Treatment of rising damp and salt decay:

The historic masonry buildings of Adelaide, South Australia

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Abstract

The City of Adelaide suffers from rapid damage to historic building materials due to salts, rising damp, and damp-proof course failures. Adelaide City Council has partially funded repairs to over 400 buildings in the past 15 years. To begin to examine the scope of this problem and the effectiveness of various treatments, 24 historic buildings in Adelaide were examined, with a focus on the building materials, historic interventions and current treatments applied to treat rising damp and salt decay. Analysis of 90 samples found high levels of sodium sulfate, sodium chloride and sodium nitrate in cellars, ground water and building materials, suggesting a clear example of rising damp. Samples of disintegrating masonry, depth profiles acquired by drilling, poultices and damp proof courses (DPC) were analyzed by Ion Chromatography (IC) and Environmental Scanning Electron Microscopy coupled with Energy Dispersive Spectroscopy (ESEM/EDS). Mercury Intrusion Porosimetry (MIP) and capillarity test were carried out in the building materials and DPCs showing that porous materials with high porosity, small pores and low strength are more prone to salt weathering. The City of Adelaide is a natural laboratory for comparing and analyzing different treatments of salt-laden masonry, with hundreds of treated buildings of the same age, in the same environment, and with similar building materials.

Keywords: *Damp proof course; Desalination treatments; Salt weathering; Rising damp; Building materials*

1. Introduction

The problem of damage to historic masonry due to salt crystallization by rising damp is well known from sites such as Venice, Italy and the Tower of London [1,2]. This problem has also long been recognized as a serious threat to heritage structures in South Australia with the formation of a Salt Damp Research Committee some 30 years ago [3]. In order to address this problem, the City of Adelaide developed a program where the City Council reimburses up to 50% of the conservation costs of listed buildings. Much of the funding goes to treat salt damp, the term used in South Australia for the combination of salt damage and rising damp. A range of treatments has seen empirical application over the past 30 years in Adelaide. Thus, Adelaide is a place where treatment evaluation can be conducted with an aim towards an epidemiological analysis, given the substantial number of similar structures that have undergone some form of intervention under similar conditions, in an unforgiving environment. While in many parts of the world, salt weathering is a slow process that results in gradual surface erosion, in Adelaide salt weathering can be a severe problem: the loss of 5 mm of stone surface in a single summer season has been observed.

Compared to the other continents, Australia has the oldest and saltiest soils, and the least recent geologic activity. During the late 19th century, it was also the wealthiest country in the world, thanks to abundant minerals and innumerable sheep [4]. Land clearance for farming and mining resulted in the loss of some 30 billion trees, raising the water table and mobilizing subsurface salts. Both dryland and irrigation salinization are now serious environmental problems in Australia.

Dryland salinity currently affects about 2.5 million hectares of land. This is caused by the removal of deep-rooted plants which results in rising water tables and the migration of salts in the soil to the surface where they are progressively concentrated as the water evaporates, according to the Australian National Action Plan for Salinity and Water Quality [5]. 15 billion native trees have been cleared for farming and ranching in the Murry-Darling river basin which is an important water source for Adelaide. Irrigation salinity occurs when excess irrigation water (not used by plants) soaks through the soil, causing the underground water-table to rise and bring salt to the surface. Thus, this human-

induced environmental problem is caused by alterations in the water regime of many catchments following either land clearing and/or artificial irrigation.

Salinization is a growing problem in Australia, affecting agricultural productivity, historical structures and archaeological sites [6]. Porous building materials, such as stone, brick and mortar are prone to the ingress of moisture and damage from salt crystallization. Rising damp occurs where ground moisture is drawn into mortar and masonry surfaces by capillary action. The extent of the rising damp is determined by the hygroscopic indices of the salts, the availability of moisture, and degree of evaporation [7]. Salts are precipitated and crystallized at different heights on the wall in a sequence according to their solubility [8], temperature and relative humidity. Above ground level, water evaporates from the wall and the solution becomes more and more concentrated while still being subject to capillary rise. As the solution becomes saturated during transport any further evaporation will cause crystallization and immobilization of the salt [9].

The weather conditions present in Adelaide favor the process of rising damp, salt crystallization and damage to porous materials. Mild, rainy winters are followed by hot, dry summers, such that salts are dissolved during winter and crystallized in summer (Table 1). Damage intensity caused by salt weathering varies considerably depending on the driving factors [10], mostly notably rapid drying or cooling leading to rapid crystallization. Adelaide has numerous rapid drying events in summer, with hot, dry winds [11]. Depending on conditions, the winds raise particulate levels, such that Adelaide suffers from dust storms on average 8.5 days per year [12].

Introduced in the mid-nineteenth century, a damp-proof course (DPC) is a horizontal layer introduced between the footing and the wall in order to prevent intrusion of moisture into the wall by means of capillary action [13]. Traditionally, walls were built on stone or brick footings [or foundations] without a DPC. After early failures, DPC's such as slate, glass, hardwood and slag blocks were used, followed by tar/sand and glazed bricks. Waterproofing additives such as stearates were also added to mortar mixes. In modern buildings, plastic sheeting such as polyethylene is normally used [14-16].

A wide range of methods has been introduced in an attempt to reduce damage from salt crystallization before and after ingress of saline water has occurred. Most of the strategies are intrusive and affect the building's fabric, such as repair of the damp-proof course, installation of perimeter drains, or injection of a chemical moisture barrier [17]. Other interventions have included poulticing, sacrificial layers, installation of electro-osmotic systems; insertion of Knapen tubes, or atmospheric siphons; and the use moisture-impermeable hard cement renders [15].

The City of Adelaide is the capital of the state of South Australia (Figure 1). The rising damp in Adelaide is locally called “salt damp” because of high salt concentrations. The combination of salt attack and rising damp causes substantial damage to the State's building stock, with particular concern in older buildings, some of which were constructed before the problem was well understood [15], and many of which now suffer from DPC failures and/or poor maintenance.

During the 1960s & 1970s serious salt problems increasingly affected previously stable buildings comprising the historic center of Adelaide. In 1987 an innovative Heritage Incentives Scheme was undertaken by the City Council and over 400 buildings have now been treated for salt damp, using several methods. City spending on heritage maintenance grants is now about one million dollars per year [18].

The aim of research presented here is to characterize the salts, damp-proof courses, and building materials of a range of buildings treated for rising damp and salt problems, in order to establish a baseline for understand the different treatments used in Adelaide and their relative effectiveness. Knowing what types of salts are present and which building materials are more affected by salt decay is important in order to evaluate the relative effectiveness of techniques used to desalinate salt-laden masonry and treat rising damp. Future work will include a more detailed study of the City database of treated buildings and following-up of selected buildings to evaluate long-term treatment effectiveness. This work represents a proof of concept, approaching a serious conservation problem as an epidemiological study where treatments can be evaluated in a situation where many variables are held constant (climate, building materials, etc.) and enough buildings have been treated to permit a

statistical analysis. Through this approach it may be possible to tease apart useful information such as if treatment failures are mostly associated with substrate type or application method.

