



# Recommendation of RILEM TC 271-ASC: New accelerated test procedure for the assessment of resistance of natural stone and fired-clay brick units against salt crystallization

B. Lubelli · I. Rörig-Daalgaard · A. M. Aguilar · M. Aškračić · K. Beck · C. Bläuer · V. Cnudde · A. M. D'Altri · H. Derluyn · J. Desarnaud · T. Diaz Gonçalves · R. Flatt · E. Franzoni · S. Godts · D. Gulotta · R. van Hees · I. Ioannou · A. Kamat · T. De Kock · B. Menendez · S. de Miranda · C. Nunes · E. Sassoni · N. Shahidzadeh · H. Siedel · Z. Slížková · M. Stefanidou · M. Theodoridou · R. Veiga · V. Vergès-Belmin

Received: 30 November 2022 / Accepted: 20 March 2023  
© The Author(s) 2023

**Abstract** This recommendation is devoted to testing the resistance of natural stone and fired-clay brick units against salt crystallization. The procedure was developed by the RILEM TC 271-ASC to evaluate the durability of porous building materials against salt crystallization through a laboratory method that allows for accelerated testing without compromising

the reliability of the results. The new procedure is designed to replicate salt damage caused by crystallization near the surface of materials as a result of capillary transport and evaporation. A new approach is proposed that considers the presence of two stages in the salt crystallization test. In the first, the accumulation stage, salts gradually accumulate on or near the surface of the material due to evaporation. In the second, the propagation stage, damage initiates and develops due to changes in moisture content and relative humidity that trigger salt dissolution and crystallization cycles. To achieve this, two types of salt were tested, namely sodium chloride and sodium sulphate, with each salt tested separately. A methodology for assessing the salt-induced damage is proposed, which includes visual and photographic observations and measurement of material loss. The

---

This recommendation has been prepared, reviewed and approved by all members of the RILEM TC 271-ASC.  
*Chair:* Barbara Lubelli.

*Deputy chair:* Inge Rörig-Dalgaard.

*TC Members:* A.M. Aguilar, M. Aškračić, K. Beck, C. Bläuer, V. Cnudde, A.M. D'Altri, H. Derluyn, J. Desarnaud, T. Diaz Gonçalves, R. Flatt, E. Franzoni, S. Godts, D. Gulotta, R. van Hees, I. Ioannou, A. Kamat, T. De Kock, B. Lubelli, B. Menendez, S. de Miranda, C. Nunes, I. Rörig-Dalgaard, E. Sassoni, N. Shahidzadeh, H. Siedel, Z. Slížková, M. Stefanidou, M. Theodoridou, R. Veiga, V. Vergès-Belmin.

---

B. Lubelli (✉) · R. van Hees · A. Kamat  
Delft University of Technology, Delft, The Netherlands  
e-mail: b.lubelli@tudelft.nl

I. Rörig-Daalgaard  
Technical University of Denmark, Copenhagen, Denmark

A. M. Aguilar  
ETH Zurich, Zurich, Switzerland

M. Aškračić  
University of Belgrade, Belgrade, Serbia

K. Beck  
Université d'Orléans, Orléans, France

C. Bläuer  
Bläuer Conservation Science Sarl, Fribourg, Switzerland

V. Cnudde  
Ghent University, Ghent, Belgium

A. M. D'Altri · E. Franzoni · S. de Miranda · E. Sassoni  
Alma Mater Studiorum, Università di Bologna, Bologna, Italy



procedure has been preliminarily validated in round robin tests.

**Keywords** Recommendation · Salt crystallization test · RILEM TC 271-ASC · Sodium sulfate · Sodium chloride

## 1 Scope of this recommendation

This procedure is aimed at evaluating the durability of porous building materials against salt crystallization through a laboratory method that allows for accelerated testing without compromising the reliability of the results.

The procedure is designed to replicate salt damage caused by crystallization near the surface of materials as a result of capillary transport and evaporation.

Damage by sodium sulfate or sodium chloride can be considered. Both salts are tested individually, at two possible concentrations.

The procedure has been validated on single materials with open porosity values between 13 vol% and 50 vol % and Water Absorption Coefficient (WAC) values between 50 and 1070  $\text{g/m}^2\text{s}^{0.5}$  [1].

The reasons for the choice of the details of the procedure can be found in [2].

The procedure and the proposed damage assessment methods aim to be as simple as possible (i.e., not requiring sophisticated equipment or specialized expertise) and to provide reliable results in a relatively short period of time, in order to be applicable in support of the building renovation and construction sector.

The procedure involves a novel approach [3], that draws from literature on reinforced concrete durability [4]. It operates under the assumption that sufficient salt needs to accumulate in the pores (pore filling) to initiate damage. As a consequence, salt damage is regarded as a two-stage process: (i) in the accumulation stage, salts accumulate in the pores of the material (but the degree of pore filling is not yet sufficient to initiate damage); (ii) in the propagation stage, repeated salt dissolution/crystallization cycles cause damage to initiate and propagate (Fig. 1).

This recommendation addresses the preparation of the specimens, the apparatus, the testing method, the damage assessment methodology and the information to be mentioned in the test report.

