Hygrothermal performance of innovative renovation renders used for different types of historical masonry

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Abstract

A combined experimental-computational approach is applied for the estimation of service life of innovative renovation renders. In the experimental part, the durability of two commercial renovation renders is determined in terms of their frost resistance, together with two newly developed renovation plasters that are supposed to be produced commercially in the near future. The computational part is aimed at the investigation of freeze-thaw cycles that may occur in surface layers of the plaster during its life time period. To achieve this, a diffusion type model of coupled heat and moisture transport is used. As a load-bearing structure several materials which are characteristic for historical buildings are chosen, namely ceramic brick, sandstone and arenaceous marl.

Keywords: service life, renovation renders, heat transport, moisture transport, experimental analysis, frost resistance.

1 Introduction

In the current practice of historical buildings renovation, the service life of new surface layers is estimated mostly on the basis of experience, because too few parameters are known for reliable durability estimate. Usually the durability is given by the producer of the renovation render, who provides a warranty period only in the case that the technological process is followed precisely. The service life of a new surface layer made of renovation render is usually declared between 10 and 15 years. Unfortunately, the real service life is much lower if we take into account climatic conditions, location of the building, local building environment.
and last but not least, the material composition. As has been proven [1–4], a proper material configuration of the building envelope may significantly extend its service life. Combination of improperly chosen materials can lead to damage caused by moisture transport through the interface between materials [5].

In this paper, a method, not frequently used until now, is applied for the solution of the problem of damage of surface layers of historical buildings. The method consists of a combination of computational and experimental approaches. In the experimental part, the durability of several innovative renders developed under laboratory condition on a lime-pozzolana basis is determined in terms of their frost resistance. In the computational part, the number of frost cycles in a real structure is identified using a computational analysis. In addition, the computer code involves the effect of hysteresis of moisture transport and storage parameters; this brings the results of the computations nearer to reality. With the knowledge of the yearly number of freeze-thaw cycles in the surface layers, the service life of renovation renders can be determined by comparison with laboratory experiments.

Prediction of moisture and temperature fields in the building envelope parts of historical buildings over a sufficiently long time makes it possible not only for a reliable assessment of durability of surface layers on the basis of a sufficient amount of input parameters, but also for a design of the time schedule of repeated repairs. It can also offer to the supervisory authorities alternative solutions of surface layers taking into account their durability and financial demand.

2 Studied building envelopes

The studied building envelope is presented in fig. 1. It consisted of a load-bearing structure and single layered renovation plaster on the exterior and interior side.

![Scheme of studied envelope](image)

**Figure 1:** Scheme of studied envelope.

Three different kinds of materials of load-bearing structure were considered – ceramic brick, sandstone and arenaceous marl – together with two commercial renovation plasters (CRP₁ and CRP₂) and two laboratory developed systems of renovation plasters which are supposed to be produced commercially in the near future (LRP₁ and LRP₂).
The thickness of the load-bearing structure was 600 mm for all materials; the thickness of renovation plaster was 10 mm for interior side and 20 mm for exterior side. The investigated point was placed into the exterior plaster, 2 mm from the exterior surface in order to determine the number of freeze/thaw cycles.

3 Experimental

In the experimental work, the frost resistance of the chosen plasters was investigated under laboratory conditions according to ČSN 72 2452 “Testing of frost resistance of mortar”. The specimen had dimensions of 40×40×160 mm. After removal from the moulds they were placed into open boxes and humidified once per day until the end of the 28-days curing period. Temperature in the laboratory was 21±1°C, relative humidity was 45±5%.

In order to measure freeze-thaw resistance of renovation renders, the water saturated testing specimens were cyclically frosted and defrosted until their damage got apparent. Three testing specimens of every plaster were put into water having temperature of 20±1°C until their full saturation. After that, the specimens were removed from water and then they were wiped by paper towel and put into plastic bag. Packed specimens were put into a freezing box for at least 4 hours at a temperature of −20±3°C. After removal, the specimens were kept in the laboratory with a temperature of 20±1°C for 2 hours, and then were put into water for 16 hours. This cycle was repeated until visible damage of specimens. The picture of plasters after 30 freeze-thaw cycles is shown in fig. 2. A little surface destruction of both coats is apparent, but the surface still seems to be compact. The overall freeze-thaw durability is shown in table 1. Commercial plasters (CRP1 and CRP2) after different number of freeze-thaw cycles are shown in fig. 2.

