Micro-Environmental Monitoring of Temperature and Moisture Changes in Building Stones Using Embedded Electrical Sensors

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Outline

Introduction
Objectives
Experimental Programme
Results
Conclusions & Future Work

Introduction: Stone Decay Sequence

Salt crystallisation on surface from capillary rise water

Rapid catastrophic decay of limestone

Introduction: Stone Decay Sequence

Surface Stabilisation and Re-growth of Gypsum Crust following Contour Scaling

St Matthias Church, Budapest

Introduction: Stone Decay Sequence

Gypsum Crust Development: Controls Exerted By Moisture Availability

The Parliament Building in Budapest is in a locally moist environment. Increased moisture availability compared to St Matthias appears to inhibit crust re-growth and promote multiple flaking

Introduction: Geo-Environmental Factors Influencing Stone Decay

Factors that allow surface crusts to form rapidly on new and newly exposed stone?

- Surface chemistry/mineralogy
- Variable atmospheric chemistry (short- medium- and long-term)
- Variable dust deposition rates/flux (short- medium- and long-term)
- Variable dust chemistry
- Façade topography, aspect
- Exposure to rain-wash (amount, frequency, intensity)
- Drying rate (R, E/T, wind speed)
- Surface colonisation – organics
- Surface wash in/wash out

Stone weathering processes
- Physical
- Chemical
- Biological

Environmental controls
- Moisture
- Temperature
- Wind
Introduction: Research Questions

Environmental factors:
- Characterisation of the stone response to different combinations of environmental temperature, humidity and air circulation.

Materials:
- Characterisation of the different stone types.
- How diverse stone types behave differently against selected simulated decay processes?
- How combination of stone types behave against simulated decay processes?
- How crusts influence the catastrophic decay?

Objectives

Part A: Micro-environmental Monitoring Of Building Stones
- To study the influence of micro-environmental exposure conditions with short term "insolation" fluctuations on temperature and moisture changes within building stone

Part B: Sorptivity of Building Stones
- To determine sorptivity of building stones from electrical resistivity measurements

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Variables to be examined
- Temperature and moisture fluctuations (in terms of electrical resistivity) in building stones in response to heating and cooling and application of wind
- Angle of Incidence of “Insolation”
- Ambient Temperature (20 & 5°C)
- With and without the application of wind

Measurement Methods:
- Electrical resistance (ER) – Moisture sensors
- Thermistor – Temperature sensors
- Infrared Thermometer – Surface temperature sensor

Electrical Resistance Sensors

Change in resistance due to
- Moisture movement
- Ions (Chlorides)
- Temperature
Not possible to distinguish between Cl- or pH change
**Part A: Experimental Plan**

- **Chamber temp**
  - Summer (20°C)
  - Winter (5°C)

- **Spray of water (3min)**
  - Wet
  - Dry

- **Wind**
  - On
  - Off

- **Insolation**
  - On
  - Off

**Cyclic heating:**
- Light ON for 15 mins and OFF for 30 mins
- Light OFF for 30 mins and ON for 15 mins

**Preparation of Stone Block**

**Part A: Experimental Setup**

- **Distance of sensor from the stone surface**
  - 0.5 cm
  - 1.0 cm
  - 2.0 cm
  - 5.0 cm
  - 10.0 cm

- **Effect of Ambient Temperature and insolation (stone dry + wind)**

- **Effect of Ambient Temperature and insolation (stone dry + no wind)**

- **Effect of Ambient Temperature and Wind on Internal Temperature**

**Effect of Ambient Temperature and insolation (stone dry + wind)**

- **Effect of Ambient Temperature and insolation (stone dry + no wind)**

**Effect of Ambient Temperature and Wind on Internal Temperature**

- **Delta Tmax : Difference in temperature from surface (°C)**
  - Summer: 2.44, 4.40, 4.55, 5.30, 6.35
  - Winter: 2.00, 3.05, 3.85, 5.60

- **Delta Tmax - Difference in temperature from surface (°C)**
  - Summer: 3.44, 4.40, 4.55, 5.30, 6.35
  - Winter: 3.00, 3.05, 3.85, 5.60

- **Summer vs Winter**
  - Insolation increased air temperature more in winter with no wind, difference small with wind
  - Stone got warmer with insolation in summer with no wind, reverse trend in winter
  - Wind enabled cooling in summer, heated the stone in winter
  - Effect of insolation confined to surface region in winter
**Temperature (°C)**

### Influence on Internal Temperature When Stone Sprayed with Water

#### No Wind

- **Summer (20°C)**
  - Time (mins):
    - No wind: 3.10 3.44
  - With wind: 3.10 3.44

- **Winter (5°C)**
  - Time (mins):
    - No wind: 3.85 4.40
  - With wind: 3.85 4.40

