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Measurement of Thermophysical Properties of Heavy Density Concrete Using Inverse Solution for One-Dimensional Heat Conduction

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Abstract **–** Present study purposes a simple methodology for the measurement of thermophysical properties of the high performance ferro siliceous sacrificial concrete. The study involve simple experiments of temperature measurement and data processing to estimate various thermophysical properties such as specific heat, thermal conductivity, thermal diffusivity, and effusivity. The combination of these properties is exceptional and crucially advantageous to determine the ablation rate during interaction of the molten metal with concrete. The study based on one-dimensional semi-infinite transient heat conduction model. The specific heat of the FSSC is found to be 827.5 J/kgK while the value of thermal conductivity lies in the range of 7.4-8.8 W/mk. The average value of thermal diffusivity and thermal effusivity is found to be 2.47×10^{-6} m^2/s and 4033.77.18 $Jm^{-2}K^{-1}s^{-1/2}$, respectively.

Keywords**:** Semi-infinite medium, Thermal conductivity, Specific heat, Thermal diffusivity, Effusivity

1. Introduction

Over the years concrete has been considered as one of the most valuable materials used in biological shielding against ionizing radiation [1]. Especially, heavy weight concrete is used in hospital and health centres for providing protection against radiations emitted from x-ray or radiological laboratories. Heavy weight concrete is achieved by using heavy density aggregates. The main purpose of this biological shielding concrete is to reduce the level of radiation to a safer extent for a people who attend protected are unfortunately. The effectiveness of the concrete in protecting the radiation depends on the types of aggregates and density of the aggregates use to fabricate the concrete. Thermal and mechanical properties of the concrete are considered to be most significant parameters to access its effeteness against X-ray radiation. For shielding walls of health centres or hospitals, estimation of thermal properties are necessary to design the optimum thickness of layers [2]. Special aggregates such as hematite or magnetite based aggregates are usually preferred to improve the shielding properties of the concrete [3].

The effective thermal properties of the heavy weight concrete highly depends on the types of aggregates used and their accurate measurement is very essential but difficult to measure. Transient heat conduction technique is widely preferred to determine the thermophysical properties of the material. Transient hot-strip method, transient hot-wire method, and transient plane source method are generally used to find the thermophysical properties of the material. Gustafsson et al. [4] applied transient hot-strip method to determine the thermal conductivity and specific heat capacity of insulating solid. Chu et al. [5] experimentally measured various thermomechanical and thermophysical properties of ferro siliceous sacrificial concrete. They used thermal constant analyser to measure thermal conductivity of the concrete specimens. The authors measured the thermal conductivity of concrete when specimens are exposed to different temperature for a 2 hours. At 200°C the thermal conductivity of the concrete was found to be 2.34 W/mK. Ibrahim et al. [6] experimentally measured the thermophysical as well as thermomechanical properties of the concrete with iron-slags as aggregates. They measured temperature, and heat flux and applied heat diffusion equation to determine the thermal conductivity and diffusivity of the concrete. Their obtained thermal conductivity were varied in the range of 0.62-3.3 W/m-K. A device called KD2 pro (Decagon Manufacturing Co., Ltd., Pullman, WA, USA) equipped with different needle type sensors (TR-1) which is worked on transient hot wire method is mostly generally used to find the thermal conductivity of concrete as well as other material [7-8]. However, these devices are very costly.

Literature suggests that evaluation of thermal properties of normal concrete is sufficient in the literature but the thermophysical properties of heavy weight concrete such as hematite based concrete is limited in the literature. Therefore in the present study, an analytical method with simple experiments are purpose to determine the various thermos-physical properties. An inverse heat conduction technique based on semi-infinite medium approach is used to determine specific heat (C_p), thermal conductivity (k), thermal diffusivity (α), and thermal effusivity ($\in$) of the concrete. A simple experiments and data processing technique is employed to obtain the thermal properties of the ferro siliceous sacrificial concrete (FSSC). The proposed method is considered simple, low cost, and relatively fast to estimate the thermal properties using a single temperature recording data and simple data processing.

2. Semi-infinite medium model

The physical model for present study is shown in Fig. 1. It comprises two identical FSSC specimens having square cross-section and a plate heater which is sandwiched between two identical specimens. It is assumed that both the specimens receives equal heat flux from the heater.

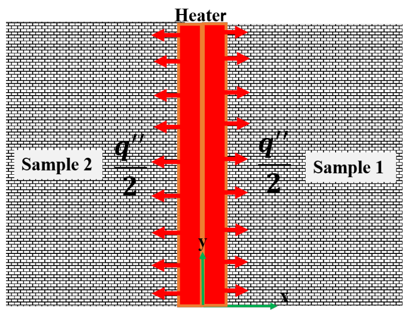

Fig. 1: Semi-infinite medium physical model.