H. Derluyn  
Université de Pau et des Pays de l'Adour, Pau, France

J. Desarnaud · S. Godts  
KIK-IRPA, Brussels, Belgium

T. Diaz Gonçalves · R. Veiga  
LNEC, Lisbon, Portugal

R. Flatt  
ETH, Zurich, Switzerland

D. Gulotta  
Getty Conservation Institute, Los Angeles,  
CA, United States

I. Ioannou  
University of Cyprus, Nicosia, Cyprus

T. De Kock  
University of Antwerp, Antwerp, Belgium

B. Menendez  
CY Cergy Paris Université, Cergy-Pontoise, France

C. Nunes · Z. Slížková  
Institute of Theoretical and Applied Mechanics of the  
Czech Academy of Sciences, Prague, Czech Republic

N. Shahidzadeh  
University of Amsterdam, Amsterdam, The Netherlands

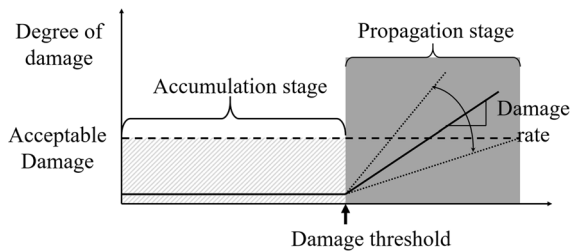
H. Siedel  
Technische Universität Dresden, Dresden, Germany

M. Stefanidou  
Aristotle University of Thessaloniki, Thessaloniki, Greece

M. Theodoridou  
Newcastle University, Newcastle upon Tyne,  
United Kingdom

V. Vergès-Belmin  
LRMH, Champs-sur-Marne, France





**Fig. 1** Schematic representation of the durability of a stone or brick subjected to salt damage [3], adapted from the concept proposed by Tuutti [4] to describe the durability of reinforced concrete

## 2 Specimens

### 2.1 Size, shape and number

The specimens consist of stone or brick cores of  $50 \pm 0.5$  mm diameter and  $50 \pm 0.5$  mm height.

At least 3 specimens should be used for each salt type and solution concentration.

### 2.2 Preparation of the specimens

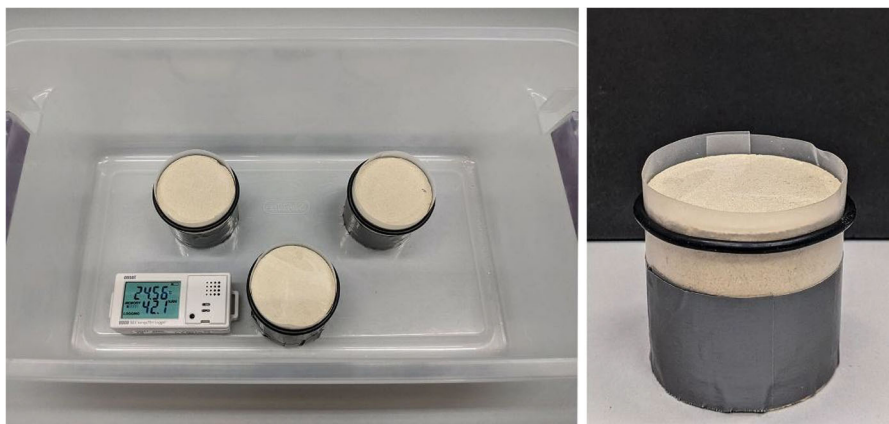
Cores should be drilled in such a way that minimum damage is inflicted to the material. Wet drilling or jet water cutting are recommended. In the case of brick, it is preferable that the test face is the stretcher or the header face of the brick. In the case of natural stone, it is preferable that the direction of the bedding is parallel to the test surface. In any case, the core drilling direction should be indicated in the report.

After drilling, the loose brick or stone powder should be removed from the surface of the drilled cores, e.g., by the use of compressed air or careful washing with water. The core specimens should be dried to constant mass in a ventilated oven at  $40 \pm 2$  °C/ $15 \pm 5\%$  RH. Constant mass is reached when the difference between two successive weighings at an interval of at least 24 h is  $\leq 0.1\%$ . Then, the specimen mass should be stabilized for 4 h at room conditions ( $22 \pm 2$  °C;  $45 \pm 15\%$  RH). The mass of the specimen at the end of this period (initial mass,  $m_i$ ), should be registered in the test report, together with the corresponding values of room temperature and relative humidity.

The lateral surface of the specimens should be sealed with paraffin film, after pre-heating them in an oven at 50 °C for 10 min, to achieve better adherence. The paraffin film should extend 0.5 cm above the top surface of the specimens. A rubber O-ring should be used to secure good adhesion between the paraffin film and the uppermost area of the lateral surface of the specimen. Textile tape (water resistant and water vapour tight) can be used to secure the ends of the paraffin film and ensure sealing tightness during the entire test (Fig. 2).

### 2.3 Apparatus

The following apparatus is necessary for the execution of the test:



**Fig. 2** Picture showing the specimens enclosed in a box with a T and RH sensor (left). Detail of a specimen (50 mm diameter and 50 mm height) sealed at the side with paraffin film, secured with tape and rubber O-ring (right)

- A climatic cabinet (or climatic room) able to reach and maintain the temperature and relative humidity conditions required by the test procedure. The cabinet is strictly necessary only in the case of the NaCl test procedure.
- A laboratory oven able to reach and maintain a temperature of  $40 \pm 2 \text{ }^\circ\text{C}$  /  $15 \pm 5\%$  RH.
- A precision balance (minimum resolution  $10^{-3}$  g and accurate to  $10^{-2}$  g)
- A digital camera
- Glass or plastic containers for the contamination of the specimens, such as small crystallizing dishes or petri dishes (one container for each specimen; it is advised to use a container with a base dimension only slightly larger than the size of the specimen in order to reduce evaporation of the solution)
- Boxes for storing the specimens during the accumulation and propagation stages
- Temperature and relative humidity sensors for monitoring the conditions in the boxes containing the specimens (NB: the conditions in the boxes may deviate from those in the climatic cabinet/oven)
- Japanese paper with grammage 10–25 g/m<sup>2</sup>
- Rubber O-rings
- Paraffin film
- NaCl and/or Na<sub>2</sub>SO<sub>4</sub> (thenardite): ACS reagents 99.0%
- Demineralized water
- A soft brush (toothbrush hardness “soft”)
- Qualitative filter paper for separating the debris from the salts

