Modelling of drying phenomena in concrete with recycled aggregates

Master’s thesis presented to obtain the degree of Master of Science (MSc) in Civil Engineering

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Promotors: L. COURARD and F. COLLIN - Academic Year 2019-2020
Purpose of this thesis

- Concrete: 1 billion tons/year in EU
- Natural Aggregates (NA): 2.8 billion tons (all uses) in EU (2017)
- C&D Waste: 374 million tons in EU (2016) (30% total)

→ Recycled Concrete Aggregates = NA + Residual cement paste
Purpose of this thesis

- RCA: increased porosity and water absorption
- Water is the cause of many degradations processes because it favours ions penetration
Purpose of this thesis

Is the use of Recycled Concrete Aggregates (RCA) inside concrete affecting its durability from a point of view of water transfers?

→ Modelling of water flows inside concrete

→ Parameters obtained through several experiments
Experimentation

Compositions

- **C-NA**: NA with CEM I (Dreux-Gorisse)
- **C-NA-CEMIII**: NA with CEM III (Dreux-Gorisse)
- **C-RCA**: RCA with CEM I (Constant volume)
- **M1-CEMI**: Mortar with CEM I (Dreux-Gorisse)
- **M2-CEMI**: Mortar with CEM I (C.E.M.)
Experiments & Concrete’s properties

- Water Absorption Immersion → Densities and porosity
- Water permeability → Intrinsic permeability
- Static (De)Sorption → WRC and Van Genuchten’s model
- DVS → WRC and Van Genuchten’s model (only mortars)
- Convective drying → Mass and heat transfer coefficients → Validation of the model
- Carbonation → Carbonation depth
Application
Mesh & Applied conditions

Initial Conditions:
• Saturated
• 21°C
• Atmospheric p.
Application
Applied conditions

\[ RH \in [40; 95] \% \]
\[ T \in [-5; 25] \degree \text{C} \]

- January: 95% of RH for a temperature of -5°C
- July: 40% of RH for a temperature of 25°C
The Table 7.9 displays the values of the parameters used for the modelling of the application for both compositions studied. As no convective drying experiments have been achieved on those concretes, it is not possible to determine experimentally the two mass and heat transfer coefficients, \( \alpha \) and \( \beta \) respectively, and it was thus decided to use the same coefficients as for the expertise. Those coefficients assume a wind speed of 3 m/s, which is not unbelievable but maybe high for a parking column. However, those are the most important in the beginning of the drying, during the CRP, and their value is therefore not critical for our application. As for the seepage penalty coefficient, it was fixed to zero as seepage isn't required while working with such environmental conditions.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>C-NA</th>
<th>C-RCA</th>
<th>Experimental source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density of the solid grains (( \rho_s )) [kg/m(^3)]</td>
<td>2630</td>
<td>2557</td>
<td>Water Absorption Immersion</td>
</tr>
<tr>
<td>Concrete’s intrinsic permeability (( k_{int} )) [m(^2)]</td>
<td>7.68E-20</td>
<td>1.04E-19</td>
<td>Water Permeability</td>
</tr>
<tr>
<td>Concrete porosity (( n )) [-]</td>
<td>0.156</td>
<td>0.205</td>
<td>Water Absorption Immersion</td>
</tr>
<tr>
<td>Van Genuchten’s model parameter (( m_{vG} )) [-]</td>
<td>0.32</td>
<td>0.31</td>
<td>Static Desorption</td>
</tr>
<tr>
<td>Van Genuchten’s model parameter (( n_{vG} )) [-]</td>
<td>1.47</td>
<td>1.44</td>
<td>Static Desorption</td>
</tr>
<tr>
<td>Air entry pressure (( \alpha_{vG} )) [MPa]</td>
<td>23.4</td>
<td>19.88</td>
<td>Static Desorption</td>
</tr>
<tr>
<td>Minimal concrete’s relative permeability [-]</td>
<td>1E-4</td>
<td>1E-4</td>
<td>-</td>
</tr>
<tr>
<td>Seepage penalty coefficient (( K )) [m/s.Pa]</td>
<td>0</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>Mass transfer coefficient (( \alpha )) [m/s]</td>
<td>0.0236</td>
<td>0.0236</td>
<td>(from expertise)</td>
</tr>
<tr>
<td>Heat transfer coefficient (( \beta )) [W/m(^2).K]</td>
<td>31.42</td>
<td>31.42</td>
<td>(from expertise)</td>
</tr>
</tbody>
</table>

