Moisture dynamics in walls: response to micro-environment and climate change

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A coupled sharp-front (SF) liquid transport and evaporation model is used to describe the capillary rise of moisture in monoliths and masonry structures. This provides a basis for the quantitative engineering analysis of moisture dynamics in such structures, with particular application to the conservation of historic buildings and monuments. We show how such a system responds to seasonal variations in the potential evaporation (PE) of the immediate environment, using meteorological data from southern England and Athens, Greece. Results from the SF analytical model are compared with those from finite-element unsaturated-flow simulations. We examine the magnitude and variation of the total flow through a structure as a primary factor in long-term damage caused by leaching, salt crystallization and chemical degradation. We find wide seasonal variation in the height of moisture rise, and this, together with the large estimated water flows, provides a new explanation of the observed position of salt-crystallization damage. The analysis also allows us to estimate the effects of future climate change on the capillary moisture dynamics of monoliths and masonry structures. For example, for southern England, predicted increases in PE for the period 2070–2100 suggest substantial increases in water flux, from which we expect increased damage rates.

Keywords: capillary rise; evaporation; sorptivity; masonry; building stone

1. Introduction

In monoliths (single blocks of stone such as standing stones, gravestones and sculptures) and in masonry walls, water movement is an important control of material deterioration. Thus, understanding moisture regimes is critical in effective heritage conservation. Water is involved in deterioration processes such as the hydrolysis of silicate minerals, dissolution of carbonates and the formation of gypsum crusts. Salt weathering, a key deteriorative process affecting many walls and monoliths, requires water to transport dissolved salts,
which can then cause decay by repeated crystallization, hydration and thermal expansion (Goudie & Viles 1997). Even purely mechanical damage processes such as insolation weathering have been shown to act more efficiently in the presence of water (Griggs 1936), while freeze–thaw weathering demonstrates the key mechanical role of water in colder climates. Detailed surveys of building facades and monolith surfaces in many different environments have shown that deterioration is often concentrated towards the top of a capillary rise zone and in other areas that experience frequent wetting and drying cycles (Fitzner et al. 2002).

An earlier paper (Hall & Hoff 2007) describes an analytical sharp-front (SF) model of capillary rise in porous materials. This provides a practical framework for calculating water movement in monoliths and masonry structures; and in addition, establishes several important scaling relations. The SF model incorporates both gravitational drainage and evaporation. We were able to show that the effect of gravity on moisture dynamics is generally weak or negligible for structures built of common materials such as brick and stone. We note that in the absence of evaporation, our SF result provides an analytical solution of the Lucas–Washburn problem for simple capillary rise with gravity. Recently, Fries & Dreyer (2008) have derived the same result, and have shown that it may be inverted by means of the Lambert W-function. Their later solution of the Lucas–Washburn problem with uniform and constant lateral evaporation (Fries et al. 2008) is essentially identical to our earlier result.

The previous paper (Hall & Hoff 2007) dealt only with cases where the potential evaporation (PE) $\epsilon$ at the wall surface is constant with time. However, in practice, $\epsilon$ is a variable property of the micro-environment, subject to daily, annual and secular variations. In this paper, our main aim is to explore the behaviour of the SF capillary-rise model in response to more realistic time-dependent evaporation conditions, and also to compare it with results from a full finite-element unsaturated-flow (UF) simulation using the same evaporation conditions. For this paper, we have also modified the SF model to incorporate distributed rather than lumped evaporation. This modification is described in appendix A. Mathematically, the modified SF model differs only slightly from the earlier model.

The UF simulations were carried out with HYDRUS (2D/3D), a finite-element program that simulates water, heat and solute transport in two and three dimensions. The program finds numerical solutions of the Richards equation for UF and the advection–dispersion equations for heat and solute transport (Simunek et al. 2006). We can take account of rainfall flows at the boundaries and if necessary also water uptake by plant roots, neither of which can easily be achieved using the SF model. Designed for use in hydrology and soil physics, the application of HYDRUS (2D/3D) to building materials and structures is novel (Hamilton 2005).

Broadly, our purpose here is to show that the evaporation conditions set by the micro-environment play a critical role in the moisture dynamics. Our analysis allows us to explain the location of decay in masonry structures. It also enables us to link moisture dynamics, meteorological data and material degradation into a single quantitative framework. This provides a scientific basis for engineering assessment of moisture regimes in masonry structures and historic buildings generally.

