

Study on Protective Concrete for Severe Accident Conditions

H. H. Abrishami,¹ M. Elgohary¹, D. Mitchell², W. D. Cook², and S. Mindess³

¹ Atomic Energy of Canada Ltd., Mississauga, Ontario, Canada, L5K 1B2

² Department of Civil Engineering and Applied Mechanics, McGill University, Montreal, Quebec, Canada

³ Department of Civil Engineering, University of British Columbia, Vancouver, British Columbia, Canada

E-mail of corresponding author: abrishamih@aecl.ca

ABSTRACT

The overall purpose of this experimental study is to provide a practical method to protect the containment structure in the event of a severe accident. A high-performance concrete is used and must have characteristics that minimize the generation of combustible gases such as hydrogen and carbon monoxide, while meeting the design requirements to protect the containment structure during a severe accident.

The influence of temperature effects on the compressive strengths and stress-strain relationships of the concrete was investigated at different temperatures. Additional testing was carried out to study the influence of residual properties of the concrete after heating to the target temperatures and then cooling to room temperature. The residual strength testing gave about the same compressive strengths and similar stress-strain relationships as the corresponding temperature tests.

A spill test, using molten pig iron heated to temperature representing the molten core, was carried out to simulate the local effects of high-temperature molten metal on the concrete.

INTRODUCTION

During a severe accident, Molten Core-Concrete Interaction (MCCI) may occur when molten core debris breaches the calandria vessel and contacts concrete surfaces, whereby the thermal and chemical properties of the corium contribute to the degradation of the concrete. The earliest phase of MCCI is characterized by very-high-temperature molten metal and oxide pouring from the calandria vessel and settling as a pool on the concrete surfaces of the vault floor. The molten material can result in spalling or fragmentation of the concrete near where the corium first contacts the concrete. As the corium settles on the concrete surface, the melt begins to react chemically with the concrete as the melt penetrates cracks and fragments produced on the initial contact, generating various gases including carbon monoxide and combustible hydrogen.

It has long been known that the mechanical properties of concrete such as the strength and modulus of elasticity decrease significantly once the concrete temperature exceeds about 300 °C [1]. There are four principal mechanisms which cause concrete to deteriorate at high temperatures including:

- Progressive deterioration of the cement;
- Deterioration of the aggregate;
- Thermal incompatibility between paste and aggregate; and
- Explosive spalling

The cement paste loses water continuously as the temperature increases, and is completely dehydrated by about 850 °C. This is accompanied by a large increase in total porosity and permeability of concrete [2,3]. The effect of temperature on aggregate properties depends very much on the particular mineral types involved. At temperatures above about 600°C, some calcareous aggregates (calcite, dolomite, magnesite) will dissociate to form CO₂ and an oxide. In the temperature range 1200-1300°C some igneous rocks show degassing and expansion. The temperatures at which aggregates melt also vary widely, from basalt at about 1060°C to quartzite at about 1700°C [1,4]. Thus the thermal behavior of concrete is very sensitive to the precise nature of the aggregate(s) used, particularly since aggregates make up about 70% of the volume of high performance concretes. Hydrated cement paste and common aggregates have quite different coefficients of expansion [1]. What is clear is that as the temperature increases from ambient to over 1200°C, the differences in thermal coefficients of the cement and the aggregates, and the other volume changes that take place, will lead to considerable cracking (both micro and macro cracks) in the concrete.

Probably the most severe and dangerous form of damage during a potential spill of molten corium onto the concrete is explosive spalling of the concrete. All concrete contains water in some form; when the concrete is

heated, the water vaporizes, and as the temperature increases, the pore pressure (vapour pressure) increases. If the concrete is very dense, as is the case with high performance concrete, and if the rate of temperature increase is rapid, the internal stresses induced can become large enough to cause explosive spalling of the concrete surface [5-8]. Gawin et al. [9] have developed a model that allows for risk assessment of thermal spalling, considering both effects of pore pressure build-up and the accumulated strain energy, together with thermo-chemical material degradation and cracking.

This paper presents the characteristics and performance of the special concrete, developed by AECL[®], to provide protection during a severe accident.

TESTING PROGRAM

The three different phases of the testing program are:

1. Choosing materials and developing a mix design to provide the required properties of the concrete to be used in the study.
2. Testing of concrete cylinders under high temperatures to determine the influence of high temperature on the compressive stress-strain characteristics and strength.
3. Carrying out a spill test to determine the influence of spillage of high-temperature molten metal on the concrete to simulate the local effects of the molten core material contacting the concrete.

Concrete specimens studied, tested and presented in this paper are labeled as C1 specimens since similar testing program have been carried out for the specimens containing polypropylene fibers.

