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EFFECT OF ELEVATED TEMPERATURES ON HEAVY CONCRETE STRUCTURAL STRENGTH IN QINSHAN PHASE 3 CANDU 6 REACTOR BUILDINGS

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ABSTRACT

Heavy concrete is commonly used inside the Qinshan Phase 3 CANDU 6 reactor buildings for radiation shielding functions in order to provide access to key areas during reactor operation. In some cases, the heavy concrete elements are also structural elements. Concerns have been raised about the functional performance of the heavy concrete structural elements, specifically the primary heat transport pump (PHTS) supporting slabs, surrounding the feeder cabinets when subjected to elevated temperatures between 42 ^{o}C and 121 ^{o}C and their corresponding temperature gradients on a long-term basis during the normal operation of the plant.

This paper presents the results of a test investigation on the strength of heavy concrete under elevated temperature conditions being experienced by the heavy concrete structural elements around the feeder cabinet to confirm that these structural elements meet their functional requirements. The loading conditions consist subjecting the specimens to the elevated temperatures and temperature gradient noted during commissioning, including the effect of epoxy coating. The heavy concrete mix proportion and materials of the test samples (ilmenite aggregate and Portland cement) are identical to those used for heavy concrete structural elements surrounding the feeder cabinet. Subsequent to the confirmation of the functional requirements of the heavy concrete structural elements, alarm limits are recommended for these structural elements.

Keywords: concrete, strength, temperature, heavy concrete, aggregators, reactor building

1. BACKGROUND

The Qinshan Phase 3 CANDU 6 reactor vault structure consists of both normal concrete and heavy concrete elements. A section showing the vault structure around the Feeder Cabinet is illustrated in Fig. 1. During the commissioning of the cooling system, the concrete surface temperatures of the vault structure of Units 1 and 2 Reactor Buildings were reported above the alarm temperatures specified in the AECL design document. These limiting alarm temperatures were based on CSA N287.3 Clause 6.6.1 for the containment structure. As the cooling air temperature was also measured above the concrete limit temperatures, it indicated that the cause for these higher temperatures on the concrete was due to leakage of heat through the insulation of the feeder cabinet. Though the vault structure is not a part of the containment structure, this exceeding of the alarm temperature limit led to concerns that the concrete in these areas may undergo strength reduction due to the continuous exposure to elevated temperatures and hence not meet its functional requirements. The highest temperature at the concrete slab surface

was reported at 121 ^{o}C, which exceeds the limits prescribed below in the CSA N 287.3 for normal operation.

CSA N287.3 [1] Clause 6.6.1 specifies that for CANDU containment structure, the concrete temperature shall not exceed:

(a) During normal operating or post accident conditions over any prolonged periods,
  (i) 65 ^{o}C over large areas; or
  (ii) 100 ^{o}C over local areas in the proximity of penetrations for hot piping; or

(b) During accident conditions or over any short periods on interior containment surfaces only
  (i) 175 ^{o}C over large areas; or
  (ii) 345 ^{o}C over local area affected by impingements from steam or water jets

Two measures were taken to clear the above concern of the elevated temperature on the vault structural concrete: one was to improve the Feeder Cabinet insulation and the cooling air system (lower the cooling air temperature, optimize the air flow and connect the chilled water system to the coolers) to bring down the concrete temperature to below the specified alarm temperature, and the other was to investigate the effect of the elevated temperature on the concrete strength. It shall be noted that the first measure successfully achieved the goal of bringing the temperatures below the specified temperature limit. This paper presents the results of the study of the effect of elevated temperature on heavy concrete strength.

Figures 2, and 3 summarize the available literatures on the effect of elevated temperature on concrete strength. The summary of the literature review is as follows:

For normal concrete (carbonate aggregates and Portland cement), Fig.2 shows that the loss of strength for temperature up to 200 ^{o}C is less than 10% (*Guide for Determining the Fire Endurance of Concrete Elements,* [2] ACI Committee 216).

