

Drying brick masonry by electro-osmosis

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ABSTRACT

When a fine grained, porous medium is subjected to an electric DC field, transport of matter occurs, and the transport mechanism in focus of the present study is that of electro-osmosis, which is transport of water. In the laboratory it was shown to be possible to transport water inside a brick and brick/mortar system in an applied electric field. Electrodes have been constructed and placed inside an old house with moisture problems due to the capillary rise of water. The water content of the experimental wall was about 14%(weight). The electro-osmotic effect was even more pronounced here than in the laboratory, and a clear movement of water towards the cathode was seen. Thus the basis for utilizing the electro-osmotic effect for drying brick masonry is presented, but proper electrodes still needs to be developed.

1. INTRODUCTION

Rising dampness is a well known problem, e.g. in Denmark rising dampness is among the 10 most serious problems in connection with existing buildings [1]. Water is sucked up in to the building structure from the groundwater by capillary forces. In areas where the groundwater is located just underneath the building foundation and where the soil is fine-grained, moisture problems in the structure will often occur if no precautions have been taken against the rising dampness. Even when precautions have been taken (e.g. plates of stainless steel pushed into the joints in a horizontal layer just above the ground) the structure is generally not protected during the whole lifetime, since the materials used for the protection are destroyed due to a combination of weather, water, salts and time. When the rising dampness reaches the building structure it will cause problems partly because of the water and partly due to the dissolved salts in the groundwater. The traditional moisture problems are wood destruction by dry-rot, frost bursting (frost damage), considerable increased energy consumption for heating in moisture related areas and plaster peeling. Furthermore humans can develop allergy from mold and fungal spores and a general feeling of discomfort. The dissolved salts may also cause salt induced decay of the masonry.

The present investigation is focused on electro-osmotic transport of water within bricks and brick masonry. Electro-osmotic water transport is obtained by applying an electric field to a porous medium, such as bricks. Laboratory experiments with setups of brick and setups with brick and mortar were conducted. Furthermore experiments at a pilot scale where electrodes were placed on a wet wall were conducted. Results from both laboratory scale and pilot scale are presented.

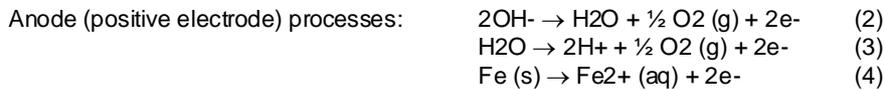
2. ELECTROKINETICS

2.2 Electrode processes

When an electric field is applied to a wet brick, the electric field is carried by ions in the pore solution inside the brick. In the metallic electrodes, from where the current is applied, the electric current is carried by electrons. The processes that transform the current carried by electrons to current carried by ions and visa versa are called "electrode processes". Which one of the electrode processes will occur depend on the electrode material, the applied potential and the type of electrolyte solution. At the anode oxidation processes occur and at the cathode reduction processes occur. At the cathode, reaction (1) will prevail, both in the case of inert electrodes (electrodes that do not take part in the reaction itself as e.g. electrodes that are platinum coated) and in the case of iron electrodes.

Cathode (negative electrode) process: $2 \text{H}_2\text{O} + 2\text{e}^- \rightarrow 2\text{OH}^- + \text{H}_2 \text{ (g)}$ (1)

Depending on the electrode material and ions present in the vicinity of the anode, several electrode processes may occur. In the case of inert anodes, the reactions (2) and (3) will take place dependent on the prevailing pH. In the case of iron anodes, reaction (4) will occur together with reaction (2) or (3).



2.1 Electro-osmosis

When a voltage is applied across a fine-grained or porous material the ions in the electric field will move by electro migration and this result in a water movement towards the positive or negative electrode dependent on the overall surface charge of the fine-grained or porous material. The porous materials have charged surfaces, and in case of bricks the surfaces are negatively charged. To obtain chemical equilibrium the surfaces will attract charges with an opposite sign from the solution, called counter-ions, and the electric double layer is formed. Ions in the solution with the same sign as the charged surface are called co-ions, and the co-ions are represented to a much lesser extent in the electric double layers than the counter ions. Figure 1 shows schematically how the negative charge of the inner surfaces is counterbalanced by positive ions in the liquid phase inside the pore. When a voltage is applied both counter-ions and co-ions will start to move towards the electrode of opposite sign. Since the counter-ions are in excess to the co-ions in the electric double layer, a net-flow of ions across the electrode of opposite sign compared to the surfaces of the porous material will occur, and the water molecules around the counter-ions are pushed or dragged towards the electrode together with the counter-ions [2].

The electro-osmotic effect has been demonstrated in many different porous materials e.g. chalk sludge, iron hydroxide sludge, wet fly ash and biomass sludge [3], but the majority of research has been conducted on electro-osmotic dewatering of clay e.g. [4].

3. EXPERIMENTAL SECTION

3.1 Laboratory experiments

The bricks used for the laboratory experiments were Danish red bricks, new from the factory and of the brand Wewers Rød. The electro-osmotic dewatering experiments were conducted with pieces of brick with the dimensions: 22.8 cm long, 2.5 cm high and 5.5 cm deep. This corresponds to 1/4 brick cut in longitudinal direction. The weight of the 1/4 bricks was about 590 ± 60 g. At each end of the brick 1.0 mm thick aluminum electrodes were fixed. The electrodes had a surface area of about 3 cm times 6 cm and the electrodes were connected with a power supply (Hewlett Packard E3612A). To decrease the resistance between the brick and the electrode steel wool (supplied by Trollull Limited) was used, see Figure 2. To minimize evaporation from the setup over time the brick, steel wool and electrodes was wrapped carefully in plastic film.

