

## Salts in the Deterioration of Porous Materials: A Call for the Right Questions

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### Abstract

On the basis of recent literature surveys and publications a brief review of the issues involved in the deterioration of porous inorganic materials induced by the presence of salt is discussed. Starting with the dissolution of salts in water to form solutions, it is pointed out that many questions need to be answered to understand their behaviour. This is followed by the behaviour of these solutions within the porous material. It is highlighted that the damage is not due to a single “salt crystallization” mechanism but that several mechanisms can be operative, such as the formation of salt-films and the resulting stresses they induce in the substrate or the wedge action exerted by growing crystals in fissures. A hypothesis for the origin of the induced damage is forwarded based on the stresses induced by hygrothermic changes on salt-films, their action on the substrate and the difference in moisture absorption with areas not covered by these films. Finally, suggestions are made regarding further research, in particular for the pore-range location of salts within a given porous material and for different materials.

**Keywords:** Salt crystallization, salt films, porous material deterioration, moisture absorption, substrate influence.

“First, of course, there’s the things you don’t know;  
then there’s the things you do know but don’t understand;  
then there’s the things you do understand but which don’t matter.”  
*“Simple Simon”* A. E. Coppard

## **Die Rolle von Salzen bei der Zerstörung poröser Werkstoffe: die richtigen Fragen müssen gestellt werden**

### **Zusammenfassung**

*Auf der Basis kürzlich erschienener Literaturübersichten und Veröffentlichungen werden wesentliche Aspekte, die bei der Zerstörung poröser inorganischer Werkstoffe im Beisein von Salzen eine Rolle spielen, diskutiert. Zunächst wird am Beispiel der Auflösung von Salzen in Wasser und der Bildung von Salzlösungen gezeigt, dass noch viele Fragen beantwortet werden müssen, bevor wir die Vorgänge wirklich verstehen. Danach wird das Verhalten dieser Salzlösungen im porösen Gefüge behandelt. Es wird besonders herausgestellt, dass der Schaden nicht von einem einzigen Mechanismus, etwa der „Salzkristallisation“, verursacht wird, sondern dass vielmehr mehrere Mechanismen zusammen wirken können, wie etwa die Bildung von Salzfilmen und die daraus resultierenden Spannungen, die dabei im Untergrund entstehen, oder die Keilwirkung, die durch wachsende Kristalle in Rissen zustande kommt. Eine Hypothese zur Erklärung der Ursache des entstehenden Schadens wird vorgeschlagen. Diese Hypothese basiert auf den Spannungen, die durch hygro-thermische Änderungen der Salzfilme entstehen. Die Wechselwirkung der Salzfilme mit dem Untergrund und der Unterschied zwischen deren Feuchtigkeitsabsorption im Vergleich mit der Absorption der nicht mit Salzfilmen bedeckten Stellen werden auch berücksichtigt. Schließlich werden Vorschläge hinsichtlich weiterer Forschungsprojekte unterbreitet. Insbesondere sollte der Porenbereich eines porösen Werkstoffes, in dem sich Salze ablagern, näher untersucht werden und es sollten unterschiedliche Werkstoffe einbezogen werden.*

**Stichwörter:** Salzkristallisation, Salzfilme, Zerstörung poröser Werkstoffe, Feuchtigkeitsabsorption, Einfluss des Untergrundes.

*"Den Anfang machen natürlich die Dinge, die du nicht weißt;  
dann kommen die, die du weißt, doch nicht verstehst;  
und endlich jene, die du verstehst, auf die es aber nicht ankommt."  
"Simple Simon" A. E. Coppard  
(aus dem Englischen übertragen von Frau Dr. Christa Seibicke)*

## 1 Introduction

The deterioration that salts induce in porous inorganic materials has been the subject of much research and although it is an undeniable fact, the mechanism that produces this damage is yet to be clearly elucidated. To advance in this objective it is important to bring together the vast amount of information collected and review it with the aim to consolidate it so that at the end it serves to determine what information is:

- incorrect, so as to eliminate it;
- not relevant, so as to separate it;
- not understood, so as to elucidate it; and, eventually,
- missing, so as to design the necessary research to find it.