For heavy concrete with ilmenite aggregates and high alumna cement, Fig.3 indicates that the loss of strength for temperature at 100 ^{o}C is 60%, and for temperature at 200 ^{o}C is 65% (*Properties of Concrete* [3], A.M. Neville).

There is no available literature for the heavy concrete with mixture of ilmenite aggregates and Portland cement. The available literature [3] does state that the strength loss will be less in this case in comparison to the mix of ilmenite aggregate with high alumna cement.

For the Qinshan Project, the wall concrete for the vault structures is normal concrete (carbonate aggregates and Portland cement) and for the PHTS Pump supporting slabs above the Feed Heater Cabinet is a heavy concrete with mixture of ilmenite aggregate and Portland cement (see Fig. 1).

Based on the field temperature measurement, the concrete surface temperatures for the wall and slab ranges from 42 ^{o}C to 121 ^{o}C. Therefore, according to the above literature and based on the stress nature of the wall (in compression), it can be concluded that the noted temperatures shall not affect the functional requirement of the walls; however tests are required for the slab heavy concrete for the confirmation of this element meeting its functional requirements. As there is no available data for ilmenite aggregate and Portland cement concrete mix, a test program was performed to confirm the functional performance of the primary heat transport pumps supporting slabs over the operating life of the plants.

2. TEST PROGRAM

Two batches of concrete were made for the 150mm cubic test specimens. The specimens had the same mix design, ilmenite aggregates and Portland cement as the actual structure. The specimens were made and tested in the Structural Laboratory of Nanjing South East University of China. All the

specimens were cured for 28 days in a controlled room in accordance with the code requirement. In addition to the cubic specimens, 70mm diameter core samples were drilled from the heavy concrete slab in the Unit 2 Reactor Building. The detailed parameters of the specimens are as follows:

a) Batch 1: Epoxy coated specimens as the actual structure

Design cubic strength: 42 MPa (cylinder strength of 35 MPa)
Date of batching: March 29, 2003
Date of epoxy applied: Aril 30, 2003 (age of 32 days)
Date of elevated temperature start: May 11, 2003 (age of 43 days)

Table 1 shows the test program for the batch 1 specimens.

b) Batch 2: The heated specimens without coating

Design cubic strength: 42 MPa (cylinder strength of 35 MPa)
Date of batching: April 11, 2003
Date of elevated temperature start: May 11, 2003 (age of 29 days)

Table 2 shows the test program for the batch 2 specimens.

c) 70mm Diameter Core Drill Samples

Design cubic strength: 42 MPa (cylinder strength of 35 MPa) with Epoxy coat
Age of concrete: > 2 years
Date of elevated temperature start: May 11, 2003

Table 3 shows the test program for the core drill specimens.

3. TEST RESULTS

In the presentation of the test results, the compressive strengths are cubic strengths based on 150mm cubes. In case of the 70mm diameter core drill samples, the compressive strengths (load/area) were used directly without considering the size effect because the strength increase for small size specimen has been offset by the strength reduction caused by the dynamics of drilling.

The specimens were heated in two electrical ovens with temperature controlled at 100 ^{o}C and 150 ^{o}C respectively. The specimens were removed from the ovens immediately before the tests and wrapped with blanks to maintain the temperature.

The specimens were tested in a MTS test machine in the Laboratory of Nanjing South East University in accordance with the Chinese standards [5] for concrete testing.

Figures 5 to 8 shows strength-time curve for the four groups of tests (coated specimens heated to 100 ^{o}C and 150 ^{o}C and un-coated specimens heated to 100 ^{o}C and 150 ^{o}C respectively).

Based on the test results, the following findings were observed:

- Up to 150 ^{o}C, the specimens did not exhibit indication of any color change or surface cracking.
- Elevated temperature reduces the compressive strength of concrete. The maximum strength reduction occurs within the first day of the heating. This finding is in agreement with Ref. 4 for normal weight concrete which states that the maximum strength reduction can occur in as little as 2.5 hours and up to 3 days.

