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Effects of Aggregate Type on the Thermal Conductivity of Normal-Density and High-Density Concrete for Nuclear Containment Structures

Christian Agih[1], Nathan Downie[2], Ean Cross[3], Nathan Villar[4], Homayoun Abrishami[5]

[1] Quality Lead, Bird Construction, Ottawa, Canada (Christian.agih@bird.ca)
[2] Project Manager, Bird Construction, Ottawa, Canada (nathan.downie@bird.ca)
[3] Project Coordinator, Bird Construction, Ottawa, Canada (ean.cross@bird.ca)
[4] Project Coordinator, Bird Construction, Ottawa, Canada (nathan.villar@bird.ca)
[5] Concrete Expert, Nuvia Canada, Toronto, Canada (homayoun.abrishami@nuvia.com)

ABSTRACT

The nuclear industry in Ontario continues to grow with initiatives to support a clean energy future. Many new nuclear projects are investigating new technologies in modern nuclear design, tackling challenges to provide safe and clean energy for future generations. Thermal loads are one of the critical load cases that should be considered in the analysis and design of new nuclear projects in Canada and globally. Thermal conductivity is one of the key elements in the thermal analysis of concrete structures, particularly in nuclear structures exposed to high temperatures. CSA N287.3 provides requirements to limit maximum temperatures in nuclear containment structures for both normal operations and accidental conditions, CSA N287.3 (2014). This paper assesses the aggregate type's effect on the thermal conductivity of both normal-density and high-density concrete as part of containment in nuclear structures. As a nuclear code requirement, high-density concrete is used in nuclear facilities to improve shielding performance. Concrete is a heterogeneous multiphase material with relatively inert aggregates held together by the hydrated Portland cement paste. Thermal conductivity is critical in understanding the radiation-shielding concrete used in nuclear facilities. Low thermal conductivity is usually advantageous for nuclear power plant concrete because it provides heat isolation; however, it can have a negative effect at extreme temperatures in nuclear vessels, as cooling from the exterior is practically impossible. The higher the thermal conductivity of the concrete used to house the nuclear reactor core, the lower the risk of an explosion. This study examines the improvement of thermal conductivity using diverse types of aggregates (such as granite, magnetite, and hematite). The thermal conductivity of these concrete mixes was evaluated utilizing the guarded hot plate method (ASTM C177) to measure the steady-state heat flux and the thermal transmission properties. The overall results of this study show that the type of aggregate has a major effect on the thermal conductivity of concrete.

INTRODUCTION

The reliability of nuclear containment structures heavily influences the safety and performance of nuclear facilities. Concrete is commonly used as the shielding material against radiation exposure in these structures. However, due to the high thermal loads in the containment areas, concrete plays a critical role in its ability to dissipate or retain heat, particularly its ability to dissipate heat during high operating temperatures or an accidental event. The concrete's ability to transfer heat depends on its thermal conductivity, which can be heavily influenced by aggregate type.

In nuclear containment design, thermal conductivity plays a crucial role in radiation shielding; a lower thermal conductivity enhances the structure's effectiveness in containing radiation. On the other hand, a low thermal conductivity can cause excessive localized heat; this increases the risk of concrete cracking due to thermal stress and reduces the structural integrity, resulting in containment failure. Concrete's low thermal conductivity compared to steel is another engineering advantage that can create extremely stable conditions for a nuclear reactor/vessel. The catastrophic consequences of the nuclear disaster that occurred at Fukushima in Japan a few years ago are still being felt. The massive concrete container serves as an insulating vessel when the reactor's temperature is quickly increased and its internal cooling system is turned off, increasing the risk of an explosion.

The steady-state and transient methods are the two primary techniques for measuring thermal conductivity. Concrete density, cementitious material, aggregate, temperature, and moisture content affect thermal conductivity. This research aims to review the effect of different aggregate types on the thermal conductivity of concrete using the steady-state method.