![Figure 2: Commercial plasters after 20/30 freeze-thaw cycles (CRP1 on the left, CRP2 on the right).](image-url)
Table 1: Number of freeze-thaw cycles causing apparent damage of renovation renders.

<table>
<thead>
<tr>
<th>Number of freeze-thaw cycles</th>
<th>CRP₁</th>
<th>CRP₂</th>
<th>LRP₁</th>
<th>LRP₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>30+</td>
<td>20</td>
<td>15</td>
<td>12</td>
<td></td>
</tr>
</tbody>
</table>

4 Computational

4.1 Materials characteristics

Basic parameters of materials involved in computer simulations are presented in tables 2 and 3, where \( \rho \) is the bulk density, \( \psi \) the porosity, \( \mu \) the water vapour diffusion resistance factor, \( w_{\text{hyg}} \) the hygroscopic moisture content by volume, \( c \) the specific heat capacity, \( \lambda_{\text{dry}} \) the thermal conductivity in dry conditions, \( \lambda_{\text{sat}} \) the thermal conductivity in water saturated conditions.

Table 2: Material parameters of renovation renders.

<table>
<thead>
<tr>
<th></th>
<th>CRP₁</th>
<th>CRP₂</th>
<th>LRP₁</th>
<th>LRP₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \rho ) [kg/m³]</td>
<td>1296</td>
<td>1384</td>
<td>1687</td>
<td>1694</td>
</tr>
<tr>
<td>( \psi ) [%]</td>
<td>50.2</td>
<td>47.3</td>
<td>34.1</td>
<td>34.4</td>
</tr>
<tr>
<td>( c_{\text{dry}} ) [J/kgK]</td>
<td>1073</td>
<td>1028</td>
<td>877</td>
<td>877</td>
</tr>
<tr>
<td>( c_{\text{sat}} ) [J/kgK]</td>
<td>1545</td>
<td>1719</td>
<td>1311</td>
<td>1311</td>
</tr>
<tr>
<td>( \mu_{\text{dry, cup}} ) [-]</td>
<td>23.32</td>
<td>12.60</td>
<td>29.03</td>
<td>31.48</td>
</tr>
<tr>
<td>( \mu_{\text{wet, cup}} ) [-]</td>
<td>6.67</td>
<td>7.10</td>
<td>11.57</td>
<td>14.12</td>
</tr>
<tr>
<td>( \lambda_{\text{dry}} ) [W/mK]</td>
<td>0.293</td>
<td>0.366</td>
<td>0.886</td>
<td>0.836</td>
</tr>
<tr>
<td>( \lambda_{\text{sat}} ) [W/mK]</td>
<td>1.383</td>
<td>1.186</td>
<td>2.190</td>
<td>2.267</td>
</tr>
<tr>
<td>( w_{\text{hyg}} ) [m³/m³]</td>
<td>0.0932</td>
<td>0.0307</td>
<td>0.0493</td>
<td>0.0437</td>
</tr>
</tbody>
</table>

Table 3: Material parameters of load-bearing structure.