- For the coated specimens, the maximum strength reduction is 44%, and for the uncoated specimens is 26 %. Part of the reason for this is due to that the bearing surface of the coated specimens, though coating was removed for some of the specimens, provided less constraint during the testing.
- After first day of heating, the strength begins to continually increase, which partially recovers the strength loss during the first day of heating. At 15 days of heating, the strength loss reduced to 28% (100^{o}C) and 16% (150 ^{o}C) for the coated specimens, and 17% (100 ^{o}C) and 26% (150 ^{o}C) for the uncoated specimens. Though there are no tests after the 15 days of heating, it can be predicted from the curves that the strength recovery trend continues after 15 days.
- The one-side heated specimen tests shows a 25% strength loss for 100 ^{o}C tests and 34% strength loss for 150 ^{o}C at 15 days for coated specimens. The temperature gradient does not indicate an obvious difference from the uniformly heated specimens.
- All the heated core drilled samples were coated with the epoxy specified for the reactor building. The test results show a mean strength of 65 MPa for unheated samples. For the heated samples, the mean strength is 34.2 MPa at 100 ^{o}C and 58.2Mpa at 150 ^{o}C for 15 days of heating, which is 53% and 90% of the un-heated specimens.
- The results for the heated core drill samples and one-side heated cubic samples are very random as a result of the bearing surface problem caused by the coating.
- The epoxy coating protects the concrete from reduction in strength due to continuous exposure to elevated temperatures as it prevents/ minimizes the loss of water from the concrete to the atmosphere. The fact that the coated specimens have more strength reduction may be due to the condition of the bearing surface of the specimens with the test machine. It is considered that the coated surface has less friction and thus has less restraint from the test machine. For those coated specimens with the coat chipped on the test bearing surfaces, the chipped surface was not flat and smooth and that may have caused reduction of bearing contact area and consequently lowered the strength of the specimens.

4. CONCLUSIONS

The final concrete surface temperatures of Qinshan Phase 3 Unit 1 and 2 have had been successfully brought to below the alarm temperature of 65 ^{o}C through the improved insulation and cooling system. However, the following conclusions were made regardless of the above fact:

1. Based on the test results, the elevated temperatures reduced the compressive strength of heavy concrete with mix of ilmenite aggregates. The strength loss occurred within the first day of the heating. After the first day, the strength recovered up to the 15 days of heating and is expected to continue the recovery after then. Based on the 15 days of heating test results, the maximum strength loss was 17% for uncoated specimens and 28% for coated specimens (with the unfavorable effect of coating on the bearing faces).

2. The Qinshan R/B vault structural concrete mix was conservatively designed. The batch plant specimen tests show that the actual concrete of the vaults were over 25% higher than the required design strength. The actual strength of the core drill samples also reached cylinder strength of 55Mpa (0.8 x 65 MPa). Hence even with a loss of 28% in concrete strength loss at 15th day after heating, the concrete had actual strength in the range of 39.6 MPa that still exceeded the design requirement of 35 MPa.

3. The reduction in strength of the heavy concrete has not affected the actual structure. The reason for this was as follows: The maximum strength loss occurred within the first day of heating. For the worst cases (coated the specimens), the maximum reduced strengths were slightly below the design strength of 42MPa (Fig. 5 and Fig. 6). However, these maximum strength deductions included the unfavorable effects of coating on the bearing faces during the testing, and as well were based on testing of fresh concrete specimens (43 days). For the Qinshan Project, the concrete was a minimum two years old and hence at a greater strength prior to exposure to the elevated temperature. Moreover, at the time the maximum strength reduction occurred, the structure was not under the governing (accident) load combination and therefore did not undergo any temporary or permanent damage.