About 60–80% of the volume of concrete is made up of aggregate. Using different kinds of aggregate can alter the concrete's thermal conductivity value. Increasing the coarse aggregate volume percentage while maintaining the same sand ratio increases the concrete's thermal conductivity value. I. Asadi et al., 2018. Concrete containing aggregates with lower thermal conductivity is less conductive, while concrete with higher thermal conductivity is more conductive. ("Neville AM. Properties of Concrete. UK: Longman, 1995.," n.d.)

This study's result highlights thermal conductivity's effect on normal and high-density concrete while focusing on the effects of aggregate type used in each mix. For this study, three mixes were tested for thermal conductivity using the guarded hot plate method, as per ASTM C177. When testing the mixes, a variation of mixes was used, 35MPa (normal density) and 45MPa (high density), with aggregate sizes of 20mm and varying aggregate types. Two main types of aggregates were used for Mix 1 and Mix 2, with the coarse and fine aggregates being a blend of primarily gneiss and granite. 20mm and 14mm aggregate sizes were used for Mix 1 and Mix 2, respectively. As for Mix 3, a blend of hematite and magnetite was used for the 20mm coarse aggregate, and the same blend of aggregate type was used to produce the fine aggregate. This aggregate was utilized to produce a higher-density mix. The results aim to provide a concrete mix that meets high thermal conductivity and requirements for strength and temperature differential properties as per CSA A23.2 (2020) and CSA N287.5 (2020).

THEORY OF METHODOLOGY

Thermal Conductivity refers to the amount of heat transferred through a material. Measuring the change in temperature across the material. Thermal conductivity is measured under steady-state conditions, constant temperature distribution, and stable heat flow. The general equation for steady-state heat flow can be described as:

$$Q = \frac{\lambda \times \Delta T \times A}{\Delta x} \tag{1}$$

Where Q is the rate of heat flow in watts, λ Represents the thermal conductivity of the material in watts per meter kelvin, A is the cross-sectional area perpendicular to heat flow in square metres, ΔT is the change in temperature across the material in Celsius, and Δx Represents the thickness of the material in metres.

This equation represents Fourier's Law of Heat Conduction, which describes the amount of heat energy that can be transferred through a unit thickness of a material per unit time Q. Where Q is proportional to the thermal conductivity, temperature gradient, and cross-sectional area, this displays the theory that materials with low values of thermal conductivity conversely have reduced heat flow compared to materials with high thermal conductivity. For this research, thermal conductivity in equation (1) is the effective thermal conductivity of a heterogeneous material where heat transfer occurs through conduction, convection and radiation.

METHODOLOGY

The testing procedure carried out for this research on the thermal conductivity of concrete is in conformance with ASTM C177. This standard represents the methodology for steady-state heat-flux measurements and thermal transmission properties by the Guarded-Hot-Plate Apparatus (GHP). The apparatus used for testing is shown in Figure 1. This method describes one-dimensional heat transfer where the apparatus used in this test method is under vacuum conditions. The apparatus consists of a hot plate that acts as the heater, sandwiched between two test specimens and enclosed by cold surface assemblies enclosing the test area. Additional guards are placed horizontally between specimen ends to ensure vertical heat flow in one dimension. For this research, two approximately 300 mm x 300 mm x 50 mm cast and cured concrete plates were used as specimens during testing. The specimens were conditioned at 22 ± 5 °C and 50 ± 10% relative humidity until a mass change of less than 1% was observed over 24 hours. The specimens were placed between the hot plate, creating an upper and lower sample. Thermocouples were placed on all guarded surfaces and metering areas.

