Structural Analysis of Historical Constructions, New Delhi 2006
P.B. Lourenço, P. Roca, C. Modena, S. Agrawal (Eds.)

Moisture and Salt Mapping by TDR in the Historical Stonework of the Finca Marina-Manresa in Mallorca

Rudolf Plagge
Dresden University of Technology, Institute of Building Climatology, Germany

ABSTRACT: To detect the moisture and salt content of the „Finca Marina Manresa" at numerous locations along a masonry transect were measured by the TDR-technique and used for mapping. The time domain reflectometry (TDR) is a non destructive measurement method to determine the dielectric water content. In the present paper, the different steps of a measurement, including sensor installation and the development of suitable calibration functions are presented. The measured moisture and salt contents along the masonry transect are used for the masonry mapping. Their spatial distribution is leading to the reasons of the salt and moisture damages in the masonry and allows suggestion for restoration.

1 INTRODUCTION

The Finca Marina Manresa was on Mallorca built around 1500 as a one-storey bastion with moats as protection against pirates. The building was extended in 1900 by an upper storey and used as a luxury dwelling. In 2000, the building was completely renovated and modernised. Damp and salt damage to the 120 cm thick north wall was a recurring problem, necessitating an investigation of the causes. Up to now, the experts have seen the damage as the result of hygroscopicity, induced by salt particles carried by the sea breezes which enter the building.

The use of TDR was intended to provide an alternative to taking samples by drilling. The damp and salt content were to be measured and mapped at many points on the north wall of the Finca Marina Manresa using TDR. Comparison of the results lead to conclusions about the causes of the damp and salt damage and to possible solutions.

2 MEASURING METHODS, PROBES

Time Domain Reflectometry is a non-destructive dielectric measuring method which determines water content. It is based on the measurement of the term of an electromagnetic wave along a metal rod, the so-called wave-guide, which is inserted into the material to be tested. The probes used had a diameter of 2 mm and were placed 16 mm apart. The rods are 100 mm long and are soldered at one end onto a special circuit board which converts the wave resistance electronically. They are connected by an RG58 or semi-rigid coaxial cable to the measuring instrument/gauge. The circuit board is sealed in a 15 cm long plastic tube with epoxy resin, to protect the electronics from damp.

The length of time taken by the magnetic pulse to travel along the probe indicates the apparent dielectric constant,ε_a, of the material. The wetter the material is, the slower the electromagnetic pulse and the bigger the dielectric constant. As the pulse moves in the sensor system, reflections occur at the entry and exit points of the probe, which can be made visible on the screen of a sampling oscilloscope. These pairs of voltage-time readings are read into the internal computer of the TDR measuring instrument and processed there. The reflections are interpolated by a smoothing function and examined in regard to the sizes to be analysed. The computer automatically takes specific data, such as the geometry of the probes and their electric characteristics, into account. Further information about the technology used can be found in Plagge (2003).

In addition, the TDR probes can be used to establish the electrical conductivity,σ_a, of a material or of the pore water solution. The conductivity is established by direct electrical measurement of the resistance. This is based on the voltage division of two resistances, where one resistance, R_2 , that of the TDR probe, is within the medium to be measured and the other, R_1, is a series-connected control resistance. Analogous to the TDR technology, voltage pulses are also generated and sent through the cable – sensor system. However, in this case, it is not the reflection images but the voltage drop in the TDR probe which is registered and processed, once the voltage in the probe is stable. This accompanies the reduction of the reflections in the coaxial cable and the sensor probes. Measuring the voltages, U_1 and U_2, at the resistances gives information about the electric resistance of the sensor and is used to determine the conductivity. The unknown probe resistance of the TDR probe is calculated using equation 1:

$$R_2 = \frac{U_2 R_1}{U_1 - U_2} \quad (1)$$

The specific resistance measured corresponds with the conductivity of the material. Because the geometry of the probes still affects the results, this must be taken into account when transforming them. Plagge (2003) show how this is done. The quantity of salt can be deduced from a mixed dielectric component approach using a calibration function Plagge et al. (1997) and Plagge (2003). In many cases, it is sufficient to know the total concentration of salts in the pore water. Since the volume measured is identical, the method is particularly suited to investigating the temporal and spatial variables of the measures.