TESTING OF CONCRETE CYLINDERS UNDER HIGH TEMPERATURES

Two types of testing under high temperatures were carried out. For the cases where the 75 mm diameter by 150 mm long cylinders were tested in the “hot” condition (T series), each cylinder was removed from an oven and quickly placed into an insulated sleeve to minimize heat lost during the compressive testing.

For the residual strength testing (R series), the 75 mm diameter by 150 mm long cylinders were subjected to the same heating cycle as for the T series, but then were allowed to cool before the compressive testing. This series investigates the stress-strain characteristics of the concrete after having been subjected to different temperature regimes.

Figure 1 shows the oven with cylinders heated to 800°C. Once the desired temperature was reached, the temperature was held constant for at least 2 hours. Figure 2 shows the compressive test setup in the 4500 kN capacity MTS rock-testing machine. The testing machine is very stiff and is computer controlled. The setup is for the 75 mm diameter by 150 mm long cylinders. The cylinders are placed between the 2 – 12.5 mm thick steel plates that are preheated to minimize heat loss during the compressive testing. Two 100 mm diameter by 95 mm long cylinders above and below the steel plates act as thermal insulators to protect the testing apparatus. Spherical ball joints above and below the test specimen ensure that the test cylinder is subjected to pure axial compression with no shear. The 334 kN load cell provides an accurate reading of the load applied, with the pressure cell of the test machine providing a second load reading.

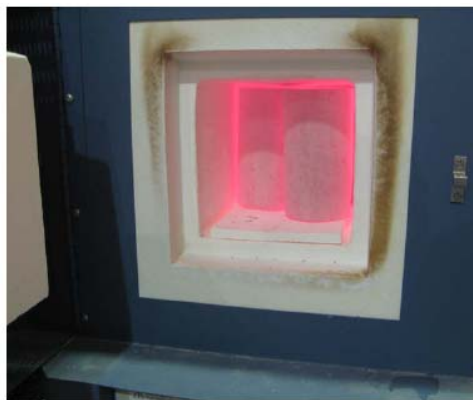


Figure 1: Oven with cylinders heated to 800°C

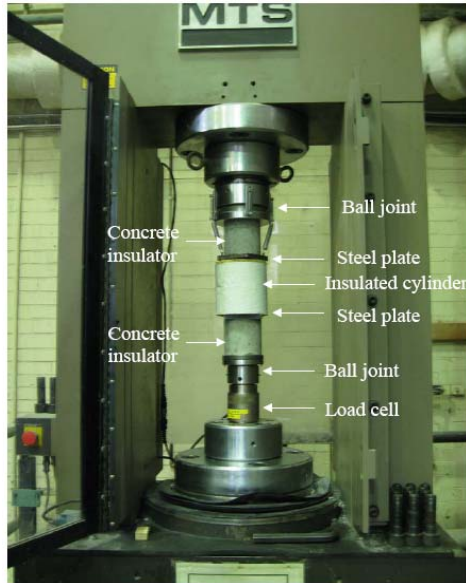


Figure 2: Compressive testing setup in MTS rock testing frame

C1 Specimens in the T Series of Tests

Figures 3 and 4 show the measured temperature-time history determined from a control cylinder placed in the oven and the stress-strain relationships determined from testing the 5 sets of 3 cylinders comprising the T series for the C1 concrete.

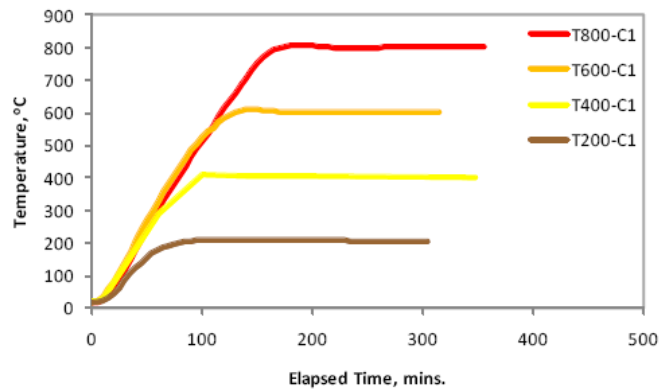


Figure 3: Measured temperature-time measurements taken on the control cylinder for the C1 series

