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**CLIMATE CHANGE AND ARCHITECTURAL HERITAGE: AN EXPERIMENTAL STUDY ON BRICKWORK MASONRY WALLS AFFECTED BY RISING DAMP**

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## Preface

Climate change is an increasingly serious issue. It impacts the human lives, the natural systems, and also the cultural heritage. Political institutions and international organizations started just over a decade ago to address the issue, and several strategies for the management of the risks coming from the climate change have been implemented.

In order to reach successful results, scientific evidences are in need, which can guide, justify and validate the choices made in practice.

In the field of cultural heritage, the knowledge of the vulnerability of cultural properties toward the climate change is a crucial point. In the last years few studies were conducted dealing with this topic so, much work must be done before an appropriate amount of useful data will be available.

Among the cultural heritage, the architectural heritage, and the structural heritage in turn, especially suffers from the effects of the climate change, because it cannot escape the environmental conditions to which it is daily exposed.

Studying their vulnerability means trying to understand what the effects of the climate change on their constitutive materials is, that is the impacts on their features and performances, from several point of view, including the perceptual and the structural ones.

The extraordinary and precious uniqueness of the architectural heritage around the world, makes arduous this challenge. In fact, not only a large variety of construction materials, but also the way there are worked, their health conditions, the causes of damages to which they are exposed, multiplies the amount of actual cases. All these aspects are influent in the study of the issue, so none of them can be neglected.

For these reasons, it is necessary to work in small steps, that is to select a case study and to focus on it. This is the approach adopted in this PhD research, where the focus is on the impact of the climate change on the brickwork masonry affected by rising damp.

*The research was conducted within the S.T.O.R.M. project (Safeguarding cultural heritage through Technical and Organisational Resources Management), founded by the E.C. community (STORM E.C. project H2020-DRS-11-2015. 700191). Some results were recently published in international journals.*

Domenico Giaccone

# CHAPTER 1

## Climate change and cultural heritage

### 1.1 Climate change: key concepts

According to the Intergovernmental Panel on Climate Change (IPCC) the climate change is defined *“a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer”* (IPCC, 2018). The term consists of two words, “change” and “clime” each referring to a key concept, deserving deepening.

The noun “change” has a neutral meaning in itself. However, the negative sense overcomes when the words change and clime are used together. The definition of climate change provided by the United Nations Framework Convention on Climate Change (UNFCCC) at the Earth Summit of Rio in 1992, clarifies the biased sense given to the noun “change” when used in this context. In the article 1 of the Convention, the following definition is provided: *“Climate change means a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods”* (UNFCCC, 1992). The definition introduces the fundamental difference between change and variation. The latter word is referring to something neutral, physiological, ascribable only to natural actions. Conversely, the former word is referring to those particular variations due to human actions.

The adjective “climate” specifies the object of the change. According to the Encyclopaedia Britannica, clime is defined *“conditions of the atmosphere at a particular location over a long period of time; it is the long-term summation of the atmospheric elements (and their variations) that, over short time periods, constitute weather”* (Encyclopaedia Britannica,

clime). This definition introduces two key concepts: the atmospheric elements, and the duration of the observation time.

The atmospheric elements are markers used to describe the clime. Several kinds of descriptors exist, and they all are linked each to the others: temperature, relative humidity, precipitation (type, frequency, and amount), wind (speed and direction), atmospheric pressure, solar radiation.

As regard the observation time, it must be at least two or three decades. In this sense, climate change differs from weather change, where the observation time usually is a day or a week.

Raw data referring to all the makers used to characterise climate change are achieved by climatologists and then elaborated statistically in order to get off useful information to understand the past and to predict the future.

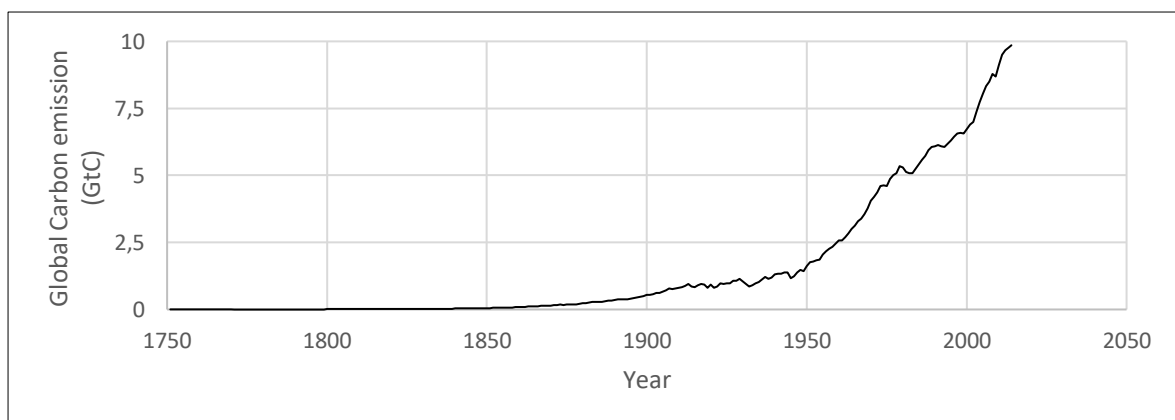
In the first case, the aim is to reconstruct the climate change which characterised the millennial history of the Earth planet, and to understand how they influenced the genesis of the Earth systems: atmosphere, biosphere, cryosphere, hydrosphere and lithosphere. The study is usually conducted through the scientific investigation of specimens taken from the Earth itself, such as the Arctic ice cores (Koerner, 1997; Brook and Buizert, 2018), or the critical analysis and interpretation of those data deduced from the historical sources (Luterbacher et al., 2016).

In the second case, the aim is to understand how the Earth system will change in the next-future, to predict the impacts of this change in the Earth systems, and to elaborate strategies of adaptation and mitigations of the risks coming from this change promptly. In this case, the study is done through mathematical algorithms which model the complexity of the Earth systems (Mudelsee, 2019).

Climate variability, as defined above, occurred several times over the millennia. According to Peixoto and Oort (1992), it is linked to factors both external and internal to the climate system, which is dissipative, non-linear and instable. Astronomic and terrestrial factors are among the former, such as the modulation of the solar radiation and the orbital parameters of the Earth, and the variation of the composition of the atmosphere, due to natural events, such as volcanic eruptions, or to anthropic activities (Baffo et al., 2009). The feedback

derived from the interaction among the Earth spheres, are among the latter. The distinction is also accepted by the committee of the IPCC which gives the following definition: “*climate variability refers to variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the climate on all spatial and temporal scales beyond that of individual weather events. Variability may be due to natural internal processes within the climate system (internal variability), or to variations in natural or anthropogenic external forcing (external variability)*” (IPCC, 2018).

Contrarily to the variability, the climate change is typical of the Modern Age, and is one of the consequences of the Industrial Revolution. Until the Modern Age, the climate variability was ascribable only to natural events, while after the Industrial Revolution, anthropic causes also contributed. Industrialization produced an increase in the consumption of the energy, a more extensive use of the soil, a growing food demand. The causes of these new needs lead also to the increase in the concentration of greenhouse gasses (GHGs) in the atmosphere, both natural, that is derived from the burning of fossil fuels, and synthetic, such as the halogenated hydrocarbons.

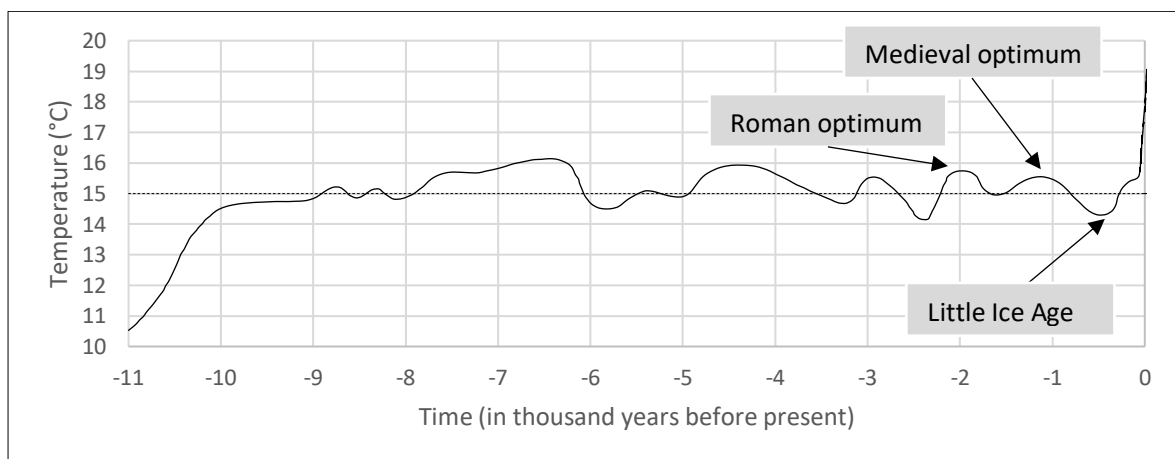


**Figure 1.1.** Total Carbon emission: 1751-2014. 1 GtC = 1 Gigatonne of carbon = 1015 grams of carbon. This corresponds to 3.667 GtCO<sub>2</sub>. (CDIAC, 2014; IPCC, 2013).

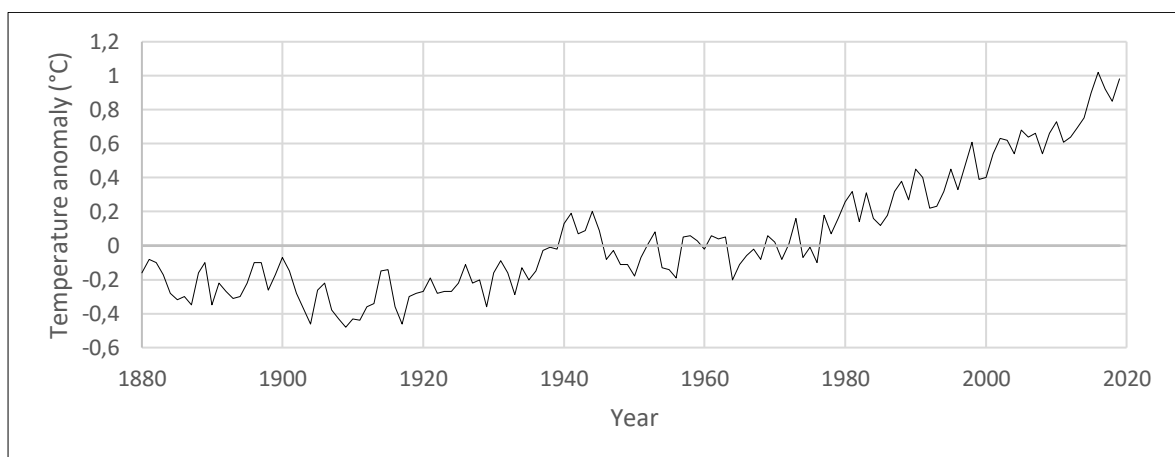
Among the greenhouse gasses, the carbon dioxide (CO<sub>2</sub>) is usually the preferred marker to describe the climate change. Figure 1.1 shows the trend of the global carbon emissions during the last 250 years. Data show that during the last 150 years the concentration of the carbon (C) in the atmosphere increased from 0.09 to 9.85 GtC, corresponding to 0.33 and

36.12 GtCO<sub>2</sub> respectively. This concentration is the highest ever recorded in the last five million years (IPCC, 2013).

Next to the carbon dioxide, many other greenhouse gasses contribute to the ongoing climate change, such as the methane ( $\text{CH}_4$ ), the nitrous oxide ( $\text{N}_2\text{O}$ ), the sulphur hexafluoride ( $\text{SF}_6$ ), the perfluorocarbons (PFC) and the hydrofluorocarbons (HFC), variously used in several sectors of the industrial production (IPCC, 2013). These gasses limit the heat exchange between the Earth and the Universe, blocking the heat dispersion. They are useful to ensure an optimal temperature for life, but if their concentration increases disproportionately, they concur to the global warming which has negative effects.



**Figure 1.2.** Reconstruction of the variation of the mean surface temperature in the northern hemisphere, in the last 10000 years (based on: Schönwiese, 1995).

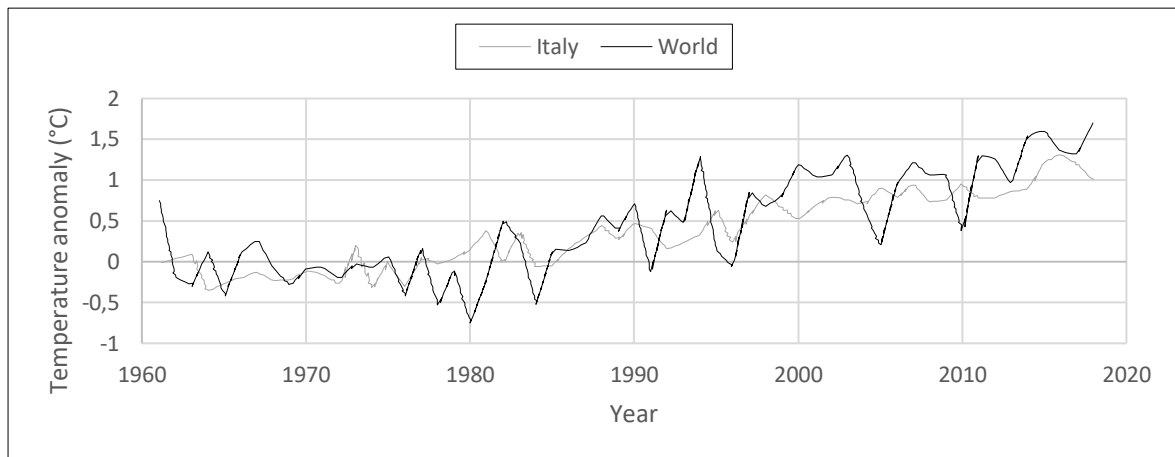


**Figure 1.3.** Global land-ocean temperature anomaly. Base period: 1951-1980 (NASA, 2020).

Figure 1.2 shows the variation of the temperature during the last ten million years (Schönwiese, 1995), while Figure 1.3 shows the temperature anomalies from the end of the eighteenth century (NASA). The former proves that in the past the climate was characterised by long cyclical variations, that is the alternance of cold and hot periods. Looking at the last thousand years, it is possible to see a brief period characterised by temperature values lower than those recorded nowadays; this period is known as the *Little Ice Age*. It is between two hot periods, the most recent of which started around the second half of the eighteenth century and is still now ongoing. According to the data provided by the NASA, from the beginning of the twentieth century the mean value of the whole surface temperature of the Earth (i.e. oceans and land mass) has increased by 1.0 °C.

The trend shows that the anomalies are not occasional, but they occur more and more frequently. This feature concerns not only the temperature but also many other weathering events which are growing in frequency and in intensity, such as tornadoes, cloudburst, lightning. They are usually defined extreme events, “*rare at a particular place and time of year*” (IPCC, 2018). The extreme weathering events, even if dangerous, do not affect the habitability of a place if they are really occasional. However, climate change is turning them into ordinary events so they undermine the habitability of a region and all the natural and anthropic activities related to it.

The climate change phenomenon can be experienced not only at the global but also at the local scale. Figure 1.4 shows a comparison among the trend of the temperature in the World and in Italy. Data updated to 2018, show that the average values of the mean temperature increased by 1.71 °C, in relation to the reference value of the period between 1961 and 1990. Moreover, the number of warm days is also increasing, while cold days and nights are decreasing, as it is possible to read in the report wrote by the Superior Institute for the Protection and Research of the Environment (ISPRA). As regard the rain, average precipitation events were quite increasing, but the distribution during the year was unbalanced and it is not firmly linked to the natural cycle of the seasons (Desiato et al., 2019).



**Figure 1.4.** Comparison between the temperature anomaly recorded in Italy and in the World. Base period: 1961-1990 (Desiato et al., 2019).

As regard the coming decades and the 21<sup>st</sup> century, a detailed summary of the prediction in the climate change is provided by the IPCC. According to most recent report, which collects data referring to 2013, some of the expected changes are (IPCC, 2013; Colette, 2007):

- Increase in the global mean surface temperature. According to the most optimistic and pessimistic predicting models, the increase in the global mean surface temperatures for 2081–2100 relative to 1986–2005 is projected to range between 0.3 °C to 1.7 °C and 2.6 °C to 4.8 °C, respectively. The increase in the warm days and nights and in the heat waves on the most part of the regions of the Earth will be a consequence of the increase in the global mean surface temperature.
- Alteration of the hydrological cycle. The natural cycle of the water consists on different steps and each of them will be influenced by the effects of the climate change. Because of the temperature increase, the cycle will become more and more faster than now. Rain events will become more extreme, intense, and less frequent than now, thus they will be more violent. The temperature increase will cause the evaporation increase in the continental regions which could be not compensated by the precipitations. Moreover, the evaporation increase will cause the increase in the relative humidity. The change in the global water cycle will be not uniform. In some regions, the contrast between wet and dry regions and between wet and dry seasons could increase.

- Decrease in the ice and sea covers and increase in the global mean sea levels. Based on the most positive and negative predicting models, the increase in the global mean sea level for 2081–2100 relative to 1986–2005 is projected to range between 0.26 to 0.55 m and 0.52 to 0.98 m, respectively.
- Extreme tropical cyclones increase. Predictive models are very uncertain regard the future development of these events. However, since the atmosphere will become more instable, from the energy point of view, the phenomena are more likely.
- Alteration of the patterns of the storms which interest the middle latitudes. Storm will move toward the north regions.
- Increase in the cumulative CO<sub>2</sub> emissions. Based on the most optimistic and pessimistic predicting models, the cumulative CO<sub>2</sub> emissions for 2012–2100 is projected to range between 140 to 410 GtC and 1415 to 1910 GtC, respectively.

## **1.2 The impact of the climate change on the natural and anthropic environment**

The scenario briefly described hereinabove summarises the results of several ongoing studies on the climate change. Overall, the phenomenon involves a large amount of aspects and scholars are studying the relationships between them. The scientific community is working to make the phenomenon easier to control, in order to prevent or to face its effects on every sector of the environment which they can involve, being the “environment”, made of all men and everything around them.

According to the IPCC, the effects of the climate change are called impacts, and they can interest the natural and the human systems (IPCC, 2018). In the natural environment, the climate change shows itself through the increase in floods, coastal erosion, storms, water level and salinity of the rivers, melting of the glaciers, tornadoes, alteration of the tides and sea waves, alteration of the deposition of the sediments, desertification. According to the IPCC reports, the effects of the climate change on the natural environment are the easiest to identify. On the contrary, the effects on the anthropic environment are more complex, because they involve physical, productive, sociological and cultural issues. Climate change can impact on the man way of live, work, transport, food. For instance, it can lead to the migration increase and to the abandonment of unhospitable places. Moreover, all the

events firmly linked to the weathering are also impacted, such as rites and routines, which characterise the identities of local societies (Colette, 2007; Petzet and Ziesemer, 2008).

### **1.3 The international debate on the impact of the climate change on the World Heritage**

From a few decades, the scientific community realised that the climate change has a negative impact on the World Heritage. As a consequence, the studies on the effects of climate change have been gradually extended to the World Heritage itself, that is the whole of the *“places on Earth that are of outstanding universal value to humanity and as such, have been inscribed on the World Heritage List to be protected for future generations to appreciate and enjoy”* (UNESCO).

The most recent assessment report published by the IPCC (2014) summarise a lot of data referring mainly to the impact of the climate change on the natural systems but nothing has still now been reported about the cultural heritage. The collaboration between the IPCC and the institutions which promote the conservation of the cultural heritage has been promoted several times, and the issue is expected to be dealt with in the next report still now in progress (UNESCO, 2015).

UNESCO is one of the international institutions involved in the challenge. The interest of the UNESCO on the impact of the climatic change on the cultural heritage is relatively new. In 2005, at the 29<sup>th</sup> session of the World Heritage Committee, it was admitted that the impact of the climatic change on the natural and cultural heritage is a serious issue (UNESCO, 2006a). On this occasion, the Report 22 *“Climate Change and World Heritage”* (Colette, 2007) was published, the first one which deals with the problem clearly. It was published only fifteen year after the first report of the IPCC (1992), and a decisive role in its drafting was done by the Kyoto Protocol (UNFCCC, 1998) and the Rio Convention in 1992. The main purpose of the Report 22 was to know and to manage the impact of the climate change on the World Heritage, and introduced several important considerations about the relationship between the World Heritage and the climate change. The report stated clearly that the latter is a threat for the former, and it layed the basis for the elaboration of management strategies, based on the collaboration among several institutions, acting at international, regional and local levels. The document deals with physical, sociological, and

cultural threats on cultural heritage. As regard the latter, the focus is on the impact of the climate change on the archaeological evidences, historic buildings, timber, other organic building materials, and movable heritage.

The UNESCO collaborates with the three advisory bodies of the World Heritage Convention. The International Council of Monuments and Sites (ICOMOS) and the International Council for the Study of the Preservation and Restoration of Cultural Property (ICCROM) are those interested in non-natural World Heritage sites. During the last 15 years, these institutions have had a positive role in the publication of documents and reports dealing with the theme, the organisation of seminars and workshops, and the preparation of training materials. The divulgation of the theme was also done by referring to case studies (Petzet and Ziesemer, 2008).

The 21<sup>st</sup> ONU conference on the climate change (Paris Climate Agreements) and the Agenda 2030 have given another important contribution to the development of the theme. The States which signed the Agreements, subscribed a plan aimed at reducing the temperature by 1.5 °C at least within the 2030. The Agenda (United Nations) consists on a global plan of action for a sustainable development, which takes into account also the battle against climate change (goal 13) and the *“strengthen efforts to protect and safeguard the world’s cultural and natural heritage”* (goal 11.4).

Nowadays, the awareness on the impact of the climate change on the cultural heritage is growing more and more. The international observatory of monuments and sites funded by the ICOMOS works to monitor the effects and to collect data from all over the world. Moreover, several research projects were pursued such as the NOAHS ARK (Global climate change impact on built heritage and cultural landscapes), the STORM (Safeguarding cultural heritage through Technical and Organisational Resources Management), and the HERACLES (Heritage Resilience Against CLimate Events on Site) projects, co-founded by the European Community. The interaction and multidisciplinary collaboration among several specialist of different scientific fields was promoted in order to find common strategies to monitor and protect cultural heritage and to enforce its resilience. They put together several research areas, such as those relating to the atmospheric chemistry and physics, climate modelling, conservation, materials science, structural engineering, social and economic impact (Petzet and Ziesemer, 2008). Despite those pioneering projects, the

research is still ongoing and several aspects have to be defined from the point of view of both the management strategies and the scientific knowledge.

#### **1.4 The impact of the climatic change on the cultural heritage**

Report 22 published by the UNESCO (Colette, 2007) contains a table which summarises the main climate change risks and impacts on the cultural heritage. The document relates the climate indicators to the climate change risks, and the physical, social and cultural impacts on the cultural heritage. The issue is dealt with by referring to the disaster risk approach, which is currently very accounted in this field of the research (Stove, 1998; Michalski and Petersoli, 2016). For this reason, hereafter it will be referred to it to argue the theme, starting from the definition of risk itself.

The risk is the result of hazard, exposure and vulnerability (Tiepolo, 2017). According to this definition, studying how the climate change impacts on the cultural heritage means understanding what its influence on the above mentioned three aspects is.

##### **1.4.1 Hazard**

According to the IPCC, the hazard is defined *“the potential occurrence of a natural or human-induced physical event or trend or physical impact that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems, and environmental resources. In this report, the term hazard usually refers to climate-related physical events or trends or their physical impacts”* (IPCC, 2018).

According to the classification provided by the UNESCO Committee (UNESCO, 2010) some hazards which can affect the cultural heritage are specifically related to the climate change, that is: the rising of the sea, the melting glaciers, the rain patterns change, the storm increase (from the point of view of the quantity and intensity), the desertification.

This list is not exhaustive, because climate change interest also other kind of hazard that are grouped into other categories: meteorological, geological, hydrogeological, biological.

They already existed before the climate change issue became serious, but it is making them more intense and likely. They are, for instance, the change of environmental temperature, and relative humidity, the change of the direction and speed of the wind, the pollution and the biological infestation.

**Table 1.1.** Classification of the Hazard that may affect cultural heritage (STORM, 2017).

| <b>Natural hazards and threats (including climate change-related events)</b> |         | <b>Anthropogenic hazards and threats</b>                                         |         |
|------------------------------------------------------------------------------|---------|----------------------------------------------------------------------------------|---------|
| Geological Hazards                                                           | (Su/SI) | Industrial/ Technological Hazards                                                | (Su/SI) |
| Hydro-meteorological Hazards<br>(including Climate Change-related events)    | (Su/SI) | Violence and conflict                                                            | (Su/SI) |
| Biological Hazards<br>(including climate change-related events)              | (Su/SI) | Inappropriate uses of heritage<br>(including social, cultural and economic uses) | (SI)    |
|                                                                              |         | Development pressure                                                             | (SI)    |

Su: hazards leading to sudden-onset disasters; SI: hazards leading to slow-onset disasters.

A unique and exhaustive classification, without misunderstanding, is difficult because hazards are usually not isolated but related each to the others. The dynamics and the relationship existing between hazards are explained, for instance, by Adams (2008). In the second chapter of this dissertation they will be shown and argued by referring to the phenomenon of the rising damp, which is specifically the theme developed. Some sources, such as the summary document provided within the STORM project, distinguish between sudden and slow hazards (STORM, 2017). The former are easy to recognise and identify because they occur immediately, while the latter require more attention and patience for their identification, so they are more insidious. The classification provided within the STORM project is summarised in Table 1.1. The table shows the major categories while the detailed list of the hazard is omitted.

#### 1.4.2 Exposure

According to the IPCC, the exposure is *“the presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected”* (IPCC, 2018).

As regard cultural properties, the exposure is linked not only to their physical presence in an adverse environment, but also to their outstanding universal value which is a necessary condition to make them worthy of safeguard.

The outstanding universal value of cultural heritage can be attributable on the basis of several point of view. Some of them are the immaterial value (emotional, historical, artistic-aesthetic), the market value, the material value, the use value, the replacement value (Ebnöther and Thurnherr, 2008). Moreover, the outstanding universal values can be recognised on the basis of some specificities which can be aesthetic, archaeological, architectonical, environmental, historic, scientific, social.

The UNESCO inserts the World Heritages sites which have those values into the List of the World Heritage sites. The criteria required to enter the list are very selective, as stated in the *Operational Guidelines for the Implementation of the World Heritage Convention* (UNESCO, 2019). If the imposed conditions do not survive, the cultural property can be deleted from the list, because the integrity of the property is a mandatory condition. Climate change can influence on it in several ways, such as causing the damage of the constitutive materials, the abandonment of inhospitable places, the disappearance of sites (Colette, 2007).

#### 1.4.3 Vulnerability

According to IPCC, the vulnerability is *“the propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt”* (IPCC, 2018).

Climate change modifies the environmental conditions to which cultural properties are exposed, not temporarily but permanently. Cultural properties were designed and made to

resist to environmental conditions, which were different from the current ones. According to the IPCC, the vulnerability is generally linked to the amplitude and the speediness of the climate change itself, but also to the sensibility of the system and its adaptability. This explanation fits perfectly also to the cultural heritage.

The concept of vulnerability is complementary to this of resilience, which is *“the capacity of social, economic and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function identity and structure while also maintaining the capacity for adaptation, learning and transformation”* (IPCC, 2018)

Several cultural properties and heritage sites have passed the centuries, undergoing wanderings. This condition must not suggest that they will always be immune. In fact, two possible scenarios can occur. On the one hand, some properties may never have been vulnerable to some events but they could become to some other, more serious. On the other hand, climate change can worsen the precarious conditions of the cultural properties.

Moreover, it is important to underline that the material which cultural properties are made of, save the memories of the past damages. The latter are not reversible and their effects are “stored”, “cumulated” and “stratified”. For this reason, even if cultural properties have supported strong events, in their past history, it cannot be excluded that in the future also much less serious events may damage them.

The vulnerability of the cultural properties is linked not only to their state of health, but also to their intrinsic properties, such as the technique and the quality of the materials used to made them. The kind of the materials, manufacturing techniques, climatic contexts, is very wide, so a complete and exhaustive classification of the relationship between the vulnerability of the cultural properties and the impacts of the climate change on them is not easy to do.

In the past, several studies were conducted on the damage of the materials which constituent the cultural heritage. For instance, several studies were conducted on the effects of freeze cycles, pollutions (Sabbioni, 2003; Fassina, 1987; Fassina, 1978; Guidobaldi, 1974), especially due to the acid rains (Camuffo, 1989; Guidobaldi, 1987; Livingston, 1985). These studies were mainly conducted with the purpose to assess the

interaction between the materials and the environment, which was considered the source of several causes of damage (De Angelis d'Ossat, 1982; Fiorani, 2004). However, they did not address the problem from the point of view of the climate change, because the awareness of this issue is relatively new. On the contrary, the most recent researches do it. Some studies refer to the impact of the climate change on the deterioration of the stone, which is one of the most common material in heritage buildings and archaeological sites. The impact of the climate change was studied by referring to the carbonate stone, Carrara marble in particular (Bonazza et al., 2009; Bonazza et al., 2009a) and sandstone (Smith et al., 2011; Smith, Warke and Curran, 2004). Moreover, the impact of the climatic change on the freezing processes on porous stones induced by the temperature variation (Grossi, Brimblecombe and Harris, 2007) and the impact on salts weathering (Benavente, Brimblecombe and Grossi, 2008) were also studied. Some researches relate also to other kind of materials, such as timber structures (Pazlar and Kramar, 2015), clay-containing materials, glass and metals (Sabbioni, Brimblecombe and Cassar, 2010; Sabbioni et al., 2006). The impact on cultural properties stored in museums was also accounted, focusing on the effects of the changes in the indoor atmosphere (Huijbregts et al., 2012; Bratasz et al., 2012).

Starting from this premise, considering that few data exist about these aspects at now, it was decided to focus the PhD research on this theme. The purpose and the field of application will be better defined hereafter.

### **1.5 Aim of the PhD program**

The article 7 of the Paris Agreement, focuses on the importance of promoting the scientific research to study the impacts of the climate change on the vulnerability of people, places and ecosystems (UNFCCC, 2015). The UNESCO adopted and shared this need. It recognises the importance of studying the relationship existing between the vulnerability of the World Heritage and the climate change, in order to predict damages and to manage interventions, promptly (UNESCO, 2007; UNESCO, 2008).