3 DAMP AND SALT MAPPING

In order to assess the effects of damp and salt, the walls of 3 north facing rooms are to be examined. It is necessary to divide the wall area into a grid. First, the wall is measured and defined grid points are marked, 50 cm apart: see the diagram in Fig. 1. The wall is 23.5 m long and 3.5 m high, resulting in 336 grid points.

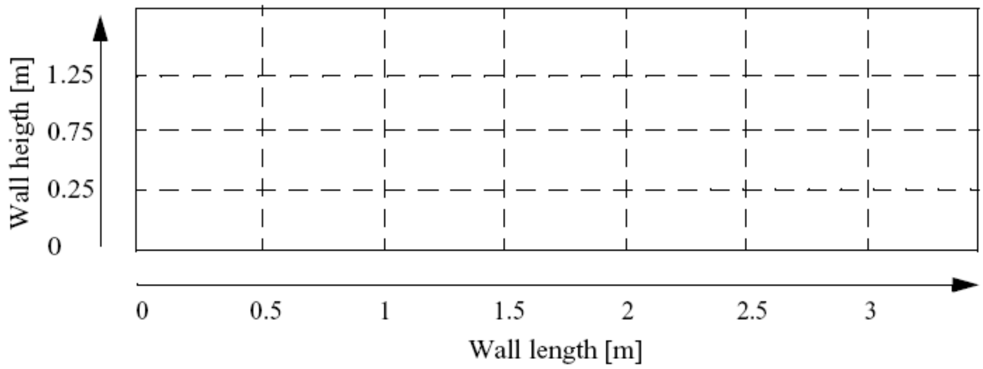

Figure 1 : Diagram of the grid measurements used for the Finca walls

In order to measure the damp and salt content of the walls, the TDR probe must be inserted into the wall. Holes must be drilled for the two 2 mm thick and 100 mm long probe rods. Titanium nitrite- coated carbide drills in different lengths were used. Starting with the shortest drill, two parallel holes were drilled in the walls at the points marked, using a drilling gauge. Progressively longer drills were then used until the hole reached the desired depth.

As the walls are built of the porous local sandstone, the Marez, with plaster, the drilling is relatively easy. All the holes were drilled within 2 days, wearing out 17 carbide drills in the process. A calibrated TDR-2 probe is inserted in the holes and the computer controlled measurements are started. The visual control of the reflection images provides an additional check of how to interpret them. In a few isolated cases, larger hollow spaces in the walls were tested, which are shown as a second reflection in the diagram. Since the measurements represent an average value along the whole probe, the water content shown in these cases is underestimated. In these cases, a further sample was taken close to the desired grid points.

4 CALIBRATION FUNCTION

4.1 Mixed dielectric model

In the simplest case, capillary porous materials can be described by a mixture of the three phases, liquid, solid and gaseous. Because water with $\varepsilon_{water} \sim 81$ has a much higher dielectric number than mineral building materials, for example, $\varepsilon_{brick} \sim 3\text{-}6$ or air, $\varepsilon_{air} \sim 1$, water content can be determined by a calibration function. The mixed dielectric approach for the three phases is according to Tinga et al. (1973):

$$\varepsilon_a = [\theta\varepsilon_w^\beta + (1-\phi)\varepsilon_s^\beta + (\phi-\theta)\varepsilon_g^\beta]^{1/\beta} \quad (2)$$

and the parameters for this are the dielectric constants of the liquid, solid and gaseous phases and are equivalent to the water content , θ, and the porosity, ϕ. From these, the volume of the three phases can be determined. β represent a geometric factor which depends on the geometric order of the 3-phase mixture and their orientation in the electric field produced. The parameters are adjusted by reference measurements and minimalising the square deviations.

In the present example, 5 core drillings were undertaken, where the TDR measurements had already been made. These served as reference water contents, which were determined gravimetrically in the laboratory after drying. The positions of the individual drilling points are shown in Figs. 3, 4 and 5. The results of the core drillings can be seen in Fig. 2. Determining the water content by equation 2 simply requires the measurement of porosity or density and the knowledge of the dielectric constant of the dry Marez. The property of the thin layer of plaster is ignored here, because it has only a negligible influence on the results.

