THE MODELLING, MONITORING AND CONTROL OF HEAT OF HYDRATION IN THE MAJESTIC CENTRE TRANSFER BEAM

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SUMMARY

The Transfer Beam at Wellington’s Majestic Centre needed to be strengthened by casting a heavily reinforced new beam of high strength concrete on to the existing beam. This required a re-assessment of the performance requirements that had been specified for the concrete; and careful modelling, monitoring and control of heat of hydration effects to ensure that the integrity and durability of the new beam weren’t compromised.

INTRODUCTION

The Majestic Centre is Wellington’s tallest building at 120m in height and provides Grade A office space for up to 2500 tenants. Fletcher Building + Interiors (FB+) are undertaking seismic strengthening works to upgrade the building to 100% National Building Standard (NBS) compliance whilst maintaining 80% tenancy.

The Transfer Beam is a reinforced concrete ring beam at Level 5 which transfers loads from the 24 tower storeys above to the substructure. The seismic strengthening works are designed to increase the capacity of the transfer beam by casting an extension to the underside of the existing beam and using post tensioned high tensile stress bar to connect the new and existing beams.

Due to the large section size and high strength concrete required, peak temperatures and temperature differentials would have exceeded those specified.

The new beam geometry was a function of the required structural performance and constraints of its connection to the existing structure. Eliminating heat of hydration problems through design was not considered possible. The beam could have been cast in a series of thin vertical sections to reduce heat of hydration, however this would have added a month to the project critical path, costing in the region of $800,000 in fixed costs alone. Casting the beam as a single pour met with design approval because concerns regarding the beam’s structural integrity if it were cast in multiple pours no longer applied. Therefore a method of providing robust quality assurance through reliably controlling temperatures in the beam was needed; so that it could be cast in a single pour.
MIX DEVELOPMENT

Specified design requirements of the transfer beam concrete were:
- Nominal 28 day strength 50MPa.
- Maximum 28 day strength 65MPa.
- Minimum cover to reinforcement 40mm.
- Maximum (Core) temperature 65°C.

Construction requirements of the concrete mix design were:
- High workability to facilitate placement using immersion vibrators within highly congested reinforcement of bars up to 32mm diameter.
- Line-pumped up to 70m horizontally and 10m vertically through 4" steel line using a static pump.
- Deep pours of varying height from 650mm to 1450mm – Refer Figure 1. Below
- Varying ambient temperatures due to transfer beam construction taking place from January to August.
- Formwork constructed from two layers of 21mm plywood.

Figure 1: Section A-A Transfer Beam Section 6 (Extract from HCG drawing SO4 – 062 Rev D)
The specified concrete strength, reinforcement, and pumping parameters all require a highly cemented mix. In combination with the large pour dimensions this tends to generate more heat of hydration than would otherwise be the case.

In contrast, the maximum strength and maximum temperature requirements tend to oppose this, requiring a lower cement content mix in order to comply. Not specified, but also of concern, was the potential for a high cement content mix to exceed a 20°C limit (Bamforth, 2007) for the differential between beam core and surface temperatures. This limit is commonly applied to reduce the potential for cracking due to internal restraint caused by differential thermal strain. The most common means of reducing heat of hydration, using a supplementary cementitious material (SCM) as a partial cement replacement, conflicted with the designer’s intent of limiting ultimate strength because of the tendency of SCM mixes to give high ultimate strengths relative to 28 day strengths.

HEAT OF HYDRATION MODELLING

Preliminary Heat of Hydration Modelling

The flange width was constant, so Firth carried out thermal modelling using a one-dimensional numerical model for varying flange heights on the 50 MPa mix and a 45MPa alternative, with and without cooled batch water. Selected results of this modelling are summarised below in Table 1.

<table>
<thead>
<tr>
<th>Nominal Strength</th>
<th>Flange Height (mm)</th>
<th>Season for Ambient Temp. Data</th>
<th>Core Temp (°C)</th>
<th>Temp Differential (°C)</th>
<th>Chilled batch water</th>
</tr>
</thead>
<tbody>
<tr>
<td>50MPa</td>
<td>1450</td>
<td>summer</td>
<td>96</td>
<td>62</td>
<td>N</td>
</tr>
<tr>
<td>50MPa</td>
<td>1450</td>
<td>winter</td>
<td>72</td>
<td>51</td>
<td>Y</td>
</tr>
<tr>
<td>50MPa</td>
<td>650</td>
<td>summer</td>
<td>71</td>
<td>36</td>
<td>N</td>
</tr>
<tr>
<td>50MPa</td>
<td>650</td>
<td>summer</td>
<td>64</td>
<td>32</td>
<td>Y</td>
</tr>
<tr>
<td>50MPa</td>
<td>650</td>
<td>summer</td>
<td>81</td>
<td>12</td>
<td>Y</td>
</tr>
<tr>
<td>50MPa</td>
<td>650</td>
<td>winter</td>
<td>43</td>
<td>23</td>
<td>Y</td>
</tr>
<tr>
<td>45MPa</td>
<td>1450</td>
<td>summer</td>
<td>86</td>
<td>35</td>
<td>Y</td>
</tr>
<tr>
<td>45MPa</td>
<td>650</td>
<td>summer</td>
<td>69</td>
<td>17</td>
<td>Y</td>
</tr>
</tbody>
</table>