4. Based on the above test results, it is concluded that continuous exposure up to 150 °C of the primary heat transport pump slabs, composed of ilmente aggregate and Portland cement concrete mix, will not affect its required functional performance. However, improvements on the feeder cabinet insulation and the concrete cooling system should continue to remain as the first priority in reducing the temperature loads on the concrete around the feeder cabinet

5. In order not to interrupt the plant operation and adversely affect plant capacity factors, it is recommended that the specified alarm temperatures be raised in areas of the internal structure, for both the heavy concrete and the normal concrete elements, which have a high probability to be subjected to elevated temperatures. Additionally, it is recommended that in future, the design of the structures, which have a high probability to be exposed to continuous elevated temperatures, should be performed based on the reduced strength in accordance with the specified alarm temperatures.

5. REFERENCES

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2. ACI Committee 216 (1981), “Guide for Determining the Fire Endurance of Concrete Elements”, Concrete International: Design and Construction, Vol.3, No.2, February 1981, pp. 13-47

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4. J.A. Sato and F.J. Vecchio (2003), “Performance of Concrete at elevated temperatures – analysis of Generic structural members”, Report of COG02-4063

5. China National Standard GBJ 81-85, “Normal Concrete Property Test Method”, 1986

6. ACKNOWLEDGEMENTS

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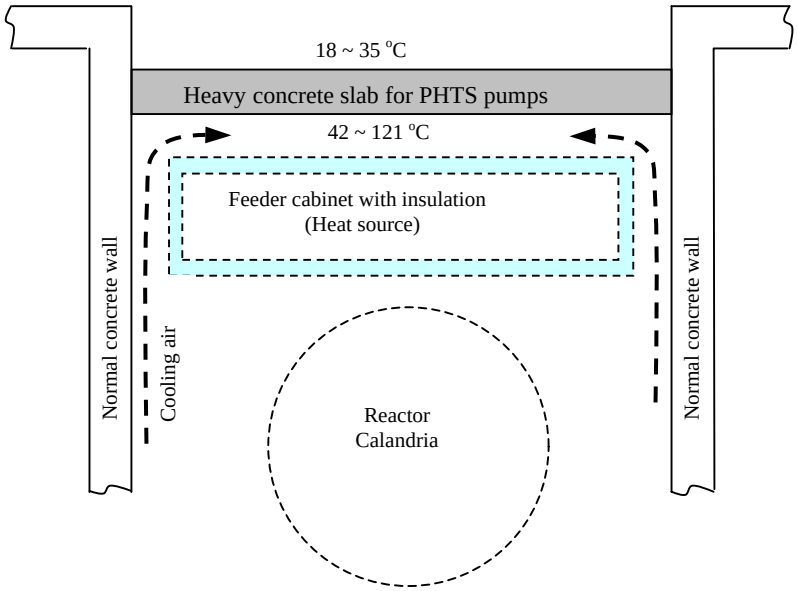