The research conducted within the PhD program, belongs to this framework, which is still now to explore in all its aspects. It was written that the large amount of hazards, materials,

and manufacturing techniques make quite difficult a complete and exhaustive classification of the relationships occurring among the cultural properties and the effects of the climate change on them, because of the great amount of possible combinations. For this reason, the theme must be addressed by limiting the study to a specific case at a time.

This research focuses the attention on the historic buildings and the heritage structures in particular. By referring to them, the purpose of the research is to study the effects that the climate change produces on the damage associated to the rising damp.

Within the World Heritage sites, the historic buildings and the heritage structure are specially high-risk categories. Their conservation is a difficult task because they are not merely objects of collections, housed into glass cases, in a museum, but they are daily exposed to severe weathering conditions and some of them are often used still now, being the seat of museums, schools, banks, institutions, and so on. For this reason, their health conditions must be carefully checked, and the effects produced by new kind of stresses derived from the climate change cannot be ignored.

Rising damp has always been one of the most common causes of damage which have affected the masonry structures and it has also always been one of the most studied. Climate change can influence the mechanism which is at the basis of the phenomenon, making it more serious, thus the structures can result weakened and more vulnerable, and their performances worsened. The impacts of the climate change on the rising damp phenomenon affecting the historic buildings are summarised in a document published by the UNESCO: *“Historic buildings have a greater intimacy with the ground than modern ones. They are more porous and draw water from the ground into their structure and lose it to the environment by surface evaporation (...). Their wall surfaces and floors are the point of exchange for these reactions. Increases in soil moisture might result in greater salt mobilisation and consequent damaging crystallisation on decorated surfaces (...).”* (UNESCO, 2006b). Starting from this assumption, the present research explores the theme. The research is organised as it follows. In the first part, the phenomenon of the rising damp is described focusing on the way the climate change can impact on it. In the second part, the methods and the materials used to study the problem are described. An experiment was conducted to simulate the rising damp phenomenon both outdoor and indoor. In the third part, the results of the measures conducted on the specimens are collected and

analysed from several point of view. This approach is in accordance with the multidisciplinary perspective currently followed in all fields of the scientific research (Masciotta et al., 2016; Gueli and Pezzino, 2015). In this way the complexity of the problem has been accounted. Finally, the results were discussed making a comparison among themselves and with data provided by other scholars, found in literature.

The dissertation is enriched by several attachments which contain details on the results of the tests conducted on the specimens, and on the instruments, designed and constructed for the purpose and used to conduct the measures.

## **CHAPTER 2**

### **Rising damp and climate change**

#### **2.1 Introduction**

Water is one of the most serious causes of damage to masonry architectural heritage; if water penetrates from the ground, the rising damp phenomenon occurs. In the past, it was widely investigated as it is proved by the large amount of scientific works existing on the theme. Several authors dealt with the theme considering all the main aspects linked to it, such as Hall and Hoff (2011), Burkinshaw and Parret, (2003), Salemi (2000), Mundula and Tubi (1997), Oliver (1988), Massari (1985). Overall, scholars dealt with the physical principles which regulate the phenomenon, the causes, the effects, the visible signs of damage, the techniques for the diagnosis, the solution for the rehabilitation of existing building affected by this kind of damage. In this chapter of the dissertation, some fundamental principles of the rising damp will be recalled, which are functional to the discussion of the main topic of the research itself. The focus will be on the effects of the climate change on the rising damp phenomenon itself.

#### **2.2 Physical principle**

Rising damp is a mechanism consisting on the capillary penetration of unwanted water from the ground upward, through any part of the building which is close to the soil, such as the walls and the ground floors.

The Washburn equation (Washburn, 1921) and the Jurin's law (Jurin, 1718; 1719) are still now considered fundamental to describe the phenomenon from a theoretical point of view. The former is used to describe the imbibition into porous materials, characterised by

fine capillaries. The latter describes the spontaneous rise of a liquid in a fine capillary tube. They are written hereafter; 2.1 is the Washburn equation, and 2.2 is the Jurin's law:

$$P_{cap} = \left( \frac{2 \sigma}{r_{cap}} \right) \cos \vartheta \quad (2.1)$$

$$h = \frac{2 \sigma \cos \vartheta}{r_{cap} \rho g} \quad (2.2)$$

where:  $P_{cap}$  is the pressure due to the capillary force;  $\sigma$  is the surface tension;  $\theta$  is the contact angle of the fluid (i.e. water) on the capillary wall;  $r_{cap}$  is the radius of the capillary;  $h$  is the water height;  $\rho$  is the density of the water;  $g$  is the gravitational acceleration.

The relation between the water height and the radius of the capillary will be:

$$h = \frac{15.16 \cdot 10^{-6}}{r_{cap}} \quad (2.3)$$

if in the equation 2.2 the following values are used:  $\theta=0^\circ$ ;  $\sigma=72.8 \cdot 10^{-3} \text{ N/m}^{-1}$  (T 20 °C);  $\rho = 998.2 \text{ kg/m}^3$  (T 20 °C);  $g = 9.81 \text{ m/s}$ . In this way, the water height is relating only to the radius of the capillary, which in turn depends on the porosity of the material.

The porosity is defined as the ratio, expressed as a percentage, between the volume occupied by the voids and the total volume of the material. In general, pores can be closed or interconnected. The latter condition characterises permeable materials and is mandatory to trigger capillary action.

As regard materials commonly used in building constructions, the porosity may have a wide range of values, even when it refers to the same material, since it is linked to the microstructure, the health condition and the way the material itself was worked (Cultrone et al., 2004; Thomson, 2004; Lafhaj et al., 2006). Moreover, as regard the parts of the building made of more than one material, the measure of the porosity is even more difficult. Brickwork is a typical example, because in this case bricks and mortar have their own porosity. As regard fired clay bricks, porosity can be more than 25%, depending on the granulometry of the raw material, the water amount used for their manufacturing, the firing procedure (Mundula and Tubi, 1997). Some scholars assessed that the radius of the pores is smaller in bricks fired at low than at high temperature (Vantangoli, 1988). As

regard mortar, the porosity ranges between 5% and 15% (Pinna, 1987). Typical values of the pore radius range between  $10^{-3}$  and  $10^{-2}$  mm, for both bricks and mortar.

The equations 2.1 and 2.2 quoted hereinabove, are merely theoretical, since they ignore several aspects which occur in actual conditions. The evaporation of the water, due to the interaction between the wall and the environment, reduces the water height in the wall, so the external temperature and relative humidity are influent. Moreover, water into the capillaries of the wall constructive materials is not deionized but rich in soluble salts which modifies some of the involved physical parameters, such as the density of the fluid, the surficial tension, the contact angle. The salts may obstruct the radius of the pores causing their narrowing, so the water rises ever further up the wall. The soil moisture content, the soil and the ground levels, the height of the water table, any obstruction in evaporation, such as dense renders on the wall are other meaningful factors (Oliver, 1988). Some scholars tried to consider their effects in the Jurin's law, and proposed alternative equations (Mason, 1974; Hall and Hoff, 2007; Rirsch et al., 2010).

### **2.3 Main causes**

According to the definition of the rising damp, water which causes it arises from the ground and interests the lowest parts of the building, such as the walls and the ground floor. The masses of water may originate from leakage due to inefficient water and sewerage systems, caused by neglected maintenance, or they can arise from the water table. In the context of this study, the latter condition is more interesting than the former because it may be affected by the climate change.

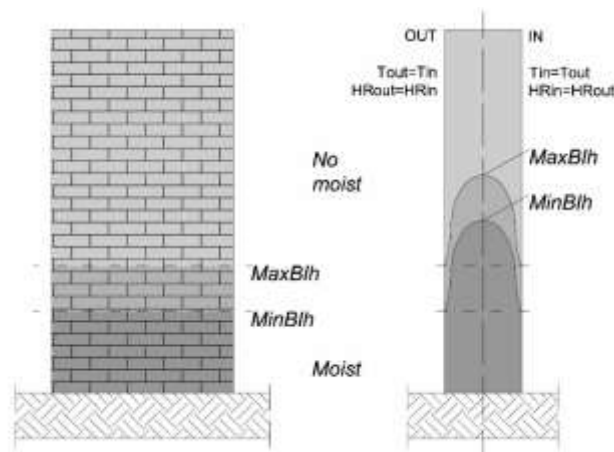
A water table originates when the soil is layered and each layer is characterised by a different permeability. The water table is the surface separating the ground-layer saturated with water from the unsaturated one. Aquifers or precipitations can supply groundwater. In the latter case, water crosses the unsaturated layers of the soil until the saturated one is reached. The higher the table water, the greater the possibility that rising damp occurs.

The causes summarised hereinabove, occur only when remedies to prevent the infiltration of the water were not provided in the construction (Aveta, 1996). In general, the problem is more evident in heritage structures which are in the archaeological sites (Castelluccio

and Vitiello, 2016), because they are more exposed to weathering events and the remedies, if existed, may not be efficient no more.

## 2.4 Visual inspection

Rising damp usually does not affect the whole wall, but only its lowest part. To simulate typical moisture conditions, Smith (1984) proposed conjectural models, validated by data collected by other scholars (Falchi et al., 2018; Hola, 2017; Hola et al., 2017; Sass and Viles, 2006). In general, it is possible to recognize at least three sections in a wall affected by rising damp: the lowest, which is always characterized by a critical water content, the uppermost, where the amount of water is not to be considered pathological, and the intermediate, where the amount of water changes cyclically depending on the environmental conditions. The latter is delimited by a lowest and a highest water marks, two borders-lines (MinBlh and MaxBlh) within which the rising front ranges periodically. These borders-lines identify iso-humidity (IH) surfaces, so called because each point of the masonry belonging to them has the same content of water (Salemi, 2000). Looking at the cross section of the wall, iso-humidity surfaces define, more or less, a Gaussian curve, as shown in Figure 2.1.

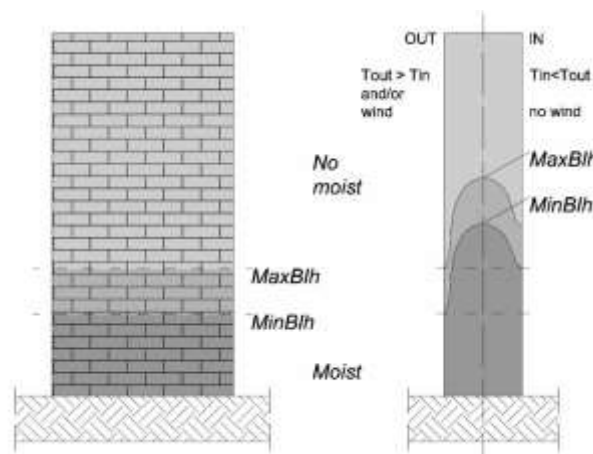


**Figure 2.1.** Typical situation of a masonry wall affected by rising damp, when the two sides are exposed to the same environmental conditions.

Water rising from the ground and investing masonry by capillary action, spreads in a way that is closely linked both to the brick bond pattern and to the thermo-hygrometric conditions to which the two sides of the wall are exposed.

In a wall characterized by a homogeneous material and which sides are exposed to the same environmental conditions,  $MinBlh$  and  $MaxBlh$  on both wall sides are approximately horizontal and have the same height from the ground. A schematic representation of this situation is shown in Figure 2.1.

On the contrary, if the two sides are exposed to different environmental conditions, the  $MinBlh$  and  $MaxBlh$  have different height from the ground; the lower is the dry capacity of the wall, the higher are the  $MinBlh$  and  $MaxBlh$ , as it is shown in Figure 2.2.



**Figure 2.2.** Typical situation of a masonry wall affected by rising damp, when the two sides are exposed to different environmental conditions.

In the Section 2.2 it was written that in the past, several scholars proposed mathematical formulas to relate the height of the rising front to the other physical parameters which characterize the phenomenon. Considering that many parameters have an influence on the height of the rising front, direct survey is the most reliable way to check the damage. Direct survey can be done by means of diagnostic instruments (Mundula and Tubi, 1997; Oliver, 1988) or through a visual inspection. The latter is the simplest and cheapest way; the lowest section of a wall affected by rising damp is easily recognizable thanks to the change of

colour due to the wetting effect. In the intermediate section, colour changes cyclically and efflorescences may be also found, due to salts carried by the water and layered down, before evaporating.

#### 2.4.1 Salts

The efflorescences are “generally whitish, powdery or whisker-like crystals on the surface. Efflorescences are generally poorly cohesive and commonly made of soluble salt crystals” (Vergès-Belmin, 2008).

**Table 2.1.** Some of the most common salts in the soil.

| Salt (1)           | Chemical formula                                     | Aspect                          | Solubility (g) (2)                           | Conductivity (mS/cm) (3) | Occurrence | Damage level |
|--------------------|------------------------------------------------------|---------------------------------|----------------------------------------------|--------------------------|------------|--------------|
| Sodium chloride    | NaCl                                                 | White microcrystal line deposit | 35.9                                         | 16.00                    | Often      | Hight        |
| Sodium sulphate    | Na <sub>2</sub> SO <sub>4</sub> · 10H <sub>2</sub> O | Arborescent and powdery         | 19.5                                         | 11.20                    | Often      | Medium       |
| Potassium sulphate | K <sub>2</sub> SO <sub>4</sub>                       | Diaphanous film                 | 11.1                                         | 11.20                    | Frequent   | Medium       |
| Magnesium sulphate | MgSO <sub>4</sub> · 7H <sub>2</sub> O                | microcrystal line deposit       | 35.1                                         | 7.60                     | Frequent   | Hight        |
| Potassium nitrate  | KNO <sub>3</sub>                                     |                                 | 31.6                                         | 10.70                    |            |              |
| Calcium nitrate    | Ca(NO <sub>3</sub> ) <sub>2</sub>                    | Small saturated strips          | 121.2                                        |                          | Rare       | Hight        |
| Calcium carbonate  | CaCO <sub>3</sub>                                    |                                 | 1.5 10 <sup>-3</sup><br>1.9 10 <sup>-3</sup> |                          | Rare       | Medium       |
| Vanadium salts     |                                                      |                                 |                                              |                          |            |              |
| Ferrous sulphate   | FeSO <sub>4</sub> · 7H <sub>2</sub> O                | Rust spots                      |                                              |                          |            |              |

(1): list based on: Pinna, 1996; (2): solubility in 100 ml of deionized water, at 20 °C; (3): Electrical Conductivity referring to saline solutions 1% by mass (Weast, 1989; Wolf, 1966).

Salts can originate both from the materials which constituent the building elements, and from the soil. They are dissolved into the water and migrate in the form of ions, until the ideal thermo hygrometric condition occur to allow the evaporation of the water and the

settling of the salts themselves, inside or outside the building elements (subflorescence and efflorescence, respectively).

A great variety of salts exists, which are naturally contained in the soils since they derive from its geological evolution. In the most part of the soils, the salts are combinations of calcium, carbonates, chlorides, nitrates, phosphates, potassium, sodium and sulphates (Oliver, 1988). Some of them are listed in Table 2.1, where their main features, aspect, solubility, dangerousness, and occurrence are summarised (based on: Pinna, 1996). Further information about the chlorides, nitrates and sulphates are written hereafter.

- *Chlorides* are the salts containing  $\text{Cl}^-$  ions, which originate from the chloride acid, dissolved into water. Chlorides can be found in freshwater and in seawater, but in the latter case they are surly more frequent and copious. For this reason, chlorides are more common in marine areas. The sodium chloride (*halite*) is the most spread among the salts belonging to this group. It can be transported by sea sprays, through particles characterised by a diameter  $1\text{ }\mu\text{m}$  about in dimension. Sodium chloride has a good solubility and low hygroscopicity, except when it is combined with others salts (Mundula and Tubi, 1997).
- *Nitrates* are the salts of the nitric acid. Nitrates rarely are inside the masonry but they come from the soil and are easily absorbed because of their solubility. They originate from sewage, organic waste, polluted groundwater (Mundula and Tubi, 1997; Pinna 1987). Moreover, they are very common in archaeological sites, cemeteries, churches and rural areas. The potassium nitrate (*saltpetre*) is one of the salts belonging to this group. Its solubility at  $20^\circ\text{C}$  is comparable to that of the sodium chloride, and it has a low hygroscopicity.
- *Sulphates* are the salts of the sulphuric acid. The sulphate ions may be found in natural groundwater, according to the geological nature of the soils where the water flows. They can originate from the dissolution of gypsum stones (calcium sulphate dihydrate:  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ), in this case the concentration is very high. Moreover, they can be in aquifers where clay is also present, or they can derive from the sulphite oxidation (Santonoceto, 2016). Even the rain water may contain sulphates, coming from pollutant substances, such as the sulphur dioxide and trioxide, spread in the atmosphere and transported by rivers and groundwater. The

sodium sulphate is one of the salts belonging to this group. Its solubility is lower than that of the sodium chloride and potassium nitrate, while its hygroscopicity is higher. When the environmental temperature ranges between 0 °C and 35 °C the salt is very instable. Mirabilite ( $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$ ) and Thenadite ( $\text{Na}_2\text{SO}_4$ ) are the two forms of the salt, corresponding to high (more than 60%) and low (less than 60%) values of the relative humidity respectively. Because of its instability, the salt causes damages linked to the internal tensions due to the cyclical variation of the volume.

## **2.5 The effects of the rising damp on masonry walls**

Rising damp triggers physical, chemical, biological processes of alteration and deterioration, very often coexisting (Amoroso, 2002).

The change of the colour and the efflorescences are two among the most common visible signs associated to the rising damp, so they are often used to make a pre-diagnosis of the damage without performing instrumental analyses.

The change of the colour is easy to identify; because of the presence of the water the original colour of the healthy material becomes more saturated. The change of the colour may influence the aesthetic perception of the part of the building affected by the rising damp, especially when its outstanding value is very high. This circumstance occurs frequently when a wall hosts precious decorations such as fresco paintings and stucco works.

The environmental discomfort is also linked to the rising damp and it is easy to experience. This effect is more important for those building elements defining closed spaces still in use, than for archaeological sites. Due to the effect of the rising damp, the humidity values recorded indoors may not be appropriate to human health and lead to hygiene problems. Humidity may, in turn, contribute to the proliferation of dangerous moulds. The problem is serious not only for human health but also for cultural properties housed in museums, which are often historical buildings.

The worsening of the mechanical performances of the historical structures exposed to rising damp, is another effect. It is more difficult to investigate than those listed

hereinabove, but as dangerous as them. From this point of view, several authors around the world have studied the problem, focusing mainly on the changes in terms of maximum strength and stiffness. Stang et al. (1929) carried out an extensive experimental campaign of tests performed on masonry walls made of fired-clay bricks and lime mortar, and proved that water reduces the compressive strength of bricks, mortar and masonry as a whole. Franzoni et al. (2014) carried out some tests on masonry triplets made of fired-clay bricks and cement mortar and proved that water causes a decrease in compressive and shear strength, and a non-relevant change in stiffness. Amde et al. (2004) obtained similar results. They conducted their research on specimens made of bricks and cement-lime mortar, and proved that the ratio between the compressive strength measured in wet and dry specimens is 0.81, while the ratio between the corresponding elastic moduli is 0.88. Graubohm and Brameshuber (2009) studied the problem considering also the effects of freeze-thaw cycles, concluding that mechanical properties of the masonry do not vary significantly.

## **2.6 Rising damp and climate change**

According to the definitions provided in the Section 1.4, within the frame of the climate change issue, the rising damp phenomenon is considered a slow hazard, because its effects are not visible immediately but develop over the time. For this reason, its impacts are underestimated compared to other hazards such as floods (Drdácký, 2010), rain (D'Ayala and Aktas, 2016) and sea-level rise (Anderson et al., 2017), which are also due to the unwelcomed presence of the water.

Climate change impacts on several factors which, in turn, influence the mechanism at the basis of the rising damp phenomenon. In the Chapter 1 it was written that the temperature increase is one of the main effects of the climate change. With reference to the rising damp, it will cause an increase in the frequency and the velocity of the evaporation of the water into the materials. As a consequence, the transport of the salts into the building elements will increase in turn, so the microstructure of the material will worsen more quickly and the effects linked to the movement of the salts will be more serious and evident.

Not only the environmental temperature increase, but also the variation of the direction and speed of the winds will influence the rising damp, because it also contributes to make the evaporation faster than now.

Sudden changes in temperature may also be dangerous. Firstly, because they will cause the variation of the volume of both the water and the microcrystals of the salts dissolved in it; freeze-thaw cycles can become more frequent. Moreover, sudden changes in temperature lead to a fast drying of the wall structure which is not recommended since this condition make them more vulnerable and can led to sudden and unexpected collapses. Finally, sudden changes in temperature influence also the thermal expansion and contraction of the materials. The thermal movement of the material occurs in normal circumstances, because it is due to the daily and seasonal changes in temperature (Brooks, 2014) but climate change can make it more serious. The problem is more evident in metals than in brittle materials, such as masonry, because the thermal coefficient of expansion is higher in the former than in the latter. However, it cannot be ignored even in this case, as it is proved by several studies (Shushakova et al., 2013; Luque et al., 2011; Siegesmund et al., 2000; Simmons and Cooper, 1978). Overall, it must be taken into account that the tensile strength of masonry is very low, so micro stresses which arise from thermal expansion can damage the material, causing microcracks. Not much studies exists on the thermal properties of brittle materials, and available data are very different (Güney and Caner, 2015; Černý et al., 2006; Ross, 1941).

In all the cases taken into account hereinabove, microcracks will occur and they cause the worsening of the material because the surface exposed to the external weathering will grow. This is an optimal condition for further damages, especially due to chemical alteration and biological infestation (Fiorani, 2006).

Next to the change of the temperature, also the variation of the rain pattern will impact on the rising damp. Extreme weathering events, such as strong rains, and the glaciers melting, will increase the amount of water absorbed by the ground and the enlargement of the aquifers from which the water is absorbed by the walls.

Before entering the ground, the water may dissolve salts and pollutants which are in the soil or in the atmosphere. Climate change will affect the salts thermodynamic (Grossi et al.,

2011). The salts will enter the building structures more and more quickly than now because of the acceleration of the dry/wet cycles due the temperature increase. Apart for the speed of the mechanism, also the kind of the salts is relevant. From this point of view, the attention must be paid to the sodium chloride because the floods and the increases of the sea levels promote its spread also in those areas which were far from the coast-lines.

## **CHAPTER 3**

### **Materials and methods**

#### **3.1 Brief notes about the masonry typologies in architectural heritage**

Masonry is one of the most common structures in architectural heritage. Several kind of masonry types exist, because the construction materials and techniques vary according to the local and the historical background. Overall, a masonry structure consists of some units, arranged together with or without mortar, according to a defined pattern.

The units may be natural or artificial lithotypes, such as stone and fired clay bricks. Stones are usually coming from local quarries. According to their origin, they may be volcanic stone, marble, tuff or limestone. They may be variously worked according to the required result. Bricks are made starting from adobe mixture, containing various kinds of minerals such as aluminates, silicates and iron oxides. The clay is fired at 1000 °C about, so the original material became more and more harder and water resistant, as a consequence. Based on the origin of the adobe mixture, and the quality of the firing procedure (Johari et al., 2010; Dondi et al., 1999), bricks can have different features, which can be detected by qualitative tests (i.e. the sound) and by instrumental tests (i.e. the microscopic vision). Microstructure can influence the final properties of the masonry units in terms of maximum strength, water proof, fire-strength and so on (Raimondo et al., 2007; Elert et al., 2003).

The mortar is a plastic mixture containing a binder, aggregate and water, at least. Each of them has a function and must satisfy specific requirements. The binder holds together the units; in the past, the most common mortar binders were clay, gypsum and lime (Kirca, 2004). Among them, the latter has always been the most used. Lime is obtained by a procedure which consists on several steps (Rattazzi, 2007):

- quarrying of limestones (Calcium Carbonate –  $\text{CaCO}_3$ );
- screening and crushing of limestones. Limestones with impurities are rejected;
- burning. Limestones are burnt at 850-1150 °C in a kiln, producing both Carbon Dioxide ( $\text{CO}_2$ ) gas which is expelled, and Calcium Oxide ( $\text{CaO}$ ) which is commonly known as quicklime;
- lime slaking. The quicklime is slaked, that is combined with water, as quickly as possible. Quicklime ( $\text{CaO}$ ) and water ( $\text{H}_2\text{O}$ ) produce Calcium Hydroxide ( $\text{Ca(OH)}_2$ ), that is slaked lime, and heat;
- lime carbonation. Carbon Dioxide ( $\text{CO}_2$ ) is absorbed from the air and the lime hardens as a consequence.

The aggregate is added to the mortar to enhance the strength of the final product, and to reduce shrinkage. From the point of view of its mineralogical composition, the aggregate may consist on siliceous sands or quartz, limestone, volcanic ash, pozzolana, cocchiopesto (i.e. cracked bricks and clay elements). Water must be without salts, and it must be enough to make easy the mixture of the constituents but not too much in order to do not undermine the strength of the mortar itself. The mixture could be completed with natural additives, such as sugar which improved some features.

As regard the construction techniques, architectural heritage proves that masonry was made arranging the units in a large variety of way. In the past, several scholars tried to classify the main kind of masonry, but here it is not possible to summarise the issue briefly. A recent critical literature review is provided by Baila and Donà in Borri et al. (2011). Among the various kind of masonry wall which can be found in the architectural heritage, here the focus is on masonry brickworks. Bricks allowed to build a large amount of structures because they were easy to produce, to transport and to use in construction practices. High-performing walls were built when the so called “Rules of the Art” were respected during the construction, precious suggestions, “immutable abstraction”, a point of comparison to evaluate the quality of masonry and the geometrical schemes, which influence the static and dynamic behaviour of the buildings (Giuffré, 1991). The Rules of the Art were known by the builders and designers of the past, and they were also collected in several building constructions handbooks. Those written by Cavallieri San Bertolo (1836), Curioni (1868), Formenti and Cortelletti (1893-1895), Breymann (1926), Donghi (1906-1925) are

fundamental works. They are, in turn, based on the treaties written in the Renaissance and in the Roman age, such as those by Alberti (1988) and Vitruvius (Vitruvius, 1960).

Some among the Rules of the Art, common to all kind of brickworks, are listed hereinafter: assuring the planarity and regularity of the courses of bricks; maintaining the horizontal continuity and vertical plumbness; avoiding the overlap of vertical joints (units should overlap by a third to a half of their length); avoiding too much high horizontal joints; using over-crossing units which assure the union of the wall masonry units as a whole; assure a good connection between the walls, through toothing or dowels.

**Table 3.1.** Mortar/Bricks volume ratio, in relation to the brickwork pattern.

| <b>Brickwork pattern</b>         | <b>Wythe</b> | <b>Mortar/Bricks volume ratio (*)</b> |
|----------------------------------|--------------|---------------------------------------|
| <i>Stretcher or running bond</i> | single wythe | 0.46                                  |
| <i>Header bond</i>               | double wythe | 0.49                                  |
| <i>English bond</i>              | double wythe | 0.48                                  |
| <i>English cross bond</i>        | double wythe | 0.48                                  |
| <i>Flemish bond</i>              | double wythe | 0.47                                  |
| <i>Diagonal bond</i>             | -            | 0.51                                  |
| <i>Herring-bone bond</i>         | single wythe | 0.47                                  |

(\*) Data are referring to 1 m<sup>2</sup> of masonry, made of 10x20x2 cm in dimensions bricks and 1.5 tick mortar joints.

Basing on the way units are arranged, it is possible to obtain different bonds. The most common ones are collected in the *Attachment 1*, where a brief description and a scheme of the pattern are provided for each of them. According to the bond, the ratio between the volume occupied by the mortar and by the bricks differs, and this aspect can affect the behaviour of the brickwork toward water absorption/release. For the purpose of this study, this information is important, as it will be explained later. For this reason, in Table 3.1 the patterns described in the *Attachment 1* are listed and the corresponding mortar/brick volume ratio is given for each of them. It was determined by considering a one-meter square of masonry, and under the hypotheses that all units have the same dimensions (10 x 20 x 2 cm) and joints are 1.5 cm thick.

### 3.2 Selection of the brickwork type for the purpose of this research

Face to the large variety of construction materials and masonry patterns existing in the field of architectural heritage, it was mandatory to select a masonry type to which refer in this research.

According to bibliographical resources, studies on the effects of the moisture and water on masonry walls have been conducted mainly on simple structures, especially when the effects on the mechanical features have been also investigated. In this way, simple mathematical models could be deduced on the basis of the experimental evidences. Experimental tests have been conducted on large masonry panels, or on small masonry specimens made of few units bonded with mortar. Table 3.2 shows a list of some studies conducted on the effect of the water on the mechanical behaviour of the masonry. A detail of the kind of masonry specimens used to conduct the experiments is also specified.

