Deterioration of Masonry and Concrete Structures Due to Salt Weathering: State of Art

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Abstract

Salt weathering is a well-known process that contributes to the deterioration of masonry and concrete structures. This article represents a review for the origin of stresses caused by salt weathering, gives a detailed explanation for the different mechanisms that occur during this process and their effect on the structure. First a review of the concept and a definition for the problem will be presented, then a historical review will be represented to show the development of the research carried out to explain the salt crystallization process within the structures, this will be followed by an explanation for the factors affecting the salt weathering process will be represented followed by illustration for the mechanism of salt crystallization. Afterwards, there will be some recommendations for practices and detailing that can be used to improve the resistance of the structure to salt weathering, and finally the conclusions of this report will be represented.

Introduction

The destruction of buildings and structures causes substantial economic damage worldwide. A significant part of the damage is due to the salts contained in the pores of the material due to the hygroscopic properties of salts and solutions as well as to crystallization and hydration of salts. In fact, water plays an important role as transport medium introducing salts into the material and moving them inside the material. Concrete and masonry materials (which are the main points of study in this report) are porous materials which are frequently observed to deteriorate under environmental conditions. Salt crystallization is considered one of the major phenomena that cause deterioration and decay of masonry and concrete, where salt crystallization is categorized as a weathering process.

The weathering process can be defined as explained by Winkler 1975, as “it is the adjustment or readjustment of minerals and rocks to conditions prevailing at the earth’s surface, by conversion of existing minerals to minerals of higher stability towards the atmosphere”. Consequently, the salt weathering is the weathering process where the formation of salt or the conversion of salt to a more stable salt is the main factor in deteriorating the structure.

Salt can be naturally present in the masonry units or in the concrete ingredients or can be entrapped in the pores of the materials when exposed to weather such as acidic rains or even can rise in the capillary pores from the soil containing salts. The presence of water containing salt ions can affect the mechanical behavior of porous materials, as these salts can crystallize during drying process causing increasing expansive forces on the solid material, which can eventually lead to damage and cracking. Figures 1-3 show some examples for Salt weathering.

Figure 1. Weathering of old buildings at Zaitoun area, Cairo, Egypt.

Figure 2. Salt weathering of stone frontage of historic Building at Moez St. Old Cairo, Egypt.

Figure 3 Salt attack for masonry wall at St. Demiana Church, Belqas Dakahlia, Egypt

The crystallization mechanism of salt occurs during drying periods, as the water evaporates from the wall leaving the salt behind to precipitate, consequently the salt solution in the wall will become more concentrated. With increasing amounts of salts are brought into the wall the salt solutions are more concentrated as the moisture evaporates. When the solution becomes saturated or supersaturated, the salt crystals will start to form.

In the case where the rate of evaporation from the wall surface is low, the evaporation process will be mainly near the outer surface leading to the formation of thin long needles of salt crystals on the surface and this process is called efflorescence Figure 4 shows an example for efflorescence.

Figure 4. Efflorescence of walls in residential building, Cairo, Egypt.

On the other hand, when the rate of evaporation is very high and the material (either masonry units or concrete) is permeable enough to allow continuous evaporation, the evaporation process will occur inside the wall and the salt crystals will form inside the wall in the pores of the masonry or concrete and this process is called sub-florescence.

Winkler (1975) mentioned that in sub-florescence process, the salts move towards the surface without reaching the surface and it crystallize beneath a crust of weathered rock substance forming a thin stiff skin with repeating of this process, layers of skin is accumulated leading to deterioration of the stone. This process creates unexpected growth of the crystals of salt within the pores. The growth of salt crystals will exert high forces that lead to disruption of the masonry units or the concrete. Some researchers assumed the existence of a thin liquid film of salt solution between the salt crystal and the pore wall which allows the crystal to grow while pushing against the wall at the same time (e.g. Theoulakis and Moropoulou 1999).

The distribution of salt in the pores of the stone is controlled by several independent kinetic processes which are: supply of water (which can be by rising damp or a leaking roof), evaporation, diffusion of dissolved ions and the nucleation and growth of the salt crystals as mentioned by Rodriguez al.(2000).

