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Thermophysical Properties and Transient Heat Transfer of Concrete at Elevated Temperatures

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ABSTRACT

The objective of this study is to produce our own experimental data of physical properties of domestic concrete used in Korean NPPs, and to study on the thermal behavior of concrete exposed to high temperature conditions. The compressive strength and chemical composition of the concrete used in the Yonggwang NPP Units 3 and 4 (YGN 3&4) were analyzed. The chemical composition of Korean concrete is similar to that of US basaltic concrete. The thermophysical properties of the concrete, such as density, thermal conductivity, thermal diffusivity, and specific heat were also measured with a wide temperature range of 20 °C to 1100 °C. The properties of concrete decrease with an increase in temperature except for the specific heat, and particularly the conductivity and the diffusivity are a 50 percent decrease at 900 °C as compared with these values at room temperature. The specific heat increases until 500 °C, decreases from 700 °C to 900 °C, and then increases again when temperature is above 900 °C. In this work, we also have performed the several experiments to simulate a transient thermal behavior of concrete exposed high temperature conditions. The measured data at the experiments includes the temperature profiles in the simulated melt and concrete. These experimental data will be compared with the results of transient heat conduction model in the concrete at initial or very late phase core/concrete interactions, which have not been modeled into the MCCI codes so far.

1. INTRODUCTION

The containment building of nuclear power plants (NPPs) is the last barrier to the dispersal of fission products to the public and the environment. During the ex-vessel progression of postulated severe accidents, the high temperature molten corium, which was ejected from the reactor vessel bottom head, may keep interacting with the concrete basemat and then threaten containment integrity. The molten corium erodes concrete to produce combustible and inert gases and release fission products from the melt. The former may lead to basemat failure, while the latter may pressurize the containment to threaten its integrity. This interaction so called molten core/concrete interaction (MCCI) is an important part of the safety assessment because of its direct impact on the containment integrity. The understanding of MCCI is important for severe accident mitigation and risk quantification of NPPs.

MCCI phenomena have been studied in the past by several analyses starting with the efforts of WASH-1400 [1]. This interaction consists of many physical and chemical processes such as heat and mass transfer, decomposition of concrete, gas generation, oxidation of metal, and aerosol release. Several separate effect tests and integral experiments using simulant and real material have been conducted to understand these processes [2]. The computer codes, such as CORCON [3] and WECHSL [4], were developed to analyze the integral behaviors of MCCI. However, it is known that most computer codes contain considerable uncertainties and are still being updated based on recent experimental data. Transient conduction is important for modeling of initial or very late phase core-concrete interactions that have not been modeled so far [3].

The physical property of concrete is an important part of calculations for the thermal behavior of the concrete structures, involve MCCI analysis. Of more importance would be the effects of the decomposition products (CaO and SiO2) on the core debris. The major factors affecting the thermal properties of concrete are composition, density, and moisture content. Few higher temperature data are available because concretes dry out and decompose at moderate temperatures. Harmarthy [5,6] has developed two transient-state methods to measure for the properties of concrete and presented theoretical considerations, which make the assessment of the thermal properties of concrete possible. Brewer [7] has reported that the curves and correlation showing the simultaneous variation in conductivity and density with increased free water contents. Thompson [8] has discussed on the difficulties of measuring the thermal conductivity of concrete using several steady and transient methods such as hot-plate method and hot-wire method. Moore et al. [9] have measured both the thermal conductivity and diffusivity of a limestone concrete and reported the effect of density on the thermal conductivity of concrete with correlation. Harada, et al. [10] have determined the variations in thermal properties such as thermal coefficient of expansion, thermal conductivity and thermal diffusivity of concrete during heating at high temperatures using aggregates of various qualities. The thermal properties and test methods were more fully discussed by Rhodes [11] and Neville [12].

The objective of this study is to produce experimental data of MCCI in Korean NPPs. To study Korean concrete behavior accurately, it is also necessary to know the property data of local concrete in Korea. In the present work, we have concerned with the measurement of the thermal properties of concrete material in the 20 °C to 1100 °C ranges. We also have performed simulant experiments of MCCI using thermite melt and concrete used in the Yonggwang nuclear power plants units 3 and 4 (YGN 3&4) in Korea.