2. Experimental Procedure

2.1. Case studies

Before starting the research we reviewed the documentation regarding all the treated buildings in the Adelaide City Council database. The database consists of reports of historic interventions and current treatments applied to treat rising damp and salt decay, photographs, notes, etc. From the 400 treated buildings by the City Council, 24 representative buildings with the most complete documentation available were selected to carry out our study (Table 2). The buildings selected include the full range of building materials and historic DPCs in Adelaide, as well as treatment failures and successes. To evaluate the scope of damage to historic masonry and the effectiveness of various treatments, the building materials, historic interventions and current treatments for rising damp and salt decay were examined on these 24 historic buildings in Adelaide. We created a file where we compiled the available data from the Adelaide City database together with the analytical results of samples collected on each visited building (examples in Table 3). Samples of mortar, brick, shale or siltstone (locally called “bluestone”), calcrete, limestone, sandstone and salts efflorescences were collected from a representative range of historic buildings. Figure 2 illustrates one of the studied buildings: St. Johns Church. In one of the walls of this church the rising damp reaches up to 1.5 m (Figure 2b). In addition to salt samples and building materials affected by them, samples of the different types of damp-proof courses were also collected (Figure 2c).

2.2. Methods

To identify the main salts present in the samples, and to distinguish salts with the same composition but different state of hydration we used X-Ray Diffraction analyses (XRD), carried out in a Siemens D5005 with a $\text{CuK}\alpha$ radiation and patterns obtained by step scanning from 10 to 60 degrees 2θ with a count of 0.1° per step and a scan speed of $8^\circ/\text{min}$ and 40kV and 30mA in the X-Ray tube.

To distinguish other salts present in the samples in minor amounts, especially when they were mixed with the building materials and in the case of poultices and DPC's, Ion Chromatography was used to identify the soluble salts as cations and anions. Quantitative analysis of the soluble salts was performed on a Dionex DX-500 Chromatograph. An IonPac #CS12A Analytical 4 mm column was used for the separation of cations. The eluent was 22mN of H₂SO₄, with a flow rate of 1ml/min, and a CSRS-ULTRA 4mm was used as the suppressor. An IonPac AS12A 4mm column was used for the separation of anions. The eluent was 1.8 mM Na₂CO₃/1.7 mM NaHCO₃, with a flow rate of 2ml/min, and an ASRS-ULTRA 4mm was used as the suppressor. A mixture of cations and anions was used for calibration.

The samples were also studied with the Environmental Scanning Electron Microscopy (ESEM) using a XL30 ESEM-FEG FEI microscope (Hillsboro, OR) with Energy Dispersive X-Ray Spectroscopy (EDS) (model 7509 Oxford Instrument Analytical, UK). ESEM/EDS was used to observe the morphology of the salt crystals, as well as to identify and corroborate some of the less abundant salts that were suggested by IC analysis.

Mercury intrusion porosimetry (MIP) in a radius range of 0.003-200 µm (using an Autopore IV 9500 Micromeritics) was used to assess the pore structure of the damp proof courses and some building materials, open porosity (P) and pore size distribution (PSD).

The water absorption by capillarity test was carried out using a continuous data-recording device. The balance device was linked to a computer which automatically records weight gain in the tested specimen at specified intervals (every 10 seconds in the current study). It allows automatic monitoring of the water uptake by the sample when its lower surface is in contact with the water reservoir. The continuous absorption method permits an extremely accurate characterisation of building materials with high absorption rates ($C > 10 \text{ Kg/m}^2\text{h}^{0.5}$) and also with narrow contact area, in comparison with the non-continuous standard method [19]. The results were plotted as absorbed water per area of the sample throughout imbibition versus the square root of time. Through this kind of representation, the capillary imbibition kinetic shows two parts. The first part defines capillary absorption and the second

part defines saturation. The slope of the curve during capillary absorption is the capillary absorption coefficient, C .

3. Results and discussion

3.1. Building materials

3.1.1. Mortars. The type of building material is very important in the amount of damage caused by salts. Salts tend to preferentially disrupt weaker and more porous materials, and in the case of Adelaide, soft lime mortars generally suffer much greater damage than brick or stone. During restoration work, a weak mortar is specified by local heritage architects because they prefer to sacrifice the bedding or jointing mortars to salt attack rather than the bricks or the stone. Therefore, in many cases, the mortar has disappeared from the joints of bricks (Figure 2d). This can be explained because in some cases a repair mortar with a binder/aggregate ratio of 1:4 was specified. This means that the percentage of sand is much higher than the proportion of lime, a weak formulation which could explain the disintegration of these mortars by the action of salt damp. This type of mortar (sacrificial mortar) is a good solution to preserve exposed stone or brickwork. However, when the disintegration of a mortar occurs behind a relatively impermeable render, it may result in their detachment from the wall. The deteriorated mortar is often present under the render as loose grains, accumulated as “sand” in Brougham Place Uniting Church and in the Adelaide Goal. Older historic mortars typically have a common ratio binder: aggregate of 1:1 to 1:2, while mortars from the early 20th century have a ratio of 1:3 to 1:4 [20]. Older lime contained more impurities such as burnt clay and charcoal than modern limes, which are made of purer limestone and marble. Such impurities had the effect of pozzolans on lime mortars, increasing their strength. Figure 3 shows the open porosity and pore size distribution for this sacrificial mortar and for the main types of building materials in historic Adelaide buildings. The mortar (Figure 3a) has 20% open porosity and a polymodal pore size distribution due to the heterogeneous aggregate and binder size, meaning that the bigger pores are controlling the transport of fluids. There are also a significant amount of smaller pores (0.1-1 μm), which also contribute to

reaching saturation over a longer term, compared to other materials according to the capillarity curve (Figure 4).

3.1.2. Bluestone. “Bluestone” was one of the main construction materials in Adelaide from 1840-1930. This type of stone is known in petrology as a siltstone (similar to a slate) and often suffers disintegration in salt-rich environments. It splits easily along the bedding plane due to its content of fine silts and clays. However, it is often in good condition when it has an adequate DPC. Bluestone shows a polymodal pore size distribution (Figure 3b) defined by the laminar rock-texture and the different sizes of embedded minerals. The relative low total porosity (9.30%) and the heterogeneous pore size distribution provide low values of capillary absorption coefficients both parallel and perpendicular to foliation ($C = 0.01 \text{ kg} \cdot \text{m}^{-2} \cdot \text{h}^{-0.5}$). That explains why it has been used in the past as a relatively damp-proof base course, although in the long term it is attacked by salts.

3.1.3. Sandstone. Much of the local sandstone from the Adelaide Hills has a high porosity and has a high proportion of clays. It seems that the stone of the Elder Hall is “melting” as the clays are leached from the matrix, and it is possible to observe the white flow of the fine powder of muscovite and kaolinite over the façade. The swelling of some clays, as vermiculite ($\text{Mg,Fe}^{++},\text{Al})_3(\text{Al,Si})_4\text{O}_{10}(\text{OH})_2 \cdot 4(\text{H}_2\text{O})$), is mainly causing problems of flaking and deterioration of this stone, very similar to what happens with the hygroscopic salts. The results of the analyses by XRD, besides vermiculite also shows the presence of quartz, muscovite ($\text{KAl}_2(\text{Si}_3\text{Al})\text{O}_{10}(\text{OH,F})_2$) and a purple variety of muscovite known as alurgite $\text{K}_2(\text{Mg,Al})_{4.5}(\text{Al,Si})_8 \text{O}_{20} (\text{OH})_4$. Other Adelaide sandstones are quite durable, particularly when protected with a good DPC. In our analysis, the sandstone used in the Elder Hall, shows a relatively low porosity (16%) and the water absorption by capillarity is also relatively low (Figure 4).