The key factor for the salt crystallization in masonry and concrete structures is the moisture penetration inside the concrete and masonry, where the moisture can be formed from three main sources which are mainly:

- The condensation of water vapor present in the air, which can be polluted with some acids or salts which can initiate the crystallization process. And the condensation of water vapour increases as the relative humidity increases and when a surface is colder than the dew point that is the temperature at which vapor condenses (Florea and Luca 2004).

- The absorption of ground water by the capillary action and this phenomenon happens in walls and foundations.
- The rain, where the water can leak through the surfaces or through the roofs into the masonry and concrete.

Scherer (2000) pointed out that the problem is that the crystallization of the salt within the pores of the structure can create a destructive pressure that can deteriorate the concrete or the masonry units. The destructive pressure is attributed either to a crystal growth or a volume increase with the formation of a hydrated crystal from its anhydrous originator. Salt weathering processes do not occur in the structures only, but also played a role in geology to shape the world as it is today.

Historical Review

The salt crystallization process passed through different of stages which were aiming to completely understand the salt crystallization process. The first scientific study about salt crystallization and pressure was done by Lavalle and was published in 1853 (Lourens Rijniers 2004). Correns (1949) studied the growth of salt crystals under linear pressure and he was the first to use a mathematical formula in calculating the super-saturation ratio in a solution. In later years, the theory of crystallization pressure which assumed that stresses can be developed before the whole porous network became filled with salt was accepted by Everett (1961).

Flatt and Scherer (2002) studied the exposure of anhydride sodium sulfate to water and rise in humidity and showed that the crystallization pressure resultant from this process is capable for causing damage to the masonry units.

Recently literature is available about salt crystallization damage, Researches about salt weathering have been written by Scherer (2004), Scherer et al (2007), Cultrone et al (2007) , Aburawi and Swamy (2008) and Lubelli et al (2009), Mohamed elgohary (2015).

Factors affecting salt weathering of structures

There is a wide range of factors that affect the salt weathering process in the structure which is mainly depending on the material itself or on the surrounding environment.

Moisture

Moisture is a major damaging factor in stone decay because it represents the transporting medium for the transport of salts within the structure. Most of the moisture present in masonry walls or concrete structures are derived from the atmosphere, rising ground moisture and rain water, the sources of moisture can be clarified as follows:

Moisture from atmosphere is the moisture existing due to high humidity in air which condenses against relatively cold masonry or concrete walls.

Moisture from rain which has minimum effect as the duration of rain and the fog is too short to permit much moisture to infiltrate.

Ground moisture which comes out of ground water, and this type of moisture contains more ions than the previous ones, this type of moisture gets into the structure by the capillary action.

There are other sources for moistures in walls that include the leaking pipes which are often hidden behind mortar and may remain undetected unless a visible sign is seen for the leakage, also there is the kitchens and bathroom showers that provide steady source of moisture in there was no good detailing in the structure to prevent the travel of moisture into the walls.

Materials

The type of construction material plays a major role in determining the behavior of the structure as the type of the material and its physical and mechanical properties affects the performance of the structure when it is subjected to weathering.

For example, when using porous aggregates in concrete, this will produce a more permeable concrete which will increase the rate of mass transport within the concrete, and that makes the concrete more vulnerable to the salt crystallization attack. Also, the variation of concrete mix ratios can change the pore structure of the concrete, as using inadequate mix ratios can produce more permeable concrete leading to the same consequent results of using porous aggregates.

On the other side, in masonry; the type of masonry units and the type of mortar used can affect the rate of mass transport within the structure. Cultrone et al (2007) examined different materials to study its effect on the durability of masonry under attack by salt crystallization and freezing, where they used two different types of masonry units which were bricks and calcarenites (which were used widely in historical buildings) and they tested four different types of mortar namely; pure lime mortar, lime mortar and air-entraining agent, lime mortar and pozzolan and lime mortar and pozzolan and air –entraining agent.

Their results showed that the brick absorbs more water and reach absorption values twice as high as those for calcarenite units, also they found out that different types of mortar have different absorption values which differs from the absorption values of masonry units as well. This fact can affect the durability of the structure because the water cannot flow at the same speed through the mortar and the masonry units and can cause water to build up in certain areas of the structure which can help the salt crystallization attack.