Dry bricks were initially wetted by capillary suction to the desired water content, by placing the bricks horizontally in a container with tap water, covering the lower 2 cm of the brick. By weighing the dry brick and the brick continuously during capillary suction was it possible to reach the desired water content. The experiments were made with an initial mean water content of 10% and experiments with and without mortar were made. It was chosen to use tap water and not distilled water because of the presence of ions in tap water. In a masonry wall moist from rising dampness, ions from the groundwater are entering the wall, and use of distilled water would be far from this situation. Electrical conductivity of the tap water used was 0.73 ± 0.02 mS/cm and $\text{pH} = 7.7 \pm 0.09$.

Reference experiments without application of current were made for comparison. An overview of the laboratory experiments is shown in Table 1. The reference experiments were wrapped in plastic film for the time period shown as duration in Table 1. In the experiments where a constant voltage of 50 V was applied the mean current density was 0.07 mA/cm^2 .

At the end of each experiment each brick was segmented into 7 pieces by hammer and chisel vertically to the longitudinal direction. Water content was measured as weight loss at 105°C in each piece. The pH of the brick segments was also measured in some of the experiments. The pH was measured in 1 M KCl at a liquid-to-solid ratio of 2.5. After 1 hour of contact time pH were measured by a combined Radiometer pH electrode. The pH measurements were made with fine-grained brick powder made in a mechanical mortar. Comparative pH measurements between pH measured on fine powder and small brick pieces where the pieces were crushed by hand have been made and there was no significant difference (results not published yet).

3.2 Pilot scale experiment

The locality for the pilot experiment was a brick masonry house in two floors. The house is unheated and built around 1950. The experiment was made in the lower floor on an internal wall. The lower floor is placed as half basement, i.e. two of the outer walls are below ground surface whereas the two other walls are above ground surface (the ground surface outside the house slopes).

The experimental wall is an internal wall of the house separating a room in two parts. It was 191 cm high, 247 cm long and 11 cm wide. Both yellow and red bricks were found in the wall and the original mortar was carbonate based (hydraulic or air lime). The wall was covered with plaster, but the unfastened plaster was removed before the pilot experiment. The plaster was cement based and from the early 1990s. Loose plaster was mainly found in the inner corner that is situated angular to an outer wall that is under ground surface. Drilling samples from both bricks and mortar were taken for measurement of the water content. These drilling holes were 0.5 cm in diameter and 3 cm deep. Even though drilling holes of 0.5 cm are known to dry out the samples to some extent, Such drilling samples were used to measure water content as this is the traditional way of measuring water content in masonry in Denmark. Furthermore the measurement was most of all used for comparison purpose, before and after the experiment. First with drilling samples with a diameter of 5.0-5.5 cm are the results showed to be reliable in accordance to measurement of water content [5], but holes of this size would interfere too much with the applied electric field.

Sampling was done in different heights in a distance of 15 cm, 70 cm and 114 cm from the inner corner (all in the north part of the wall). The concentrations of NO_3^- and Cl^- were measured in the drilling samples, too, to evaluate the possibility for hygroscopic moisture. The concentrations of these two anions were measured by ion chromatograph after extraction of the drilling powder in water for one hour at the solid to liquid ratio of 2.5.

Inert electrodes are expensive and thus it was chosen to use cheaper iron electrodes in the pilot scale. In addition to being cheaper the iron electrodes also have the advantage that less H^+ is produced because two electrode processes occurs at the same time (2) and (4). When choosing the composition of the electrode units, it is important that H^+ produced at the anode will not be transported into the masonry. This is important when dealing with masonry, because the acidic pore fluids can destroy the mortar. On the other hand, electromigration of OH^- from the cathodic reaction (1) into the brick is not known damaging the masonry. From electrokinetic soil remediation, it is known that an acidic front develops very slowly in calcareous soils [6] and due to this it was chosen to place the metallic electrodes in clay with high carbonate content and place the clay on the surface of the masonry to avoid the acidic front in reaching the masonry. It was chosen to use clay from a local brickwork. The clay contained 17-18% carbonates and had a water content of about 20%. It was decided to place the electrodes outside the wall because in this case it is possible to remove the electrodes after the action without any sign on the masonry. This would not have been the case if the electrodes had been placed in holes in the wall. The external electrodes can be used even in heritage buildings.

Figure 3 shows two electrodes placed at the experimental wall. As seen, they are placed at the same side of the wall to simulate a situation, where it is only possible to get to the wall at one side as e.g. in a basement. Between the wall and the metallic electrodes was a clay layer of 1.5 – 2.0 cm thickness. To keep the metallic electrode in place it was covered with about 1 cm clay. Three set of electrodes have been tested so far and they have had different heights, which is described in the discussion section. The electrodes were covered by plastic to avoid evaporation, drying of the clay and poor electric contact. The anodes were covered carefully since the water will be transported away from these by electro-osmosis, whereas the cathodes were covered on the outer surface but a small distance between the wall and the clay was not covered. This was in order to allow the water arriving by electro-osmosis evaporate continuously.

