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Inspection Report

Twelve-Year Inspection of Tyfo® Fibrwrap® System Applied in Marine Environment

Long-Term Performance of Tyfo® Fibrwrap® System Applied to ASR damaged Concrete Structures

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Inspection of Tyfo® Fibrwrap® System Retrofitted ASR Damaged Concrete Structures

In 1996, the Tyfo® Fibrwrap® System was applied to repair and retrofit Alkaline-Silica Reaction (ASR) damaged concrete columns and beams on an upscale ocean front residence building, which was in poor condition structurally and aesthetically. After 12-years of service in a harsh environment, the repaired structure was visually inspected. As this report shows, the Tyfo® Fibrwrap® System is still in perfect condition. There is no debonding between the reinforcement layers and the substrate, and no cracks or deformations were found, indicating the reliable performance of the Tyfo® Fibrwrap® System in strengthening/retrofitting ASR deteriorated concrete structures.

1. Background on Deterioration of Concrete Structures due to ASR

1.1 Mechanisms of ASR (Alkali-Silica Reaction)

Alkali-silica reaction (ASR) is one of the important factors leading to the deterioration of concrete structures. In ASR, aggregates containing certain forms of silica react with alkali hydroxide in concrete to form a gel that swells as it absorbs water from the surrounding cement paste or the environment. These gels can swell and induce enough expansive pressure to damage concrete. Once this has occurred, water is able to penetrate the concrete to a deeper level. In winter, freeze/thaw actions can cause the concrete to break up even more. In addition, the reinforcing steel bars inside the concrete structures may break due to ASR, which will cause more serious concerns for the safety of a structure [1].

Typical indicators of ASR are random map cracking and, in advanced cases, closed joints and attendant spalled concrete. It is also reported that ASR deteriorated concrete shows white exudates. This product is identified as zeolite-like structures, responsible for concrete expansion and cracking [2]. Cracking due to ASR usually appears in areas with a frequent supply of moisture, such as close to the waterline in piers, near the ground behind retaining walls, near joints and free edges in pavements, or in piers or columns subject to wicking action.

The mechanisms of ASR in a concrete structure can be traced back to the chemical reaction of the cement and the type of concrete aggregate (e.g., andesite). Cement itself is made by roasting together crushed chalk (calcium carbonate) and clay slurry in giant steel kilns to a temperature of 1,450^{o}C. During this process some calcium carbonate decomposes to calcium oxide, but does not then become neutralized by the clay, so the cement, and the subsequent concrete, contain unreacted calcium oxide:

$$CaCO_3 \rightarrow CaO + CO_2 \quad 1$$

Concrete is quite a porous material and, as water soaks through it, the calcium oxide dissolves to form calcium hydroxide solution (limewater):

$$CaO + H_2O \rightarrow Ca(OH)_2 \quad 2$$

Calcium hydroxide is a kind of alkaline. The level of alkali in the powder determines the levels of additives to mix in to make viable concrete.

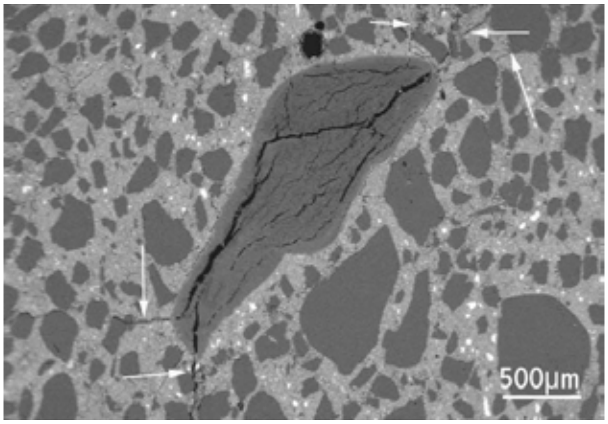

Figure 1[4]: Polished section of concrete, viewed with a scanning electron microscope, showing a chert aggregate particle with extensive internal cracks due to alkali-silica reaction. The cracks extend from the aggregate into the nearby concrete (arrowed).

Silica, SiO_2, the oxide of a non-metallic element, is acidic and in the presence of water, reacts with the alkali in the cement in what is called an 'Alkali-Silica Reaction' (ASR) - sometimes 'Alkali-Aggregate Reaction' (AAR).

During the Alkali-Silica Reaction, a gel is formed that swells as it draws water from the surrounding cement paste[3].

Alkali hydroxide + reactive silica gel → reaction product (alkali-silica gel)

The amount of gel formed in the concrete depends on the amount and type of silica and alkali hydroxide concentration. In absorbing water, these gels expand, thus inducing pressure and subsequent cracking of the aggregate and surrounding paste. This process can be clearly illustrated in Figure 1 and 2, which are micro-sized scanning electron microscope pictures of concrete cross-section subjected to ASR [4].

