

# Wick action in cultural heritage

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## Abstract

Salts crystallization is one of the main degradation mechanisms of historical objects, e.g., masonry. In this study we looked at a special case often encountered in marine environment, i.e., wick action. This is a steady state situation in which one end of an object is continuously absorbing a salt solution, e.g., sea water, whereas at the same time at other side there is continuous drying. As a result there will be a continuous flux of ions towards the drying surface and the concentration at the drying surface will slowly increase, resulting eventually in crystallization. In this study we looked at wick action for a 1 m NaCl solution using a biomicritic limestone from Sardinia, which is found in many cultural heritage objects. To measure both moisture and salt content simultaneously, we have used a specially designed Nuclear Magnetic Resonance (NMR) set-up. The wick action experiment was performed for over 40 days. The results show that the concentration over 40 days slowly increases at the top until the saturation concentration is reached. It is shown that the concentration profiles can be modeled by a simple analytic solution of the advection-diffusion equation describing the ion transport.

Keywords: Wick action, drying, salt crystallization, Nuclear Magnetic Resonance

## 1. Introduction

Salts crystallization is one of the main degradation mechanisms of historical heritage objects, such as masonry. Moisture penetration can advect dissolved ions along with it, into a porous material. The salt ions can accumulate and crystallize in the pores and can as a result produce cracks due to crystallization pressure. To get a better insight into the salt transport mechanism we picked up on a special case when a porous material is in contact with salt solution on one side and, at the same time, exposed to drying conditions on the opposite side. This situation is often encountered in cultural heritage in marine environment.

A well-known example is the housing along the canals in the historic city of Venice. Here there is a continuous supply of fresh sea water as a source of salt which is absorbed, whereas the top of the masonry is drying, giving rise to continuous salt damage. This continuous transport of a salt solution, combined with drying, is often referred to as wick action (*see also Fig. 1*).

During wick action salt ions will move by two mechanisms, advection and diffusion.<sup>1,2</sup> Advection is the process of ions moving along with the moisture flow, whereas diffusion is dependent on the concentration gradient, i.e., diffusion tries to level off any concentration gradient. As a result the net ion flux will be a competition of these two processes. Due to the continuous flow of salt ions towards the drying face there will be a continuous accumulation and as soon as

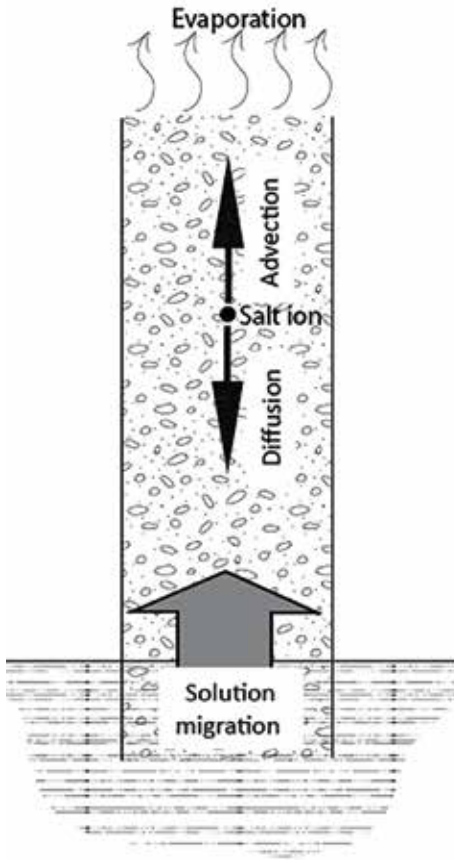


Figure 1: A schematic representation of wick action: one side of an object is absorbing a salt solution, whereas at the same time other side is drying. As a result there will be a continuous flow of ion towards the drying surface.

the maximum solubility limit has been reached, there will be crystallization, either inside the materials (subflorescence) or outside (efflorescence). In this study we have focused on wick action in the stable situation where the drying front stays at the top of the sample, i.e., the surface where the evaporation takes place. We have used Nuclear Magnetic Resonance (NMR) to measure both moisture and ion profiles non-destructively and quasi-simultaneously during wick action experiments. These experimental results have been compared to a simple analytic solution of the advection-diffusion equation describing the ion transport.