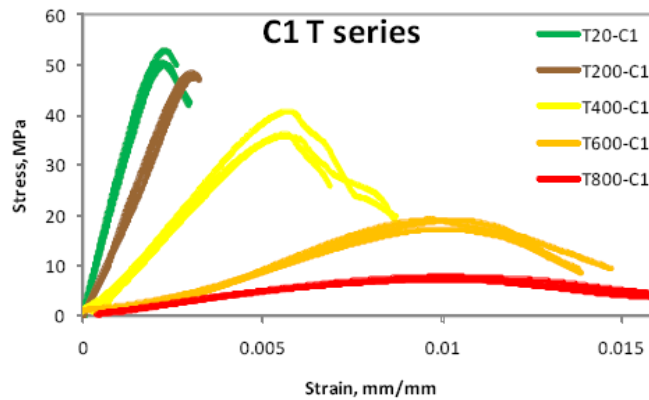


Figure 4: Measured Compressive stress-strain relationships for the C1 cylinders tested in the T series

Figure 5 shows the stress ratio, f'_{ct}/f'_c , of the compressive strength at temperature, T, divided by the strength at 20°C for the C1 concrete specimens.

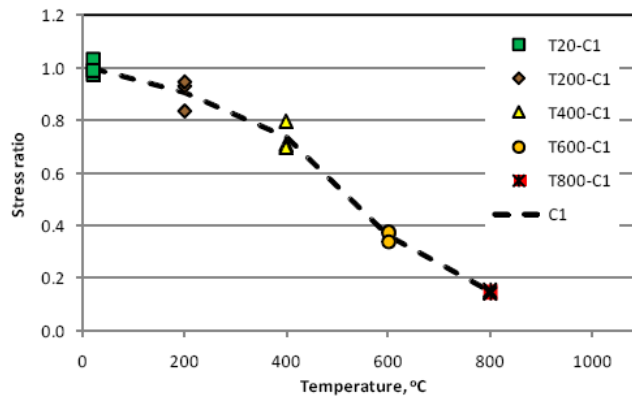


Figure 5: Stress ratio, f'_{ct}/f'_c , for the C1 cylinders tested in the T series

C1 Specimens in the R Series of Tests

Figure 6 shows the measured temperature-time history determined from a control cylinder placed in the oven and the stress-strain relationships determined from testing the 5 sets of 3 cylinders comprising the R series for the C1 concrete. The heating period lasted about 6 hours followed by a gradual cooling period to 20°C. Figure 7 gives the compressive stress-strain relationships for the C1 compressive cylinders tested in the R series.

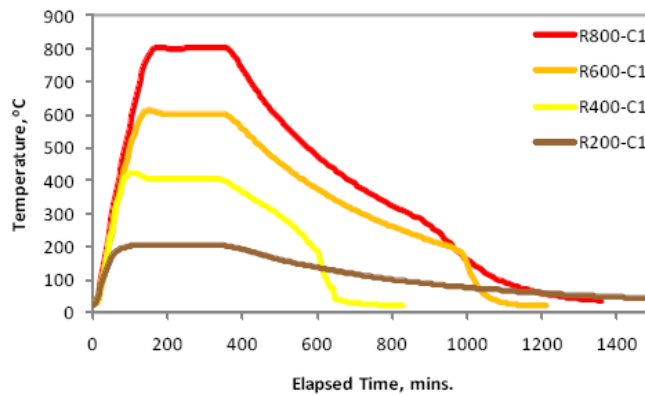


Figure 6: Measured temperature-time measurements taken on the control cylinder for the C1 series

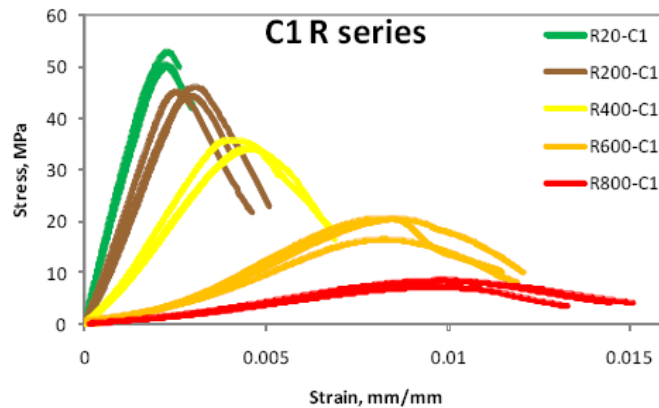


Figure 7: Measured Compressive stress-strain relationships for the C1 cylinders tested in the R series

Figure 8 shows the stress ratio, f'_{ct}/f'_c , of the compressive strength at temperature, T, divided by the strength at 20°C for the C1 concrete specimens tested in the R series.