2. EXPERIMENTAL METHODS

In this work, the experiment was composed of three measurement parts - chemical composition, thermal property and transient heat transfer of concrete. These physical properties of concrete which influence in design of the containment shall be established in the Construction Specification. The containment building has to design by the rules for the construction in ASME and the mixing design of concrete is to be stated plainly in CC-2230 [13]. The concrete used for the experiments was made by using YGN3&4's materials. The characteristics of the concrete are tabulated in Table 1. The specimens for the property measurement were cylinder 100 mm in diameter and 200 mm in length.

2.1 Chemical Composition

It is known that the type of concrete is the main parameter of the MCCI phenomenon. In this study, the chemical composition of YGN 3&4 concrete was analyzed. The chemical analysis was conducted by standard method for ASTM C 114 and KS 5120. The measurement was done using an atomic absorption spectrometer (Philips, model 251) and X-ray fluorescence (Philips, model PW 1400).

Table 1 Engineering Compositions of concrete.

Item	YGN 3&4	wt %
Compression Strength	5500 psi (387 kg/cm^2)	
Water/Cement (W/C)	42 %	-
Sand/Aggregate (S/G)	45.9 %	-
Water (W)	169.1 kg	7.6
Cement (C), type V	402.2 kg	18.1
Sand (S)	756.3 kg	34.1
Aggregate (G), 19 mm	893 kg	40.2
Water Reducing Agent	1207 ml	-
Air Entraining Agent	21 ml	-
Slump	12.5 cm	-
Air Containing	5.2 %	-

2.2 Thermal Property

Thermal properties are important in the overall behavior analysis of concrete at elevated temperature because concrete structure in the containment is served as a heat sink during an accident. The experiments were also conducted on the thermal property - density, conductivity, diffusivity and specific heat at elevated temperatures of concrete.

Concrete is a non-homogeneous, anisotropic medium, composed of particles of aggregate held together by hydrated cement paste. The cement paste is porous, and usually contains moisture in the pores, which affects the pore conductivity. The commonly used steady-state methods are no particularly well suited for measuring the thermal properties of the concrete that are liable to physicochemical changes as a result of heating. At higher temperatures the formation of structurally or chemically different layers perpendicular to the direction of heat flow causes difficulties in the interpretation of the test result. For instance, the steady-state methods (hot plate and hot box) yield the same thermal conductivity for dry concrete, but give too low a value for most concrete because the temperature gradient causes migration of moisture. For this reason, it is preferable to determine the conductivity of moist concrete by transient methods; the hot-wire method has been found successful [7]. However, several known transient methods were scrutinized and discarded, partly because of their failure to yield the expected accuracy and partly because of the difficulty of specimen preparation. Consideration of the thermal gradients and the measurements times for the hot-wire transient method indicates that moisture movement should affect the measurements. Therefore, the transient method requires much shorter time than the steady-state method for measurement of thermal conduction properties.

The hot-wire method was conducted by standard method for ISO 8894 [14]. The hot-wire method (parallel) is a dynamic measuring procedure based on the measurement of the temperature increase at a certain location and at a specified distance from a linear heat source embedded between two test specimens. The test specimens are heated in a furnace to a specified temperature and maintained at that temperature. Further local heating is provided by a linear electrical conductor (the hot wire) that is embedded in the test specimen and carries an electrical current of known power that is constant in time and along the length of the test specimen. A thermocouple is fitted at a specified distance from the hot wire, the thermocouple leads running parallel to the wire. The increase in temperature as a function of time, measured from the moment the heating current is switched on, is a measure of the thermal conductivity of the material of which the test specimens are made. Calculate the thermal conductivity, κ, of the material, in watts per meter, at each test temperature from the Eq. (1),

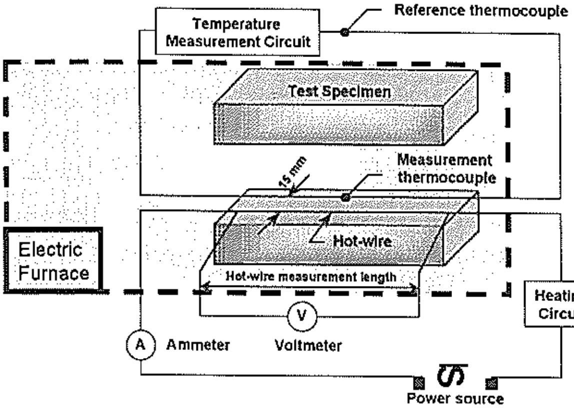

Fig. 1 Schematic of measurement apparatus with hot-wire method (parallel).