4. RESULTS AND DISCUSSION

4.1 Laboratory experiments

The profiles of mean water content within the brick for experiment 1-12 after 72 days, where a voltage of 0 V and 50 V was applied, are showed in Figure 4. The initial water content was 10 % in all these experiments. It is seen, that in the reference experiments (no electric current) the water content was generally higher towards the ends than in the center of the brick. This was a common pattern to all reference bricks and may be related to in-homogeneities in the brick or the method of wetting the brick. For the reference bricks with a water content of 10% the total loss of water due to evaporation corresponded to a decrease in water content of less than 0.5% during 72 days, so the wrapping did not totally prevent loss of water.

The profile of water content after application of current differs from the profile of the reference samples and the water content is higher in the cathode end than in the anode end after the experiments (Figure 4). No water has been removed by electro-osmosis from the bricks during the tests because they were carefully wrapped in plastic film, however redistribution due to electro-osmosis is visible, when comparing the profiles of water content after application

of current with the reference profiles. The standard deviation was 0.15% at the anode end and 0.40% at the cathode end with an applied voltage. The standard deviation was 0.30 at each end of the brick without an applied voltage. The results from Figure 4 show that it is possible to move water by electro-osmosis in bricks. After having shown this it is interesting to see how mortar in between two bricks influences the water transport in order to simulate a brick wall. Therefore experiments were carried out just similar to the experiments showed in Figure 4 with the one difference mortar was placed in the middle of the brick that was cut into two. The mean of the results from experiment 13-24 is shown in Figure 5.

The standard deviation of the results at Figure 5 with applied voltage was 0.26 at the anode end and 0.11 at the cathode end. For the bricks where no voltage had been applied the standard deviation was 0.07 for the segments at each end. The profile of water content with no applied voltage shows the same pattern of higher water content in the outer ends as was found in Figure 4. The water content in the mortar is significantly lower than in the brick due to the lower porosity in the mortar.

Figure 5 shows the electro-osmotic dewatering effect in the setup with brick and mortar. The changes was registered to be 0.4% in water content in the brick just next to the anode and just next to the cathode 0.5%. When the results from the experiments with and without mortar are compared it at first sight seems as if the dewatering effect is higher in the experiments without an intervening layer of mortar but due to the scattering there is no significant difference between the dewatering effect in the experiments with and without mortar. In every experiment, where an electric field had been applied, the water content of the brick was higher in the cathode end than in the anode end (with or without mortar). This show, that there is electro-osmotic transport of water in the brick or brick/mortar system.

The material characteristics of brick and mortar are very different, including e.g. internal surface charge, ion concentration, water content and pH, which are of importance to the electroosmotic dewatering process. This will influence the electroosmotic effect in the two materials. If no salts are added to the materials and they are water saturated, the conductivity of mortar is higher than that of brick due to the higher amount of free ions in the mortar (regardless the lower water content if both materials are water saturated). Determination of the electroosmotic effect in different bricks and different mortars is highly relevant and will be carried out in the near future.

From Electrokinetic soil remediation it is known, that soil pH changes significantly during remediation due to the electrode processes [7]. Acidification occurs from the anode end due to electrode process (2) and (3) while an alkaline front develops from the cathode end due to electrode process (1). Whether such pH changes are found in brick masonry during electro-osmotic dewatering is important to know because especially acidification can lead to destruction of some building materials as hydraulic mortar and carbonated lime based concrete.

The pH changes within the brick due to the electrode processes were measured at the end of some of the experiments 13-20. The pH was measured at different distances from the anode in a brick with mortar in the middle (11.4-12.0 cm from the anode) and the results are shown in Figure 6, which shows a significant variation in the pH after 72 hours of applied current. In the brick material which was placed just next to the anode a pH drop is seen due to electrode processes (1) from the natural pH of 9.7 to 5.8. The high natural pH of the mortar (12.7) influenced pH in the brick. Figure 6 shows that the pH in the brick just next to the mortar was 11.9 and 10.6 closest to the anode and the cathode, respectively. This increase in pH is related to the presence of the mortar and can be expected to occur due to diffusion of OH^- from the mortar into the brick and pH is higher in the direction of the anode because of electromigration of OH^- in this direction. In the middle between the mortar and the electrodes on both sides which means 5.7 cm and 17.7 cm from the anode pH was increased slightly to 10.5 and 10.3. In the experiment a general pH increase was observed except from the first 2 cm from the anode. These results are indicating that OH^- ions from the mortar are moved not only to the brick material just next to the mortar but further into the body of the brick.

Some materials have pH dependent surface charges (e.g. [8]) and as shown in Figure 6 significant pH changes are found due to the electrode processes. If this is the case for these red bricks the pH changes found may have influenced the electro-osmotic effect in the brick. However, in full scale the electrodes should be constructed in a way where especially the acidification is avoided. Another important aspect in the construction of electrodes that was seen in these laboratory experiments was that a rusty color was found where the anode had been placed and such discoloration must be avoided. The discoloration was due to corrosion of the steel wool from electrode process (4).

4.2 Pilot scale experiment

The water content, the concentration of nitrate and chloride in the drilled samples from the experimental wall are shown in Figure 7(a), 7(b) and 7(c), respectively. It is seen that the water content is between 10% and 15% in the bricks and between 3% and 6% in the mortar and as it was the case in the laboratory experiments the difference is related to the lower porosity of the mortar. The masonry of the experimental wall must be considered very moist. The concentrations of both nitrate and chloride are highest in the distance of 114 cm from the inner corner and the highest

concentrations were found in the samples taken in 145 cm height. Water is entering the wall both from the soil below and from the soil next to the corner (which is below ground level) and the salts will concentrate where the moisture content starts to decrease which in a case like this is in a certain distance from both floor and corner.