## 2. Theory

In order to get a better understanding of the salt concentration profiles which will develop during wick action we can have a look at combined ion and moisture transport. As long as the sample stays saturated during the wick action, the ion transport can be described by an advection-diffusion equation as given by:

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial x} \left( D \frac{\partial c}{\partial x} + uc \right) \quad (1)$$

where  $c$  [m] is ion concentration, which will be a function of both the time  $t$  (s) and position  $x$  (m),  $D$  [m<sup>2</sup>/s] is the effective diffusion coefficient of the ions in the porous material and  $u$  [m/s] is the macroscopic liquid velocity of the liquid in the porous material, i.e, the Darcy speed. This equation will be valid as long as there is no crystallization taking place else a sink term has to be added to the right-hand side of this equation.

Therefore the right hand side is describing the total ion flux, consisting of diffusion, whereas the second part describes the advection of the ions along with the liquid flow. The competition of these two can be characterized with a dimensionless number, i.e., the Peclet number. In this case, based on Eq 1. it can be defined as:

$$Pe = \frac{uL}{D} \quad (2)$$

where  $L$  is a so-called characteristic length scale which in this case can be chosen as the length of the sample. In the case  $Pe > 1$  advection will be dominant and there will be concentration gradient. Whereas in the case of  $Pe < 1$ , diffusion is dominant and we expect a homogenous distribution of salt. This  $Pe$ -number was also found to be very useful to give an indication of the effect of poulticing.<sup>3</sup>

In the case of drying as studied here, the boundary condition for ions at the drying surface is given by a no flux boundary, i.e.,  $q=0$ , and hence:

$$D \frac{\partial c}{\partial x} + uc = 0 \quad (3)$$

As in our experiment we have a constant boundary condition we can assume that in first order the liquid flow is constant, i.e.,  $u = \text{constant}$ . As also the concentration of the absorbed salt solution is constant, i.e.,  $c = c_0$ , we can in this case solve the differential equation giving the concentration  $c(x,t)$  as a function of time and position, i.e.;

$$c(x, t) = a(t) e^{-\frac{u}{D}x} + c_0 \quad (4)$$

Where  $a(t)$  is a constant which is a function time. Hence this solution tells us that the concentration in the sample can be described by an exponential decay. In addition, it indicates that characteristic width of the salt concentration peak given by  $4D/u$ , is determined by the ratio of the liquid velocity and the diffusivity.

### 3. Material and methods

For this study we have looked at a bi-micritic limestone from Sardinia which has been used in many objects there. It has a porosity of 0.34, a pore size with the maximum distribution around  $1.6 \mu\text{m}$  and has only very minor magnetic impurities. For the experiments we used cylindrical samples with a diameter of 20 mm and length of 100 mm, which were drilled out of a larger block. After rinsing the sample in clean water, the sample was dried at  $400^\circ\text{C}$  until constant weight. The experiments were started with samples

which were vacuum saturated with distilled water. In order to perform 1D experiment the specimens were isolated on the sides with an epoxy coating. The experimental setup is given in *Figure 2*.

The sample holder is a Teflon cylinder with a reservoir at the bottom and air flow inlet and outlet at the top to provide drying at the top of the sample. The bottom of the sample is in contact with a 1m NaCl solution. In order to maintain a constant level the pump is controlled by using an electrical sensor (max level fluctuations are in the order of 3 mm). To induce drying, the top of the sample is

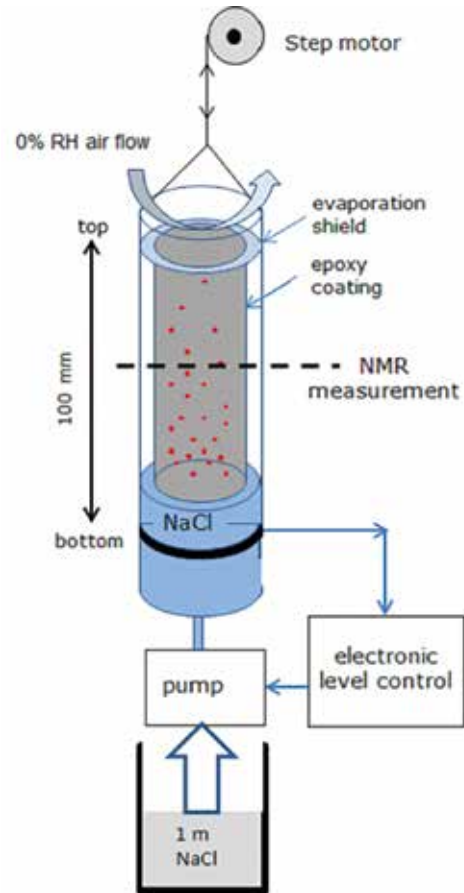


Figure 2: A schematic representation of the setup for measuring the wick action using NMR. With an electronic level control and a pump the reservoir level is kept constant.