$$\kappa = \frac{VI}{4\pi l} \times \frac{-Ei\left(-r^2/4\alpha t\right)}{\Delta\theta(t)} \tag{1}$$

where, I is the heating current, V is the voltage, l is the length of the hot wire between the voltage taps, $\Delta\theta(t)$ is the temperature difference between the measurement and reference thermocouples at time t, t is the period of time between switching on and switching off the heating circuit, r is the separation of the hot wire and the measurement thermocouple, α is the thermal diffusivity, and $-Ei(-x)$ is an exponential integral of the form $\int_x^\infty \frac{e^{-u}}{u} du$. After determining $\Delta\theta(2t)/\Delta\theta(t)$, the expression $-Ei\left(-r^2/4\alpha t\right)$ is calculated from table data by Grosskopf and Kilian [15]. The values of κ which can be considered accurate are those which correspond the values of $\Delta\theta(2t)/\Delta\theta(t)$ between 1.5 and 2.4.

Figure 1 shows the schematic diagram of the hot-wire method, with a hot-wire and a thermocouple at the center of the base of the test specimens. The specimens for the property measurements were cylinder 100 mm in diameter and 200 mm in length. The electric furnace used in a high-precision temperature chamber that can control temperature stability and uniformity up to ± 0.5 °C. The test concrete is initially placed in the electric furnace with temperature set at T = 20 °C until equilibrium is reached. The test concrete was heated gradually in the electric furnace (rate of temperature rise approximately 1.67 °C/min) to the designated temperature and after maintaining that temperature the thermal property was measured. Subsequently, the temperature of the electric furnace is reset to next temperatures. The experiments have to be repeated as any single test value may give a wrong estimation of the thermal properties. A minimum of three repetitions is recommended.

In this study, the measurement results in the simultaneous measurement of the thermal conductivity and diffusivity from the hot-wire method. To obtain the value of the specific heat, a separate experiment has to be conducted to measure the density, from the Eq. (2),

$$C_p = \frac{\kappa}{\rho\alpha} \tag{2}$$

where C_p is specific heat, κ is thermal conductivity, ρ is density and α is thermal diffusivity.

At the separate test, the three concrete specimens were used to measure the density in a cube shape 50 mm^3 (50 × 50 × 50 mm) in volume. The specimens for density that means bulk density were also heated gradually in the electric to the designated temperature. The density was measured at normal temperature after cooling concrete specimen. Subsequently, the measurement of density was repeated at the other designed temperature conditions such as 500 °C, 700 °C, 900 °C and 1100 °C.

3. RESULT AND DISCUSSION

The design value of average compressive strength was prescribed for mixing design as shown in Table 1. The compressive strength of concrete specimen was confirmed on curing period by the separate test. Figure 2 shows compressive strength of test concrete related to curing period. After 9 day, the compressive strength of concrete was to be acceptable to the design value and partially there was a small increasing rate of the strength after 28 day. The age of the concrete specimens that used to measure the property was approximately 3 months.

3.1 Chemical Composition

Table 2. Chemical compositions of concretes mostly used in NPP's basemat.

Composition (weight %)	YGN 3&4	BAS	LCS	LS
SiO_2	55.70	54.84	35.80	3.60
CaO	15.80	8.82	31.30	45.40
Al_2O_3	10.30	8.32	3.60	1.60
K_2O	2.86	5.39	1.22	0.68
Na_2O	2.04	1.80	0.082	0.078
$MgO/MnO/TiO_2$	1.61	7.21	0.69	5.80
Fe_2O_3	2.60	6.26	1.44	1.20
Cr_2O_3	0.021	0.00	0.014	0.004
H_2O	7.23	5.86	4.70	5.94
CO_2	2.78	1.50	21.154	35.698
Total	100.941	100	100	100

The concrete mostly used in NPPs are basaltic aggregate concrete (BAS), limestone common sand aggregate concrete (LCS) and limestone aggregate concrete (LS). In this study, the chemical composition of YGN 3&4 concrete was analyzed. The composition of the various kinds of concrete, including Korean local concrete, is given in Table 2. The concrete composition may be specified either in terms of $CaCO_3$ and $Ca(OH)_2$, or their decomposition products, CaO, CO_2, and H_2OCHEM (chemically bound water). The silicon dioxide (SiO_2) content of Korean local concrete is similar to that of BAS. However, the Korean local concrete has twice the content of calcium monoxide (CaO) and carbon dioxide (CO_2) as the BAS. These differences may reduce the ablation rate during the MCCI on Korean concrete.