4.2 Component approach

The electric conductivity of the material is a combination of the conductivity of the pore water and the surface conductivity of the matrix. To determine the conductivity of the pore solution, a model from Plagge (2003) is used.

$$\sqrt{\sigma_a} = \sqrt{\sigma_\theta}\theta T + \sqrt{\sigma_s} \quad (3)$$

where the conductivity, $\sqrt{\sigma_s}$, is appropriate to the solid matrix of the building material, here Marez, and is measured in the dry material. θ is the moisture content measured by TDR, available for each measuring point. The parameter T provides an empirical correction factor, which is determined by the reference measurements of the core drillings. The segments of the cores are cut up and shaken in bottles of distilled water for 10 days. After setting the balance, the dissolved salts are chemically analysed, revealing a clear dominance of sodium chloride in the present case, whereas only small quantities of sulphate are found. Figure 2 shows the results for the core drillings of areas L, M and R.

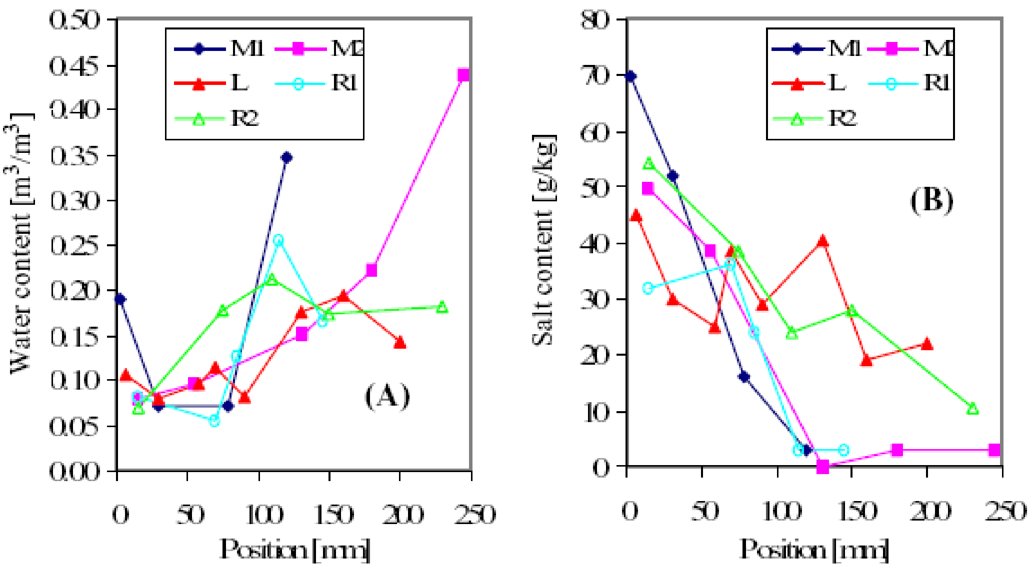

Figure 2 : (A) Results of the water content (B) and salt concentrations in the core drillings at 5 sampling points in the areas L, M and R.

The core drillings showed rising water content with increasing depth. The moisture content is reduced through evaporation at the wall surface. Near the surface, the water content varies between 0.07 and 0.17 m^3/m^3; inside the walls, the content rises to 0.17 m^3/m^3. In the core sample M2, the Marez is almost saturated, apart from the pores. Additional measurements of the relative humidity with capacitive humidity sensors in the core drillings revealed nearly 100% humidity in all areas. If the moisture content of the walls was caused only by the sodium chloride content, the water content would be at <0.02 m^3/m^3 at 75% humidity and could not reach the level measured.

On the surface, the salt accumulates by evaporation and reaches c. 40 – 50 g NaCl per kg material, which is equivalent to 4 – 5 mass-% of the Marez. In the gypsum plaster, up to 7 mass-% could be found. According to the leaflet of the WTA, the International Association for Science and Technology of Building Maintenance and Monument preservation, a maximum chloride level of 0.1 mass% is given, above which salt removal followed by the application of plaster is recommended. Thus the salt content in the areas near the surface are 40 to 70 times above recommended levels.

5 RESULTS OF THE MAPPING

The test results of the TDR measurements for the north facing walls of the room with the fireplace, the entrance hall and the dining room are shown in Figs. 3, 4 and 5, in the form of false colour graphs. Since only the values for discrete positions in the transect are available, it will be necessary to use a suitable procedure to interpolate and smooth the data for visual presentation. In the graphs presented here, a locally weighted regression algorithm is used, which delivers useful results for measurements non-Gaussian distribution or non-monotonous progression (Cleveland 1979).

