SPONTANEOUS ELECTRICAL EFFECTS IN MASONRY AFFECTED BY CAPILLARY WATER RISE: THE ROLE OF SALTS

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ABSTRACT

The investigation of the electrical effects accompanying capillary water rise from ground in old masonries is of great practical interest, as such effects might be exploited for both measurement purposes (determination of moisture and soluble salts) and for dehumidification purposes (techniques based on electrokinetic principles).

In the present paper, the spontaneous dc voltages arising in a real-scale masonry model subject to a steady-state capillary flux of saline solutions (0.05 M sodium chloride and 0.05 M sodium sulphate in water) were measured. The resulting voltage depends on the amount and distribution of salts, rather than on moisture content in the masonry.

Keywords: soluble salts, efflorescence, rising damp, electrokinetic effects, spontaneous potential, brick masonry.

1. Introduction

Capillary water rise is one of the main and most diffused problems affecting old masonry walls [1], as it causes materials degradation [2], as well as hygienic and safety concerns for the building users [3]. The presence of moisture in historic structures is among the causes responsible for the emptying of old town centres and rural buildings, with great damage for local cultural identity. Thus, the investigation of capillary water rise in masonry walls, especially in terms of degradation mechanisms, measurement techniques and remediation systems, is of paramount importance and still requires a strong research effort [4].

In particular, the current techniques for the dehumidification of old masonries are often not fully satisfactory due to several reasons (invasiveness, scarce effectiveness, poor long-term performance, bad aesthetic impact, etc.) and some promising results were shown by systems based on electrokinetic principles [5]. The occurrence of electrical effects in moist masonry walls is due to the electrical double layer arising at the water/solid interface in moist porous building materials [6]: when capillary water flux is present, e.g. from ground in the case of masonry, a spontaneous potential (streaming potential) takes place [7]. Nevertheless, the information on the electrokinetic phenomena occurring on site, in actual masonry walls, are still very scarce [8] and a better knowledge of them could enhance the development of more reliable dehumidification systems and might also be exploited for on-site measurement of moisture and salts. E.g. dehumidification systems based on electro-osmosis are usually applied to masonry without any preliminary investigation on the existing spontaneous potential and with no subsequent monitoring (except for

the current consumed by the system, which however is not indicative of the actual dehumidification along the entire height of the wall), with strong prejudice for their real effectiveness. Moreover, the measurement of electrokinetic phenomena connected with rising moisture and salts might be a further tool for the smart monitoring of historic structures, which are often affected by dampness. As a matter of fact, the issue of smart monitoring of masonry buildings has raised strong interest in recent years [9-11].

In this paper, the spontaneous potential occurring in masonry due to capillary rise of salts-contaminated water is investigated, by means of an experimental masonry model. The focus is on the role of soluble salts in the final spontaneous potential. Sodium chloride and sodium sulphate were chosen for the experimental survey, as they are the most common salts in historic building walls [12-13].

2. Background and research aims

In a previous paper, a reliable methodology for monitoring moisture, salts and bias voltage in masonry walls was presented, taking advantage of some purposely designed experimental fixtures [14]. The fixtures are real-scale masonry models ($25 \times 63 \times 105$ cm^3), where ground brick is used for the joints instead of mortar, in order to enhance capillary suction. Capillary rise is provided by a constant height (3 cm) of deionised water lapping the bottom of the masonry models.

Not negligible spontaneous potentials were detected and their values appeared related mainly to the small amount of salts originally contained in the bricks (and driven along the capillary path by rising water) rather than to the amount of moisture [14]. For this reason, in the present paper, the role of soluble salts on the final spontaneous potential is investigated by means of the same kind of experimental fixture: chlorides and sulphates were added to rising water, in order to reproduce the state of actual masonries, where water from ground usually carries on various kind of salts, responsible for the well-known efflorescence (i.e. crystallisation on the surface) and subflorescence (i.e. crystallisation below the surface) [15].

At the end of the paper, a comparison will be made with the results of the previous investigation [14], where a masonry model made with the same batch of bricks and having the same size had been built, but deionised water had been used for the capillary suction instead of saline solution.

3. Materials and methods

3. 1. Bricks and experimental masonry models

Commercial fired-clay bricks $25 \times 12 \times 5.5$ cm^3 (RDB, Pontenure, Italy) were used for the construction of a one-brick-thick masonry model ($25 \times 63 \times 105$ cm^3), according to the scheme in Fig. 1. As mentioned above, a 3 mm layer of brick powder (obtained by milling some bricks from the same batch to a grain size < 63 μm) was put among the bricks, instead of conventional mortar joints, in order to: i) enhance the capillary suction (due to the larger capillary suction ability of fine powder respect to mortars), and ii) take into account only the role of bricks in the final electrokinetic effects.