- Parameters for the modelling obtained from experimentations
- Main differences: Permeability, Porosity and WRC
Application

Results

Evolution of the mass with respect to time

- C-NA
- C-RCA
- RH=40% and T=25°C
- RH=95% and T=-5°C

Time [month]

$m/m_0$ [-]
Evolution of the Saturation Degree after $t_0 = 36$ months (Sorption)

Liquid water and vapour flows
Application

Results

Evolution of the Saturation Degree

- C-NA : H/2 from D.S.
- C-NA : H/4 from D.S.
- C-NA : Drying Surface (D.S.)
- C-RCA : H/2 from D.S.
- C-RCA : H/4 from D.S.
- C-RCA : Drying Surface (D.S.)

Saturation Degree $S_{r,w}$

Time [month]

0 10 20 30 40 50 60

0.4 0.5 0.6 0.7 0.8 0.9 1

20cm
Application

Results

Evolution of the saturation with time for C-NA

Evolution of the saturation with time for C-RCA
Conclusion

- Using RCA → Increased porosity, permeability and WRC
  → More water flows and easier exchanges
  → Decrease of durability

The use of Recycled Concrete Aggregates (RCA) inside concrete reduces the durability of concrete due to its composition and physical properties.

- 100% substitution of NA by RCA
- RCA from concrete made in laboratory
- Other degradation processes to be experimentally studied
Thank you for your attention.
Perspectives

• Further testing and replications of the experiments conducted
• Convective drying for our C-NA and C-RCA (among others)
• Mercury porosimetry
• Resistance to chloride attacks
• Implementing the WRC’s hysteresis in Lagamine
• Using real RCA from real C&DW
Literature Review

Porosity of Concrete

From [Ollivier & Torrenti, 2008]

From [Bentur & Odler, 1996]
Literature Review

Porosity of Concrete

From [Bertolini et al., 2004]

From [Hubert, 2018]
Literature Review

Convective Drying (Kinetics)

From [Hubert, 2018]
Literature Review
Convective Drying (Kinetics)

Preheating Period

Time increases with decreasing water content

From [Hubert, 2018]
Literature Review
Convective Drying (Kinetics)

Constant Rate Period (CRP)

Time increases with decreasing water content

Drying Surface
Saturation Front

From [Hubert, 2018]
Literature Review
Convective Drying (Kinetics)

From [Lehmann et al., 2008]
Literature Review
Convective Drying (Kinetics)

Falling Rate Period (FRP)

- Time increases with decreasing water content
- Drying rate vs. water content
- From [Hubert, 2018]
Boundary Layer Model

Fick’s Law

Darcy’s Law

Solid matrix
Air + vapour
Liquid water

Porous medium surface

\[ \beta = \frac{L \bar{q}_{CRP}}{T_{air} - T_{wb}} \]

\[ \alpha = \frac{\bar{q}_{CRP}}{\rho_{v,surf} - \rho_{v,air}} \]

From [Hubert, 2018]
Experimentation
Micro-photography

Composition: C-NA
Experimentation
Micro-photography

Composition: C-NA-CEMIII
Experimentation
Micro-photography

Composition: C-RCA
Experimentation

Micro-photography

Composition: M1-CEMI
Experimentation
Micro-photography

Composition: M2-CEMI
**Experimentation**

**Water Absorption by Immersion**

![Graphs showing dry density, humid density, theoretical density, and density after unmoulding for different samples.](chart)