**Table 3.2.** Specimens used in studies on the effect of water on masonry wall.

| Scholar                   | Specimens                                | Units             | Mortar                 |
|---------------------------|------------------------------------------|-------------------|------------------------|
| Graus et al., 2019        | Triplet                                  | Granite blocks    | Lime mortar            |
| Niu et al., 2018          | Panels<br>(75 x 37 x 24 cm)              | Fired clay bricks | Portland cement mortar |
| Goetzke-Pala et al., 2018 | Prisms<br>(25 x 25 x 29 cm)              | Fired clay bricks | Various                |
| Sathiparan et al., 2018   | Triplet                                  | Fired clay bricks | Portland cement mortar |
| Uranjek et al., 2015      | Triplets and Panels<br>(51 x 52 x 12 cm) | Fired clay bricks | Lime mortar            |
| Gentilini et al., 2015    | Triplet                                  | Fired clay bricks | Portland cement mortar |
| Rirsch et al., 2010       | Panels                                   | Fired clay bricks | Portland cement mortar |
| Amde et al., 2004         | Panels                                   | Cored bricks      | Cement mortar          |
| Stang et al., 1929        | Panels                                   | Various           | Various                |

To conduct the present research, it was chosen to build specimens which reproduce a single wythe wall with a stretching bond pattern. According to bibliographical sources, experimental works aimed to characterize wet masonry are usually conducted on single

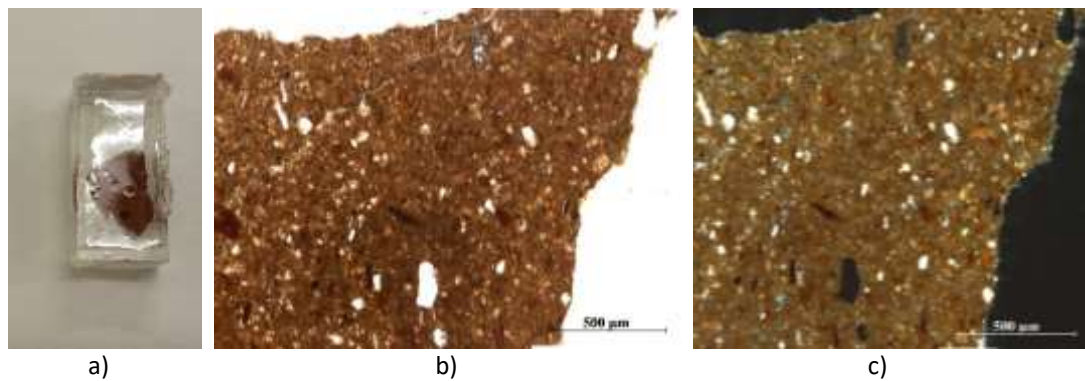
wythe masonry specimens with stacking or running bond patterns (Sathiparan et al., 2018; Forgani et al., 2016). In this study, the second was preferred because it allowed us to take into account vertical mortar joints (head joints). According to Massari (1985), this is a significant feature because water rises with a different velocity in bricks and in mortar joints due to their different responses to water intrusion. Since the research aims also to the mechanical characterization of the specimens, large panels would have preferred. A recent study conducted by Thamboo and Dhanasekar (2019) proves that mechanical measures conducted on small specimens overestimate the real performances of the masonry. Within this research program, it was not possible to made too much big specimens due to technical and management problems. However, since all the data acquired refer to the same kind of specimen, the results will be meaningfully compared anyway.

### **3.3 Making of the masonry specimens**

This study was carried out on small brickwork masonry specimens, made of few units joined by mortar courses (bed joints). They were made in the laboratory, following traditional building techniques and using materials readily available in northern Latium, Italy.

Units used for the construction are fired clay bricks with nominal dimensions of 100 x 210 x 20 mm. They were manufactured in a local kiln following a traditional procedure consisting of several steps: hand-molding of the pieces using wooden molds; natural drying; firing in a wood-fired oven reaching a temperature of about 1000 °C, for 85 hours consecutively; natural cooling for five days.

Figure 3.1 shows the morphology of the brick used, determined through the analysis of a thin section, according to the standard UNI 19022: 2001 and UNI 11084: 2003, while Table 3.3 summarizes some features.



**Figure 3.1.** Tiny section of the fire clay brick used for the construction of the masonry specimens. a) preparation; b) *light microscope – 10x*; c) *polarizing microscope – 10x*.

**Table 3.3.** Morphology of the bricks.

|                                 |                                        |
|---------------------------------|----------------------------------------|
| <b>Grain size of aggregates</b> | 1 $\mu\text{m}$ – 2 $10^2 \mu\text{m}$ |
| <b>Homogeneity</b>              | Yes                                    |
| <b>Shape of aggregates</b>      | Angular and elongated                  |
| <b>Range aggregates/matrix</b>  | 20%                                    |
| <b>Observations</b>             | Presence of microcracks                |

The analysed brick sample is characterized by a fine, homogeneous matrix of a micaceous nature with abundant biotite, quartz and feldspar fragments and medium-fine grain, poorly arranged, which have an angular or sub-rounded shape. Optically inactive *chamotte* inclusions also exist, although they are not visible in Figure 3.1. The matrix is beige-brown with parallel Nicols and red-brown with crossed Nicols and it is optically moderately active. Iron oxides are present. The voids are circular and ovoid, canals and vesicles are visible on the edge of the section, having a section equal to 5 microns. They are presumably due to the drying and firing phases which characterised the production of the brick.

As regard the mortar, a pozzolanic one was used (EN 16572: 2015). It was prepared by mixing three parts of aggregate and one of binder, according to a traditional method already known by the Romans (Adam, 1999) and widely reproduced in the following centuries (Arcolao, 1998). The mixture was prepared in the laboratory where the environmental temperature was 24 °C and the relative humidity 70%. Elements were mixed through a trowel, until an adequate blend and consistency were obtained. The

water/binder ratio by volume was 1/4. The binder was a commercial-available lime-putty, and its physical features are collected in Table 3.4. They were determined according to the EN 459-1: 2015 standard and provided by the manufacturer. The aggregate consisted in pozzolana coming from a local quarry. It was characterized through a sieving test, performed in laboratory in accordance with the EN 933-1: 2012 standard. Test results are shown in Figure 3.2 and in Table 3.5.

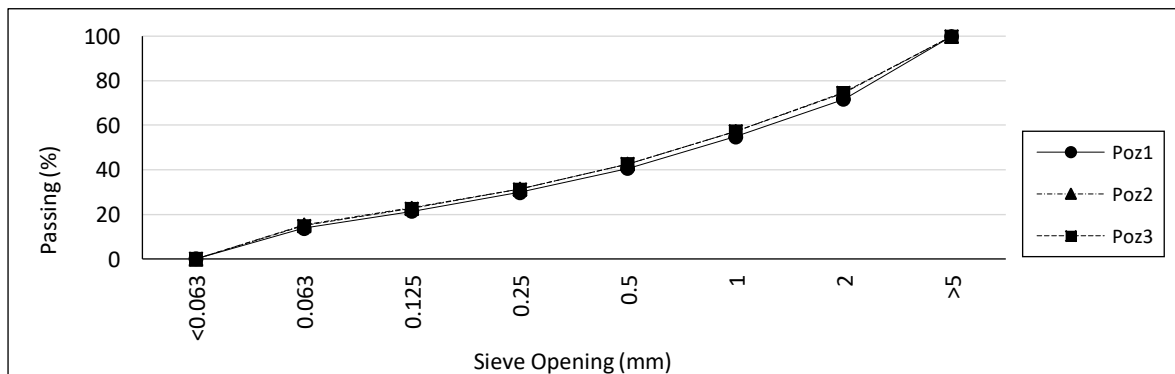
**Table 3.4.** Properties of the lime putty.

|                         |                           |
|-------------------------|---------------------------|
| <b>Apparent density</b> | 1300 kg/m <sup>3</sup>    |
| <b>Type of lime</b>     | CL 90 S-PL                |
| <b>Grain size</b>       | min 98% lower than 0.1 mm |
| <b>CaCO<sub>3</sub></b> | max 4%                    |

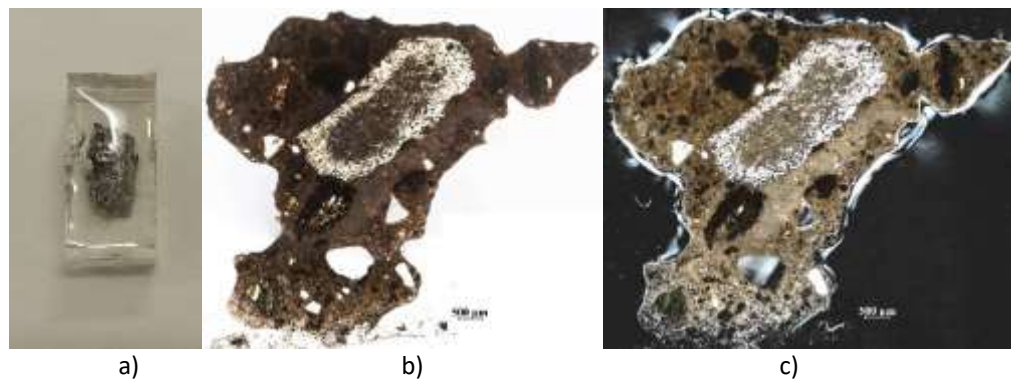
CL 90 S-PL = Calcium lime with CaO + MgO content  $\geq 90$  %, in the form of lime putty, in accordance with 4.4 of EN 459-1:2010.

**Table 3.5.** Cumulative passing fraction of pozzolana after sieving test.

| <b>Sieve size (mm)</b> | <b>Poz1 (%)</b> | <b>Poz2 (%)</b> | <b>Poz3 (%)</b> |
|------------------------|-----------------|-----------------|-----------------|
| <0.063                 | 0.09            | 0.09            | 0.03            |
| 0.063                  | 13.77           | 14.95           | 15.37           |
| 0.125                  | 21.46           | 22.66           | 22.97           |
| 0.25                   | 29.84           | 31.37           | 31.42           |
| 0.5                    | 40.72           | 42.74           | 42.69           |
| 1                      | 54.86           | 57.28           | 57.36           |
| 2                      | 71.65           | 74.71           | 74.41           |
| >2                     | 100             | 100             | 100             |



**Figure 3.2.** Grain-size distribution of the *pozzolana*.



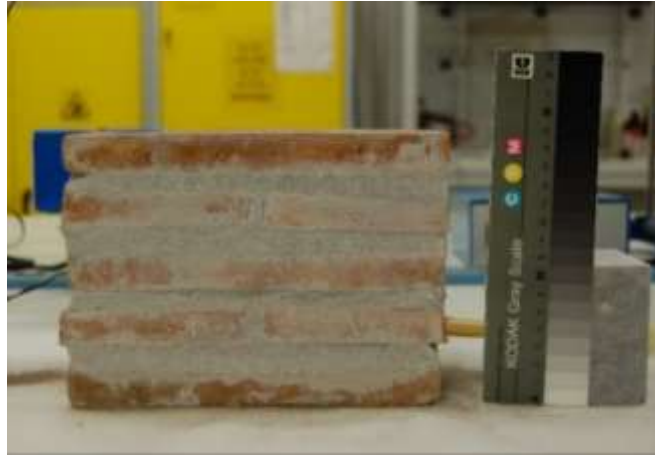
**Figure 3.3.** Tiny section of the mortar used for the construction of the masonry specimens. a) preparation; b) *light microscope – 10x*; c) *polarizing microscope – 10x*.

**Table 3.6.** Morphology of the mortar.

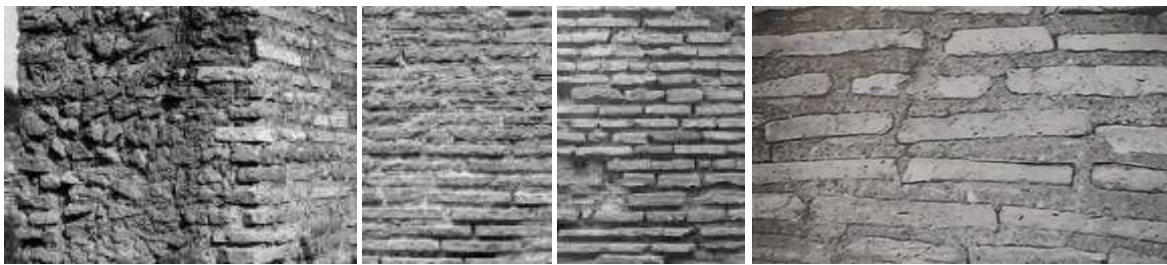
|                                 |                                        |
|---------------------------------|----------------------------------------|
| <b>Grain size of aggregates</b> | 1 $\mu\text{m}$ – 4 $10^3 \mu\text{m}$ |
| <b>Homogeneity</b>              | No                                     |
| <b>Shape of aggregates</b>      | Angular                                |
| <b>Range aggregates/matrix</b>  | 30%                                    |
| <b>Observations</b>             | Presence of CaO                        |

Even the morphological structure of the mortar was analysed through a thin section, as well as for the brick. The specimen is shown in Figure 3.3 and some meaningful results are summarized in Table 3.6. The mortar sample has a fine and homogeneous carbonate matrix, where abundant volcanic glass inclusions of varying size and shape, quartz fragments and well-arranged feldspar are clearly visible. The sample reproduced in Figure 3.3 shows also a large carbonate inclusion. No voids are visible.

Figure 3.4 shows one of the masonry specimens made to conduct the research. Each masonry specimens had a nominal size of 100 x 210 x 155 mm. The ratio between the mortar and the brick volume in each masonry specimen was 0.58. The ratio between the brick and the bed joint thicknesses was 1.4. This value was rather low compared to that suggested by the “Rule of the Art”, according to which the thickness of bed joints should be as small much as possible (see Section 3.1). However, the use of thick bed joints was very common in Latium, especially during Roman times and Middle Ages (Montelli, 2011; Marta, 1989). Some examples are shown in Figure 3.5.



**Figure 3.4.** A brickwork masonry specimen.



a)

b)

c)

d)

**Figure 3.5.** Examples of historic brickwork masonry with thick bed joints: a) archaeological site of Ostia Antica; b) Baths of Caracalla, Rome; c) Flavian Amphitheatre (*Colosseum*), Rome; d) *Santi Nereo e Achilleo* Church (from Marta, 1989), Rome, Italy.

Masonry specimens were built using the following procedure: the bricks were initially cut in half using a hand-held disc cutter with a diamond blade. The bricks were subsequently soaked in deionized water for a duration of about six hours, in order to prevent them from absorbing the water from the mortar joints. Meanwhile, the lime mortar was prepared and specimens were assembled. They were left outdoor for curing, for a duration of four months, sheltered from rain and wind, in thermo-hygrometric conditions which allowed the phenomenon of setting without risk of deterioration (Temperature (T) = 18-20 ° C; Relative Humidity (RH) = 80-95%).

In addition to the masonry specimens, six brick specimens, measuring 20 x 20 x 20 mm, were cut out from one brick, and three mortar specimens, 40 x 40 x 40 mm in dimensions, were made by pouring the same mixture used for the construction of the masonry specimens into polymethylmethacrylate (PMMA) molds. The complete set of the

specimens is shown in Figure 3.6. Moreover, a set of three mortar specimens 40 x 40 x 160 mm was also made, used to perform mechanical tests. The specimens were designated by an alphanumeric code: two letters specified the type of the material (Br=Brick, Mo=Mortar, Ma=Masonry) while a couple of numbers was used to identify the treatment to which specimens underwent and the tested specimen, respectively.

Overall, 9 triplets of masonry specimens, 4 triplets of mortar specimens 40 x 40 x 40 mm, 1 triplet of mortar specimens 40 x 40 x 160 mm and 5 groups of six bricks specimens were prepared.

Four complete sets of masonry, mortar and brick specimens were used to study their properties toward water or salts aqueous solution intrusion, according to the procedure described in the Section 3.4. Then, they also underwent the ageing treatment which will be described in the Section 3.8.

One triplet of masonry specimens, one group of six brick specimens and the triplet of mortar specimens 40 x 40 x 160 mm in dimension were used to conduct the mechanical tests, according to the procedure described in the Section 3.5.

Four triplets of masonry specimens were used to reproduce the rising damp phenomenon in the external field, according to the procedure described in the Section 3.7.



**Figure 3.6.** Different typologies of tested specimens (letter designation: Br=Brick, Mo=Mortar, Ma=Masonry).

**Table 3.7.** Geometric features of the specimens.

| Material | Number of specimens | Dimensions (mm) | Volume (mm <sup>3</sup> ) | Total surface area (mm <sup>2</sup> ) | Base surface area (mm <sup>2</sup> ) | Total surface area / Volume (mm <sup>-1</sup> ) |
|----------|---------------------|-----------------|---------------------------|---------------------------------------|--------------------------------------|-------------------------------------------------|
| Brick    | 6                   | 20 x 20 x 20    | 8.0 10 <sup>3</sup>       | 2.4 10 <sup>3</sup>                   | 4.0 10 <sup>2</sup>                  | 0.30                                            |
| Mortar   | 3                   | 40 x 40 x 40    | 6.4 10 <sup>4</sup>       | 9.6 10 <sup>3</sup>                   | 1.6 10 <sup>3</sup>                  | 0.15                                            |
| Masonry  | 3                   | 100 x 210 x 154 | 3.2 10 <sup>6</sup>       | 1.4 10 <sup>5</sup>                   | 2.1 10 <sup>4</sup>                  | 0.04                                            |

Masonry specimens were photographed and their colour was recorded both in correspondence of the bricks and the mortar, by making a comparison with the palettes which are in the Munsell's Book of colours (Glenn et al., 1940; Newhall et al., 1943), according to the approach suggested by Lazzarini (2004). The results are shown in Table 3.8 and in Figure 3.7. According to the Munsell reference, the color of any material can be defined using three components that are Hue, Value (degree of lightness/darkness) and Chroma (color purity). By referring the masonry specimens used in this research, the color of the bricks is dull orange, while this of mortar joints is greenish-white, belonging to the neutral color palettes.

**Table 3.8.** Color of bricks and mortar.

| Condition  |        | Hue   | Value | Chroma | Reflectivity (%) |
|------------|--------|-------|-------|--------|------------------|
| Un-Treated | Brick  | 5YR   | 6     | 4      | -                |
|            | Brick  | 7.5YR | 6     | 4      | -                |
|            | Mortar | 7.75N | 7     | 0      | 54.8             |
|            | Mortar | 7.5N  | 7     | 0      | 50.7             |

**Figure 3.7.** Colour of bricks and mortar joints.

### 3.4 Measure of the hygroscopic properties of the specimens

A complete set of specimens was used to conduct measurements aimed to study their attitude toward water intrusion and expulsion. The tests for the determination of the water absorption by capillarity, the water absorption at atmospheric pressure, and the drying properties were performed according to the standards EN 15801: 2010, EN 13755: 2008 and EN 16322: 2013 respectively. The requirements of the EN 13755: 2008 standard were partially changed and adapted to the specific test program: deionized water was used instead of tap water, in order to avoid the introduction of external salts into the tested materials. For the brick and masonry specimens, the ratio between the surface area and the apparent volume was 0.30 and 0.04 mm<sup>-1</sup>, respectively. Geometrical features of the specimens are summarized in Table 3.7.

According to the standard, data derived from these tests were used to calculate the water absorption coefficient by capillary action (AC), the water absorption coefficient at atmospheric pressure (Ab), the drying index (ID).

Moreover, data were also used to calculate the flow velocity of the water ( $v$ ), 24 hours after the start of the tests, and the sorptivity, a material property which characterizes the tendency of a porous material to absorb and transmit water by capillarity (Hall and Hoff, 2012). The flow velocity of the water was determined by using the inverted formula of the mass flow rate:

$$v = \frac{\dot{m}}{\rho A} [\text{m/s}] \quad (3.1)$$

where:  $\dot{m}$  is the mass flow rate (kg/s),  $\rho$  is the density of water (0.997 g/ml at 24 °C),  $A$  is the absorbent/dispersive surface (m<sup>2</sup>), consisting in the base surface area (for absorption by capillarity) or in the total surface area (for absorption at atmospheric pressure).

The sorptivity ( $S$ ) was determined by using the following equation:

$$S = \frac{\Delta W}{A \rho t^{0.5}} [\text{m/s}^{0.5}] \quad (3.2)$$

where:  $t$  is the elapsed time;  $\Delta w$  is the change in weight;  $A$  is the surface area of the specimen through which water penetrated;  $\rho$  is the density of water (0.997 g/ml at 24 °C). Sorption was determined 30 minutes and 24 hours after the start of the test.

Some scholars proved that salts which may be dissolved into the water, modify the sorptivity property of the specimens. A linear relationship exists between the sorptivity, defined hereinabove, and the ratio between the surface tension and the viscosity of the liquid entering the material (Marzal and Sherer, 2008). This means that the influence of the salts on the capillary action depends only on the effect that the salts themselves have on the physical properties of the penetrating solution.

Within this research program, specimens underwent an ageing treatment which includes the exposure to several salts aqueous solutions, as it will be better described in Sections 3.7 and 3.8. For this reason, the absorption by capillary action and the sorptivity were measured not only using deionized water, but also several salts aqueous solutions, used in the experiment:

- 14% NaCl solution by mass;
- 14% Na<sub>2</sub>SO<sub>4</sub> solution by mass;
- 14% KNO<sub>3</sub> solution by mass.

The concentration of the salts aqueous solutions was selected on the basis of the indications provided in the standard EN 12370: 2001.

#### *3.4.1 Properties of the specimens toward deionized water*

The attitude of brick, mortar and masonry specimens toward water intrusion and release was studied according to standard tests. AC, Ab, and ID were determined, and the flow velocity ( $v$ ) of water absorbed or released was also calculated, using eq. (1.3).

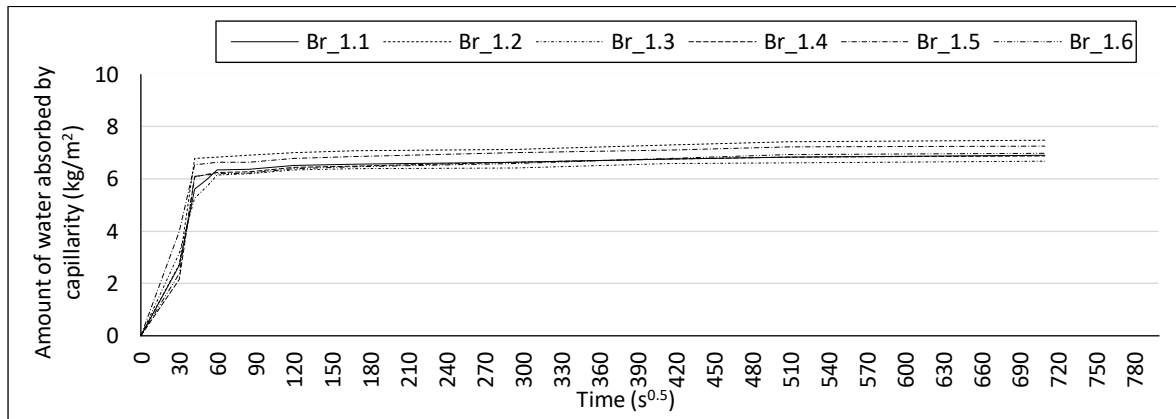
As regard the absorption by capillary action, test results are summarized in Table 3.9, while Figures 3.8-3.10 show the amount of water soaked by the three different types of specimens as a function of the square root of the time.

Bricks and mortar absorbed a high amount of the water in the first hour of the test, while the absorption rate was almost constant for masonry specimens. It can be noted that the flow velocity was higher in the masonry than in the brick and mortar specimens.

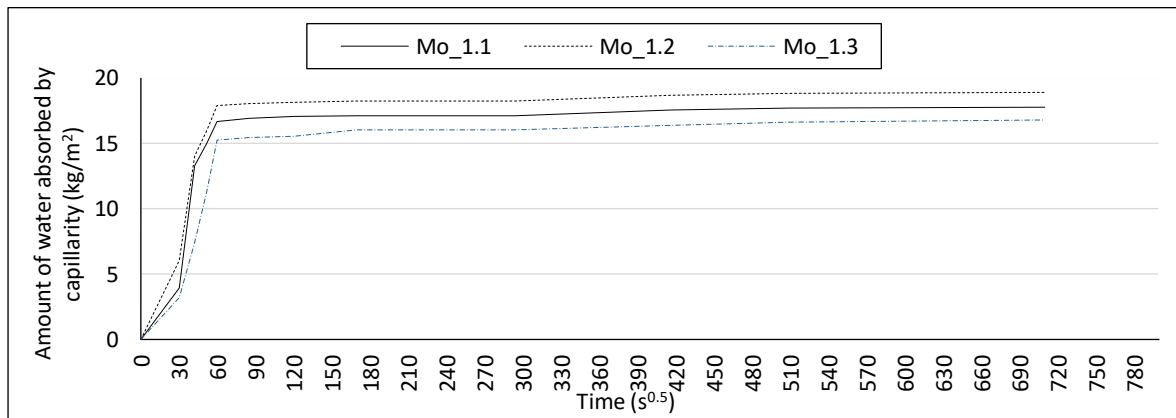
**Table 3.9.** Water absorption by capillary action (mean test conditions: T = 24 °C, RH = 53%).

|         | AsA<br>(mm <sup>2</sup> ) | W <sub>bAT</sub><br>(g) | W <sub>Dry</sub><br>(g) | W <sub>cap24h</sub><br>(g) | M <sub>cap24h</sub><br>(%) | W <sub>cap7d</sub><br>(g) | M <sub>cap7d</sub><br>(%) | $\nu$<br>(m/s)        | AC<br>(kg/m <sup>2</sup> s <sup>0.5</sup> ) |
|---------|---------------------------|-------------------------|-------------------------|----------------------------|----------------------------|---------------------------|---------------------------|-----------------------|---------------------------------------------|
| Brick   | 4 10 <sup>2</sup>         | 14.14                   | 13.93                   | 16.63                      | 19.32                      | 16.76                     | 20.31                     | 1.17 10 <sup>-6</sup> | 0.05                                        |
| (Sdev)  |                           | (0.11)                  | (0.10)                  | (0.09)                     |                            | (0.10)                    |                           |                       |                                             |
| Mortar  | 1.6 10 <sup>3</sup>       | 78.86                   | 78.06                   | 105.4                      | 35.06                      | 106.6                     | 36.63                     | 1.48 10 <sup>-6</sup> | 0.21                                        |
| (Sdev)  |                           | (0.82)                  | (0.91)                  | (0.95)                     |                            | (0.85)                    |                           |                       |                                             |
| Masonry | 2.1 10 <sup>4</sup>       | 5012                    | 4957                    | 5294                       | 6.81                       | 5834                      | 17.70                     | 3.46 10 <sup>-6</sup> | 0.07                                        |
| (Sdev)  |                           | (39)                    | (37)                    | (35)                       |                            | (68)                      |                           |                       |                                             |

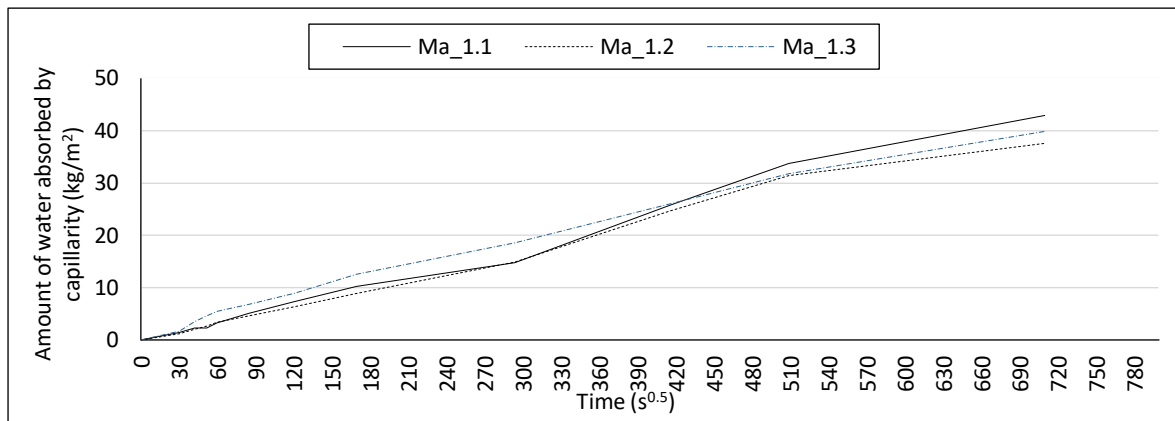
AsA = Absorbing Surface Area, W<sub>bAT</sub> = weight of the specimens before the ageing treatment, W<sub>Dry</sub> = weight of the dried specimens, W<sub>cap24h</sub> = weight of the specimens 24 hours after the start of the test, M<sub>cap24h</sub> = mass of water absorbed by capillary 24 hours after the start of the test, W<sub>cap7d</sub> = weight of the specimens 7 days after the start of the test, M<sub>cap7d</sub> = amount of water absorbed by capillary 7 days after the start of the test,  $\nu$  = flow velocity, AC = capillary water absorption coefficient, Sdev = Standard Deviation.



**Figure 3.8.** Water absorbed by capillary action (brick specimens).



**Figure 3.9.** Water absorbed by capillary action (mortar specimens).

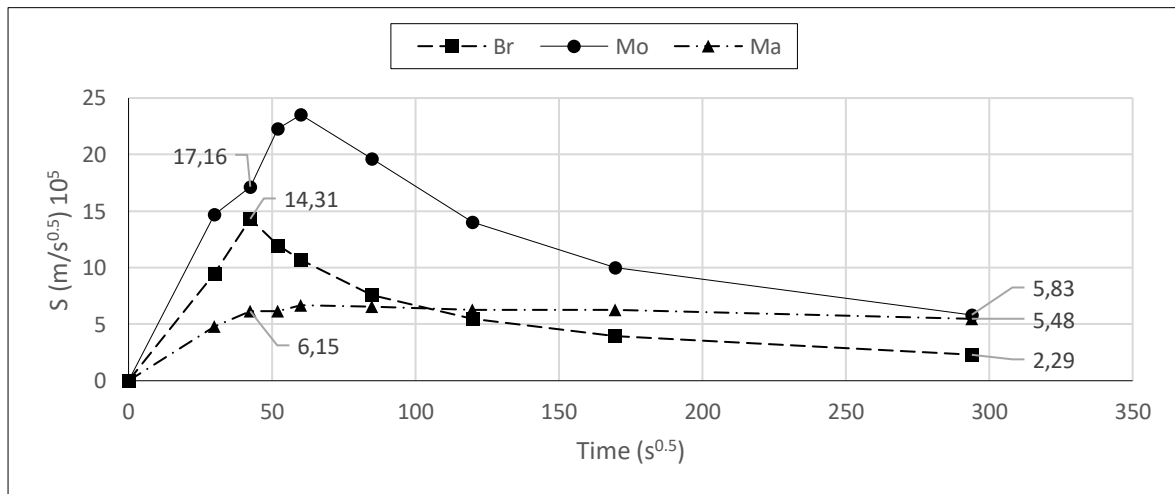


**Figure 3.10.** Water absorbed by capillary action (masonry specimens).

**Table 3.10.** Sorptivity ( $\text{m/s}^{0.5}$ )  $10^5$ .

| Specimen | 0.5 h | 24 h |
|----------|-------|------|
| Bricks   | 14.31 | 2.29 |
| Mortar   | 17.16 | 5.83 |
| Masonry  | 6.15  | 5.48 |

Data reference: RH 40%; T= 20 °C; water density: 0.998 g/cm<sup>3</sup>



**Figure 3.11.** Sorptivity of the brick, mortar and masonry specimens.

As regard the sorptivity, test results are summarized in Table 3.10 and in Figure 3.11. Sorptivity was calculated 30 minutes and 24 hours after the start of the test.