The bricks used are averagely characterised by total porosity 34.9% and pore mean size 2.47 μm (determined by mercury intrusion Porosimeter 2000 Carlo Erba with a Fisons Macropore Unit 120).

Their mean soluble salts amount was determined by extraction with deionised boiling water (electrical conductivity < 0.02 µS), filtration by blue ribbon filter and final ion chromatography (Dionex ICS-1000; anion-exchange column kept at 30°C; measuring cell temperature 35°C) and resulted the following: $Cl^- = 0.017$ wt%, $SO_4^= = 0.021$ wt%.

3. 2. Conditioning procedure

The masonry model was kept at room conditions (T = 21-24°C, RH =30-50%) and was subjected to continuous capillary suction by keeping its bottom under a constant 3 cm head of saline solution (0.05 M NaCl, 0.05 M Na_2SO_4). Chlorides and sulphates were chosen as they are the most diffused salts in ancient masonry walls [16-18].

3. 3. Testing

Permanent sampling points for the measurement of moisture/salts and electrodes for the measurement of electrical potential were set at different heights in the masonry, in the positions shown in Fig. 1. According to the measuring methodology described in [2, 19], moisture and salts were measured in permanent sampling holes, where brick fragments (taken by chisel from the same brick where each hole was drilled) were placed and sealed. The fragments were periodically used for the determination of moisture (by oven drying at 100±2°C) and soluble salts (by ion chromatography, according to the procedure described in § 3.1).

For the measurement of the electrical potential, the procedure described in [14] was followed. Electrical potential was measured close to the permanent sampling points (on the right and on the left respectively) by stainless steel nails ($\varnothing = 2.1$ mm) fixed about 2 cm deep into previously drilled holes in the bricks, with a nickel-based conductive paste. The electrical potential in each nail was measured by a high impedance (10^{14} Ω) Keithley Electrometer 602 (accuracy ±10^{-5} V) referred to earth; the water at the bottom of the masonry was earthed as well, by keeping an earth-connected stainless steel plate permanently immersed in the tank. The electrical potential at each height was obtained averaging the values of the two nails (one on the right and one on the left of the sampling hole used for moisture and salts determination).

Moisture was measured 60, 90, 120 and 150 days after pouring the saline solution into the tank. After 150 days, when a steady-state capillary flux was certainly attained (§ 4. 1), salts and electrical potential were measured as well.

4. Results and discussion

4. 1. Moisture

The moisture detected in the masonry at 60, 90, 120 and 150 days is reported in Fig. 2, where a progressive decrease in the moisture amount with height, which is typical of actual masonries, can be observed. The slight increase in moisture in the bottom part of the masonry can be ascribed to a progressive filling of the finest pores of the bricks, taking longer time than the large ones. At 150 days, a steady-state capillary flux was considered as attained.

4. 2. Salts

At the end of the experimental campaign, the masonry was characterised by evident white efflorescence (Fig. 3). Remarkably, efflorescence were located mainly at a height of about 20-50 cm, where the amount of moisture in the bricks makes the salts crystallise on the external surfaces. Conversely, in the upper part of the masonry, where lower moisture amount is present, the occurrence of brick flaking due to subflorescence can be noticed (Fig. 4). This is fully consistent with the schematisation of capillary rise and evaporation in a wall in contact with damp soil reported in [15].

In Fig. 5 the chloride (Cl^-), sulphate ($SO_4^=$) and total anions amounts in the masonry model are reported, as a function of sampling height, and the following remarks can be done:

- the distribution of salts with height is pretty the same for both chloride and sulphate, hence the two salts seem to be jointly carried on by rising water, with no evidence of stratification at different heights due to the different nature and size of the salts;

- the amount of salts is maximum at the top of the masonry, due to the rising water transporting the salts up. The maximum amount of anions (0.7 wt% in Fig. 5) is fully consistent with the amounts currently found in actual masonry, according to the authors' on-the-field experience [20];

- the wt% amount of sulphate is obviously higher than that of chloride, because the identical molar concentration of NaCl and Na_2SO_4 corresponds to a weight concentration of $SO_4^=$ approximately 2.7 times higher than that of Cl^-;