<table>
<thead>
<tr>
<th></th>
<th>Brick</th>
<th>Sandstone</th>
<th>Arenaceous marl</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \rho ) [kg/m³]</td>
<td>1670</td>
<td>1809</td>
<td>1400</td>
</tr>
<tr>
<td>( \psi ) [%]</td>
<td>37.5</td>
<td>31.0</td>
<td>63.1</td>
</tr>
<tr>
<td>( c ) [J/kgK]</td>
<td>1202</td>
<td>850</td>
<td>837</td>
</tr>
<tr>
<td>( \mu ) [-]</td>
<td>19.5</td>
<td>7.5</td>
<td>5.0</td>
</tr>
<tr>
<td>( \lambda_{\text{dry}} ) [W/mK]</td>
<td>0.500</td>
<td>1.100</td>
<td>0.710</td>
</tr>
<tr>
<td>( \lambda_{\text{sat}} ) [W/mK]</td>
<td>0.648</td>
<td>3.650</td>
<td>0.890</td>
</tr>
<tr>
<td>( \kappa ) [m²/s]</td>
<td>2.65 \cdot 10⁻⁷</td>
<td>2.5 \cdot 10⁻⁶</td>
<td>1.0 \cdot 10⁻⁸</td>
</tr>
<tr>
<td>( w_{\text{hyg}} ) [m³/m³]</td>
<td>0.0480</td>
<td>0.00567</td>
<td>0.01</td>
</tr>
</tbody>
</table>
All parameters were measured in the Laboratory of Transport Processes of the Department of Materials Engineering and Chemistry, Faculty of Civil Engineering, Czech Technical University in Prague [12]. The adsorption and desorption isotherms of studied renovation plasters are shown in fig. 3.

Figure 3: Adsorption and desorption isotherms of studied renovation plasters.

In fig. 4, the moisture diffusivity of the studied plasters is presented; this was obtained for the absorption phase only. Contrary to the adsorption isotherms, where desorption curves can be obtained by common experimental techniques, the desorption curve of moisture diffusivity had to be set empirically as for its experimental determination no quite reliable techniques are available at present. Based on the results of experiments and computational analyses described in [6], it was estimated to be one order of magnitude lower than the absorption curve.

Figure 4: Moisture diffusivity of studied renovation plasters.
4.2 Computer simulation tool and mathematical model

The computational analysis was performed using computer code HEMOT [7], which was developed at the Department of Materials Engineering and Chemistry, Faculty of Civil Engineering, Czech Technical University in Prague in order to support the investigation of the coupled heat, moisture and salt transport in porous building materials. It enables simulation of thermal and hygric behaviour of structural building details in 1-D or 2-D arrangement. The building of the code is based on the application of the general finite element computer simulation tool SIFEL (Simple Finite Elements) developed at the Department of Mechanics, Faculty of Civil Engineering, Czech Technical University in Prague [8]. The Kunzel’s diffusion model was used for the description of coupled heat and moisture transport [9]:

\[
\frac{d\rho_v}{d\varphi} = \text{div}\left[ D_{\varphi,\text{grad}\varphi} + \delta_p \text{grad} (\varphi p_r) \right]
\]

(1)

\[
\frac{dH}{dT} = \text{div}(\lambda \text{grad} T) + L_v \text{div}[\delta_p \text{grad}(\varphi p_r)]
\]

(2)

where \(\rho_v\) is the partial density of moisture, \(\varphi\) the relative humidity, \(\delta_p\) the permeability of water vapour, \(p_r\) the partial pressure of saturated water vapour, \(H\) the enthalpy density, \(L_v\) the heat of evaporation, \(\lambda\) the thermal conductivity, \(T\) the temperature,

\[
D_{\varphi} = D_w \frac{d\rho_v}{d\varphi}
\]

(3)

is the liquid moisture diffusivity coefficient, \(D_w\) the capillary transport coefficient.

Since the computational code involves the effect of hysteresis of moisture transport and storage parameters, which brings the computations nearer to reality, it was necessary to describe the path between adsorption and desorption phase. For that purpose an empirical procedure was chosen which follows Pedersen’s hysteretic model [10],

\[
\xi = a_d \left( w_p - w_a \right)^2 \xi_d + a_a \left( w_p - w_d \right)^2 \xi_a,
\]

(4)

where \(w_p\) is the value of moisture content from the previous calculation step, \(w_a\) and \(w_d\) are the values of moisture content for adsorption and desorption cycles, respectively, \(\xi_a\) and \(\xi_d\) the corresponding values of tangent adsorption and desorption at points \(w_a\) and \(w_d\), \(a_a\) and \(a_d\) the corresponding correction coefficients.

For describing the path between adsorption and desorption phase of moisture diffusivity, a modification was needed in order to express the hysteretic effect in more accurate way (see [11] for more details).
As boundary conditions in the exterior, climatic data for Ostrava were used, Czech Republic, obtained using Meteonorm software, version 6.1, which is a meteorological database and computer program for climatological calculations for every location on the globe.