3.1.4. Dolomite. Crushed dolomite aggregate ($\text{MgCa}(\text{CO}_3)_2$, magnesium and magnesium calcium carbonate), which in Adelaide may contain Pyrite (FeS_2 , Iron sulfide), was used under pavers during the period 1970-2000. Pyrite reacts with moisture to form sulfuric acid (H_2SO_4), which dissolves the dolomite and produces magnesium sulfate salts. In the case of the Armory building, substantial

magnesium sulfate efflorescences ($\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$, epsomite) were found on the limestone and mortar under the damp proof course indicating the likely use of pyrite-contaminated material.

3.1.5. Calcrete. A calcareous stone containing pellets and nodules as aggregates is another local type of stone that has been used in many buildings of Adelaide and regional South Australia. When this stone is attacked by salts it easily disaggregates, giving rise to large cavities. This decay was found in areas where the tar/sand DPC displayed structural failures, such as in the Moonta Museum, located 2 hours north of Adelaide.

3.1.6. Bricks. Some bricks show very good conservation state in Adelaide buildings. However, when they are fired at low temperature they can be prone to salt attack resulting in flaking and powdering. The damage that may occur due to salt crystallization is strongly influenced by both pore structure and strength properties. Pore structure has a great influence on salt crystallization, including nucleation and precipitation, capillary rise of solutions, evaporation of water and the effects of the wetting and drying cycles [21]. High fired glazed bricks were also used as a DPC in Adelaide.

3.2. Salts

The City of Adelaide is built on marine terraces with a high salt content adjacent to salt flats used for the commercial production of salt [22]. A sample of ground water collected from a well located at the cellars of Torrens Building in Victoria Square was analyzed by ion chromatography. The composition of this water is (ppm): Na^+ 318; K^+ 14; Mg^{2+} 25; Ca^{2+} 20; Cl^- 277; NO_3^- 2; SO_4^{2-} 126. This ground water is classified according to Piper diagram (a widely used trilinear diagram to represent the chemical composition of natural waters) as a sodium-chloride type showing high concentrations of salts, mainly chlorides and sulfates.

3.2.1. Sodium chloride.

This salt was present in almost all the samples from Adelaide, in a pure form (such as a sample taken in a salt pan one hour north of Adelaide) or mixed with other salts, as sodium sulfates and nitrates. It usually was found as a crust over the building materials or mixed with bricks, stone or powdered mortars.

3.2.2. Sodium sulfate. From the cellars of Torrens building (Figure 5a) sodium sulfate was identified by XRD as two different mineral phases, mirabilite ($\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$) and thenardite (Na_2SO_4), respectively (Figure 5b).

3.2.3. Magnesium sulfate. This salt seems to show a slower rate of decay compared with sodium sulfate, however the damage is still harmful. Magnesium sulfate was found in the Adelaide Gaol and in the Armory building. This salt has been found to be associated with the reaction of sulfates from pollution or mortars and building materials with high magnesium content [23-25]. As was explained before, in the case of the Armory building, the source of sulfates and the magnesium appear to come from dolomite aggregate containing iron sulfide as an impurity.

3.2.3. Mixtures of Sodium sulfate, sodium chloride and nitrates. These are the most common salts in Adelaide and are found in high quantities at the cellars of Torrens and Treasury buildings. These results suggest a clear example of rising damp. Table 4 shows the results of salt analyses by XRD and IC of the salt samples collected in these cellars, where they were present mainly as a crust or efflorescences. In some cases the salts were not visible, however the building materials were powdered or disintegrated, and in these cases the salt analyses were carried out by ion chromatography (IC). The detection of nitrates was only possible through the analyses of IC. Sodium sulfate is well known as the most dangerous salt for porous materials due to its unique crystallization behavior [26,27].

Damage to porous building materials was most evident where many different types of salts were found, such as magnesium, sodium and calcium sulfates; sodium chlorides and sodium carbonates and calcium nitrates, as in the case of the Adelaide Gaol (Jail). Laboratory experiments carried out in two types of magnesian limestone cubes impregnated with a salt mixture (magnesium sulfate, calcium sulfate and sodium chloride) [28], have shown that a salt mixture can give rise to deliquescent salts (such as magnesium chloride) of low equilibrium relative humidity (RHeq) and producing earlier damage by flaking of stone by humidity fluctuations compared to a single salt (magnesium sulfate) that tends to form a crust but with little damage observed in the stone. This has also been observed in the field, in some of the Adelaide buildings as the Torrens building, where we found mainly sodium

chloride as a crust over the surface of the cellars but little damage caused to the materials. However, in the case of the Gaol (Jail) and other buildings we found a mixture of salts causing powdering and flaking of bricks, stone and mortars (even with a percentage of total soluble salts, detected by ion chromatography, of about 1% by weight). Furthermore, several sections of the Gaol lack a damp-proof course, contributing significantly to the salt problem. Out of all the buildings visited, sodium carbonate was only found at the Gaol where modern cement has been used to repair portions of the building. Sodium carbonate salts are often associated with alkaline materials. Alkaline salts introduced into the walls by modern repair materials not only adds to the salt load but can also transform some relatively harmless salts into more harmful ones, accelerating the deterioration processes [8]. In the Gaol gypsum plasters were also found on interior walls. According to Arnold (1982), sulfates, chlorides and nitrates of Ca and Mg can be transformed into sulfates, chlorides and nitrates of Na and K and sparingly soluble carbonates of Ca and Mg, which can explain the precipitation of many different types of salts found in the Adelaide Goal. The sources of the salts in the cases studied by Arnold and Zehnder (1988) are attributed to the extensive use of cement-based mortars and concrete in large restoration programs over the past 50 years, as well as salts from air pollution and rising damp [29].

3.3. Types of Damp proof courses (DPC) to stop rising damp

A damp proof course is a physical or chemical layer introduced between the footing and the wall of the building in order to prevent intrusion of moisture into the wall by means of capillary action. Historic DPCs are those that belong to the original construction of the building, whereas modern DPCs are those that are installed as a later intervention due to the lack or failure of an original DPC.

3.3.1. Historic damp proof courses. Several different types of original or historic DPC have been used in Adelaide over the past 160 years to prevent rising damp:

3.3.1.1. Glazed bricks. A very effective damp-proof course used in Adelaide in the late nineteenth century is constructed of glazed hard-burnt ceramic tiles. Perforations provide ventilation, while lack of mortar in vertical joints prevents moisture passage [15].

The glazed bricks were also called engineering bricks in the 1930's. These glazed or very high-fired bricks have a matrix that is almost glass, resulting in almost no open porosity and permeability in order to prevent rising damp.

3.3.1.2. Tar and sand. A very common historic DPC in Adelaide was made using a mixture of tar and sand, and was laid hot. It seems that the effectiveness of this DPC is often reduced with time, after 100 to 150 years. Two samples of this type of DPC have been analyzed, and both show much larger pore size compared to the tar and calcite aggregate DPC, and also a high total open porosity of 32% on St John's Church Hall (c. 1908) (Sample DPC 1, Figure 6a) and of 48% of total open porosity from a DPC of Tynte Street Baptist Church stables (c. 1861-63) (Sample DPC 2, Figure 6b). The difference in open porosities (from 32% at about 100 years old to 48% at about 150 years old) may be explained by changes with time, indicating declining effectiveness as a DPC. The capillary absorption coefficients also increase from $0.49 \text{ Kg/m}^2\text{h}^{0.5}$ in DPC1 to $1.22 \text{ Kg/m}^2\text{h}^{0.5}$ in DPC2, which could suggest a significant increase of permeability with time, since the capillary absorption coefficient is related to the square root of the permeability, $C \propto \sqrt{k}$, taking into account that the rock is comprised of parallel capillary tubes [30]. Other factors, such as different construction practices, may be also responsible for the observed variation between the two samples. Furthermore, under the ESEM, some cracking was found in the tar, among the sand grains contacts, that was not observed in the case of the tar mixed with fine calcite aggregate. This suggests that oxidation of the tar has taken place and that physical changes in the material have greatly reduced its effectiveness. The progressive loss of effectiveness of this common DPC may explain the increase in problems with salt damage in Adelaide over the past few decades.

