Estimation of the heat evolution during the hydration of concrete, mix design of hot concrete, drying and coating of concrete structures

Exercise 6
Estimation of the heat evolution of concrete

- Initial temperature
- Heat of hydration
- Heating
- Heat evaporation
According to the Finnish bridge work specifications the temperature of hardening concrete should not exceed 50 °C, temperature rise 25 °C and the maximum temperature difference between different parts of the structure should not be over 20 °C.

From previous knowledge (tests and calculations) general conclusions can be made when using normal hardening cement:

- The 50 °C value is not generally exceeded when the initial temperature of concrete is ≤ 20 °C, amount of cement ≤ 350 kg/m³ and thickness of the structure 0,9 m
- The 50 °C value is generally exceeded when the initial temperature of concrete is ≥ 20 °C amount of cement ≥ 400 kg/m³ and thickness of the structure ≥ 1,2 m
• 25 °C temperature rise is generally exceeded when the cement content is \( \geq 350 \text{ kg/m}^3 \), thickness \( \geq 1,0 \text{ m} \) and outside temperature \( \geq 0 \text{ °C} \)

• 20 °C maximum temperature difference between different parts of the structure is in general exceeded when the outside temperature is below 5 °C and the only coating is a protective cover (suojapeite)
When low-heat cements are used, the maximum temperature does not in general exceed 50 °C nor does the 25 °C temperature rise if the cement amount is below 400 kg/m$^3$ and thickness ≤ 1,5 m. The only limiting matter is the slow strength development of low-heat cements.

When roughly estimating the temperature rise and maximum temperatures during hydration it’s beneficial to use:

- Previous measurements
- Calculate the temperature rise during a so-called adiabatic state
• The temperature of hardening concrete can be influenced by lowering the initial temperature of the concrete.

• The temperature of concrete is determined by the temperatures of its components after the following formula:

\[
T_b = \frac{T_c m_c c_c + T_a m_a c_a + T_w m_w c_w}{m_c c_c + m_a c_a + m_w c_w}
\]
The specific heat of water is 4.2 kJ/kg °C and for the aggregate and cement 0.8...0.9 kJ/kg °C. Thus the specific heat of water is 5 times larger than the specific heats of other components!

\[
T_b \approx \frac{T_s m_s + T_r m_r + T_v m_v \times 5}{m_s + m_r + m_v \times 5}
\]
The factors affecting the most in the temperature rise of concrete are the amount of cement in concrete and the heat evolution of the cement.

The cement content can be lowered in a concrete composition by:

- Using water reducing admixtures
- Depending on the circumstances using as stiff mix as possible
- Increasing the maximum size of the aggregate
- Using an aggregate composition with favourable grading
By using low-heat cements the temperature rise in the structure can be essentially lowered. The greatest benefit can be achieved if the strength is evaluated at the age of 91 days.
According to the formula all of the following actions lower the temperature of concrete by about 1 °C

- The temperature of cement is lowered by 10 °C
- The temperature of aggregate is lowered by 1,6 °C
- The temperature of water is lowered by 3,6 °C
- Part of the water is replaced with ice slush (jäähile) 6kg/m³
Estimation of the heat evolution of concrete

\[ T_b = T_{bo} + \frac{C}{c_b + \rho_b} \times W + \frac{A_1}{Vc_b \times \rho_b} \times W_u - \sum_{0}^{t} \frac{k_1 A_2}{Vc_b \times \rho_b} \left( T_b - T_u \right) \Delta t \]