Table 1: Thermal Modelling Results for Cement Only Mixes

Each scenario modelled was optimised for formwork stripping time to minimise the impact this would have on exceeding the recommended temperature limits. Even with this optimisation, the majority of likely scenarios would exceed these limits, as indicated in red in Table 1 above. This reinforced the initial conclusion that the specified parameters and additional requirements were incompatible in terms of keeping heat below safe limits; and that some compromises therefore needed to be agreed on.

SCM Strength Modelling

Firth then proposed a reduction in specified nominal 28 day strength and a relaxation of the specified maximum 28 day strength in order to allow use of a Supplementary Cementitious Material (SCM) in the concrete mix to reduce heat of hydration. Firth also proposed a relaxation of the 65°C limit to a more common limit of 70°C.
To support this decision, Firth supplied theoretical estimates of lower and upper bounds of strengths at 28 and 90 days for 50MPa and 45MPa mixes using GP cement only, and mixes modified by the addition of Microsilica 600, Huntly Fly Ash, and Ground Granulated Blast Furnace slag. This data supported our initial hypothesis that a high volume fly ash mix with a specified strength of 45MPa would provide the most cost effective means of reducing the heat generated in the transfer beam while still providing an ultimate strength that exceeded the 50MPa nominal strength originally specified.

After reviewing the data, Holmes Consulting Group (HCG) supported these proposals, and the concrete supply specification was altered accordingly.

Detailed Heat of Hydration Modelling

Following this specification change, further modelling was carried out, summarised in Table 2 below. Historical Metservice data was used to provide likely temperature extremes for the month in question. A full-scale workability/consolidation trial on the original 50MPa cement-only mix provided valuable strength data used to fine-tune the mix proportions of the 45MPa cement/fly ash mix; and FB+I’s program had advanced enough to give more certainty regarding pour dates relative to flange height. This allowed the modelling to be considerably more detailed than the first iteration done six weeks earlier.

<table>
<thead>
<tr>
<th>Flange Height (mm)</th>
<th>Month for Ambient Temp. Data</th>
<th>Core Temp (°C)</th>
<th>Temp Differential (°C)</th>
<th>Chilled batch water</th>
</tr>
</thead>
<tbody>
<tr>
<td>650</td>
<td>Sept.</td>
<td>57</td>
<td>8</td>
<td>N</td>
</tr>
<tr>
<td>650</td>
<td>Nov.</td>
<td>62</td>
<td>8</td>
<td>N</td>
</tr>
<tr>
<td>1450</td>
<td>Jan.</td>
<td>66</td>
<td>40</td>
<td>Y</td>
</tr>
</tbody>
</table>

Table 2: Thermal Modelling Results for 45MPa Cement/Fly Ash Mix

As before, each scenario was optimised to provide the lowest combination of peak temperature and temperature differential. In this case the parameters were:

- Whether polystyrene insulation would benefit the reduction of the temperature differential without adversely effecting peak temperature.
- If so, the optimum thickness of polystyrene sheet to apply as insulation.
- The optimum time elapsed from the start of the pour to stripping the formwork and insulation.
- Whether cooling the batch water would benefit either core temperature or temperature differential.

The results of Table 2 indicate that even when cooling the batch water (an option which would have added to the cost of the concrete), the temperature differential would still exceed the 20°C limit, so although the peak temperature had reduced satisfactorily as result of concrete mix design changes, the temperature differential had not. Firth and FB+I therefore concluded that the concrete should be cooled in-situ to overcome this problem.

FB+I decided that the best method to ensure satisfactory placement and management of heat of hydration was to use the proposed 45MPa mix with a piped cooling system to actively control temperatures. It was agreed with HCG that 25mm steel water pipe could be used and subsequently grouted without negatively affecting the beams structural performance. FB&I undertook further thermal modelling to predict temperature profiles in the beam and help develop a cooling methodology. The thermal analysis was an idealised model based on design guidance outlined in ACI 207.1 R-96 and ACI 207.4 R-93 (Refer to Figure 2). The modelling used formulae and graphical techniques to plot temperatures and thermal gradients across the beam section.
The analysis made the following assumptions:

- No significant thermal effects due to the dense reinforcement cage.
- Concrete supplied at 21°C.
- Minimum coolant water supply temperature of 15 °C.
- Thermal resistivity of insulation (0.7m²K)/W.
- Concrete diffusivity parameters \( K = 5400 \) to 6480 j/hr-m-°C.