The height of the longest electrodes was about 130 cm. The concentration was highest in the brick compared to in the mortar. There is no relation between water content and salt content in the samples and at the same time the salt concentration is low in most samples. Thus the moisture in the wall is expected to be originating from rising dampness rather than of hygroscopic origin.

Electrodes were placed at the same side of the experimental wall as described in the experimental section. The distribution of the electric field between the electrodes is expected distributed like illustrated at Figure 8, however, Figure 8 represents the ideal case in a homogeneous porous materials which a brick masonry is certainly not. This means that the field lines will not be as smooth as illustrated, but it is expected, that all masonry between the electrodes is covered by the electric field.

The first set of electrodes was placed close to the corner. The center of the metallic anode was placed 9 cm from the corner and the distance between the centers of these two electrodes was 35 cm. The clay of the electrodes had the height of 127 cm and the metallic electrode/clay was placed directly on the cement floor. A low constant current of initially 20 mA which was manually increased to 60 mA was applied to the electrodes (corresponding to 0.16 and 0.47 mA/cm electrode). The experiment lasted for 9 days. The electric resistance (voltage/current) was almost constant for the first 6 days but then the resistance started to increase (the current was constant 60 mA but the voltage increased from about 60 V to about 100 V in this period). Then it was decided to end this experiment. When the electrodes were removed from the wall it was noticed that the contact between the anode and the wall was very poor and this is considered to be the main reason for the increasing voltage. The by electroosmosis lowered water content in the clay and possibly also in the wall close to the anode had resulted in the poor contact.

After 2-3 days of current a moist area spread in the cement floor around the cathode. This moist area can be seen at Figure 2. The first electrode from the left in the figure is the anode and at the floor close to this a bucket had discolored the floor before the experiment was initiated. The second electrode is the cathode and a half circle of moist is seen in the cement floor in front of this. The moist area grew throughout the experiment and reached a diameter of about 30 cm. To develop such moist area in the floor is certainly not appropriate but in this case the electro-osmotic transport of water was clearly seen from it. It was decided not to make drilling holes in the wall after this test because it was known that the wall had not at all been dried sufficiently. The water content in the clay at the electrodes was measured in 13 different heights. The mean water content of the clay at the anode was $15.2 \pm 0.5\%$ and at the cathode $18.7 \pm 1.1\%$. The clay water content was lower in all the samples from the anode than in any of the samples from the cathode.

The initial pH of the clay was 8.4 ± 0.1 . The pH was measured at the same 13 samples as the water content and at the anode pH was 8.4 ± 0.1 and at the cathode 9.9 ± 0.4 . Thus it is seen, that the buffering capacity of the clay has been sufficient to buffer the acidification from the anode process (2) since pH in the clay at the anode was the same before and after the experiment. There is no buffering capacity in the clay against development of an alkaline front and it is seen, that pH in the clay samples had increased from the cathode process (1). The clay had a rusty red color next to the anode and this originates from electrode process (4), but there was no discoloration of the wall.

In the present wall the moisture problem is not related to salts (hygroscopic moisture). However, this may be the case in some situations and thus the removal of Cl^- and NO_3^- was investigated by measuring the concentration in the clay around the electrodes. Figure 9 show the concentration of these two ions in different heights of the clay. It is noticed that the concentration of both anions are much higher in the clay at the anodes than at the cathodes which shows that electromigration has transported both ions from the masonry into the clay (the initial concentrations in the clay were 0 mg NO_3^-/kg and 49 ± 6 mg Cl^-/kg). When comparing the concentrations in the wall (figure 7 b and c) at the distance 15 and 70 cm from the corner (the area where the electrodes were placed) and the concentrations measured in the clay at the cathodes it is seen that the concentration of both ions are higher in the clay. This shows that electromigration can be an effective method for removal of salts from masonry, which is in consistency with findings from another pilot plant similar to this but aiming at removing especially nitrates from masonry of an old stable (Ottosen & Rørig-Dalgård, 2006). This high concentration in the clay also suggests that the salt ions are transported out from the clay and are not concentrated inside the wall. Had that been the case there could be a risk for salt induced decay.

For the second set of electrodes the developing moist area in the floor was avoided by placing a piece of plastic between electrode and floor. The electrodes were not as high as the first set (see Figure 3), they were 86 cm from floor to top and the distance between the electrodes was 35 cm. A constant current of 60 mA was applied to the electrodes (0.7 mA/cm electrode) and the voltage was initially 36 V and it increased to 48 V during the 19 hours the

experiment lasted, which indicate that the current density was too high. The reason for such a short duration was that the water content of the clay at the cathode had increased from about 20% to 25% in the lowest 20 cm and 22% in the top. With such a high water content the clay was somewhat liquidized, the clay slipped to the floor and the cathode fell off the wall. Thus it is necessary to construct the electrodes so the water arriving with electro-osmosis to the cathode can escape from the clay.

The third set of electrodes was lifted 5 cm from the floor and placed on a plastic grating with holes of about 2x2 mm². Between the grating and the clay of the electrodes was placed a piece of cloth to keep the clay in place. Underneath the grating water could be collected in a plastic bag. The electrodes were 125 cm from grating to top.