Weather

The weather or the atmosphere affects the crystallization process as it supports a reservoir of aggressive impurities such as SO_2, SO_3, CO_2, H_2O, Cl_2,etc. And these impurities can settle out on the surface of the structure and react with the stone or concrete in aqueous solution which can initiate the process of salt crystallization and assist in its continuation.

High temperatures also increase the rate of hydration of cement which accelerates the setting of cement and lower the strength of hardened concrete and grout. Moreover, the high temperatures cause a rapid evaporation which results in plastic shrinkage and crazing in the concrete and make the concrete more vulnerable to salt attack, results obtained by Bosunia et al. (2001) supports this concept.

Another effect for the weather is the wetting and drying of the structure, and this is a common case in the coastal areas, where the structures are subjected to cycles of wetting and drying leading to the formation of salt crystals in the drying cycle after the evaporation of the water, which increase in volume with repeating cycles of wetting and drying leading to crystallization damages, Bosunia et al. (2001) conducted a series of tests which had similar results.

Environment

The environment where the structure is being constructed influence the weathering of the structure. The soil for example can contain salts that can be transferred to the structure through the capillary pores with the moisture transfer. Also, if the structure is constructed in coastal areas, it will be more likely prone to salt weathering more than other structure away from the coasts. The atmospheric sulfur dioxide concentrations which are still high in most cities, (and are not likely to undergo a rapid decline in the immediate future). Sulfur dioxide dissolves in dew

or rainwater produces dilute sulfurous acid that can affect the structure.
In general, lack of durability can be caused by external agents arising from the environment. Causes can be categorized as chemical, physical and mechanical. The physical causes arise from the action of alternate wetting and drying and difference between thermal properties of aggregates and cement paste.

Weathering Processes

The weathering processes include different mechanisms that can deteriorate the masonry or concrete structures such as chemical weathering and physical or mechanical weathering.
Chemical Mechanism is the breakdown of exposed minerals by chemical reaction with water, dissolved chemicals and air until they reach equilibrium with surface processes.
Mechanical Mechanism is the physical process of breaking down the material (concrete or masonry) into smaller particles without changing the chemical composition of the material, this mechanical weathering includes:-

- Variation in temperature which causes repeated expansion and contraction.
- Freeze-thaw
- Salt crystallization; which is the main point of this research.

Crystallization Theory

Salts are generally considered as a main cause of deterioration of porous building materials. The crystallization of salts inside the pores of the building materials creates high pressure due to its own surface energy, because a solute in a supersaturated solution has higher potential energy than in a corresponding saturated solution. Thaulow and Sahu (2004) showed that excess potential energy can be used to perform work against an external retaining pressure when the solute crystallizes out of its super-saturation solution.
Some researchers assume that a thin liquid film salt solution exists between the salt crystal and the pore wall which allows the crystal to grow while pushing against the wall at the same time e.g. Shahidzadeh et al 2008, who also showed that the Sodium Sulfate can be found in two different stable phases at the room temperature; an anhydrous phase Na_2SO_4 which is called thenardite and a decahydrated phase $Na_2SO_4.10H_2O$ which is mirabilite, in addition to a third metastable heptahydrated phase. They observed that the hydrated sodium sulfate and anhydrous sodium chloride formed within the square capillary in thick wetting films in the corners, and this observation showed that the salts car remain within the pores and had the ability to cause sub-florescence.
Lubelli and Rooij (2009) showed that the pore system is not only responsible for transport and location of salt crystallization but also has a large influence on the rate of crystallization.

To have a better understanding for the transport of salts within the pores we have to keep in mind that the distribution of salt in the pores of a stone is controlled by several independent kinetic processes: supply of water (which can be by rising damp or a leaky roof), evaporation, diffusion of dissolved ions away from the site of evaporation (toward the source of attacking water), and nucleation and growth of crystals. Scherer (2000) indicated that as water evaporates from a body with a pore size distribution, the larger empty first, while the smaller ones remain full by using their greater capillary suction to drain liquid from their larger neighbors.

Solid Volume Change

Solid volume change is the most popular assumption introduced by many researchers e.g. Novak 1989, Thaulow and Sahu 2004. The main deficiency of this mechanism is that it does not account for the volume of water in the net calculation. The solid volume change hypothesis accounts only for the solid volumes and the hydrous salt has higher volume than the anhydrous salt. But if we consider the volume of water included in the calculations, we will find that the hydrous salt reduces in the total volume.
Chatterji (1997) showed that the crystallization of sodium thiosulfate (which does not have anhydrous form) it cracks the testing tube.