- a somewhat complex and irregular salts distribution was detected. This might be due to possible differences in bricks microstructure and to possible local changes in air temperature and flow, but it seems mainly ascribable to a different equilibrium locally attained between water rise and evaporation (leading to crystallisation on the surface or at different depths under the surface). As a matter of fact, the first peak in the total anions amount (H = 35 cm) is in the zone were efflorescence formed (Fig. 4), the second peak (H = 80 cm) is in the zone were disruptive subflorescence mainly occurred and the third peak (H = 102 cm) seems to correspond to the top zone of the masonry, where salts driven by water accumulated deep inside the brick pores, with no disruptive action. As the brick fragments used for the measurement of salts were located at different depths inside the masonry, they seem to have been affected by salts crystallisation along the whole brick depth.

4. 3. Electrical effects

The spontaneous potential at 150 days is reported in Figure 6, where not negligible voltage values can be observed, i.e. up to -0.17 V.

At height 0-60 cm, potential seems quite constant (about -0.17 V), except for a small peak at 25 cm: this peak approximately corresponds to the first peak in the anions curve (Fig. 5). At heights 80 and 102 cm, potential exhibit two high peaks, which again perfectly match with the height of the peaks in the anions curve. This correspondence between dc voltage values and anions amount (Fig. 5 and 6) confirms that the spontaneous potential in masonry affected by rising moisture is due to salts concentration difference rather that to moisture amount. Where high salts concentration differences are present, remarkable potential differences (up to ~0.2 V) were detected.

4. 4. The role of salts

In Fig. 7, the spontaneous dc potential of the masonry model subject to a steady-state capillary flux of deionised water (data used for the chart are taken from [14]) and of saline solution are shown. As the two masonry models in [14] and in the present paper were built with same brick batch, had the same size and were placed in the same laboratory (same environmental conditions), the data reported in Fig. 7 can be considered comparable.

Fig. 7 clearly points out that the higher the amount of soluble salts in the masonry, the higher the potential values. However, such relationship is not proportional, as an increase in salts by approximately 10 times (mean anions amount from ~0.04 wt% [14] to ~0.3 wt%) leads to an increase in the baseline potential by about 2 times, while the maximum potential difference increases by approximately 4 times (Fig. 7). This can be explained on the basis of the electrochemical double layer theory [7]. According to this theory, the streaming potential generated at the ends of a porous medium where water is forced through the pores by capillary forces depends on the magnitude of the potential difference arising across the double layer. i.e. at the brick/solution interface (the so called ζ-potential). Such ζ-potential depends on the specific conductance of the solution, i.e. on the nature and concentration of the dissolved ions [21-22], which explain the fact that the measured spontaneous potential in the masonry model is governed by the salts presence in the rising damp rather that on the moisture amount. Nevertheless the relationship between ζ-potential and salts concentration is quite complex: high concentrations of ions may make the double layer thickness decrease and the potential even change sign [22]. As a matter of fact, experimental measurements of ζ-potential at the interface between glass and various electrolytes reported in literature show that it usually varies in the range $\pm$ 0.2 V [22].

5. Conclusions

The occurrence of not negligible spontaneous dc voltages in masonry model affected by capillary rise of water and soluble salts (sodium chloride and sodium sulphate) was ascertained, after a 150 days time, necessary for attaining the steady-state flux conditions. Amount of anions around 0.3 wt% in the bricks (i.e. fully comparable with the amounts currently present in actual masonries) led to spontaneous dc voltage about -0.2 V respect to earth. Remarkably, the voltage is not related to moisture amount, but to the occurrence of differences in salts amount along the masonry height. The occurrence of such differences in the salts amount in the masonry model perfectly matched the different equilibrium attained between the rising capillary flux and the evaporation rate, according to the scheme in [15], hence the laboratory-scale masonry model used in the present investigation can be considered representative of actual masonry walls.

Remarkably, the relationship between spontaneous dc voltage and salts amount in the masonry is not proportional: an increase in salts by approximately 10 times leads to an increase in the potential by about 2 times. This is compliant with the electrical double-layer theory and with the expected variation of the zeta-potential in presence of salts.

The investigation of spontaneous potential in masonry with different kind of mortar joints is presently in progress, as well as the application of the present methodology to real masonry buildings affected by rising dampness.

References

[1] Rirsch E, Zhang Z. Rising damp in masonry walls and the importance of mortar. Constr Build Mater 2010;24(10):1815-1820.

[2] Sandrolini F, Franzoni E. An operative protocol for reliable measurements of moisture in porous materials of ancient buildings. Build Environ 2006;41:1372–1380.