### 3 Procedure

#### 3.1 Accumulation stage procedure

The specimens are contaminated by capillary absorption of a salt solution from their bottom surface. Salt solutions are prepared using demineralized water and NaCl or Na<sub>2</sub>SO<sub>4</sub> (thenardite) salts. The following salt solution concentrations are used:

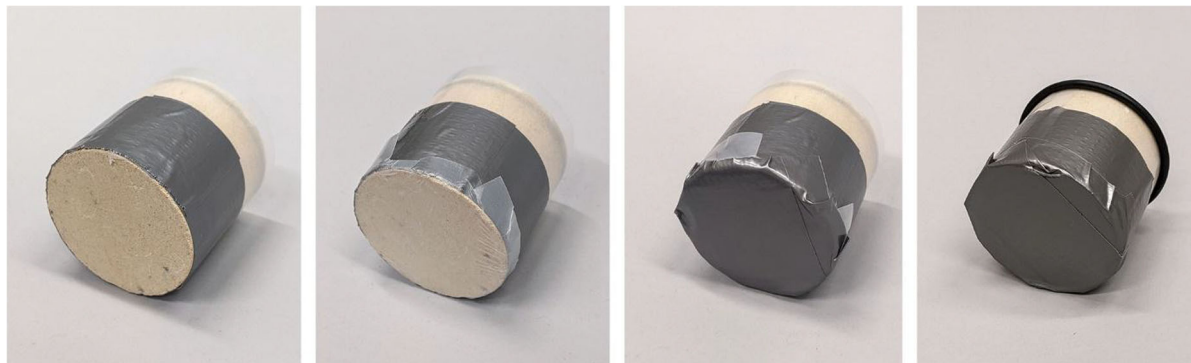
- Na<sub>2</sub>SO<sub>4</sub>: 5% and 10% by weight (expressed as salt weight / solution weight)
- NaCl: 5% and 10% by weight (expressed as salt weight / solution weight)

Contamination takes place at room conditions ( $T = 22 \pm 2 \text{ }^\circ\text{C}$  at  $45 \pm 15\%$  RH).

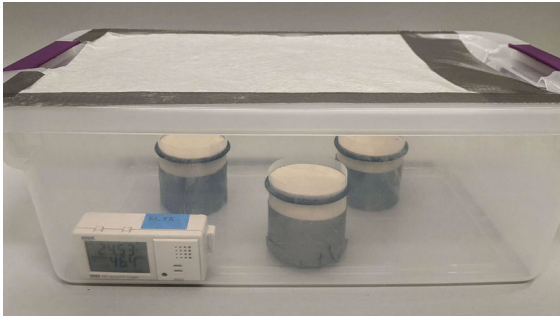
The weight of salt solution used to contaminate a material should be equal to the capillary moisture content of the material, and determined as reported in Appendix 1. The evaporation of the solution can be minimized during absorption by covering the solution reservoir. This is particularly relevant in the case of materials with slow water absorption rate.

Immediately after the full absorption of the salt solution, the bottom surface of the specimens is sealed by covering it with a first layer of paraffin film and a second layer of tape, as shown in Fig. 3. Afterwards, the specimens are weighed again, and their mass is recorded ( $m_s$ ).

The specimens are set to dry at  $40 \pm 2 \text{ }^\circ\text{C}/15 \pm 5\%$  RH. In order to limit the influence of the ventilation rate, the specimens should be placed in a box. This is covered with a layer of Japanese paper to have nil air flow inside, while allowing for air exchange to keep the desired temperature and relative humidity conditions during the



**Fig. 3** Bottom of the specimen (left) is first sealed with paraffin film (middle) and then with textile tape to ensure perfect sealing (right)



**Fig. 4** Example of a box for storing the specimen during the test. The top of the box is closed with Japanese paper to allow for air exchange while limiting air velocity

test (Fig. 4). The distance between specimens and between these and the box walls should be at least 2 cm. The temperature and relative humidity in the box should be monitored with a sensor. The weight of each specimen should be recorded over time.

The accumulation stage ends when 80% or more of the introduced water is evaporated. For example, if 100 g of salt solution at 10% concentration has been used to contaminate the specimen, the drying ends when at least 72 g of water ( $0.8 \cdot 90 \text{ g} = 72 \text{ g}$ ) has evaporated.

At the end of the drying period, the presence of efflorescence and/or damage is photographically recorded and described according to the methodology reported in Sect. 4.1.

### 3.2 Propagation stage procedure

The propagation stage differs depending on the salt type.