exposed to a constant air flow of 10 L/m at approximately 0% relative humidity. An plastic evaporation shield has been added as to separate the drying and absorption part, i.e., to limit the influence of the drying on the bath concentration. Both the moisture and Na-content are measured using Nuclear Magnetic Resonance (NMR).<sup>4,5</sup> Using NMR we are able to non-destructive and quantitatively measure the moisture and Na-content at a fixed position, with a 1D-resolution in the order of 2 mm for hydrogen and 8 mm for Na. Hence every point represents an average over 2 to 8 mm. A stepper motor was used to move the sample holder vertically inside the NMR to be able to measure the moisture and Na profiles over the complete sample. Measuring both a

moisture and Na-profile takes in the order of 3 hours. The total experiment lasted up to 40 days.

#### 4. Experimental results

The NMR signal was collected from cross sections of the sample in 1.27 mm steps along the axis of the cylindrical sample. Both the moisture and Na-concentration profiles were measured every 3 hours for 40 days. The resulting Na concentration profiles for every 4 days are given in *figure 3*.

At position  $x=100$  the sample is in contact with the reservoir of 1 molal NaCl solution, whereas at  $x=0$  the sample is drying. As can be seen the concentration

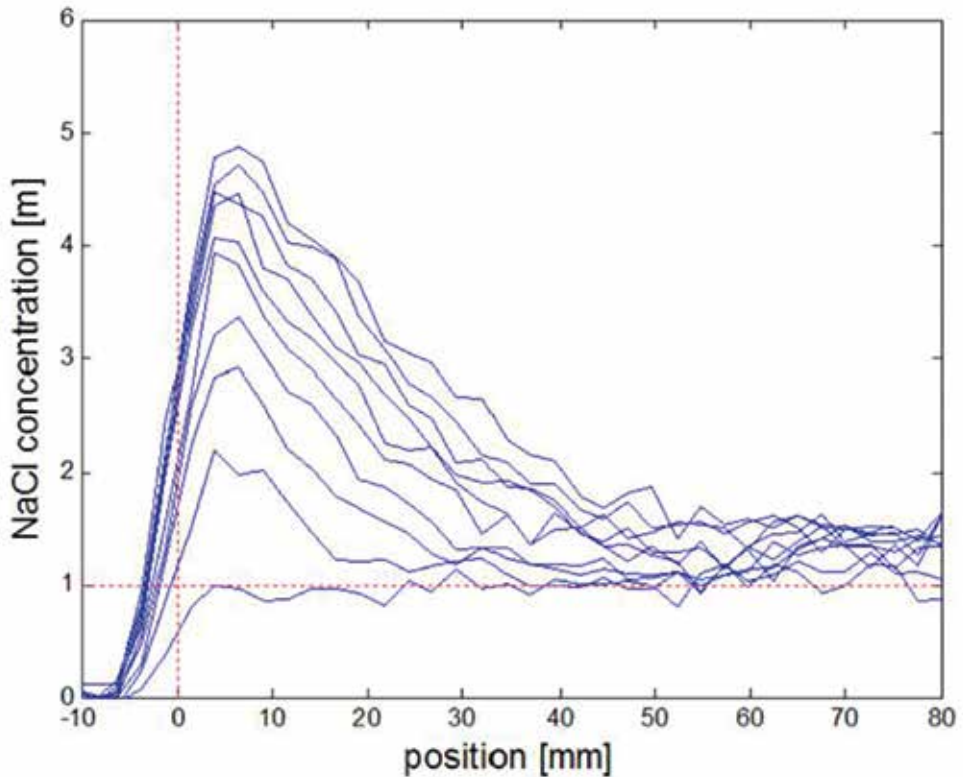


Figure 3: The measured Na-concentration profiles using NMR during wick action of a sample of 100 mm in length and a reservoir of 1m at  $x=100$  mm. The profiles are given for every 4 days for a total time of 40 days.