The visual presentations cover the north-facing walls with the connecting interior walls up to the double doors, or the outer walls of the corner rooms to the window embrasures of the outer side walls. The beginning and end of the outer wall sections are each marked by thick vertical lines. The white areas show the windows or the terrace door.

The locally high water content is not just the result of the hygroscopicity of NaCl. There must be another source of moisture, through which water enters the construction, dissolves NaCl, and transports it to the surface, where the salt crystallises and causes the damage discovered. Possible sources of moisture include the leaky balcony, driving rain striking the outer walls, or the rainwater from the gargoyles which are directed at the side walls.

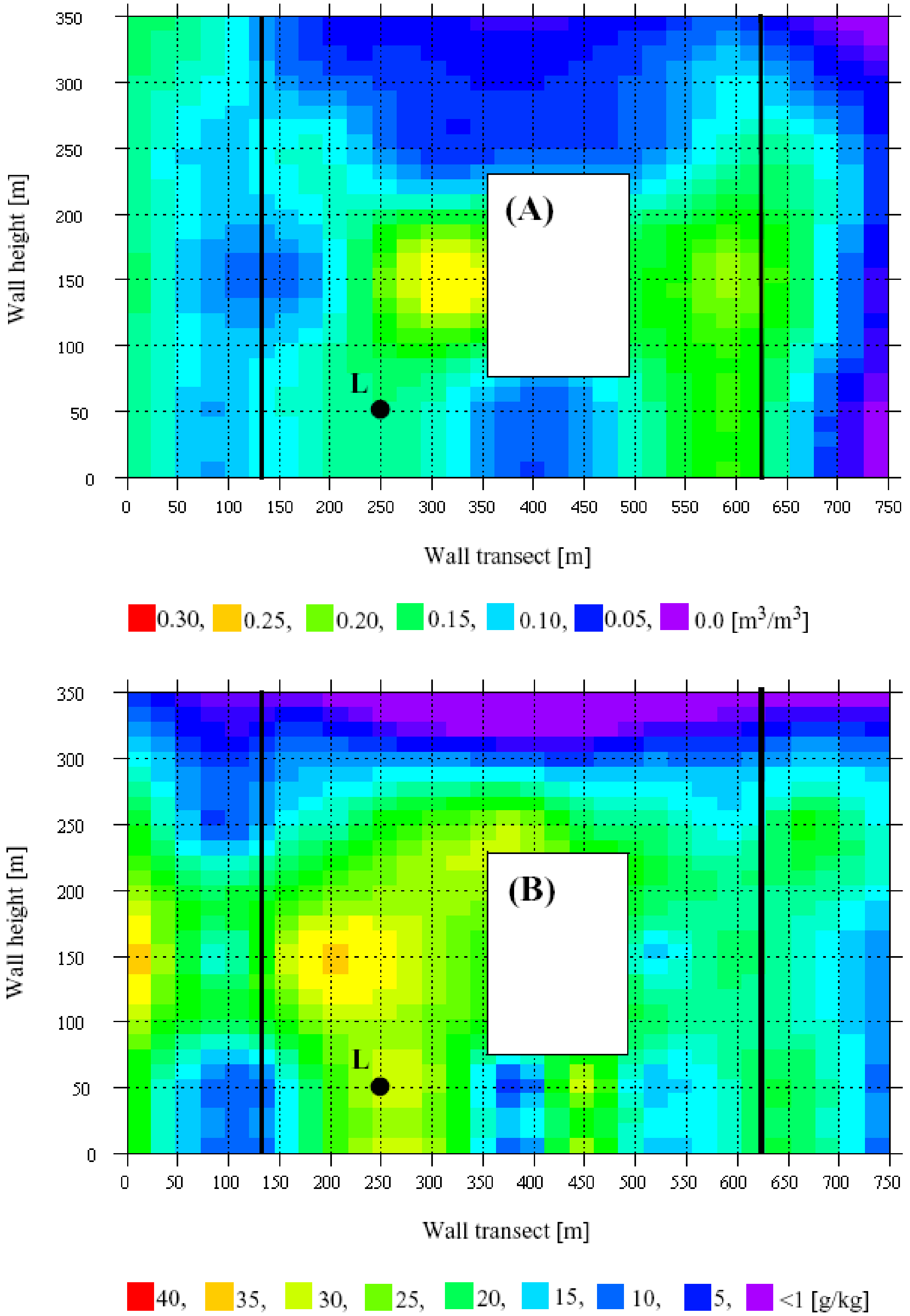

Figure 3 : (A) Water content (B) and salt content in transect of the room with the fireplace, L.

