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Modelling Early-Age Thermal Gradients in Mass Concrete Pours

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Abstract:
A transient heat transfer model has been established to determine thermal cycling and cracking risks in mass concrete dam construction. The model uses finite difference techniques and Python programming to simulate core heating caused by the exothermic hydration reaction of cement. Temperature data was taken from three test blocks of 30cm, 45cm and 60cm that had been cast within the batching plant. Using waterproof DS18B20 sensors, core, middle and surface temperatures were recorded every 15 minutes over a seven day period using an Arduino micro-controller. Maximum temperature differences between core and surface temperatures where greater than the critical cracking point of 20 degree celsius in lifts greater than 45cm (60cm lift recorded a max difference of 23.4 degree celsius). However, thermal insulation on the surface of the blocks reduced the maximum temperature differences by 38%. Thermal stresses were found to be greater than the tensile strength of the concrete in early ages when using lift heights of 1.5m and 3.0m that are representative of real situations. This provides specific lift thickness values and curing guidelines to reduce cracking due to thermal stress.

I. Introduction:

Mass concrete as classed by the American Concrete Institute (ACI) is concrete that has dimensions in such great volumes that consideration must be given to control the heat of hydration and temperature changes to reduce cracking. Early thermal stress will occur due to the exothermic reaction of Portland cement and water. As concrete is a poor conductor of heat, this heat will transfer through the outside surface quickly causing the heat to build up inside the concrete. This causes large temperature differences (ΔT) between the inside and outside of the concrete. The cooler outside layer of concrete will contract and cause tensional stress as it is being restricted by the hotter inner concrete expanding. This causes cracking if the thermal stress exceeds the tensile strength at an early age. This can cause problems with the structure, reducing durability and watertightness.

To prevent thermal stress cracks forming at an early stage in construction, guidelines have been produced that limit the temperature difference between the centre and surface to a maximum of 20 °C. Previous studies have looked into the analytical and numerical methods used to predict the early age temperatures within the concrete. These range from basic graphical models by Schmidt to complex three dimensional finite element models. However, using a high end finite element programme can require a lot of computing power and specialist knowledge meaning that it cannot always be used on site by engineers. Active cooling methods such as post-cooling pipes are very effective but passive methods are the cheapest way to control temperature within medium scale dam lifts. This can be done by controlling the lift thickness and choosing an appropriate curing method.

This study aims to understand how varying the lift thickness and surface curing method (water vs thermal insulation) will affect the maximum temperature difference between the centre and surface of the concrete over the first 7 days. It will also find the critical lift thickness where ΔT will exceed 20 °C. A one dimensional transient finite difference model has been created and calibrated. It has been coupled with low cost experimental data taken from test blocks at batching plant to provide a useful tool for planning pours on site for dam construction.

II. Methodology:

A combination of physical and numerical techniques were used to assess the early thermal performance of concrete test blocks. The physical testing was undertaken in a working batching plant on a dam construction site ensuring the concrete mix design reflected actual placement conditions.

Experimental Setup and Data Acquisition :

Three unreinforced concrete blocks with cross-sectional dimensions of 100cm x 100cm and thicknesses (L) of 30cm, 45cm and 60cm were cast to mimic single-direction heat transfer through the vertical axis of the blocks. The vertical faces of the blocks were insulated using 50mm expanded polystyrene (EPS) foam board to ensure the sides of the blocks followed the adiabatic boundary condition. This resulted in minimal heat loss to the side faces with most occurring through the top and bottom faces of the blocks. All concrete blocks used the standard structure concrete mix for dams. This consisted of 340kg/m3 Ordinary Portland Cement (OPC 43 Grade) with a water: cement ratio of 0.45. Before casting the blocks three waterproof DS18B20 Digital Temperature Sensors (Accuracy ± 0.5oC) were affixed to a rigid PVC pole at the centre of the blocks. These were placed at the

centre (z=L/2), middle (z=L/4) and close to the surface (z=2cm from top face). This was all connected to an Arduino Uno micro-controller with a real time clock module and SD card data logger. The controllers were programmed to log the temperatures from all sensors every 15 minutes for a total of 168 hours (7 days). One set of blocks was cured by ponding in accordance with standard methods. This meant they were exposed to variations in air temperatures (24oC - 34oC). The other sets were placed under closed-cell polyethylene insulation with a thickness of 25mm. The data from all the sensors was logged with no filtering. During the middle of the day there were small temperature spikes which were also recorded.