In which,
- \( T_b \) = average temperature of concrete(°C)
- \( T_{bo} \) = initial temperature of concrete(°C)
- \( C \) = amount of cement (kg/m\(^3\))
- \( c_b \) = specific heat of concrete (kJ/kg °C)
- \( \rho_b \) = density (specific gravity) of concrete (kg/m\(^3\))
- \( W \) = heat of hydration during the period 0-t (kJ/kg cement)
- \( A_1 \) = area of the heated concrete (m\(^2\))
- \( A_2 \) = area of the cooling concrete (m\(^2\))
- \( V \) = volume of the heated structure (m\(^3\))
- \( W_u \) = during the heating the amount of outside energy brought into the concrete (kJ/m\(^2\))
- \( k_t \) = heat transfer coefficient of surface A2 at the time of calculation(W/ °C m\(^2\))
- \( T_u \) = temperature of outside air(°C)
- \( \Delta t \) = a period which is chosen according to the rate of change of the temperature (h)
Proportion the following mix as heated concrete (+ 50 °C)

- Cement  325 kg/m³
- Water    188 kg/m³
- Aggregate 1835 kg/m³ (moisture content of aggregate 4,2 %)
From empirical data we know that a concrete mix at 50 °C is 1-2 consistency classes stiffer than the same concrete at 20 °C.

From the mix design form we can see that a change of one consistency class requires about 10 l/m³ water. Thus the temperature change requires about 15 l/m³ extra water.
The mix composition is:
WATER $188 + 15 = 203$ kg/m$^3$

The new cement amount from the mix design form when the strength of the concrete stays the same:

$$\frac{188 + 20}{325} = \frac{203 + 20}{C}$$

$\rightarrow C = 348$ kg/m$^3$

AGGREGATE amount by using the basic equation of concrete
$665$ l $\rightarrow 1775$ kg/m$^3$
The temperature of the concrete \( (T_b) \) can be *estimated* using the formula:

\[
T_b \approx \frac{T_s m_s + T_r m_r + T_v m_v \times 5}{m_s + m_r + m_v \times 5}
\]

(or one can use a more precise formula:

\[
T_b = \frac{T_s m_s c_s + T_r m_r c_r + T_v m_v c_v}{m_s c_s + m_r c_r + m_v c_v}
\)
Choose the temperatures

<table>
<thead>
<tr>
<th>Material</th>
<th>m (kg)</th>
<th>T (°C)</th>
<th>T*m</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEMENT</td>
<td>348</td>
<td>20</td>
<td>6960</td>
</tr>
<tr>
<td>AGGREGATE</td>
<td>1775</td>
<td>55</td>
<td>97625</td>
</tr>
<tr>
<td>WATER from aggregate</td>
<td>74,55</td>
<td>55</td>
<td>4100,25</td>
</tr>
<tr>
<td>WATER added</td>
<td>128,45</td>
<td>65</td>
<td>8349,25</td>
</tr>
</tbody>
</table>

\[ T_b = \frac{6960 + 97625 + 5 \times (4100,25 + 8349,25)}{348 + 1775 + 203 \times 5} \]

\[ \rightarrow 53 °C \quad \text{OK} \]
A conventional concrete structure dries slowly

- When the height of the structure is 100 mm and it can dry to both directions, about half of the structural humidity exits during 3 to 12 months, depending on the density of the structure.

- The time to dry quadruples when the thickness of the structure doubles!

- The time to dry quadruples when the structure can only dry to one direction.
• Raising the temperature +20 °C → +50 °C speeds up the drying process 2 to 4 times. However the relative humidity of the surrounding air must be kept sufficiently low.

• By choosing the right concrete composition, the drying can be speeded up by 2 to 10 times

• Especially harmful for concrete drying is if excess water (from wet curing, exposure to the weather) comes into contact with the structure after casting
A preliminary drawing of equilibrium moisture contents of different concretes

Picture from by 45 / BLY 7
Betonilattiat 2002
page 140
The hysteresis phenomenon causes the equilibrium moisture content in weight -% to be higher while drying.

From by 45 / BLY 7
Betonilattiat 2002
page 140
Determination of moisture content in concrete:

1. **Plastic sheet test.** 1 m x 1 m piece of plastic is placed on the concrete and sealed around the edges by taping them down to the concrete. After 24 hours (or a week) the sheet is removed and the area inspected for evidence of moisture.