2. Sharp-front model

We represent a ground-supported monolith or composite masonry structure as a porous slab of unlimited height and of constant thickness \( b \) (figure 1), as in Hall & Hoff (2007). Water enters the structure at the base, which is considered to be in contact with a free-water reservoir, and rises under the action of capillary forces. In an SF model (e.g. Hall & Hoff 2002), the height of rise \( h(t) \) is well defined as the position of the boundary of demarcation between wetted and dry zones. Evaporation occurs from the wetted vertical surface (here, \( N = 1 \) for a wall subject to evaporation from one face and \( N = 2 \) for two-sided evaporation). Evaporation per unit area of the wetted region occurs at a rate equal to the PE of the immediate environment. The only transport property of the porous material that we need to know is the sorptivity \( S \).

The assumption that water is freely available at the base of the wall is less restrictive than it may appear. The capillary suction of common masonry materials such as brick and stone is considerably greater than that of most soils, so that higher water contents are established in the masonry than in the soil with which it is in contact. Furthermore, the buried part of a wall generally draws water not only vertically from below but also laterally, in much the same way as a tree draws water to its root system. Soil moisture entering the wall is replenished both by upward flow from the water table and from rainfall at the surface. In any case, we shall see later that if necessary, the full UF model is able to couple water transport in the subsoil directly to that in the wall structure to simulate effects of restricted soil moisture on the evaporative flux.

The fundamental differential equation for the height of capillary rise (neglecting gravity) is

\[
\frac{dh}{dt} = -a'h^2 + c, \quad (2.1)
\]

where \( a' = Ne/2\theta_w b \) and \( c = S^2/2\theta_w^2 \). Here, \( \theta_w \) is the effective volume-fraction porosity of the porous material and \( e \) is the evaporation rate per unit surface area. We take \( e = eascimento, the PE adjacent to the evaporation surface. We note also that the total stored water is \( Q = \theta_w bh \). The rate of flow into the system at the base \( U_0 = bS^2/(2\theta_w h) + Neh/2 \) and the total evaporative rate of flow out of the system is \( E = Neh \). For constant evaporation, a steady state is eventually reached when \( U = E \); the steady-state height of rise \( h_{ss} = S(b/Ne\theta_w)^{1/2} \). The differences between this SF model (which incorporates uniformly distributed evaporation throughout the wetted region) and the lumped SF model of Hall & Hoff (2007) are set out in appendix A. With a time-dependent evaporation rate \( e(t) \), equation (2.1) can no longer be integrated analytically and accordingly is solved numerically. All the SF results given in this paper are obtained using MATHEMATICA solvers.

3. Potential evaporation

The PE, denoted as \( e \), is a meteorological quantity that describes the rate at which water evaporates from a free-water surface. PE is either measured directly by determining the rate of evaporation of water from open pans or else calculated using other meteorological data. Of the several formulae available,
the most widely used is the Penman equation (Penman 1948), which uses values of temperature, relative humidity, wind speed and solar radiation to estimate the PE.

We have statistical PE data for two locations: one in southern England (Silwood Park, Berkshire, UK) and the other in Greece (Helliniko Station, Athens). These datasets (which we refer to here as the London and Athens datasets) are discussed in detail in papers by Yang et al. (2005) and by Kotsopulos & Svehlik (1989), respectively. In both cases, the PE is calculated using the Penman equation (or variants of it); and in both cases, the authors derive Fourier regression equations to represent the variation of the mean daily potential evaporation over a calendar year. The regression equations used for the two datasets are similar but not identical in form (see appendix B for details). The London data extend over a period of 5 years (1989–1994); the Athens data over a 9 year period (1977–1985). Raw PE data from the London study have been made available to us by Chandler (R. E. Chandler 2008, personal communication). In figure 2, we show the smoothed daily London and Athens PE data over 3 years calculated from the regression equations. For London, we also show the raw daily data. Some numerical information for the two sites is given in table 1.

A few comments. The total PE over a full year at the Athens site is 1750 mm; and at the London site is 485 mm. The winter minimum daily PE for London is extremely low, 0.21 mm d$^{-1}$. The ratio of winter minimum to summer maximum is 0.175 in Athens; but only 0.075 in London. The winter minimum occurs about 14 days later in Athens than in London; and the summer maximum about 20 days later.
Figure 2. Daily PE. Lower: raw daily data from Silwood Park, Berkshire UK (London) with regression curve calculated from equation (B1) (superimposed solid line). Upper: regression curve for data from Helliniko Station, Athens, calculated from equation (B2).

Table 1. Potential evaporation at the London and Athens sites.