[3] Lourenço PB, Luso E, Almeida MG. Defects and moisture problems in buildings from historical city centres: a case study in Portugal. Build Environ 2006;41(2):223-234.

[4] Bertolini L, Coppola L, Gastaldi M, Redaelli E. Electroosmotic transport in porous construction materials and dehumidification of masonry. Constr Build Mater 2009;23:254-263.

[5] Sandrolini F, Franzoni E, Vio E, Lonardoni S. Challenging transient flooding effects on dampness in brick masonry in Venice by a new technique: the narthex in St. Marco Basilica. In: Fletcher CA, Spencer T, editors. Flooding and Environmental Challenges for Venice and its Lagoon: State of Knowledge, Cambridge: Cambridge University Press; 2005 p. 181-188.

[6] Sandrolini F, Franzoni E. Repair Systems for the restoration of ancient buildings – Dampness Rise Problem. Restoration of Buildings and Monuments 2007;13(3):161-171.

[7] Glasstone S. An Introduction to electrochemistry. Princeton: Van Nostrand; 1956.

[8] Pisarenko D, Morat P, Le Mouel JL. On a possible mechanism of sandstone alteration: evidence from electric potential measurements. Compt Rend Acad Sci Paris Ser IIa 1996;322:17-24.

[9] Maksimovic M et al. Application of a LTCC sensor for measuring moisture content of building materials. Constr Build Mater 2012;26:327–333.

[10] Antunes P, Varum H, Andréa P. Optical FBG Sensors for Static Structural Health Monitoring. Procedia Engineering 2011;14:1564-1571.

[11] Chintalapudi K et al. Monitoring civil structures with a wireless sensor network, IEEE Internet Computing 2006;10:26–34.

[12] Larsen ES, Nielsen CB. Decay of bricks due to salts. Mater Struct 1990;23:16-25.

[13] Tsui N, Flatt RJ, Scherer GW. Crystallization damage by sodium sulphate. J Cult Herit 2003;4:109–115.

[14] Franzoni E, Sandrolini F, Bandini S. An experimental fixture for continuous monitoring of electrical effects in moist masonry walls. Constr Build Mater 2011;25:2023–2029.

[15] Scherer GW. Stress from crystallization of salt. Cem Conc Res 2004;34:1613 – 1624.

[16] Tsui N, Flatt RJ, Scherer GW. Crystallization damage by sodium sulphate. J Cult Herit 2003;4: 109–115.

[17] Rodriguez-Navarro C, Doehne E, Sebastian E. How does sodium sulfate crystallize? Implications for the decay and testing of building materials. Cem Concr Res 2000;30:1527-1534.

[18] Lubelli B, van Hees RPJ, Groot CJWP. The role of sea salts in the occurrence of different damage mechanisms and decay patterns on brick masonry. Constr Build Mater 2004;18:119-124.

[19] Franzoni E, Sandrolini F, Bandini S. Metodologia per il monitoraggio congiunto dei sali e dell'umidità nelle murature storiche: sperimentazione su modelli di laboratorio. In: Atti del IV Convegno Monitoraggio e conservazione preventiva dei beni culturali (Mascolo G Ed.), Cassino 27-29 maggio 2010. Avellino: Poligrafica Ruggiero; 2010, p. 60-67.

[20] Sandrolini F, Franzoni E, Cuppini G, Caggiati L. Materials decay and environmental attack in the Pio Palace at Carpi: a holistic approach for historical architectural surfaces conservation. Build Environ 2007;42:1966-1974.

[21] Gallone P. Principi dei processi elettrochimici. Milano: Tamburini; 1970.