The random distribution of moisture content can only be adequately explained by the structure of the outer walls. In the past, thick walls were usually constructed with an inner and an outer shell, between which all the left-over mortar and rubble were thrown when the structure was complete. The hollow spaces which were discovered during the core drilling lead to the conclusion that the walls treated here were built according to this method.

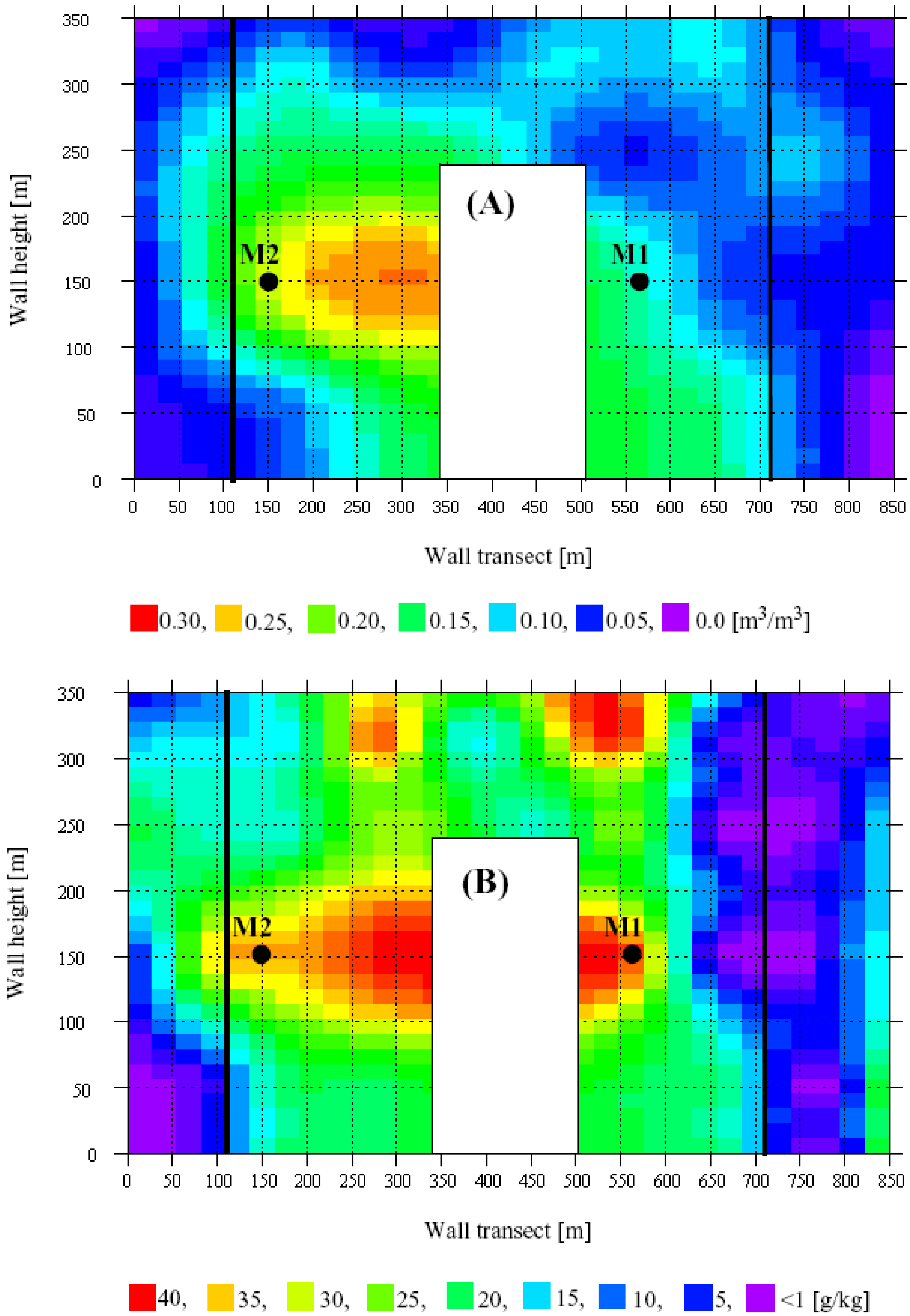

Figure 4 : (A) Water content (B) and salt content in the transect of the entrance hall, M.