A constant current of 40 mA was applied to the electrodes for 6 days. For the first 3-4 days the electric resistance was about constant but then it started to increase. The main increase in resistance occurred in the interface between clay and wall, which was discovered by pressing the clay hard to the wall with an immediate decrease in resistance. It was also tried to fill a little tap water between the interface, also with an immediate decrease in resistance as result, and this decrease was larger than when the clay was applied pressure for better contact. The problem was probably that the clay at the anode was too dry from electro-osmotic transport of water away from the interface towards the cathode.

About 30 to 40 mL water were collected from below the cathode after this experiment. This represents the minimum of water transported by electro-osmosis since the evaporation factor is not known.

New pilot experiments will be conducted in the near future, but so far these three experiments have been made.

4.3 Overall discussion

From both the experiments in laboratory scale and in pilot scale electro-osmotic water transport from anode end towards cathode end was seen, and this is the most important finding from this study. In the laboratory experiments the system was sealed so water was hindered in leaving the system and by this it was seen, that there is an electroosmotic effect in the brick and brick/mortar system. However, the drying out of masonry walls is dynamic. The drying surfaces are typically exposed to atmosphere, and moisture is lost by evaporation. When applying this technique to masonry walls there are several variables of which temperature and humidity are very important. Also the inhomogeneous pattern of water and salt in the masonry (both in depth and over the surface area) will influence the electroosmotic effect. In general it is not possible to control these variables and the method must be robust enough to cover the common different situations. One example of a common extreme could be frost and it has been shown in an other pilot plant for electrokinetic salt removal, that this process is possible even at temperatures between 0°C and -10 °C [9]. In the masonry wall the electric field will tend to flow in the areas with the highest conductivity and that is where the water and the ion concentration are highest i.e. in the most problematic areas of the masonry, which is an advantage of the method. If the salt concentration in the masonry is high the electroosmotic dewatering will not be effective before these salts are removed by electromigration. This is because there is almost equal transport of ions towards anode and cathode in this situation. Over time, when the salts have been removed, the current must pass in the electric double layers, where there is an excess of cations as described above, and at this point electroosmosis is efficient.

Since electro-osmotic water transport occurs in the systems with brick/mortar there is basis for further development of an electrokinetic method for drying brick masonry. However, there are still many questions to be answered and also development of proper electrodes is needed. An optimization of the placement of the electrodes must also be made. In the present work the electrodes were placed vertically and this does not hinder water in continuing entering the wall from the soil. It may be a possibility to place the electrodes horizontally and close to the floor and by this hinder the transport of water further than the anode (placed above the cathode). This work is on-going. In some situations it may be advantageous to combine electroosmotic dewatering with isolation of the masonry from rising dampness by inserting a damp proof course in order to prevent the masonry continuously in receiving new water. In cases where there is a problem with hygroscopic moisture in the masonry, a damp proof course cannot solve the problem alone and in such a situation a combination of damp proof course and an applied electric field could also be advantageous.

From the experiments presented here several important points for discussion can be extracted. The first and very important is that it seems that the electro-osmosis was even more efficient in pilot scale than in laboratory scale, though a direct comparison is not possible. The voltage was kept constant 50 V in the laboratory experiments which corresponds to 2.9 V/cm at a mean current density of 0.07 mA/cm². In the pilot scale experiments different constant current densities were tested and the best (as high as possible but slowest increase in resistance) was used in experiment 3 was 0.32 mA/cm² electrode. At this current the voltage was varying between 40 and 55 V corresponding to between about 1.1 and 1.6 V/cm in the shortest distance between the electrodes. It must though be remembered that the electric field is not evenly distributed since the electrodes are placed at the same side of the wall. The current

density was generally higher in the pilot plant and the voltage lower (i.e. the electric resistance lower). In the laboratory experiments the electro-osmosis could be seen as small changes in water content at cathode and anode. The changes in water content in the clay at the electrodes of the pilot plant were much larger (water did even drip off) and this at the lower voltage/cm that was applied - the electro-osmotic water flow depends on the applied voltage [2]. It must however be taken into account that the electrodes were constructed differently in the two cases and the electric contact between clay and wall may have been better than the electric contact between steel wool and brick in the laboratory. This is influencing the voltage over the brick/masonry system. Also differences in the internal surfaces of the new bricks used in the laboratory and the older bricks in the experimental wall may influence the result.

The acidification of the brick that was found in the laboratory scale experiments was successfully avoided in the pilot scale experiments by placing the metallic electrodes in clay rich in carbonates. Also discoloration of the masonry surface from corrosion of the iron anode was avoided since the corrosion products precipitated in the clay. Prevention of the development of an alkaline front from the cathode end was not in focus of the present study. However, it may be necessary in the future to avoid a high transport number of OH⁻ in the masonry, which may slow down the electro-osmotic effect. This is a subject for further research.

The clay solved the problem of acidification and is also ensuring a good electric contact between masonry and metallic electrode to some extent. The problem was though that the interface between clay and brick dried relatively fast with an increase in electric resistance as result. Electro-osmotic dewatering experiments with the same clay as used in the pilot scale have been made in laboratory scale (results not published yet) and with a voltage/cm that is twice as high as in the pilot scale. The resistance has not increased significantly in these experiments even after 1½ month. This underlines that it is the drying out of the interface, which is the problem, and this is probably because the electro-osmotic effect is larger in the masonry than in the clay.

