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An Experimental Investigation on Thermal Properties of immature Concrete

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Abstract: Since the heat of hydration of cement is highly temperature dependent, variation of thermal properties of concrete at early ages is essential to predict the temperature rise and distribution due to heat of hydration of cement in concrete. Experimental investigation was carried out to obtain the temperature response of fresh concrete sample of 150mm cube with time under known thermal boundary condition. The specific heat capacity of fresh concrete was estimated based on the specific heat capacities of cement and products of cement hydration using Dulong – Petit Rule (DPR) and Neumann– Kopp Rule (NKR). The thermal conductivity (λ) was determined by fitting the temperature response curve of the cube with the temperature history predicted by transient heat conduction analysis based on the estimated specific heat capacity of concrete using ANSYS software. Tests were conducted for concrete at early age, i.e. from one hour to 1 day, for several mix proportions. It was found that thermal conductivity increases rapidly within the first 5 to 12 hours and reached a constant value which depends on the mix proportion.

Keywords: thermal conductivity, specific heat capacity, early age concrete, transient heat conduction analysis

1. Introduction

Thermal properties of concrete is required to obtain temperature rise and distribution in early age concrete which depends on the exothermic hydration process, chemical and physical properties of concrete materials and thermal boundary conditions [1, 2]. Temperature rise and thermal gradient developed at early age can cause cracking in concrete which can affect the long term performance of concrete structures [3, 4].

In cement hydration process, a large quantity, typically 70 ~ 90% of total heat, is released within a day [5] and significantly increase the temperature even above 70 ~ 90 °C depending on the cement type, cement quantity and size of the element[6].

A Multicomponent hydration model has been developed by Maekawa et al. [1, 2] to predict the heat of hydration based on chemical composition and physical properties of cement. This model can be implemented into transient heat conduction analysis program to predict the temperature and temperature gradient for any thermal boundary conditions [6].

Essential thermal and physical input parameters to solve a transient heat conduction analysis are thermal conductivity (λ), specific heat capacity (c), and density (ρ) of concrete.

Results reported in literature on Experimental investigations of thermal conductivity and specific heat capacity of fresh concrete are highly scattered with contradictory results [7, 8, 9, 10, 11, 12]. Thermal conductivity of concrete with limestone aggregates is reported as 3.0 J/s/m/K [9, 10], and concrete with siliceous aggregates such as quartz with higher thermal conductivity is reported in the range of 5.0 ~ 8.0 J/s/m/K [9, 11, 12].

Specific heat capacity of mineral components of cement powder can be estimated based on Dulong-Petit Rule (DPR) and Neumann-Kopp Rule (NKR), and the results are accurate at room temperature [20]. Jindrich et al. [13] reports that many researchers use the estimated specific heat data from DPR & NKR with 3.3% mean deviation to the absolute data. Many authors [14, 15] reported that the specific heat capacity of OPC powder is 0.7 J/g/K which is approximately equal with DPR & NKR estimation. Once the specific heat capacity of components in cement paste is known, the overall specific heat capacity of concrete can be calculated based on mixing theory [24].

Conventional steady state methods to estimate thermal conductivity of fresh concrete, which is a heterogeneous, saturated porous material, produce large errors as the parameters used in estimation are very sensitive [8]. Transient measurement methods reducing moisture movements are desirable to estimate thermal properties of fresh concrete [9].

In this study, with the view of the lack of data on the behaviour of thermal properties of fresh concrete, a specially designed experimental program to determine thermal properties of fresh concrete was conducted.

2. Theoretical Background

2.1 3D Transient Heat Conduction Analysis

The heat diffusion differential equation derived based on Furrier Law and Laplacian with Cartesian coordinate system describing three dimensional heat conduction through homogeneous medium is given by equation 1 [17];

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} + \frac{\dot{q}}{\lambda} = \frac{1}{\alpha} \cdot \frac{\partial T}{\partial t} \tag{1}$$

Where; λ -Thermal conductivity(J/s/m/K), $\alpha = \lambda/\rho c$ thermal diffusivity(m^2/s), c - specific heat capacity(J/kg/K), ρ - density(kg/m^3), and $\dot{q}$ - volumetric heat generation rate (J/s/m^3).