<table>
<thead>
<tr>
<th></th>
<th>London</th>
<th>Athens</th>
</tr>
</thead>
<tbody>
<tr>
<td>annual total evaporation (mm)</td>
<td>485</td>
<td>1750</td>
</tr>
<tr>
<td>$\epsilon_{\text{total}}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>potential evaporation, PE (mm d$^{-1}$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\epsilon_{\text{max}}$</td>
<td>2.76</td>
<td>9.28</td>
</tr>
<tr>
<td>day of year</td>
<td>180</td>
<td>200</td>
</tr>
<tr>
<td>$\epsilon_{\text{min}}$</td>
<td>0.21</td>
<td>1.62</td>
</tr>
<tr>
<td>day of year</td>
<td>350</td>
<td>364</td>
</tr>
</tbody>
</table>

4. Benchmark problem with seasonal variation in evaporation

We previously illustrated (Hall & Hoff 2007) the behaviour of the SF capillary-rise model by means of a benchmark problem in which water rises into a slab 150 mm thick with evaporation from one side only ($N = 1$). We chose single-sided evaporation to mimic the external face of a masonry structure. We note that this is equivalent to a 300 mm slab with evaporation from both faces ($N = 2$). (Although we model a uniform slab with no mortar joints, earlier work (Hall & Hoff 2002) shows that an averaged composite sorptivity can adequately describe the flow through two dissimilar materials in hydraulic contact, so this method is also applicable to composite masonry structures). We use a sorptivity $S = 1.0 \text{ mm min}^{-1/2}$, typical of building limestones and sandstones (Hall & Hoff 2002); and an effective porosity $\theta_w = 0.2$, typical of the capillary moisture content of such stones. Taking the evaporation rate $e = 0.001 \text{ mm min}^{-1}$ (a constant value approximately equal to the UK PE averaged over one calendar year), we find that the steady-state height of rise $h_{\text{ss}} = 865 \text{ mm}$ and the steady flow rate through the wall is about $1.25 \text{ L d}^{-1}$ per metre length of wall.
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Figure 3. The benchmark case with London and Athens evaporation boundary conditions. SF height of rise $h$ against elapsed time $t$. Vertical lines mark 1 and 2 years. Computed curves start with an initially dry system, $h = 0$ at $t(0)$ at 1 January.

Now we solve equation (2.1) with the dry-wall initial condition $h = 0$, $t = 0$ and with a time-dependent evaporation rate $e(t)$ equal to the London mean daily potential evaporation $e(t)$. (The corresponding London annual mean PE is 1.32 mm d$^{-1}$, or 0.00092 mm min$^{-1}$, a figure only slightly lower than the constant evaporation rate of 0.001 mm min$^{-1}$ used previously for illustration.) The SF height of rise $h(t)$ is shown in figure 3 for a 1000 day period (slightly less than 3 years), starting at the beginning of the calendar year. First, there is a rapid increase of $h$ over about 50 days as water rises into the initially dry slab, after which time, the repeating seasonal variation is established. The height of rise $h$ swings between a summer minimum of 630 mm and a winter maximum of 1660 mm. The annual mean height of rise is about 1080 mm. The height of rise for constant evaporation rate set at the London annual mean PE is 905 mm. The difference arises because $h$ varies as $e^{-1/2}$, not as $e^{-1}$, so that the low PE (and high height of rise) in winter months contributes disproportionately to the mean annual height of rise. Numerical results are given in table 2.

If we solve the benchmark case with the Athens PE evaporation rate, we see (figure 3) a similar strong seasonal variation of $h$. Heights of rise lie in the range 340–800 mm, and the annual mean is 545 mm. The height of rise for constant evaporation rate set at the Athens annual mean PE is 475 mm. These values assume of course that adequate water is available from soil moisture (Philandras et al. 2010).

Of paramount interest in relation to material damage is the total water flow through the structure. In the benchmark case with time-varying London evaporation rate, the mean flow averaged over the whole year is 1.13 L d$^{-1}$ (i.e. 415 L yr$^{-1}$) per metre length of wall. In the course of the year, the height of rise changes continuously in response to imbalances between the inflow (at the base of the wall) and the outflow (by evaporation at the wall surface). In figure 4, we show how inflow and outflow vary through the annual cycle. In spring, outflow exceeds inflow as the PE of the environment increases rapidly, and as a result, the height $h$ falls. During the autumn, inflow exceeds outflow and $h$ rises. Total evaporative outflow (per metre length of wall) lies between a winter minimum of 0.30 L d$^{-1}$ and a summer maximum of 1.78 L d$^{-1}$.

Philandras et al. 2010
Table 2. SF model: results of various cases subject to seasonal variation in potential evaporation.