2. **Hygrometer test.** A hole is drilled into the concrete, left to stand for 1 to 7 days to allow the air in the hole to achieve equilibrium and a probe then placed into the hole to measure the relative humidity. The hygrometer test is the most widely used method in Europe for determining whether the concrete is dry enough.

3. **Gravimetric moisture content test.** A full-depth core sample from the slab is taken using a dry-cut process. The sample is dried in an oven until a constant weight is reached and the moisture content is determined from the mass of the core and difference between initial and final weights.

4. Other methods and additional information, see for example: RT 14-10675, BETONIN SUHTEELLISEN KOSTEUDEN MITTAUS KOSTEUDEN MITTAUSMENETELMIEN VERTAILUA, Erika Halsas BETONIRAKENTEIDEN KOSTEUSMITTAUS JA KUIVUMISEN ARVIOINTI, Tarja Merikallio MOISTURE IN CONCRETE AND MOISTURE-SENSITIVE FINISHES AND COATINGS, CCAA
Taulukko 4.9
Likimääräinen aika lattiabetonin kuivattamiseksi 90% suhteelliseen kosteutteen /3/. Suhteellinen kosteus tulee mitata ennen pinnoittamista. Taulukon kertoimet ovat ohjelliset.

PERUSTAPAUS

- Betonin ilmanäärä normaali 2...4 %
- Kuvumisaika 28 d ennen kuivumisajan aikua
- Kuvun värin ärsyyttäminen
- Jälkikatto
- Betoniin ei saa joutua lisävetää (kastelu, sade ym.)

Perustapauksen kuivumisaika
60 d

PERUSTAPAUKSESTA POIKKEAMINEN

Perustapauksesta poikkeavat rakenne, betonin laatuvaiheisuuat ja ympäristöolosuhteet otetun huomioon kertomalla perustapauksen terpeellinen kuivumisaika 60 d seuraavilla kehyksissä olevilla kertoimilla.

<table>
<thead>
<tr>
<th>Muuttuja</th>
<th>Kerroin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Betonin laatu</td>
<td>Muokkamaton, Kuivukostos noin 10%</td>
</tr>
<tr>
<td>1...2 viikkoa</td>
<td>0,7...0,8</td>
</tr>
<tr>
<td>3...4 viikkoa</td>
<td>0,9...1,0</td>
</tr>
<tr>
<td>Kuivumis- olosuhteet</td>
<td></td>
</tr>
<tr>
<td>Suht. kosteus</td>
<td>20...50%</td>
</tr>
<tr>
<td>Lämpötila</td>
<td>10°C</td>
</tr>
<tr>
<td>Kuivumisaika 60 d</td>
<td>&lt;150</td>
</tr>
<tr>
<td>Laatan paksuus</td>
<td>[mm]</td>
</tr>
<tr>
<td>Betonin ikä kuivustusta aloitettaessa</td>
<td></td>
</tr>
<tr>
<td>Alapuolen lämmöneriste</td>
<td>50 mm solumuovi, 150 mm kveitsora, 50 mm minerailukvi</td>
</tr>
<tr>
<td>Betonin koostumus</td>
<td>Suurin raeokko, 18 mm, 8 mm</td>
</tr>
<tr>
<td>Lentotuhka ja masuunikuona</td>
<td>1,0</td>
</tr>
<tr>
<td>Silika</td>
<td>K&gt; K35</td>
</tr>
<tr>
<td>Notkeus</td>
<td>2...3 sVb, 1...2 sVb, 1...2 sVb notkisitamin lisääneellä</td>
</tr>
</tbody>
</table>
The flooring is to be done with plastic/vinyl plates (muovilaatta). How long must one wait from the casting until the flooring can be installed? The structure, environment and the concrete specifics are:

- Concrete slab, thickness 80 mm, strength K30
- Under the slab 50 mm cellular plastic, plastic film and gravel
- The slab is not wetted, curing is done with plastic sheets for 2 weeks
- At the time of drying the temperature is estimated at +16 °C and relative humidity at 60 %
- The maximum size of aggregate in the concrete is 8 mm, binder 50 % CEM II A 42,5 R and 50 % GGBS, consistency 1...2 sVB
<table>
<thead>
<tr>
<th>Relative Humidity of the Hole Drilled into the Concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>80</strong> Betonin Pintaosien (2...3 cm) oltava alle 75%</td>
</tr>
<tr>
<td>Mosaickiparketti 1)</td>
</tr>
<tr>
<td>Puudajaokhtainen (esim. pyökkö 80 %, tamm 85 %)</td>
</tr>
<tr>
<td>Lautaparketti 2)</td>
</tr>
<tr>
<td>Huopa- tai solumuovipohjai-set muovimatkot</td>
</tr>
<tr>
<td>Kumi matot</td>
</tr>
<tr>
<td>Korkkilaatit, laatojen alopinnassa kosteudeneristys</td>
</tr>
<tr>
<td>Tekstiliimatot, jossa on alusrakenne (kumi, PVC, kumitekoiselly)</td>
</tr>
<tr>
<td>Luonnont materiaalista tehdty tekstiliimatot ilman alusrakenne</td>
</tr>
<tr>
<td>Kosteusliikkueet</td>
</tr>
<tr>
<td>Kosteus liikkueet, puulakiho (esim. pyökkö 80 %, tamm 85 %)</td>
</tr>
<tr>
<td><strong>85</strong></td>
</tr>
<tr>
<td>Muovilastat</td>
</tr>
<tr>
<td>Puulakihojaan kuvaajan huopa- tai solumuovipohjaa</td>
</tr>
<tr>
<td>Linoleum</td>
</tr>
<tr>
<td>Alustaan kiinnittämätömät puulat (lautaparkeet 3)</td>
</tr>
<tr>
<td>Puun ja betonin välissä kosteudeneristys ja sen alla kosteuden poistokanavointi</td>
</tr>
<tr>
<td>Polyyuretan muovimassat</td>
</tr>
<tr>
<td>Täysysteettiset tekstiliimatot ilman alusrakenne (enikoistapauksissa suht. kosteus &lt;97%)</td>
</tr>
<tr>
<td>Keraaminen laatoitus</td>
</tr>
<tr>
<td><strong>90</strong></td>
</tr>
<tr>
<td>Epoks-, akryyli- ja polyeet-rimuovimassat</td>
</tr>
<tr>
<td>Sementtipolymeripinnoteet</td>
</tr>
<tr>
<td>Betonin pinnan on oltava muovi-massaa levitetussa kivila sekä riittävän lämmön, muussa tapauksesessa pinta on kuivattava välittömästi ennen massan levitystä esim. säteilylämmityksellä kovettuun missionary ja tarkunnan varmistamiseksi</td>
</tr>
<tr>
<td>Betonin pinta kostea mutta ei rovettua, Huom. valmistajan ohjeet!</td>
</tr>
</tbody>
</table>

From by 45 / BLY 7
Betonilattiat 2002 page 132
A chart from the by 45 / BLY 7 can be used to estimate the time for the structure to dry

Coefficients:

1. Concrete no air entrainment (1,0), K30 (1,0)
2. The age of concrete at the beginning of the drying process 2 wks, thickness of the slab 80mm (< 150mm) (0,8)
3. At the time of drying the temperature is estimated at +16 °C (about 1,2) and relative humidity at 60 % (1,2)
4. thickness of the slab 80mm (0,7)
5. Under the slab 50 mm cellular plastic, plastic film and gravel (1,0)
6. Effect of the concrete composition:
   - Maximum size of aggregate 8mm (1,0)
   - Binder (1,0)
   - consistency (1,2)
Time from casting

14 + (1*0,8*1,2*1,2*0,7*1,0*1,0*1,2)*60
= 14 + 0,97*60 = 72 days
\approx 2,5 months!
How long would it take for the concrete to dry so that parquet/hard wood floors could be installed?

From practice it is known that drying concrete to RH of 80 % takes 2 to 4 times longer than to 90 %. Thus it would take about 4...8 months!
How to shorten the time for drying?