Salt Hydration Pressure

The salt hydration pressure is developed when the salt hydrates causing expansion which creates a pressure on the pore walls. The key factor in inducing the hydration of the salt is the relative humidity. Rodriguez-Navarro et al (2000) showed that at a small increase in humidity above 70%, thenardite dissolves and with a drop in humidity, mirabilite or thenardite re-precipitates.
According to this mechanism, the anhydrous salt absorbs water (moisture) and undergoes solid-state hydration. In this mechanism, the crystal structure of the anhydrous salt is transformed into another different crystal form of the hydrous salt
under certain conditions. An example of this mechanism is thenardite, anhydrous sodium sulfate, which is orthorhombic in crystal structure, where its hydrous analog, mirabilite is monoclinic and this transformation cannot occur only by imbibition of moisture and hydration (Thaulow2004).

Salt crystallization Pressure

The salt crystallization pressure is induced after the salt crystals in pores grow in size and reaches the same size of the pores, and then the pore walls prevent the salt crystals from further growth, and this creates a mutual pressure on both the pore
walls and the salt crystals. And this can happen when the salt concentration in the liquid in pores is higher than the saturation.
The state of saturation condition is the key factor in salt crystallization, where it is impossible to have crystallization in an under-saturated condition, and in case of saturation condition, the salt growing will not cause a crystallization pressure. But in the super-saturation, the growing of salts will exert high pressure which will be destructive pressure if it is in confined space.

Factors affecting crystallization pressure

There are many factors that affect the pressure resulting from the crystallization of salts such as type of salt, relative humidity and the temperature.

Type of Salts

The nature (composition) of salt present in the concrete or masonry is critical to the crystallization pressure, as different types of salts can create different crystallization pressures as explained by Rothert et al. (2007).
Rothert et al. carried out salt loading tests on stone cubes to verify the weathering susceptibility of two different types of lime stone; they used solutions of halite, thenardite and epsomite. The samples were submitted to wetting and drying cycles as follows: loading with 10% salt solution for 4 h followed by a drying cycle for 16
h at 60oC and after the cooling to the room temperature the change in weight was determined.

The results of the test showed that the salt crystallization pressure resulted from sodium sulfate had the most destructive effect because the water-free thenardite was transformed to hydrate phase mirabilite associated with increase in volume by about 300%, which led to the severe deterioration of the samples subjected to sodium
sulfate. While the increase in volume associated with the transformation of magnesium sulfate was 173%.

Humidity

The change in the humidity within the pores structure can have a significant effect on the crystallization process. The soluble salts will take up moisture from the air when the RH of the air exceeds the equilibrium RH of the particular salt (Watt et al.2000) For example, the equilibrium RH of sodium chloride at 20oC is 75%, (and this value increase with the increase in temperature). When the ambient RH drops below this value, sodium chloride salt will exist as solid crystals, but when the ambient RH increase more than this value sodium chloride will absorb the moisture from the air and dissolve. Consequently, the fluctuation in RH above and below 75% can lead to damage cycles of salt crystallization and dissolution.

Temperature

The temperature affects the crystallization process, as the salt (in specified concentration levels) can be stable at certain temperature range and can be transformed to another crystalline phase if the temperature changes.
Temperature also affects the resistance of materials to physic-chemical decay. Daily
and seasonal alteration in air temperature and the corresponding cycles of swelling and contraction may create or increase previous cracks which can trigger or accelerate deterioration, by aiding the penetration of polluting agents and the mechanical action or ice as described by Florea and Luca (2004).

Durability and Improved Construction Practices

In order to ensure adequate performance of masonry and concrete structures built in different environmental conditions and climates, some appropriate practices and improvements can be used to achieve a durable structure and to lower or prevent the occurrence of salt crystallization mechanism in the structure.

Water

When choosing the water for mixing and curing, it should be free from salts or contains minimum content of chlorides and sulphates.