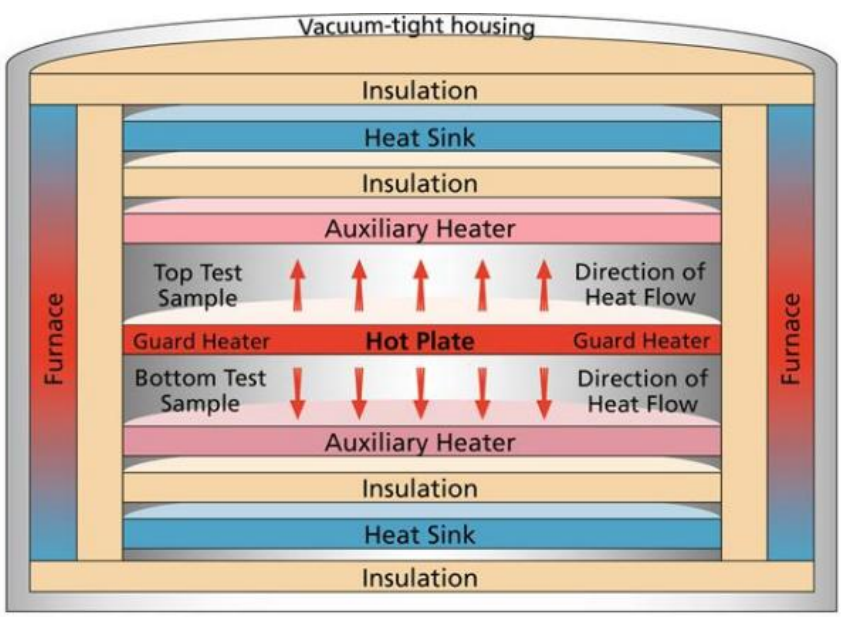

Figure 1. Schematic diagram of Guarded Hot Plate Apparatus

Temperature equilibrium was obtained and maintained during testing for at least 120 minutes. The required difference in temperature between each sample is between 6-8 Kelvin, with the metering area

heater power being adjusted to meet this set point. Temperature measurements were collected on each of the hot and cold sides, and the power to the metering area heater was measured. Measurement was taken at 20, 65, 100 and 120 Degrees Celsius setpoints during heating and cooling. Silicone rubber interface sheets provided better thermal contact between the sample instrument plate and surface-mounted thermocouples. The results of thermal conductivity and thermal resistance were calculated using equations (2) and (3), respectively:

$$\lambda = \frac{Q \times \Delta x}{\Delta T \times A} \tag{2}$$

$$R = \frac{A \times \Delta T}{Q} \tag{3}$$

Where λ Is the apparent thermal conductivity in Watts per meter Kelvin, Q is the power dissipation in the metering heater in watts, Δx Represents the total thickness of both test specimens in meters, A is the area of the metering surface in square meters, ΔT is the change in temperature between both specimens in Degrees Celsius, and R is the thermal resistance in meters squared Kelvin per Watt.

RESULTS & DISSUCSSION

Table 1: 28-day Compressive Strength and Density for Tested Concrete Mixes

Mix #	Mix Code	Aggregate Type	Avg. 28-Day Strength (MPa)	Avg. Dry Density (kg/m3)
1	ES435201V	Coarse: 20mm Gneiss & Granite Fines: Granite & Gneiss Sand	38.6	2242.88
			37.7	2275.22
			36.3	2223.58
2	ES435131V	Coarse: 14mm Gneiss & Granite Fines: Granite & Gneiss Sand	41.2	2225.34
			39.6	2239.51
			40.5	2219.70
3	145800V	Coarse: 20mm Hematite and Magnetite Fines: Hematite and Magnetite Sand	48.8	3610.97
			48.0	3657.25
			43.0	3635.67

Table 1 highlights the average 28-day compressive strength for each subjected mix tested for thermal conductivity. Mixes 1 and 2 were designed to achieve a minimum of 35 MPa, and mix 3 to obtain 45 MPa compressive strength. The compressive strength was tested to ensure proper control of design requirements was met before beginning to test the thermal conductivity of each of the respective mixes. Average dry cylinder densities were measured, as they play a critical role in the thermal conductivity of each mix.