The analysis indicated that the greatest thermal gradient would occur between concrete adjacent to the cooling pipes and the core concrete. The thermal modelling estimated that the coolant would gain approximately 5°C through the beam, but heat loss of the coolant outside the beam was unknown. Therefore it wasn’t possible to ascertain whether the coolant would gain temperate at a similar rate to the concrete or lag significantly behind. If the coolant temperature increase lagged significantly behind that of the concrete, too large a thermal gradient between pipes and beam core would have been created. To ensure this gradient was less than 20 °C it was necessary to be able to control the coolant delivery temperature.

![Figure 2: Thermal Modelling Graph of Time vs Temperature at Core](image)
COOLING SYSTEM DESIGN

The analysis suggested that to ensure the thermal gradient didn’t exceed 20 °C it would be necessary to vary coolant temperatures between 25°C and 35°C, and flow rates between 0.1L/s and 0.2 L/s. This would allow the coolant to act as a heat sink whilst limiting the thermal gradient sufficiently to avoid thermal cracking.

In order to provide adequate scope and a safety margin in controlling temperatures, the cooling system was designed to deliver incoming coolant at between 15°C and 40°C irrespective of thermal gains and losses within the circulatory system. This was a greater range of input temperature than the analysis indicated was necessary.

With reference to Figure 3, probes linked to a remote monitoring system provided real time temperature data to the site team so that coolant temperatures and flow rates could be altered as necessary.

Figure 3: Section Showing Cooling Pipe and Temperature Sensor Layout
With reference to Figures 4 and 5, 70m of 25mm diameter steel pipe was installed in two layers of horizontal loops. This pipework was then linked to a circulatory system with a cold and hot water feed and overflow discharge. The system was installed and tested prior to the pour because reliable performance was imperative.

![Diagram of Cooling System](image)

**Figure 4: Cooling System Schematic**

**Figure 5: Schematic Elevation on Cooling System**
POUR EXECUTION AND OPERATION OF THE COOLING SYSTEM

With reference to Figure 7 below, the probes allowed the concrete temperatures to be plotted against time across the beam section which provided a temperature profile. Because monitoring output was in real time, the site team could not only see what the core temperature and temperature differentials were, they could make predictions as to what they would be in the future based on the rate of change of these variables. This allowed them to react and modify the coolant delivery temperatures accordingly.

Coolant temperature gain through the beam was as anticipated, however coolant temperature losses within the circuit but outside the beam were negligible, so the temperature rise in the concrete was faster than anticipated. Therefore, without modification of the coolant temperature, it increased proportionally to that of the concrete. Comparison of the heat of hydration modelling data and the graphs of real time data indicated that the temperature gain of the concrete was on course to reach temperatures above 70°C. However the greatest thermal gradient across the beam section was less than anticipated (approximately 5°C - 7°C).
A limitation of the heat of hydration modelling was that there was no accurate way to consider the effect of the reinforcement on lowering the thermal gradient – possibly due to the “averaging” effect of the reinforcement transferring heat around the beam.

The low thermal gradient provided scope to reduce the coolant delivery temperature and increase its flow rate, which slowed the temperature gain of the concrete and ultimately limited the peak temperature to 58°C, whilst maintaining a thermal gradient of less than 20°C.

The remote monitoring system allowed the site team to understand temperature conditions inside the beam and react to the reality of what was happening rather than what the modelling had anticipated.

**CONCLUSIONS**

Time spent understanding the designer’s requirements allowed the 28 day concrete target strength to be reduced, allowing a reduction in cement content, and therefore reducing some of the potential for heat generation from the concrete. This optimisation resulted in a mix which was line pumped and placed without defects; and all but one section of the transfer beam could be cast without active cooling to control heat of hydration.
For the 1650mm deep pour, thermal analysis provided data on which to make sound construction decisions regarding management of heat of hydration. The thermal analysis had limitations due to the necessary assumptions made during modelling and was used as a guide rather than as an absolute prediction. It was imperative that the influences on heat of hydration and the effect of exceeding temperature limits were understood by the site team and that this informed their methodology.

The cooling system provided the flexibility required to react to and control temperatures in the beam. Altering coolant delivery temperature was done manually after interpreting the remote monitoring data received from inside the beam, and monitoring the coolant pipe thermometers on site.

The end result was a high strength concrete pour, successfully delivered within safe temperature limits; and supported by robust quality assurance data from the thermal monitoring undertaken. The methodology provided programme and cost savings to the client and met all structural requirements.

REFERENCES

ACI Committee report ACI207.1R-96
ACI Committee report ACI207.4R-93
ACI Committee report ACI207.2R-95

ACKNOWLEDGEMENTS

Matt Sullivan - FB+I thermal modelling
Markus Reiberg - peer review of FB+I thermal modelling