Figure 1. Qinshan Phase 3 CANDU 6 Reactor Vault Structure And Temperature

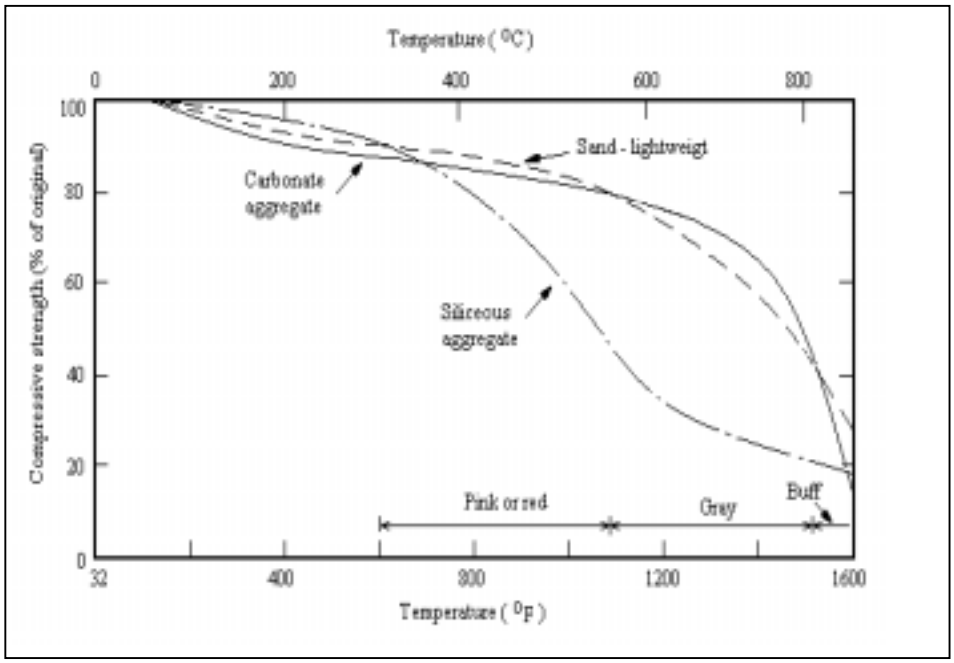

Figure 2. Compressive Strength of Normal Concrete At High Temperature [2]

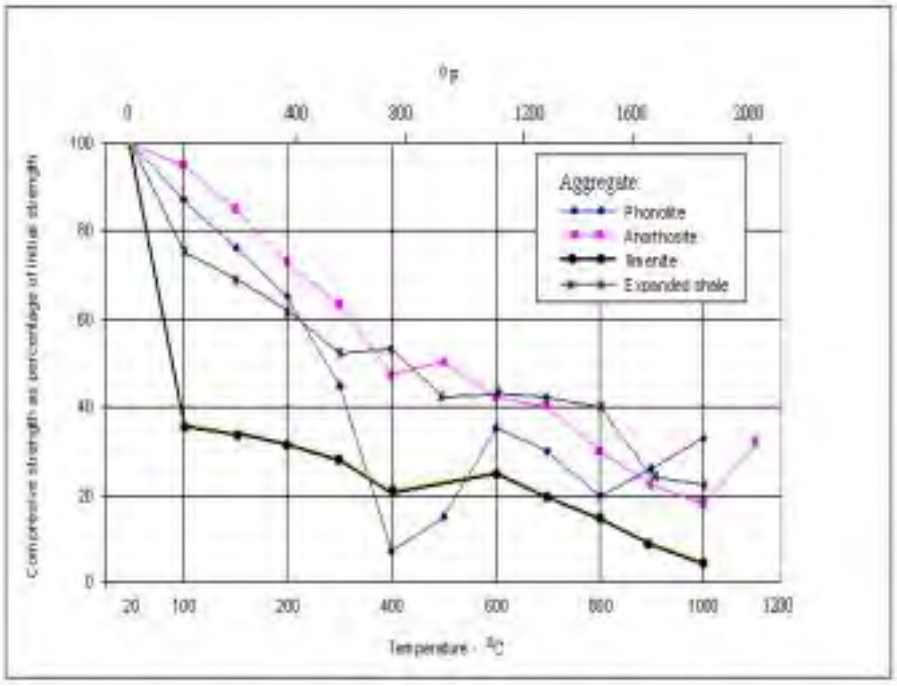

Figure 3. Strength of High-Alumna Cement Concrete made with Different Aggregates as a Function of Temperature [3]