2.2 Dulong – Petit and Neumann– Kopp Rules for Estimation of Specific Heat Capacity of OPC Concrete

Dulong-Petit and Neumann-Kopp rules can be used to estimates the specific heat capacity of concrete mineral components and cement hydrates with the degree of hydration [21, 22]. Dulong-Petit Rule (DPR) states that regardless of the nature of the substance, the specific heat capacity, c_i (J/kg/K) of a solid element is given by equation 2 [21];

$$c_i = \frac{3R}{M} \tag{2}$$

Where, R is the gas constant equal to 8.3144621 J/mole/K, and M kg/mole is the molar mass of solid substance.

Neumann-Kopp Rule (NKR) states that the specific heat capacity, c per unit mass for alloys can be calculated from the following equation 3 [22];

$$c = \sum_{i=1}^{N} (c_i . f_i) \tag{3}$$

Where, i is the subsequent number from 1 to N which is the total number of alloy constituents, and f_i is the mass fraction of the ith constituent.

Mixing theory which is similar to NKR states that the specific heat capacity of cement paste and concrete can be given by the equations 4 and 5 [23];

$$c_{paste} = c_{CH}.m_{CH} + c_{UC}.m_{UC} + c_{FW}.m_{FW} \tag{4}$$

$$c_{conc} = c_{paste}.m_{paste} + c_{sand}.m_{sand} + c_{cagg}.m_{cagg} \tag{5}$$

Where, c denotes the specific heat capacity of cement paste (CH – cement hydrates, UC – unhydrated cement, and FW – free water), sand and coarse aggregates. Symbol “m” denotes the mass fraction of concrete materials and cement hydrates.

2.3 Sensitivity of Specific Heat Capacity of Concrete to transient heat conduction

A transient heat conduction analysis which is briefed in section 3.3, was carried out using ANSYS software to determine the sensitivity of thermal properties to temperature rise at the centre of a concrete specimen under external heat input. The specimen was modelled as shown in Figure 3.

Initial inside and steady state boundary temperatures were set as $T_{t=0}$ = 30 °C, and T_o = 40 °C respectively. Thermal conductivity and specific heat capacity of steel (0.5% Carbon) mould were considered as 54 J/s/m/K, 465 J/kg/K respectively [17].

As many authors reported [9, 10, 11, 12], the thermal conductivity of concrete was selected with an average value of 2.907 J/s/m/K.

Torban C et al. [26] reports that the degree of hydration that can be achieved within a day for OPC is 30%. Bentz [7] reveals that the specific heat capacity of saturated OPC paste with w/c of 0.3 to 0.4, linearly decreases by 14.5%, when the degree of hydration is 30%. Based on this hypothesis, the overall linear reduction in specific heat capacity of concrete including fine and coarse aggregate computed using equation 5, is less than 5.4% from the initial specific heat capacity of OPC concrete. Therefore specific heat capacity of concrete was selected with the maximum value of 1339 J/kg/K adding 5.4% decrease for the sensitivity analysis (see Table 1).

Density of concrete is estimated based on the densities of material in the concrete mix as reported by many authors [7, 8, 14, 15, and 16] and remains unchanged as the total volumetric or mass changes do not occur thorough out the hydration process [26]. Charnockitic gneiss or charnockite, quartzite, marble, dolomite, granulite, migmatite, gneisses and amphibolite are the common Precambrian metamorphic rocks in Sri Lanka [28]. The thermal properties of sand and coarse aggregates are in similar range as sand are naturally created from same rocks origins [29]. The specific heat capacity of gneisses and granulite type rocks are reported in the range of 670 to 1550 J/kg/K [30]. Therefore, the density of concrete was estimated as 2271kg/m^3 to calculate the thermal diffusivity of concrete based on mix M-3.

Table 1: Selected Thermal Properties of Concrete

Thermal Conductivity, λ J/s/m/K	Specific Heat Capacity, c J/kg/K	Thermal Diffusivity, α m^2/s
2.422	1266.69	8.4195E-07
2.422	1339.00	7.9648E-07

Transient heat conduction analysis was performed for a 150 mm concrete cube under external temperature of 40 ^oC. It took nearly 1 hour and 40 minutes to reach the centre temperature to external temperature as shown in Figure 1. It can be also seen that change of specific heat from 1339 to 1276 J/kg/K (i.e.5.4% change) has not significantly affected the temperature response curve.