Many reviews have been recently published [1-3] but the vastness of the literature, and the breadth of the field makes it nearly impossible for a single person to obtain a clear, overall perspective. This results in the re-publishing of hypothesis and/or theories that have already been proven wrong in otherwise good and valuable publications. And, what is worse, most of these disproven theories, because they appear plausible, i.e., damage is due to the volume expansion that salts suffer upon hydration, are still presented in text books, so that new researchers have to unlearn what was earlier taught to them. Even in these times of instant publication and information availability on the internet, the rate at which this information is assimilated has not increased significantly. It might even decrease, because the amount of information readily available hampers the selection of that which is really valuable. As a consequence, reading all the available material leaves little time to really think about and elaborate the important information.

A parallel with crystal growth can be drawn here: information is now at a supersaturation point, the salts that will precipitate are small, practically amorphous structures. To understand something, it needs to crystallize, and requires what chemists called a “digestion” process, in which the poorly crystallized salts redissolve and only the well formed crystals will grow, leading to an organized structure. The word “crystal” means clear, transparent. On the point of the deterioration of porous materials by salt crystallization, we are far from a clear understanding of the process.

## 2 Salts in Water

While focusing on the deterioration mechanism of salt crystallization in porous materials, issues such as the interaction of salts with water are not given sufficient attention. For example, Correns [4] states that for most known inorganic salt solutions—ammonium chloride is mentioned as an exception—the volume of the supersaturated solution is smaller than that of the sum of the volumes of the saturated solution and the precipitated salt. This would lead to what is called the hydrostatic crystallization pressure when the salt precipitates out and the total volume increases.

Other exceptions to this rule reported by Baxter [5] are ammonium nitrate—relevant to the deterioration of porous building materials—as well as ammonium bromide and halogen salts of cesium, but interestingly not ammonium iodide. These salts would induce a volume increase during dissolution. This volume increase, if it indeed occurs, could possibly result from the supposition that larger monovalent alkali metals, such as cesium or ammonium, are essentially unassociated with water molecules [6]. However, according to the experiments of Correns and Steinborn [7] sodium chlorate ( $\text{NaClO}_3$ ) would also belong to these exceptions, and therefore the above explanation could not apply.

But it is very likely that whether there is an expansion or a contraction upon the precipitation of salts out of a supersaturated solution may be irrelevant to the deterioration produced as has been clearly shown for the case of freezing liquids [8]. In this study, it was shown that similar damage was obtained with water, that expands upon freezing, and organic liquids such as benzene or nitrobenzene, that contract upon freezing. This would clearly indicate that the damage is produced by the appearance of a new solid phase regardless of whether there is a total volume increase or decrease.

When contraction occurs upon dissolution of the salt, the contraction is greater the more dilute the solution and continues with the dilution of the solution. In some cases, the volume of the solution is even less than the volume of the water alone [9]. The practical implications resulting from the volume contraction upon dissolution of the salt when this occurs in a porous material is enhancement of capillary rise. Although this may be minor influence on the existing capillary absorption centuries

of this phenomenon will assure an increased salt deposition in the material as compared to that resulting from plain capillary absorption.

A clear discussion of ion solvation and ion-interaction that occurs upon dissolution of salts in water and the formation of saturated solutions, has as yet to be published for the case of salts relevant to the deterioration of masonry. This would allow a better understanding of the behaviour of the different ions in solution and perhaps explain why some salts would expand upon dissolution in water. Unfortunately, the expert chemical model that has been worked out [10] does not include a description of the actual water-salt interactions, since it focuses on the means to calculate molar volumes of solutions and other parameters necessary to estimate the eventual amount of solid salts present at different RH or the volume occupied by these salts under these conditions.

### 3 Salts in Porous Structures

A valiant effort has been made by Doehne in trying to enumerate the factors that influence the damage induced in porous materials and trying to highlight those that are most important [1]. He points out that the key to the damage is based on the supersaturation of the solution and the location of crystal growth within the porous matrix. He lists the important factors in the formation of supersaturation of solutions as:

- evaporation rate;
- cooling rate;
- the presence of pre-existing salts; and,
- nucleation/growth rates.