Using semi-infinite medium assumptions the transient temperature distribution $T(x,t)$ at any location (x) inside the specimens from the heater surface is given by Eq. (1).

$$T(x,t) - T_0 = \frac{2q''\left(\frac{\alpha t}{\pi}\right)^{\frac{1}{2}}}{k} exp\left(\frac{-x^2}{4\alpha t}\right) - \frac{q''x}{k} erfc\left(\frac{x}{2\sqrt{\alpha t}}\right) \quad (1)$$

Where, T_0 is the initial temperature, q'' is the supplied heat flux, and $erfc$ is the complementary error function. Eq. (1) can be solved using inverse technique to estimate the thermal properties if we able to measure transient temperature distribution and heat flux values. Here we first determine a guess value of specific heat and thermal conductivity by assuming temperature sensors are placed very close to the heater surface ($x \approx 0$). This assumption reduces Eq. (1) to a simple linear Eq. as follows.

$$T(0,t) - T_0 = \frac{2q''\left(\frac{\alpha t}{\pi}\right)^{\frac{1}{2}}}{k} = \left(\frac{2q''}{\sqrt{\pi}} \frac{1}{\in}\right)\sqrt{t} = \mu.\sqrt{t} \quad (2)$$

Where, $\in = \sqrt{k\rho C_p}$ is the thermal effusivity and $\mu = \frac{2q''}{\sqrt{\pi}}\frac{1}{\in}$ is the slope of the linear Eq. (2). With the help of experimental temperature data the initial guess of thermal effusivity ($\in$) can be determined. To determine the guess value of thermal conductivity the initial guess of specific heat needs to be determined. The initial guess of specific heat can be determined using energy balance Eq. (3) as follows.

$$P = \frac{VI}{2} = mC_p\frac{dY}{dt} \quad (3)$$

Where $\left(\frac{VI}{2}\right)$ is the power (P)supplied to each concrete specimen, m is the mass of the specimen, $\frac{dY}{dt}$ is the slope of linear plot between temperature vs. time. Guess value of specific heat can easily be determined if we can measure the voltage (V) and current (I) supplied to the heater. Therefore, with the guess value of C_p and $\in$ the thermal conductivity $\left(k = \frac{\in^2}{\rho C_p}\right)$ of the concrete specimens can easily be determined. With the help of these guess value, the theoretical temperature distributions in the concrete are determined using Eq. (1) and it is compared with the experimental temperature distribution on the same co-ordinate axis. The initial guess values of k and C_p are now varied around their guess value such that theoretical and experimental temperature distributions shows a good match. The value k and C_p at which theoretical and experimental transient temperature distribution shows excellent match with least deviation are considered to be final value of k and C_p. Subsequently, final α and $\in$ can be determined. Table 1 gives the mixture proportion of various aggregates used to fabricate the specimens.

3. Test methodology

The square cross-section of concrete test specimens with hematite based aggregates having dimensions of 150×150 mm^2 and 50 mm thick are considered to estimate the thermophysical properties. The mixture proportions of coarse aggregates (20 mm NMSA (SSD)) in kg/m^3 is taken as 906.6 while coarse aggregates (10 mm NMSA (SSD)) in kg/m^3 is considered as 961.7. The fine aggregates proportion in the specimens is 1400.2 kg/m^3. The experimental set up involved for the measurement of transient temperature distribution in the concrete specimens is shown in Fig. 2. It comprises test specimens with embedded heater and thermocouples, data logger, transformer, a laptop, multi meter and clamp meter. A glasswool insulation is provided to reduce the heat loss. Thermocouples are placed at a distance of 1 mm from the heater surface. Transformer is used to provide the constant heat flux and data logger with the help of thermocouples are used to measure the temperature inside the specimens. Multi meter and clamp meter are used to measure the voltage and current supplied to the heater.

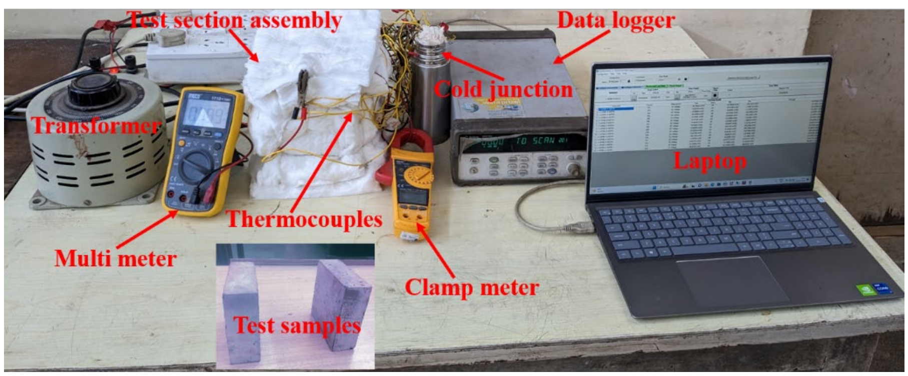

Fig. 2: Experimental setup.