Material Selection

Material selection provides the first opportunity to reduce efflorescence potential, however the ability to eliminate these salts is somewhat limited and less practical than minimizing water penetration. The chemical composition of efflorescing salts is usually alkali and alkaline earth sulfates and carbonates, although chlorides may also be present. The most common salts found in efflorescence are sulfate and carbonate compounds of sodium, potassium, calcium, magnesium and aluminum.
Bosunia and Choudhury (2001) indicated that when chlorides occur as efflorescence, it is usually a result of the use of calcium chloride as a mortar accelerator, contamination of masonry units or mortar sand by salt water, or the improper use of hydrochloric acids in cleaning solutions. The ingredients of concrete also shall be well chosen, as the properties of the ingredients influence the behavior of the concrete and masonry units. For example, the strength and the porosity of the aggregates affect the strength and the durability of the concrete. And it is recommended to use

crushed angular and well graded aggregate in concrete to reduce its porosity and consequently reduce the effect of weathering.

For cement, the principal contributor to efflorescence in mortar and grout is the alkali content of Portland cement. The tendency of cement to effloresce may be predicted with reasonable accuracy from a chemical analysis of the cement. Cements high in alkalis are more prone to produce efflorescence than cements of owner alkali content. So it is recommended to use cements with lower alkalinity in the areas where the structure will be exposed to severe conditions.

Storage of Materials

Bosunia and Choudhury (2001) also showed that method of storing materials at a construction project site may influence future occurrence of efflorescence. Masonry units, cementitious materials, sand and water should be stored off the ground, in such a manner as to avoid contact by rain or snow, or contamination by dirt, plant life, organic materials or ground water, any of which may contribute to efflorescence. These materials should also be covered by a waterproof membrane to keep them dry.

Workmanship

Workmanship is considered an important factor affecting the durability of the masonry and concrete structures, where in masonry workmanship characterized by the complete filling of all mortar joints intended to receive mortar is critical, as is the need to keep all cavities and air spaces clean and free of mortar droppings.

Attention to both of these items is of primary importance in preventing efflorescence. Full mortar joints are more effective at reducing water penetration and clean cavities help masonry dry faster and separate brickwork from backings containing salts. For example, the masonry works that is characterized by partially filled joints and improper flashing of the mortar joints is subjected to increased rain penetration.

Detailing

Detailing also is very important in construction to avoid as much as possible the formation of salt crystallization in masonry. From the good detailing in construction practices is to avoid horizontal masonry copings in wet climates. Specify mortars with proven resistance to efflorescence, tool mortar joints to produce concave or V-joint in climates exposed to high rain or freezing. This will help to reduce the water presence of the mortar. Select caulking and sealant materials compatible with the masonry and other adjoining materials. Provide flashings and weeps in masonry walls at locations where water can accumulate. Provide weep holes and air vents wherever possible. Vents allow for evaporation to occur on the inside of a wall which helps to keep the salts suspended in the wall.

Conclusions

- Salt weathering is a destructive process that leads to extensive damage to various masonry and concrete structures.
- There are three different physical mechanisms for salt weathering which are solid volume change, salt hydration pressure and salt crystallization pressure.

- The crystallization of salts depends on many factors such as super saturation of the salt, size of the pores within the structure and the moisture content.
- Moisture is a major factor in the crystallization process as it represents the transporting medium for the ions and salts.
- Crystallization pressure can only be exerted on the pore walls when disjoining forces create a film of liquid between the crystal and the pore walls.
- The crystallization pressure only exists in case of super saturation of solution.
- The salts tend to accumulate in the transition zones between the cement (or binder) and the aggregate in the matrix.
- The distribution of salts in the pores is controlled by several processes such as evaporation, diffusion of dissolved ions and the growth of salt crystals.
- Sodium sulfate is one of the most destructive salts in nature that can affect the masonry and concrete structures as it undergoes the largest volume change when compared to other salts when it changes from thenardite to mirabilite (nearly 300% increase in volume).
- There are many factors affecting the crystallization pressure, some of them are: Temperature, nature of salt, relative humidity, pore structure and moisture content.
- Using materials with big differences in absorption rates can cause buildup of water within the pores of structure that can affect the durability.
- There are some recommendations for good construction practices to improve the resistance of the structure to the salt crystallization attack.
- Detailing in construction is a major factor in resisting the attack of salt crystallization.

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