<table>
<thead>
<tr>
<th></th>
<th>case 1, benchmark</th>
<th>case 2</th>
<th>case 3</th>
<th>case 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b$ (mm)</td>
<td>150</td>
<td>1500</td>
<td>1500</td>
<td>1500</td>
</tr>
<tr>
<td>$S$ (mm min$^{1/2}$)</td>
<td>1.0</td>
<td>1.0</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>$\theta_w$</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>evaporation factor $\gamma$</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0.1</td>
</tr>
</tbody>
</table>

London

height of rise (mm)

- $h_{mean}$: 1080, 2900, 870, 2530
- $h_{max}$: 1660, 3240, 970, 2555
- day of year: 31, 80, 80, 102
- $h_{min}$: 630, 2545, 765, 2505
- day of year: 192, 248, 248, 252

outflow (L d$^{-1}$)

- $Q_{mean}$: 1.13, 3.74, 1.12, 0.33
- $Q_{max}$: 1.78, 7.79, 2.34, 0.70
- $Q_{min}$: 0.30, 0.60, 0.18, 0.05

inflow (L d$^{-1}$)

- $U_{mean}$: 1.12, 3.75, 1.12, 0.36
- $U_{max}$: 1.73, 5.80, 1.74, 0.54
- $U_{min}$: 0.52, 2.13, 0.64, 0.21

Athens

height of rise (mm)

- $h_{mean}$: 545, 1585, 475, 1425
- $h_{max}$: 800, 1985, 595, 1475
- day of year: 15, 66, 66, 96
- $h_{min}$: 340, 1160, 350, 1370
- day of year: 203, 233, 233, 259

outflow (L d$^{-1}$)

- $Q_{mean}$: 2.17, 7.03, 2.11, 0.68
- $Q_{max}$: 3.17, 12.11, 3.63, 1.31
- $Q_{min}$: 1.26, 2.85, 0.85, 0.23

inflow (L d$^{-1}$)

- $U_{mean}$: 2.17, 7.04, 2.11, 0.68
- $U_{max}$: 3.17, 10.13, 3.04, 1.00
- $U_{min}$: 1.32, 4.46, 1.34, 0.46

In Athens conditions, the total annual flows are roughly double than those in London (Table 2). Thus, although the total stored water is less in Athens, the higher PE draws water more rapidly through the wetted part of the wall. Taken over the entire year, the cumulative flux (flow per unit wetted wall area) is about 3.6 times greater than in London (of course, equal to the ratio of the mean annual evaporation rates).

These calculations show that the quantities of water that flow through walls and other ground-supported structures under the combined action of capillarity and evaporation are prodigious. These flows largely control the rates of the chemical processes causing stone decay (Hamilton 2005). In 100 years, under
Figure 4. The seasonal variation of inflow and outflow in the benchmark case calculated from the SF model. Lower: the London evaporation conditions; upper: the Athens evaporation conditions. Solid lines: inflow by capillary absorption; dashed lines: outflow by evaporation.

London conditions, we estimate that the water flow is sufficient to dissolve as much as 2.0 kg of calcitic limestone (or slightly more dolomitic limestone) per metre length of structure. Such calcite dissolution is enough to wreak havoc also with the cementation of a calcareous sandstone; and to remove much of the carbonated lime in mortar joints. If the absorbed water contains dissolved salts, these are also carried into the structure year by year and deposited at or near the surface where evaporation occurs. In 100 years, groundwater containing as little as 100 ppm of dissolved salts transports 4.2 kg salt into each metre length of wall. These estimates are dramatic and show clearly why the combination of capillary water absorption and evaporation may be so harmful to building structures.

5. Unsaturated-flow model

The SF model is a simple representation of the full nonlinear diffusion model of UF built on the Buckingham–Richards equation (e.g. Hall & Hoff 2002). Here, we use HYDRUS 2D/3D for the UF simulations. A more comprehensive description of material properties is required than is provided by the sorptivity and porosity alone. Information is required also on the unsaturated hydraulic conductivity and water-retention (capillary-potential) behaviour.

It has been shown (e.g. Hall & Hoff 2002) that the van Genuchten equation describes the capillary potential of brick, stone and concrete materials just as for soils, although data are sparse. The van Genuchten equation describes the dependence of the capillary potential $\psi$ on water content $\theta$ and can be written as $\Theta = (\theta - \theta_r)/(\theta_s - \theta_r) = [1 + (\alpha \psi)^n]^{-n}$, where $\alpha$ and $n$ are material parameters. $\theta_r$ is a residual water content (taken here as equal to the initial water content $\theta_i = 0.01$); $\theta_s$ is the maximum water content (taken here as the effective volume fraction porosity of the material $\theta_v = 0.2$). In these UF simulations, we have used $\psi(\theta)$ data for a British fired-clay brick (Gummerson et al. 1980), fitted to the van Genuchten equation (Hall & Hoff 2002). The data were obtained by a standard pressure membrane procedure. The hydraulic conductivity
Figure 5. Winter and summer water distributions for the one-sided benchmark problem (London conditions) computed using the UF model. Water content contours are at 11 intervals in the range of 0.01–0.20 volume fraction. The corresponding SF heights of rise are shown. The winter distribution is calculated at the mid-winter evaporation minimum, day 350; the summer distribution at the summer evaporation maximum, day 180. Van Genuchten–Mualem parameter values: $\alpha = 8.63 \times 10^{-4}$ cm$^{-1}$; $K_s = 7.6 \times 10^{-5}$ cm min$^{-1}$; $n = 1.7961$.