4. Results and Discussion

The thermophysical properties such as C_p, k, α, and $\in$ of the concrete is obtained using the methodology explained in the preceding sections. The value of k, and C_p at which both experimental and theoretical temperature profile matches each other is the final value of k, and C_p. At heat flux of 15.0 kW/m2, the initial value of thermal conductivity and specific heat are 8.3 W/mK, 827.5 J/kgK, respectively. Fig. 3(a) presents the variation of k, and C_p around guess value to get the final k, and C_p value. It is observed that when $k = 8.8$ W/mK and $C_p = 800$ J/kgK the experimental and theoretical temperature profile shows exact match. The value of k, C_p, α, and $\in$ are calculated at heat flux of 15.0 and 20.0 kW/m2 and is shown in Table 1. Fig. 3(b) presents the comparison of experimental and theoretical results for 20.0 kW/m2. For both heat flux, the values of thermal properties is higher than the normal concrete. This is because of the presence of hematite aggregates in the mixture.

Table 1: Thermal properties for various heat fluxes for the thermocouples located at 1 mm from the heater surface

Heat flux (kW/m^2)	k (W/mK)	C_p (J/kgK)	$\alpha \times 10^6$ (m^2/s)	$\in$ ($J/m^2.K.s^{1/2}$)
15.0	8.8	827.5	2.58	4234.1325
20.0	7.4	827.5	2.29	3833.4125

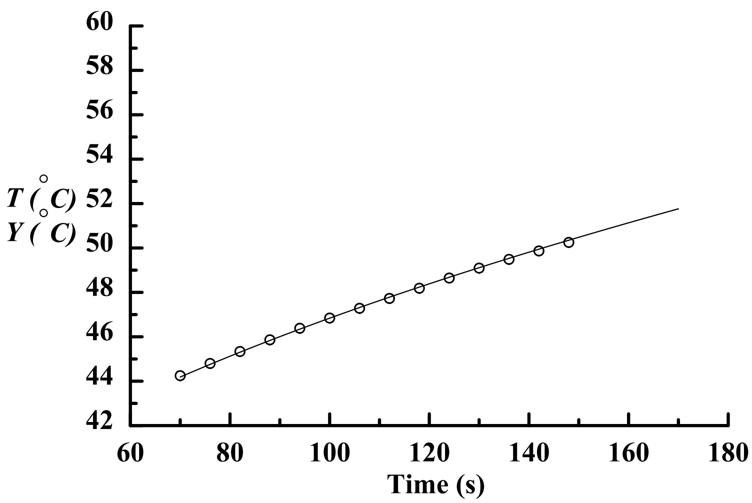

Fig 3: (a) Comparison of the measured and calculated temperature distribution using different values of thermal conductivity and specific heat around their first estimates (b) Comparison of experimental and the theoretical results at 20.0 kW/m^2

5. Conclusions

In the present study a simple experiments and data processing technique is proposed to find the thermophysical properties of FSSC concrete. The inverse heat conduction based semi-infinite medium heat conduction model is proposed to estimate thermal conductivity, specific heat, thermal diffusivity, and effusivity of the concrete. The obtained thermal conductivity is higher than the normal concrete while specific heat is lesser than the normal concrete.

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References

[1] T. Piotrowski, M.A. Gryzieski, “Effectiveness evaluation of new generation shielding concrete against ionizing radiation based on measurements,” *J. Civil Eng.*, vol. 63, no. pp. 141-148, 2016.

[2] R. Jaskulski, W. Kubissa, P. Reiterman, O. Holcapek. "Thermal properties of heavy concrete for small pre-cast shielding elements," In *AIP Conference Proceedings on special concrete and composites* , Czech Republic, 2020, vol. 2210, no. 1, pp. 020011.

[3] A. M. Ibrahim, A. R. Mohamed, A. M. Khatib, M. T. Alabsy, M. Elsalamawy, "Effect of hematite and iron slag as aggregate replacement on thermal, mechanical, and gamma-radiation shielding properties of concrete," *Cons. Build. Mat.*, vol. 310, pp. 125225, 2021.

[4] S.E. Gustafsson, E. Karawacki, M.N. Khan, "Determination of the thermal-conductivity tensor and the heat capacity of insulating solids with the transient hot-strip method," *J. App. Phys.*, vol. 52, no. 4. pp. 2596-2600, 1981.

[5] H. Y. Chu, J. Y. Jiang, W. Sun, and M. Zhang, "Thermal behavior of siliceous and ferro-siliceous sacrificial concrete subjected to elevated temperatures," *Mat. Desig.*, vol. 95, pp. 470-480, 2016.

[6] A. M. Ibrahim, A. R. Mohamed, A. M. Khatib, M. T. Alabsy, M. Elsalamawy, “Effect of hematite and iron slag as aggregate replacement on thermal, mechanical, and gamma-radiation shielding properties of concretes," *Const. Build. Mat.*, vol. 310, pp. 125225, 2021.

[7] H. R. Talebi, B. A. Kayan, I. Asadi, Z. Hasan, “Investigation of thermal properties of normal weight concrete for different strength classes," *J. Environ. Tret. Tech* ., vol. 8, no. 3. pp. 908-914, 2020.

[8] D. Kim, S. Oh, “Measurement and comparison of thermal conductivity of porous materials using box, dual-needle, and single-needle probe methods-A case study," *Int. Commun. Heat Mass Transf.*, vol. 118, pp. 104815, 2020.