Modelling of Heat of Hydration in Early Age Concrete

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Abstract

Current industry practices rely on the CIRIA C766 spreadsheet program to estimate thermal cracking and temperature development from heat of hydration of concrete. It has certain limitations as it was developed based on Eurocode. The project seeks to utilize finite element modelling which offers more accurate predictions, providing insight into the thermal behaviour of mass concrete structures before construction begins. The primary objectives are to analyse the thermal behaviours of early age mass concrete structures by predicting temperature development under local conditions using finite element modelling software, MIDAS civil, validate those findings with on-site recordings, investigate the effects of supplementary cementing materials (SCMs) on heat of hydration and highlighting mitigation strategies for thermal cracking. This will be achieved by conducting a literature review, isothermal calorimetry test, hot box test and compressive strength test at 7 and 28 days on low heat concrete mixes. Modelling of the Roe Kalamunda Abutment footing has shown that MIDAS civil is successful in predicting the peak temperature achieved in the concrete member during the hydration process. However, there are still discrepancies in terms of heat dissipation which suggests further refinement of the model is necessary.

1. Introduction

The current industry method for predicting thermal cracking and temperature development from heat of hydration in early age mass concrete structures is the CIRIA C766 spreadsheet program which has certain limitations when used in Australia as it is developed based on Eurocode (BS EN 1992-3). Finite element modelling offers more accurate thermal cracking and temperature prediction provided that the inputs are correctly entered. An added benefit of finite element modelling is that the stresses due to temperature can be visualised.

In 2021, Main Roads undertook modelling using the MIDAS civil software for the Roe Kalamunda Bridge abutment footing, however, the model requires further refinement to obtain results that better match the on-site data. Lin (2015) undertook thermal stress analysis of early age concrete structures using experimental testing and finite element modelling. The study predicted temperature and stress development, but the study is based on West Virginia practices and environment and may not fully apply to Western Australia conditions. The study also did not consider external insulation, which could result in higher thermal stresses and temperature developing in the concrete.

1.1 Literature Review

Thermal cracking is a major issue in early-age concrete structures, compromising safety, integrity, and durability. This problem arises from the heat of hydration produced by the exothermic reaction between water and cement. During the early hydration stages, substantial heat is generated. The low thermal conductivity of early-age concrete creates an insulating effect, making it challenging for accumulated heat to escape, which raises the internal temperature of the concrete core. This temperature difference between the core and the surface leads to a non-uniform temperature field. As the concrete cools, tensile stress develops, and when this stress exceeds the concrete's tensile strength, it causes uneven contractions and expansions, eventually resulting in surface cracks (Nguyen et al., 2021).

To address thermal cracking from excessive early-age hydration heat, supplementary cementing materials (SCMs) like granulated blast furnace slag (GGBFS), fly ash (FA), and condensed silica fume (CSF) are used as partial replacements. These materials reduce the heat generated during early-age hydration by altering the time-temperature profile of the concrete (Balim & Graham, 2009; Bourchy et al., 2019). Sarker and McKenzie (2009) investigated fly ash as a partial cement replacement, finding that 30% and 40% fly ash replacements achieved 84% and 63% of the control concrete's strength at 28 days, respectively. At 90 days, the 30% fly ash concrete matched the control strength, and a 20% reduction in maximum temperature was observed with 40% fly ash. Jozic et al. (2023) studied GGBFS, finding that a 40% GGBFS content reduced the total heat released during the first 48 hours by 26.36%. Although GGBFS concretes showed lower initial mechanical properties, these improved over time.

A finite element study on hydration heat using MIDAS/FEA modelled a bridge pier at a quarter scale due to symmetry. The temperature results at three measurement points were compared between measured and simulated data. The simulated data closely aligned with the measured data during initial warming and rapid cooling phases, but simulated temperatures were generally lower. This discrepancy is attributed to real-world factors, such as light affecting concrete hydration heat, leading to slightly higher temperatures than those simulated. During the later slow cooling phase, there is a convergence between simulated and measured data, followed by simulated temperatures exceeding measured ones. This occurs because finite element modelling simulations lack the continuous time representation of concrete hydration and cause slight delay in temperature changes over time (Cui et al., 2022).