[22] Kortum G, Bockris JO'M. Textbook of electrochemistry. Amsterdam: Elsevier; 1951.
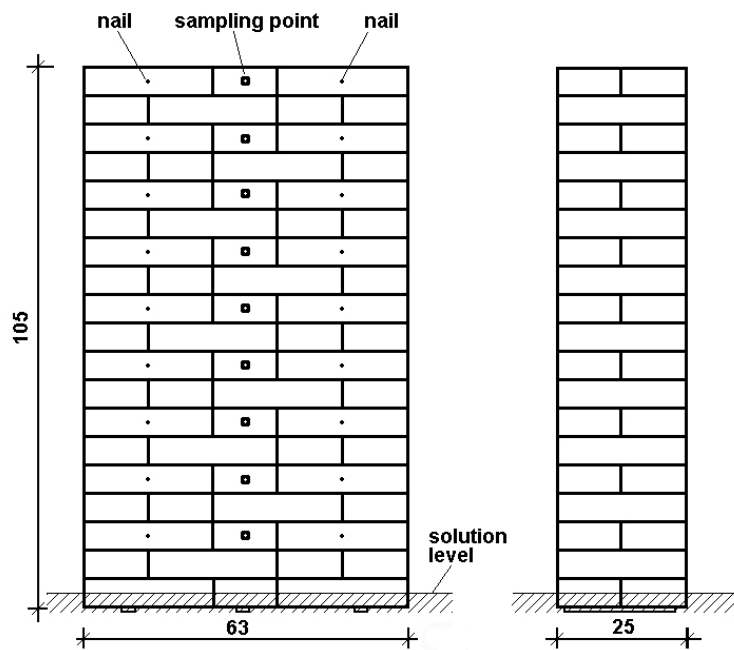
FIGURES

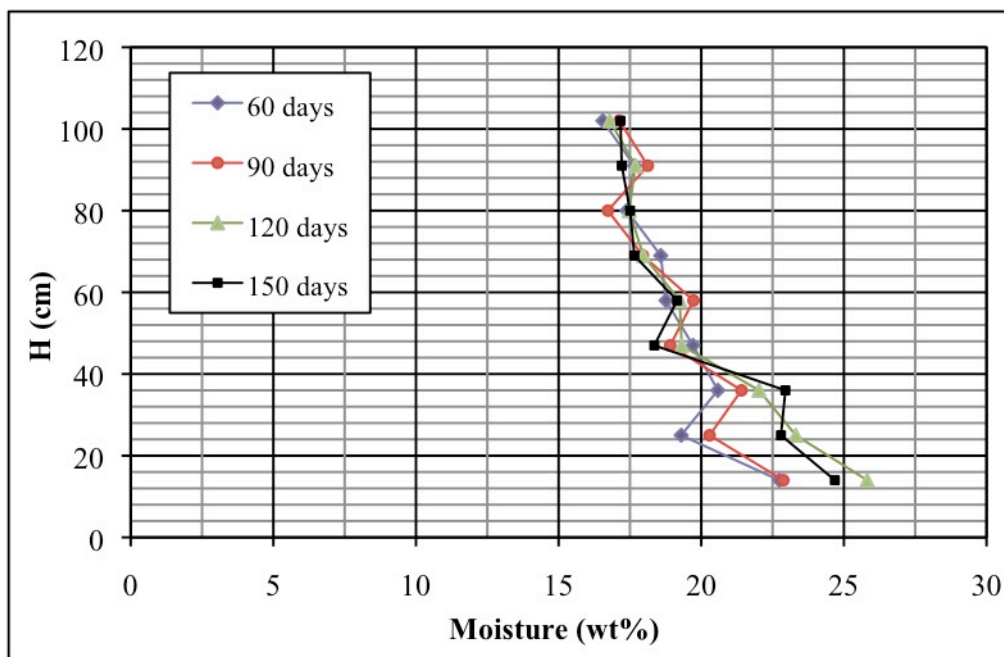Fig. 1. Masonry model used for the investigation.

Fig. 2. Moisture amount in the masonry model.

Fig. 3. The masonry at the end of the experimental campaign (150 days).

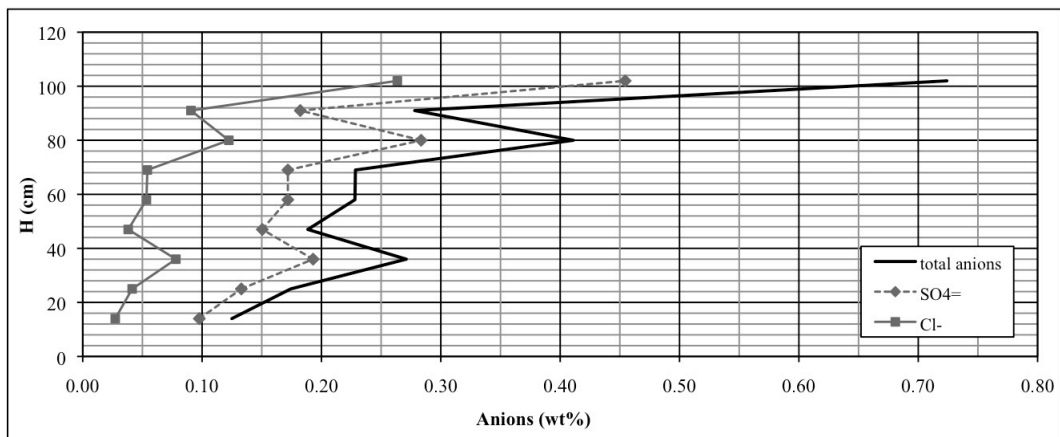Fig. 4. Details of the brick flaking due to sub-efflorescence formation.