Figure 4. Specimens tested

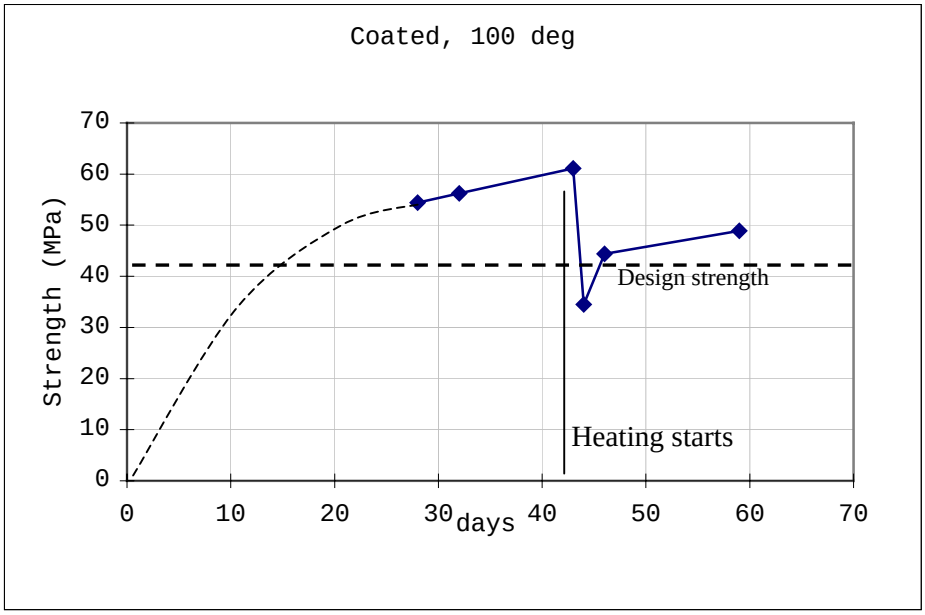

Figure 5. Strength-Time, Coated Specimens with 100 ^{o}C.

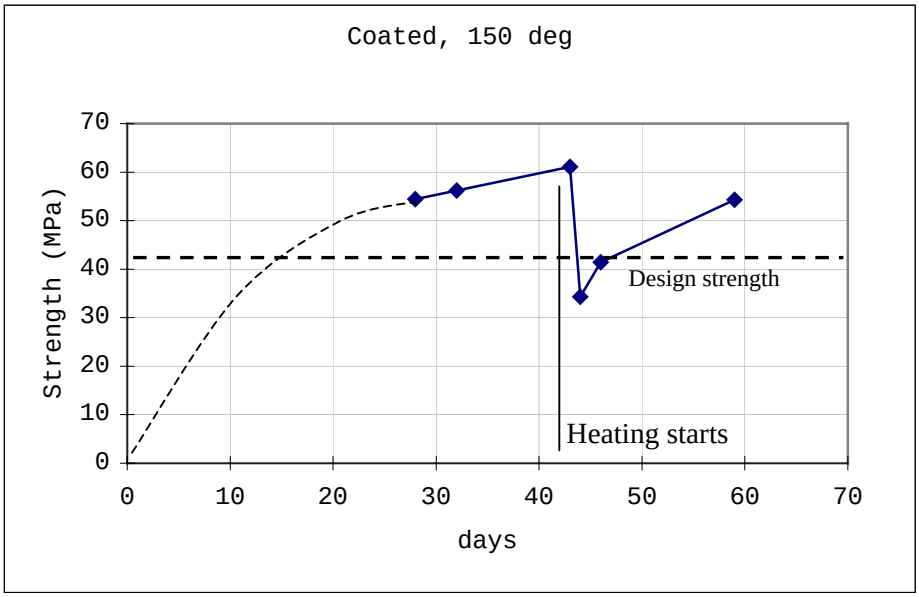

Figure 6. Strength-Time, Coated Specimens with 150 ^{o}C.