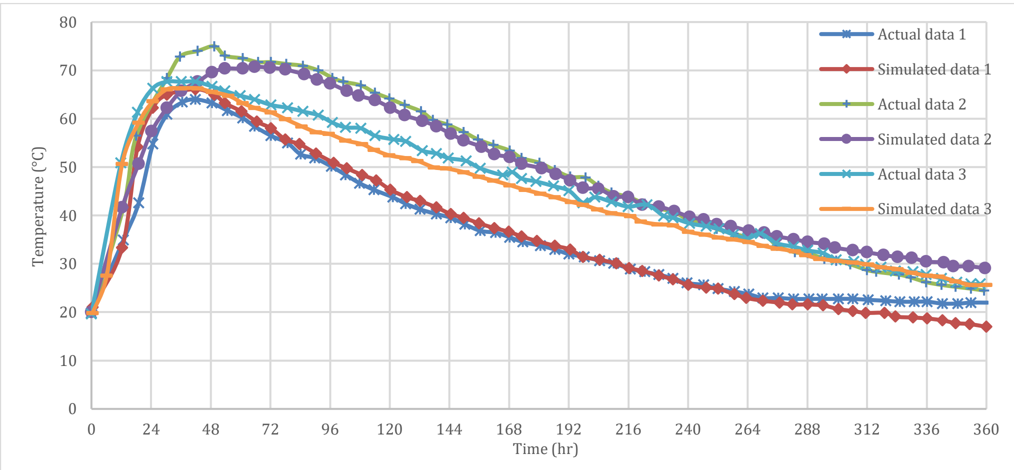

Figure 1 Comparison of measured and simulated values at 3 points recreated (Cui et al., 2022)

2. Modelling and Experimental work

2.1 Modelling

2.1.1 Geometry and Meshing

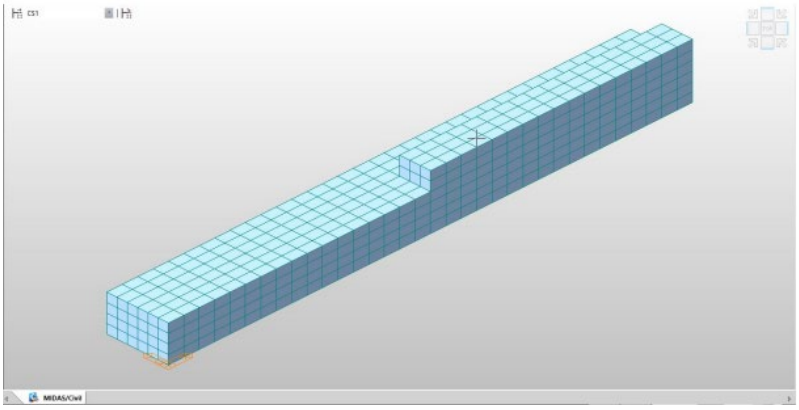

Figure 2 Quarter of Roe Kalamunda Bridge Abutment Footing on soil finite element model in MIDAS Civil

Due to symmetry, only a quarter of the Roe Kalamunda Bridge Abutment footing geometry is required to be created using MIDAS civil as shown in Figure 2. The model has 1613 nodes and 1124 elements. From the structural drawings, the footing has dimensions of 30.6m long x 3.6m wide x 1m high and the soil dimensions are assumed to be double those of the concrete footing at 61.2m long x 7.2m x 2m high. The geometry is meshed with appropriate refinements by conducting a mesh analysis.

2.1.2 Model Inputs

Property	Concrete	Subsoil
Specific Heat (kcal/kg °C)	0.29	0.29
Density (kgf/m^3)	2400	2000
Rate of Heat Conduction (kcal/mhr°C)	2.3	1.7
Convection Coefficient (kcal/m^{-2}hr°C)	4.5	-
Ambient Temperature (°C)	20	-
Casting Temperature (°C)	20	-
91-day compressive strength (kgf/m^2)	4078864.85	-
Modulus of Elasticity (kgf/cm^2)	3.5486×10^5	2.5493×10^3
Thermal Expansion Coefficient	1.0×10^{-5}	1.0×10^{-5}
Poisson's Ratio	0.2	0.2
Unit Cement Content (kg/m^3)	420	-

Table 2 Material and thermal properties input for Roe Kalamunda Bridge Abutment footing modelling

The input information such as convection coefficient and rate of heat conduction presented in table 2 is sourced from a combination of literature, standard MIDAS civil values, and reports from the site. A user defined heat source function for the cement is obtained from the CIRIA C766 temperature prediction in walls and slabs spreadsheet.

2.2 Experimental work

Mix	Total Cementitious Materials (kg/m^3)	Cement (kg/m^3)	Fly Ash (kg/m^3)	GGBFS (kg/m^3)	Water (kg/m^3)	Sand (kg/m^3)	10 mm aggregate (kg/m^3)	20 mm aggregate (kg/m^3)	Water/binder ratio
OPCA	**400**	**400**	**0**	**0**	**171**	**760**	**440**	**701**	**0.43**
FA40A	**415**	**249**	**166**	**0**	**171**	**760**	**440**	**643**	**0.41**
GGBFS65A	**430**	**150.5**	**0**	**279.5**	**171**	**760**	**440**	**654**	**0.40**
OPCB	**450**	**450**	**0**	**0**	**171**	**760**	**440**	**658**	**0.38**
FA40B	**465**	**279**	**186**	**0**	**171**	**760**	**440**	**594**	**0.37**
GGBFS65B	**480**	**168**	**0**	**312**	**171**	**760**	**440**	**608**	**0.36**
FA20	**400**	**320**	**80**	**0**	**171**	**760**	**440**	**680**	**0.43**
GGBFS40	**400**	**240**	**0**	**160**	**171**	**760**	**440**	**689**	**0.43**

Table 2 Concrete mix design

Experimental work will be undertaken to study the thermal power of cement paste as well as compressive strength and hydration heat of concrete with mixes proportions being shown in table 2. These design mixes are commonly used low heat concrete mixes in mass concrete structures. The binder content and water-binder ratio is selected in accordance with Main Roads specification 820 to ensure that the required target strength is achieved. Input from Main Roads personnel also contributed significantly to the concrete mix design.