And for location of the damage, as:

- evaporation rate/solution transport rate;
- solution properties (surface tension, viscosity); and
- pore size distribution.

This summarized list can be misleading, because the substrate only appears mentioned as the pore size distribution, however it's nature will have a significant effect on the nucleation and growth rates. Nonetheless it provides a good starting point to further elaborate our understanding of the problem.

While the importance of the supersaturation of solutions was one of the first factors identified in the early 20<sup>th</sup> century [4, 7, 9] the location of the

induced damage was mainly obtained from observation in nature and correlated to environmental conditions. Only twenty years ago was an attempt made at developing a theory to explain the location of the damage as a function of the properties of the salt solution and the porosity of the substrate [11]. Further studies have succeeded at developing numerical model calculations to determine the depth at which deterioration will occur for stones of different porosity and confirming the model with actual measurements carried out on a test wall [12,13].

Although this is certainly an advance in understanding the problem it will not as yet be able to predict the intensity of the damage. For this purpose, the dynamics of the process needs to be integrated. As has been pointed out, there is a distinct correlation between the rate at which reactions occur and the degree of damage [14]. As an example, the rate of volume expansion suffered by a solution upon precipitation of the salt—for the case of sodium sulphate—depends on the supersaturation ratio, since precipitation from a saturated solution is slow [15]. Or damage will be more significant if fast changes of humidity (or temperature) occur rather than if the same change occurs slowly [16].

The theoretical framework proposed by Scherer [17,18] is applicable to both ice or salt crystal growth. For the latter, it confirms the original suggestion by Correns [19] that the pressure generated by crystal growth is a function of the supersaturation of the solution in which the crystal grows. It also explains that the crystallization stress is lower in larger pores, that damage will occur first in smaller pores within the 4 nm to 50 nm range and that fracture of the porous body requires that crystals grow through a region of the porous material comparable in size to the strength-controlling flaws. These last three points had already been recognized by observations in nature and practical studies such as those of Fitzner[20], Arnold and Zehnder [21] and Hoffmann and Grassegger [22], respectively and the original observations by Taber [9]. However, they do not explain why sodium sulfate and sodium chloride crystallize in different pore sizes, as shown by Rodrigues Navarro et al. [23], neither do they take into account the reaction kinetics that influence significantly the resulting degree of damage [14].

As pointed out earlier, the damage is apparently induced by the appearance of a new solid phase.

This implies that if a salt has the possibility of producing a second solid phase, such as a hydrate, it should be more damaging than salts that only form one solid phase. Experience appears to prove this hypothesis, however further testing is required to prove it unequivocally.

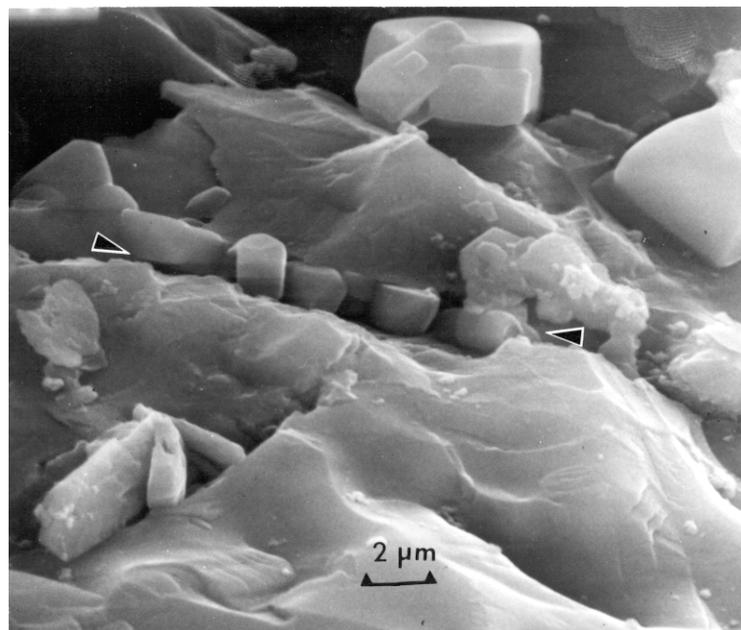
Although much effort has been put into studying the crystallization of salt solutions, pure and in mixture, the contribution of the porous material itself to its deterioration process has not received as much attention. For example, the varying location of crystal growth within the pores of a same stone and similar environmental conditions for two different salts has only been reported for sodium chloride and sodium sulphate [23]. Further systematic studies of these interesting results are yet to be continued.