Figure 8: Stress ratio, f'_{ct}/f'_c , for the C1 cylinders tested in the R series

SPILL TEST

The spill test was carried out in the Metals Processing Centre in the Department of Mining and Materials at McGill University. The spill tests involved first heating 8 kg of pig iron to a temperature of 1300 °C in a crucible located in the induction furnace. Spill test specimen contained two thermocouples identified as TC1 and TC2 located 10 mm and 35 mm below the bottom of the spill cavity respectively. A temperature probe was used to determine when the desired temperature was reached. The pig iron was preheated in a crucible inside the furnace. The spill test specimen was confined by steel collars during the spill testing.

Figure 9 shows the pouring of the molten pig iron from the crucible into the spill test specimen. Figure 10 shows the reaction between the molten metal and the concrete just after placing the pig iron into the spill test specimen and Fig. 11 shows two different stages of cooling and hardening of the molten pig iron.



Figure 9: Pouring of molten pig iron from crucible into spill test specimen



Figure 10: Reaction between molten pig iron and concrete



Figure 11: Cooling and hardening of molten pig iron

Concrete Spill Test Results

It is noted that during the placement of the molten pig iron into the spill test specimen the specimen cracked and experienced leakage of water through the cracks (see Fig. 12) even though the specimens had been air dried for two months before testing and the cavities were preheated heated to remove moisture near the spill surface prior to testing.



Figure 12: Water seeping out of cracks in spill test specimen

Figure 13 shows the measured temperatures in thermocouples TC1 and TC2 located a distance of 10 mm and 35 mm below the bottom surface of the spill test cavity. The maximum measured temperature was 391°C at a time of 728 seconds after spilling the molten pig iron. Figure 14 gives a more detailed plot of the temperature versus time variation during the early stages of the spill test. It is evident that there is a slight time lag between the temperatures recorded at TC2 compared to those measured at TC1.

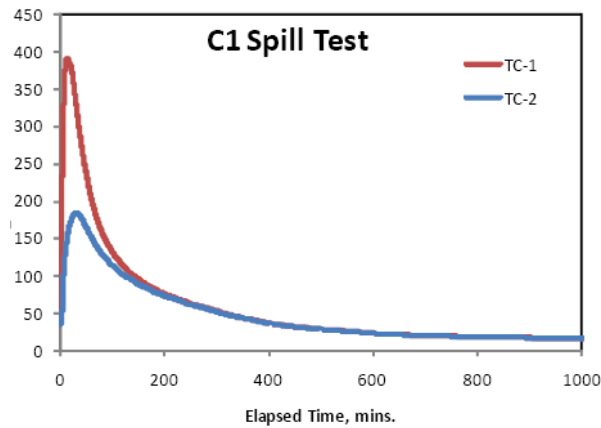


Figure 13: Variation of temperature with time during the spill test for spill test specimen C1

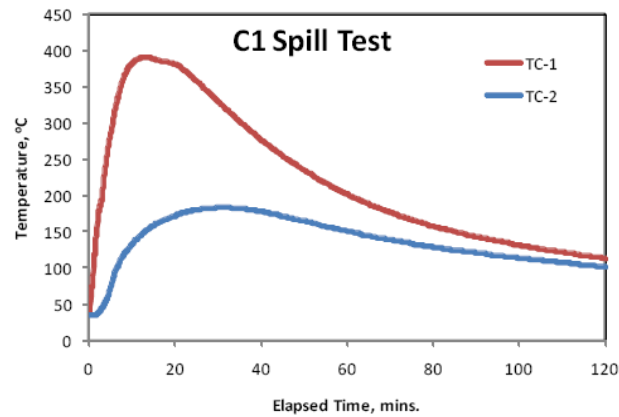


Figure 14: Temperature versus time variation during the first two hours for spill test specimen C1

The spill test specimen was cut into half using a diamond concrete saw. Figure 15 shows the two halves of the spill test specimen C1. The hardened block of pig iron was removed to observe the damage done to the concrete. The concrete suffered ablation on the bottom surface and to the sides of the spill test cavity. The maximum measured ablations on the bottom surface and on the side surfaces were 10 mm and 5 mm, respectively.



Figure 15: View of spill test specimen C1 after cutting in half

CONCLUSION

The following conclusions were made from this experimental program:

1. The effect of increasing the temperature results in reductions in the concrete strength, with about 15% of the strength remaining at a temperature of 800 °C.
2. The effect of increasing the concrete temperature results in reductions in the concrete stiffness.
3. The effect of increasing the concrete temperature results in increases in the strain at which the concrete reaches its maximum strength.
4. The residual strength testing (R series) gave about the same compressive strengths and similar stress-strain relationships as the corresponding temperature tests (T series).
5. The spill tests, using molten pig iron heated to 1300°C demonstrated that there was very little damage to the C1 concrete specimens. The maximum ablation measured was 10 mm.

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