3.3.1.3. Tar mixed with calcite aggregate. This is another historic DPC but is less common than those of tar and sand. The tar (or asphalt) and calcite DPC in the Brookman Building (1900, University of South Australia) seems to have worked very well as the materials are in very good condition and there are no signs of rising damp above the DPC. The pore size distribution reveals very small pores ($<1\mu\text{m}$)

and the total open porosity is very low (1.8%) (Sample DPC3, Figure 6c). The physical appearance is much more compact than the tar and sand DPC, and in some areas this particular DPC appears to have been partly squeezed out of some joints by the load of the overlying masonry.

3.3.2. Modern damp proof courses. When the original or historic DPC is not working properly or has lost its effectiveness, salts can migrate into the wall and other measures to stop the rising damp may have to be applied. The following have been used as interventions in Adelaide with the goal of reducing the impact of salt damp.

3.3.2.1. Chemical impregnation or Chemical DPC. The most common treatment used in Adelaide to treat salt damp and DPC failures is chemical impregnation of a zone at the base of the wall with siloxane, which leaves a hydrophobic film of silicone resin on the surface of the pores. In some cases this method has had to be re-applied, since the rising damp was not stopped (Figure 7a). Various “rules of thumb” have been adopted by local contractors in Adelaide to ensure a better result from this method, with some preferring low pressure injection over gravity feed and some applying substantially more siloxane fluid than might be necessary to ensure thorough penetration through the wall thickness. A preliminary examination of Adelaide City records shows this method appears to work better in homogenous and more porous materials such as brick and sandstone and less well in materials such as calcrete (a non-homogenous limestone) and bluestone where there are considerable differences in porosities between the stone and the lime mortar.

3.3.2.2. Electro-osmosis system. “The technique known as electro-osmosis has a notorious reputation in South Australia due to its many failures in the 1960s and 70s” [15]. Trotman et al. (2004), also find little hard evidence for the effectiveness of electro-osmosis in the UK [16]. In the case of the Adelaide Gaol, with one of the worst cases of salt damage in Adelaide, the passive electro-osmosis system has been attempted with little success. The passive treatment also failed in two other cases of homeowners where the salt damage was not as significant as the case of the Gaol (Figure 7b). A newer, active version called ‘Lectros’, with titanium cables and platinum-coated electrodes (to overcome corrosion problems), is being trialed and will be monitored by the Adelaide City Council Heritage section.

3.3.2.3. Polyethylene sheeting. Modern plastic DPCs (0.5 mm polyethylene sheeting) appears to have a very good record as a conservation treatment for rising damp in Adelaide. Typically, the lower part of the masonry wall is disassembled and rebuilt in sections with the DPC installed as work progresses. The original bricks may be re-used after immersion desalination and the wall re-plastered. This method is known as "undersetting" and is seen by some as the most permanent way of dealing with salt damp, particularly as it also removes the salt. However, it is the most expensive, most inconvenient and also disrupts the historic fabric (Figure 7c). An alternative method known as slot sawing uses a saw to cut through the wall along a lime mortar joint and install a new DPC. This method has seen limited application in Adelaide due to the common use of irregular (rubble) construction, dense materials that are too hard to saw, and the need for thorough desalination by poulticing above the saw cut line.

With the exception of undersetting, in which all salt-contaminated material is replaced, these treatments to stop rising damp require desalination of the materials previously contaminated with salts as complementary treatments. If a new DPC is installed without removing the salts, damage will continue due to the hygroscopic nature of many salts and salt mixtures.

3.4. Complementary desalination treatments

Desalination procedures are additional treatments that should be linked with treatments to stop moisture ingress.

3.4.1. Substitution of salt-laden building materials. Decaying old mortars are usually raked out to a certain depth and replaced with new pointing mortars. In many cases, salt-laden renders and interior plasters are removed and replaced as part of the treatment for salt damp. The upper limit of the moisture (and salt) is monitored using a capacitance or conductivity meter and the plaster is typically removed some distance (30–40 cm) above this level. Replacement material can be new or recycled masonry units [demolition stone or brick]. In some cases, immersion desalination and re-use of sound masonry is performed. In many of the brick buildings examined, the lime mortar may suffer substantial damage from salts, with little effect on the locally produced bricks. In extreme cases, undersetting is undertaken as a last resort, which involves the sequential disassembly of the salt-affected zone,

followed by replacement with substitute material (or re-use of desalinated bricks) and the installation of a modern polyethylene sheeting damp proof course.

3.4.2. Salts and desalination of building materials. If the building materials, bricks for example, are in good condition they can be immersed in repeated changes of fresh water to extract the salts, until the conductivity levels of the water reaches low levels. This is rarely done, as demolition materials are usually available, though they carry the risk of also being salt-contaminated.

Desalinating salt-contaminated masonry by poulticing is limited to a depth of about 20-30mm at evaporation zones, it can be beneficial in saving high value masonry or brickwork, although is ineffective in powdery mortars, decaying masonry and hard masonry. These shortcomings limit the effectiveness of some modern treatments such as siloxane injection after a DPC failure. Poulticing with modified paper pulp is a common desalination treatment in Adelaide that is often coupled with the chemical impregnation treatment. In the north wall of St. John's Church Hall a sample of the second application of this poultice being applied in April 2006 was analyzed by IC, and contained ~2 wt. % of salts. Analysis of a sample of the jointing mortar was collected deep in the same wall at 4-8 cm depth, showed that the desalination had not reached that depth (Table 5). From these analyses it appears that there are salts still deep in the wall, and additional poulticing or alternative methods may be needed. As these salts are deeply buried in the wall, away from the evaporation zone at the surface of the stone, it may be some years before further desalination is required. Observations in February 2007 showed no evidence of further salt attack, or visible dampness.

Lime plaster has been used as a desalination treatment and as a sacrificial layer for the crystallization of salts, as this example in the Torrens building shows (Figure 8). Samples of the sacrificial plaster were taken with a drill, and the results show that the concentration of total soluble salts decreases with height but slightly increases with depth (Figure 9). Chlorides decrease with height from 35 cm up to 1.20 cm and about the same amount can be found at 0.5 cm and between 2.5-4 cm deep in the wall. Nitrates increase with height and depth from 0.5 cm until 4 cm deep in the wall. Sulfates decrease with height but slightly increase with depth. This behavior is easily explained by the different solubility of

sulfates with respect to chlorides and nitrates. Salts are transported vertically by capillary rising damp and when water evaporates there is a fractionated precipitation of the different salts, according to their solubility [29,31]. Table 6 shows the solubility and the deliquescence relative humidity (RHeq) of the most common salts in Adelaide.