5 Results of computer simulation

The results of computational simulations performed by the HEMOT code with the input parameters and boundary conditions presented in the previous sections are presented in figs 5–10. All the performed computations were for a period of five years. The results are given for the last year of the simulation.

5.1 Load-bearing structure made of ceramic brick

The differences between commercial plasters (CRP₁ and CRP₂) and laboratory-prepared plasters (LRP₁ and LRP₂) are quite significant. While commercial renovation plasters CRP₁ and CRP₂ exhibit 4 and 5 freeze-thaw cycles,
respectively, both laboratory-prepared renovation plasters showed only 1 freeze-thaw cycle.

5.2 Load-bearing structure made of sandstone

A similar situation as in brick masonry occurred in the sandstone masonry. Both laboratory-prepared plasters showed better results than commercial plasters. There occurred only 1 freeze-thaw cycle in LCP₁, 2 freeze-thaw cycles in LCP₂, 3 freeze-thaw cycles were discovered in CRP₁ and 4 cycles in CRP₂.

![Figure 7](image1.png)

**Figure 7:** Time behaviour of temperature and moisture content in renovation plasters on load-bearing structure made of sandstone; CRP₁ on the left, CRP₂ on the right.

![Figure 8](image2.png)

**Figure 8:** Time behaviour of temperature and moisture content in renovation plasters on load-bearing structure made of sandstone; LRP₁ on the left, LRP₂ on the right.

5.3 Load-bearing structure made of arenaceous marl

The worst results for all tested renovation renders were calculated for masonry made of arenaceous marl. Both laboratory-prepared renovation plasters showed 4 freeze-thaw cycles, the commercial plasters exhibited one and two cycles more, respectively (5 cycles for CRP₁ and 6 cycles for CRP₂).
6 Discussion

In this paper, phase changes of water were assumed as the only factor affecting the service life of innovative plasters. In reality, there are more factors playing the key role in the damage of surface layers of renovation renders, such as salt transport, microbiological damage and acid rains. On the other hand, this simplification based on separation of the particular effect of damage (frost resistance) from a variety of other effects can provide valuable information indeed.

All performed computations proved that freeze-thaw cycles may occur in surface layers of renovation renders, even when the reference year is taken into account. In table 4, all results calculated using computer simulations are summarized.
Table 4: Summary of freeze/thaw cycles appearance during a reference year.

<table>
<thead>
<tr>
<th>Masonry Type</th>
<th>LRP₁</th>
<th>LRP₂</th>
<th>CRP₁</th>
<th>CRP₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceramic brick</td>
<td>1</td>
<td>1</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Sandstone</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Arenaceous marl</td>
<td>4</td>
<td>4</td>
<td>5</td>
<td>6</td>
</tr>
</tbody>
</table>

The best results were achieved for LRP₁ but all investigated plasters fared well. The most significant differences between studied plasters were discovered in brick masonry. The other types of masonry resulted in very similar appearance of freeze-thaw cycles.

Taking into account the frost resistance of each renovation render (table 1), its service life can be predicted. From this point of view, it may be recommended to use LRP₁ or LRP₂ for brick masonry, LRP₁ or CRP₁ for sandstone masonry and CRP₁ for masonry made of arenaceous marl. An interesting finding is that both commercially available products CRP₁ and CRP₂ sold for a similar price showed very different results. The average service life of CRP₁ was approximately two times higher than that of CRP₂, with respect to frost resistance.

7 Conclusions

The computational results presented in this paper dealing with the hygrothermal performance of innovative renovation renders showed that a proper choice of materials for renovation, with respect to the material of the load-bearing structure, could significantly extend the service life of a renovated building envelope. In general, the best results were achieved for brick masonry, whereas the worst results were obtained for masonry made of arenaceous marl. It is important to say that the durability of renovation renders is not only affected by cyclic freezing and wetting. A crucial contribution to reducing the service life of all types of renovation renders comes from salt accumulation and crystallization due to their high open porosity. Therefore, in future work, the mathematical model should be extended to include salt transport as well.

Acknowledgement

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References