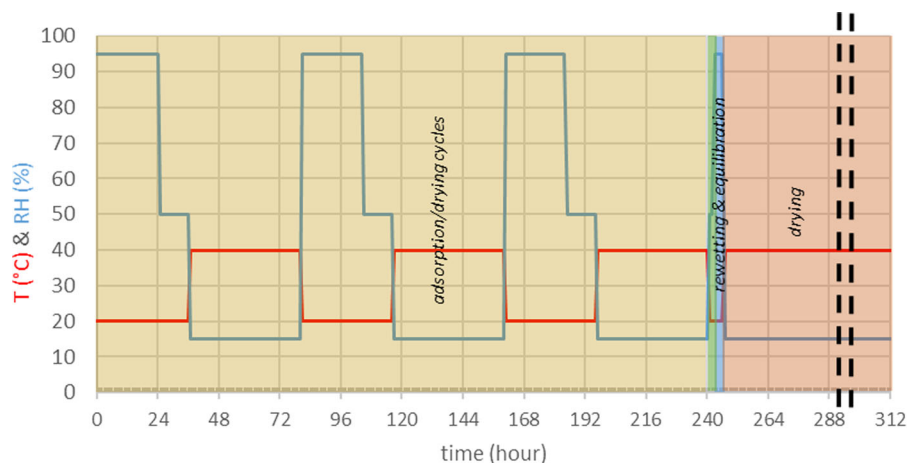
#### 3.2.1 Sodium chloride

The propagation stage consists of four 3-week cycles. Each of these cycles consists of 3 sub-cycles of temperature and relative humidity, plus one rewetting of the specimens with demineralized water through their bottom surface. More specifically, each 3-week cycle consists of (Fig. 5):

- 24 h hygroscopic adsorption at 20 °C/95% RH
- 12 h drying at 20 °C 50% RH
- 44 h drying at 40 °C 15% RH
- 24 h hygroscopic adsorption at 20 °C/95% RH
- 12 h drying at 20 °C 50% RH
- 44 h drying at 40 °C 15% RH
- 24 h hygroscopic adsorption at 20 °C/95% RH
- 12 h drying at 20 °C 50% RH
- 44 h drying at 40 °C 15% RH

After this period of 240 h, the specimens are removed from the climatic cabinet and the following steps are followed:

- The specimens are stored for 2 h at room conditions ( $22 \pm 2 \text{ °C} / 45 \pm 15\% \text{ RH}$ ) to cool down. After this cooling period, the sealing is removed from the bottom of the specimens and the mass of the specimens is recorded ( $m_{\text{rew } n\text{-before}}$ , where n is the number of the rewetting)
- The specimens are rewetted at  $22 \pm 2 \text{ °C} / > 95\% \text{ RH}$  via their bottom surface with 30% of the water amount used for the initial contamination. After rewetting, the weight of the specimen is recorded ( $m_{\text{rew } n\text{-after}}$ , where n is the number of the rewetting)



**Fig. 5** Representation of a 3-week T and RH cycle of the propagation stage—NaCl test

and the bottom of the specimen is sealed again. Rewetting takes place at room temperature.

- The specimens are stored at  $22 \pm 2 \text{ }^\circ\text{C}$  /  $> 95\% \text{RH}$  for a total of 4 h (rewetting + storing time = 4 h) to allow for salt dissolution.
- The specimens are then dried at  $40 \text{ }^\circ\text{C}$  /  $15\% \text{RH}$  for 258 h.

At the end of each 3-week cycle, the presence of damage and/or efflorescence on the surface of the specimens is photographically documented and described according to the methodology reported in Sect. 4.1. The specimens are not brushed. A new 3-week cycle can then start.

After four complete 3-week cycles, the condition of the specimens (presence of damage and/or efflorescence) is photographically documented and described according to the methodology reported in Sect. 4.1. The paraffin film is removed and the mass of the specimen is recorded ( $m_{\text{final}}$ ). The surface of the specimen is brushed using the toothbrush, and the material loss is assessed according to the procedure reported in Sect. 4.2.

### 3.3 Sodium sulfate

The propagation stage consists of four 3-week cycles. Each 3-week cycle consists of rewetting of the specimens with demineralized water through their bottom surface, followed by drying. More specifically, each 3-week cycle consists of (Fig. 6):

- 4 h cooling of the specimens at room conditions ( $T = 22 \pm 2 \text{ }^\circ\text{C}$  at  $45 \pm 15\% \text{RH}$ ). The sealing is removed from the bottom and the mass of the

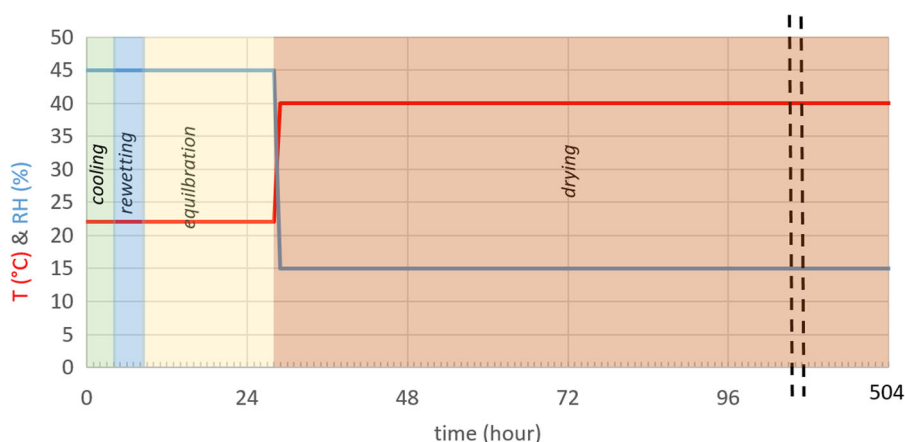
specimens is recorded ( $m_{\text{rew } n\text{-before}}$ , where n is the number of the re-wetting).