#### With Wind

- **Summer (20°C)**
  - Time (mins):
    - No wind: 3.55 4.30
  - With wind: 3.55 4.30

- **Winter (5°C)**
  - Time (mins):
    - No wind: 3.00 3.55
  - With wind: 3.00 3.55

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### Effect of Water Spray and Wind on Internal Temperature

#### ΔTmax : Difference in temperature from surface (°C)

#### Summer

- **Cycles**
  - Dry: 0.5 cm, 1.0 cm, 2.0 cm, 5.0 cm, 10.0 cm
  - Wet: 0.5 cm, 1.0 cm, 2.0 cm, 5.0 cm, 10.0 cm

#### Winter

- **Cycles**
  - Dry: 0.5 cm, 1.0 cm, 2.0 cm, 5.0 cm, 10.0 cm
  - Wet: 0.5 cm, 1.0 cm, 2.0 cm, 5.0 cm, 10.0 cm

- **No Wind**
  - Dry: 1.44 4.40 4.55 6.30 6.55
  - Wet: 2.00 2.05 2.00 2.00 2.00

- **With Wind**
  - Dry: 2.10 2.35 2.30 1.90 1.65
  - Wet: 2.15 2.70 2.65 2.10 2.15

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### Influence on Electrical Resistance When Stone is Wet

#### Summer (20°C)

- **No wind**
  - Time (mins):
    - Dry: 2.65 2.80
  - Wet: 2.65 2.80

- **With wind**
  - Time (mins):
    - Dry: 2.65 2.80
  - Wet: 2.65 2.80

#### Winter (5°C)

- **No wind**
  - Time (mins):
    - Dry: 2.95 2.95
  - Wet: 2.95 2.95

- **With wind**
  - Time (mins):
    - Dry: 3.00 3.00
  - Wet: 3.00 3.00

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Spray of water – decreased internal temperature (cooling)

Wind – led to a significant increase in surface temperature

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**Resistance Ratio (Rt/Ro)**

- **0.0**
- **0.1**
- **0.2**
- **0.3**
- **0.4**
- **0.5**
- **0.6**
- **0.7**
- **0.8**
- **0.9**
- **1.0**
- **1.1**
- **1.2**
- **1.3**
- **1.4**
**Time of Arrival of Moisture Front at Different Depths**

<table>
<thead>
<tr>
<th>Ambient temperature</th>
<th>Wind conditions</th>
<th>Arrival of moisture front (mins)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer (20°C)</td>
<td>Without wind</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>With wind</td>
<td>20</td>
</tr>
<tr>
<td>Winter (5°C)</td>
<td>Without wind</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>With wind</td>
<td>11</td>
</tr>
</tbody>
</table>

**Arrival of moisture front (mins)**
- Summer: No significant effect due to wind
- Winter: Delayed water penetration
- Ambient Temp: Slower penetration in winter compared to summer

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**Part B: Sorptivity of Building Stone**

**Capillary Absorption Test – ER Sensors**

**Sorptivity Coefficient**

- Weight gain measurement
  \[ W/A = S \sqrt{t} + W_0 \]
  - \( S \) is the sorptivity coefficient
- Time of arrival of moisture front (Electrical resistance method)
  \[ d = S \sqrt{t} + d_0 \]
  - \( S_o \) is the sorptivity coefficient

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Conclusions

- Electrical resistance (ER) method can be used to monitor the moisture front in building stones
  - ER Ratio to determine the time of arrival of moisture front at different depths in building stones
  - Variations in moisture profiles within the stone due to variations in exposure
- Sorptivity coefficient can be determined using the ER method - from the depth of penetration of water front and the corresponding time

Conclusions

- Micro-environmental changes around stone resulted in significant variations in internal temperature and moisture distributions:
  - Influence of wind on internal temperature profile different in summer and winter.
    - Wind led to a cooling effect on surface in summer and heating effect in winter
  - Wind did not affect the moisture penetration in summer, but resulted in slower penetration in winter.

Conclusions

- Micro-environmental changes around stone result in significant variations in internal temperature and moisture distributions:
  - Water penetration depth different in summer and winter due to a short duration of water spray:
    - Faster penetration in summer compared to winter
  - Application of simulated insolation on the surface of stone brought higher temperature gradients inside the stone within the near-surface region.

Future Work

- Differences in internal microenvironment due to variations in ambient microenvironment can significantly influence patterns of stone decay.
  - Effect of retreat of stone blocks
  - Influence of water temperature on moisture ingress
  - Establish the reliability of the ER method to determine the sorptivity for a range of different stone types
  - Influence of ambient temperature and water temperature on sorptivity of building stones
  - Relate sorptivity to stone decay
  - Relate micro-environmental variations to stone decay

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Engineering and Physical Sciences Research Council (EPSRC) in the UK through project grant EP/D08603/1

Thank you.

Any Questions?