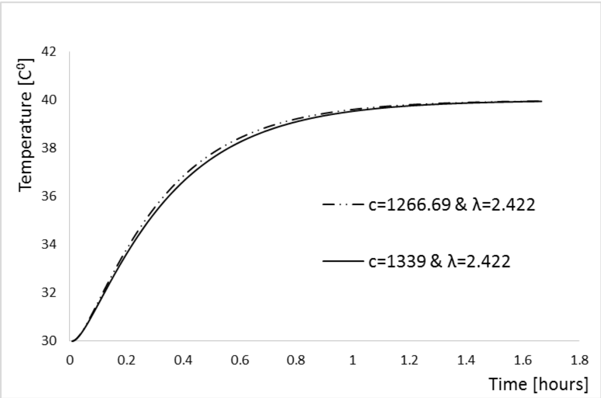

Figure 1: Sensitivity of Temperature Response to Specific Heat Capacity of Concrete

Therefore, thermal conductivity of concrete can be obtained by matching the maximum temperature rise rate of temperature history curves from experiments and transient heat conduction analysis while assuming specific heat capacity being a constant in early age concrete.

3. Experimental Investigation

3.1 Material

In this study the thermal properties of concrete produced with OPC, fine and coarse aggregate available in the local market are considered. The chemical composition, and physical properties of the selected OPC sample are given in Table 2 & Table 3.

Table 2: Percentage of Chemical Composition of OPC

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O
20.94	5.31	3.26	63.40	1.22	2.41	0.20	0.00

Table 3: Physical Properties of OPC

Water Demand %	Soundness (mm)	Setting Time		Residue 45 um	Finenes s (cm^2/g)
		Initial (min)	Final (min)		
29.6	1.1	158.0	202.0	9.6	3093

Mineral components in OPC are Alite (C_3S), Belite (C_2S), Aluminate (C_3A), Ferrite (C_4AF), and Gypsum (($C\dot{S})_3H_2$), where C=CaO, A=Al_2O_3, F=Fe_2O_3, H=H_2O, and $\dot{S}$=SO_3 [6]. Mass proportions of each mineral components were estimated using Bogue method [27] and given in Table 4.

Table 4: Mass Proportions of Mineral Components of OPC

C_3S	C_2S	C_3A	C_4AF	Gypsum
58.59	15.86	8.56	9.92	5.21

3.2 Experimental Setup

The experimental setup shown in Figure 2, consisted of hot water bath connected with thermostat (TST) and thermocouple to maintain constant temperature T_o, Four numbers of standard steel mould were used to cast specimens. Thermocouples were embedded in specimens to measure temperature at the centre of each specimen.

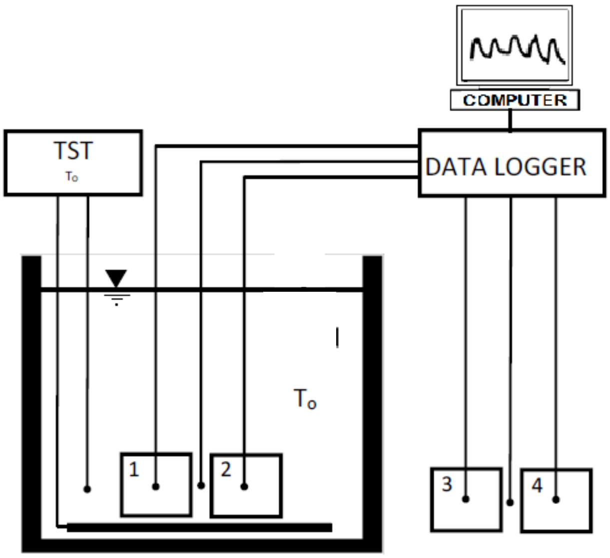

Figure 2: Experimental setup to measure internal temperature rise of specimens using a hot water bath

The steel moulds were carefully filled with the concrete continuously applying vibrations in order to minimize air entrapment. Top surface of the specimens were sealed as shown in Figure 3, to avoid water movement into the specimens.