- Rewetting with 80% of the water amount used for the initial contamination, by capillarity from the bottom at room conditions ( $T = 22 \pm 2 \text{ }^\circ\text{C}$  at  $45 \pm 15\% \text{RH}$ ). After rewetting, the weight of the specimen is recorded ( $m_{\text{rew } n\text{-after}}$ , where n is the number of the re-wetting), and the bottom of the specimen is sealed.
- Drying at room conditions ( $T = 22 \pm 2 \text{ }^\circ\text{C}$  at  $45 \pm 15\% \text{RH}$ ) up to 24 h from the start of the re-wetting.
- 476 h drying at  $40 \pm 2 \text{ }^\circ\text{C}$  /  $15 \pm 5\% \text{RH}$

At the end of each cycle, the state of the specimens (presence of damage and/or efflorescence) is photographically documented and described according to the methodology reported in Sect. 4.1. The specimens are not brushed.

A new 3-week cycle can then start.

After 4 complete 3-week cycles, the state of the specimens (presence of damage and/or efflorescence) is photographically documented and described according to the methodology reported in Sect. 4.1. The sealing is removed from the bottom and the mass of the specimen is recorded ( $m_{\text{cycle } 4\text{-after}}$ ). The paraffin film is removed, and the mass of the specimen is recorded ( $m_{\text{final}}$ ). The surface of the specimen is brushed, and the material loss is assessed according to the procedure reported in Sect. 4.2.



**Fig. 6** Representation of a 3-week T and RH cycle of the propagation stage— $\text{Na}_2\text{SO}_4$  test



## 4 Test results

The assessment of damage consists of 3 steps (see Table 1).

The results of this assessment are summarized in a report (see Appendix 2).

### 4.1 Damage assessment

#### 4.1.1 Observation and documentation

The damage evolution is monitored by visual observation of the specimens and the conditions are photographically recorded. Three types of photos are taken at specific moments:

- from above, angle of 90 degrees in relation to the horizontal plane; photos taken before the test (as a reference), after accumulation and after each propagation cycle to monitor the damage evolution;
- under an angle of 45 degrees in relation to the horizontal plane; photos taken before the test (as a reference) and after the end of the test;
- under an angle of 0 degrees in relation to the horizontal plane; photos taken only after the end of the test.

An example of these photographs is provided in Appendix 2.

#### 4.1.2 Description of the alterations and damage

For the description of the damage and/or any alteration resulting from the test, two existing atlases of damage types can be used:

- ICOMOS illustrated glossary on stone deterioration patterns [5]
- MDCS atlases for stone, brick, mortar, and plaster [6]

To support the identification of damage types, Appendix 3 reports the most common ones due to salt crystallization, with links to the aforementioned atlases. The list illustrates the main types of damage, grouped into categories, and provides detailed descriptions of each one of them.

#### 4.1.3 Determination of the damage extent

Several types of damage may come into existence during the test, sometimes developing at the same time. Therefore, the assessment of the severity of the damage is an overall evaluation of the specimen's condition at the end of the test, considering all types of damage. The damage extent is assessed according to three categories: none, initial, and extensive. It is assumed that this qualitative judgment is mainly useful for comparative evaluation. (e.g., when test specimens of the same or different materials are to be compared within the same lab, possibly by the same operator).

For more in-depth and quantitative description, additional methods can be used.

### 4.2 Material loss

The loss of material for each specimen is measured at the end of the propagation stage (i.e., after the drying phase of the last cycle) according to the procedure described hereafter.

The surface of the specimen is brushed with a soft toothbrush, after removing the paraffin film wrapping) and the debris is collected (including salt efflorescence and salt crust).

The debris is dried at  $40 \pm 2$  °C and  $15 \pm 5\%$  RH until constant weight and cooled down in a desiccator for at least 2 h prior to weighing. The weight of the debris is recorded ( $d_1$ ).

**Table 1** Overview of the assessment of damage

Objective	Methodology
1. Observation and documentation (see Sect. 4.1.1)	Photographic documentation (see Appendix 2 for details)
2. Description of the alterations and damage (see Sect. 4.1.2)	Main categories/types of damage (A.–F. in Appendix 3); additional detailed description (1–16 in Appendix 3) can be applied if needed
3. Determination of the damage extent (see Sect. 4.1.3)	Qualitative estimation (none, limited, extensive) Additionally, the material loss at the end of the test is calculated Further quantitative methods can be applied if needed

A filter paper for medium/fast filtration is used. The filter is dried at  $40 \pm 2$  °C and  $15 \pm 5\%$  RH until constant weight and cooled down in a desiccator for at least 2 h prior to weighing. The weight of the dry filter paper is recorded ( $m_{\text{paper}}$ ).

The debris is put in a glass beaker with demineralized water, manually stirred and left for 24 h at room conditions to dissolve the salt efflorescence. The amount of demineralized water used for dissolution should be at least 10 times the weight of the debris, in order to ensure full dissolution of the salts.

After 24 h, the solution is filtered using the filter paper. The filter paper and the material left in it are then dried at  $40 \pm 2$  °C and  $15 \pm 5\%$  RH until constant mass, cooled down in a desiccator for at least 2 h, and the cumulative mass (filter paper + material) is recorded ( $m_{\text{loss cum}}$ ).

The material loss ( $d_2$ ) is calculated as follows:

$$\text{Material loss } (d_2) = m_{\text{loss cum}} - m_{\text{paper}}$$

The weight of the salt efflorescence and salt crust ( $m_{\text{eff}}$ ) is calculated as follows:

$$\text{mass of salt efflorescence} = d_1 - d_2$$

The simplified procedure for assessing the material loss, described above, is intended for the comparative evaluation of the results from the same laboratory.

**Acknowledgements** The procedure presented in this paper is the final version developed by the RILEM TC 271-ASC. The TC has previously published draft versions of (part of) the procedure [1, 2]. H. Derluyt acknowledges support from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No 850853).