Removal of moisture will ultimately reduce the conductivity of the masonry especially in the part closest to the anode and once a critical point is reached, continued dewatering by this method will not be possible since the passage of current is hindered by the dry area. One solution, both to the drying of the interface between clay and masonry and drying out the masonry closest to the anode, that is to be investigated is to either turn off the current some hours a day or even to use alternating current (short period with current in one direction and a long period with current in the other direction). The idea of both these suggestions is to obtain a more smooth water profile during the dewatering. Another idea could be to keep the interface moist by placing a thin layer of e.g. cloth in the interface, but this means adding water to the masonry and is it then possible overall to obtain dewatering or will it just be exchange of water? This is also a question for a study.

The most important issue of development is now considered being electrodes that will not limit the process of electro-osmotic water transport.

5. CONCLUSION

Rising dampness is a well known problem in connection to masonry buildings. Removal of the water from the masonry may be possible by application of an electric DC field, in which an electro-osmotic transport of water can be obtained in direction from the anode towards the cathode. The electro-osmotic effect was shown both in laboratory scale and in pilot scale. In laboratory scale it was found that it was necessary to avoid the products from the electrode process at the anode in reaching the brick (acid and corrosion product from the iron electrode). Acidification of the brick was seen when the metallic electrode was placed directly at the brick surface and the surface was discolored.

In pilot scale this problem was solved by placing the electrodes in a layer of clay that was attached to the wall. The clay type that was chosen was rich in carbonates and buffered the acidification as expected. Also the corrosion products precipitated within the clay and left the surface of the wall clean.

The electro-osmotic transport of water seemed more efficient in pilot scale than in laboratory scale, and in pilot scale it was possible to collect water underneath the cathode after few days of current. Thus the overall concept with water movement in an applied electric field is working, but still proper electrodes must be developed. The duration of the pilot scale experiments was limited by drying out of the interface between clay and wall at the anode.

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FIGURES AND TABLES

Table 1: Overview of the laboratory experiments. All experiments were made with the brick type "Wewers Rød".

Experiment number	With or without mortar +/-	Voltage applied (V)	Duration (h)	Initial water content (weight%)
1-8	-	50	72	10
9-12	-	0	72	10
13-20	+	50	72	10
21-24	+	0	72	10

Figure 1: Schematic presentation of a pore in the brick. The internal surfaces are negatively charged and this charge is balanced by positive ions in the solution. The ions are mobile but must be replaced so electroneutrality is maintained. In an applied electric field, the current is carried mainly by positive ions in such pore and this will force movement of water molecules in the same direction.

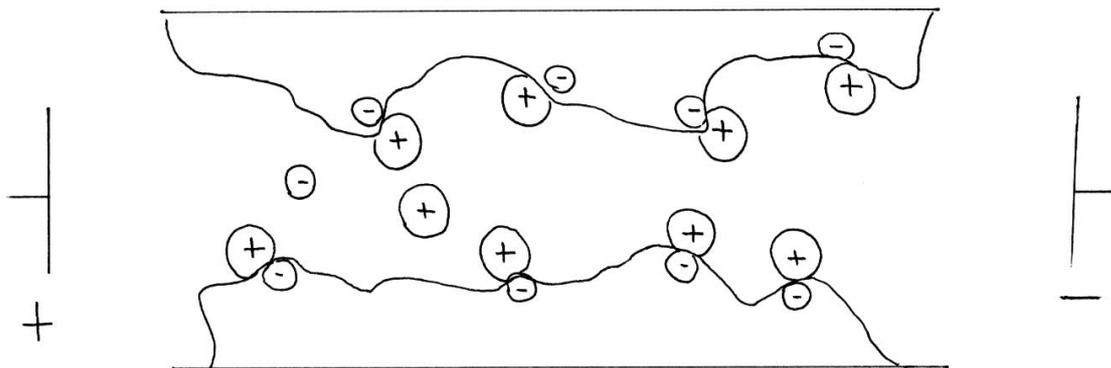


Figure 2: Brick with electrodes attached at each end. Between the plate electrodes and the brick steel wool was placed to improve the electric contact.

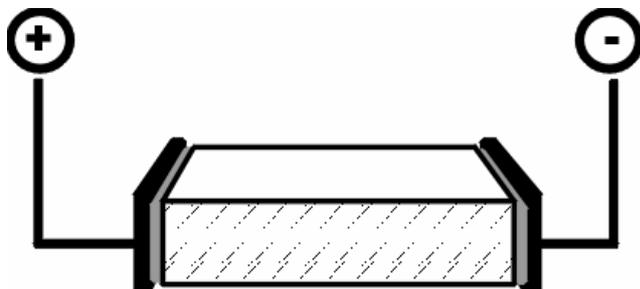


Figure 3: Two sets of electrodes of the pilot plant (first and second set)

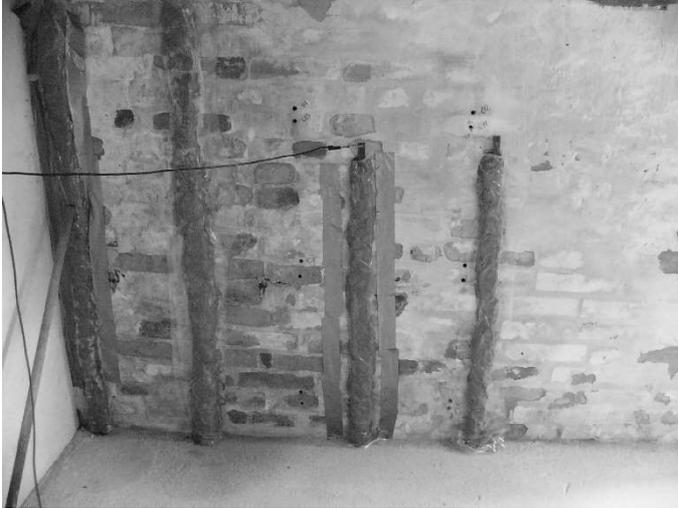


Figure 4: Water content in blind bricks (0 V) and bricks that were applied an electric field of 50V. Mean initial water content was 10% and the duration 72 hours.