$K(\theta)$ is described by the Mualem equation as $K(\theta) = K_s \Theta^{1/2}[1 - (1 - \Theta^{1/n})^n]^2$. The material parameter $n$ is common to both the equations. The saturated conductivity $K_s$ is adjusted to give the same sorptivity as that used in the SF calculations. For building materials, sorptivity is the more easily measured parameter, which is why initial brick values of $K_s$, $\alpha$ and $n$ are adjusted to match the required sorptivity value of 1.0 mm min$^{-1/2}$ used for the benchmark case discussed here. Parameter values used in simulations are given in the caption of figure 5. We have not included any effects of wetting–drying hysteresis.

The benchmark case is modelled in two dimensions as a single material, 150 mm thick and 2000 mm high. Flow is defined in terms of pressure heads set by the environment and a critical pressure potential ($P_{\text{crit}}$) that controls drying behaviour. Dry-state initial conditions are used, with the initial capillary potential ($P_i$) set to a large negative value corresponding to 50 per cent ambient relative humidity $H$ and calculated from the Kelvin equation $-P_i = \ln(H/100)RT/gM$, where $M$ is the molar mass of water. At this $P_i$, the initial volume fraction water content $\theta = 0.01$. A free-water boundary condition (constant capillary potential $P = 0$) is applied along the 150 mm long inflow face at the base of the slab $z = 0$. On unsealed vertical faces $z > 0$, we apply the atmospheric boundary condition such that evaporation occurs at a constant rate provided that the surface moisture content remains above a value set by a critical value of $P = P_{\text{crit}}$. Here, we take
Table 3. Comparison of SF and UF simulations: benchmark problem. $Q$, total water content (stored water); litre per metre length; $U$, total inflow, L d$^{-1}$; $E$, total evaporative outflow, L d$^{-1}$. The effects of enhanced PE due to climate change (see text) are shown in italics.

<table>
<thead>
<tr>
<th></th>
<th>sharp-front (SF) model</th>
<th>unsaturated-flow (UF) simulation</th>
</tr>
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<tbody>
<tr>
<td>constant evaporation rate $e = 0.001$ mm min$^{-1}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>case 1, benchmark</td>
<td></td>
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</tr>
<tr>
<td>$Q$ (L per m length)</td>
<td>26.0</td>
<td>24.1</td>
</tr>
<tr>
<td>$U, E$ (L d$^{-1}$)</td>
<td>1.25</td>
<td>1.31</td>
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<tr>
<td>time-varying evaporation rate, London conditions</td>
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<tr>
<td>$Q_{\text{mean}}$</td>
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<td>$E_{\text{min}}$</td>
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<td>Athens conditions</td>
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<tr>
<td>$U_{\text{mean}}$</td>
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<td>1.26</td>
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</table>

$P_{\text{crit}} = P_i$, the initial capillary potential. This boundary condition represents the well-known two-stage drying behaviour of soils and building materials (van Brakel 1980). On the top surface and on any vertical surface not subject to evaporation, a no-flux boundary condition is applied.

The UF simulations yield the water content distributions at each time step. The total stored water $Q(t)$, and the inflow $U(t)$ and outflow $E(t)$ provide the best quantities for comparing SF and UF models. A crude equivalent height of rise in the UF model can be defined as $Q/\theta_w b$. In addition, we obtain information on water content and flow along the boundaries.

For the benchmark case, SF and UF models are in excellent agreement: summary results are given in table 3. For constant PE with $e = 0.001$ mm min$^{-1}$, UF and SF stored water, inflow and outflow are similar. The UF equivalent steady-state height of rise is 800 mm compared with the SF value of 865 mm.
Figure 6. Evaporation flux (UF model) along the vertical wall surface for the winter (a) and the summer conditions (b) of figure 5. The corresponding SF heights of rise are shown (solid bars).

Of great interest are the results of simulations using London and Athens environmental conditions. We show in figure 5 the water-content distributions under London conditions at times corresponding to the winter minimum and to the summer maximum in PE. These distributions support our use of an SF model. The UF simulations show only low volume-fraction moisture contents above the SF levels. Therefore, the calculated SF level provides a good measure of the position of the bulk of the water.