Comparing curves related to the three kind of specimens, it emerges that at the start of the test, masonry and brick have quite the same behaviour, while after 30 minutes the

behaviour differs more and more. On the contrary, after 24 hours the sorptivity of the masonry is similar to this of the mortar. This behaviour occurs because within the first period water penetrating the masonry is absorbed only by the lowest brick, while after 24 hours water penetrates the lowest mortar joint.

As regard the absorption at atmospheric pressure, test results are summarized in Table 3.11. Results are consistent with those obtained from the previous tests, but the amount of water absorbed both after 24 hours and 7 days is now higher because of the larger dimensions of the absorbing surface area.

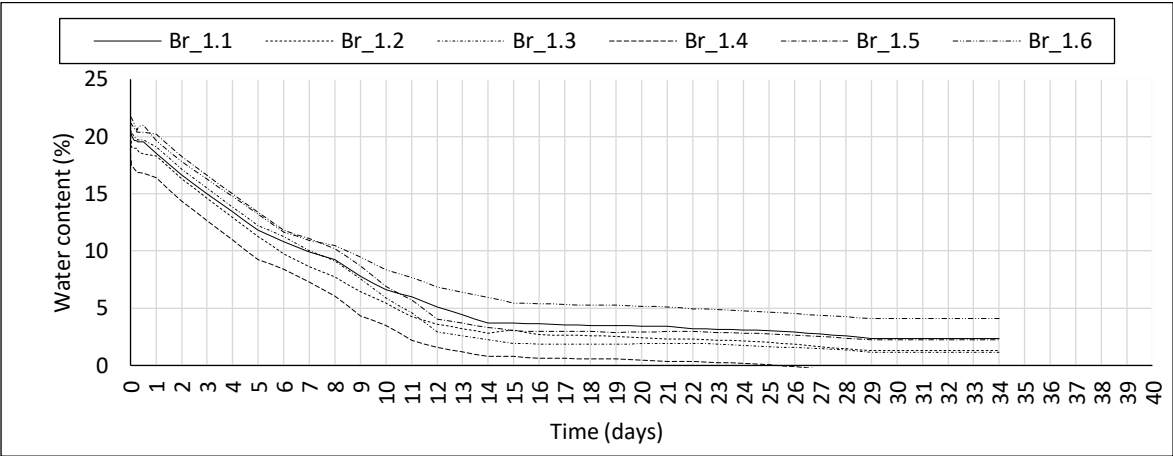
**Table 3.11.** Water absorption at atmospheric pressure (mean test conditions: T = 24 °C, RH = 53%).

| Specimen          | AsA<br>(mm <sup>2</sup> ) | W <sub>bAT</sub><br>(g) | W <sub>Dry</sub><br>(g) | W <sub>Ab24h</sub><br>(g) | M <sub>Ab24h</sub><br>(%) | W <sub>Ab7d</sub><br>(g) | M <sub>Ab7d</sub><br>(%) | v<br>(m/s)            | Ab<br>(%) |
|-------------------|---------------------------|-------------------------|-------------------------|---------------------------|---------------------------|--------------------------|--------------------------|-----------------------|-----------|
| Brick<br>(Sdev)   | 2.4 10 <sup>3</sup>       | 14.14<br>(0.11)         | 13.93<br>(0.10)         | 16.67<br>(0.11)           | 19.64                     | 16.79<br>(0.13)          | 20.59                    | 1.98 10 <sup>-7</sup> | 20.59     |
| Mortar<br>(Sdev)  | 9.6 10 <sup>3</sup>       | 78.86<br>(0.82)         | 78.06<br>(0.91)         | 106.0<br>(0.87)           | 35.80                     | 108.9<br>(0.86)          | 39.52                    | 5.31 10 <sup>-7</sup> | 39.52     |
| Masonry<br>(Sdev) | 1.4 10 <sup>5</sup>       | 5012<br>(39)            | 4956<br>(37)            | 5382<br>(51)              | 8.58                      | 6202<br>(75)             | 25.13                    | 1.50 10 <sup>-6</sup> | 25.13     |

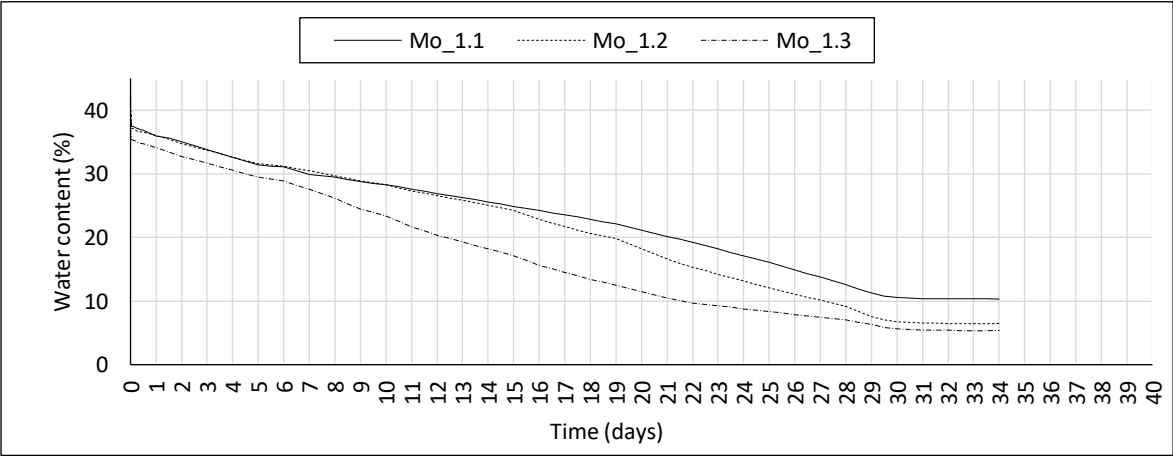
W<sub>Ab24h</sub> = weight of the specimens 24 hours after the start of the test, M<sub>Ab24h</sub> = mass of water absorbed by the specimens 24 hours after the start of the test, W<sub>Ab7d</sub> = weight of the specimens after 7 days, M<sub>Ab7d</sub> = mass of water absorbed by the specimens after 7 days, Ab = water absorption coefficient at atmospheric pressure.

As regard the drying test, results are summarized in Table 3.12 and the drying curves related to brick, mortar and masonry specimens are shown in Figures 3.12, 3.13 and 3.14, respectively. Since the specimens were initially fully imbibed, the maximum amount of water which was into the specimens at the start of the test was 20.59%, 39.52% and 25.13% of the dry mass for bricks, mortar and masonry, respectively. For the bricks, it is possible to distinguish two drying phases (Figure 3.12): the water content highly decreased during the first 12 days of drying, while it was almost constant for the remaining 22 days. On the contrary, for mortar and masonry specimens, the loss of water during the drying phase had a constant negative gradient (Figures 3.13 and 3.14). Drying was rather slow for all specimens. This is proved both by the timeframe, and by the values of the flow velocity which was several times lower compared to the absorption tests (Table 3.9). The weight of bricks and mortar specimens stabilized (i.e. it decreased by 0.06% and 0.74% respectively between two measures in a row) after 34 days, while masonry specimens did not reach this

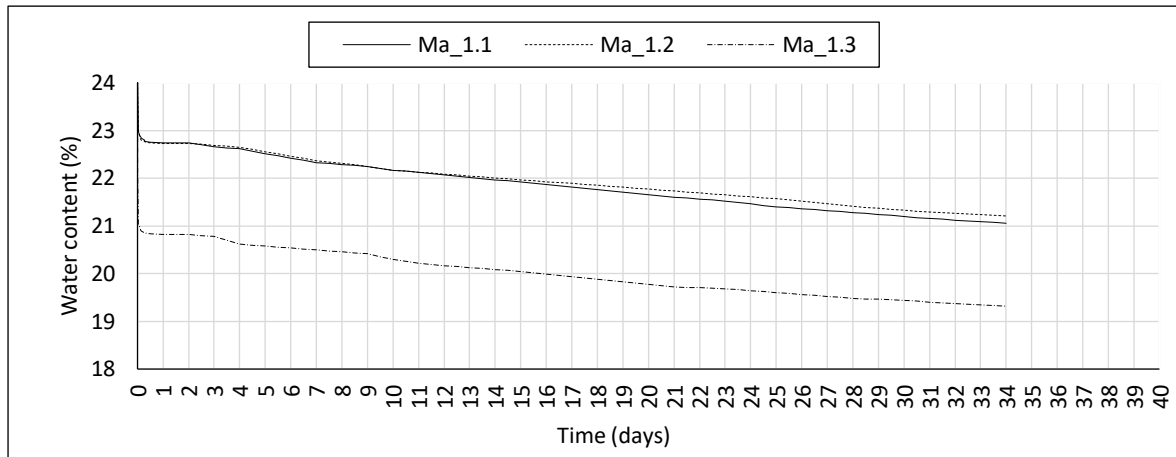
condition; in this experiment, the test was interrupted after 34 days. In order to compare these data with those referring to the absorption tests, Table 3.12 reports the weight of the specimens after seven days. The amount of water lost by the bricks during this period was less than half compared to that absorbed, while for mortar and masonry specimens, it is less than a fifth and a tenth, respectively.



**Figure 3.12.** Drying test. Amount of water vs. time (brick specimens).



**Figure 3.13.** Drying test. Amount of water vs. time (mortar specimens).



**Figure 3.14.** Drying test. Amount of water vs. time (masonry specimens).

**Table 3.12.** Water release by natural drying (mean test conditions: T = 24 °C RH = 53%).

| Specimen | DsA<br>(mm <sup>2</sup> ) | W <sub>bDRY</sub><br>(g) | W <sub>Dry24h</sub><br>(g) | M <sub>Dry24h</sub><br>(%) | W <sub>Dry7d</sub><br>(g) | M <sub>Dry7d</sub><br>(%) | v<br>(m/s)             | ID<br>(-) |
|----------|---------------------------|--------------------------|----------------------------|----------------------------|---------------------------|---------------------------|------------------------|-----------|
| Brick    | 2.4 10 <sup>3</sup>       | 16.79                    | 16.54                      | -1.51                      | 15.28                     | -9.88                     | -1.74 10 <sup>-8</sup> | 0.88      |
| (Sdev)   |                           | (0.13)                   | (0.14)                     |                            | (0.18)                    |                           |                        |           |
| Mortar   | 9.6 10 <sup>3</sup>       | 108.9                    | 105.6                      | -3.12                      | 100.9                     | -7.93                     | -3.34 10 <sup>-8</sup> | 0.86      |
| (Sdev)   |                           | (0.86)                   | (0.92)                     |                            | (0.80)                    |                           |                        |           |
| Masonry  | 1.4 10 <sup>5</sup>       | 6202                     | 6052                       | -2.47                      | 6034                      | -2.78                     | -1.09 10 <sup>-7</sup> | 0.97      |
| (Sdev)   |                           | (75)                     | (91)                       |                            | (90)                      |                           |                        |           |

DsA = dispersant surface area, W<sub>bDRY</sub> = weight of the specimens before drying, W<sub>Dry24h</sub> = weight of specimens after 24 hours of natural drying, M<sub>Dry24h</sub> = mass of water lost by natural drying after 24 hours, W<sub>Dry7d</sub> = weight of specimens after 7 days of natural drying, M<sub>Dry7d</sub> = mass of water lost by natural drying after 7 days, ID = Drying Index.

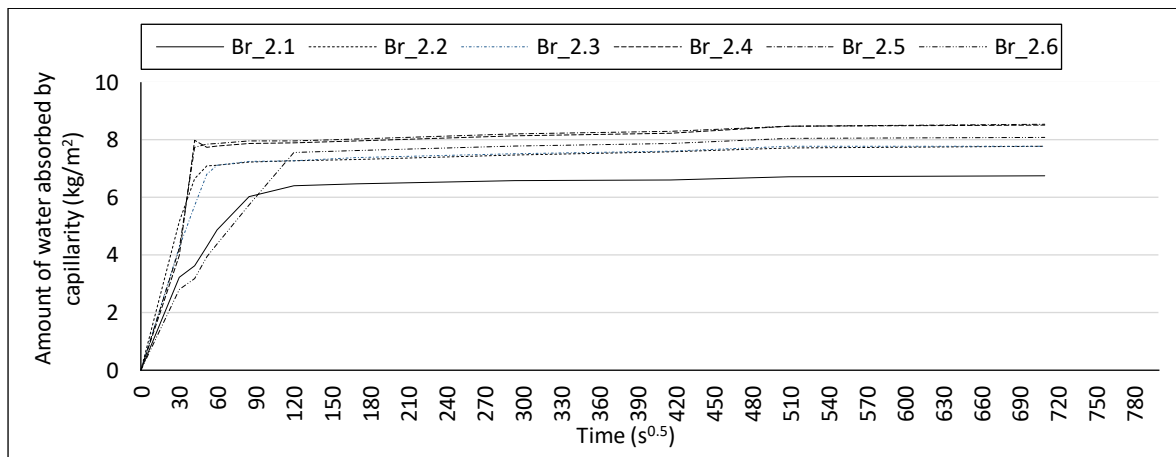
Overall, the tests conducted to study the aptitude of the specimens toward water intrusion prove that:

- mortar, brick and masonry exhibit a very different attitude toward the water absorption and release, in terms of both amount and velocity;
- In the brief period, sorptivity is higher in mortar than in masonry and in bricks, but in 24 h it is the same in mortar and in masonry;
- the behavior of the masonry specimens cannot be determined as a sum of the behavior of their construction materials. Test results also demonstrate the critical influence of the bond pattern, and proves the importance of the specimen's choice.

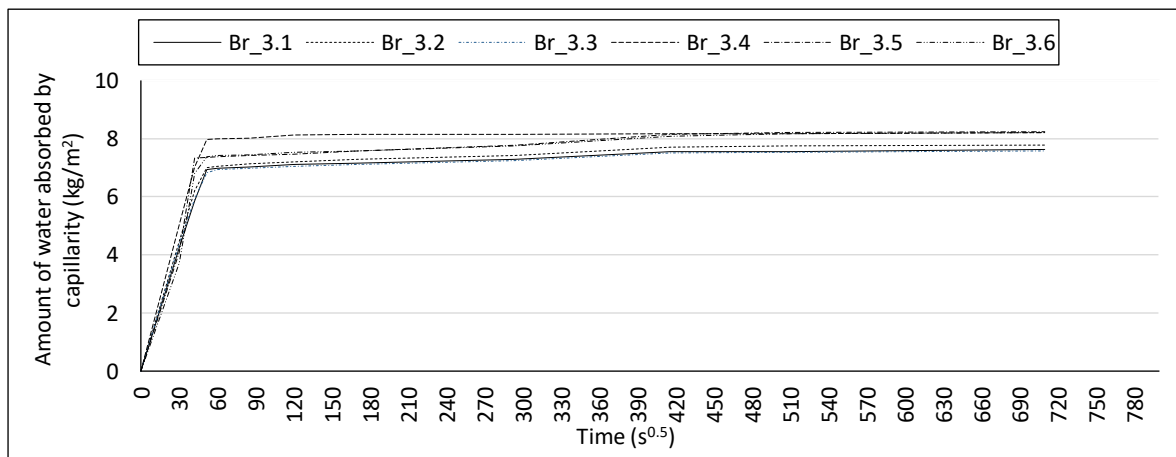
### 3.4.2 Properties of the specimens toward salts aqueous solutions

The tests for the determination of the water absorption coefficient and sorptivity were conducted not only using deionized water but also salts aqueous solutions. Results referred to all kind of specimens and to the different kind of solutions are exposed and argued in this chapter.

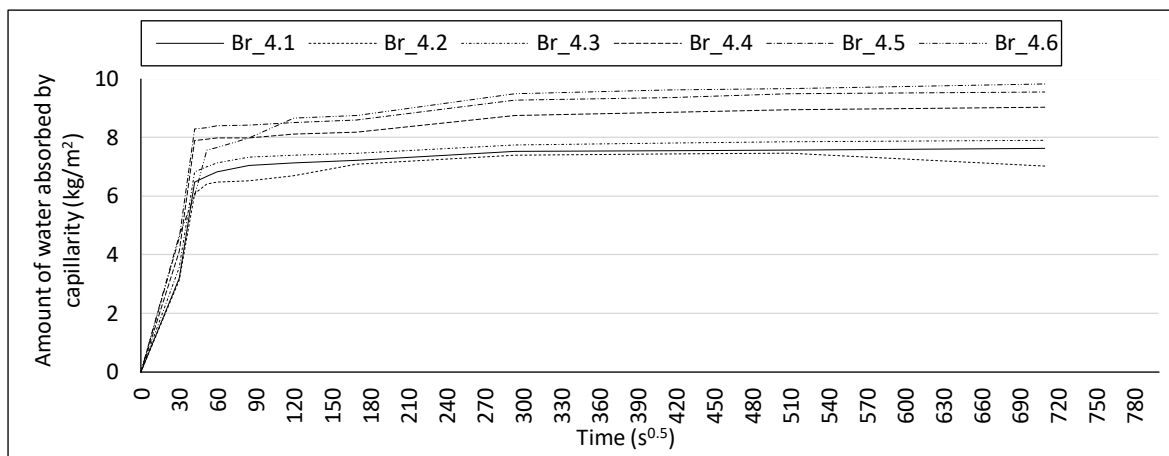
Figures 3.15, 3.16 and 3.17 show the curves of absorption of the brick specimens exposed to sodium chloride, sodium sulphate and potassium nitrate aqueous solutions respectively. Table 3.13 summarises the different values of the coefficient of absorption by capillary action (AC), and they are compared to that relating to the standard test, conducted using deionized water (Section 3.4.1).



**Figure 3.15.** NaCl 14% solution absorbed by capillary action (brick specimens).



**Figure 3.16.** Na<sub>2</sub>SO<sub>4</sub> 14% solution absorbed by capillary action (brick specimens).



**Figure 3.17.** KNO<sub>3</sub> 14% solution absorbed by capillary action (brick specimens).

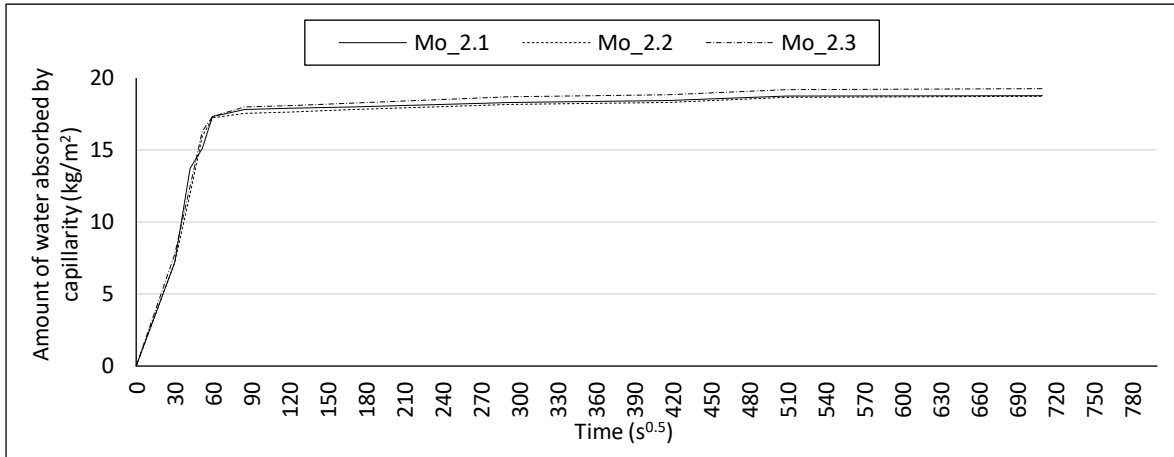
**Table 3.13.** Coefficient of water absorption by capillary action: AC (kg/m<sup>2</sup> s<sup>0.5</sup>) 10<sup>-2</sup>. Brick specimens.

|                                 | Br_1 | Br_2 | Br_3 | Br_4 | Br_5 | Br_6 | Average value | Sdev  | AC/AC <sub>w</sub> |
|---------------------------------|------|------|------|------|------|------|---------------|-------|--------------------|
| H2O                             | 5.7  | 5.9  | 4.9  | 5.9  | 3.8  | 5.5  | 5.3           | (0.8) | -                  |
| NaCl                            | 5.3  | 3.3  | 5.2  | 5.4  | 5.3  | 5.5  | 5.0           | (0.9) | 0.94               |
| Na <sub>2</sub> SO <sub>4</sub> | 4.7  | 4.3  | 4.3  | 4.9  | 4.7  | 5.6  | 4.8           | (0.5) | 0.90               |
| KNO <sub>3</sub>                | 5.7  | 5.0  | 5.6  | 5.5  | 5.5  | 5.9  | 5.5           | (0.3) | 1.04               |

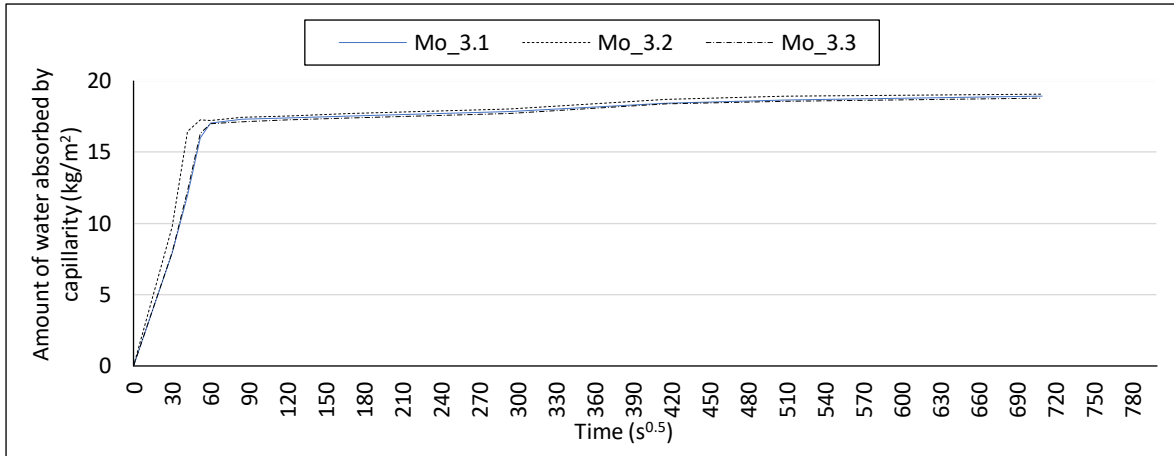
AC/AC<sub>w</sub> = ratio between the coefficient of water absorption of the specimens determined using salts aqueous solution or deionized water.

Curves are similar to those obtained using deionized water (Figure 3.8). However, some differences are visible. Sodium salts cause the AC decrease, while potassium salts cause its increase. The decrease is 6% and 10% in the case of sodium chloride and sodium sulphate respectively. The increase is 4% in the case of potassium nitrate.

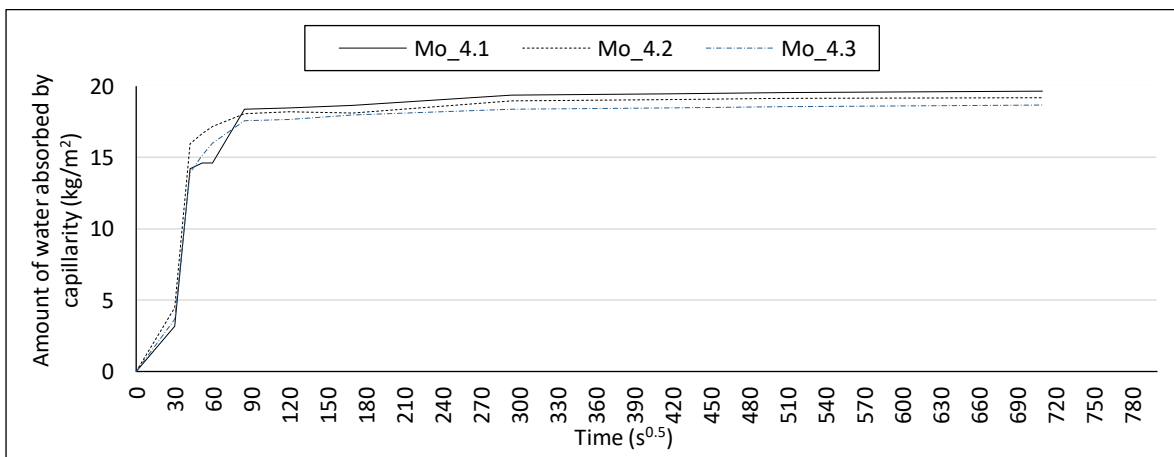
Figures 3.18, 3.19 and 3.20 show the curves of absorption of the mortar specimens exposed to sodium chloride, sodium sulphate and potassium nitrate solutions respectively. Table 3.14 summarises the different values of the coefficient of absorption by capillary action (AC), and they are compared to these relating to the test conducted using deionized water (Section 3.4.1).



**Figure 3.18.** NaCl 14% solution absorbed by capillary action (mortar specimens).



**Figure 3.19.** Na<sub>2</sub>SO<sub>4</sub> 14% solution absorbed by capillary action (mortar specimens).



**Figure 3.20.** KNO<sub>3</sub> 14% solution absorbed by capillary action (mortar specimens).

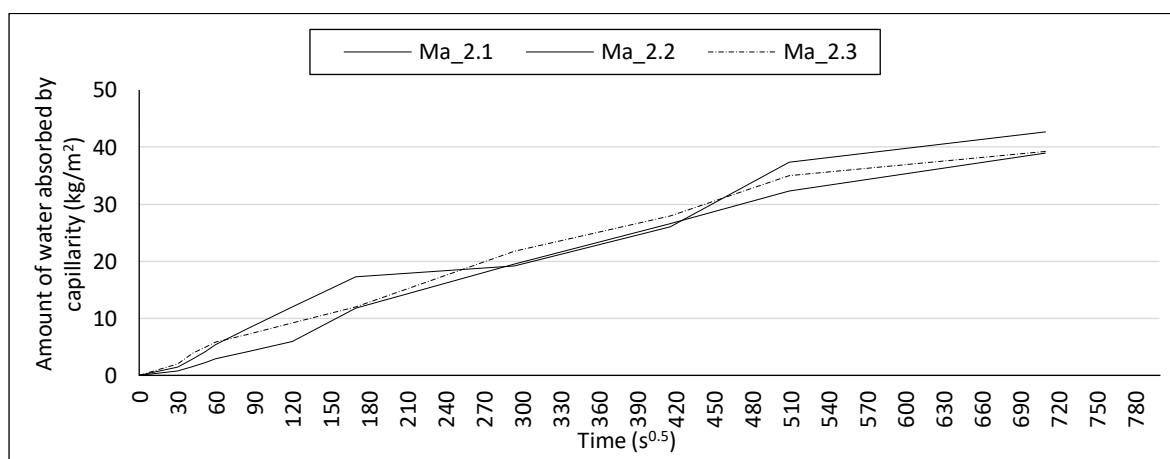
**Table 3.14.** Coefficient of water absorption by capillary action: AC ( $\text{kg/m}^2 \text{s}^{0.5}$ )  $10^{-2}$ . Mortar specimens.

|                                 | Mo_1 | Mo_2 | Mo_3 | Average value | Sdev  | AC/AC <sub>w</sub> |
|---------------------------------|------|------|------|---------------|-------|--------------------|
| H <sub>2</sub> O                | 20.7 | 19.7 | 22.9 | 21.1          | (1.7) | -                  |
| NaCl                            | 17.8 | 18.4 | 18.0 | 18.0          | (0.3) | 0.85               |
| Na <sub>2</sub> SO <sub>4</sub> | 16.7 | 11.3 | 16.1 | 14.7          | (3.0) | 0.70               |
| KNO <sub>3</sub>                | 23.2 | 20.3 | 21.6 | 21.7          | (1.4) | 1.03               |

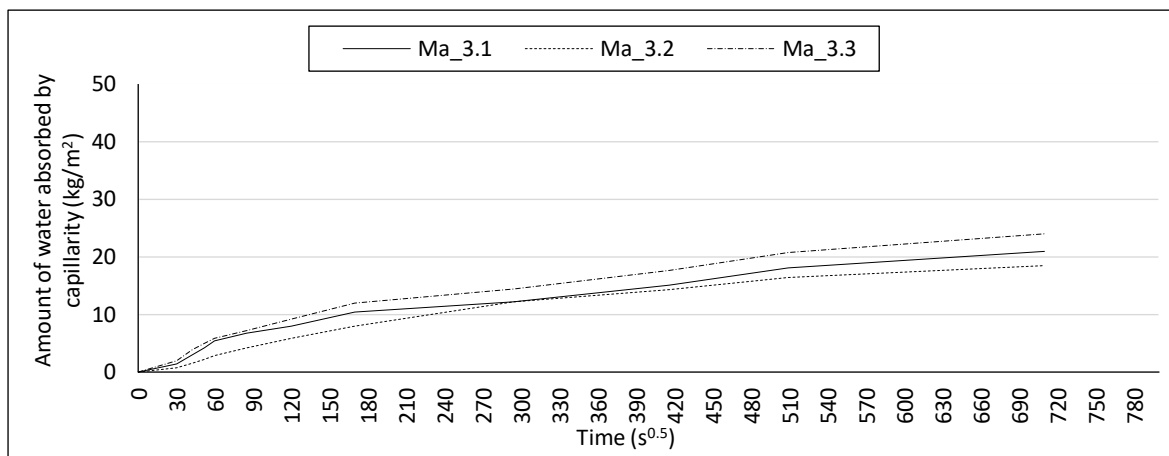
Even in this case, the curves are similar to those obtained using deionized water (Figure 3.9). However, some differences are visible. Sodium salts cause the AC decrease, while potassium salts cause its increase. The decrease is 15% and 30% in the case of sodium chloride and sodium sulphate respectively. The increase is 3% in the case of potassium nitrate.

Comparing data relating to bricks and mortar, AC are ten time greater in the latter than in the former. This is due to the different dimension of specimens used to perform the test.