A methodical study of the deterioration of different stones—including artificial porous materials produced by the sintering of glass beads—by salt crystallization lead to the conclusion that one of the most damaging factors for a porous material is the presence of angles between crystalline particles [24]. Hence, platy minerals leading to plate-like pores, will foster growth of crystals in these locations giving rise to an effective wedge action that increases deterioration. Figure 1 shows a row of crystals of alkali chloride salts (halite and sylvite) wedging open with their growth a fissure in a quartz grain from a flake of granite [25].

A similar explanation was suggested by studies on the deteriorating effect of gypsum in a clay-rich sandstone [13, 26, 27]. Furthermore, the high damage induced by air-pollution generated gypsum in marbles and calcareous stones could be attributed to the typical platy shapes of the resulting gypsum crystals that can act as wedges as they grow both inter- and intra-granularly in these materials [28].

Another important point for the eventual damage induced to a porous material are the conditions under which salts crystallize. If moisture, and in particular, liquid water is readily available, well formed crystals will develop as discussed by Zehnder and Arnold [29]. However, if cycling between wet and dry conditions predominate, with spells of high humidity in between, then cryptocrystalline formations are the result, as observed by Doehne [30] under an ESEM, where the relative changes in RH fostered the formation of such cryptocrystalline aggregates. As pointed out by Brüll [31], such cryptocrystalline aggregates can be a mixture of phases and in this case the water vapour pressure over these aggregates will be a function of the particle size and the mixture no longer falls under the phase rule.

The importance of these cryptocrystalline salt formations in the deterioration of porous materials has been repeatedly highlighted by Pühringer [32, 33, 34]. The reason for their importance in the study of



**Figure 1:** Arrows point to a row of alkali halides (halite and/or sylvite) crystallizing in a fissure in a grain of quartz of an exfoliating granite (from Charola and Lewin [25]).

stone deterioration lies in the fact that they have enormous specific surfaces so that reactions, such as dissolution and moisture absorption, will be much faster than for larger crystals. Thus the reaction rates will be accelerated, providing an easy path for the generation of saturated (or supersaturated) solutions, as mentioned by Doehne [1]. As mentioned previously, kinetics is one of the key factors in determining the degree of the resulting deterioration.