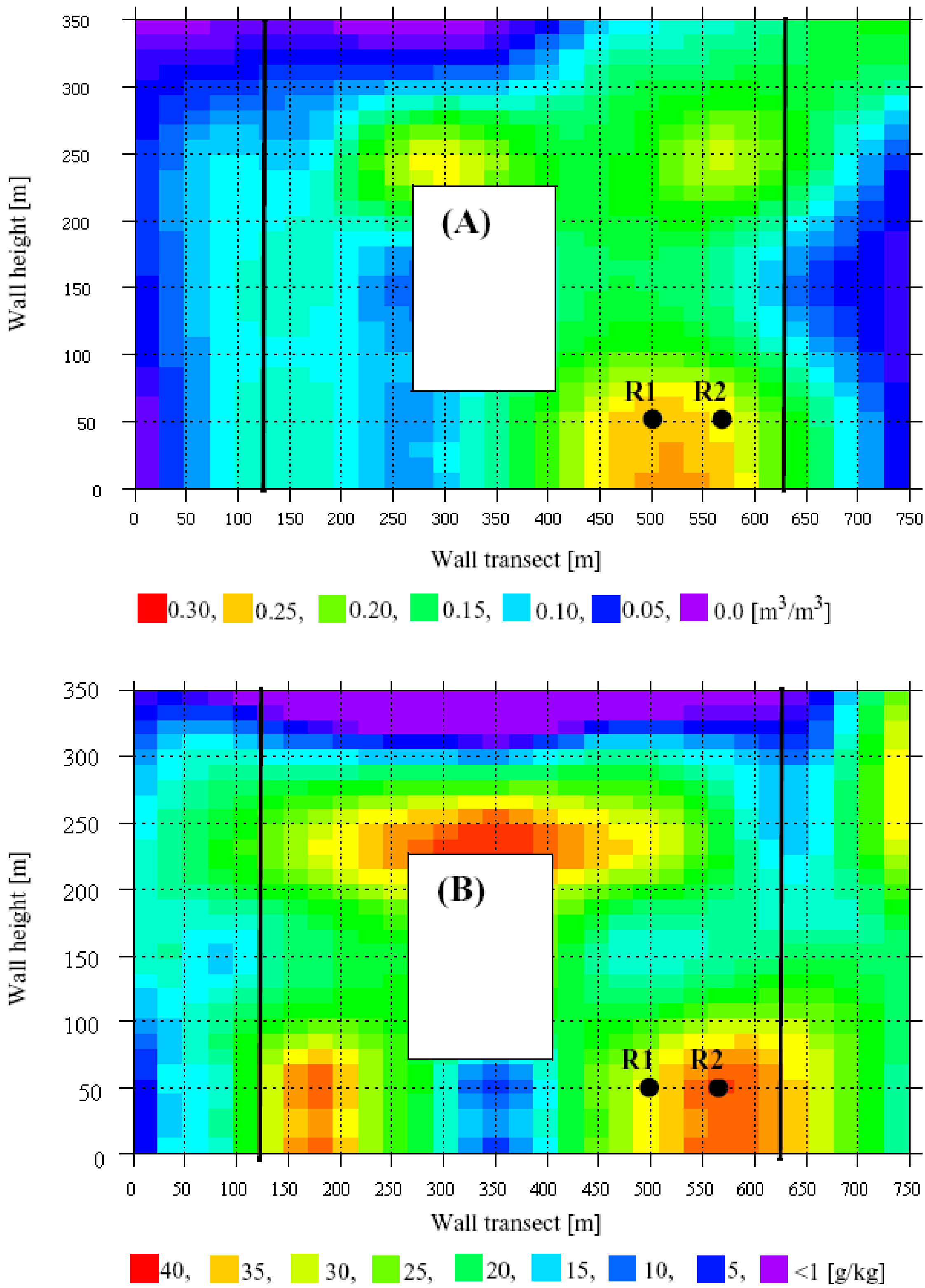

Figure 5 (A) Water content (B) and salt content in the transect of the dining room, R.