## Declarations

**Conflict of interest** The authors have no relevant financial or non-financial interests to disclose.

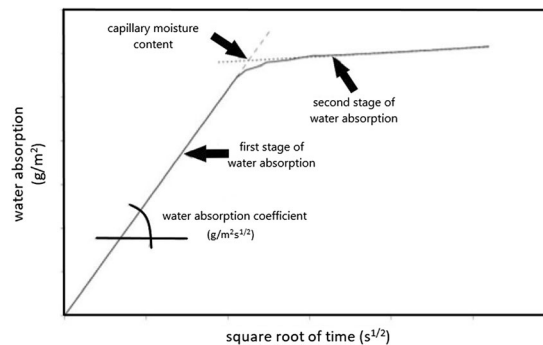
**Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The

images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

## Appendix 1: Determination of capillary moisture content (CMC)

The capillary moisture content of the material must be determined first by performing the water absorption test according to EN 1925:1999 ("Determination of water absorption coefficient by capillarity" [7]). The capillary moisture content of the material is the mean water content at the end of the first stage of water absorption. It is determined as the point of intersection of straight lines drawn through the first and second stages of water absorption on a  $t^{1/2}$  plot (Fig. 7).

The test must be carried out on a minimum of 3 specimens. In the case of a non-homogenous material, a larger number of specimens is recommended. The highest value among all tested specimens will then be used to calculate the amount of solution for the initial contamination (accumulation stage of the specimens).





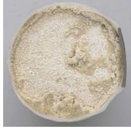






**Fig. 7** Schematic of a typical water absorption by capillarity test result showing the point where the capillary moisture content of the material is determined



**Appendix 2: Reference scheme for the description of damage or alteration**

**Table 2** Reference scheme for the description of damage or alteration

Cycle	Photographic documentation	Main categories or types of damage (A-F Appendix 3) and detailed damage and alteration types (if needed, 1–16 Appendix 3)	Extent of damage or alteration: 0. None, 1. Limited, 2. Extensive	Remarks
Reference—before testing				
				
After accumulation				
1st cycle				
2nd cycle				
3rd cycle				
4th cycle—end of the test (after brushing)				
				
				

### Appendix 3: Types of damage and alterations

**Table 3** Type of damage and alterations

Main category/type of damage and alteration	Detailed damage type and alteration	References to existing atlases	
A. Surface change <i>The material acquires a different appearance from how it originally looked. It includes, for example, the deposit of salt crystals (efflorescence)</i>	1. Chromatic alteration (incl. fading, moist spots, staining, discoloration)	ICOMOS (stone) <a href="https://openarchive.icomos.org/id/eprint/434/">https://openarchive.icomos.org/id/eprint/434/</a> pg 46 MDCS (brick, mortar, stone, plaster) <a href="https://mdcs.monumentenkenis.nl/damageatlas/2/category">https://mdcs.monumentenkenis.nl/damageatlas/2/category</a> <a href="https://mdcs.monumentenkenis.nl/damageatlas/248/category">https://mdcs.monumentenkenis.nl/damageatlas/248/category</a> <a href="https://mdcs.monumentenkenis.nl/damageatlas/100/category">https://mdcs.monumentenkenis.nl/damageatlas/100/category</a> <a href="https://mdcs.monumentenkenis.nl/damageatlas/58/category">https://mdcs.monumentenkenis.nl/damageatlas/58/category</a>	
	2. Efflorescence (incl. salt crust)	ICOMOS (stone) <a href="https://openarchive.icomos.org/id/eprint/434/">https://openarchive.icomos.org/id/eprint/434/</a> pg 48 MDCS (brick, mortar, stone, plaster) <a href="https://mdcs.monumentenkenis.nl/damageatlas/10/category">https://mdcs.monumentenkenis.nl/damageatlas/10/category</a> <a href="https://mdcs.monumentenkenis.nl/damageatlas/249/category">https://mdcs.monumentenkenis.nl/damageatlas/249/category</a> <a href="https://mdcs.monumentenkenis.nl/damageatlas/104/category">https://mdcs.monumentenkenis.nl/damageatlas/104/category</a> <a href="https://mdcs.monumentenkenis.nl/damageatlas/62/category">https://mdcs.monumentenkenis.nl/damageatlas/62/category</a>	
	3. Subflorescence / Cryptoflorescence	ICOMOS (stone) <a href="https://openarchive.icomos.org/id/eprint/434/">https://openarchive.icomos.org/id/eprint/434/</a> pg 62 MDCS (brick, mortar, stone, plaster) <a href="https://mdcs.monumentenkenis.nl/damageatlas/10/category">https://mdcs.monumentenkenis.nl/damageatlas/10/category</a> <a href="https://mdcs.monumentenkenis.nl/damageatlas/249/category">https://mdcs.monumentenkenis.nl/damageatlas/249/category</a> <a href="https://mdcs.monumentenkenis.nl/damageatlas/104/category">https://mdcs.monumentenkenis.nl/damageatlas/104/category</a> <a href="https://mdcs.monumentenkenis.nl/damageatlas/62/category">https://mdcs.monumentenkenis.nl/damageatlas/62/category</a>	
	B. Layering <i>Detachment within a material in the form of parallel layers. Layering leads to material loss</i>	4. Exfoliation / Delamination	ICOMOS (stone) <a href="https://openarchive.icomos.org/id/eprint/434/">https://openarchive.icomos.org/id/eprint/434/</a> pg 18 MDCS (brick, mortar, stone, plaster) <a href="https://mdcs.monumentenkenis.nl/damageatlas/508/category">https://mdcs.monumentenkenis.nl/damageatlas/508/category</a> <a href="https://mdcs.monumentenkenis.nl/damageatlas/264/category">https://mdcs.monumentenkenis.nl/damageatlas/264/category</a> <a href="https://mdcs.monumentenkenis.nl/damageatlas/114/category">https://mdcs.monumentenkenis.nl/damageatlas/114/category</a> <a href="https://mdcs.monumentenkenis.nl/damageatlas/71/category">https://mdcs.monumentenkenis.nl/damageatlas/71/category</a>
		5. Spalling	ICOMOS (stone) <a href="https://openarchive.icomos.org/id/eprint/434/">https://openarchive.icomos.org/id/eprint/434/</a> pg 26 MDCS (brick, mortar, stone, plaster) <a href="https://mdcs.monumentenkenis.nl/damageatlas/508/category">https://mdcs.monumentenkenis.nl/damageatlas/508/category</a> <a href="https://mdcs.monumentenkenis.nl/damageatlas/114/category">https://mdcs.monumentenkenis.nl/damageatlas/114/category</a> <a href="https://mdcs.monumentenkenis.nl/damageatlas/71/category">https://mdcs.monumentenkenis.nl/damageatlas/71/category</a>
		6. Scaling / Flaking	ICOMOS (stone) <a href="https://openarchive.icomos.org/id/eprint/434/">https://openarchive.icomos.org/id/eprint/434/</a> pg 26 MDCS (brick, mortar, stone, plaster) <a href="https://mdcs.monumentenkenis.nl/damageatlas/508/category">https://mdcs.monumentenkenis.nl/damageatlas/508/category</a> <a href="https://mdcs.monumentenkenis.nl/damageatlas/114/category">https://mdcs.monumentenkenis.nl/damageatlas/114/category</a> <a href="https://mdcs.monumentenkenis.nl/damageatlas/71/category">https://mdcs.monumentenkenis.nl/damageatlas/71/category</a>