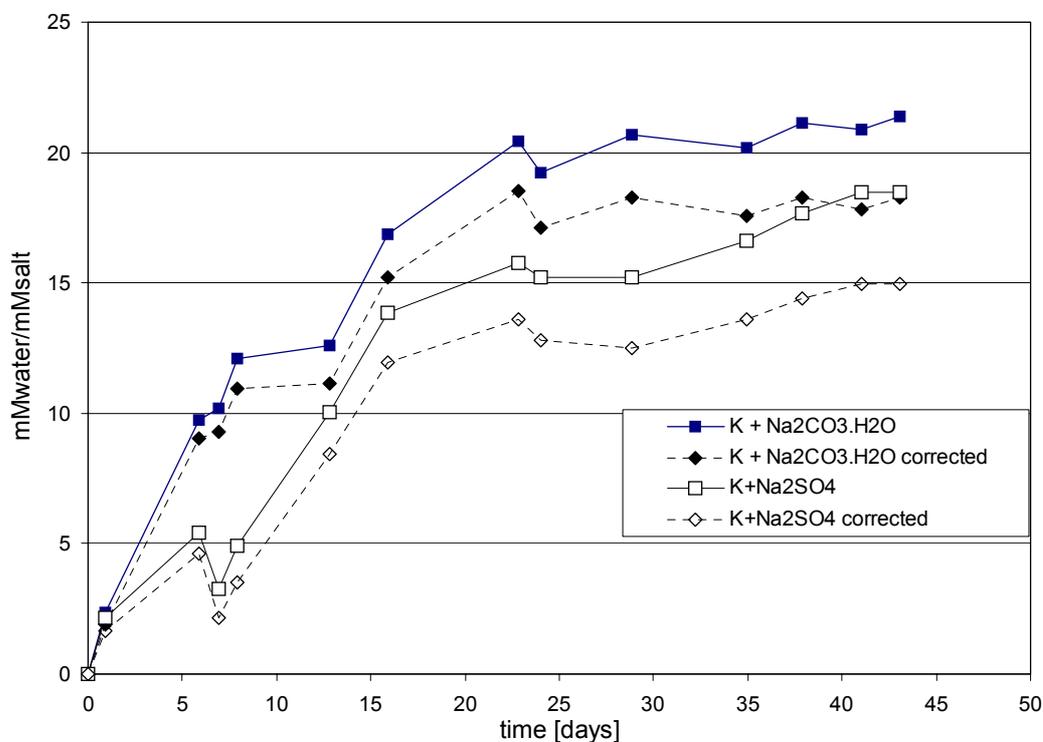
The distribution of these fine “salt structures” within a porous material enhances their hygroscopicity, a phenomenon that is also dependent on the nature of the substrate, as was shown for the case of sodium sulphate [35]. Recently carried out tests with sodium sulfate and sodium carbonate monohydrate, have confirmed that the contribution of the substrate to this hygroscopic absorption is relatively small, even for an absorptive substance such as Kieselguhr as shown in Figure 2. The graph shows that thermonatrite is more hygroscopic than thenardite and is slower in following thermohygric changes, as indicated by the higher moisture con-

tent fluctuations of thenardite. This could be part of the reason for the higher damaging potential of sodium sulphate.

Cryptocrystalline formations will also result from the creep of salt solutions and enhance further creep. The importance of this salt transport mechanism resides in its contribution to the formation of salt films on the substrate. And these may induce shear stresses as suggested by Pühringer [32, 33, 34].

#### 4 Salt Deterioration Mechanism: A Theory

Recent publications [36, 37] suggest a deterioration mechanism based on the capability of these salt films—left behind in a porous material by evaporation of a salt solution—to absorb moisture. As confirmed in simple laboratory experiments, oscillations in the relative humidity of the environment, even in ranges well below the equilibrium RH of the salt in question, are capable of inducing some damage [38].



**Figure 2:** Moisture absorption for Kieselguhr mixed with 4 % salt, thenardite or thermonatrite, stationed over water (approx. 1000 % RH). The results are expressed as mMoles of absorbed water per mMole of thenardite or thermonatrite in the mixture. Dotted lines correspond to the absorption values corrected for the absorption of Kieselguhr by itself. Oscillations are due to temperature fluctuations in the laboratory (courtesy J. Weber).

The postulated mechanism is based on the fact that salts precipitating from a supersaturated solution will induce a volume increase for the total salt/water system, i.e., hydrostatic crystallization pressure. Upon drying, the residual mass will be attached in parts of the porous material as a thin film of salt or as cementing material. This is capable of moisture sorption, and, upon dissolution, will result in a shrinking of the total volume of the salt/water mass. The stresses induced to the underlying material are based on the shear stresses induced by the repeated swelling-shrinking phenomenon. For salts that do not induce a volume reduction upon dissolution, the deterioration mechanism would be the similar though opposed in direction.

For the case of hydrating salts, one of the important points is the fact that once the salt dries as the anhydrate within the porous body—and this always results in a cryptocrystalline aggregate when the anhydrate forms by dehydration—the presence of moisture (either as water vapour or as liquid) will induce a partial or total hydration of the solid salt [39]. Furthermore, if a saturated solution of the same salt comes in contact with the anhydrate, the latter will hydrate thus prompting an immediate supersaturation of the solution and the precipitation of the hydrate [37]. Thus, thermodynamically unstable situations may arise within the pores of the material.