Numerical Heat-Transfer and Thermal Stress Modelling :

We formulated a one-dimensional transient heat-conduction model in Python (using NumPy and Matplotlib) governed by the Fourier heat equation with an internal volumetric heat generation term:

$$\rho c_p \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial z^2} + \dot{q}(t)$$

where ρ is concrete density ($2400 kg/m^3$), c_p is specific heat capacity (900 J/kg *K), k is thermal conductivity (2.1 W/m * K), T is temperature (°C), t is time (s), and z is vertical position (m). We modelled the volumetric heat generation rate $\dot{q}(t)$ from the derivative of an exponential adiabatic temperature-rise curve:

$$T_{ad}(t) = T_{max}\left(1 - e^{-\alpha_h t^{\beta}}\right)$$

where T max is the maximum adiabatic temperature increase, α h and β are parameters describing hydration kinetics. The spatial domain was divided up into discrete nodes with Δ z = 0.01 m, and the system was solved using an explicit finite difference scheme (FTCS). A value of Δ t = 10 s was used to ensure stability of the solution according to the Courant-Friedrichs-Lewy criteria. (Fo = α Δ t/Δz 2 ≤ 0.5). Convective boundary conditions were applied to the top surface of the blocks. These had a convection coefficient of 18 W/m 2K for the water cured blocks and an effective convection coefficient of 2.8 W/m 2K for the insulated blocks. Parameters T max , α h and β were found by minimising the Root Mean Square Error (RMSE) between the curves and the measured 7 day block data. Using these parameter values the model was scaled and used to calculate the lift thicknesses for 1.5m and 3.0m scale dams. Peak tensile stresses due to thermal strain σ t were calculated using the following equation;

$$\sigma_t = E(t) \cdot \alpha_T \cdot \Delta T_{max} \cdot R$$

where E(t) is the age dependent elasticity modulus of concrete, αT is the thermal expansion coefficient (10×10 -6 °C -1), ΔT max is the maximum difference between the temperatures of the core and surface and R is the restraint factor of the structure (0.5 was taken for intermediate lifts poured onto hard concrete)

III. Results:

Test Block Temperature Profiles and Model Calibration :

The core temperature increased quickly in the early stages of curing (24-36h) due to rapid hydration of cement before decreasing gradually over the remaining period of monitoring. The surface temperature fluctuated with ambient conditions throughout the water curing process. This created the largest temperature difference between the core and surface at ambient minimums in the early morning (between 36-48h). The adiabatic curing parameters were calculated to give a maximum temperature of 44.2 C, a hydration rate constant of 0.048 h -1 and a heat dissipation constant of 1.12. The results from the 1-D finite difference model showed good agreement with the DS18B20 sensors, with all three block thicknesses showing a low root mean square error of 0.68 C at the core nodes and 0.84 C at the surface nodes.

Effect of Lift Thickness and Curing Strategy :

Table 1 shows the maximum temperatures of core and the maximum temperature difference between core and surface (ΔT max) plus estimated thermal tensile stresses for the test blocks and scaled lifts of full dams during water curing and insulation.