Table 2: Heating and Cooling Thermal Conductivity Results for Mixes 1-3

Sample	Mean Temperature	Thermal Conductivity	Thermal Conductivity	Percent Decrease (Cooling - Heating)
	ºC	W/m·K	W/m·K	
	Setpoint	Heating	Cooling	
ES435201V	20	1.187	0.987	-17%
	65	1.246	1.011	-19%
	100	1.38	1.018	-26%
	120	1.135	1.059	-7%
	150	1.121	1.121	NA
ES435201V	20	1.241	1.003	-19%
	65	1.317	1.04	-21%
	100	1.318	1.068	-19%
	120	1.239	1.116	-10%
	150	1.158	1.158	NA
145800V	20	1.75	1.587	-9%
	65	2.029	1.702	-16%
	100	2.025	1.785	-12%
	120	1.934	1.843	-5%
	150	1.91	1.91	NA

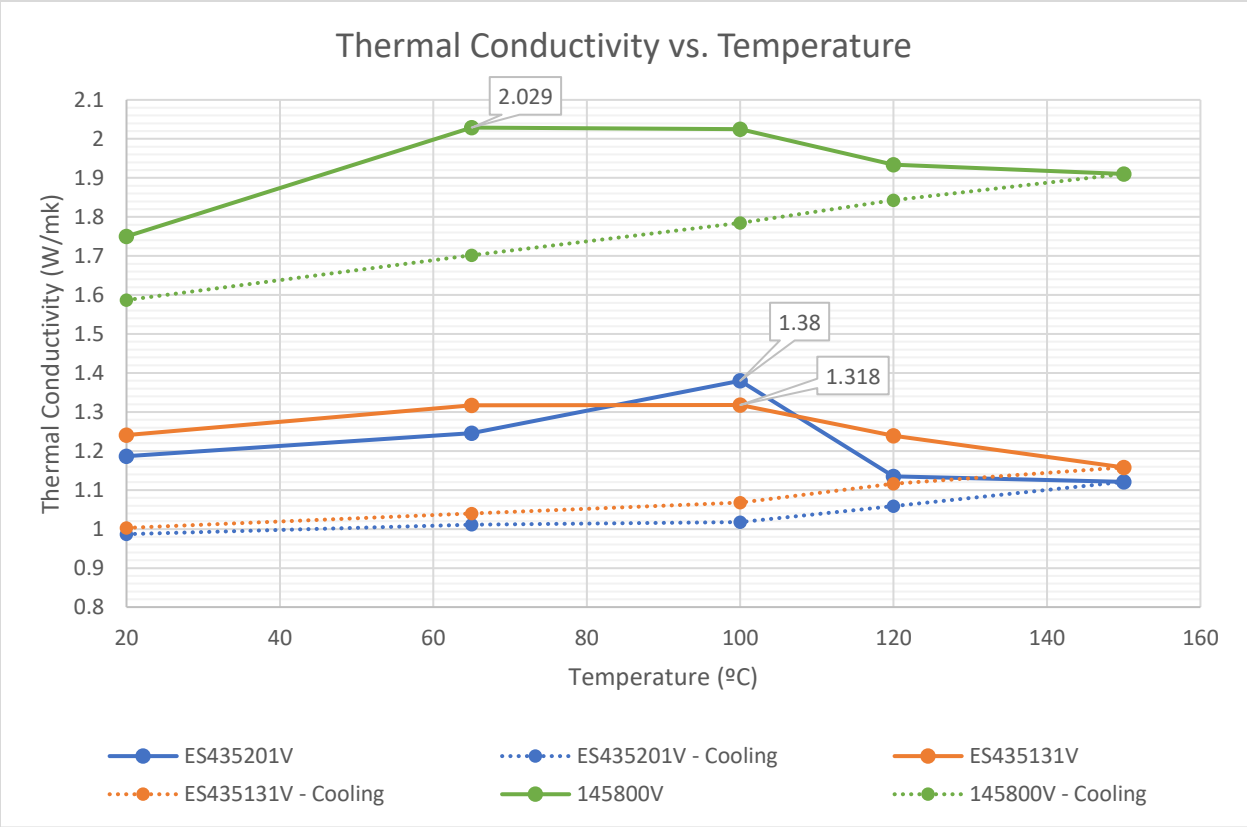

Figure 2. Heating and Cooling Thermal Conductivity Results for Mixes 1-3

The collected results for the thermal conductivity of the three sampled mixes are summarized above, and they are presented numerically and graphically in Table 2 and Figure 2, respectively. Measurements were performed during heating and cooling. Differences in the measured apparent thermal conductivity were observed after the sample was heated to a 150°C mean temperature, as can be seen below in Table 2 and Figure 2.

The result shows that Mix 1 with granite blend with gneiss aggregate 20mm size stone had a max thermal conductivity of 1.38W/m-k as seen in Table 2 above. While Mix 2 with the same aggregate type but a 13mm size stone had a maximum thermal conductivity of 1.312W/m-k, there was no significant difference in the thermal conductivity value in the aggregate size change, as seen in Figure 2. This result corresponds with the work of I. Asadi et al., 2018, that by increasing the coarse aggregate volume percentage while maintaining the same sand ratio, the concrete's thermal conductivity value increases.
Mix three with a blend of magnetite and hornblende aggregate (denser stone) has a maximum thermal conductivity of 2.025w/m k, as seen in Table 2, showing a significant increase in thermal conductivity value. The results support the findings of Lee et al., 2016, that thermal conductivity increases with the use of magnetite and hornblende aggregate. Also, the higher density of the magnetite and hornblende aggregate plays a major role in increasing the thermal value of the concrete mix Chan, 2014; Kim et al., 2003.

Moisture and temperature also affect thermal conductivity, as seen in all the mix data above. Due to the porous nature of concrete and the pre-test sample conditioning, the sample was initially tested to have some water content. Upon the initial heating, the sample is assumed to have experienced some water loss/drying during the test using the guarded hot plate Klarsfeld 1984. The difference in thermal conductivity between the “wet” and “dry” samples was as much as approximately 26-36%; this is in concurrence with Bessenouci et al. 2014 and Shin et al. 2012. Thermal conductivity of materials such as concrete typically shows an increase in thermal conductivity with an increase in temperature. As can be seen in this data, thermal conductivity continues to increase until 100°C, where the thermal conductivity reaches a maximum. However, thermal conductivity then decreases at 120°C as seen in all the mixes and further at 150°C as the sample dries.