As has been summarized by Snethlage and Wendler [13] from various experimental studies, the expansion/contraction suffered by the porous materials during wet-dry cycling, particularly if these materials contain clays, is enhanced by the presence of salts which induce the opposite effect: contraction upon wetting and expansion upon drying. This suggests that since it is unlikely that the porous material be uniformly covered with a salt film, there will be a significant difference in moisture absorption between the salt film attached to the substrate and the bare substrate. This difference is likely to induce opposing stresses at the edge of the salt films and these may explain the differences in damages observed by the same salt in different substrates.

## 5 Conclusions

From the above synthesis of studies the following research areas promise to advance our understanding of material deterioration induced by the presence of salts. These are:

- the behaviour of salts, i.e., their ions, in solutions, including saturated and super-saturated solutions;
- the behaviour of salts at phase boundaries;
- the influence of kinetics in determining the degree of deterioration;
- the systematic investigation of the location of different salts within the pore structure of a given material at given conditions; and complemented with
- the systematic investigation of different materials.

It is clear that the salt induced deterioration cannot be explained by a single mechanism. Different mechanisms, such as wedge action of larger crystals or salt-film induced shear stresses, can apply depending on the kind salt in question, the environmental conditions and the type of substrate affected. While this has been long known and has served to suggest solutions to remediate the deterioration induced by salts [39, 40], the elucidation of actual mechanism operative under a given condition has yet to be worked out.

In part this is the result of poorly formulated questions because an interdisciplinary team is required to correctly formulate them. For example, salt weathering studies were initiated by geomorphologists, who attributed the deterioration to pressures generated by crystal growth and these were compared to the compressive strength of materials without taking into account that pressures applied in round pores of a material will result in tensile stresses for the material.

Hence, to further the development of theories explaining the deterioration resulting from the presence of salts within a porous material, the right questions need to be asked. As worded by the Nobel laureate José Saramago of Portugal: “Everything in the world is providing answered, the delay is caused by the time it takes to formulate the questions” (*Tudo no mundo está dando respostas, o que demora é o tempo das perguntas. From “Memorial do Convento” 1982*).

## References

1. Doehne, E. (2002) *Salt Weathering: A Selective Review* In: Geomaterials, Weathering Phenomena, Conservation Strategies and Case Studies, Special Publication, The Geological Society of London (in press)