3.5. Decay of building materials

The average percentage of salts found in deteriorated (powdered or flaked) building materials of Adelaide from 22 samples is summarized in Figure 10. Mortars show the highest salt content, followed by bricks, and in stone the amount of salt is much lower. This result likely reflects the state of decay and porosity of the materials. Mortars and bricks, with higher salt content (8% and 6.7%, respectively), have higher open porosity and smaller pore sizes (Figure 3) compared to the stones (with 1.8% salt content). In terms of decay, it can be said that mortar is more prone to deterioration than brick, and both deteriorate more than the stone does (mortar>brick>stone). This is, besides the salt content, due to the susceptibility of materials to salt attack: i) mortars (Figure 3a) have small pores, high porosity (20.1%) and low mechanical strength; ii) bricks (Figure 3d) have medium size pores, high porosity (30.9%) and strength; stones have larger pores, lower porosity (9.3% for bluestone (Figure 3b) and 16% for sandstone (Figure 3c)) and a higher mechanical strength. This shows that materials with high porosity, small pores and low strength are more prone to salt weathering [32].

On the other hand, the percentage of chlorides and nitrates is higher in the disintegrated mortars and bricks (approx. 3.5% of chlorides and 0.8% of nitrates) compared with the disintegrated stones (with percentages of chlorides of 0.5% and nitrates of only 0.1%). The percentage of sulfates in bricks is only 0.2% while in the stone is 0.6% and in the mortar is 1.1%. Mortars and bricks, with higher open porosity and small and medium size pores, are more affected by chlorides and nitrates and less by sulfates, compared with the stones which display lower porosity and larger pores.

Nitrates and chlorides of Ca, Mg and Na form very hygroscopic salt mixtures. The Ca and Mg Chlorides will dissolve at relative humidity above 30%, Ca and Mg nitrates above 55%. If the relative humidity becomes lower than these values, the respective salts will crystallize. In Adelaide the relative

humidity (RH) is often lower than 55%, since the average RH during summer time, October to March is about 35% in the pm hours and about 43% during am hours (Table 1). During wintertime, the months from April to September, the RH is about 56% during pm hours and 67% during am hours [11]. So, while in humid regions such as Switzerland, salts will remain in solution, keeping the stone or mortar humid, with the height of rising damp zone reaching between 1.5 m and 3 m, in a dry region such as Adelaide this zone usually only reaches to between 1 m and 1.5 m, although some severe cases have also occurred reaching heights of above 2 m. However, the greater the evaporation, in conjunction with fluctuations in temperature and relative humidity, the more salt precipitation and more decay of porous materials takes place. The damage observed in Adelaide is best explained by a combination of increasing failures of a common historic DPC, high salt load with regular soil recharge from salt-laden dust storms, salts with high damage potential, and a climate with strong seasonal temperature and humidity fluctuations. Other common causes of salt damp are poor building maintenance such as owners allowing garden irrigation to spray onto masonry walls - such mains water can contain up to 450 ppm total soluble salts.

Conclusions

The City of Adelaide (South Australia) is a natural laboratory for comparing and analyzing different treatments of salt-laden masonry, with hundreds of treated buildings about the same age, in the same environment, and with similar building materials. The city suffers from rapid damage to historic building materials due to salts, rising damp and damp-proof course failures:

1. Some of the historic buildings of Adelaide have deteriorated up to 1.5 m above ground due to rising damp containing sodium sulfate, sodium chloride and nitrates. Salt concentrations are highest in cellars, indicating that these are the most common salts coming from the soil and a clear example of rising damp.

Special attention should be taken when the building materials are affected by salt mixtures. It has been observed that a mixture of salts produces more damage by flaking or powdering of bricks, stone and

mortars (even with a percentage of total soluble salts, detected by ion chromatography, of about 1%) compared to a single salt that tends to form a crust.

2. In terms of decay, it can be said that mortar used in Adelaide is more prone to deterioration than brick, and both deteriorate more than the stone does (mortar>brick>stone). Besides the salt content, materials susceptible to salt damage tend to be porous materials with high porosity; small pores and low strength are more prone to salt weathering.

The experience of the Adelaide City Council Heritage section has found that a combination of methods is often the best strategy to treat decay, with replacement of recent, hard cement mortars with softer lime-based ones most important. The use of weak sacrificial re-pointing mortars (4:1) aggregate: binder is a good solution to preserve the adjacent stones or bricks from salt attack.

3. The best historic damp-proof courses used to stop the rising salt damp in Adelaide appear to be glazed bricks or tar with calcite aggregate as historic preventive treatments, and polyethylene sheeting as a modern damp-proof course treatment. The relatively common tar-sand DPCs in Adelaide appear to be suffering from an increasing rate of failure after 100 years. If the historic building is in danger due to extreme “salt damp” problems that could affect the whole structure and the extraction of these salts by desalination procedures is not effective, so far, the best treatment appears to be the installation of polyethylene sheeting DPC (undersetting) and the replacement or desalination of salt-laden building materials.

Complementary methods are used to extract salts from the materials, such as, sacrificial plasters as a media for crystallization of salts, or desalination with poultices. Although, the salt content can increase with depth inside the wall, and additional poulticing or alternative methods may be needed.

4. Some general conclusions can be made about the long-term performance of chemical damp proof course treatment in Adelaide: the method appears to work better in homogenous and more porous materials such as brick and sandstone, while more failures are experienced in materials such as heterogeneous limestone. Pressure injection of siloxane appears to work better than gravity feed and buildings with more closely spaced injection holes (two per brick), experience fewer failures.

It is important to collect larger case studies such as Adelaide where possible, so that the masonry conservation community can learn what works and what doesn't in a way that helps overcome the difficulties of comparing single case studies of unique buildings with limited treatment documentation. The next step for Adelaide is to have a closer and more statistical look at the failures and successes among the 400 treated historic structures, now that the concept of building epidemiology has begun to provide some intriguing and useful results.

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References

1. Bowley M (1975) Desalination of stone: a case study. Watford, England, Building Research Establishment, Paper CP46/75.
2. Bakolas A, Biscontin G, Moropoulou A, Zendri E (1996) Salt impact on brickwork along the canals of Venice. *Mater. Struct.* 29(1):47-55.
3. Salt Damp Research Committee (1976) Salt damp in South Australia. The first report of the Salt Damp Research Committee.
4. The Economist Magazine (2004) Australia, History in Brief. <http://www.economist.com/countries/Australia/profile.cfm?folder=History%20in%20brief>. Cited 26 Jan 2004.

5. Australian Government, Department of Agriculture, fisheries and forestry. National Action Plan for Salinity and Water Quality. <http://www.daff.gov.au/forestry/plantation-farm-forestry/farm-forestry/napsqwq>. Cited 24 Nov 2006.
6. Spennemann Dirk (2001) The Creeping disaster. Dryland and urban salinity and its impact on heritage. *Cultural Resource Management* 24(8):22-25.
7. Lewin SZ (1982) The mechanism of masonry decay through crystallization. In: *Conservation of Historic Stone Buildings and Monuments*, National Acad. Press, Washington, D.C., pp 120-144.
8. Arnold A (1982) Rising damp and saline minerals. In: Gauri KL, Gwinn JA (Eds) *Proceedings of the 4th International Congress on the Deterioration and Preservation of Stone Objects*, Louisville; The University of Louisville, Kentucky, 7-9 July 1982, pp 11-28.
9. Steiger M (2002) Salts and Crusts. In: Brimblecombe P (ed.) *Air Pollution Reviews, The Effects of Air Pollution on the Built Environment*, vol. 4, London, Imperial College Press.
10. Doehne E (2002) Salt weathering: A selective review, *Geological Society Special Publication*, pp 51-64.
11. Australian Government, Bureau of Meteorology (2008) Climate statistics for Australian locations: Adelaide. http://www.bom.gov.au/climate/averages/tables/cw_023000.shtml#11.
12. Williams P, Young M. (1999) Costing Dust: How much does wind erosion cost the people of South Australia?. *Natural Resource Management Economics* 99_001: Adelaide, Australia, Policy and Economic Research Unit, CSIRO Land and Water.
13. Schmidt H (1999) Historical waterproofing - Traditional and modern methods of moisture protection and wall drainage: Historische bauwerksabdichtungen: Traditionelle und neuzeitliche maßnahmen zum schutz gegen bodenfeuchtigkeit und zur trockenlegung feuchter wände 76:581-598.
14. Smith BM (1986) *Moisture Problems in Historic Masonry Walls: Diagnosis and Treatment*, U.S. Department of the Interior, National Park Service, Preservation Assistance Division, Washington, D.C., p 48.
15. Young D (1995) *Rising Damp and Salt Attack*. South Australia, Department of Environment and Natural Resources and the City of Adelaide, p 21.

