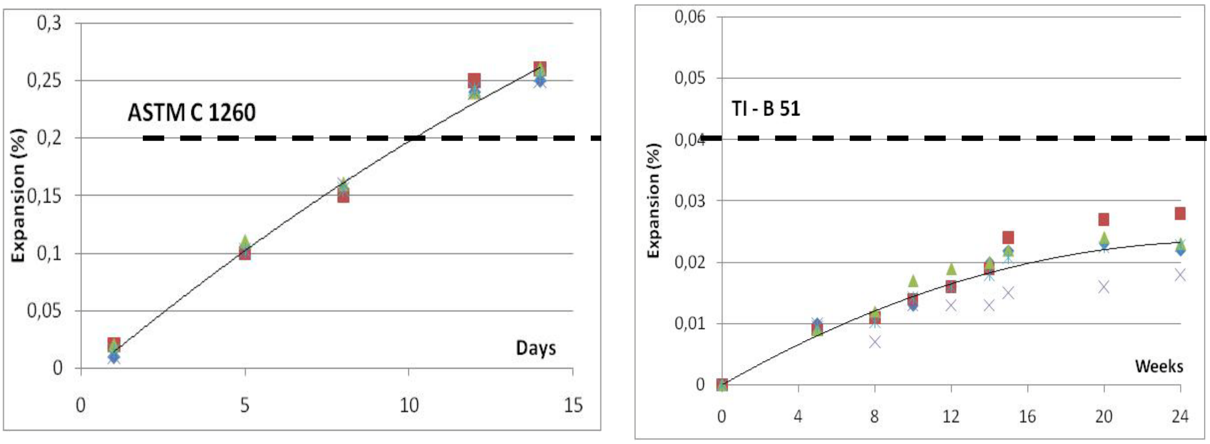


Figure 3. Expansion test results of natural sand

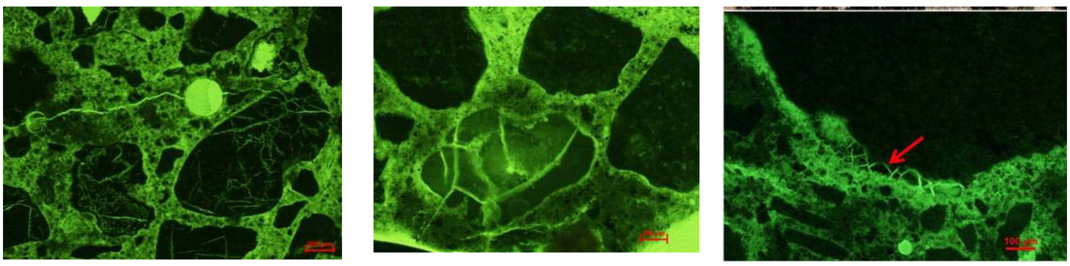


Figure 4. UV light views of reacted porous sandstone (left, x50), porous chert (middle, x100), biomicritic limestone with disseminated secondary microquartz (x50).

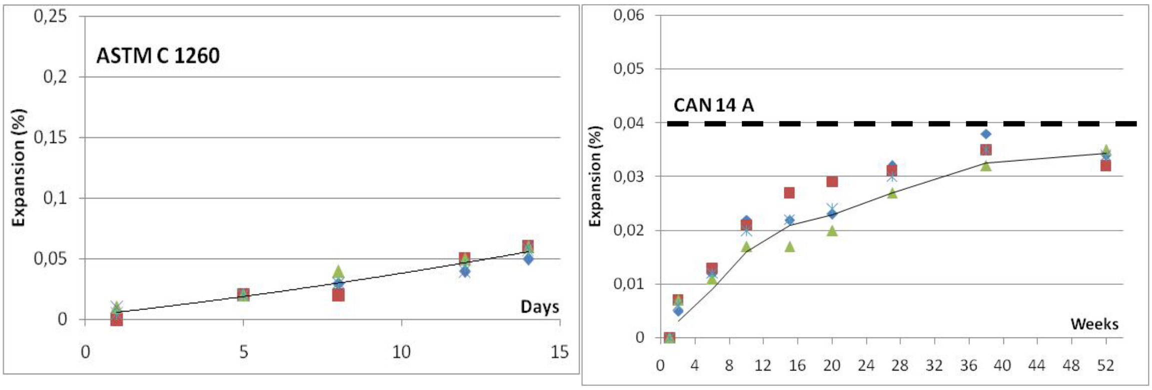


Figure 5. Expansion test results of crushed sand

5. CONCLUSIONS

The required service life of the Marmaray Project, including the deepest immersed tube tunnel, NATM and TBM tunnels and the stations is 100 years in environmental conditions that are aggressive to concrete such as, marine environment, deicing agents, carbonation, freeze-thaw cycles and water pressure. A comprehensive concrete specification is used to control the quality of the concrete and its constituents in the Project. Materials and concrete mixture designs are selected based on pretesting and full scale trials. However, since the properties of binders and aggregates, seasonal changes, production methods and workmanship continue to affect the properties of concrete, testing for quality assurance continues during the production phase.

Inspection sections for materials are essential tools for providing strict quality control on the constituents of concrete. A strong network among the contractor, testing agency, concrete producer and the representatives from the aggregate quarry, cement factory and chemical admixture suppliers is needed to quickly respond and evaluate the material related problems during production.

By correlating the results between long term tests and accelerated tests (for such as, alkali-silica reactivity, chloride diffusion) during the pretesting period, the quality control and assurance during the production period can be effectively performed only with accelerated tests. Simulation for early age cracking risk of the structures, enhances the ability of the contractor for decision making (related to formwork type and removal time, casting sequence, need for postcooling, precautions against weather conditions, curing type and period..) during construction. Full-scale trials provide an excellent experience for the contractor about the situations (such as life-time of concrete, effeciency of workmanship, vibration and curing methods..) that may occur during construction. Petrography of hardened concrete provides an excellent tool to assess the insitu quality of concrete (homogeneity and internal stability, w/c ratio, microcracks and air void system) in the structure.

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