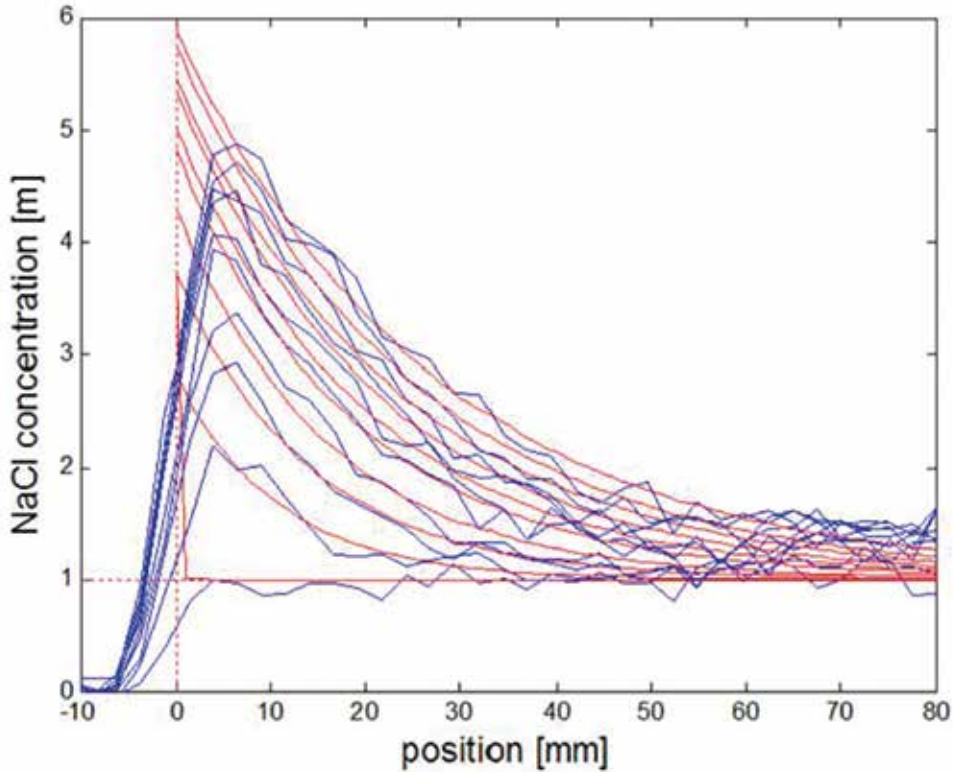


Figure 4: The measured Na-concentration profiles during wick action of a sample of 100 mm in length and a reservoir of 1m. The profiles are given for every 4 days for a total time of 40 days. The smooth curves represent fits of the model to each individual profile.

at the top is slowly increasing with time indicating  $Pe > 1$ , whereas at the bottom of the sample the concentration remains almost constant reflecting the constant concentration of the reservoir.

However at the top of the sample the concentration does not raise to 6.1 molal as to be expected. Here one has to take into account the 1D resolution of 8 mm, i.e., each point represents the average over 8 mm. Indeed looking in more detail one can see the concentration, which is measured every 1.27 mm, is slowly rising from almost zero molal at -4 mm representing a point outside of the sample, to 5 molal at 4 mm inside of the sample. Hence the 1D resolution is smoothing off the real concentration profile within the sample, and the maximum concentrati-

on reached within the sample, i.e., the top, will be higher.

In order to correct for this problem, we have fitted the model as derived (see Eq. 4) to each individual profile. The results are given in figure 4. As can be seen each profile can be approximated well by an exponential function. We can also see that the interpolation with  $x=0$  indicates that the maximum salt concentration of 6 molal is reached after 40 days, which could also be seen from crystals forming at the top of the sample.

## 5. Conclusions

Wick action in combination with evaporation at the top of a sample can

be described by a simple analytic model, which only takes into account the liquid speed and the diffusivity. The measured concentration profiles match well with a simplified model. Also NMR has been shown to be an effective method to measure the concentration profiles during wick action over a long time and non-destructively.

## References

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