Note: Tensile stress estimates assume a 3-day concrete elastic modulus $E = 22GPa$,
α_T = 10 x 10^{-6} $°C^{-1}$ and restraint factor $R = 0.5$.
↓

Lift Thickness (L)	Curing Strategy	Peak Core Temp (∘C)	Peak ΔTmax (∘C)	Time to Peak ΔT (h)	Estimated Tensile Stress (MPa)	Cracking Status (20 ∘C Limit)
0.30 m (Block)	Water-Cured	46.8	12.1	28.5	1.33	Safe
0.30 m (Block)	Insulated	49.2	7.4	34.0	0.81	Safe
0.45 m (Block)	Water-Cured	53.4	18.6	36.0	2.05	Marginal / Safe
0.45 m (Block)	Insulated	56.1	11.2	43.5	1.23	Safe
0.60 m (Block)	Water-Cured	58.9	23.4	42.5	2.57	Exceeds Limit
0.60 m (Block)	Insulated	61.8	14.5	51.0	1.59	Safe
1.50 m (Field Scale)	Water-Cured	69.5	34.8	68.0	3.83	Exceeds Limit
1.50 m (Field Scale)	Insulated	71.9	19.4	84.0	2.13	Safe
3.00 m (Field Scale)	Water-Cured	74.1	40.2	112.0	4.42	Exceeds Limit
3.00 m (Field Scale)	Insulated	75.4	24.6	138.0	2.71	Exceeds Limit

Threshold Identification :

The parametric analysis showed that without any insulation, at an average ambient temperature of 29 °C, the core/surface temperature gradient would rise above 20 °C at a lift thickness of 0.49 m. With 25 mm of Polyethylene insulation applied to the surface, the heat is trapped within the surface of the concrete and therefore the critical safe lift thickness increased to 1.62 m. This meant an increase by 230% in the single pour maximum lift height. In reality, with the lift height being 3.0 m, the passive water curing (ΔT max = 40.2 °C) and one layer of surface insulation (ΔT max = 24.6 °C) were not sufficient to keep the thermal gradients within safe limits.

IV. Conclusions And Discussions:

This shows that lift height and surface boundary conditions are key factors in controlling early age thermal gradients in mass concrete. Using the validated 1D transient heat conduction model it was shown that any lift heights greater than 0.49m will result in concrete poured without insulation reaching the critical temperature of 20°C for the risk of thermal cracking. This is due to rapid convective and evaporative losses from the top surface of the water cured concrete. Whereas the water curing does help create hydration at the surface, the large amount of heat loss results in high temperature gradients. Insulated surfaces help reduce heat loss from the surface. This means lift heights can be increased to 1.62m before any risk of thermal cracking. However, when using insulated surfaces the temperature at the surface is reduced resulting in lower ΔTmax values (<20°C). However, the peak temperature of the core has increased by 2.4°C compared to the water cured blocks (2.9°C). In structural concrete, if the peak temperatures exceed 70oC then there is also a risk of DEF (Delayed Ettringite Formation). This can cause long term expansion and cracking within the concrete . Therefore, for lift heights of 1.5m using insulated surfaces, since the core reaches 71.9°C , site engineers will have to use low heat cementitious materials (fly ash/slag) or use pre-cooled mixing water alongside the insulated surface to ensure the core temperature doesn't exceed 70°C. For large lift heights of 3.0m, passive insulation alone isn't enough, with ΔTmax reaching 24.6°C. The temperature at the surface will cause a tensile stress of 2.71MPa. It would be necessary to decrease the lift heights or add cooling pipes. The small error in the model compared to the data from the physical concrete blocks (0.84°C RMSE) is due to the lack of consideration for solar radiation gained during the day. Different wind speeds across the batching plant yard were also a factor. Including solar irradiance and wind convection correlations will help increase the accuracy of the surface temperature. Overall this work has shown that cheap sensors (Arduino DS18B20) and a well calibrated Python finite difference solver can produce reliable charts for each concrete mix. Using the charts to determine critical values for active dam projects means site engineers can choose the best lift

height and curing blanket to use. This will significantly reduce the risk of cracking in the early ages of the concrete and help reduce the cost of repairing the structure.

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