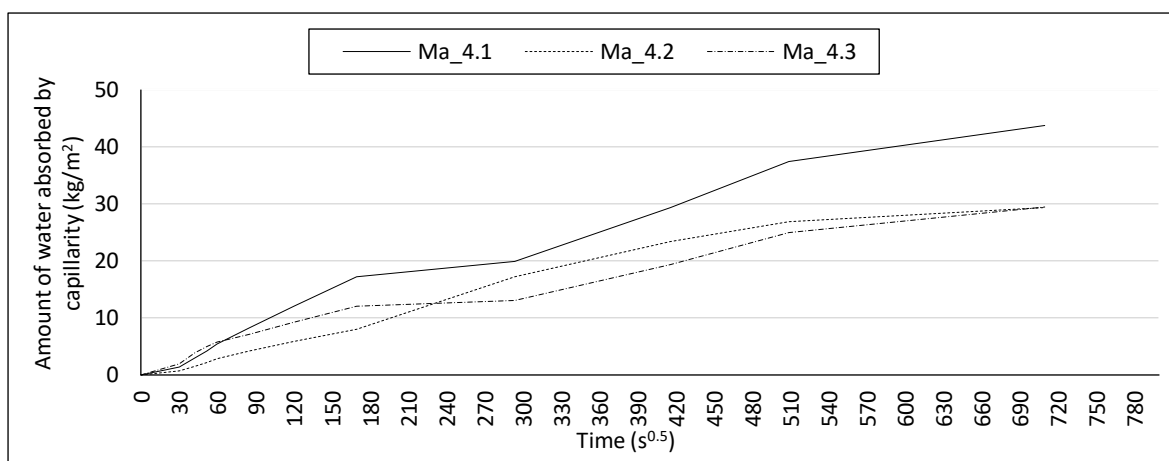
Finally, Figures 3.21, 3.22 and 3.23 show the curves of absorption of the masonry specimens exposed to sodium chloride, sodium sulphate and potassium nitrate solutions respectively. Table 3.15 summarises the different values of the coefficient of absorption by capillary action (AC), and they are compared to that relating to standard test, conducted using deionized water (Section 3.4.1).



**Figure 3.21.** NaCl 14% solution absorbed by capillary action (masonry specimens).



**Figure 3.22.** Na<sub>2</sub>SO<sub>4</sub> 14% solution absorbed by capillary action (masonry specimens).



**Figure 3.23.** KNO<sub>3</sub> 14% solution absorbed by capillary action (masonry specimens).

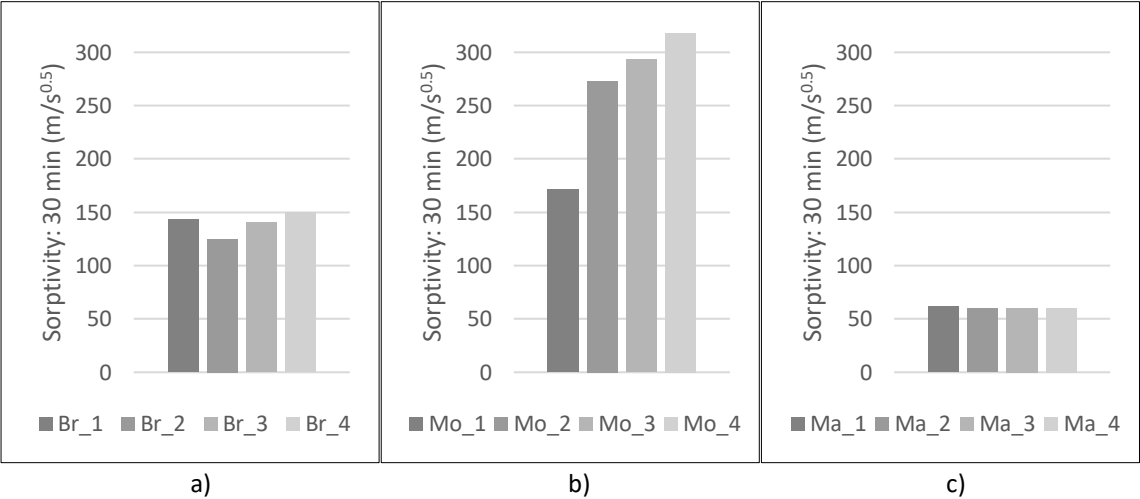
**Table 3.15.** Coefficient of water absorption by capillary action: AC (kg/m<sup>2</sup> s<sup>0.5</sup>) 10<sup>-2</sup>. Masonry specimens.

|                                 | Ma_1 | Ma_2 | Ma_3 | Average value | Sdev  | AC/AC <sub>w</sub> |
|---------------------------------|------|------|------|---------------|-------|--------------------|
| H <sub>2</sub> O                | 6.7  | 6.3  | 9.1  | 7.4           | (1.5) | -                  |
| NaCl                            | 12.4 | 6.3  | 9.1  | 9.3           | (3.1) | 1.26               |
| Na <sub>2</sub> SO <sub>4</sub> | 9.8  | 6.3  | 9.1  | 8.4           | (1.9) | 1.14               |
| KNO <sub>3</sub>                | 12.4 | 6.3  | 9.1  | 9.3           | (3.1) | 1.26               |

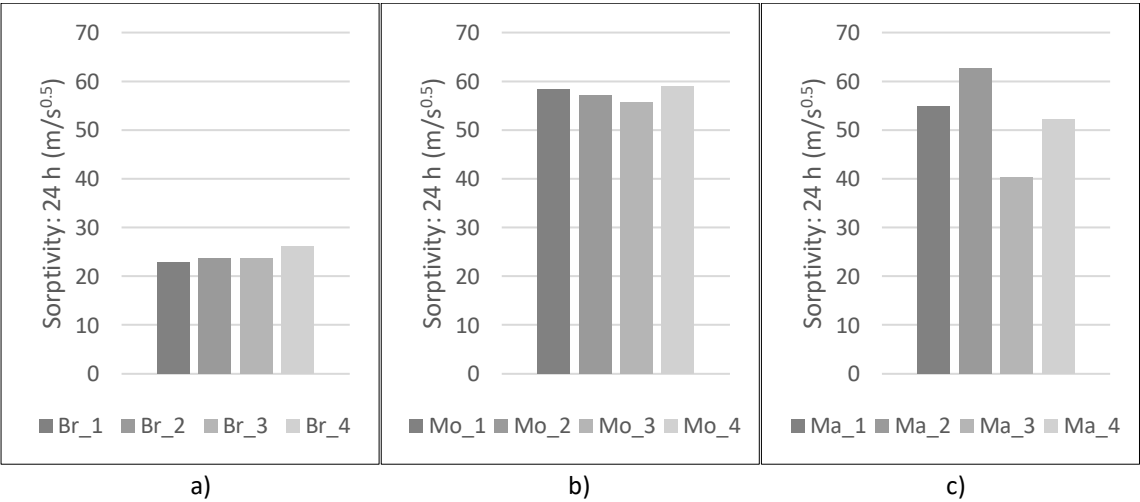
The AC is higher in specimens exposed to salts aqueous solutions than in those exposed to deionized water. The difference between the average values is 26%, 14% and 26% in the case of sodium chloride, sodium sulphate and potassium nitrate respectively.

Table 3.16 and Figures 3.24 and 3.25 summarise data concerning the sorptivity of all kind of specimens. The parameter was determined 30 min and 24 hours after the start of the

test. The values of the density of the aqueous solutions are also listed in the table. They are referring to the values of temperature and humidity recorded during the test.



**Figure 3.24.** Sorptivity after 30 minutes: a) brick specimens; b) mortar specimens; c) masonry specimens.



**Figure 3.25.** Sorptivity after 24 hours: a) brick specimens; b) mortar specimens; c) masonry specimens.

**Table 3.16.** Sorptivity (mean test conditions: T = 20 °C, RH = 54%).

|      | Density of the<br>solution<br>(g/cm <sup>3</sup> ) | S_30min                                                |                            | S_24h                                                  |                            |
|------|----------------------------------------------------|--------------------------------------------------------|----------------------------|--------------------------------------------------------|----------------------------|
|      |                                                    | Average value<br>(m/s <sup>0.5</sup> 10 <sup>5</sup> ) | Sdev<br>(10 <sup>5</sup> ) | Average value<br>(m/s <sup>0.5</sup> 10 <sup>5</sup> ) | Sdev<br>(10 <sup>5</sup> ) |
| Br_1 | 0.998                                              | 14.31                                                  | (4.40)                     | 2.29                                                   | (0.09)                     |
| Mo_1 |                                                    | 17.16                                                  | (1.96)                     | 5.83                                                   | (0.38)                     |
| Ma_1 |                                                    | 6.15                                                   | (1.91)                     | 5.48                                                   | (0.75)                     |
| Br_2 | 1.097                                              | 12.50                                                  | (4.40)                     | 2.36                                                   | (0.18)                     |
| Mo_2 |                                                    | 27.31                                                  | (1.96)                     | 5.70                                                   | (0.09)                     |
| Ma_2 |                                                    | 6.00                                                   | (2.58)                     | 6.25                                                   | (0.47)                     |
| Br_3 | 1.097                                              | 14.01                                                  | (1.31)                     | 2.36                                                   | (0.11)                     |
| Mo_3 |                                                    | 29.31                                                  | (5.43)                     | 5.56                                                   | (0.05)                     |
| Ma_3 |                                                    | 6.04                                                   | (2.59)                     | 4.03                                                   | (0.39)                     |
| Br_4 | 1.090                                              | 14.98                                                  | (2.08)                     | 2.61                                                   | (0.29)                     |
| Mo_4 |                                                    | 31.81                                                  | (2.39)                     | 5.90                                                   | (0.15)                     |
| Ma_4 |                                                    | 6.04                                                   | (2.59)                     | 5.22                                                   | (0.11)                     |

Data relating to the sorptivity prove that:

- the average values of the sorptivity of brick and mortar specimens 30 minutes after the start of the test are from five to six times higher than those measured after 24 hours;
- the average values of the sorptivity of masonry specimens 30 minutes after the start of the test are quite similar to those measured after 24 hours;
- as regard the masonry specimens, the average values measured after 30 minutes and referring to salts aqueous solutions are about 2% lower than those referring to deionized water. On the contrary, the ratio between the average values of the sorptivity measured after 24 hours, referring to salts aqueous solutions and to deionized water, ranges from 0.95 (in the case of potassium nitrate) to 1.14 (in the case of sodium chloride).

### 3.5 Mechanical parameters

From the mechanical point of view, the compressive strength and the stiffness of the specimens were measured. The tests were performed by adapting the standard EN 772-1: 2011, EN 1015-11: 2019, EN 12390: 2013 and EN 1052-1: 2011, to the brick, mortar and masonry specimens used in the experiment. The difference introduced consists on the

dimension of the specimens. However, this change is not significant for the purpose of this research, since all tested specimens have the same dimensions and so data were compared successfully.

Tests on masonry specimens were performed through a Metrocom testing machine (3000 kN), equipped with strain gauges to measure deformations. Because of the dimensions of the specimens, strain gauges were installed between the plates of the machines. The homogeneous distribution of load was improved by means of corrugated cardboard, put between the bases of the specimens and the plates of the machine. The test was conducted at a constant speed, i.e. 3N/min, as imposed by the standard. The set-up of the test is showed in Figure 2.26.

The compressive test on the brick and mortar specimens was performed through an Instron 3382 pressing machine (200 kN). All those tests were conducted at the Mechanical Testing Laboratory (LASTRU) of the University of Perugia (Italy).



**Figure 3.26.** Testing machine used for the masonry specimens (University of Perugia).

**Table 3.17.** Mechanical features of mortar specimens (mean test conditions: T = 23.4 °C RH = 60%).

| Specimen      | Weight<br>(g) | Water content<br>(%) | $\sigma_{\max}$<br>(N/mm <sup>2</sup> ) | E<br>(N/mm <sup>2</sup> ) |
|---------------|---------------|----------------------|-----------------------------------------|---------------------------|
| Mo_0.1A       | 83.02         | 1.16                 | 2.45                                    | 182.2                     |
| Mo_0.1B       | 83.04         | 1.17                 | 2.18                                    | 119.7                     |
| Mo_0.2A       | 83.12         | 1.15                 | 2.31                                    | 482.8                     |
| Mo_0.2B       | 83.15         | 1.16                 | 2.09                                    | 141.8                     |
| Mo_0.3A       | 84.19         | 1.17                 | 2.41                                    | 310.4                     |
| Mo_0.3B       | 84.21         | 1.16                 | 2.08                                    | 522.2                     |
| Average value | 83.46         | 1.16                 | 2.26                                    | 231.6                     |
| Sdev          | (0.58)        | (0.01)               | (0.16)                                  | (155.6)                   |

**Table 3.18.** Mechanical features of brick specimens (mean test conditions: T = 23.4 °C RH = 60%).

| Specimen      | Weight<br>(g) | Water content<br>(%) | $\sigma_{\max}$<br>(N/mm <sup>2</sup> ) | E<br>(N/mm <sup>2</sup> ) |
|---------------|---------------|----------------------|-----------------------------------------|---------------------------|
| Br_0.1        | 13.93         | 1.11                 | 53.44                                   | 3565                      |
| Br_0.2        | 13.95         | 1.15                 | 30.33                                   | 1440                      |
| Br_0.3        | 14.05         | 1.14                 | 51.67                                   | 3656                      |
| Br_0.4        | 13.88         | 1.15                 | 44.31                                   | 3830                      |
| Br_0.5        | 14.05         | 1.21                 | 48.09                                   | 3179                      |
| Br_0.6        | 13.84         | 1.16                 | 52.55                                   | 4053                      |
| Average value | 13.95         | 1.15                 | 46.73                                   | 3287                      |
| Sdev          | (0.09)        | (0.03)               | (3.37)                                  | (371)                     |

**Table 3.19.** Mechanical features of masonry specimens (mean test conditions: T = 24.0 °C, RH = 53%).

| Specimen      | Weight<br>(g) | Water content<br>(%) | $\sigma_{\max}$<br>(N/mm <sup>2</sup> ) | E<br>(N/mm <sup>2</sup> ) |
|---------------|---------------|----------------------|-----------------------------------------|---------------------------|
| Ma_0.1        | 4838          | 1.13                 | 8.74                                    | 189.2                     |
| Ma_0.2        | 4922          | 1.11                 | 9.22                                    | 166.4                     |
| Ma_0.3        | 4974          | 1.14                 | 8.14                                    | 161.4                     |
| Average value | 4911          | 1.13                 | 8.68                                    | 172.3                     |
| Sdev          | (69)          | (0.01)               | (0.44)                                  | (12.1)                    |

The results of the mechanical tests performed on bricks, mortar and masonry specimens are collected in Tables 3.17, 3.18 and 3.19 respectively. Each table contains the value of the maximum compressive strength, and the modulus of elasticity, relating to the weight of the specimen and to the water content. As regard data relating to the mortar, the test for the determination of the compressive strength was performed on both the two half parts of the same specimens, as prescribed by the EN 1015-11: 2019 standard. These data will be

compared with those relating to the specimens undergoing the ageing treatment described in the Section 3.8.

Data proved that the average value of the compressive strength and that of the modulus of elasticity of masonry specimens were  $8.68 \text{ N/mm}^2$  and  $172.3 \text{ N/mm}^2$  respectively. Comparing these data to those relating to bricks and mortar, it was possible to note that the average value of the compressive strength of the masonry specimens was more than 5 time lower than this of the former, and 26% higher than this of the latter.

As regard the modulus of elasticity, the average value referring to the mortar specimens is 34% higher than that referring to the masonry specimens, but also the standard deviation is very high. The modulus of elasticity is higher in bricks than in mortar specimens by an order of magnitude. The modulus of elasticity of the masonry specimens is highly influenced by that of the mortar, that is the weakest material among those constituting masonry itself.

*Attachment 2* contains the stress-strain curves of all the masonry specimens and some photographs of one of them, taken during the compressive test.

### **3.6 Salts distribution in the masonry specimens**

Next to the mechanical tests, the distribution of the salts into the masonry specimens was also measured. This was done in order to make a comparison between the values referring to the untreated and treated specimens, according to the procedure described in the Section 3.7 and 3.8.

Damage caused by salts into the construction materials and masonry has been widely studied and a lot of examples can be found in literature (Charola and Bläuer, 2015; Pel et al., 2003; Gasparoli and Valentini, 2003; Binda et al., 1999; Bakolas et al., 1996; Evans, 1970). Salts can enter from the environment into the material, but they can also be inside it congenitally. For this reason, it is important to understand what the effects of salts in the untreated specimens is, in order to rightly evaluate the influence of the salts introduced during the ageing treatment.

The study can be done directly or indirectly, from a quantitative or a qualitative point of view. The former approach consists on the measure of the salts themselves, so it is more exact and complete. The latter approach consists on the measure of some physical property firmly linked to the salts distribution; a change of the former can be read as the effect of the latter. In the study of Franzoni, Sandolini and Bandini (2011) they are both used referring to the same masonry specimen.

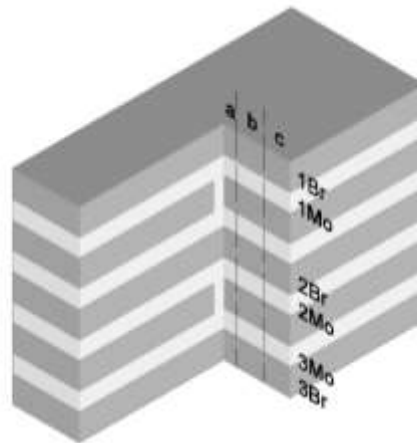
In this research the qualitative approach was preferred because it is cheaper and faster and it is sufficient to answer the stated purpose. Data deriving from the measurement conducted on the untreated masonry specimens will be compared to those deriving from the measurement conducted on the treated masonry specimens. In this case, the kind and the amount of salts introduced in the specimens is known, so the qualitative measure allow us to make a meaningful comparison among the specimens.

Several methods can be used to measure the content of salts into porous materials. One among them consists on the measure of the conductance. This approach is suggested by the European standard EN 11087: 2003. According to the standard the following procedure must be followed. Firstly, the soluble salts are extracted through a known volume of double-distilled water; then the conductance of the obtained salts aqueous solutions is measured; finally, the content of the salts ions which are into the solution itself is determined through a chromatographic test. In this research, this approach was adopted, except for the characterisation of the ionic species in solution. The conductometer used to perform the test is a portable Hanna 8733 instrument.

The sampling of masonry specimens was carried out after the performing of the mechanical tests. In this way, the mechanical behaviour of the specimens was not affected by the cores taken out.

Several studies reveal what the most common salts distribution in masonry is (Falchi et al., 2008; Hola et al., 2017; Gentilini et al., 2012; Foraboschi and Vanin, 2014; Lubelli et al., 2004). They prove that the amount of salts is greater on the surface than inside the specimens, and that a distribution gradient exists, according to which salts are more copious on the bottom than on the top parts of the masonry wall. Starting from these results, a sampling scheme was defined and it was used in this experimental research. One

among the three masonry specimens, which underwent the same treatment, was selected and bricks and mortar samples were collected at different heights and depths on the same half-plane on the masonry specimens, according to the sketch shown in Figure 3.27.



**Figure 3.27.** Sampling scheme of masonry specimens: Br: Brick; Mo: Mortar joint.

**Table 3.20.** Electrical conductivity of salts aqueous solutions referring to untreated specimens (mean test conditions: T = 22 °C, RH = 51%).

|      | a: innermost<br>( $\mu\text{S}/\text{cm}$ ) | b: middle<br>( $\mu\text{S}/\text{cm}$ ) | c: outermost<br>( $\mu\text{S}/\text{cm}$ ) |
|------|---------------------------------------------|------------------------------------------|---------------------------------------------|
| 1Br  | 64                                          | 61                                       | 74                                          |
| 1Mo  | 289                                         | 260                                      | 87                                          |
| 2Br  | 61                                          | 59                                       | 68                                          |
| 2Mo  | 298                                         | 273                                      | 143                                         |
| 3 Br | 262                                         | 296                                      | 100                                         |
| 3 Mo | 64                                          | 72                                       | 65                                          |

Measures conducted according to the standard: EN 11087:2003. Conductivity of deionized water:  $5\mu\text{S}/\text{cm}$ .

The values of the conductance referring to the aqueous solutions prepared using samples taken from the untreated specimen, are shown in Table 3.20. Data reveal that the ratio between the average values referring to mortar and bricks is between 3.2, on the top, and 3.8 in the middle. This means that the soluble ions are more copious in mortar than in bricks. Reading data horizontally, they prove that the gradient is more evident for mortar than for bricks, since the ratio between the values referring to the outermost and the

innermost samples range from 0.30 to 0.48 in the first case, and from 1.02 to 1.16 in the second. On the contrary, reading data vertically, not meaningful changes occur.

### **3.7 Experimental reproduction of the phenomenon**

As it was explained in the Chapter 2, rising damp produces several effects which may variously overlap. This research mainly focuses on the mechanical aspects, which must be investigated by means of some destructive tests. For this reason, it was not possible to conduct the research by referring to an existing case study, since the principles of non-invasiveness and respect of the architectural heritage would be denied, which are fundamental in the field of restoration (Binda et al., 2011; Carbonara, 1997). For this reason, a case-study was simulated by putting some masonry specimens outside, and meanwhile an experimental set was constructed inside the laboratory. In both cases, the same kind of masonry specimens was used, described in the Section 3.3, in order to make the comparison between the achieved data meaningfully.

The place chosen for the setting of the case-study consists on a field which is outside the Laboratory of Diagnostics and Materials Science at the Tuscia University. The field is well ventilated and no obstacles or barriers exist, that could alter the solar radiation, the wind and the rain. Weather data were measured by means of a home-made weather station, that is a project developed through the Arduino platform. Further details of the weather station are in the *Attachment 3*. Data on the environmental temperature and humidity, and the rainy periods were recorded every 15 minutes for one year.

Four graves were made in the soil, about 0.5 x 1.0 x 0.3 m in dimensions. Three among them were filled-in with sieved soil, while the other with gravel. Salts aqueous solutions similar to those used to study the hygroscopic properties of the specimens (Section 3.4) were poured on the first three graves. Overall, 8 litres of salts aqueous solutions were prepared, then they were divided in 4 parts and each part was poured into the graves every three months. Three masonry specimens were put into each grave. They had one of the two largest vertical faces, facing south. Figure 3.28 show the complete setting, while Figure 3.29 shows a detail of the weather station.

The masonry specimens stayed outside for one year. During this period, they were moved into the laboratory only three times, that is after 3, 6 and 12 months. On these occasions, the specimens were weighted, photographed and an overall evaluation of their damage conditions was done. Finally, at the end of the year, the specimens underwent the mechanical tests according to the method described in the Section 3.5.



**Figure 3.28.** Setting of the external field.



**Figure 3.29.** Detail of the weather station.

### **3.8 Setting of the experiment inside the laboratory**

Data acquired during the observation of the ongoing damage of the specimens in the external field were used to perfect the ageing treatment of the specimens inside the laboratory.

Several overlapping phenomena cause the damage of the masonry specimens outside, and they cannot be easily controlled and monitored. On the contrary, the reproduction of the experiment inside the laboratory allows us to select some concurrent aspect and to understand their influence and significance more consciously. For this reason, the treatment to which the masonry specimens underwent, was studied in laboratory, in order to simulate the effects of wetting/drying cycles, induced by rising damp and temperature changes with the presence of soluble salts.

In literature, several ageing procedures are described. Overall, they are based on the cyclical reproduction of the ageing factors or conditions and on the continuous control of the environmental parameters. The climatic chamber is one of the most common instruments used to reproduce these conditions (Cultrone et al., 2008; Lanas et al., 2006). However, since it was not available, it was necessary to invent a procedure using simple instruments which can be easily found in a laboratory.

The ageing treatment was draw up starting from past experimental procedures, such as those described in Graus et al. (2019), Uranjek and Bokan (2015), Binda et al. (2011) and Cultrone et al. (2007) and from some relevant standards (EN 11186: 2008; R.D. 2233, 1939). The aim was to study the effects of placing the specimens in contact with water and exposing them to thermal variations. The range of the temperature to which specimens were exposed was chosen in such a way that a notable thermal excursion was produced, according to the worst predictions on climate change, described in the Section 1.1.

Brick, mortar and masonry specimens underwent the same ageing treatment. The same aqueous solutions used to study the hygroscopic features of the specimens (Section 3.4.2) and to reproduce the phenomenon in the external field (Section 3.7) were used, namely:

- A complete set of specimens (brick, mortar and masonry) underwent the absorption of deionized water;

- A complete set of specimens underwent the absorption of 14% sodium chloride solution by mass;
- A complete set of specimens underwent the absorption of 14% sodium sulphate solution by mass;
- A complete set of specimens underwent the absorption of 14% potassium nitrate solution by mass;



**Figure 3.30.** Masonry specimens inside the PMMA boxes.



**Figure 3.31.** Masonry specimens inside the PE bags.



**Figure 3.32.** Masonry specimens buried into the refrigerating mixture.



**Figure 3.33.** Masonry specimens into the oven.

Specimens were initially dried in an oven at  $60 \pm 5$  °C for 48 hours, photographed and weighed, and their surface temperature was measured. Then, they were placed into closed PMMA boxes, laid on a 5 mm thick absorbent paper substrate soaked with deionized water,

as showed in Figure 3.30. They remained in this condition for seven days, during which water was absorbed by capillary action.

Subsequently, each specimen was inserted into a polyethylene (PE) bag, in order to protect it (Figure 3.31), and buried into a refrigerating mixture made by adding 23 g of sodium chloride per kg of ice (Figure 3.32). Specimens were left curing for 8 hours. During this period, the environmental temperature gradually reduced to -18 °C, and then increased again. As a consequence, the surface temperature of the specimens also varied, in order to reach the thermal balance. Finally, the specimens were removed from the PE bags and placed into the oven at 60 °C for 16 hours (Figure 3.33).

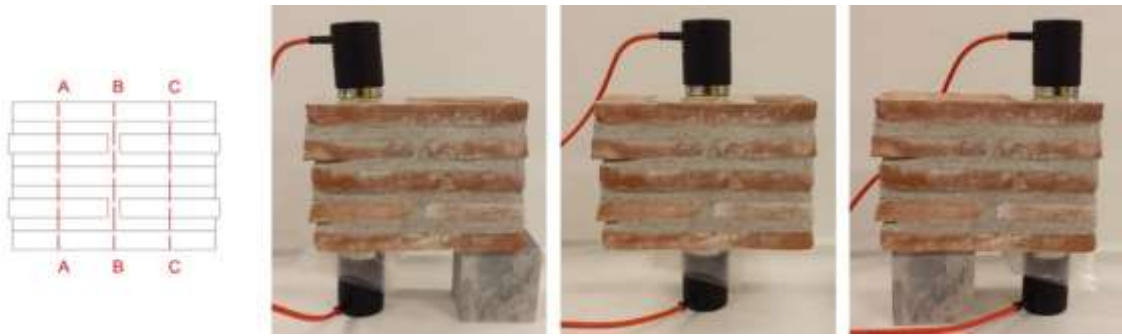
At the end of the cycle, specimens were weighed and photographed again, and the surface temperature was recorded. They were placed again into the PMMA boxes, over a sheet of soaked paper, and underwent a new ageing cycle. This was repeated 8 times. During this period, specimens were accurately weighed on a daily basis (24 hours), in order to record the amount of absorbed water.

### **3.9 Achieved data**

#### *3.9.1 Visual inspection and instrumental diagnosis*

At the end of the 8 cycles, a complete assessment of the damage status of the masonry specimens was conducted. The characterisation of the visible signs of damage was done according to the approach commonly adopted in the restoration field (Carbonara, 1997). Firstly, the specimens were photographed. Then the change of colour was recorded, according to the Munsell standard. Acquired data were compared with those relating to the untreated specimens (Section 3.3). Then, the efflorescences and the detachments due to salts migration were detected and characterised. The latter were represented in thematic maps. Their deepness was evaluated through an ultrasonic (US) test. The US system used consists on a Boviari Solgeo CMS pulsar-receiver and two piezoelectric transducers, a transmitting (TT) and a receiving (RT). The US frequency was 50 kHz. To take into account the effects of the heterogeneity of the specimens, a through transmission setup was chosen, where transmitting and receiving transducers face one another (Lester and Schmerr, 2013), as shown in Figure 3.34. Because of the irregularity of the surfaces of

the bricks, and since the measurement is significantly affected by the voids, the adherence between these and the transducers was improved through a film of modelling clay. Three measurements were carried out on each masonry specimens, along three paths: one of them crosses the vertical joints, while the other two do not.



**Figure 3.34.** Layout of the US test.

**Table 3.21.** Results of the US test carried on the masonry specimens exposed to deionized water.

| Specimen | Path | Length of the path<br>(cm) | t.o.f.<br>( $\mu$ s) | v<br>(m/s) | v/v <sub>B</sub><br>(-) |
|----------|------|----------------------------|----------------------|------------|-------------------------|
| Ma_0.1   | A    | 15.2                       | 74                   | 2043       | 1.10                    |
|          | B    | 15.2                       | 82                   | 1854       |                         |
|          | C    | 15.2                       | 76                   | 2000       |                         |
| Ma_0.2   | A    | 15.4                       | 72                   | 2129       | 0.97                    |
|          | B    | 15.4                       | 70                   | 2202       |                         |
|          | C    | 15.4                       | 72                   | 2129       |                         |
| Ma_0.3   | A    | 15.5                       | 79                   | 1974       | 1.26                    |
|          | B    | 15.5                       | 99                   | 1566       |                         |
|          | C    | 15.5                       | 91                   | 1703       |                         |

t.o.f. = time of fly; v = velocity of the US wave; v/v<sub>B</sub> = ratio between the velocity of the US wave measured in paths A or C the one hand and B on the other hand.

The results of the test are summarised in Table 3.21. The average values of the velocity measured in path A, B and C are 2049 m/s (Sdev 78), 1874 m/s (Sdev 218) and 1944 (Sdev 318) m/s, respectively. The velocity is higher in the lateral than in the central paths, because bricks are denser than mortar. The only exception is on specimen Ma\_0.2, but the difference of the values is not very high. Perhaps, in this case, voids existed between the bricks and the mortar joints or the mortar was more compact. The last hypothesis is more likely because the values are the highest absolutely.

### 3.9.2 Unit weight

Data on the weight of the brick, mortar and masonry specimens were acquired daily, in order to trace the variation of the unit weight in relation to the amount of water absorbed and to the temperature and relative humidity, during the whole period of the ageing treatment.