16. Trotman P, Sanders C, Harrison H (2004) Understanding Dampness. Watford, England, British Research Establishment, p 224.
17. Spennemann Dirk HR (1999) Mitigation of salt damage to the historic built environment. In: Nico E, Marcar, Afzal Hossain AKM (eds.) Productive Use and rehabilitation of saline land. Managing salt land into the 21st century: dollars and sense from salt. Proceedings 5th National Conference Tamworth, NSW, Australia, Canberra: National Committee for the Productive Use and Rehabilitation of Saline Land, 9-13 March 1998, pp 13-19.
18. Adelaide City Council. Heritage Incentives Scheme. <http://www.adelaidecitycouncil.com/heritage>.
19. Benavente D, Cueto N, Martinez-Martinez J, Garcia del Cura MA, Cañaveras, JC (2007) The influence of petrophysical properties on the salt weathering of porous building rocks. *Environ Geol* 39:105-113.
20. Klemm W, Siedel H (1996) Sources of sulphate salt efflorescences at historical monuments – a geochemical study from Freiberg, Saxony. In: Riederer J (ed.) Proceedings of the 8th International Congress on Deterioration and Conservation of Stone. Berlin, Moller Druck und Verlag, Germany, Sep 30–Oct 4 1996, pp 489-495.
21. Benavente D, Linares-Fernandez L, Cultrone G, Sebastian E (2006.) Influence of microstructure on the resistance to salt crystallisation damage in brick. *Mater Struct* 39(1): 95-101.
22. Selby J (1984) Geology and the Adelaide Environment. Department of Mines and Energy. South Australia. Handbook No.8. D.J. Woolman Government Printer, Adelaide, p.168.
23. Schaffer RJ (1932) The weathering of Natural Building Stones. His Majesty's Stationery Office, London, p.149.
24. Carretero MI, Galán E (1996) Marine spray and urban pollution as the main factors of stone damage in the cathedral of Málaga (Spain). In: Riederer J (ed.) Proceedings of the 8th International Congress on Deterioration and Conservation of Stone. Berlin, Moller Druck und Verlag, Germany, Sep 30–Oct 4 1996, pp 311-324.

25. González Limón T, Álvarez de Buergo Ballester M (2002) Los revocos de cal de las fachadas de la plaza de la Corredera de Cordoba – The lime renderings from plaza de la Corredera, Cordoba. *Mater Construcc* 52(267):19-30.
26. Doehne E, Selwitz C, Carson D (2002) The Damage Mechanism of Sodium Sulfate in Porous Stone. In: *Proceedings of the SALTeXPert Meeting, Prague, ARCCHIP, Nov 27 - Dec 1 2002*, pp 126-146.
27. Flatt R J (2002) Salt damage in porous materials: how high supersaturations are generated. *J Cryst Growth* 242(3-4): 435-454.
28. Lopez-Arce P, Doehne E, Martin W, Pinchin S (2008) Magnesium sulfate salts and historic building materials: Experimental simulation of limestone flaking by relative humidity cycling and crystallization of salts / Sales de sulfato magnésico y materiales de edificios históricos: simulación experimental de laminaciones en calizas mediante ciclos de humedad relativa y cristalización de sales. *Mater Construcc* 58 (ISSN 0465-2746).
29. Arnold A, Zehnder K (1988) Decay of stony materials by salts on humid atmosphere. In: Ciabach J (ed.) *Proceedings of the 6th International Congress on Deterioration and Conservation of Stone*. Torun, Nicolas Copernicus University, Press Dept., Poland, 12–14 Sept 1988, pp 138-148.
30. Zimmerman RW, Bodvarsson GS (1991) A simple approximate solution for adsorption in a Brooks-Corey Medium. *Transport Porous Med* 6:195-205.
31. Arnold A, Kueng A (1985) Crystallization and habits of salt efflorescences on walls. In: Félix G (ed.) *Proceedings of the 5th International Congress on Deterioration and Conservation of Stone*. Lausanne, Presses Polytechniques Romandes, 25-27 Sep 1985, pp. 255-267.
32. Benavente D, García del Cura MA, Fort R, Ordóñez S (2004) Durability estimation of porous building stones from pore structure and strength. *Eng Geol* 74(1-2):113-127.
33. Price C (2000) An Expert Chemical Model for Determining the Environmental Conditions Needed to Prevent Salt Damage in Porous Materials. In: Price C (ed.) *Protection and Conservation of the European Cultural Heritage*. European Commission Project ENV4-CT95-0135 (1996-2000).

34. Weast Robert C, Astle Melvin J, Beyer William H (1985-1986) Handbook of Chemistry and physics, 66th edition, CRC Press, Inc., Boca Raton, FL.

Table 1. Average weather conditions in Adelaide, South Australia

	Summer				Winter			
Average Conditions ^(a)	Average		Record		Average		Record	
	Min	Max	Min	Max	Min	Max	Min	Max
Temperature (°C)	14.5	27.3	5.6	44.6	9.2	18.2	1.5	29.7
Monthly precipitation								
(mm)	26.5				62.7			
Wet days (>0.25 mm)	6.5		n/a		13.8		n/a	
Relative humidity (%)	35 (pm)	43 (am)			56 (pm)	67 (am)		

^(a)Data from [11]: Australian Government, Bureau of Meteorology, 2008

Table 2. Selected historic buildings in Adelaide City for examination and research

