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An investigation of tendon corrosion-inhibitor leakage into concrete

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Abstract

During inspections performed at US nuclear power plants several years ago, some of the prestressed concrete containments had experienced leakage of the tendon sheathing filler. A study was conducted to indicate the extent of the leakage into the concrete and its potential effects on concrete properties. Concrete core samples were obtained from the Trojan Nuclear Plant. Examination and testing of the core samples indicated that the appearance of tendon sheathing filler on the surface was due to leakage of the filler from the conduits and its subsequent migration to the concrete surface through cracks that were present. Migration of the tendon sheathing filler was confined to the cracks with no perceptible movement into the concrete. Results of compressive strength tests indicated that the concrete quality was consistent in the containment and that the strength had increased relative to the strength at 28 days age.

Introduction

The prestressing system plays a vital role in ensuring the structural integrity of a nuclear power plant (NPP) prestressed concrete containment (PCC) throughout its service life. Because the prestressing tendons and their anchorage hardware are fabricated from high-strength, high hardness materials that are subjected to sustained high stresses, they are susceptible to stress-corrosion cracking and hydrogen embrittlement. In all but two of the PCCs in the US (Three Mile Island 2 and H.B. Robinson 2), corrosion protection of the prestressing system is provided by a tendon sheathing filler.

In general, the performance of the PCCs has been very good (1). However, during inspections performed at some of the plants several years ago, streaks of tendon sheathing filler were observed on the outer surfaces of the containment structures (e.g., Calvert Cliffs and Arkansas Nuclear One Unit 1). These observations led the USNRC Staff to include in Revision 3 to Regulatory Guide 1.35, as a precautionary measure, a provision that covers measurement of voids in the tendon ducts of tendons selected for lift-off testing (2). This was intended to help assure that adequate tendon sheathing filler remained in the tendon ducts to provide corrosion protection.

Since that time, leakage of tendon sheathing filler has occurred through the concrete in PCCs of at least four additional plants (Point Beach, Trojan, Palisades, and Fort Calhoun). This has raised an additional concern relative to the effects of the tendon sheathing filler on the

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concrete properties (e.g., strength and bond to the steel reinforcement) and to what extent these effects may impact containment capacity.

Scope of Investigation

Pertinent literature were reviewed to assess the effect of tendon sheathing filler intrusion on concrete mechanical properties. Also, concrete core samples were obtained from the Trojan Nuclear Plant and tested to determine the extent of tendon sheathing filler migration into the concrete, and the concrete tensile and compressive strengths.

Prestressing Tendon Sheathing Filler Materials

The petroleum-petrolatum wax type base plus additives used as tendon sheathing filler materials in PCCs of NPPs have evolved over the years. Initially, "off-the-shelf" industrial materials, such as from the automotive industry, containing additives (e.g., low molecular weight sulfonate materials) were utilized. Early products contained polar wetting agents, rust-prevention additives, microcrystalline waxes, and proprietary constituents formulated to displace water, exhibit self healing characteristics, and resist electrical conductivity. The next generation of materials added a plugging agent to raise the low-flow point of the products to 39°C to help keep them from exiting loose tendon sheathing joints and flowing into hairline concrete cracks. A subsequent refinement incorporated a light base number to provide alkalinity (3 mg KOH/gm product) for improved corrosion protection. Current products modified the original additives by chemical reactions of organic compounds with microcrystalline waxes and petroleum oils to (1) increase viscosity, (2) raise congealing point to 57°C, (3) permit tendon wire or strand removal for surveillance, (4) increase water-displacing characteristics, (5) raise base number (higher alkalinity), and (6) exhibit improved self healing characteristics (3).