2. Doehne, E. (2002) *Salt Weathering and Building Material Decay: A Selected Bibliography*. In: Geomaterials, Weathering Phenomena, Conservation Strategies and Case Studies, Special Publication, The Geological Society of London (in press)
3. Charola, A.E. (2000) *Salts in the Deterioration of Porous Materials: An Overview*. Journal of the American Institute for Conservation **39** 327-343
4. Correns, C.W. (1926) *Ueber die Erklärung der sogenannten Kristallisationskraft*. Ber. d. Preuß. Akad. d. Wiss. **11** 81-88
5. Baxter, G.P. (1911) *Changes in Volume upon Solution in Water of the Halogen Salts of the Alkalies*. J. Amer. Chem. Soc. **33** [6] 922-940
6. Langmuir, D. (1979) *Techniques of Estimating Thermodynamic Properties for Some Aqueous Complexes of Geochemical Interest*. In: Chemical Modeling in Aqueous Systems. E.A. Jenne, Ed., American Chemical Symposium Series 93, Washington, DC. pp. 353-387
7. Correns, C.W. and Steinborn, W. (1939) *Experimente zur Messung und Erklärung der sogenannten Kristallisationskraft*. Zeitschrift für Kristallographie **101** 117-123
8. Taber, S. (1929) *Frost Heaving*. Journal of Geology **37** 428-461
9. Taber, S. (1916) *The Growth of Crystals Under External Pressure*. Amer. Journal of Science **41** 532-556
10. Price, C., Ed. (2000) *An Expert Chemical Model for Determining the Environmental Conditions Needed to Prevent Salt Damage in Porous Materials*. Protection and Conservation of the European Cultural Heritage. Research Report No. 11. Archetype Publications, Ltd. London.
11. Lewin, S.Z. (1982) *The Mechanism of Masonry Decay through Crystallization*. In: Conservation of Historic Stone Buildings and Monuments. Report of the Committee on Conservation of Historic Stone Buildings and Monuments. National Academy Press, Washington DC, pp. 120-144
12. Wendler, E. (1991) *Zum Mechanismus der Schalenbildung bei tonigen Sandsteinen*. Jahresberichte Steinzerfall – Steinkonservierung 1989, R.Sneathlage, Ed., Ernst & Sohn, Berlin. pp. 71-76
13. Sneathlage, R., and Wendler, E. (1997) *Moisture Cycles and Sandstone Degradation. Saving Our Architectural Heritage. The Conservation of Historic Stone Structures*, N.S. Baer and R. Sneathlage, Eds., Elsevier, Chichester, pp. 7-24
14. Charola, A.E. (n.d.) *Salt Deterioration: Open Questions*. Proceedings of the Seminar “Mauersalze und Architekturoberfläche” Hochschule für Bildende Künste, Dresden 2002 (in press)
15. McMahon, D.J., P. Sandberg, K. Folliard, and P.K. Mehta. (1992) *Deterioration Mechanisms of Sodium Sulfate*. In: Proceedings of the 7<sup>th</sup> International Congress on the Deterioration and Conservation of Stone. J. Delgado Rodrigues, Telmo Jeremias and F. Henriques, Eds., Laboratorio Nacional de Engenharia Civil, Lisbon. pp. 705-714
16. von Konow, T. (2001) *Mechanisms of Brick Deterioration due to Salts: New Results on Salt Behaviour from in-situ studies at the Suomenlinna Fortress in Finland*. International Journal for Restoration of Buildings and Monuments **7** [6] 675-688
17. Scherer, G.W. (1999) *Crystallization in pores*. Cement and Concrete Research **29** 1347-1358
18. Scherer, G.W. (2000) *Stress from crystallization of salt in pores*. In: Proceedings of the 9<sup>th</sup> International Congress on Deterioration and Conservation of Stone, V. Fassina, Ed., Elsevier, Amsterdam Vol. 1, 187-194
19. Correns, C.W. (1949) *Growth and dissolution of crystals under linear pressure*. Disc. Faraday Soc. **5** 267-271
20. Fitzner, B. (1993) *Porosity properties and weathering behaviour of natural stones—Methodology and examples*. In: 2<sup>nd</sup> Course on Stone Material in Monuments: Diagnosis and Conservation. Heraklion-Crete; F. Zezza, Ed., Mario Adda Editore, Bari, pp. 43-54
21. Arnold, A. and Zehnder, K. (1990) *Salt weathering on monuments*. In: Proceedings of the 1<sup>st</sup> International Symposium on the Conservation of Monuments in the Mediterranean Basin. F. Zezza, Ed., Grafo, Bari, pp. 31-58
22. Hoffmann, L. and Grassegger, G. (1995) *Salzsprengeneffekte an Naturbausteinen mit verschiedenen umweltrelevanten Salzen*. In: Umwelteinflüsse. Erfassen, Simulieren,