### 3.9.3 Compressive strength and stiffness

After the above-mentioned analyses, brick, mortar and masonry specimens underwent destructive test aimed to achieve data on the compressive strength, the stiffness and the stress-strain curve, according to the procedure described in the Section 3.5. The test on the masonry specimens were conducted through a 3000 kN Metrocom testing machine at the Mechanical Testing Laboratory (LASTRU) of the University of Perugia (Italy), while the tests on the bricks and mortar specimens were conducted in a private laboratory through a testing machine equipped with a 50 kN Laumass strain gauge.

### 3.9.4 Moisture content

The values of the weight of the brick, mortar and masonry specimens acquired during the ageing treatment were used to determine the water content of the specimens, through the following equation:

$$m_w = \frac{m_i - m_{dry}}{m_{dry}} 100 [\%] \quad (3.3)$$

where  $m_w$  is the amount of water in percentage;  $m_i$  is the mass of the specimen at the  $i^{\text{th}}$  cycle;  $m_{dry}$  is the mass of the dry specimen.

### 3.9.5 Salts distribution

The distribution of the salts into the masonry specimens which underwent the ageing treatment was determined according to the procedure described in the Section 3.6. Data acquired were compared to those relating to the untreated specimens.

### **3.10 Extension of the acquired results to other types of brickworks**

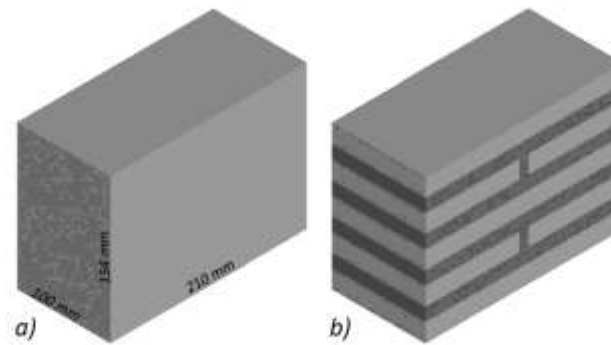
The results of the mechanical test conducted on the masonry specimens are referring to a kind of masonry which was selected among several possible ones (Section 3.2). The purpose of the last part of the research is to understand if it is possible to extend these results to other kind of masonry, starting from the data referring to bricks and mortar specimens. This study will be done using virtual structural models of the masonry specimens used in the previous part of the research, and analysing them through a Finite Element Analysis approach.

Finite Element Analysis (FEA) is an analytical approach which uses a mathematical technique known as the Finite Element Method (FEM) in order to simplify the solving of problems characterised by complex geometries, several loadings and materials. FEM is based on the discretization, that is the approximation of the real object (or scheme design) with a finite number of small elements; the finer their dimension, the better is the approximation. The principle at the basis of the technique can be easily understood when comparing it to the ancient problem of the approximation of the circle through polygons, where the former stands for the object to analyse and the sides of the polygon stand for the elements (Felippa et al., 2004). These can have from one to three spatial dimensions and they are defined and linked to each other by a finite number of points, called nodes. The aim of the analysis is to determine the displacement of all the nodes, which is, in turn, used to calculate stresses and other unknown quantities.

In the field of the building constructions, three main approaches can be used to discretize the analysing object: the macro model, the simplified micro model and the detailed micro model (Laurenço, 1996). Referring to a wall, that is the building element referred to in this research, according to the first approach, it is modelled as a continuous solid, to which a unique homogeneous material is smeared. According to the second approach, bricks are modelled separately but mortar joints are simulated through interface virtual elements. Finally, according to the last approach, both bricks and mortar joints are modelled as independent parts and a different material is assigned to each of them. Despite the deep exemplification, the first approach is widely used in actual applications, when the overall structural behaviour is to be investigated (Castori et al., 2017; Preciado et al., 2017; Betti et al., 2016). However, for the analysis of small parts, or for theoretical applications, the

last two approaches are preferred to the first, because they are more exact (Komurcu and Gedikli, 2019; Abdulla et al., 2017; Zucchini and Lourenço, 2002).

For the purpose of this research, both the macro model and the detailed micro model approach were used. The masonry specimens were modelled both as a unique prism and as a composite object made of independent parts which are bricks and joint. The two models are shown in Figure 3.35.



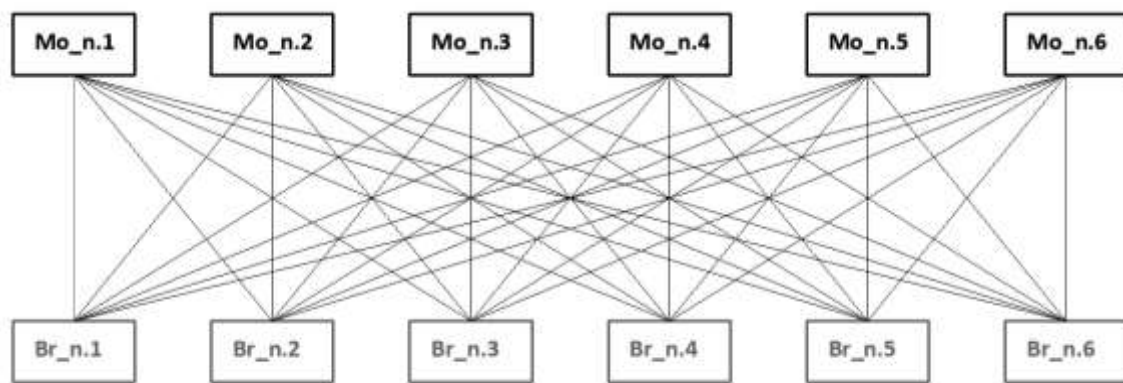
**Figure 3.35.** Masonry virtual specimen used for the FEA. a) macro-model; b) micro-model.

A unique homogeneous material was assigned to the macro-model. It was defined using the values of the unit weight of the masonry specimens acquired during the ageing treatment, and the stress-strain curves obtained from the mechanical tests. As regard the latter, the experimental curves were simplified in two parts. The first part is linear and is defined through the modulus of elasticity. This part ranges from 0 N/mm<sup>2</sup> to the 60% of the maximum value of the stress obtained with the experimental measures. The second part is multilinear, and was defined through the couples of stress-strain points from the value corresponding to the 60% of the maximum, to this one. The Poisson ratio was not determined experimentally, so a constant standard value of 0.25 was assigned to it.

Similarly, the values of the unit weight of the brick and mortar specimens acquired during the ageing treatment, and the stress-strain curves obtained from the mechanical tests, were used to define both the materials assigned to the two parts which constituent the

masonry according to the micro model approach. The Poisson's coefficient used for bricks and mortar is the same used for masonry.

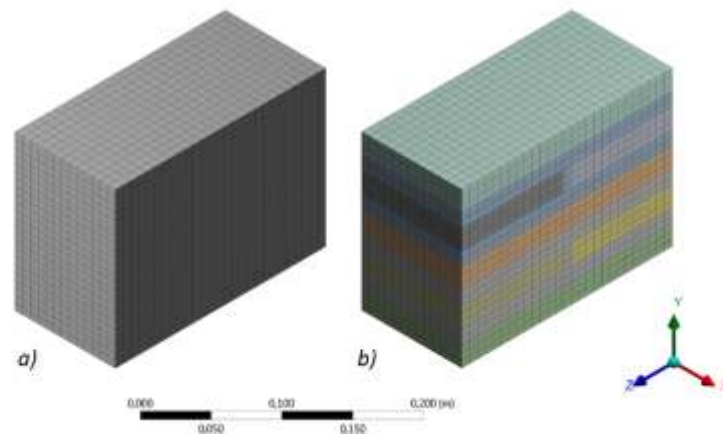
Data derived from the experimental measures and used to define the materials assigned to brick, mortar and masonry, both untreated and treated, were not averaged. For this reason, 36 and 18 different micro-model were made for the untreated specimens, and for each group of the treated specimens respectively, by combining data referring to the brick and the mortar specimens according to the scheme showed in Figure 3.36. Micro-models referring to the untreated specimens are twice compared to those referring to the treated specimens because in the first case six mortar specimens underwent the mechanical test, while they were three in the second case.



**Figure 3.36** Combination criterion of the data used to define materials in FEA. n=0: untreated specimens; n=1: specimens which absorbed deionized water; n=2: specimens which absorbed sodium chloride aqueous solution; n=3: specimens which absorbed sodium sulphate aqueous solution; n=4: specimens which absorbed potassium nitrate aqueous solution.

3D models were created in AutoCAD (Autodesk, 2017 release) and were analysed in Ansys Workbench (Ansys, 18.0 release), which are general-purpose software, used for CAD (Computer-Aided Design) and FEA respectively. The “Solid 186” element type (characterised by 20 nodes and having three degrees of freedom per node) was assigned to them. In micro models, “Contact 174” elements (3D surface-to-surface contact elements) were employed for the interfaces between bricks and masonry. The mesh was generated by using a hexahedron-dominant method of control. The correspondence

between macro and micro-model was assured setting the number of elements of the mesh in the three dimensions. The length, the height and the width of the virtual models were divided in 27, 23 and 13 segments respectively. Figure 3.37 shows the mesh of a macro and micro model.

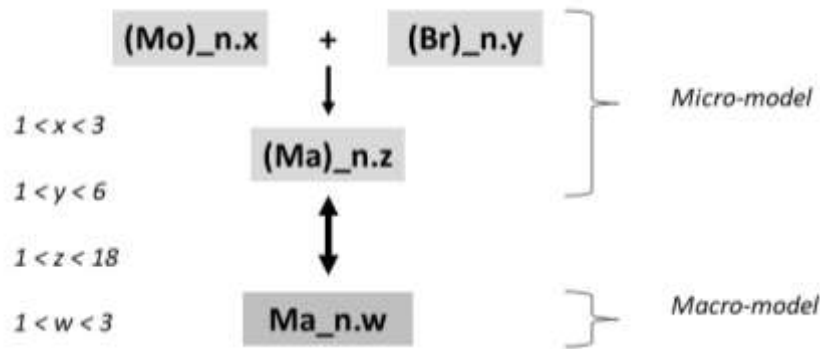


**Figure 3.37.** Virtual model of the masonry specimens used for FEA: a) macro-model; b) micro-model.

The compressive test, performed on the actual specimens, was reproduced in the virtual environment. Virtual models were constrained at the basis and the load was applied in two different steps. In the first step, the standard earth gravity load was applied. Afterward, a vertical displacement of 0.03 m was applied to the uppermost surface of the geometric model, while the displacement in the other two directions was set at 0 m.

Within this research, FEA was used to compare the behaviour of the two kind of masonry virtual models, in order to evaluate if they can be considered equivalent or not. If yes, the micro model approach can be used to model other kind of masonry.

Combining data according to the criterion shown in Figure 3.36, 36 and 18 different results were obtained for the untreated specimens and for each kind of the treated specimens, respectively. These results will be compared to those relating to the macro models and the real specimens, in turn, which underwent the same kind of treatment. The overall logical scheme of the approach used to compare data is shown in Figure 3.38.



**Figure 3.38.** Overall logical scheme of the approach used to compare data. (Mo); (Br); (Ma): virtual specimen; n=0: untreated specimens; n=1: specimens which absorbed deionized water; n=2: specimens which absorbed sodium chloride aqueous solution; n=3: specimens which absorbed sodium sulphate aqueous solution; n=4: specimens which absorbed potassium nitrate aqueous solution.

### 3.11 Discussion of the results

The results of the measures conducted will be discussed during the exposition of the data. Moreover, in the final chapter some considerations on the whole research project will be given, and the main results achieved will be pointed out. The focus will be on the following aspects:

- Assessment of the effectiveness of the ageing treatments designed for the purpose of the research;
- Assessment of the impact of the dry/wet cycles on the variation of the unit weight of the specimens;
- Assessment of the impact of the strong thermal variations on the mechanical performances of the specimens and its construction materials;
- Assessment of the influence of the salts, transported by the water absorbed by capillary action, on the mechanical performance of the specimens;
- Assessment of the effectiveness of the analytical simulations to extend the experimental results to other kind of specimens;
- Limits of the data acquired and further developments of the research.

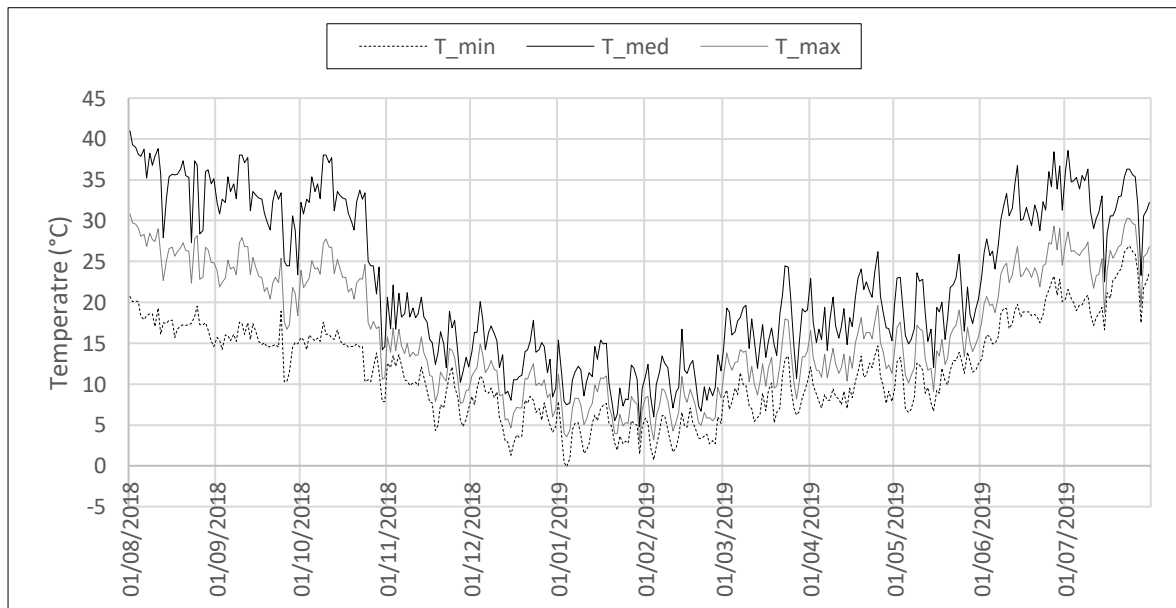
## CHAPTER 4

### Results and discussion

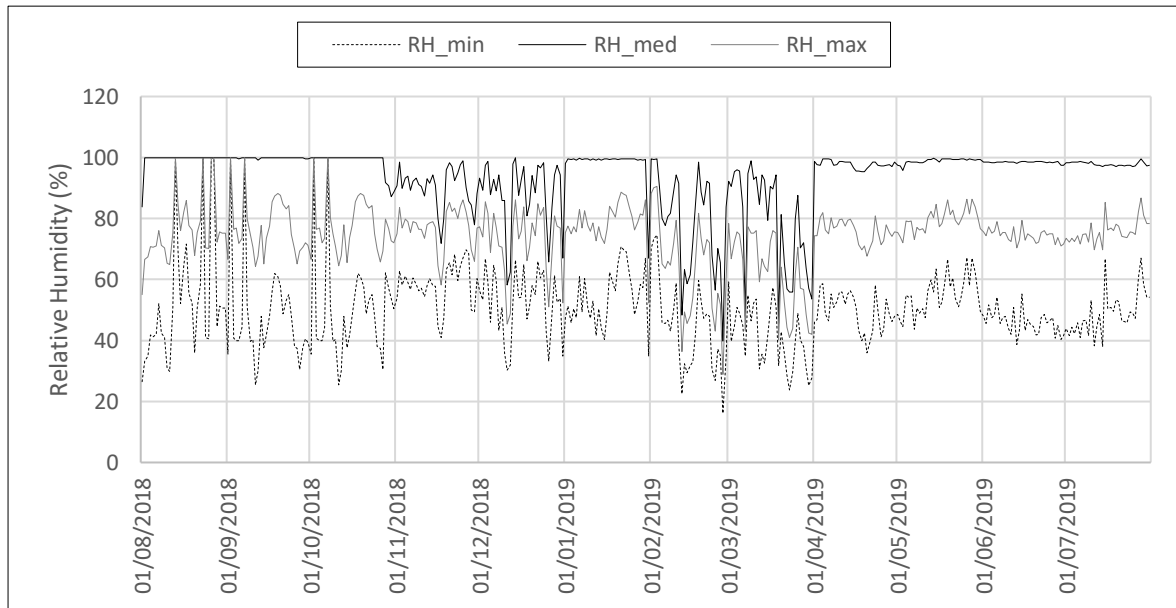
#### 4.1 Reproduction of the phenomenon in the external field

As it was written in Section 3.7, the studied phenomenon was firstly simulated outside. Four triplets of masonry specimens were put in a field, underwent weather events and were forced to absorb water or aqueous solution from the soil.

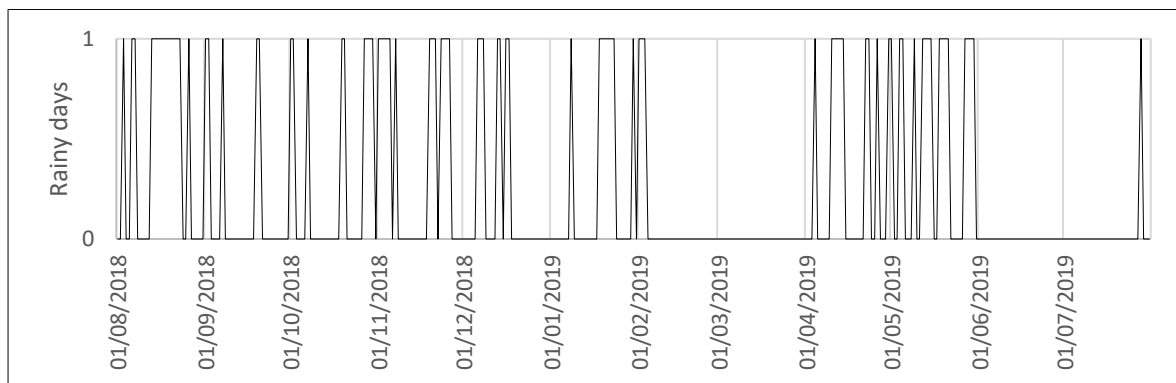
Weather data were measured through a home-made weather station, a project developed by means of the Arduino prototyping system. Data on the environmental temperature and humidity and the rainy periods were recorded every 15 minutes for one year. Figures 4.1 and 4.2 show the curves of the temperature and the relative humidity, while Figure 4.3 shows the distribution of the rainy days over the observation period.



**Figure 4.1.** Curves of the environmental temperature. Data recorded over one year.



**Figure 4.2.** Curves of the relative humidity. Data recorded over one year.



**Figure 4.3.** Rainy days. 0: no rain; 1: rain. Data recorded over one year.

Data reveal that the maximum thermal change occurred in a day was 23.1 °C, recorded in October, while the minimum was 2.7 °C recorded in January. The thermal change was between 0 °C and 10 °C for the 56.44% of the observation period (i.e. 206 days); between 10 °C and 20 °C for the 39.73% (i.e. 145 days) and higher than 20 °C for the 3.84% (i.e. 14 days).

As regard the relative humidity, the maximum values were always around the 99%, recorded during the night or during rainy days, while the minimum value ranged from 16.1% and 43.8%, recorded in February and May respectively.

As regard the rain, data reveal that 87 rainy days occurred in the year of observation. The longest periods occurred in August (11 days consecutively), from the end of October to the beginning of November (10 days), and in May (8 days).

#### 4.1.1 Visual inspection

Figures 4.4 - 4.7 show the sequence of photographs of one among the three masonry specimens belonging to the four groups put outside. For each masonry specimen, the photographs were taken when it was put on the field and after three, six and twelve months. Table 4.1 summarises the weather data relating to the day when the photographs were taken.

**Table 4.1.** Weather parameters referring to the day of the observation of the masonry specimens.

| Date                           | T<br>(°C) | RH<br>(%) |
|--------------------------------|-----------|-----------|
| 1 <sup>st</sup> August 2019    | 35.0      | 38.3      |
| 9 <sup>th</sup> November 2019  | 13.9      | 64.6      |
| 20 <sup>th</sup> February 2019 | 6.1       | 56.2      |
| 29 <sup>th</sup> July 2019     | 25.4      | 61.4      |

The following changes were recorded for all the specimens. After three months, their colour became more saturated, in correspondence of both the mortar and the bricks. Moreover, a part of the lime of the mortar joints was kept away and the pozzolana grains emerged.

Six months later, the condition of the specimens was quite similar. Biological colonization and deposits of earth were visible especially on the surface of the lowest courses of bricks and mortar.

Twelve months later, the biological colonization and the deposits became more and more evident. It is interesting to note that also the sun exposure was significant, since biological colonization was more evident in the north than in the south face of the specimens. Moreover, several detachments between the mortar horizontal joints and the bricks occurred, especially in the specimens exposed to the Na<sub>2</sub>SO<sub>4</sub> aqueous solution.



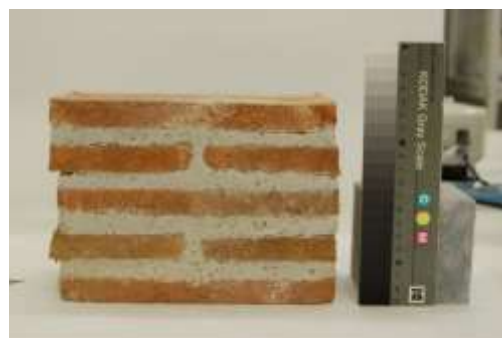
a)



b)



c)

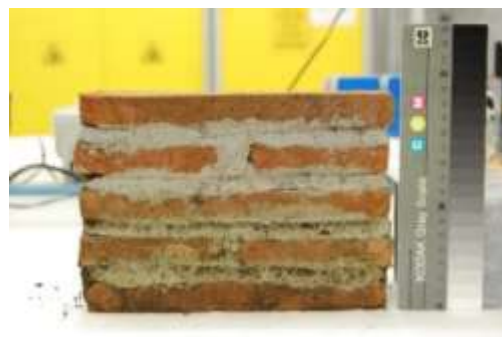


d)

**Figure 4.4.** Masonry specimen Ma\_1.1.1 (no salts in the grave). a) photograph at the start of the treatment; b) photograph after three months; c) photograph after 6 months; d) photograph after 12 months.



a)



b)



c)

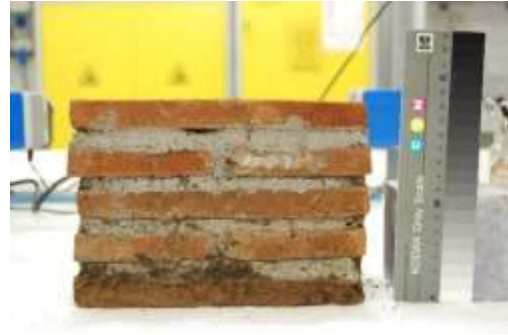


d)

**Figure 4.5.** Masonry specimen Ma\_2.1.1 (NaCl aqueous solution in the grave).



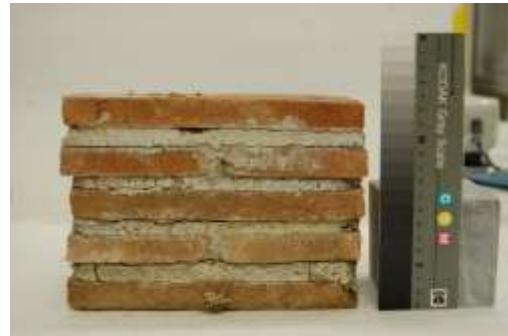
a)



b)



c)

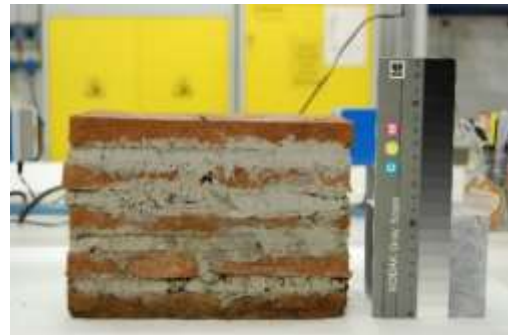


d)

**Figure 4.6.** Masonry specimen Ma\_3.1.1 ( $\text{Na}_2\text{SO}_4$  aqueous solution in the grave).



a)



b)



c)



d)

**Figure 4.7.** Masonry specimen Ma\_4.1.1 ( $\text{KNO}_3$  aqueous solution in the grave).

#### 4.1.2 Weight

Since the specimens were exposed to variable thermal and hygrometric conditions, even their weight changed continuously, according to the amount of water absorbed and released by themselves. As wrote in Section 3.7, the weight of the specimens was recorded only three times over the observing period. Data relating to all kind of specimens are summarised in Tables 4.2 – 4.5. They are compared to the dry weight and to the weight measured before exposing specimens outside. The values of the external temperature and relative humidity, which measures are referring to, are those in Table 4.1.

Data reveal that the weight changed according to the external temperature and relative humidity, recorded when the measure was done. The maximum increase in the weight was recorded after 12 months. It was 24.60% (average value) for the specimens exposed to water, and 22.53%, 24.07%, 24.98% for the specimens exposed to sodium chloride, sodium sulphate and potassium nitrate aqueous solutions, respectively.

**Table 4.2.** Weight of the specimens exposed to water.

| <b>Specimen</b> | <b>Dry<br/>(g)</b> | <b>At the start of<br/>the treatment<br/>(g)</b> | <b>After 3<br/>months<br/>(g)</b> | <b>After 6<br/>months<br/>(g)</b> | <b>After 12<br/>months<br/>(g)</b> |
|-----------------|--------------------|--------------------------------------------------|-----------------------------------|-----------------------------------|------------------------------------|
| Ma_1.1.1        | 4740               | 5214                                             | 5668                              | 5256                              | 5916                               |
| Ma_1.2.1        | 5056               | 5562                                             | 6100                              | 5567                              | 6280                               |
| Ma_1.3.1        | 5186               | 5704                                             | 6206                              | 5779                              | 6446                               |
| Average         | 4994               | 5493                                             | 5991                              | 5534                              | 6214                               |
| Sdev            | (229)              | (252)                                            | (285)                             | (263)                             | (271)                              |

**Table 4.3.** Weight of the specimens exposed to NaCl aqueous solution.

| <b>Specimen</b> | <b>Dry<br/>(g)</b> | <b>At the start of<br/>the treatment<br/>(g)</b> | <b>After 3<br/>months<br/>(g)</b> | <b>After 6<br/>months<br/>(g)</b> | <b>After 12<br/>months<br/>(g)</b> |
|-----------------|--------------------|--------------------------------------------------|-----------------------------------|-----------------------------------|------------------------------------|
| Ma_2.1.1        | 4754               | 5228                                             | 5756                              | 5452                              | 5914                               |
| Ma_2.2.1        | 4846               | 5330                                             | 5828                              | 5484                              | 5904                               |
| Ma_2.3.1        | 4900               | 5390                                             | 5896                              | 5546                              | 5946                               |
| Average         | 4833               | 5316                                             | 5827                              | 5494                              | 5921                               |
| Sdev            | (74)               | (82)                                             | (70)                              | (48)                              | (22)                               |

**Table 4.4.** Weight of the specimens exposed to Na<sub>2</sub>SO<sub>4</sub> aqueous solution.

| Specimen | Dry<br>(g) | At the start of<br>the treatment<br>(g) | After 3<br>months<br>(g) | After 6<br>months<br>(g) | After 12<br>months<br>(g) |
|----------|------------|-----------------------------------------|--------------------------|--------------------------|---------------------------|
| Ma_3.1.1 | 4776       | 5250                                    | 5800                     | 5232                     | 6016                      |
| Ma_3.2.1 | 4904       | 5394                                    | 5982                     | 5468                     | 6054                      |
| Ma_3.3.1 | 4964       | 5460                                    | 5948                     | 5446                     | 6096                      |
| Average  | 4881       | 5368                                    | 5910                     | 5382                     | 6055                      |
| Sdev     | (96)       | (107)                                   | (97)                     | (130)                    | (40)                      |

**Table 4.5.** Weight of the specimens exposed to KNO<sub>3</sub> aqueous solution.

| Specimen | Dry<br>(g) | At the start of<br>the treatment<br>(g) | After 3<br>months<br>(g) | After 6<br>months<br>(g) | After 12<br>months<br>(g) |
|----------|------------|-----------------------------------------|--------------------------|--------------------------|---------------------------|
| Ma_4.1.1 | 4774       | 5250                                    | 5774                     | 5302                     | 5972                      |
| Ma_4.2.1 | 4748       | 5222                                    | 5746                     | 5236                     | 5938                      |
| Ma_4.3.1 | 4988       | 5486                                    | 6066                     | 5568                     | 6224                      |
| Average  | 4837       | 5319                                    | 5862                     | 5369                     | 6045                      |
| Sdev     | (132)      | (145)                                   | (177)                    | (176)                    | (156)                     |

It is important to note that the weight measured takes into account also the presence of earth deposits, efflorescences, and biological colonization. It was not possible to set these effects aside.

#### 4.1.3 Compressive strength and stiffness

After 12 months, masonry specimens were taken away from the field and underwent a mechanical test to evaluate their compressive strength ( $\sigma_{\max}$ ) and their modulus of elasticity (E), according to the method described in Section 3.5. *Attachment 4* contains the stress-strains curves referring to all the specimens.

Data acquired are summarised in Tables 4.6 - 4.9. They relate to the weight the specimens had when the test was performed, and so to their water content. The test was not performed immediately after the specimens were taken away from the field. However, the difference between the last two values of the weight was less than 0.01%.