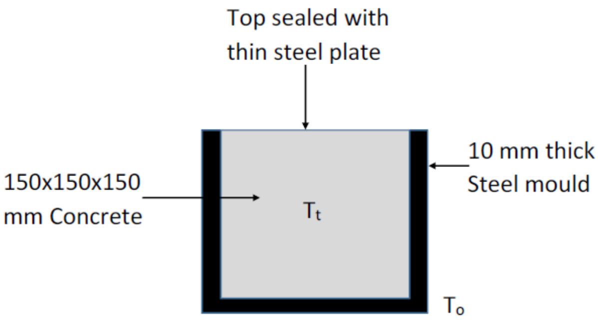

Figure 3: Specimen geometry, dimensions, and boundary conditions

Specimens 1 and 2 were immersed in hot water bath first 2 hours after concrete batching, and the specimens 3 and 4 were placed outside the hot bath exposing to ambient temperature. The temperature at the centre of all specimens were measured at every 30 sec. intervals using a data logger. The specimen 1 & 2 were retained in hot water bath, until the temperature at the centre of specimens were stabilized at the hot bath temperature (T_o). After that, specimens 1 & 2 were removed from the water bath and immersed the specimen 3 & 4 in the hot water bath. Those specimens were kept in the water bath until the temperature at the centre was stabilized. This process was repeated for a duration of 24 hrs. Two specimens were used simultaneously for measuring the temperature response of concrete specimen at a particular age of concrete to minimize the experimental errors. Further these two set of specimens were used to measure temperature response with 10 consecutive time intervals within a day to obtain thermal property variation pattern. Temperature readings were taken at 30 sec. intervals with an accuracy of 0.01 °C, and recorded by data logger.

3.3 Finite Element Model to Estimate Thermal Conductivity

A macro program was written to create FEM with APDL (ANSYS Parametric Design Language) to carry out transient heat conduction analysis incorporating initial (T_i) and boundary temperatures (T_0), thermal conductivity, and specific heat capacity of concrete as input parameters to ANSYS software to predict the temperature variation with time at the centre of concrete cube specimen. Time interval was set as 30 seconds as per the experimental conditions.

A three dimensional isoperimetric and eight node solid element was selected for the thermal analysis. In ANSYS, this element type is called SOLID70. The predicted temperature response curves were fitted with temperature response measured from the experiment by adjusting thermal properties of concrete within the relevant time interval.

3.4 Experimental Plan

Initially, same size concrete specimens with similar arrangement were prepared for the selected mix proportions and peak temperature rise due to heat of hydration was monitored. It was found that maximum temperature difference due to hydration was 2.1 °C at around 07 hours after batching concrete. Therefore for each time interval (approximately 90 minutes), temperature rise due to heat of hydration is approximately 0.7 °C which will not significantly affect the temperature rise due to external heat input from hot water which was kept at 10 °C above the ambient temperature.

Furthermore, keeping the temperature difference, T_o–T_i, around 10 °C helped to minimize the effect of acceleration of cement hydration process due to heating in the hot water bath [6].

The experimental plan was prepared to investigate thermal properties of fresh concrete with different cement contents, w/c, and aggregate contents as given in Table 5.

Table 4: Mix Proportions considered in the experimental investigation

Mix	Cement (kg/m^3)	Sand (kg/m^3)	Coarse agg. (kg/m^3)	Water (kg/m^3)	w/c Ratio
M-1	395	1032	777	201	0.508
M-2	464	930	758	178	0.384
M-3	482	901	732	156	0.324

Mix proportions were selected by varying the w/c in the range of 0.3 ~ 0.5, and total fine and coarse aggregate content in the range of 1633 ~ 2079 kg/m^3.

Hot water bath temperature for all the specimen was maintained approximately at 40 °C and the initial temperature for all the specimens was around 30 °C, which was the mean ambient temperature inside the laboratory. Core temperature of each cube was measured until the inside temperature reached the outside temperature. It took around 01 hour and 40 minutes to achieve this status.

4. Results and Discussion

4.1 Specific Heat Capacity

Specific heat capacities of cement, and concrete were estimated based on equation 2, 3, 4, and 5, and found that the all the measured temperature response curves can be fitted with the specific heat capacity of aggregates at 1150 J/kg/K which is in agreement with the range reported by Julia Chan [30].

Based on DPR, NKR, and mixing theory, the specific heat capacity of cement (OPC) was estimated using the specific heat capacities of C_3S, C_2S, C_3A, C_4AF, and $(C\dot{S})_3H_2$ as 983.3, 1013.7, 1015.5, 923.9, 1347.0 J/kg/K respectively and found as 985.6 J/kg/K. Estimated Specific heat capacities of three mix proportions of concrete considered are given in Table 5.