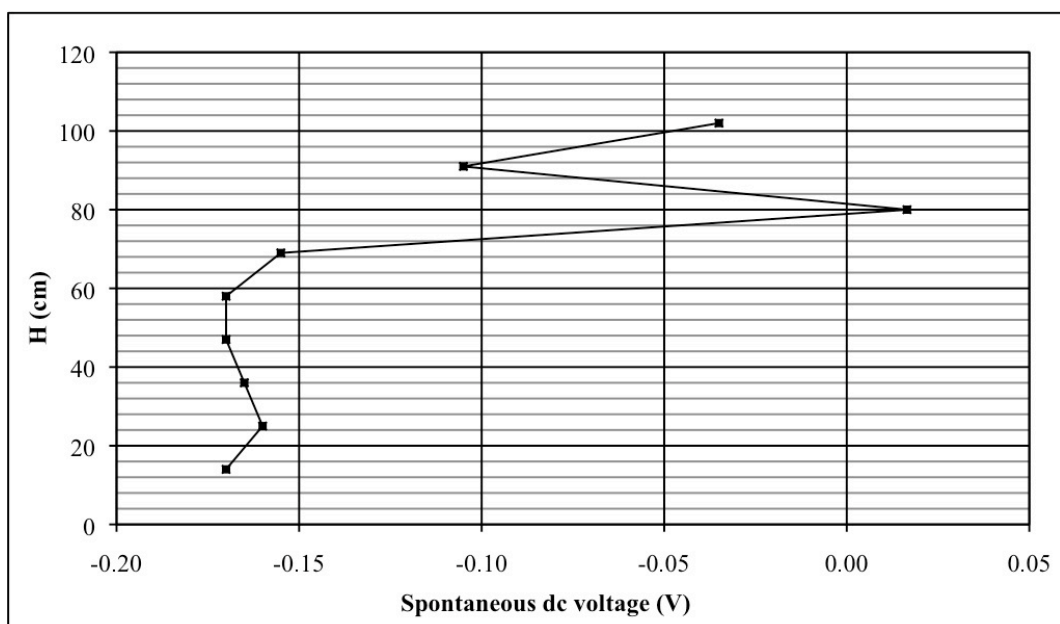Fig. 5. Chloride, sulphate and total anions amount in the masonry model.

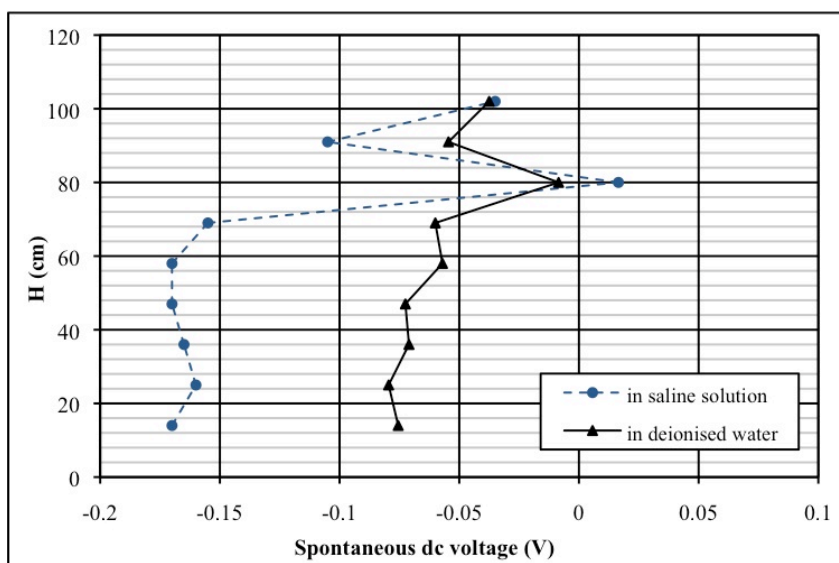Fig. 6. Spontaneous dc voltage in the masonry model.

Fig. 7. Spontaneous dc voltage of the masonry model subject to capillary rise of deionised water (data from [14]) and of saline solution, in steady-state flux conditions.