Although a review of literature identified several articles on effects of organic-based materials on concrete, these studies generally involved use of crude or lubricating oils known to cause damage to concrete, particularly at elevated temperature. However, these materials have significantly different characteristics from those used as tendon sheathing fillers. The only study identified addressing tendon sheathing filler leakage into concrete at a NPP containment was conducted about 20 years ago when staining of the outer containment surface at the San Onofre Nuclear Generating Station was observed about three days after sheathing filler injection (4). Based on field observations and structural analysis, it was decided that the leakage was due to the high fluidity of the sheathing filler at elevated temperatures and the separation of oil from the petroleum waxes. It is conjectured that the separated oil leaked from the tendon sheathing through non-leaktight sheathing couplers and spiral seams and migrated to the exterior PCC surface through cracks that were present in the concrete. The concrete cracks were thermally induced by heat generation as the cement hydrated and subsequent cooling producing a thermal gradient across the containment wall. The study concluded that the presence of sheathing filler in the concrete cracks did not compromise the structural integrity of the PCC and the sheathing filler was non-reactive with the concrete. The initial tendon sheathing filler was replaced with a current generation sheathing filler. No new exterior surface leakage has been detected since the product change.

Containment Description

The Trojan Plant containment is a post-tensioned concrete structure in the shape of a cylinder with a hemispherical roof and a flat foundation slab. Dimensions of the containment are 37.8-m inside diameter, 61.9-m inside height, 1.07-m wall thickness and 0.74-m dome thickness. Concrete materials used to fabricate the containment had a design compressive strength at 28-days age of 41.4 MPa. Post-tensioning was provided by a BBRV (Prescon) prestressing system. Each tendon was composed of 180 stress-relieved, high-strength wires of 6.35-mm diameter. The cylindrical portion was prestressed by a system consisting of horizontal and vertical tendons. The vertical tendons are anchored into the base slab and are continuous across the hemispherical dome (i.e., inverted-U). The dome has a two-way post-tensioning system consisting of hoop tendons and the continuous vertical tendons. There are three equally spaced buttresses around the containment. Hoop tendons are anchored at buttresses 240 degrees apart, bypassing the intermediate buttress. Each hoop tendon is progressively offset 120 degrees from the one beneath. The tendons are housed in spiral wrapped, semirigid, corrugated tubing having an outside diameter of 13.3 cm. A coupler of galvanized, semirigid, corrugated tubing 0.46-m long was used to join the tubing to make it continuous. Leaktightness of the coupler during concrete placement and filling with corrosion inhibitor was provided by wrapping each joint with duct tape. Corrosion protection of the prestressing tendons prior to installation was provided by a thin film of petrolatum containing rust inhibitors (e.g., Dearborn Chemical Co. Product No-Ox-Id 500). After post-tensioning, corrosion protection was provided by filling the tendon sheaths with Visconorust 2090P or 2090P-2 material* (Viscosity Oil Co.).

Sample Procurement

Leakage of corrosion inhibitor at the Trojan Plant containment became evident when sheathing filler streaks were observed on the containment outside surfaces. The time when the leakage was first observed and the exact reasons for the corrosion inhibitor leakage are uncertain. During site visits and obtaining test articles, it was noted that a vertical crack was visible in the containment concrete over most, if not all, of the vertical tendons. Although the cause of the cracking was uncertain, it possibly could be attributed to loadings during the initial structural integrity test or subsequent integrated leakage-rate testing; however, the containment concrete is designed to remain in compression under these loading conditions. The cracks were most apparent in the region of the containment wall near the base where hoop tendons were not located. Constraint provided by the massive base mat as the containment was being post-tensioned probably contributed to cracking in this region. Concrete shrinkage also may have been a factor. Leakage of sheathing filler from the tendon conduits probably initiated when there was a breakdown in the seal (taped joint) between adjacent tendon sheaths due to the build-up of excessive pressure. Although the exact cause of excessive pressure was not identified, possible sources could have been the result of either overpressurization or overfilling when the sheathing filler was initially installed or reinjected, hydrostatic pressure of the tendon sheathing filler, the effects of thermal gradients due to diurnal temperature change, or a combination of these potential causes. In order to study the migration of the tendon sheathing filler and its possible effects on the containment concrete, several concrete cores were obtained at different locations in the Trojan Plant containment exterior wall where tendon sheathing filler material had been observed.