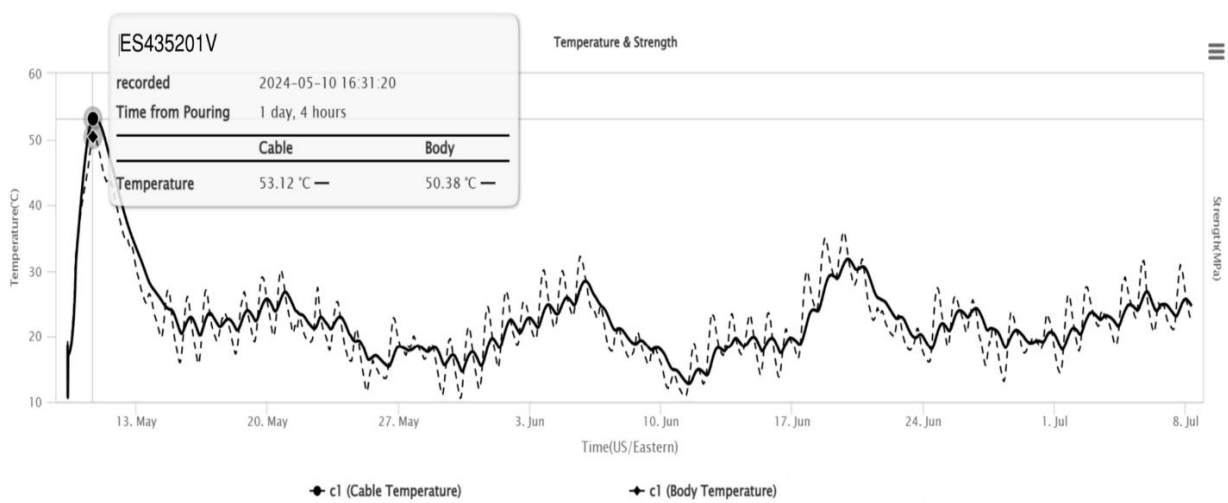

Figure 3. Concrete Temperature Differential Graph for ES435201V (cable temperature is temperature at the centre or core of the concrete and body temperature is temperature at 75mm from the top of the concrete)

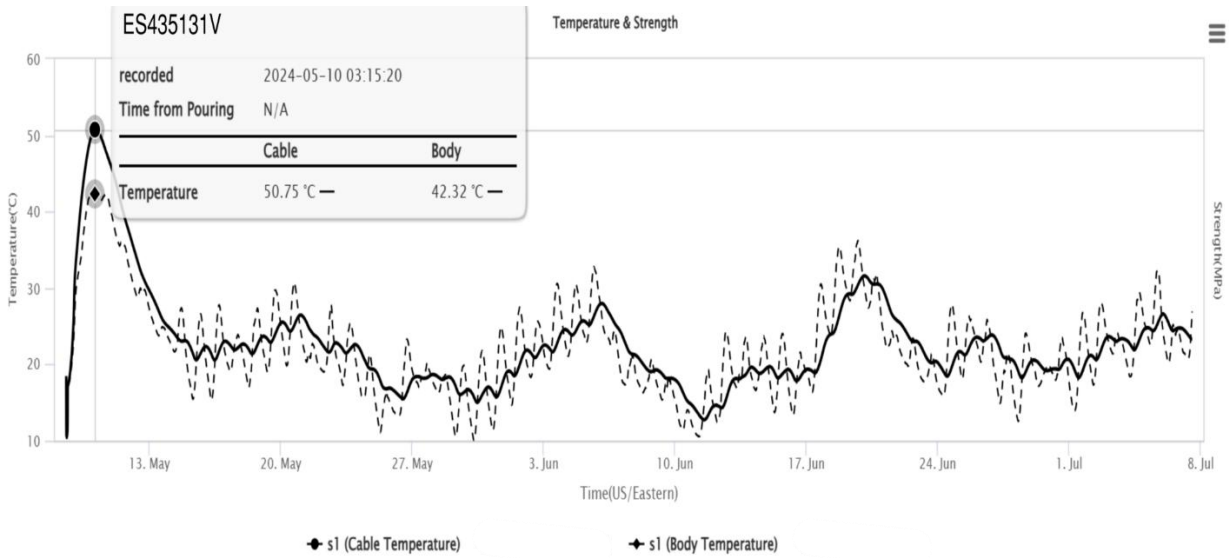

Figure 4. Concrete Temperature Differential Graph for ES435131V (cable temperature is temperature at the centre or core of the concrete and body temperature is temperature at 75mm from the top of concrete)