**Table 4.6.** Mechanical properties of the specimens exposed to water  
(mean test conditions: T = 23.4 °C RH = 60%).

| Specimen | Weight<br>(g) | H <sub>2</sub> O content<br>(%) | $\sigma_{\max}$<br>(N/mm <sup>2</sup> ) | E<br>(N/mm <sup>2</sup> ) |
|----------|---------------|---------------------------------|-----------------------------------------|---------------------------|
| Ma_1.1.1 | 5906          | 24.60                           | 7.54                                    | 167.4                     |
| Ma_1.2.1 | 6268          | 23.97                           | 9.07                                    | 215.7                     |
| Ma_1.3.1 | 6434          | 24.06                           | 10.42                                   | 323.5                     |
| Average  | 6203          | 24.21                           | 9.01                                    | 235.5                     |
| Sdev     | (270)         | (0.34)                          | (1.18)                                  | (65.3)                    |

**Table 4.7.** Mechanical properties of the specimens exposed to NaCl aqueous solution  
(mean test conditions: T = 23.4 °C RH = 60%).

| Specimen | Weight<br>(g) | H <sub>2</sub> O content<br>(%) | $\sigma_{\max}$<br>(N/mm <sup>2</sup> ) | E<br>(N/mm <sup>2</sup> ) |
|----------|---------------|---------------------------------|-----------------------------------------|---------------------------|
| Ma_2.1.1 | 5904          | 24.19                           | 6.34                                    | 117.2                     |
| Ma_2.2.1 | 5896          | 21.67                           | 6.57                                    | 116.8                     |
| Ma_2.3.1 | 5938          | 21.18                           | 6.62                                    | 167.6                     |
| Average  | 5913          | 22.35                           | 6.51                                    | 133.9                     |
| Sdev     | (22)          | (1.61)                          | (0.12)                                  | (23.9)                    |

**Table 4.8.** Mechanical properties of the specimens exposed to Na<sub>2</sub>SO<sub>4</sub> aqueous solution  
(mean test conditions: T = 23.4 °C RH = 60%).

| Specimen | Weight<br>(g) | H <sub>2</sub> O content<br>(%) | $\sigma_{\max}$<br>(N/mm <sup>2</sup> ) | E<br>(N/mm <sup>2</sup> ) |
|----------|---------------|---------------------------------|-----------------------------------------|---------------------------|
| Ma_3.1.1 | 6004          | 25.71                           | 7.52                                    | 145.6                     |
| Ma_3.2.1 | 6042          | 23.21                           | 7.15                                    | 85.9                      |
| Ma_3.3.1 | 6084          | 22.56                           | 6.28                                    | 92.6                      |
| Average  | 6043          | 23.83                           | 6.98                                    | 108.0                     |
| Sdev     | (40)          | (1.66)                          | (0.52)                                  | (26.7)                    |

**Table 4.9.** Mechanical properties of the specimens exposed to KNO<sub>3</sub> aqueous solution  
(mean test conditions: T = 23.4 °C RH = 60%).

| Specimen | Weight<br>(g) | H <sub>2</sub> O content<br>(%) | $\sigma_{\max}$<br>(N/mm <sup>2</sup> ) | E<br>(N/mm <sup>2</sup> ) |
|----------|---------------|---------------------------------|-----------------------------------------|---------------------------|
| Ma_4.1.1 | 5962          | 24.88                           | 8.46                                    | 194.8                     |
| Ma_4.2.1 | 5928          | 24.85                           | 7.95                                    | 199.9                     |
| Ma_4.3.1 | 6212          | 24.54                           | 7.48                                    | 181.2                     |
| Average  | 6034          | 24.76                           | 7.96                                    | 192.0                     |
| Sdev     | (155)         | (0.19)                          | (0.40)                                  | (7.9)                     |

**Table 4.10.** Comparison among the mechanical properties of all the specimens in the field and the untreated specimens.

| Untreated                               |                           | H <sub>2</sub> O                        |                           | NaCl                                    |                           | Na <sub>2</sub> SO <sub>4</sub>         |                           | KNO <sub>3</sub>                        |                           |
|-----------------------------------------|---------------------------|-----------------------------------------|---------------------------|-----------------------------------------|---------------------------|-----------------------------------------|---------------------------|-----------------------------------------|---------------------------|
| $\sigma_{\max}$<br>(N/mm <sup>2</sup> ) | E<br>(N/mm <sup>2</sup> ) | $\sigma_{\max}$<br>(N/mm <sup>2</sup> ) | E<br>(N/mm <sup>2</sup> ) | $\sigma_{\max}$<br>(N/mm <sup>2</sup> ) | E<br>(N/mm <sup>2</sup> ) | $\sigma_{\max}$<br>(N/mm <sup>2</sup> ) | E<br>(N/mm <sup>2</sup> ) | $\sigma_{\max}$<br>(N/mm <sup>2</sup> ) | E<br>(N/mm <sup>2</sup> ) |
|                                         |                           | 10.42                                   | 323.6                     |                                         |                           |                                         |                           |                                         |                           |
| 9.22                                    | 166.4                     |                                         |                           |                                         |                           |                                         |                           |                                         |                           |
| 8.74                                    | 189.2                     | 9.07                                    | 215.7                     |                                         |                           |                                         |                           | 8.46                                    | 194.7                     |
| 8.14                                    | 161.4                     |                                         |                           |                                         |                           |                                         |                           | 7.95                                    | 199.9                     |
|                                         |                           | 7.54                                    | 167.4                     |                                         |                           |                                         |                           | 7.48                                    | 181.2                     |
|                                         |                           |                                         |                           |                                         |                           | 7.52                                    | 145.6                     |                                         |                           |
|                                         |                           |                                         |                           |                                         |                           | 7.15                                    | 85.9                      |                                         |                           |
|                                         |                           |                                         |                           | 6.62                                    | 167.6                     |                                         |                           |                                         |                           |
|                                         |                           |                                         |                           | 6.57                                    | 716.8                     |                                         |                           |                                         |                           |
|                                         |                           |                                         |                           | 6.34                                    | 117.3                     |                                         |                           |                                         |                           |
|                                         |                           |                                         |                           |                                         |                           | 6.28                                    | 92.6                      |                                         |                           |

Table 4.10 shows data referring to all kind of specimens and compared to those relating to the untreated ones (Section 3.5).

The values of the compressive strength of the specimens exposed to water are very similar to those referring to the untreated specimens. The average value of the compressive strength is even 3.56% greater in the former than in the latter, while the modulus of elasticity is 36.71% greater. This result may be due to the fact that specimens are handmade.

As regard the specimens exposed to sodium chloride aqueous solution, the average value of the compressive strength is 25.17% lower than that referring to the untreated specimens, while the average value of the modulus of elasticity is 93.75% greater.

As regard the specimens exposed to sodium sulphate aqueous solution, the average value of the compressive strength and the average value of the modulus of elasticity are 19.73% and 37.33% lower respectively.

As regard the specimens exposed to potassium nitrate aqueous solution, the average value of the compressive strength is 8.47% lower than that referring to the untreated specimens, while the average value of the modulus of elasticity is 11.39% greater.

Overall, specimens exposed to sodium chloride aqueous solution has the lowest values of the compressive strength. They are followed by the specimens exposed to sodium sulphate and potassium nitrate, respectively. These results prove that the effect of the salts on the mechanical features of the specimens is surely one of the most meaningful, so it was a start point to organise the ageing treatment in laboratory.

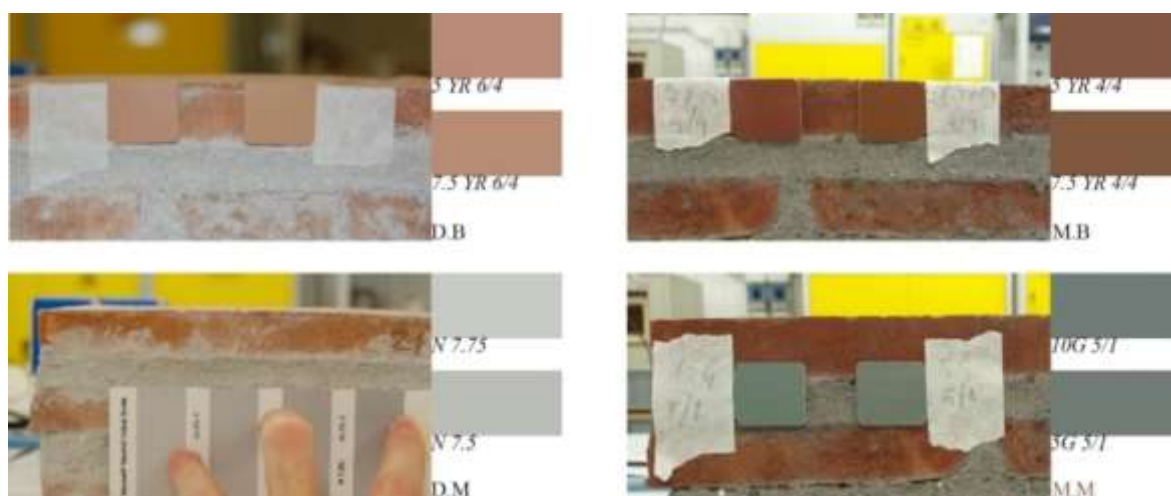
## 4.2 Ageing treatment in the laboratory

### 4.2.1 Visual inspection and instrumental diagnosis

As it was written in Section 3.9.1, the analysis of the visible signs on the masonry specimens which underwent the ageing treatment in laboratory was done by recording the colour changes, the efflorescences and the detachments between mortar joints and bricks.

**Table 4.11.** Color changes of bricks and mortar.

| Condition  |        | Hue   | Value | Chroma | Reflectivity (%) |
|------------|--------|-------|-------|--------|------------------|
| Un-Treated | Brick  | 5YR   | 6     | 4      | -                |
|            | Brick  | 7.5YR | 6     | 4      | -                |
|            | Mortar | 7.75N | 7     | 0      | 54.8             |
|            | Mortar | 7.5N  | 7     | 0      | 50.7             |
| Treated    | Brick  | 5YR   | 4     | 4      | -                |
|            | Brick  | 7.5YR | 4     | 4      | -                |
|            | Mortar | 10G   | 5     | 1      | -                |
|            | Mortar | 5G    | 5     | 1      | -                |



**Figure 4.8.** Color changes between untreated (left) and treated (right) bricks and mortar joints.

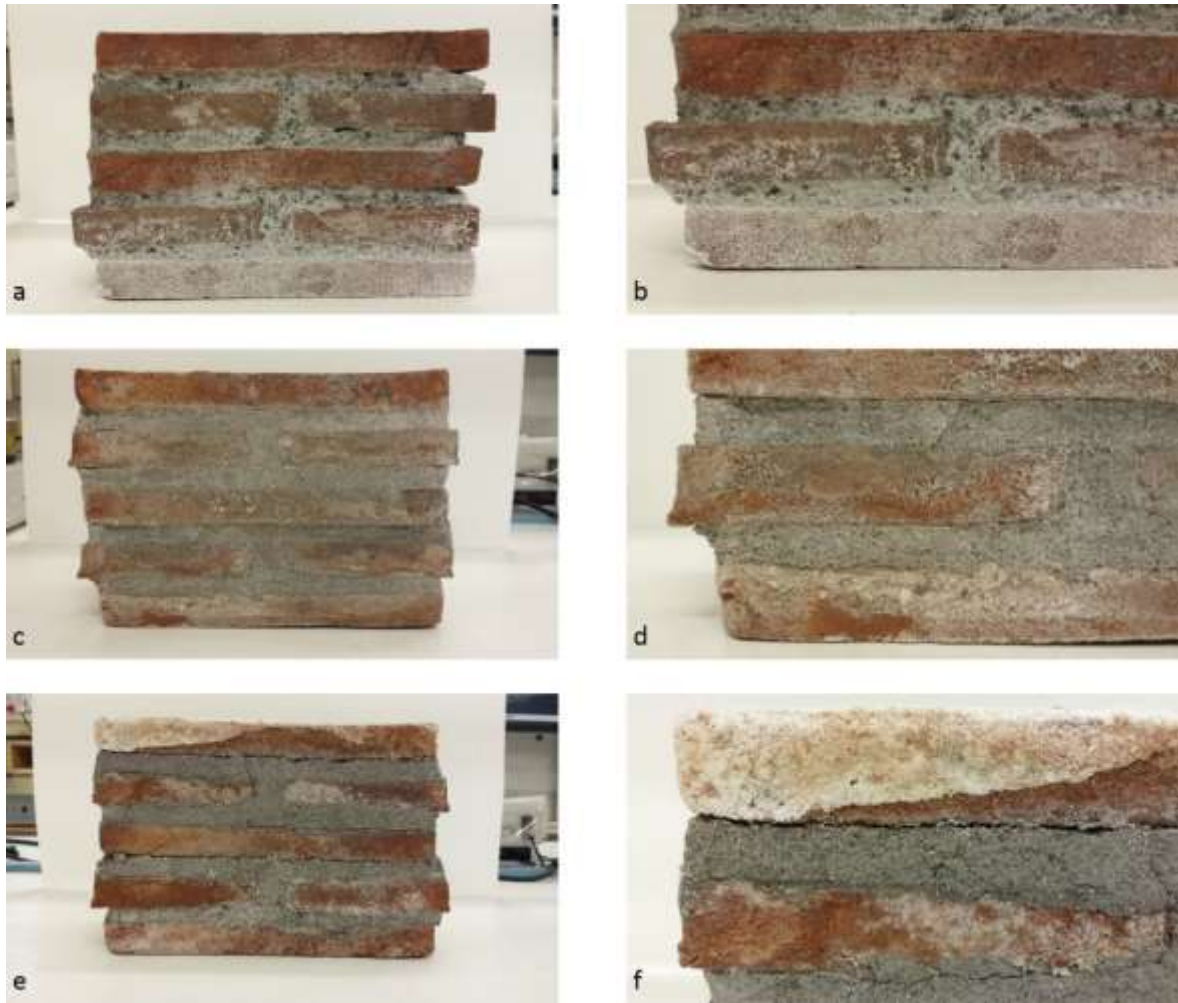
As regard the colour changes, a comparison with the palettes of the Munsell's book of colour was done. Treated wet masonry specimens showed a change of color, compared to the untreated ones. Test results relating to the bricks and the mortar joints in one of the masonry specimens exposed to deionized water are summarized in Table 4.11, and in Figure 4.8.

According to the Munsell reference, the color of any material can be defined using three components that are Hue, Value (degree of lightness/darkness) and Chroma (color purity). By referring to the masonry specimens used in this research, the color of the bricks changed from dull orange to dull reddish brown, that is, Hue and Chroma did not change, while Value decreased. As regard mortar joints, in untreated condition they were greenish-white, belonging to the neutral color palettes, while after the treatment, they turned to greenish grey, belonging to the green tonal palettes.

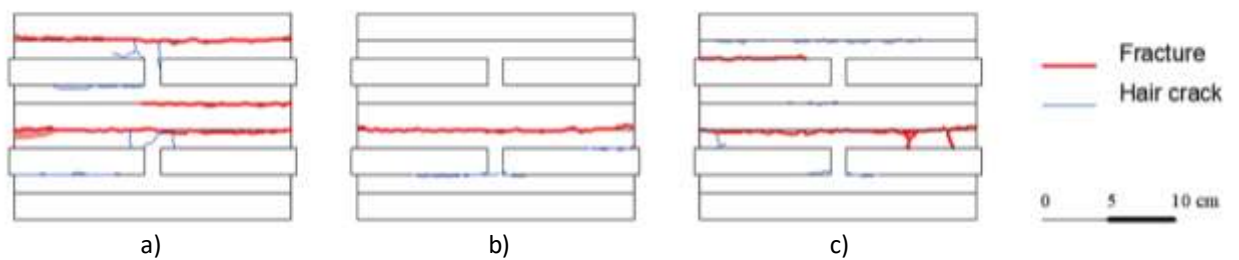
The results shown hereinabove relate only to one among the treated specimens, but they are representative of all of them.

Specimens exposed to the absorption of sodium chloride and potassium nitrate aqueous solutions show both a change of colour and efflorescences, visible in the Figure 4.9 a) b) c) d). In the first case they are whitish and form small regular polygons on the surface of the brick and mortar. In the second case they look like little white needles coming out of the specimen surfaces.

Efflorescence and colour variation are also visible in the specimens exposed to the absorption of sodium sulphate aqueous solution, but in this case the salts have also produced cracks in the mortar, expulsions of some parts and detachments between bricks and mortar joints, due to the increase in volume of the salts crystals. The efflorescences on one among the three specimens and a detail of them are shown in Figure 4.9 e) f), while the map of the cracks on the three specimens is shown in Figure 4.10.



**Figure 4.9.** Damages in masonry specimens exposed to: a) b) sodium chloride; c) d) potassium nitrate; e) f) sodium sulphate.



**Figure 4.10.** Maps of the detachments and cracks in masonry specimens exposed to sodium sulphate: a) Ma\_3.1; b) Ma\_3.2; c) Ma\_3.3.

Results are consistent with data found in literature, quoted in Section 3.6. It is interesting to underline that efflorescences appeared immediately after the first cycle. In the specimens exposed to sodium chloride aqueous solution they spread not only in the lower

part of the specimen, but also in the uppermost part. As regard specimens exposed to potassium nitrate aqueous solution, salts rose slowly. As regard specimens exposed to sodium sulphate aqueous solutions, they rest mainly in the lowest part.

For all masonry specimens, detachments and cracks were characterised through a US test. The method used to conduct the US test was described in the Section 3.9.1. The results of the test are summarised in Tables 4.12 – 4.15 which contain the following data: the length of the path; the time of fly (t.o.f.) of the US wave, the velocity of the US wave, and the ratio between the velocity measured in the lateral and the central paths.

**Table 4.12.** Results of the US test carried on the masonry specimens exposed to deionized water.

| Specimen | Path | Length of the path<br>(cm) | t.o.f.<br>( $\mu$ s) | v<br>(m/s) | v/v <sub>B</sub><br>(-) |
|----------|------|----------------------------|----------------------|------------|-------------------------|
| Ma_1.1   | A    | 15.5                       | 104                  | 1490       | 1.69                    |
|          | B    | 15.5                       | 175                  | 884        | -                       |
|          | C    | 15.5                       | 106                  | 1462       | 1.65                    |
| Ma_1.2   | A    | 15.4                       | 78                   | 1977       | 1.16                    |
|          | B    | 15.4                       | 91                   | 1699       | -                       |
|          | C    | 15.4                       | 79                   | 1957       | 1.15                    |
| Ma_1.3   | A    | 15.5                       | 106                  | 1467       | 0.98                    |
|          | B    | 15.5                       | 103                  | 1502       | -                       |
|          | C    | 15.5                       | 99                   | 1562       | 1.04                    |

**Table 4.13.** Results of the US test carried on the masonry specimens exposed to sodium chloride aqueous solution.

| Specimen | Path | Length of the path<br>(cm) | t.o.f.<br>( $\mu$ s) | v<br>(m/s) | v/v <sub>B</sub><br>(-) |
|----------|------|----------------------------|----------------------|------------|-------------------------|
| Ma_2.1   | A    | 15.6                       | 83                   | 1875       | 1.13                    |
|          | B    | 15.6                       | 94                   | 1659       |                         |
|          | C    | 15.6                       | 91                   | 1720       | 1.04                    |
| Ma_2.2   | A    | 15.5                       | 85                   | 1825       | 1.20                    |
|          | B    | 15.5                       | 102                  | 1525       |                         |
|          | C    | 15.5                       | 96                   | 1619       | 1.06                    |
| Ma_2.3   | A    | 15.5                       | 98                   | 1575       | 0.92                    |
|          | B    | 15.5                       | 91                   | 1704       |                         |
|          | C    | 15.5                       | 98                   | 1575       | 0.92                    |

**Table 4.14.** Results of the US test carried on the masonry specimens exposed to sodium sulphate aqueous solution.

| Specimen | Path | Length of the path (cm) | t.o.f. ( $\mu$ s) | v (m/s) | v/v_B (-) |
|----------|------|-------------------------|-------------------|---------|-----------|
| Ma_3.1   | A    | 15.5                    | 150               | 1030    | 0.96      |
|          | B    | 15.5                    | 144               | 1077    | -         |
|          | C    | 15.5                    | 112               | 1386    | 1.29      |
| Ma_3.2   | A    | 15.5                    | 99                | 1562    | 1.33      |
|          | B    | 15.5                    | 132               | 1171    | -         |
|          | C    | 15.5                    | 121               | 1284    | 1.10      |
| Ma_3.3   | A    | 15.5                    | 129               | 1201    | 0.98      |
|          | B    | 15.5                    | 127               | 1225    | -         |
|          | C    | 15.5                    | 122               | 1275    | 1.04      |

**Table 4.15.** Results of the US test carried on the masonry specimens exposed to potassium nitrate aqueous solution.

| Specimen | Path | Length of the path (cm) | t.o.f. ( $\mu$ s) | v (m/s) | v/v_B (-) |
|----------|------|-------------------------|-------------------|---------|-----------|
| Ma_4.1   | A    | 15.6                    | 89                | 1753    | 1.13      |
|          | B    | 15.6                    | 101               | 1545    | -         |
|          | C    | 15.6                    | 94                | 1660    | 1.07      |
| Ma_4.2   | A    | 15.4                    | 85                | 1812    | 1.24      |
|          | B    | 15.4                    | 105               | 1467    | -         |
|          | C    | 15.4                    | 87                | 1770    | 1.21      |
| Ma_4.3   | A    | 15.5                    | 90                | 1722    | 1.17      |
|          | B    | 15.5                    | 105               | 1476    | -         |
|          | C    | 15.5                    | 94                | 1649    | 1.12      |

Table 4.12 shows data relating to the specimens exposed to deionized water. The average values of the velocity measured in paths A, B and C are 1645 m/s (Sdev 288), 1362 m/s (Sdev 425) and 1661 (Sdev 262) m/s, respectively. The velocity is higher in the lateral than in the central paths; the only exception is on specimen Ma\_1.3, where one of the two measures referring to the lateral paths is lower, but the difference of the values is not very high. Comparing these results with those relating to the untreated specimens, it is clear that the presence of the water causes a decrease in the velocity. The ratio between the average values referring to paths A, B, And C in the treated and untreated specimens is 0.80, 0.73, 0.85, respectively.

Table 4.13 shows data relating to the specimens exposed to sodium chloride aqueous solutions. The average values of the velocity measured in paths A, B and C are 1758 m/s (Sdev 161), 1629 m/s (Sdev 94) and 1638 (Sdev 74) m/s, respectively. The velocity is higher

in the lateral than in the central paths, except for the specimen Ma\_2.3. Perhaps, in this case, the mortar was more compact than in the other specimens, or inborn voids existed between the bricks and the mortar joints, but they are not visible from outside. Overall, comparing these results with those relating to the untreated specimens, it is clear that the presence of the water causes a decrease in the velocity, as well as in the previous group.

Table 4.14 shows data relating to the specimens exposed to sodium sulphate aqueous solutions. The average values of the velocity measured in paths A, B and C are 1265 m/s (Sdev 272), 1158 m/s (Sdev 75) and 1315 (Sdev 72) m/s, respectively. In this case, only in the specimen Ma\_3.2 the velocity is higher in the lateral than in the central paths, while in the others it is not. Really, this result could be due to the presence of cracks which are also naked-eye visible, as shown in Figure 4.10. The effect of the detachments is also proved by the values of the velocity which are even lower than those relating to the other treated specimens. The number of detachments is also meaningful, since the greater is it, the lower is the US velocity.

Table 4.15 shows data relating to the specimens exposed to potassium nitrate aqueous solutions. The average values of the velocity measured in paths A, B and C are 1762 m/s (Sdev 46), 1496 m/s (Sdev 42) and 1693 (Sdev 67) m/s, respectively. In all the specimens, the velocity is higher in the lateral than in the central paths, and the values are the highest among those relating to all the treated specimens.

#### *4.2.2 Unit weight*

Measures conducted on the specimens exposed outside, proved that the weight of the specimens themselves changes according to the environmental conditions. The ageing treatment described in the Section 3.8 allowed to study carefully how the weight of the specimens changed because of the presence of the water, when they were exposed to different environmental conditions.

Table 4.16 reports the values of the environmental parameters which the specimens underwent during the ageing treatment ( $T_{env}$  and RH). These data relate to the surface temperature ( $T_{surf}$ ), and the average values of the weight ( $w$ ). It is worth noting that the specimens were exposed to a severe temperature, ranging between +60 °C to -18 °C, but

during each cycle, their surface temperature ranged only from -5.2 to +46.1 °C. These values reflect the actual weather conditions in the external field.

**Table 4.16.** Mean values of the RH,  $T_{env}$ ,  $T_{surf}$  and weight of masonry specimens in different conditions.

| Conditions          | RH (%) | $T_{env}$ (°C) | $T_{surf}$ (°C) | w (g) |
|---------------------|--------|----------------|-----------------|-------|
| Untreated           | 40     | 20.8           | 20.4            | 5012  |
| Before ice          | 34     | 21.5           | 21.3            | 6165  |
| In ice (-18 °C)     | 100    | 20.5           | -5.2            | -     |
| After oven (+60 °C) | 37     | 20.6           | 46.1            | 6008  |

The values of the unit weight were determined during all the cycles, in order to evaluate how this parameter changed over the time, according to the environmental conditions which the specimens were exposed to.

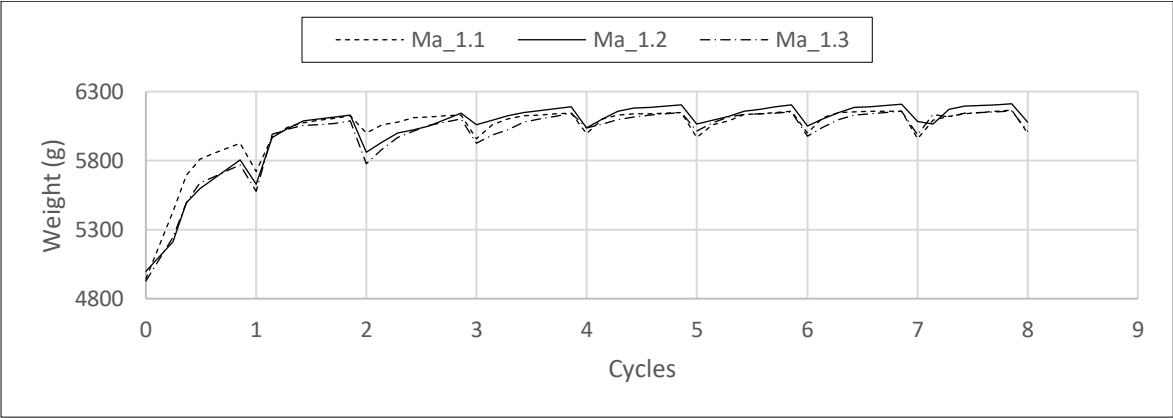
As regard the masonry specimens exposed to deionized water, Figure 4.11 shows the variation of the weight during the ageing treatment, while Figure 4.12 shows the maximum and minimum values of the weight measured for each cycle. They are averaged over the three specimens and related to the respective average values over the last seven cycles (dashed line and continuous line), and to the average value before the start of the ageing treatment (dashed-dot line).

The weight of the masonry specimens increased by 12.59% (from 5012 g to 5643 g) during the first ageing cycle, and it further increased by 8.36% during the second (from 5643 g to 6115 g). The minimum and the maximum values of the weight stabilized at the end of the second and third cycle, respectively. The mean values were 6030 g and 6166 g respectively, corresponding to an increase of 20.31% and 23.02% from the initial weight (5012 g). The standard deviation was 20 and 116 g respectively. The two values of the weight are the thresholds within which the weight of the treated masonry specimens varied. The latter is very similar to that obtained from the absorption test at atmospheric pressure (6202 g).

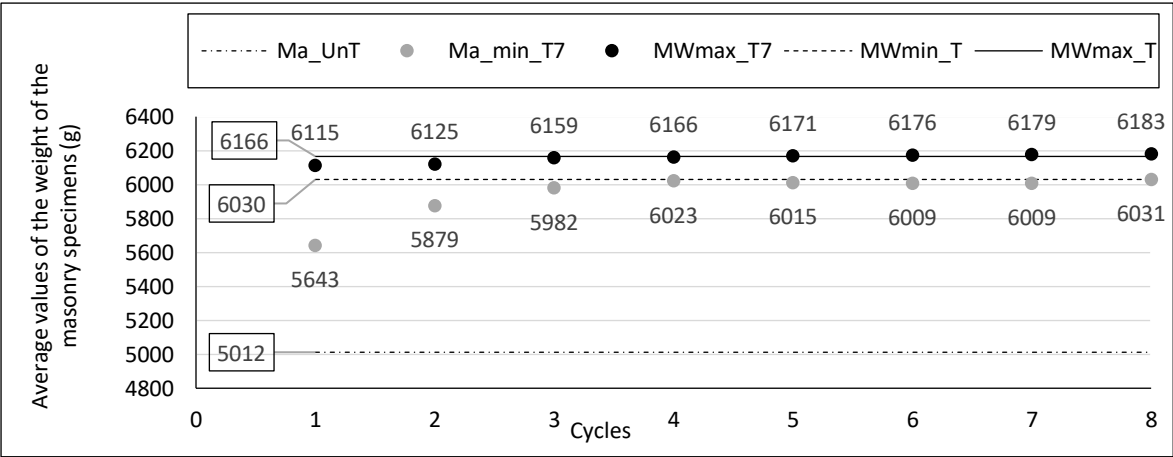
Table 4.17 summarises the average values of the weight of the same masonry specimens, untreated and exposed to deionized water. For the treated specimens, seven weight values

are reported, one for each step (i.e, 24 hour) of the ageing treatment. Starting from these data, the unit weight of the untreated and treated specimens was determined.

Similarly, data referring to the masonry specimens exposed to the other salts aqueous solutions are summarised in Figures 4.13 – 4.18 and in Tables 4.18 - 4.20.



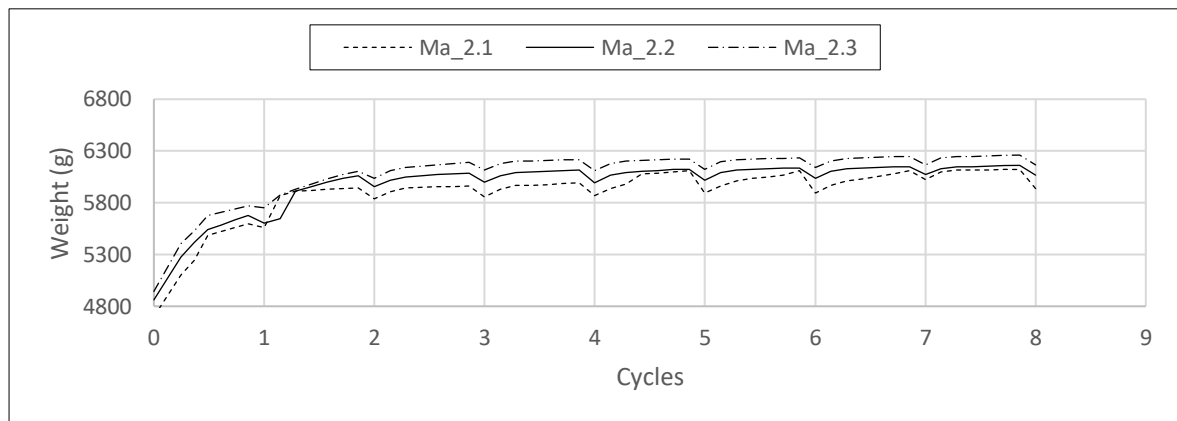
**Figure 4.11.** Variation of the weight during the ageing treatment (masonry specimens exposed to water).