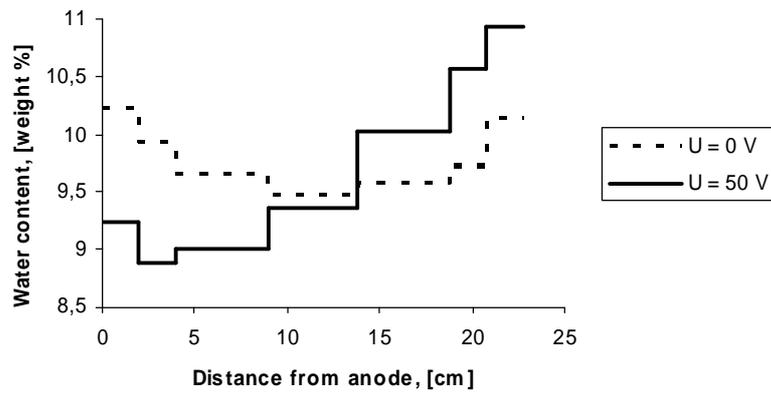


Figure 5: Water content in blind bricks with mortar (0 V) and bricks with mortar that were applied an electric field of 50V. Mean initial water content was 10% and the duration 72 hours.

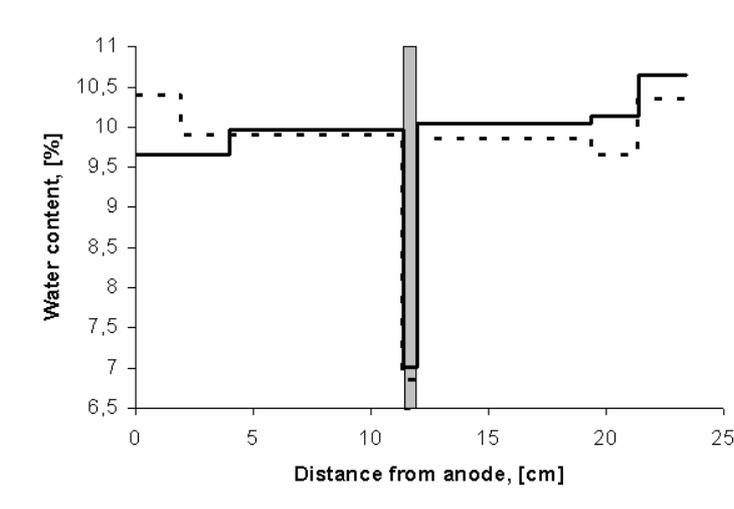


Figure 6: pH in blind bricks with mortar (0 V) and bricks with mortar that were applied an electric field of 50V for 72 hours.

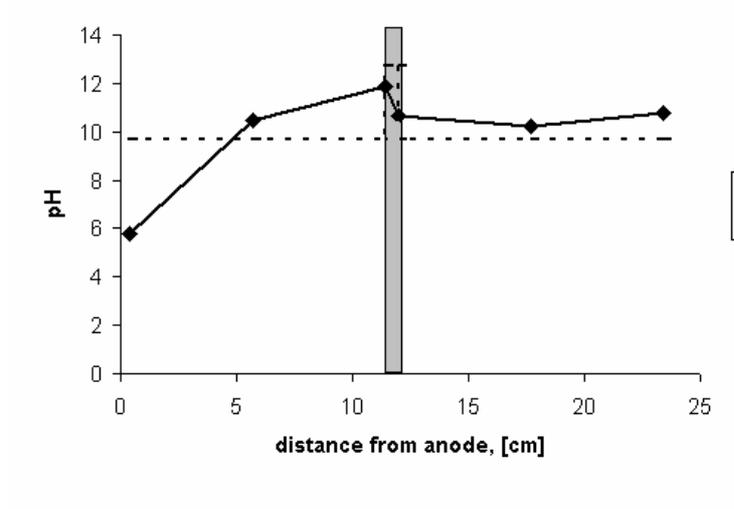


Figure 7a: Water content in in experimental wall at different heights and distances from corner next to outer wall under ground surface. (S = brick and M = mortar)

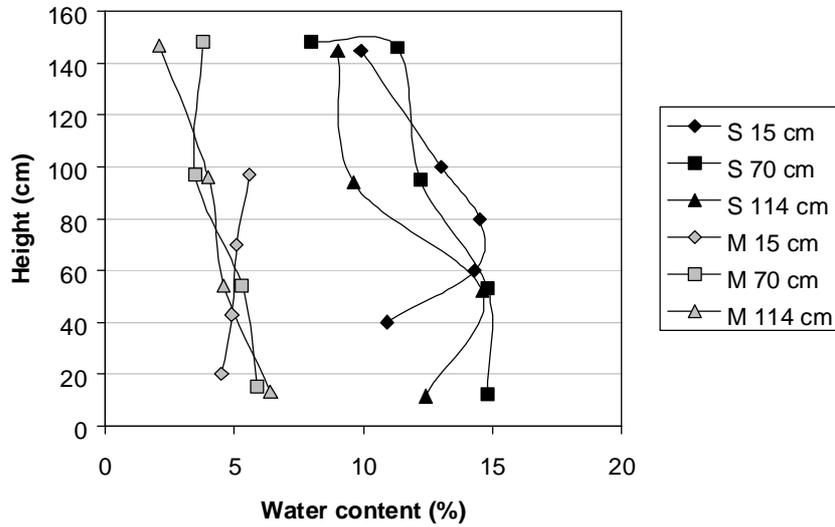


Figure 7b: Nitrate concentration in the experimental wall at different heights and distances from corner next to outer wall under ground surface. (S = brick and M = mortar)