In figure 6, we show how the evaporative flux varies along the vertical surface at these same two times. We see that the atmospheric boundary condition ensures that the flux $e$ is equal to the PE $e$ up to the height $z_{\text{crit}}$ at which the surface water content falls to the equilibrium value set by the environmental humidity. We note that for the benchmark case, $z_{\text{crit}}$ is very close to the SF height of rise $h$. Thus, in this case, the SF height of rise may be identified with the position at which the surface moisture content falls to a low value.

In figure 7, we show the variation (for the benchmark problem) of the inflow and outflow under London and Athens conditions from UF simulations. These may be compared with the SF results in figure 4. Numerical data are given in table 3. Clearly, the seasonal variation is well captured in both models, which are in good agreement.

6. Effects of wall thickness, sorptivity and impeded evaporation

In the benchmark case just discussed, the wall is relatively thin and the sorptivity relatively high. The thinness of the wall means that the stored water is correspondingly small (over the course of the year under London conditions, it lies in the range of 19–68 L per metre length of wall). This together with the
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Figure 7. Total daily flux for the benchmark problem calculated from the UF model. London and Athens conditions. Inflow (solid lines) and outflow (dashed lines) for the benchmark (case 1) problem. Compare with figure 4.

Figure 8. Height of rise calculated from the SF model subject to the London evaporation conditions. The effect of changes in wall thickness, sorptivity and impeded evaporation rate. Solid line: benchmark case 1; short dashes: case 2; long dashes: case 3.

high sorptivity of the material means that the height of rise $h$ responds both quickly and strongly to the seasonal changes in PE. However, when the wall is thicker and the sorptivity lower, the response of the wall is more sluggish, and the system dynamics damped. We illustrate the effects of wall thickness and sorptivity on the height of rise in London PE conditions in figure 8. SF results are given in table 2. Increasing the wall thickness by a factor of 10 to 1500 mm (case 2) causes water to rise much higher (by a factor of roughly $\sqrt{10}$). The large amount of stored water produces sizeable lags. For example, under London conditions, the maximum height of rise is reached 46 days after the minimum in the PE. Reducing the sorptivity to 0.3 mm min$^{-1/2}$ (case 3) largely cancels the effect on $h$ of the increased wall thickness, but the peak-to-trough changes in $h$ are considerably smaller when compared with the benchmark case 1.

Furthermore, in any situation in which evaporation is impeded (as it is whenever the evaporation surface is sheltered, for example by vegetation, or by the deposition of salts within brick or stone), the behaviour of $h(t)$ can change dramatically. For example, if we set $e = 0.1e$ (rather than $e = e$ as previously),
thus reducing the evaporation rate by a factor of 10 throughout the annual cycle, we find (case 4) that from an initial dry state at $t = 0$, it takes around 12 years for the seasonal variations in $h$ to stabilize under London conditions (figure 9). Under Athens conditions, the considerably greater evaporative flux causes the long-term seasonal variation to be established within about 4 years. Once stabilized, the seasonal variation in $h(t)$ is slight. Results are set out in table 2.

SF results for the same cases under Athens PE conditions are also given in table 2. Higher PE leads to lower heights of rise, higher flow rates and a more rapid response to the seasonal change in PE.

7. Comparisons with real walls

Quantitative field data are sparse, but where available, observations can be compared with the dynamic behaviour of the SF and UF models. For example, Fitzner et al. (2002) have mapped in detail the deterioration of stone in the El Merdani Mosque in Cairo. They find that decay of the external facades is most severe at elevations of 1.2–2.8 m, where there is a band of intense damage, as we show on the southeast facade in figure 10. Here, the wall thickness is 1.67 m. The PE value for Cairo (Müller 1983) is 1170 mm in a full year. The winter minimum is $0.79 \text{ mm day}^{-1}$ (average over 3 months); the summer maximum is $5.7 \text{ mm day}^{-1}$ (average over 3 months). If we take our typical sorptivity $S = 1.0 \text{ mm min}^{-1/2}$ and effective porosity $\theta_w = 0.2$, then the calculated SF height of rise varies with the season in the range 1.0–2.8 m for two-sided evaporation. Thus, it appears that the severe damage is confined to the part of the wall that is subject to a seasonal rise and fall of the wet front (or capillary fringe), as we see vividly in figure 10. Such a distribution of stone damage in a broad band well above ground level, with comparatively undamaged stone below, is found widely on the facades of the El Merdani Mosque and, indeed, extensively in historic buildings in Cairo. These remarkable observations are entirely consistent with the moisture dynamics described here. Both SF and UF models show that this is the only part of the wall where evaporation occurs beneath the surface, and it is in this zone that salts accumulate and crystallize deep into the fabric. Lower in the wall, some surface efflorescence may occur (and is observed), but crystallization within the fabric is
Figure 10. A section of the southeast facade of the El Merdani Mosque (Mosque of Altinbugha al-Maridani), Cairo, Egypt, showing severe stone decay in the region of the wall bounded by the estimated minimum and maximum heights of rise (photograph Prof. Bernd Fitzner). The staff is 3 m long.

prevented by the high moisture content and by the upward flow of groundwater. As a consequence, despite the large water flows, there is much less damage at lower levels.