Locations for obtaining concrete core samples were selected on the basis of accessibility for coring and to provide specimens from areas of the containment that had slightly different diurnal effects due to exposure to the sun. Redundancy also was included in the selection of coring sites. Prior to obtaining core samples, a grid covering an area 40-cm wide by 120-cm high was marked on the exterior concrete surface at each of the four sampling locations. Each grid was located so that it was aligned with the longitudinal direction of the containment wall

*A few of the tendon sheathings initially were injected with Visconorust 2090P materials and then the material was changed to Visconorust 2090P–2.

(i.e., crack direction) and centrally located horizontally (i.e., hoop direction of containment) over the apparent primary crack from which the tendon sheathing filler was leaking.

After marking the grid, a limited number of nondestructive examinations were performed using the standard method for obtaining rebound number of hardened concrete (5). The rebound number measurements were obtained by impacting the hammer normal to the containment wall. A total of 300 measurements were made at each location. If the rebound hammer measurements were obtained in an area where it was obvious that tendon sheathing filler was present, a note was made on the data sheet. Generally, in subsections of the grid where tendon sheathing filler was present on the concrete surface, six readings were obtained outside the stained region and four readings were obtained directly over the stained region. This procedure was then repeated at the other three locations. The purpose of these examinations was to evaluate the potential of this method to detect the presence of tendon sheathing filler in concrete and determine its affect on the mechanical strength of the concrete, if any.

After completion of the nondestructive examinations, a covermeter survey was conducted at each of the four sampling locations in an attempt to indicate locations and orientations of the containment wall reinforcement. Indicated locations of the longitudinal and circumferential reinforcement were marked with crayon on the containment wall. Concrete coring then was initiated using the standard method for obtaining concrete cores (6). Unfortunately the effectiveness of the covermeter in locating the mild steel reinforcement was compromised because of the large amount of steel reinforcement present and the concrete cover depth over the reinforcement (i.e., $\geq$50.8 mm). Coring locations had to be selected using a combination of covermeter results and results of previous coring operations at the location (i.e., when the core bit encountered an embedment the coring process was halted, the concrete core removed, and the embedment orientation noted and marked on the containment wall). After obtaining a concrete core from the containment wall suitable for testing, the specimen was marked according to location from which it was obtained. Concrete cores were obtained from locations exhibiting evidence of corrosion inhibitor leakage and from control areas where no corrosion inhibitor was present. Upon completion of all coring operations, the cores were sealed in plastic bags, placed into plywood boxes, and shipped to ORNL.

Specimen Preparation and Testing

A total of 54 concrete core specimens, primarily 127-mm in diameter (nominal), were provided from the Trojan Plant containment. After taking photographs, each specimen was sawn to obtain a test article having relatively smooth ends that were perpendicular to the longitudinal axis. Depending on the location from which a specimen was obtained (e.g., area with or without tendon sheathing filler present), and somewhat on the length of the core provided, a specimen was allocated for loading by either a splitting-tensile strength or compressive strength test procedure (e.g., 21 splitting-tensile specimens and 29 compressive strength specimens). Four of the cores were not suitable for testing due either to the presence of embedded steel reinforcement or being of inadequate length.

Splitting-tensile strength test procedures were conducted in accordance with standard methods (7). Nine of the specimens tested by this procedure contained known cracks. By testing the specimens in this manner, the concrete cylinder could be separated perpendicular to the plane of the crack and examined visually to determine the extent of tendon sheathing filler migration into the concrete. A solution containing a number of phenolphthaleins indicating different pH-values was then sprayed onto the fracture surface as an optical aid. Fracture surfaces of the concrete that were uncontaminated by the tendon sheathing filler turned purple in color (pH $\geq$ 11) after spraying whereas the locations containing tendon sheathing filler did not experience this color change.