- **Dry density from WAI**

- **Humid density from WAI**
  - C-NA: 2376, C-NA-CEMIII: 2354, C-RCA: 2238, M1-CEMI: 2266, M2-CEMI: 2226

- **Theoretical density**
  - C-NA: 2300, C-NA-CEMIII: 2314, C-RCA: 2189, M1-CEMI: 2161, M2-CEMI: 2122

- **Density after unmoulding**
  - C-NA: 2300, C-NA-CEMIII: 2313, C-RCA: 2182, M1-CEMI: 2135, M2-CEMI: 2122
Experimentation

Water Absorption by Immersion

Water absorption from WAI

<table>
<thead>
<tr>
<th>Material</th>
<th>Water Absorption [% mass]</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-NA</td>
<td>7</td>
</tr>
<tr>
<td>C-NA-CEMIII</td>
<td>7.7</td>
</tr>
<tr>
<td>C-RCA</td>
<td>10.1</td>
</tr>
<tr>
<td>M1-CEMI</td>
<td>7.4</td>
</tr>
<tr>
<td>M2-CEMI</td>
<td>12</td>
</tr>
</tbody>
</table>

Porosity from WAI

<table>
<thead>
<tr>
<th>Material</th>
<th>Porosity [% volume]</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-NA</td>
<td>15.6</td>
</tr>
<tr>
<td>C-NA-CEMIII</td>
<td>16.8</td>
</tr>
<tr>
<td>C-RCA</td>
<td>20.5</td>
</tr>
<tr>
<td>M1-CEMI</td>
<td>15.1</td>
</tr>
<tr>
<td>M2-CEMI</td>
<td>23.8</td>
</tr>
</tbody>
</table>
Experimentation
Vapour Control Drying

Static Sorption:
Evolution of the Relative Humidity

Static Desorption:
Evolution of the Relative Humidity
Experimentation
Vapour Control Drying

Cumulative mass gain of the Chamber 1:
Sorption at RH = 83.79%

Cumulative mass loss of the Chamber 1:
Desorption at RH = 84.66%

[Graphs showing mass gain and loss over time for different materials]
Experimentation
Vapour Control Drying

Water retention curve for C-NA (desorption)
\(n_{VG}=1.47\) and \(\text{Alpha}_{VG}=23.4\) MPa

Relative permeability for C-NA (desorption)
\(m_{VG}=0.32\)
Experimentation

Vapour Control Drying

Water Retention Curve

Saturation Degree $S_r$ [-]

Suction $s$ [MPa]

- C-NA in Desorption
- C-RCA in Desorption
- M1-CEMI in Desorption
- M2-CEMI in Desorption
- C-NA-CEMIII in Desorption
- C-NA in Sorption
- C-RCA in Sorption
- M1-CEMI in Sorption
- M2-CEMI in Sorption
- C-NA-CEMIII in Sorption
Experimentation
Dynamic Vapour Sorption (DVS)

Time vs. Mass

RH vs. Mass

Complete
Final value

M1-CEMI
Experimentation
Dynamic Vapour Sorption (DVS)

Water retention curve
\( n_{VG} = 2.51 \) and \( \text{Alpha}_{VG} = 72.55 \) MPa

Relative permeability curve
\( m_{VG} = 0.6 \)
Experimentation
Dynamic Vapour Sorption (DVS)

Time vs. Mass

RH vs. Mass
Experimentation
Dynamic Vapour Sorption (DVS)

Water retention curve
\( n_{VG} = 2.45 \) and \( \alpha_{VG} = 69.62 \) MPa

Relative permeability curve
\( m_{VG} = 0.59 \)
Experimentation
Convective Drying (Micro-dryer)

Mass loss with time

Krischer's curve

Sample 1
Sample 1 - Filter
Sample 2
Sample 2 - Filter

Drying rate [kg/(m²s)]