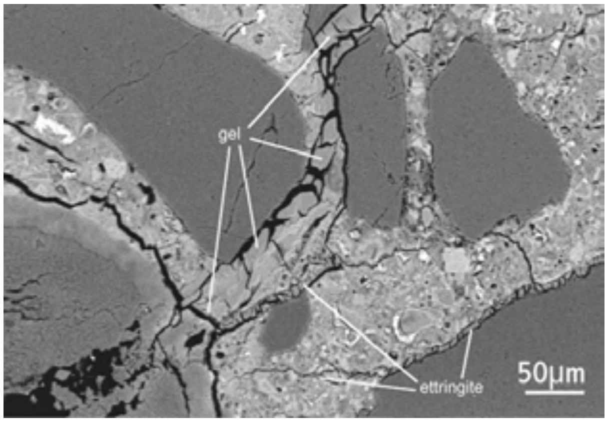

Figure 2[4]: Detail of the chert particle in the previous image and adjacent cement paste, showing alkali-silica gel extruded into cracks within the concrete. Ettringite is also present within some cracks.

The conditions required for ASR to occur are [3]:

- A sufficiently high alkali content of the cement (or alkali from other sources);
- A reactive aggregate, such as chert;
- Water - ASR will not occur if there is no available water in the concrete, since alkali-silica gel formation requires water.

ASR can be controlled using certain supplementary cementitious materials. In proper proportions, silica fume, fly ash, and ground granulated blast-furnace slag have significantly reduced expansion due to alkali-silica reactivity. Another remedy technique is to use lithium compounds instead of sodium compounds as the external electrolyte. The basic idea is to use the inward migration of lithium ions to reduce ASR. Lithium compounds can effectively reduce the ASR potential of concrete. This is mainly due to the high affinity of the lithium and silica (in aggregate). Lithium silicate will form before the formation of other alkali silicates, such as sodium silicates, and lithium silicate is not expansive, and therefore, there will be no ASR expansion [5]. Another method is the application of surface coatings to prevent moisture penetration from the outside[1]. However, it has become clear in some cases that preventing moisture penetration fails to completely stop the expansion due to ASR.

1.2 Application of Fiber Reinforced Polymers (FRPs) to Strengthen / Retrofit ASR Damaged Concrete Structures

In recent years, externally bonded Fiber Reinforced Polymers (FRP) have been proposed as a promising method to strengthen and retrofit ASR damaged concrete structures [6-7]. The high stiffness-to-weight and strength-to-weight ratios of FRP composites, combined with their inherent corrosion resistance and tailorability, make them attractive for use in infrastructure rehabilitation. As discussed, one of the necessary conditions required for ASR is water ingress in the concrete. FRPs possess a much lower water permeability compared to the concrete structure. As an example, the water diffusion coefficient of TYFO® SCH 41S-1 composite is about 3 x 10^{-15} m^2/s, while concrete shows a 4 order higher water diffusion coefficient, around 10^{-11} m^2/s [8]. This fact further indicates the potentials of the application of FRP's to strengthen and retrofit ASR damaged concrete structures.

As an example of this type of FRP application, TxDOT (Texas Department of Transportation) restored ASR damaged bridge (FM 1929 Lake Ivie Bridge in Concho County) columns to their original strength and stiffness by wrapping them with CFRP[5]. The system does not fully encase the columns, but rather confines them using separate vertical and horizontal strips of fabric. This method prevents wicking of moisture under the wrap and allows the concrete surface to be examined for future cracking.

2. Inspection of Tyfo® Fibrwrap® System Retrofitted ASR Damaged Concrete Structures.

2.1 Introduction of the Project

The ocean front residence building, located in Malibu, California, had been pounded by the surf over the years. The supporting columns and beams had been extensively damaged due to ASR. Columns suffered moderate to severe cracks and general spalling, which reflects the deteriorative effects of the ASR on the concrete. The photograph (see Figure 3), taken prior to the testing, shows the extensive cracks around the columns and the chalks of concrete, especially on the bottom of the column.

The Tyfo Fibrwrap System was used to repair and strengthen the columns and beams. The first step in the repair process was to remove all degraded concrete. Then the exposed steel reinforcement was treated with Tyfo® CIS corrosion inhibitor to prevent future corrosion. It is worth noting that the safety of a concrete structure is considered not to be seriously compromised as long as the reinforcing steel is not broken due to ASR-caused expansion[1]. After the treatment of the steel, Tyfo® products are used to patch the missing concrete and restore the column shape. Based on estimations of the loss of the steel reinforcement, engineers from Fyfe Co. designed the Tyfo® Fibrwrap System to add the necessary strength to replace flexural, shear and confinement deficiencies. A Tyfo ® coating in white was applied to finish the FRP surface. The finish coatings are to protect the Tyfo® FRP system from the abrasive nature of ocean tides, sand, sun irradiation etc.