2.2.1 Isothermal Calorimetry Test

Figure 3 TAM air isothermal calorimeter with 8-channel configuration

The isothermal calorimetry test is a commonly used method to measure the thermal power of cement hydration. The experiment will be performed with the TAM air isothermal calorimeter shown in Figure 3. Each cement paste will be mixed thoroughly by hand and approximately 6g is immediately transferred into glass ampoules and sealed. The temperature of the calorimeter will be set to ambient temperature to reflect the curing method. Once the ampoules are loaded into the calorimeter, the monitoring software will be activated to track the thermal power for a period of three days. The glass ampoule will be in contact with a heat flow sensor that detects the heat leaving the vial to a constant temperature heat sink.

2.2.2 Hotbox Test and Concrete Compressive Strength Test

Figure 4 350mm x 350mm x 350mm cube-shaped moulds for heat of hydration specimens (Sarker and McKenzie, 2009)

The hotbox test is adopted to quantify the heat of hydration of concrete. Each concrete specimen will be cast in cube-shaped moulds with internal dimensions of 350mm x 350mm x 350mm. The moulds were constructed using 18mm plywood and lined with 25mm polystyrene, acting as insulation to reduce heat loss from concrete to simulate the semi-adiabatic temperature rise in mass concrete structures. The mould design in Figure 4 is based off previous research by Sarker and McKenzie (2009). Two thermocouples will be inserted, at the centre and surface of the concrete specimen, to measure temperature during the hydration process. A hole is drilled through the mould to allow the thermocouple to be inserted within the concrete samples. The thermocouples are connected to an electronic data logger, which logs the temperature with respect to time for a period of four and a half days. Placement and ambient temperature will also be recorded during casting. The moulds will be placed on timber sheets so there is no heat transfer to the ground. Compressive strength tests will be carried out using 100mm x 200mm plastic cylinder samples cured in ambient temperature. The cylinders are tested at the ages of 7 and 28 days to measure the compressive strength at early age.

3. Results and Discussion

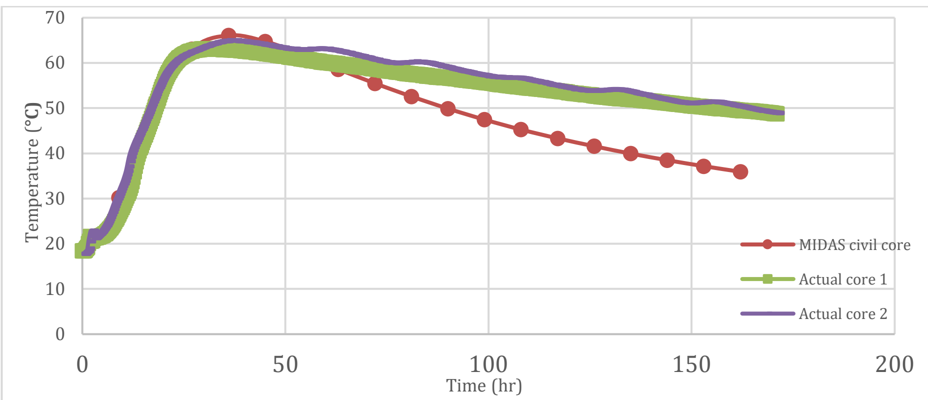

Figure 5 Comparison of temperature result for MIDAS civil modelling and on-site data for Roe Kalamunda abutment footing

The temperature prediction in the core for finite element modelling and on-site data of the footing over a period of 171 hours is plotted on a single graph for comparison as shown in Figure 5. A peak temperature of 66.1 °C at 36 hours is achieved for finite element modelling, whereas the on-site data shows a peak of 65°C and 63.1°C at 36 hours. Overall, the result shows similar peak temperature being achieved at the same time. However, heat dissipates quicker in the finite element model resulting in a larger discrepancy as time passes, indicating that the model still requires some improvements.

4. Conclusions and Future Work

Previous literature clearly shows that finite element modelling can theoretically accurately predict heat of hydration of mass concrete structures. While the current Roe Kalamunda Abutment Footing modelling result shows an accurate prediction in peak temperature, there is a large discrepancy in heat dissipation, which is likely attributed to the lack of heat source and convection coefficient data. In this project, the moulds used for the hotbox test are still under construction. Once the hotbox tests are completed, finite element models will be created using MIDAS civil for temperature prediction comparison. Future works should consider carrying out a concrete adiabatic temperature test to obtain the heat generation data for finite element modelling. Additionally, the hotbox test can be carried out in accordance with the method proposed by CIA Z7/07, which uses a $1m^3$ mould.

5. Acknowledgements

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