**Table 3** continued

Main category/type of damage and alteration	Detailed damage type and alteration	References to existing atlases
C. Loss of cohesion <i>The particles in a material are no longer bound. The damage may be differently defined, depending on the type of and/or the size and form of the loose particles of the affected material</i>	7. Crumbling	ICOMOS (stone) <a href="https://openarchive.icomos.org/id/eprint/434/">https://openarchive.icomos.org/id/eprint/434/</a> pg 20 MDCS (brick, mortar, stone, plaster) <a href="https://mdcs.monumentenkenis.nl/damageatlas/21/category">https://mdcs.monumentenkenis.nl/damageatlas/21/category</a> <a href="https://mdcs.monumentenkenis.nl/damageatlas/269/category">https://mdcs.monumentenkenis.nl/damageatlas/269/category</a> <a href="https://mdcs.monumentenkenis.nl/damageatlas/116/category">https://mdcs.monumentenkenis.nl/damageatlas/116/category</a> <a href="https://mdcs.monumentenkenis.nl/damageatlas/79/category">https://mdcs.monumentenkenis.nl/damageatlas/79/category</a>
	8. Granular disintegration (incl. sanding, sugaring, powdering, chalking, selective weathering/differential erosion, alveolation)	ICOMOS (stone) <a href="https://openarchive.icomos.org/id/eprint/434/">https://openarchive.icomos.org/id/eprint/434/</a> pg 20 MDCS (brick, mortar, stone, plaster) <a href="https://mdcs.monumentenkenis.nl/damageatlas/21/category">https://mdcs.monumentenkenis.nl/damageatlas/21/category</a> <a href="https://mdcs.monumentenkenis.nl/damageatlas/269/category">https://mdcs.monumentenkenis.nl/damageatlas/269/category</a> <a href="https://mdcs.monumentenkenis.nl/damageatlas/116/category">https://mdcs.monumentenkenis.nl/damageatlas/116/category</a> <a href="https://mdcs.monumentenkenis.nl/damageatlas/79/category">https://mdcs.monumentenkenis.nl/damageatlas/79/category</a>
	9. Bursting	ICOMOS (stone) <a href="https://openarchive.icomos.org/id/eprint/434/">https://openarchive.icomos.org/id/eprint/434/</a> pg 16 MDCS (brick, mortar, stone, plaster) <a href="https://mdcs.monumentenkenis.nl/damageatlas/269/category">https://mdcs.monumentenkenis.nl/damageatlas/269/category</a> <a href="https://mdcs.monumentenkenis.nl/damageatlas/79/category">https://mdcs.monumentenkenis.nl/damageatlas/79/category</a>
	10. Blistering	ICOMOS (stone) <a href="https://openarchive.icomos.org/id/eprint/434/">https://openarchive.icomos.org/id/eprint/434/</a> pg 14 MDCS (brick, mortar, stone, plaster) <a href="https://mdcs.monumentenkenis.nl/damageatlas/20/category">https://mdcs.monumentenkenis.nl/damageatlas/20/category</a> <a href="https://mdcs.monumentenkenis.nl/damageatlas/265/category">https://mdcs.monumentenkenis.nl/damageatlas/265/category</a> <a href="https://mdcs.monumentenkenis.nl/damageatlas/115/category">https://mdcs.monumentenkenis.nl/damageatlas/115/category</a> <a href="https://mdcs.monumentenkenis.nl/damageatlas/75/category">https://mdcs.monumentenkenis.nl/damageatlas/75/category</a>
D. Detachment <i>Loss of adhesion at the interface of different materials (e.g., brick and mortar within masonry)</i>	11. Loss of adhesion	ICOMOS (stone) – MDCS (brick, mortar, stone, plaster) <a href="https://mdcs.monumentenkenis.nl/damageatlas/20/category">https://mdcs.monumentenkenis.nl/damageatlas/20/category</a> <a href="https://mdcs.monumentenkenis.nl/damageatlas/265/category">https://mdcs.monumentenkenis.nl/damageatlas/265/category</a> <a href="https://mdcs.monumentenkenis.nl/damageatlas/115/category">https://mdcs.monumentenkenis.nl/damageatlas/115/category</a> <a href="https://mdcs.monumentenkenis.nl/damageatlas/75/category">https://mdcs.monumentenkenis.nl/damageatlas/75/category</a>
	12. Peeling	ICOMOS (stone) <a href="https://openarchive.icomos.org/id/eprint/434/">https://openarchive.icomos.org/id/eprint/434/</a> pg 24 MDCS (brick, mortar, stone, plaster) <a href="https://mdcs.monumentenkenis.nl/damageatlas/20/category">https://mdcs.monumentenkenis.nl/damageatlas/20/category</a> <a href="https://mdcs.monumentenkenis.nl/damageatlas/265/category">https://mdcs.monumentenkenis.nl/damageatlas/265/category</a> <a href="https://mdcs.monumentenkenis.nl/damageatlas/115/category">https://mdcs.monumentenkenis.nl/damageatlas/115/category</a> <a href="https://mdcs.monumentenkenis.nl/damageatlas/75/category">https://mdcs.monumentenkenis.nl/damageatlas/75/category</a>