The retrofitted columns in white are shown in Figure 4.

2.2 August 2008 Inspection

12 years after the installation was completed, the Tyfo® Fibrwrap® system was visually inspected on August 18, 2008. The inspection aimed to determine if the Tyfo® Fibrwrap® System still works effectively in the harsh environment for a long term application period.

Figure 3: The ASR deteriorated concrete columns, with extensive cracks on the concrete surface and concrete chalking (on the bottom of the column).

Figure 4: Columns retrofitted with Tyfo® Fibrwrap® System.

The inspection is mainly focused on the possible occurrence of debonding between FRP layers and the substrate, any cracks in the Tyfo® Fibrwrap® System, and any irregular deformation of the structure and/or surfaces. If any of these abnormal phenomena appear, it may indicate that ASR is still present, leading to further damage of the structure.

The retrofitted columns and beams, 12-years after FRP application, are shown in Figure 5. There are no signs of debonding, cracks or any irregular deformations, which indicate the Tyfo® Fibrwrap® System is effectively preventing the concrete structure from further damage from ASR.

Figure 5: The retrofitted columns and beams on August 18, 2008.

Columns

All columns are in perfect condition. No delaminations, blisters or any signs of degradation were found along the whole column. Due to the long-term wearing effects of the sea water with sand, on the bottom of columns in the area facing the sea, some coating was worn out as shown in Figure 6. As shown in Figure 6 and 7, no defects in the FRP on the surfaces facing the ocean or on the opposite surfaces were found.

Figure 6: a column with some coating worn out on the side facing the sea due to the abrasive action of sea water with sand. The small yellow area shows the FRPs under the coating

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Figure 7: the opposite side of the column to the sea.

It is worth noting that the bottom column was seriously damaged with concrete chalking due to the ASR before retrofitting (see in Figure 4). After 12-years of service in sea water and high humidity, the column retrofitted with Tyfo® Fibrwrap® System retains its structural integrity, without any cracks or deformation on the surfaces. This indicates that there is no further propagation of the ASR.

Joints between the column and beam

No cracks are visible on the joints between the column and the beam, as shown in Figure 8. This indicates all columns effectively support the whole structure as originally designed. No column shows weakness or defects.

Figure 8: joints between the retrofitted column and the beam

Beams

Also in Figure 8, the retrofitted beam appears in perfect condition. No signs of debonding between FRP and the concrete substrate, cracks or abnormal deformation of the whole beam.

Un-retrofitted concrete structures in the same building

It is worthwhile to note the condition of the concrete steps of the same building that were not retrofitted with the Tyfo® Fibrwrap® Systems (Figure 9). It is remarkable to see the concrete cracks and concrete chalking, indicating the severity of the ASR effect.

As previously discussed, the occurrence of ASR is due to the concrete type (e.g., including high alkali cement and reactive aggregate) with sufficient water/moisture ingress. The concrete structures used for this building are expected to be the type for ASR. With sufficient water/moisture in the ocean front environment, it is not surprising to see the serious occurrence of ASR. As the ASR damaged concrete structures can be retrofitted and strengthened with the Tyfo® Fibrwrap® System, the concrete structure can perform in the harsh environments (for ASR this means high humidity or water immersion) with proven long-term durability. At the same time, due to the high water-proofing effect of the Tyfo® Fibrwrap® System, it is expected that it will be difficult for water to penetrate through the system into the concrete. Therefore, the ASR will be retarded significantly. As believed, the ASR caused expansion will lead to the cracks and/or irregular deformation on the column / beam surfaces. The lack of any cracks or irregular deformation formed on the retrofitted column / beam surfaces indicates the retarded or ceased ASR in the retrofitted structures.

Figure 9: Concrete steps in the same building. Note the back column was retrofitted with Tyfo® Fibrwrap® systems.

3. Remarks

Concrete columns and beams which had been seriously degraded by ASR were retrofitted with the Tyfo® Fibrwrap® System in 1996. After 12-years of service in a marine environment, the retrofitted column and beams are still in perfect condition. No signs of delaminations, cracks or irregular deformation are found. The excellent performance of the Tyfo® Fibrwrap® System in this project indicates the feasibility of using the Tyfo® Fibrwrap® System to strengthening and retrofit ASR damaged concrete columns and beams.

The success of the Tyfo® Fibrwrap® System in retrofitting ASR damaged concrete structures is expected mainly due to the prevention of water penetration into the concrete, which is one necessary factor for the occurrence of ASR. In addition, the exceptional long term durability of the Tyfo® Fibrwrap® System in harsh environments assures the strengthening effect for the service life.

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