Table 5: Estimated Specific Heat capacity of Concrete for three Concrete Mixes

Mix	w/c Ratio	Cement Content (kg/m^3)	Water Content (kg/m^3)	Total Aggregate Content (kg)	Specific Heat Capacity, c (J/kg/K)
M-1	0.508	395	201	1809	1377
M-2	0.384	464	178	1688	1348
M-3	0.324	482	156	1633	1323

It can be seen that there is only insignificant variation (4%) in specific heat capacity of concretes with wide variation of w/c (0.508 ~ 0.324) and cement contents (395- 482 kg/m^3).

4.2 Thermal Conductivity

Thermal conductivity of concrete were obtained by fitting with temperature response curve predicted with transient heat conduction analysis using ANSYS, and experimental temperature response data for mixes M-1, M-2, and M-3. Sample analytical fit with measured temperature response data of M-3 specimen 1 & 2 for the time interval between 4 hours 20 minutes ~ 6 hours are given in Figure 4. These curves were fitted with specific heat capacity of 1323 J/kg/K, and thermal conductivity of 2.471 J/s/m/K.

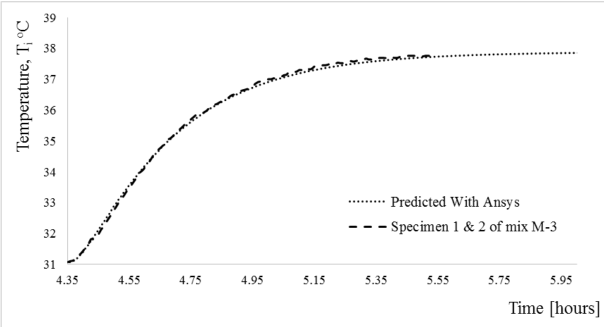

Figure 4: Fitted temperature response curves with relevant experimental data of M-3 specimen 1 & 2

Thermal conductivity obtained based on above described method for three Mixes are shown in Figure 5. The variation of thermal conductivity with time can be expressed as nonlinear curve as shown in Figure 5.

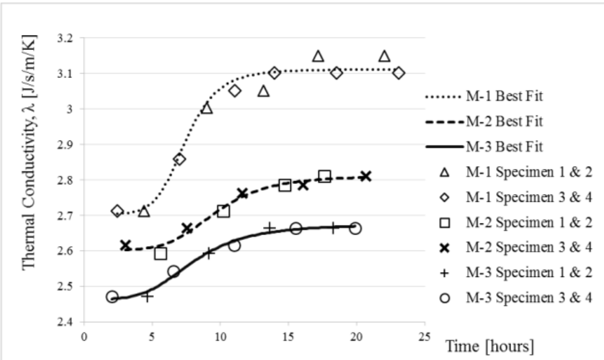

Figure 5: Variation of Thermal Conductivity of Concrete Mixes

It can be seen that the thermal conductivity of OPC concrete follows a unique pattern irrespective of the mix proportions, where it remains constant up to 4 ~ 5 hours and starts to increase up to a maximum value in the range of 2.62 ~ 3.10 J/s/m/K which is fairly in good agreement with values proposed by Kim et al. (2.1 ~ 3.0 J/s/m/K) [9], and Vosteen et al. [10] in previous studies for hardened concrete.

5. Conclusions

Proposed simplified method can be used to investigate thermal properties of fresh and early age concrete.

Specific heat capacities of concrete mixes estimated based on the experimental investigation and rules of Dulong – Petit and Neumann– Kopp are in good agreement with the previous studies.

It was found that the thermal conductivity of concrete increases rapid at early age. The variation of thermal conductivity at fresh state of concrete follows a unique variation irrespective mix proportions, where it remains constant up to 4 ~ 5 hours and starts to increase rapidly and reached a constant value in the range of 2.62 ~ 3.10 J/s/m/K which depends on the mix proportion.

This method can be further developed to study the effect of mix proportion on variation of thermal properties of concrete with hydration and to develop a model to predict the variation of thermal conductivity once the chemical compositions of cement, w/c, and aggregate contents is known.

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