In the rather different climate of Oxford, UK, Sass & Viles (2010) have used a two-dimensional resistivity method to map moisture contents in a limestone wall 800 mm thick and comprising two ashlar faces with rubble core (shown in figure 1). The moisture extends to a height of about 1.2 m. A band of stone deterioration occurs at this level. A simple SF calculation predicts a mean height of rise of 1200 mm, assuming an annual PE of 650 mm (mean measured PE 1988–1996, Radcliffe Meteorological Station, Oxford, UK), material properties as before, and two-sided evaporation.

In both cases, observations support the essential correctness of our models of moisture dynamics, and thus of the flow rates that control decay mechanisms.

8. Effects of climate change on predicted flows

We have shown how strikingly the capillary-transport behaviour of a wall (described with either the SF or the UF model) differs in the distinct climatic environments of London and Athens, mainly as a result of differences in PE.
It is then a simple step to use the same methods to see how projected changes in climate at any location affect the capillary dynamics in masonry structures.

A difference in capillary dynamics between Athens and London is accompanied by differences in deterioration-process regimes. The hot, dry summer conditions and mild wet winters in Athens encourage the dominance of salt weathering, localized especially at the top of the capillary fringe, together with dry deposition of pollutants and subsequent chemical transformations. In the colder, wetter conditions of London, such salt weathering also occurs, but deterioration is probably dominated by a combination of rain-induced chemical weathering alongside wet deposition of air pollutants. Frost weathering may be important during particularly cold spells. As a consequence of predicted future climate changes (IPCC 2007), we expect both the moisture regimes and the associated deterioration patterns in the UK to tend towards those found today in Athens and other Mediterranean areas.

Climate-change models commonly predict future PE, and therefore our models allow us to estimate the effects of climate change on moisture regimes directly. For the UK, published work from various sources agrees in predicting that PE will rise substantially in future decades. For purposes of illustration, we take the data of Ekström et al. (2007), who report estimates of monthly average PE for the period 2070–2100 for northwest England based on a Penman–Monteith calculation. The PE over a full year increases by about 55 per cent as a result of higher temperatures and lower summer rainfall. The increase in PE is considerably greater in summer than in winter. It is easy to apply these monthly factors in calculating the capillary flux (either by SF or UF methods). In our benchmark problem (case 1 with a wall of 150 mm exposed to single-sided evaporation), the mean height of rise is reduced by about 15 per cent. The total annual flow through the wall increases by about 22 per cent, but there is a much larger rise in the evaporative flow during the summer months. The results of SF and UF simulations are included in table 3 and are in close agreement. At the summer maximum, the rate of evaporation per unit area increases by 55–60%, from 2.8 to 4.4 mm d$^{-1}$. As a result of this, we anticipate a consequent marked increase in the rate of material damage. Results for cases 2–4 are broadly similar.

9. Some conclusions

The aim of this paper is to look at how natural variation in evaporation rate alters water flow through building structures and to compare the simpler SF model of moisture regimes with a full UF model. For a benchmark problem, the SF and UF models are generally in excellent agreement. The comparison of SF and UF models indicates that the SF height of rise closely tracks the position on the wall surface at which the capillary potential falls below the critical value for stage I drying. The SF model is mathematically simple and provides practical scaling formulae, although it provides no information about internal water-content distributions apart from the position of the wet front. The UF model is fully two dimensional. The further benefit of using the UF model is that precipitation and transpiration can be taken into account.
Since evaporation drives the water flow, this work has a practical benefit in increasing our understanding of how climatic conditions can impact on water movement and hence on water-driven deterioration. One of the most remarkable results of our analysis of water flow from the ground is the finding that such large volumes of water (normally carrying dissolved salts) move into and through these structures. When the evaporation rates are increased, the area of masonry affected is reduced, but the fluxes are increased. This has important implications for damage to masonry in warmer climates. Comparisons of moisture behaviour using meteorological data from London and Athens show that the annual water flow through simple slabs and masonry walls is about three times as great in Athens as in London and that the height of rise in Athens is considerably lower. Increased water fluxes at low heights of rise considerably increase vulnerability to damage. Because there will be an ever increasing salt accumulation in the zone defined by the upper and lower limits in height of rise, the seasonal variation in evaporation rate is particularly significant for salt-crystallization damage, as seen in practice. The lower parts of the structures are relatively undamaged.

