2.12 Inadequate Strength Properties

Description:

The main concrete strength properties used in design are compressive strength (f'_c) and Tensile strength (f_t). Of those, the most commonly used is f'_c which is easy to measure and can be related to all other properties through empirical expressions.
Direct tensile strength is difficult to measure accurately and is normally replaced with Splitting Tensile Strength (f_{tsp}) that is measured with the "Brazilian" test. (In-depth description of the various tests is beyond the scope of this document)

Concrete strength properties are influenced by multiple parameters, the most important of which include the water to cement (W/C) ratio, aggregate properties, and total voids.

When evaluating strength properties for failure analysis it is advantageous to analyze the strength at three distinct time frames (if data is available): the strength at twenty eight (28) days compared to the specifications and design parameters; strength development during the early period (up to 90 days) to evaluate potential variations in material properties and curing conditions; and strength changes over the life of the structure to evaluate potential degradation caused by chemical or physical interactions.

Data to be collected and Analyzed:

1. Original project specifications (FM 2.12 Exhibit 1)
2. Analysis of original design (FM 2.12 Exhibit 2 is analysis prepared by Progress Energy in 2000)
3. Code requirements at time of the containment structure construction (FM 2.12 Exhibit 4 is from ACI 318-63)
4. Cylinder strength test results from original construction (FM 2.12 Exhibits 7, 8 and 9 are database analysis of all samples from the Reactor Building at ages 7, 28 and 90 days respectively; FM 2.12 Exhibit 3 is a graphic representation of the average cylinder strength at early ages for concrete in two panels (out of six) of the containment structure; FM 2.12 Exhibit 6 is original cylinder test records for panel RB-0015 (where delamination occurred).
5. Core tests in 2009-2010 and their correlation to original cylinder tests at the containment structure (FM 2.12 Exhibit 5 is a graphical representation of core tests and original cylinder strength results taken from the core test location; FM 2.12 Exhibit 10 is a table summary of all the available information for these locations)
6. Analysis of locations where the four different mix-designs were used in the containment structure (FM 2.12 Exhibit 12 is a graphical presentation of the mix- design and cylinder strength test overlaid on a plan of panels RB-0015 and RB-0012; these two panels were placed during the same period of time using the same materials; panel RB-0015 is the delaminated panel).

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Verified Supporting Evidence:
None

Verified Refuting Evidence:

a. Original cylinder compressive strength tests were in compliance with the requirements of ACI 318-63 (FM 2.12 Exhibit 4) for concrete with specified strength, f'_c, of 5000 psi. At 28 days the average concrete cylinder strength exceeded 5700 psi.

b. Strength development during the first ninety (90) days followed the expected trend for concrete of the type used at CR3 (Type II cement without pozzolanic admixtures). By the time the structure was pre-stressed the concrete gained more than 15% over the 28 days average compressive strength.

c. In the following 30 years the concrete gained, on average, 28% more compressive strength compared to the tested 28 days strength (see discussion f. below).

Discussion:

a. Project specifications (FM 2.12 Exhibit 1) require twenty eight (28) days minimum compressive strength of 5000 psi. There are no specifications for tensile strength – splitting, direct or flexural.

b. Design documents use the relationship $3(f_c)^{1/2}$ for allowed tensile stress (212 psi for concrete with f'_c=5000)

c. Analysis of cylinder tests (FM 2.12 Exhibit 8) shows compliance with ACI 318 requirements for 5000 psi concrete when evaluated according to ACI 214 methods. Design analysis/Calculation (FM 2.12 Exhibit 8) performed in the year 2000 provides a detailed analysis of the strength gain and compliance for the as-built condition.

d. Analysis of cylinder strength development during the first 90 days (FM 2.12 Exhibit 3 is a graphical representation of the strength development in panel RB-0015 and RB-0012 respectively) reveals the following:

   i. Early age strength development was in the normal range expected for concrete made with Type II cement.

   ii. There was significant difference in strength (mostly for 7 and 28 days tests) between pours. This may be explained by the four (4) different mix-designs used in the structure (FM 2.12 Exhibit 9 is a plan of the wall overlaid with pour numbers and data for concrete mix-designs and 28 days strength). By age 90 days the strength differences between pours were smaller as seen in the statistical analysis (average and standard deviation) in FM 2.12 Exhibit 10.

e. Empirical relationships between concrete compressive strength (f_c) and splitting tensile strength (f_{tsp}) have been established through long

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term experience. Such relationships are provided in ACI 318, CEB-FIB and numerous published papers. Of those, the one that best fit experimental data from tests on concrete cores from CR3 is the CEB-FIB formula ($f_{tsp}=0.3f_c^{2/3}$ in Metric units). When applied to the average compressive strength of all cores (7505 psi) it accurately predicts the measured splitting tensile strength average of 604 psi. The ACI 318 expression used in design ($f_{tsp}=0.56f_c^{0.5}$) predicts f_{tsp} that is lower (more conservative) than the average CR3 concrete. Based on the above it can be concluded that the tensile strength properties of the concrete were adequate.

f. Analysis of strength development over the life of the structure (FM 2.12 Exhibit 10 is a table summary of concrete properties at locations where both original cylinder data and current core test data are available; FM 2.12 Exhibit 11 is a graphical representation of the relationship between common strength properties from the table in Exhibit 10) reveals the following:

  i. The ratio of seven (7) days strength to twenty eight (28) days strength was in a range (71% to 88%) normally expected for concrete made with Type II cement and no pozzolans.

  ii. The 2009-2010 core strength ranged from 1% to 35% above the ninety (90) days average cylinder strength. This spread reflects the possibility that the cores and the cylinder location were not from the same ready-mixed truck (within the same pour). It can also be explained by fast early age strength gain, core damage (ACI 318 allows 15% adjustment to core strength when compared to cylinders for acceptance criteria), or exposure over the life of the structure. This type of variation is not uncommon in investigations of older structures and the exact cause is often left unexplained.

  iii. On average, concrete strength development is in line with that expected from high strength concrete made with Type II cement and Florida Limestone aggregate. Seven (7) days strength was 78% of the twenty eight (28) days strength. Beyond 28 days the concrete gained another 14% by age 90 days, and another 14% by the year 2010. Total strength gain after age 28 days was on average 32%.

  iv. When comparing core strength to cylinder strength for design analysis it is possible to estimate equivalent in-place strength of the concrete at the location from which the cores were taken. According to ACI 214.4R section 8.1 it is allowed to multiply the core measured strength by 1.06 to account for damage due to drilling (our cores were 4" diameter and tested "as-received" – so no other corrections were allowed). This calculation was not performed since the purpose of the long term analysis was to determine trends and not establish design values.

Conclusion:

Based on the analysis above it is concluded that strength properties were adequate and met design criteria established for CR3. Concrete strength properties did not contribute to the delamination.