This means that water which enters via the balcony does not just spread through capillaries, but also flows downwards by gravity until it reaches a thicker layer or window lintel. From there it spreads to the inside and causes damp and salt efflorescence through evaporation where the wall is less waterproof.

A further suggestion must be added to the assumption that the salt content of the outer walls was caused by the tiny salty drops of seawater carried by the wind over the centuries, namely the possibility that salty sand from the nearby beach and sea water were used for the mortar when the wall was built. Thus loose sand with seashells and lumps of limestone were found between the inner and outer shells of the walls. It is also possible that the Marez stone itself was quarried close to the coast and therefore was already contaminated with salt.

The extremely high salt content found is the result of a high degree of evaporation of rainwater flowing in from the balcony to the inner surface of the walls. The water entry is limited to certain points, so it is necessary to view the rainwater control and the sealing of the balcony separately. The concept for sealing the balcony involved an inner drainage which led water to the outside. Between the side boundaries of angular edge bars of galvanised steel and the outer wall of the upper storey is a lower level of screed above an impervious layer. Both the impervious layer and the screed on top of it form a longitudinal gutter which should direct the rainwater to the two gargoyles on the end wall and from these to the eaves. 35 mm thick teak boards, screwed onto laths bedded in the screed, provide a walkway.

However, the drainage concept given fails to fulfil elementary demands.

- The drainage capacity is too small, given the expected amount of rain. The gargoyles have a diameter of only 3 cm^2 and are thus too small by a factor of 20 and are easily blocked by falling leaves. In addition, the gargoyles direct the water onto the western and eastern outer walls.
- The laths are laid parallel to the outer walls, acting as a dam between the inner lath and the outer wall, as well as between the outer lath and the angular edge bars.
- The rubber-type seal is not glued to the angular edge bars, but only laid loosely against them. The seal is only as high as the teak boards and not glued to the walls. The edges of the sealing strips are not properly glued.
- The sills of the balcony doors are only 2 cm above the surface of the teak boards or above the angular edge bars.

Satisfactory drainage of the balcony is impossible because of the poor design and execution. Even in moderate rainfall, the water collects between the inner lath and the outer wall and the outer lath and the angular edge bars, reaching the upper surface of the laths and flowing between the angular edge bars and the non-glued seal into the lower structure. Heavy rainfall of 10 l/m^2h overloads the gargoyles and the balcony floods, causing the water to flow over the seal at the edge into the outer wall and thus into the ceilings and the outer wall of the ground floor. Subtropical rainfall of >50 l/m^2h overloads the system even more, because the water running down the outer walls flows as far as the door sill in the upstairs rooms.

Even near the coast, heavy rain contains little salt, but it can dissolve the wind-borne salts already present and transport them into the outer walls with the water. This effect is fairly small, so the faulty balcony seal can not be solely responsible for the salt content of the outer walls. However, the dissolving of the salt crystals in the outer walls, their transport into the inner surface and all the damage this causes, necessitating the repairs to the balcony, are the result of the inflow of water due to the faults in water guidance and the sealing of the balcony. The fact that humidity of more than 75%, which is often the case on Mallorca, dissolves some salts anyway, does not alter these facts.

REFERENCES

Cleveland, W.S. 1979: Robust locally weighted regression and smoothing scatterplots. *Journal of the American Statistical Association*, 74, 829-836.

Plagge, R., P. Häupl & J. Grunewald 1997: TDR-SS-Methode, ein Meßverfahren zur kombinierten Bestimmung der Materialfeuchte und der elektrischen Leitfähigkeit kapillar poröser Medien. 9. Feuchtetag am 17./18. September 1997 in Weimar. 9, 161-173.

Plagge, R., 2003: Bestimmung von Materialfeuchte und Salzgehalt in kapillar porösen Materialien mit TDR. Kolloquium mit Workshop Innovative Feuchtemessung in Forschung und Praxis, Karlsruhe, 3.-4. Juli 2003, pp28.

Tinga, W.R., W.A.G. Voss & D.F. Blossey 1973: Generalized approach to multiphase dielectric mixture theorie. J. Appl. Phys. 44, 3897-3902.