Compressive strength specimens were capped with a high-strength capping compound to provide parallel and plane ends. Compressive strength test procedures were conducted in accordance with standard methods (8). The majority of compressive strength procedures were conducted on uncracked specimens to determine the present concrete compressive strength. Five of the cracked specimens were loaded in compression to determine the combined effect of the crack and the presence of tendon sheathing filler on the fracture mode.

Test Results

At least 300 rebound number determinations of the hardened concrete were obtained at each of the four locations selected for concrete coring. An average rebound number was then calculated for each subsection of the grid at a location. Results of these readings indicate that the concrete quality was relatively consistent from location to location. No quantitative results relative to the strength of the concrete could be derived from the rebound numbers because insufficient concrete core samples had been obtained to develop the required correlation curve between rebound number and concrete compressive strength. Differences in average rebound numbers between areas that had experienced leakage of tendon sheathing filler and those unaffected were relatively small, especially when compared to the range of values that were obtained from subsection to subsection at each location. Determination of the presence of tendon sheathing filler based on rebound hammer number results does not appear to be feasible. The only significant difference in rebound numbers between areas with and without tendon sheathing filler was obtained where there was a relatively thick layer of tendon sheathing filler on the concrete surface. Visual inspections are most effective for detection of the presence of tendon sheathing filler.

Twelve splitting-tensile strength test procedures were conducted on uncracked specimens. Splitting-tensile strength values ranged from 2.85 to 4.55 MPa. Nine splitting-tensile strength test procedures were conducted on specimens obtained directly over cracks from which the tendon sheathing filler had flowed onto the concrete surface. Visual examinations of each of the specimens indicated that the primary path of migration of the tendon sheathing filler was essentially confined to the cracks that formed over the vertical prestressing tendon. Since the tendon sheathing filler is composed of soft wax crystals that are very easily sheared, the tendon sheathing filler can flow easily and thus confined itself to the cracks in the concrete where the resistance to flow was lowest.

Twenty-four compressive strength test procedures were conducted on uncracked specimens. Compressive strength values ranged from 51.5 to 65.8 MPa. The increase in compressive strength, relative to the 28-day value, was consistent with that obtained from other US nuclear power facilities (9). Compressive strength test procedures conducted on the five cracked specimens indicated that the presence of a crack containing tendon sheathing filler tended to result in a preferential fracture related to the presence of the crack. Depending on the positioning of the crack, the fracture mode tended to shift from the typical "cone or hourglass" fracture toward shear, columnar, or a combination of these modes. The effect of the crack and tendon sheathing filler needs to be evaluated on the basis of loading conditions (e.g., multiaxial and orientation) as well as location. Factors, however, that tend to mitigate the potential significance of a crack containing tendon sheathing filler are the large quantity of steel reinforcement present in the containment, and by being post-tensioned, the containment is designed to place the concrete in compression under normal operating conditions.

Summary

Review of the Final Safety Analysis Reports of six plants that had experienced leakage of tendon sheathing filler onto the concrete surface indicates that all these plants initially used early formulations of the tendon sheathing filler. No known incidences of leakage of tendon sheathing filler have been identified where the current formulation of tendon sheathing filler has been utilized. Although a review of literature identified several articles on the effects of organic-based materials on concrete, these materials have significantly different characteristics relative to materials that are used as tendon sheathing fillers. Although very limited, information identified tends to indicate that there are no harmful interactions of tendon sheathing fillers used in commercial nuclear power plants with concrete. Nondestructive examinations conducted in the form of rebound hammer tests indicates that detection of the presence of tendon sheathing filler based on rebound hammer number results does not appear to be feasible. Visual inspections are most effective for detection of tendon sheathing filler. Examination of concrete core samples removed from the containment at the Trojan Plant indicates that the appearance of tendon sheathing filler on the concrete surface was due to leakage of the filler from the conduits and its subsequent migration to the concrete surface through cracks. Migration of the tendon sheathing filler was confined to the crack and there was no perceptible movement into the concrete. Results of compressive strength tests indicated that the concrete quality was consistent in the containment and that the concrete compressive strength had increased over 40% in 25.4 years relative to the average compressive strength at 28-days age.

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