Normalized moisture content [-]
Experimentation
Convective Drying (Macro-dryer)

Mass loss with time

Krischer's curve

Drying rate [kg/(m²·s)]

Normalized moisture content [-]
Resistance to Carbonation

Experimentation

Final value of the Carbonation depth
(after 61 days)

Carbonation depth [mm]

Face 1  Face 2  Face 3  Face 4

C-NA  C-NA-CEMIII  C-RCA  M1-CEMI  M2-CEMI
Experimentation
Water Permeability

Intrinsic permeability of each composition

<table>
<thead>
<tr>
<th>Composition</th>
<th>Intrinsic Permeability [m^2]</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-NA</td>
<td>7.68e-20</td>
</tr>
<tr>
<td>C-NA-CEMIII</td>
<td>1.22e-20</td>
</tr>
<tr>
<td>C-RCA</td>
<td>1.04e-19</td>
</tr>
<tr>
<td>M1-CEMI</td>
<td>4.08e-19</td>
</tr>
<tr>
<td>M2-CEMI</td>
<td>9.01e-21</td>
</tr>
</tbody>
</table>
Experimentation
Water Permeability

Water Permeability for C-NA ($k_{int,mean} = 7.68 \times 10^{-20} \text{ m}^2$)

- Sample 1
- Sample 2

$k_{int} = 2.76 \times 10^{-20} \text{ m}^2$

$k_{int} = 1.26 \times 10^{-19} \text{ m}^2$
Experimentation

Water Permeability

Water Permeability for C-RCA ($k_{\text{int,mean}} = 1.04\times10^{-19} \text{ m}^2$)

- Sample 1: $k_{\text{int}} = 8.28\times10^{-20} \text{ m}^2$
- Sample 2: $k_{\text{int}} = 1.26\times10^{-19} \text{ m}^2$
Water Permeability

Water Permeability for M1-CEMI ($k_{\text{int,mean}} = 4.08\times10^{-19} \text{ m}^2$)

- **Sample 1**
  - $k_{\text{int}} = 3.88\times10^{-19} \text{ m}^2$
- **Sample 2**
  - $k_{\text{int}} = 4.27\times10^{-19} \text{ m}^2$
Modelling
Validation (M1-CEMI)
Modelling
Validation (M1-CEMI)

Evolution of the mass with respect to time

- Experimental Results (Raw)
- Experimental Results (Filter)
- Model from Experimental Data (RH = 3% and measured porosity)
- Model from Experimental Data (RH = 17% and increased porosity)
- Fitting
Modelling
Validation (Expertise’s concrete)
Modelling

Validation (Expertise’s concrete)

Evolution of the mass with respect to time

Time [hours]
Application
Mesh and applied conditions

FMIVP: Water flux depends on the RH ($p_c$) and $T^\circ$ of the environment as well as on the $\neq$ of densities between the vapour of the drying air and the vapour of the drying surface.

Initial Conditions:
- Saturated
- 21°C
- Atmospheric p.
Water Retention Curve

Application

Water retention curve

Relative permeability curve
Application

Results

Water retention curve

Relative permeability curve

- C-NA
- C-RCA

RH = 40%
RH = 95%
RH = 40% and T = 25°C
RH = 95% and T = -5°C

Saturation Degree $S_r$ [-]

Relative permeability [-]

Suction $s$ [MPa]

Saturation Degree $S_r$ [-]
Application

Results

Evolution of the mass with respect to time (variable temp.)

- C-NA
- C-RCA
- WRC
- Porosity
- Intrinsic permeability
- RH=40% and T=25°C
- RH=95% and T=-5°C
Application

Results

Evolution of the Saturation Degree (variable temp.)

Saturation Degree $S_w$

Time [month]

C-NA : H/2 from D.S.
WRC : H/2 from D.S.
n : H/2 from D.S.
k_{int} : H/2 from D.S.
C-RCA : H/2 from D.S.