Building	Date (AD)	Materials	Type of DPC(a)	Treatments	Type of deteriorations and Remarks
St John's Church, Halifax Street	1887	Sandstone, brick	Tar-sand	c 1970's bituminous paint underground;	Salts above tar sand DPC show visible deliquescence under moist atmospheric conditions, which disappears in dry conditions. Masonry in fair condition. Some rising damp; flaking of bricks, lack of jointing mortar. "Blue stone" under the DPC is very deteriorated. Area of sampling: North wall of the Church Hall
St. Johns Church Halifax Street (The Hall)	1872	Bricks, siltstone (bluestone)	Tar-sand	1999-2003: Lowering ground level below original DPC, installing DP membrane; 2003: re- installation of chemical DPC, paper poulticing; 2005-2006: re-treated for rising damp with poulticed sacrificial mortar joints, then paper poultice of affected wall. .	Lawn sprinklers had caused damage to west wall, Sprinklers adjusted, and wall injected and tar-sand DPC repaired. Fair state of conservation; North wall showing no further signs of decay after re-treatment.
House: 86-88 Halifax St.	1870	Bricks	GEB(b)	n/a(c)	Bricks and mortars below the DPC are slightly deteriorated; Very good state of conservation.
Rob Roy Hotel, 108 Halifax Street	Pre 1860 and 1881	Cement render and limestone	N/a	n/a	Cement render on early part, limestone on later part. Building not studied; only fast visit; Very good state of conservation.
General Havelock Hotel rear stables. 162 Hutt Street	1873	Siltstone	None evident	Chemical injection (siloxane)	Mortar has disappeared between the stone where the rising damp reaches 1m high; Poor state of conservation. Since then, owner has done unauthorized pointing with cement mortar – problem will worsen.
House: 24, Corryton St.	~1910	Cavity bricks	Tar-sand	2005: undersetting outside skin, siloxane injection of inside skin	Powdering of jointing mortar; flaking of bricks; powdering of brick and mortar behind the vent bricks and inside wall cavity; poor state of conservation.
House: 16, Mansfield Street	1910	Cavity bricks	Tar/sand	Electrochemical DPC [c1970's] ; 2005: Undersetting ("Viscourse DPC") outer skin, chemical injection of inside skin.	Efflorescences on outside bricks; Failure of electrochemical DPC; very poor state of conservation.
House: 18 William Buik Court	1882	Bricks, siltstone	Tar/sand	1990: Chemical injection DPC; removing and replace of plasters, renders pointing, bricks and stones, internal and externals; 2005: Lectros system by Ace Waterproofing. [did not proceed]	The plaster mortar inside the house is being detached and the powdered materials behind are expanding. Failure of chemical DPC and failure to desalinate has resulted in poor state of conservation 15 years later.
House: 147 Gover St.	1870	Calcrete limestone, brick	N/a	Currently-Undersetting inside walls- ("Viscourse" DPC)	Calcrete limestone external and brick internal. Salt efflorescences, powdering of bricks and jointing mortars; poor state of conservation.
Rear Stables (Tynte Street Baptist Church) 154 Tynte Street	1870	Calcrete limestone, brick	Tar-sand	n/a	Salt damp to 1 meter height; disappearance of the mortar.
House: 122 Jeffcott Street	1880	Bricks, siltstone, mortar (4:1)	Tar-sand	1998: Gravity feed 1999: Adding extra bitumen/sand DPC	Salt-damp; powdering of the mortar; poor state of conservation due to residual salt activity.

Christ Church former School, 81 Jeffcott St	1868	Calcrete limestone, brick.	Tar-sand	2000: Chemical injection	Powdering of limestone, desegregation of mortars and calcrete; failure to remove salts-should have been under-set; very poor state of conservation: rising damp up to 1.5 m
Aquinas College, Roche House, 21 Palmer Place,	1905	Bricks	Tar/sand [buried]	n/a	Powdering of bricks and mortars from brick pillar; poor state of conservation
Carclaw Youth Arts, 11 Montefiore Hill – boundary wall	1901	Calcrete limestone, bricks	n/a	1990: repointing in lime/cement mortar	Disintegration of limestone, due to repointing in lime/cement. The wall is only deteriorated in the part that faces the street.
Brougham Place Uniting Church	1859	Limestone, siltstone, marble, bricks	unknown	1984: restorations works: sacrificial internal plasters, lime/cement external render.	Salt efflorescences and crusts; powdering of limestone with consequent detachment of plasters and renders; the building is below ground level; very poor state of conservation. Sacrificial plaster is performing well.
Torrens Building, 202 Victoria Square	1877	Sandstone, siltstone and bricks	GEB	Sacrificial renders	Sandstone is above ground, and siltstone and bricks in cellars Salt efflorescences, brick and mortar powdering. The main damage is under the DPC in cellars; fair state of conservation. Sacrificial renders performing well.
Treasury Building, 142 King William St	1857 to 1867	Limestone, bricks	Tar-sand	Salt removal, limewash	Salt crusts and efflorescences; fair state of conservation under the conditions.
Pilgrim Church, 2 Flinders Street	1867	Sandstone, siltstone, limestone	n/a	Tar-sand. Extensive sacrificial render sub-floor spaces in 2001	Only powdering in one bluestone block over a pillar; very good state of conservation.
Ayers House, 300 North Tce	1859	Siltstone, brick	n/a	n/a	Only powdering of mortar where the ventilation brick is located; good state of conservation.
University of SA, Brookman Building	1900	Brick, limestone, siltstone	Asphalt and carbonate aggregate	n/a	In some places moisture is above the DPC because the ground level is above the DPC; very good state of conservation.
Mitchell Building, University of Adelaide	1879	Sandstone, siltstone	GEB	n/a	Above the very effective DPC there is no deterioration. Siltstone and mortar below the DPC are decaying.
Elder Hall, University of Adelaide	1900	Limestone, sandstone	Tar-sand (90 years)	1990: plastic membrane DPC (2 layers)	The porous sandstone has a lot of clays (white: kaolinite, and gray: sericite); very poor state of conservation.
The Armory, rear of Museum	1855	Sandy limestone, brick	Tar-sand	n/a	Salt efflorescences in the mortar under the DPC. For the construction of the pavement, crushed dolomite stone was used; fair state of conservation.
SA Museum [North Wing]-	1890	Brick, siltstone	Tar-sand	n/a	Disaggregating mortar, flaking of bluestone and previous cement render repairs which bridged the DPC; poor state of conservation.
Adelaide Gaol (Jail)	1850's	Brick	n/a	Passive Electro Osmosis (trial of active Lectros System being monitored)	Powdering of mortar, salt efflorescences; failure of the passive DPC treatment; very poor state of conservation.

^(a)DPC: Damp proof course; N/a: Not applicable (missing information); GEB: Glazed engineering bricks

Table 3. Example of the files prepared to compile the data obtained from the visited buildings in Adelaide

Building		Address	Pictures	
St. Johns Church Hall		373-383 Halifax St.	Church north wall	
Construction materials		Bricks, shale (bluestone)		
Original DPC^(a)		Tar-sand over shale		
Treatments		1997-Chemical DPC-siloxane 1999-2003-Lowering ground level below original DPC, installing DP membrane 2003-Re- installation of chemical DPC, paper poulticing 2005-2006-Re-treatments for rising damp		
Conservation state		-Good -Bluestone under the DPC is much deteriorated.		
Deteriorations types -observations-		Rising Damp; No efflorescences, flaking of bricks, lack of jointing mortar	Church hall	
Area of sampling		North wall of the Church Hall		
Samples	#	8	Original-repointing mortars	Poultice DPC
Salt Analyses	XRD	Quartz, calcite	n/a	
	Tot.	0.01-1%	1.9%	0.3%
	IC	Ions	Chlorides, Nitrates, $\pm$ sulfates	
Building		Address	Pictures	
Brougham Place Uniting Church		196-210 Brougham Place (North Adelaide)
Construction materials		Limestone, sandstone, "bluestone", marble, bricks		
Treatments		Sacrificial plasters, varnished walls		
State of Conservation		Poor		
Deteriorations types -observations-		Salt efflorescences and crusts; powdering of mortars with consequent breaking of plasters and renders. The rising damp here is more serious due to the construction well below ground level in a light well.		
Samples	#	11	Salts on walls (inside)	Salts on bricks Powdered mortars (inside and outside)
Salt Analyses	XRD	NaCl, Trona (Na_2CO_3)	NaCl Thenardite (Na_2SO_4)	NaCl Thenardite (Na_2SO_4) Gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$)
	IC	Tot. Ions	N/a	2.2-5%

^(a) DPC: Damp proof course; ^(b) XRD: X-ray diffraction; ^(c) IC: Ion chromatography

Table 4. Analyses of samples by X-ray diffraction and Ion Chromatography from the Cellars of Torrens (A-TB) and Treasury (TRE)