- Bewerten. GUS- Gesellschaft für Umweltsimulationen, Karlsruhe, pp. 32.1-23.13
23. Carlos Rodriguez-Navarro and Eric Doehne. 1999. *Salt Weathering: Influence of Evaporation Rate, Supersaturation and Crystallization Pattern*. Earth Surface Processes and Landforms **24** (1999) 191-209
  24. Hoffmann, L. (1994) *Untersuchungen zur Ursache des Salzspengphänomens an Bausteinen*. Doctoral Dissertation, Ruprecht-Karls Universität, Heidelberg.
  25. Charola, A.E. and Lewin, S.Z. (1979) *Examples of stone decay due to salt efflorescence*. In: Proceedings of the 3<sup>rd</sup> International Congress on the Deterioration and Preservation of Stones, Venice, Università degli Studi di Padova, pp. 153-163
  26. Snethlage, R., Wendler, E. and Klemm, D.D. (1996) *Tenside im Gesteinsschutz—Bisherige Resultate mit einem neuen Konzept zur Erhaltung von Denkmälern aus Naturstein*. In: Denkmalpflege und Naturwissenschaft, Natursteinkonservierung I. R. Snethlage, Ed., Ernst & Sohn, Berlin, pp. 127-146
  27. Wendler, E. and Rückert-Thümling, R. (1992) *Gefügezerstörendes Verformungsverhalten bei salzbefrachteten Sandsteinen unter hygrischer Wechselbelastung*. In: Proceedings of the 3<sup>rd</sup> International Colloquium on Materials Science and Restoration. F.H. Wittmann, Ed., Technische Akademie Esslingen, Ostfildern, pp. 1818-1830
  28. Charola, A.E. and Koestler, R.J. (1985/86) *SEM Study of the Deterioration of Monumental Stones in Vienna*. In: Wiener Berichte über Naturwissenschaft in der Kunst. Verlag Orac, Vienna, pp. 176-185
  29. Zehnder, K. and Arnold, A. (1989) *Crystal growth in salt efflorescence*. Journal of Crystal Growth **97** 513-521
  30. Doehne, E. (1994) *In situ dynamics of sodium sulfate hydration and dehydration in stone pores: observation at high magnification using Environmental Scanning Microscopy*. In: Proceedings of the 3<sup>rd</sup> International Congress on the Conservation of Monuments in the Mediterranean Basin. V. Fassina, H. Ott and F. Zezza, Eds., Soprintendenza ai Beni Artistici e Storici, Venice, pp. 1453-150
  31. Brüll, W. (1929) *Ueber die Beziehungen verschiedener Hydrate eines Salzes zueinander*. Zeitschrift anorg. u. allg. Chem. **183** 347-352
  32. Pühringer, J. (1983) *Salt Disintegration. Salt Migration and Degradation by Salt—a Hypothesis*. D15:1983. Swedish Council for Building Research, Stockholm
  33. Pühringer, J. (1983) *Salzwanderung und Verwitterung durch Salze*. In: Proceedings of the International Colloquium on Materials Science and Restoration. F.H. Wittmann, Ed., Edition Lack+Chemie, Filderstadt, pp. 361-366
  34. Pühringer, J. (1996) *Deterioration of Materials by Hydraulic Pressure in Salt/Water Systems. An Outline Model*. In: Proceedings of the 8<sup>th</sup> International Congress on the Deterioration and Conservation of Stone. J. Riederer, Ed., Möller Druck und Verlag, Berlin, pp. 545-556
  35. Charola, A.E. and Weber, J. (1992) *The hydration-dehydration mechanism of sodium sulphate*. In: 7<sup>th</sup> International Congress on the Deterioration and Conservation of Stone. J. Delgado Rodrigues, Telmo Jeremias and F. Henriques. Laboratorio Nacional de Engenharia Civil, Lisbon. pp. 581-590
  36. Pühringer, J. (2002) *Hygrothermic Deterioration of Materials by Salts—A Technical Approach*. International Journal for Restoration of Buildings and Monuments **8** [4] 349-370
  37. Pühringer, J. (2002) *Deterioration of Materials by Salt Precipitation: Technical Aspects of “Crystallization/Hydration”* International Journal for Restoration of Buildings and Monuments **8** [5] 513-536
  38. Nunberg, S. and Charola, A.E. (2001) *Salts in Ceramic Bodies II: Deterioration due to Minimal Changes in Relative Humidity*. International Journal for Restoration of Buildings and Monuments **7** [2] 131-146
  39. Pühringer, J. (1985) *Unconventional Methods for the Prevention of Salt Damage*. In: Proceedings of the 5<sup>th</sup> International Congress on Deterioration and Conservation of Stone. G. Félix, Ed., Presses Polytechniques Romandes, Lausanne, pp. 241-250
  40. Pühringer, J. (1986) *Möglichkeiten zur Verhinderung von Schäden durch Salze*. In: Proceedings of the 2<sup>nd</sup> International Colloquium on Materials Science and Restoration, F.H. Wittmann, Ed., Technische Akademie Esslingen, Ostfildern, pp. 359-364



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Received September 19, 2005