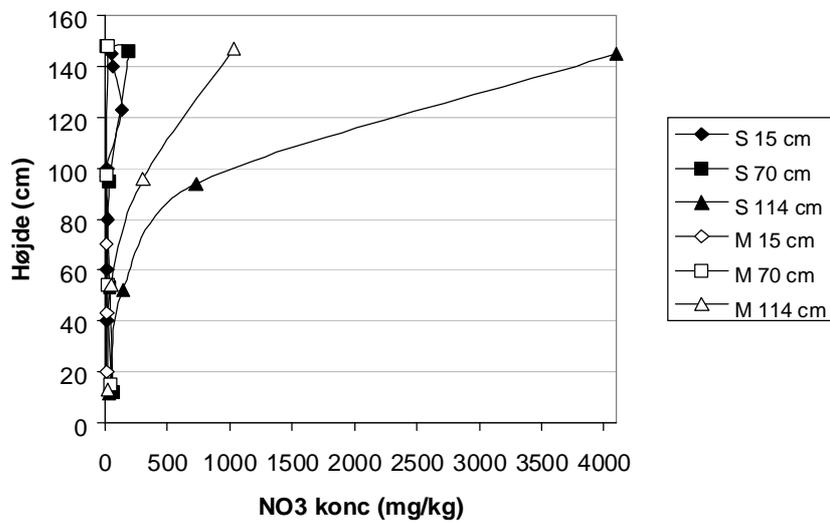


Figure 7c: Chloride concentration in the experimental wall at different heights and distances from corner next to outer all under ground surface. (S = brick and M = mortar)

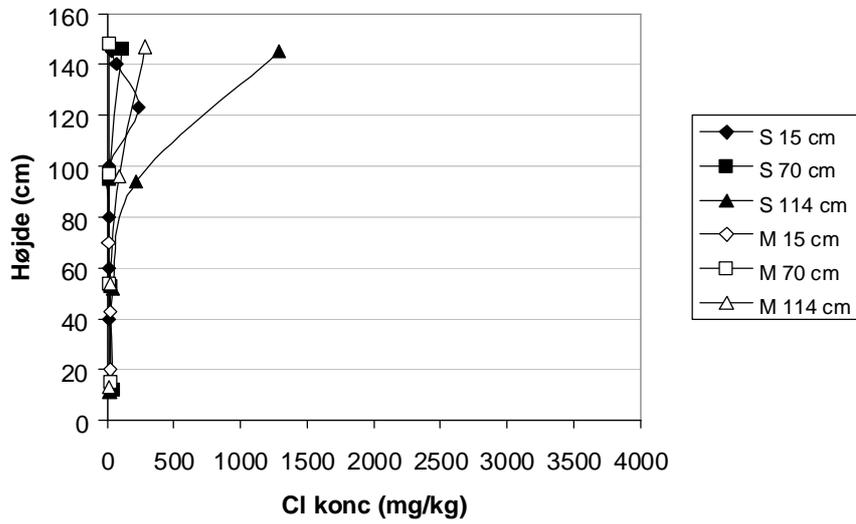


Figure 8: Concentrations of chloride and nitrate in the clay surrounding the metallic electrodes at the end of pilot experiment 1.

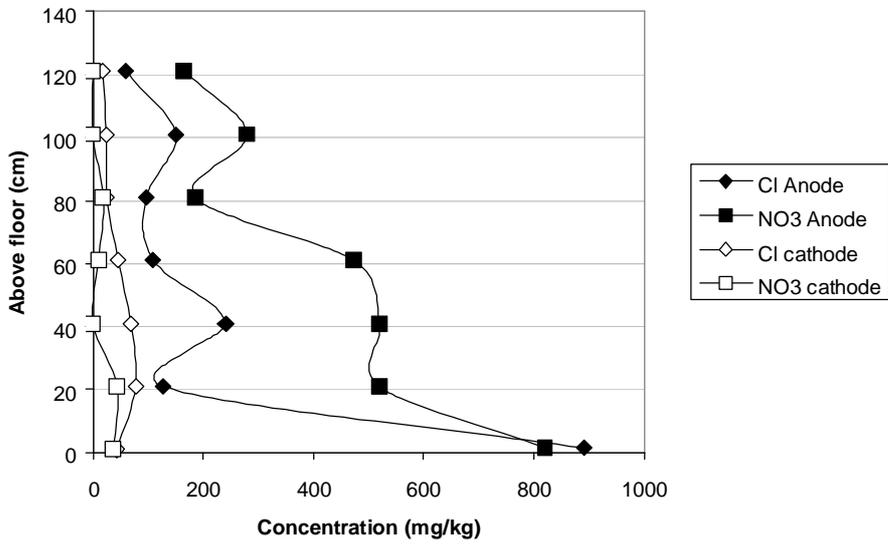


Figure 9: Potential and current distribution in a vertical plane along the line of electrodes [10]