Building	Sample	Ion chromatography					Main salts	X-Ray Diffraction
		Total % Soluble salts	Anions (%)					
			F ⁻	Cl ⁻	NO ₃ ⁻	SO ₄ ²⁻		
ATB-1	Salt Crust on the floor	100	0.4	71.83	0.18	3.13	Sodium Chloride Magnesium Sulfate	Sodium Chloride (NaCl)
ATB-2A	Salt efflorescence (under DPC ^(a))	n/a					Mirabilite (Na ₂ SO ₄ · 10H ₂ O) + Thenardite (Na ₂ SO ₄)	
ATB-2B	Salt efflorescence (under DPC)	n/a					Sodium Chloride (NaCl)	
ATB-3	Powdered brick under DPC	21.36	0	11.68	2.21	0.09	Sodium Chloride Calcium Nitrate	n/a
ATB-4	Powdered mortar (under DPC)	1.74	0	0.47	0.65	0.02	Sodium Chloride Calcium sodium nitrates	n/a
ATB-5	Salt efflorescence (under DPC)	n/a					Sodium Chloride (NaCl)	
ATB-TotD1	Drill (4 cm depth, 35 cm height) in sacrificial plaster	16.80	0	8.72	1.28	0.84	Sodium Chloride Calcium Nitrate Calcium Sulfate	n/a
ATB-TotD2	Drill (4 cm depth, 1.5 m height) in sacrificial plaster	7.16	0	2.16	2.28	0.06	Sodium Chloride Calcium Sulfate	n/a
ATRE-1	Salt crust	n/a					N/a	Sodium Chloride, Calcium Sulfide, Thenardite
ATRE-2	Salt efflorescences	n/a						Sodium Chloride

^(a) DPC: Damp proof course

Table 5. Analyses of samples by Ion chromatography and X-Ray Diffraction in St. Johns Church Hall

Building	Ion chromatography								X-Ray Diffraction
	Sample	Description	Total % Soluble salts	Anions (%)				Main salts	
				F ⁻	Cl ⁻	NO ₃ ⁻	SO ₄ ²⁻		
St. Johns Church Hall 373-383 Halifax St.	ASJ4	Original white lime mortar	0.13	0	0.02	0.01	0.05	Sodium Sulfate	calcite
		0-4cm before poultice							
	ASJ-Tot6	Original white lime mortar	0.93	0	0.37	0.21	0.02	Sodium Chloride	calcite
		4-8cm after 2 poultices						Calcium Nitrate	
	ASJ-DPC	Tar/sand Damp proof course	0.26	0	0.12	0.03	0.01	Sodium Chloride	n/a
								Calcium sulfate	
	ASJ-P	Paper Poultice	1.87	0	0.71	0.54	0.04	Sodium Chloride	n/a
								Calcium Chloride	
								Calcium Nitrate	

Table 6. Solubility and deliquescence humidity (RHeq) of the most common salts in Adelaide

Salt	Solubility in grams per		
	100cc ^(a)		RHeq (%) at 20°C ^(b)
	Cold water	Hot water	
Sodium chloride (halite: NaCl)	35.7 ⁰	39.12 ¹⁰⁰	75
Sodium sulfate (mirabilite: Na ₂ SO ₄ ·10H ₂ O)	11 ⁰	92.7 ³⁰	95
Sodium sulfate (thenardite: Na ₂ SO ₄ ·	4.76 ⁰	42.7 ¹⁰⁰	-
Magnesium chloride (bischofite: MgCl ₂ ·6H ₂ O)	54.25 ²⁰	72.7 ¹⁰⁰	34
Magnesium sulfate (epsomite: MgSO ₄ ·7H ₂ O)	71 ²⁰	91 ⁴⁰	90
Calcium Chloride (antarcticite:CaCl2·6H ₂ O)	74.5 ²⁰	159 ¹⁰⁰	33
Calcium sulfate (gypsum: CaSO ₄ · 2H ₂ O)	0.241	0.222 ¹⁰⁰	99.96
Calcium Nitrate (CaNO ₃)	121.2 ¹⁸	376 ¹⁰⁰	56
^(a) Data from [33]: Weast Robert et al., (1985)		^(b) Data from [34]: Price (2000)	

^(a)Data from [33]: Weast Robert et al., (1985)

^(b)Data from [34]: Price (2000)

Figure Captions

Figure 1. Location of Adelaide City in South Australia showing the map of the city with the buildings treated for rising damp.

Figure 2. Example of historic building with rising damp problems: a) St. Johns Church, built mainly with bricks; b) walls displaying rising damp where it reaches up to 1.5 m high; c) damp proof course (DPC) over slates (“bluestone”) installed during the construction of the church to stop the rising damp; d) sacrificial bedding mortar used to preserve the bricks from salt attack.

Figure 3. Pore size distribution (PSD) as pore radius (r) in μm , and Total open porosity (P) of the main type of building materials in Adelaide City, obtained by mercury intrusion porosimetry (MIP). a) Mortar ($P=20.1\%$); b) Bluestone ($P=9.3\%$); c) sandstone ($P=16.0\%$); d) Brick ($P=30.9\%$).

Figure 4. Water absorption by capillarity curves of damp proof courses (DPC) and building materials from Adelaide City. The slope of the curve during capillary absorption is the capillary absorption coefficient, C . The results are plotted as absorbed water per area of the sample throughout imbibition ($W(t)/s$ [g/m^2] versus the square root of time [$\text{s}^{0.5}$].

Figure 5. a) Collection of sodium sulfate from the Cellars of Torrens Building; note how the materials are damaged below the glazed brick DPC (Damp proof course), but not above it; b) sodium sulfate identified by XRD (X-ray diffraction, patterns obtained by step scanning from 10 to 60 degrees 2θ), as two different mineral phases, with (mirabilite) and without water in the structure (thenardite).

Figure 6. Pore size distribution (PSD) as pore radius (r) in μm , and Total open porosity (P) of the main type of damp proof courses (DPC) in Adelaide City, obtained by mercury intrusion porosimetry (MIP). a) Sample DPC 1 (from St John’s Church Hall, c. 1908), $P= 31.70\%$; b)

Sample DPC 2 (from Tynte Street Baptist Church stables, c. 1861-63), P=48.05%; c) Sample DPC 3 (from University of SA in Adelaide (Brookman building). c. 1886), P=1.84%).

Figure 7. Different types of treatments applied to fix the rising damp: a) chemical injection (siloxane); b) chemical injection and Electro osmosis system; c) polyethylene sheeting or “geomembrane”.

Figure 8. Plaster poultice used as a desalination treatment and as a sacrificial layer in the Torrens Building. The graph displays the results from the ion chromatography analyses of the drilled samples collected at different heights and depths in the wall.

Figure 9. Percentage of the different types of soluble salts with height and depth from the cellars of the Torrens Building (Adelaide).

Figure 10. Average percentage of salts mixed with deteriorated building materials of Adelaide from 22 samples that have become powder or have been disintegrated and analyzed by ion chromatography.

Adelaide City, South Australia

Built on an ancient flat

Established in 1836

Construction booms in
Victorian era (1870-1890)

1500 City historic buildings
2100 State historic buildings

400-500 buildings treated for
salt damp problems by the
Heritage incentive program

Figure 1
Lopez-Arce et al.

Figure 2
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Figure 5
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Figure 6
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Figure 7
Lopez-Arce et al.

Figure 8
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Figure 9
Lopez-Arce et al.

Figure 10
Lopez-Arce et al.