Climate-change predictions suggest that by 2070–2100, the average annual total flow through masonry structures in southern England will increase by over 20 per cent, with increases of up to 60 per cent in the summer months. These effects are huge and point to a potentially large increase in water-driven deterioration, through mechanisms such as salt crystallization, leaching and various forms of chemical weathering.

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Appendix A

In Hall & Hoff (2007), we described an SF model in which the water content $Q$ of the system was calculated from a simple integral (lumped) mass balance. We obtained a differential equation for the position of the SF $h(t)$ from the relation $dQ/dt = U - E$ by setting the inflow $U = bS^2/(2\theta_w h)$ and the outflow $E = eh$. $U$ was taken to be a constant throughout the wetted region. We now show that this model can be modified to incorporate a distributed-evaporation process in which evaporation occurs uniformly throughout the wetted region.

We modify our previous SF model by requiring that $U$ varies linearly from the inflow boundary at height $z = 0$ to the wet front at height $z = h$, such that $U - U_0 = -ez$, $0 \leq z \leq h$. Thus, water is lost uniformly from the wetted region. It follows then that the capillary-pressure potential varies nonlinearly from the inflow face to the wet front. We find that the total flow through the inflow boundary $U_0 = bS^2/(2\theta_w h) + eh/2$. At steady state, $U(h) = 0$, so that the steady-state height of rise is $h_{ss} = (bS^2/e\theta_w)^{1/2}$. This differs from our previous result by a factor of $1/\sqrt{2}$ only.

Further, we find that the differential equation of the system is

$$h \frac{dh}{dt} = -a'h^2 + c,$$

exactly as before, except that the constant $a' = e/(2\theta_w b)$ instead of $e/(\theta_w b)$. 

This modified SF model incorporates a contribution to the total flow from the capillary-potential gradient generated by the evaporation process itself. This somewhat increases the height of rise, the quantity of stored water and the total flow through the system. The main features of the dynamics of the system are little changed.

Appendix B

The Fourier regression equation for potential evaporation $\epsilon(t)$ used by Yang et al. (2005) for the London data can be written as follows:

$$\epsilon = A_1 + \frac{\alpha_1 A_2}{A_3} + \frac{\alpha_2 A_4}{A_5}, \quad (B\ 1)$$

where

$$A_1 = \frac{\alpha_0}{(1 - \alpha_3)},$$

$$A_2 = \cos \left[ 2\pi \left( \frac{t}{t_1} \right) - \phi_1 \right] - \alpha_3 \cos \left\{ 2\pi \left[ \frac{(t + 1)}{t_1 - \phi_1} \right] \right\},$$

$$A_3 = 1 - 2\alpha_3 \cos \left( \frac{2\pi}{t_1} \right) + \alpha_3^2,$$

$$A_4 = \cos \left[ 2\pi \left( \frac{2t}{t_1} \right) - \phi_2 \right] - \alpha_3 \cos \left\{ 2\pi \left[ \frac{2(t + 1)}{t_1 - \phi_2} \right] \right\},$$

and

$$A_5 = 1 - 2\alpha_3 \cos \left( \frac{4\pi}{t_1} \right) + \alpha_3^2,$$

with $\alpha_0 = 0.7830$, $\alpha_1 = 0.75804$, $\alpha_2 = 0.107664$, $\alpha_3 = 1.31574$, $\phi_1 = 0.47924$, $\phi_2 = 0.00547064$ and $t_1 = 366$. Units are millimetres and days.

The regression equation for $\epsilon$ obtained by Kotsopoulos & Svehlik (1989) for the Athens data is

$$\epsilon = \exp(\beta_1 B_1 + \beta_2 B_2 + \beta_3 B_3 + \beta_4 B_4 + \beta_5), \quad (B\ 2)$$

where

$$B_1 = \cos \left( \frac{2\pi t}{t_2} \right),$$

$$B_2 = \sin \left( \frac{2\pi t}{t_2} \right),$$

$$B_3 = \cos \left( \frac{4\pi t}{t_2} \right)$$

and

$$B_4 = \sin \left( \frac{4\pi t}{t_2} \right),$$

with $\beta_1 = 0.8556$, $\beta_2 = -0.04758$, $\beta_3 = -0.09995$, $\beta_4 = 0.05993$, $\beta_5 = 1.38668$ and $t_2 = 365$. Units are also millimetres and days.

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References