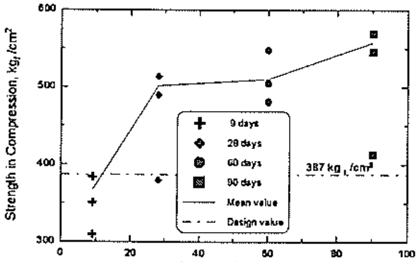

Fig. 2 Compressive strength of YGN 3&4 concrete related to curing period.

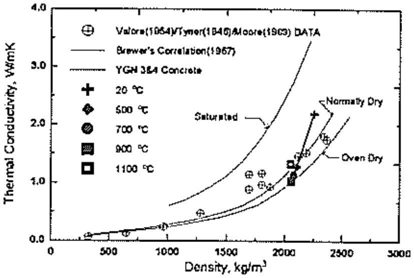

Fig. 3 Thermal conductivity of concrete as a function of density and moisture content.

Table 3 Thermophysical properties of YGN 3&4 concrete as a function of temperature.

Temperature (°C)	Density (kg/m^3)		Conductivity (W/mK)		Diffusivity ($\times 10^{-6} m^2/s$)		Specific Heat (J/kgK)	
	Mean	Error	Mean	Error	Mean	Error	Mean	Error
20	2252.43	5.49	2.194	0.032	0.8824	0.0243	1104	15
500	2104.97	5.16	1.283	0.018	0.4505	0.0099	1354	27
700	2077.71	4.67	1.136	0.031	0.4031	0.0185	1357	25
900	2057.44	3.30	1.027	0.026	0.4170	0.0241	1199	62
1100	2051.15	2.29	-	-	-	-	-	-
Correlative Function of T (°C)	ρ=0.000189575 T^2 - 0.39802 T + 2259.62 (±0.4%)		κ=1.36469E-6 T^2 - 0.00256908 T +2.24266 (±2%)		α=9.16391E-7 T^2 - 0.00136982 T +0.909062 (±1%)		$C_p = \frac{\kappa}{\rho\alpha}$	

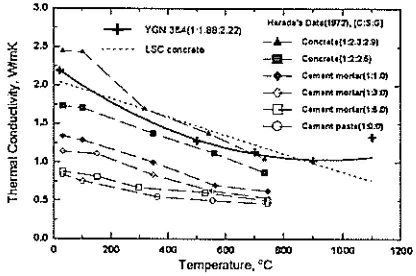

Fig. 4 Thermal conductivity of concrete as a function of temperature.

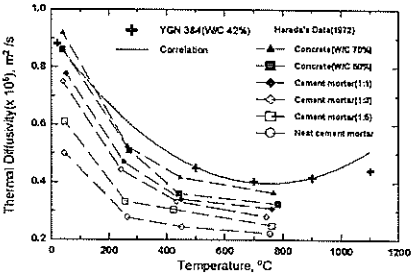

Fig. 5 Thermal diffusivity of concrete as a function of temperature.

3.2 Thermal Property

Thermal properties are important in the overall behavior analysis of concrete at elevated temperature because the concrete structure in the containment is served as a heat sink during an accident. The thermophysical properties of the concrete were also measured at elevated temperatures in the range of 20 °C to 1100 °C. These properties are strongly depending on the temperature. In generally, the density, the conductivity and the diffusivity decrease with an increase in temperature. For each conditions of temperature, thermal properties were determined, whose values and correlation functions are summarized in Table 3. Measurements made beyond 1100 °C are not acceptably accurate because of the concrete decomposition from solid to liquid phase.

The density decrease with an increase in temperature because to decrease of the concrete weight by decompositions of free water, chemically bound water, calcium monoxide, and carbon dioxide. The thermal conductivity varies directly with the density (unit weight), the moisture (free water) content and the temperature of the concrete. The moisture content of the concrete has a major effect upon the thermal conductivity. Figure 3 shows the thermal conductivity of concrete as a function of density and moisture content.