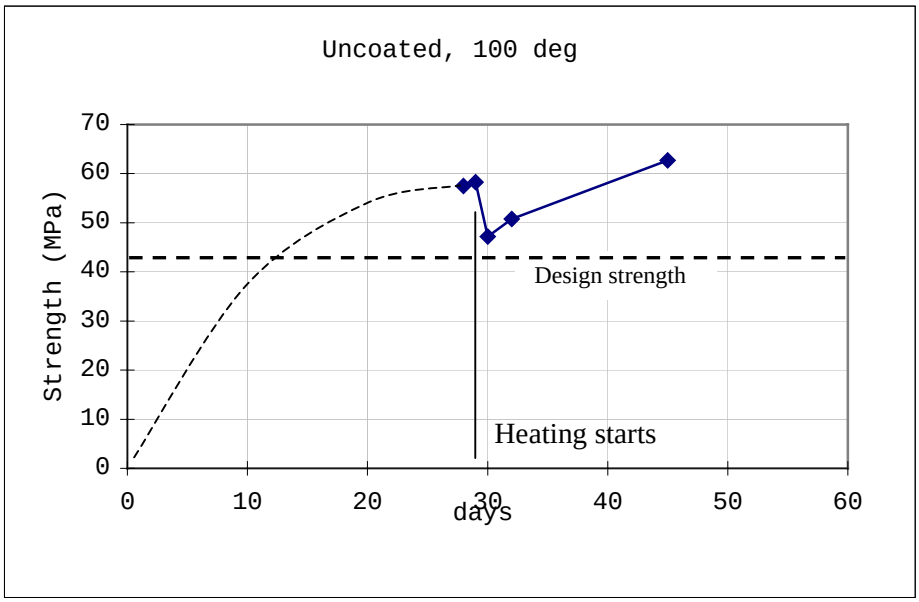

Figure 7. Strength-Time, Un-Coated Specimens with 100 ^{o}C.

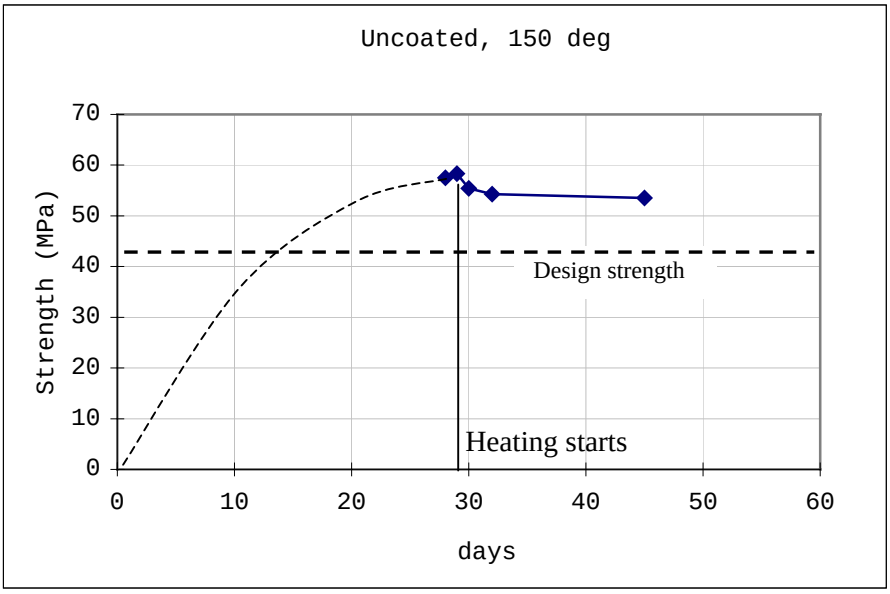

Figure 8. Strength-Time, Un-Coated Specimens with 150 ^{o}C.

Table 1. Specimens for Batch 1 Testing

DURATION OF HEATING (DAYS)	100 °C		150 °C		ROOM TEMPERATURE (NO COATING)
	UNIFORM HEATED	ONE SIDE HEATED	UNIFORM HEATED	ONE SIDE HEATED	
1	2 X 3		2 X 3		4 X 3
3	2 X 3		2 X 3		
15	2 X 3	2 X 3	2 X 3	2 X 3	

Table 2. Specimens for Batch 2 Testing

Duration of heating (days)	100 °C (Uniform heating)	150 °C (Uniform heating)	Room temperature
1	3	3	2x 3
3	3	3	
15	3	3	

Table 3. Core Drill Specimen Testing

Duration of heating (days)	100 °C (Uniform heating)	150 °C (Uniform heating)	Room temperature
15	4	4	3

Figure 9 Qinshan Phase 3 CANDU Power Plant