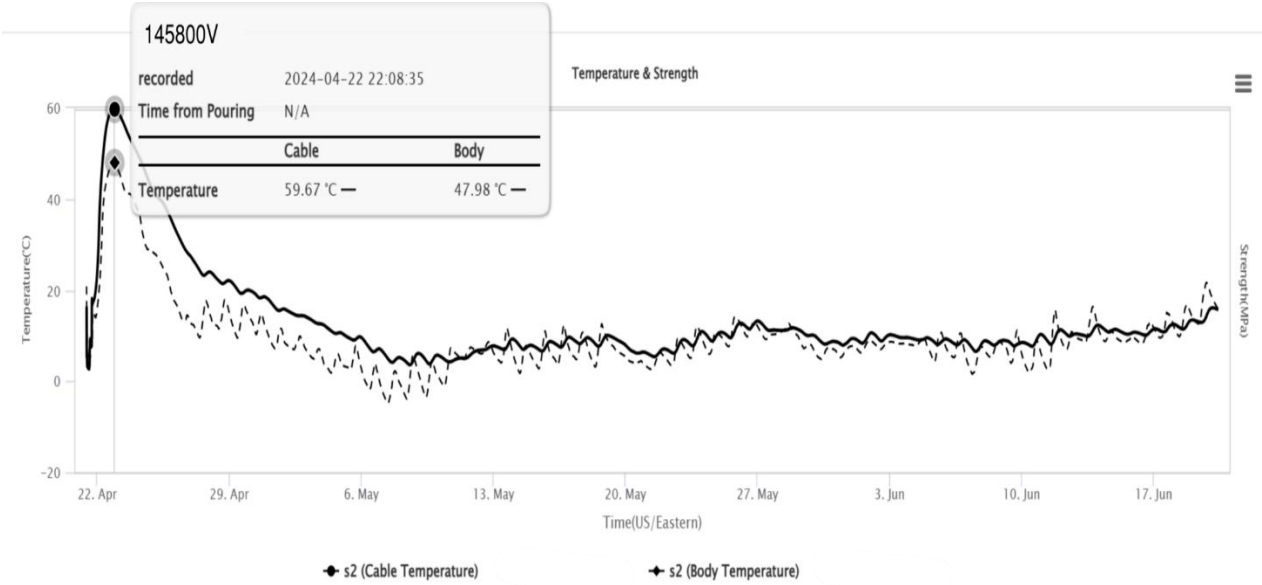

Figure 5. Concrete Temperature Differential Graph for 20mm High-Density 145800V (cable temperature is temperature at the centre or core of the concrete and body temperature is temperature at 75mm from the top of concrete)

Other key design parameters, such as temperature differential and concrete strength, were checked to ensure that the change in the aggregate does not negatively affect the required concrete strength and temperature differential. Figures 3, 4, and 5 show that the temperature differential was all below the required 20-degree C temperature differential from the concrete core (500mm) to record the cable thermocouple temperature and 75mm below the surface to record the body thermocouple temperature, over 1m thick pours as per CSA A23.2 and CSA 287.5. Furthermore, the concrete strength, as per Table 1, was above the design requirement of a Minimum of 35 MPa at 28 days for regular concrete and a minimum of 45 MPa for high-density concrete.

CONCLUSION

This study has shown that a change in aggregate type has significant effects on the thermal conductivity of concrete. The results confirm that heavy-density aggregates such as hematite and magnetite have higher thermal conductivity than normal-weight aggregates such as granite for regular concrete mixes. By also testing mixes of the same aggregate type while varying aggregate size, it can be concluded that the aggregate size of the same composition has minimal effect on thermal conductivity. This is compared to the density and type of aggregate playing the most critical role.

In addition, it can be observed that moisture content will affect the overall performance and value of thermal conductivity. As collected through this study, when concrete is heated, and the sample loses moisture content, it adversely lowers the thermal conductivity. This is especially a notable finding for nuclear containment structures that may experience extended durations of elevated temperature.

In conclusion, this study has proven that the effect of aggregate plays a critical role in the thermal conductivity of concrete, which, when aggregate density is increased, can provide a more thermally conductive concrete. Through standardized testing, it can be determined that while improving thermal conductivity values in concrete mix design, minimum design parameters in strength, density and thermal differentials during placement can still be met, ensuring the mix design optimizes thermal performance for applications in nuclear containment applications.

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