Figure 4 and Figure 5 show the mean thermal conductivity and thermal diffusivity measured by hot-wire method compared to some data. There is good agreement in the values of property for the concrete by hot-wire method and other data. The relation between thermal conductivity and temperature is given in Figure 4. Thermal conductivity of concrete is reduced with rise in temperature and at 900 °C is approximately 50 % of the rates at normal temperature. In generally, the thermal conductivity of concrete is defined as the average thermal conductivity of a region instead of at a single point. The practice of regarding the thermal properties of concrete as constants may lead to serious errors in heat transfer calculations. There is the same tendency for thermal diffusivity at in the thermal conductivity with exactly the same order of magnitude while at 900 °C the rates is approximately 50 % of the rates at normal temperature, as shown in Figure 5. The effect of mineral composition upon specific heat is relatively insignificant, except for the water content and the entrained air. In general, the specific heat varies with variation in the temperature. The specific heat increases up to 500 °C, decreases from 700 °C to 900 °C, and then increases again at temperatures above 900 °C. These thermal property data as functions of temperature will be used for the modeling of transient conduction in concrete at initial or very late phase core-concrete interactions.

3.3 Transient MCCI Experiments

In this study, we also examined the several tests for MCCI, pouring 20kg of thermite as a corium simulant onto the local concrete used in YGN 3&4, Korea. The measured data in the experiments include temperature profiles in the melt and concrete and the concrete erosion. The peak melt temperature was measured to be 2230 °C by the C-type thermocouple. The measured maximum downward heat flux to the concrete specimen was estimated to be about 2.1 MW/m^2 and the maximum erosion rate of the concrete to be 175 cm/hr with a total erosion depth of 2 cm. The experimental data were validated using the CORCON code. Figure 6 shows the erosion depth obtained from the experiments and CORCON code analysis. When compared with the TURC-1T experiment, where 200 kg of thermite was used as melt simulant, the interaction in our experiment using 20 kg thermite early finished. The CORCON code predicts well the ablation rate in Korean concrete, which was a difference against BAS and LCS. These differences may cause the generation of a large amount of gas during the MCCI on Korean concrete. These experimental data will be compared with the results of transient heat conduction model in the concrete at initial or very late phase core/concrete interactions, which have not been modeled into the MCCI codes so far.

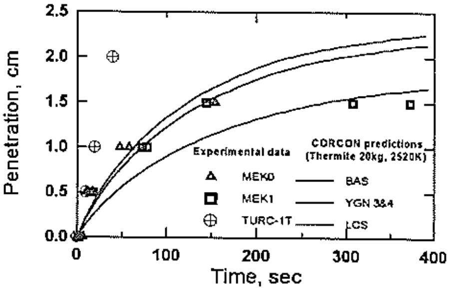

Fig. 6 Concrete erosions obtained from experiments and CORCON

4. CONCLUSION

Thermophysical properties and compressive strength of concrete used in nuclear power plants in Korea were measured. The chemical composition of the concrete was also analyzed. The chemical composition of Korean concrete is similar to that of US basaltic concrete. The measured thermophysical properties include density, thermal conductivity, thermal diffusivity and specific heat for a wide temperature range of 20 °C to 1100 °C. The chemical composition of Korean concrete is similar to that of US basaltic concrete and the thermophysical properties are strongly temperature dependent. The density, the conductivity and the diffusivity decrease with an increase in temperature, and particularly the conductivity and the diffusivity are a 50 percent decrease at 900 °C as compared with these values at room temperature. The specific heat increases until 500 °C, decreases from 700 °C to 900 °C, and then increases again when temperature is above 900 °C. The measurement beyond 1100 °C is not acceptably accurate because the concrete decomposes to a liquid phase from a solid phase at that temperature. In this work, we also have performed several experiments to simulate a transient thermal behavior of concrete exposed high temperature conditions. The measured data at the experiments include the temperature profiles in the simulated melt and concrete. These experimental data will be compared with the results of transient heat conduction model in the concrete at initial or very late phase core/concrete interactions, which have not been modeled into the MCCI codes so far.

The results of this study can be applied, for example, to an analysis of the molten core-concrete interaction (MCCI) phenomenon of severe nuclear accidents. Various engineering calculations for the thermal behavior of concrete structures at high temperature will also require those property data, especially for high temperature ranges.

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