**Table 3** continued

Main category/type of damage and alteration	Detailed damage type and alteration	References to existing atlases
	13. Push out	ICOMOS (stone) — MDCS (brick, mortar, stone, plaster) <a href="https://mdcs.monumentenkennis.nl/damageatlas/265/category">https://mdcs.monumentenkennis.nl/damageatlas/265/category</a>
E. Cracking <i>Cracking can be minute and limited to the material surface, but it can also be large and affect the material deeper inside, or even cause it to fall into parts</i>	14. Crack	ICOMOS (stone) <a href="https://openarchive.icomos.org/id/eprint/434/">https://openarchive.icomos.org/id/eprint/434/</a> pg 10 MDCS (brick, mortar, stone, plaster) <a href="https://mdcs.monumentenkennis.nl/damageatlas/4/category">https://mdcs.monumentenkennis.nl/damageatlas/4/category</a> <a href="https://mdcs.monumentenkennis.nl/damageatlas/277/category">https://mdcs.monumentenkennis.nl/damageatlas/277/category</a> <a href="https://mdcs.monumentenkennis.nl/damageatlas/131/category">https://mdcs.monumentenkennis.nl/damageatlas/131/category</a> <a href="https://mdcs.monumentenkennis.nl/damageatlas/86/category">https://mdcs.monumentenkennis.nl/damageatlas/86/category</a>
	15. Crazing / craquelé	ICOMOS (stone) <a href="https://openarchive.icomos.org/id/eprint/434/">https://openarchive.icomos.org/id/eprint/434/</a> pg 10 MDCS (brick, mortar, stone, plaster) <a href="https://mdcs.monumentenkennis.nl/damageatlas/4/category">https://mdcs.monumentenkennis.nl/damageatlas/4/category</a> <a href="https://mdcs.monumentenkennis.nl/damageatlas/277/category">https://mdcs.monumentenkennis.nl/damageatlas/277/category</a> <a href="https://mdcs.monumentenkennis.nl/damageatlas/131/category">https://mdcs.monumentenkennis.nl/damageatlas/131/category</a> <a href="https://mdcs.monumentenkennis.nl/damageatlas/86/category">https://mdcs.monumentenkennis.nl/damageatlas/86/category</a>
F. Deformation <i>Deformation may include an increase of volume or a deviation from the original form in various ways</i>	16. Bulging	ICOMOS (stone) <a href="https://openarchive.icomos.org/id/eprint/434/">https://openarchive.icomos.org/id/eprint/434/</a> pg 12 MDCS (brick, mortar, stone, plaster) <a href="https://mdcs.monumentenkennis.nl/damageatlas/5/category">https://mdcs.monumentenkennis.nl/damageatlas/5/category</a> <a href="https://mdcs.monumentenkennis.nl/damageatlas/91/category">https://mdcs.monumentenkennis.nl/damageatlas/91/category</a>

## References

- Lubelli B, Aguilar AM, Beck K et al (2022) A new accelerated salt weathering test by RILEM TC 271-ASC: preliminary round robin validation. Mater Struct. <https://doi.org/10.1617/s11527-022-02067-8>
- Lubelli B and RILEM TC 271-ASC members (2021) New accelerated laboratory test for the assessment of the durability of materials with respect to salt crystallization. In: Lubelli B, Kamat A, Quist W (eds) SWBSS2021 - Fifth International Conference on Salt Weathering og Buildings and Stone Sculptures. TU Delft Open, pp 55–67
- Flatt RJ, Mohamed NA, Caruso F, et al (2017) Predicting salt damage in practice: a theoretical insight into laboratory tests. RILEM Tech Lett 2:108–118. <https://doi.org/10.21809/rilemtechlett.2017.41>
- Tuutti K (1982) Corrosion of steel in concrete. Stockholm
- ICOMOS ISCS (2008) Illustrated glossary on stone deterioration patterns. <https://openarchive.icomos.org/id/eprint/434/>. Accessed 7 April, 2023
- MDCS Damage Atlas. <https://mdcs.monumentenkennis.nl/damageatlas>. Accessed 28 Oct 2022
- CEN (1999) NEN-EN 1925 - Natural stone test methods - Determination of water absorption coefficient by capillarity

**Publisher's Note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