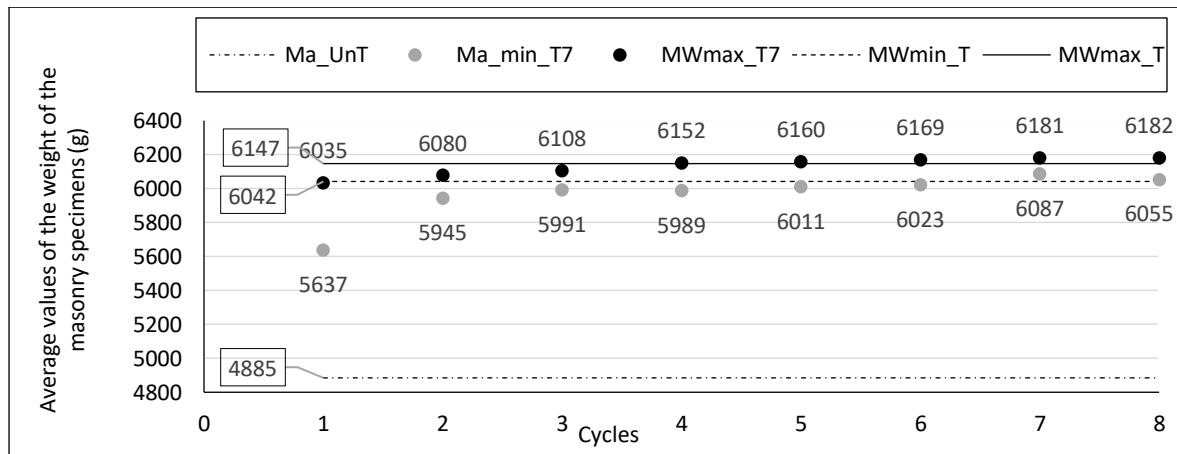
**Figure 4.12.** Average values of the weight over each cycle (masonry specimens exposed to water), MW\_UnT = mean weight of the untreated specimens, MWmin\_T = minimum mean weight of the treated specimens, MWmax\_T = maximum mean weight of the treated specimens; MWmin\_T7 = minimum mean weight of the treated specimens, over the last 7 cycles, MWmax\_T7 = maximum mean weight of the treated specimens, over the last 7 cycles.

**Table 4.17.** Variation of the weight during one cycle (masonry specimens exposed to water).

| Conditions | Weight            |          | Water content |      | Unit weight (g) |
|------------|-------------------|----------|---------------|------|-----------------|
|            | Average value (g) | Sdev (g) | (g)           | (%)  |                 |
| Untreated  | 5012              | (39)     | 0             | 0    | 1550            |
| Treated    | Step 1            | 6031     | (42)          | 1019 | 20.33           |
|            | Step 2            | 6073     | (24)          | 1061 | 21.18           |
|            | Step 3            | 6114     | (26)          | 1102 | 21.99           |
|            | Step 4            | 6138     | (25)          | 1126 | 22.47           |
|            | Step 5            | 6153     | (24)          | 1141 | 22.77           |
|            | Step 6            | 6168     | (25)          | 1156 | 23.07           |
|            | Step 7            | 6183     | (26)          | 1171 | 23.37           |



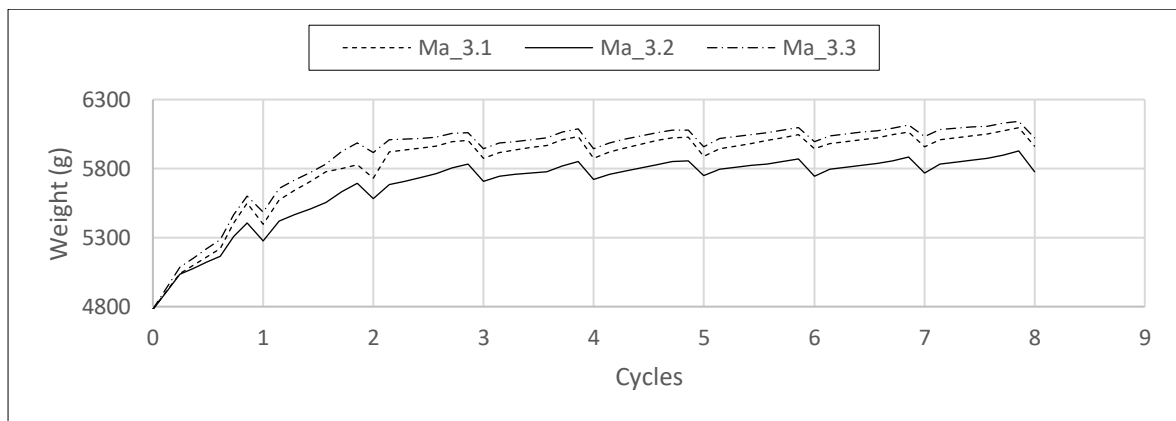
**Figure 4.13.** Variation of the weight during the ageing treatment (masonry specimens exposed to sodium chloride aqueous solution).



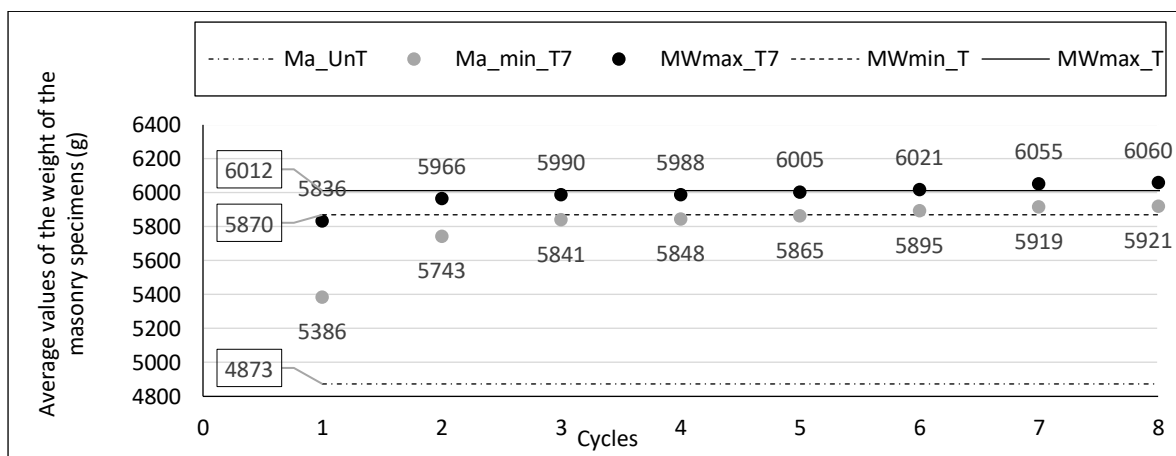
**Figure 4.14.** Average values of the weight over each cycle (masonry specimens exposed to sodium chloride aqueous solution).

**Table 4.18.** Variation of the weight during one cycle (masonry specimens exposed to sodium chloride aqueous solution).

| Conditions | Weight            |          | Water content |       | Unit weight (g) |
|------------|-------------------|----------|---------------|-------|-----------------|
|            | Average value (g) | Sdev (g) | (g)           | (%)   |                 |
| Untreated  | 4885              | (122)    | 0             | 0     | 1510            |
| Treated    | Step 1            | 6055     | 1170          | 23.95 | 1872            |
|            | Step 2            | 6111     | 1227          | 25.11 | 1890            |
|            | Step 3            | 6136     | 1252          | 25.62 | 1897            |
|            | Step 4            | 6138     | 1254          | 25.67 | 1898            |
|            | Step 5            | 6141     | 1256          | 25.72 | 1899            |
|            | Step 6            | 6145     | 1260          | 25.80 | 1900            |
|            | Step 7            | 6182     | 1297          | 26.55 | 1911            |



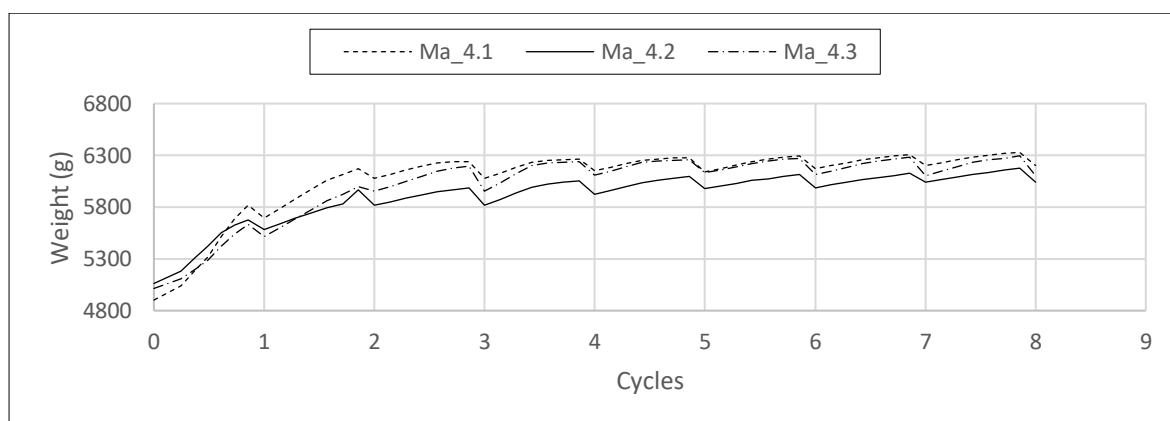
**Figure 4.15.** Variation of the weight during the ageing treatment (masonry specimens exposed to sodium sulphate aqueous solution).



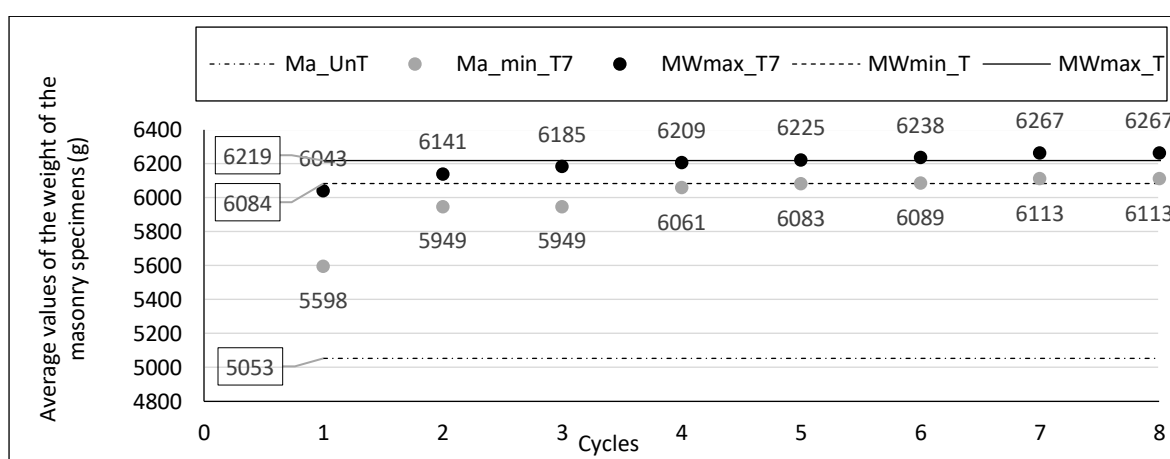
**Figure 4.16.** Average values of the weight over each cycle (masonry specimens exposed to sodium sulphate aqueous solution).

**Table 4.19.** Variation of the weight during one cycle (masonry specimens exposed to sodium sulphate aqueous solution).

| Conditions | Weight            |          | Water content |      | Unit weight (g) |
|------------|-------------------|----------|---------------|------|-----------------|
|            | Average value (g) | Sdev (g) | (g)           | (%)  |                 |
| Untreated  | 4873              | (61)     | 0             | 0    | 1507            |
| Treated    | Step 1            | 5921     | (128)         | 1048 | 21.50           |
|            | Step 2            | 5980     | (120)         | 1107 | 22.71           |
|            | Step 3            | 5992     | (118)         | 1119 | 22.95           |
|            | Step 4            | 6004     | (115)         | 1131 | 23.20           |
|            | Step 5            | 6016     | (113)         | 1143 | 23.45           |
|            | Step 6            | 6039     | (112)         | 1165 | 23.91           |
|            | Step 7            | 6060     | (104)         | 1187 | 24.35           |



**Figure 4.17.** Variation of the weight during the ageing treatment (masonry specimens exposed to potassium nitrate aqueous solution).



**Figure 4.18.** Average values of the weight over each cycle (masonry specimens exposed to potassium nitrate solution).

**Table 4.20.** Variation of the weight during one cycle (masonry specimens exposed to potassium nitrate aqueous solution).

| Conditions |        | Weight            |          | Water content |       | Unit weight (g) |
|------------|--------|-------------------|----------|---------------|-------|-----------------|
|            |        | Average value (g) | Sdev (g) | (g)           | (%)   |                 |
| Untreated  |        | 5053              | (79)     | 0             | 0     | 1563            |
| Treated    | Step 1 | 6113              | (82)     | 1059          | 20.96 | 1890            |
|            | Step 2 | 6145              | (82)     | 1092          | 21.61 | 1900            |
|            | Step 3 | 6178              | (84)     | 1124          | 22.25 | 1910            |
|            | Step 4 | 6210              | (87)     | 1157          | 22.89 | 1920            |
|            | Step 5 | 6231              | (87)     | 1178          | 23.31 | 1927            |
|            | Step 6 | 6247              | (83)     | 1194          | 23.63 | 1932            |
|            | Step 7 | 6267              | (80)     | 1213          | 24.01 | 1938            |

Overall, the following results can be deduced from the analysis of the acquired data:

- The variation of the unit weight is similar for all kind of masonry specimens exposed to deionized water or to salts aqueous solution. It ranges from 23.37% (in the case of water) to 26.55% (in the case of sodium chloride aqueous solution);
- The deionized water or the salts aqueous solutions absorbed through the capillary action in the first step caused an increase in the weight ranging from 20.33% (in the case of water) to 23.95% (in the case of sodium chloride aqueous solution);
- The deionized water or the salts aqueous solution absorbed through the capillary action in the steps from 2 to 7 caused a further increase in the weight of about 3%;
- The results are consistent with data relating to the absorption coefficient by capillary action (AC) determined using deionized water and salts aqueous solutions (Section 3.4.2). In fact, the lowest and the highest values were obtained for those specimens exposed to the deionized water and sodium chloride aqueous solutions, respectively.

#### 4.2.3 Compressive strength and stiffness

After the ageing treatment, the masonry specimens underwent mechanical tests to evaluate their compressive strength ( $\sigma_{\max}$ ) and their modulus of elasticity (E), according to the method described in the Section 3.5 and used to characterise masonry specimens exposed outside (Section 4.1.3).

Data acquired are summarised in Tables 4.21 - 4.24. They refer to the weight the specimens had when the test was performed, and so to their water content, in turn. *Attachment 5* contains the stress-strains curves of all the specimens.

**Table 4.21** Mechanical properties of the specimens exposed to deionized water  
(mean test conditions: T = 24.0 °C, RH = 53%).

| Specimen | Weight<br>(g) | H <sub>2</sub> O content<br>(%) | $\sigma_{\max}$<br>(N/mm <sup>2</sup> ) | E<br>(N/mm <sup>2</sup> ) |
|----------|---------------|---------------------------------|-----------------------------------------|---------------------------|
| Ma_1.1   | 6178          | 24.96                           | 7.48                                    | 183.7                     |
| Ma_1.2   | 6212          | 24.29                           | 9.08                                    | 264.5                     |
| Ma_1.3   | 6160          | 25.00                           | 8.67                                    | 269.1                     |
| Average  | 6183          | 24.67                           | 8.41                                    | 239.1                     |
| Sdev     | (26)          | (0.36)                          | (0.68)                                  | (39.2)                    |

**Table 4.22.** Mechanical properties of the specimens exposed to NaCl aqueous solution  
(mean test conditions: T = 24.0 °C, RH = 53%).

| Specimen | Weight<br>(g) | H <sub>2</sub> O content<br>(%) | $\sigma_{\max}$<br>(N/mm <sup>2</sup> ) | E<br>(N/mm <sup>2</sup> ) |
|----------|---------------|---------------------------------|-----------------------------------------|---------------------------|
| Ma_2.1   | 6126          | 30.32                           | 5.76                                    | 96.9                      |
| Ma_2.2   | 6161          | 26.72                           | 7.07                                    | 111.5                     |
| Ma_2.3   | 6259          | 26.60                           | 6.39                                    | 114.7                     |
| Average  | 6182          | 27.88                           | 6.41                                    | 107.7                     |
| Sdev     | (69)          | (2.11)                          | (0.53)                                  | (7.8)                     |

**Table 4.23.** Mechanical properties of the specimens exposed to Na<sub>2</sub>SO<sub>4</sub> aqueous solution  
(mean test conditions: T = 24.0 °C, RH = 53%).

| Specimen | Weight<br>(g) | H <sub>2</sub> O content<br>(%) | $\sigma_{\max}$<br>(N/mm <sup>2</sup> ) | E<br>(N/mm <sup>2</sup> ) |
|----------|---------------|---------------------------------|-----------------------------------------|---------------------------|
| Ma_3.1   | 6102          | 27.60                           | 6.54                                    | 124.3                     |
| Ma_3.2   | 5942          | 24.36                           | 7.02                                    | 173.1                     |
| Ma_3.3   | 6136          | 28.31                           | 7.36                                    | 227.3                     |
| Average  | 6060          | 26.76                           | 6.97                                    | 174.9                     |
| Sdev     | (104)         | (2.11)                          | (0.34)                                  | (42.1)                    |

**Table 4.24.** Mechanical properties of the specimens exposed to KNO<sub>3</sub> aqueous solution

(mean test conditions: T = 24.0 °C, RH = 53%).

| Specimen | Weight<br>(g) | H <sub>2</sub> O content<br>(%) | $\sigma_{\max}$<br>(N/mm <sup>2</sup> ) | E<br>(N/mm <sup>2</sup> ) |
|----------|---------------|---------------------------------|-----------------------------------------|---------------------------|
| Ma_4.1   | 6328          | 20.09                           | 7.91                                    | 138.7                     |
| Ma_4.2   | 6176          | 22.01                           | 7.65                                    | 161.1                     |
| Ma_4.3   | 6296          | 25.57                           | 8.46                                    | 166.0                     |
| Average  | 6267          | 25.56                           | 8.01                                    | 155.3                     |
| Sdev     | (80)          | (3.54)                          | (0.34)                                  | (11.9)                    |

**Table 4.25.** Comparison among the mechanical properties of all the specimens which underwent the ageing treatment in laboratory and the untreated specimens.

| Untreated                               |                           | H <sub>2</sub> O                        |                           | NaCl                                    |                           | Na <sub>2</sub> SO <sub>4</sub>         |                           | KNO <sub>3</sub>                        |                           |
|-----------------------------------------|---------------------------|-----------------------------------------|---------------------------|-----------------------------------------|---------------------------|-----------------------------------------|---------------------------|-----------------------------------------|---------------------------|
| $\sigma_{\max}$<br>(N/mm <sup>2</sup> ) | E<br>(N/mm <sup>2</sup> ) | $\sigma_{\max}$<br>(N/mm <sup>2</sup> ) | E<br>(N/mm <sup>2</sup> ) | $\sigma_{\max}$<br>(N/mm <sup>2</sup> ) | E<br>(N/mm <sup>2</sup> ) | $\sigma_{\max}$<br>(N/mm <sup>2</sup> ) | E<br>(N/mm <sup>2</sup> ) | $\sigma_{\max}$<br>(N/mm <sup>2</sup> ) | E<br>(N/mm <sup>2</sup> ) |
| 9.22                                    | 166.39                    | 9.08                                    | 264.5                     |                                         |                           |                                         |                           | 8.46                                    | 166.0                     |
| 8.74                                    | 189.2                     |                                         | 269.1                     |                                         |                           |                                         |                           |                                         |                           |
| 8.14                                    | 161.4                     |                                         |                           |                                         |                           |                                         |                           |                                         |                           |
|                                         |                           | 7.48                                    | 183.7                     | 7.07                                    | 111.5                     | 7.36                                    | 227.3                     | 7.91                                    | 138.7                     |
|                                         |                           |                                         |                           |                                         |                           | 7.02                                    | 173.1                     | 7.65                                    | 161.1                     |
|                                         |                           |                                         |                           |                                         |                           | 6.54                                    | 124.3                     |                                         |                           |
|                                         |                           |                                         |                           | 6.39                                    | 114.8                     |                                         |                           |                                         |                           |
|                                         |                           |                                         |                           | 5.76                                    | 96.9                      |                                         |                           |                                         |                           |

Table 4.25 shows data referring to all the kind of treated specimens and compared to those relating to the untreated ones (Section 3.5).

The values of the compressive strength of the specimens exposed to deionized water are very similar to those referring to the untreated specimens. The average value of the compressive strength of the former is 3.33% lower than that of the latter, while the modulus of elasticity is 38.73% greater. This result may be due to the fact that specimens are handmade.

As regard the specimens exposed to sodium chloride aqueous solution, the average value of the compressive strength and that of the modulus of elasticity are 26.36% and 37.49% lower than those referring to the untreated specimens.

As regard the specimens exposed to sodium sulphate aqueous solution, the average value of the compressive strength is 19.85% lower than that referring to the untreated specimens, while the modulus of elasticity is 1.49% greater.

As regard the specimens exposed to potassium nitrate aqueous solution, the average value of the compressive strength and that of the modulus of elasticity are 7.97% and 9.90% lower than those referring to the untreated specimens.

Overall, the specimens exposed to sodium chloride aqueous solution has the lowest values of the compressive strength. They are followed by the specimens exposed to sodium sulphate and potassium nitrate aqueous solution, respectively. This result is consistent with that referring to the masonry specimens exposed outside (Section 4.1.3), and confirms that the effects of the salts on the mechanical features of the specimens is capital.

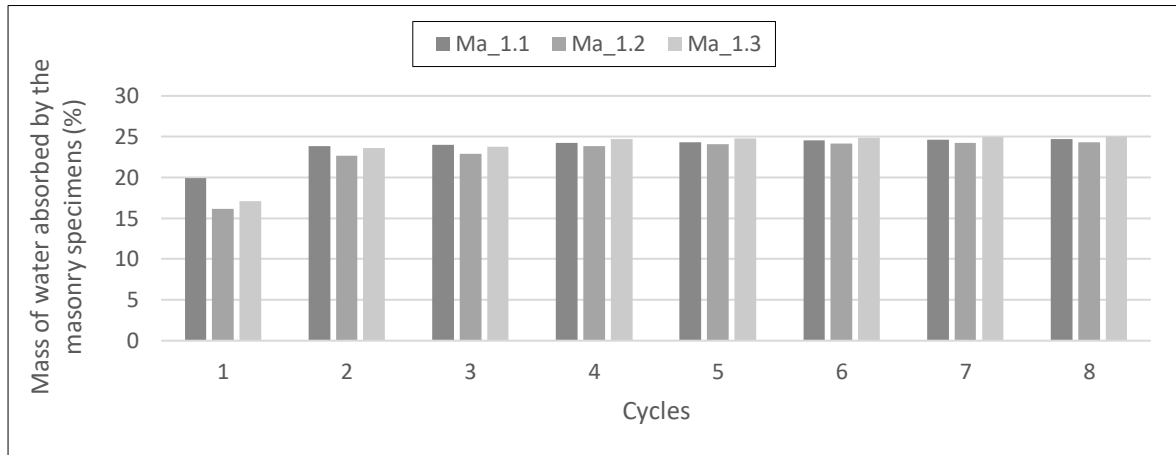
#### *4.2.4 Moisture content*

The values of the weight of the masonry specimens recorded in Section 4.4.2 allow us to determine the moisture content through the equation (3.3). Data referring to the masonry specimens exposed to deionized water are shown in Figure 4.19 and in Table 4.26. All data refer to the last step of each cycle. Moreover, the values of the environmental temperature and relative humidity were also reported.

Data reveal that the greatest amount of the water was absorbed during the first cycle. This is because at the start of the ageing treatment, the masonry specimens were dry. Starting from the second cycle, the content of water increased slowly.

As regard the specimens exposed to sodium chloride aqueous solution, data are summarised in Figure 4.20 and Table 4.27. As regard the specimens exposed to sodium sulphate aqueous solution, data are summarised in Figure 4.21 and Table 4.28. As regard the specimens exposed to potassium nitrate aqueous solution, data are summarised in Figure 4.22 and Table 4.29.

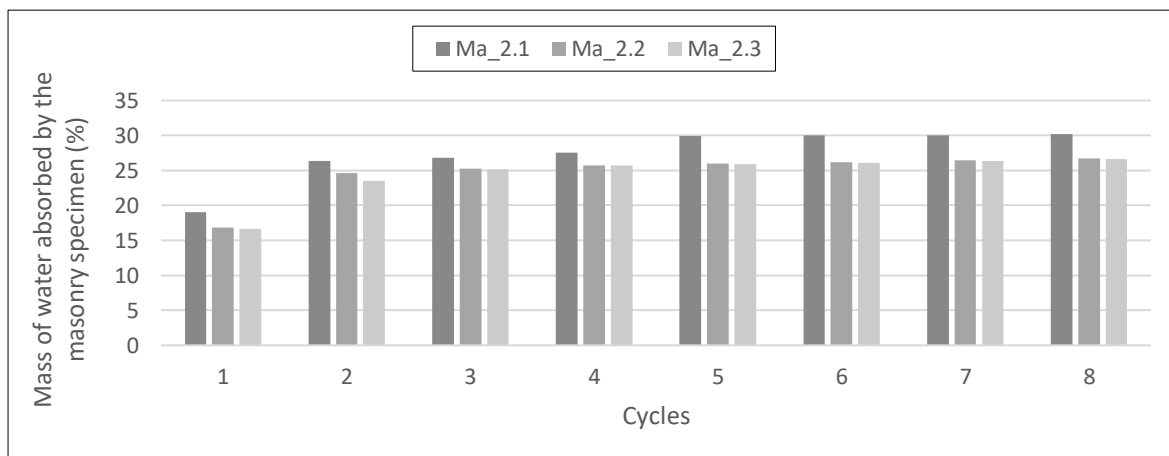
All these specimens behave in the same way as those exposed to deionized water. However, an additional consideration must be done. The amount of water absorbed in consecutive cycles is higher for the specimens exposed to the salts aqueous solutions than for specimens exposed to deionized water. This difference is more evident in specimens exposed to sodium sulphate aqueous solution.



**Figure 4.19.** Mass of the deionized water absorbed by the masonry specimens.

**Table 4.26.** Mass of the deionized water absorbed by the masonry specimens.

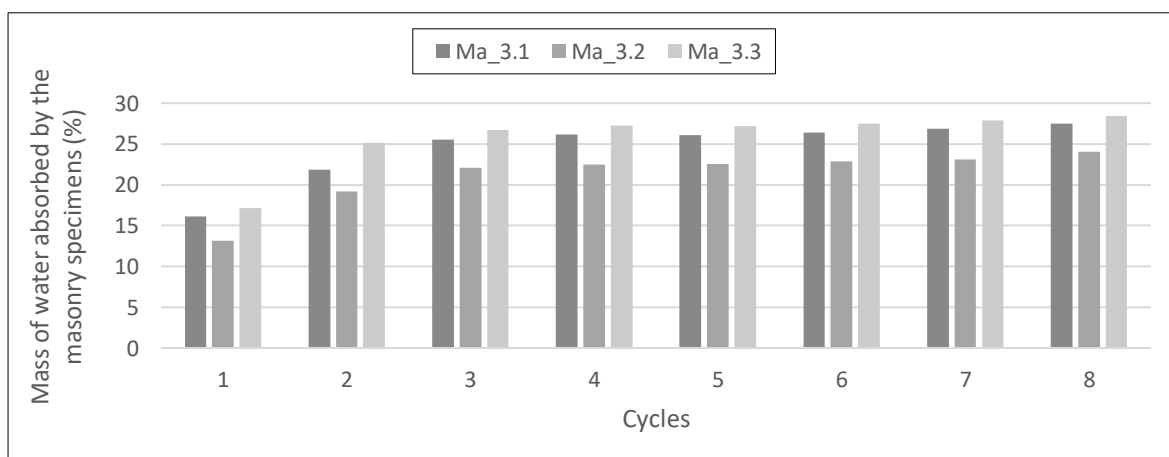
| Cycle | T<br>(°C) | RH<br>(%) | Specimens     |               |               | Average<br>(%) | Sdev<br>(%) |
|-------|-----------|-----------|---------------|---------------|---------------|----------------|-------------|
|       |           |           | Ma_1.1<br>(%) | Ma_1.2<br>(%) | Ma_1.3<br>(%) |                |             |
| 1     | 21.80     | 40        | 19.90         | 16.13         | 17.09         | 17.71          | (1.96)      |
| 2     | 21.60     | 35        | 23.87         | 22.65         | 23.58         | 23.37          | (0.64)      |
| 3     | 20.40     | 27        | 23.99         | 22.93         | 23.78         | 23.57          | (0.56)      |
| 4     | 21.20     | 39        | 24.27         | 23.85         | 24.68         | 24.27          | (0.41)      |
| 5     | 21.60     | 45        | 24.35         | 24.09         | 24.76         | 24.40          | (0.34)      |
| 6     | 21.20     | 42        | 24.51         | 24.13         | 24.84         | 24.49          | (0.35)      |
| 7     | 21.60     | 33        | 24.60         | 24.21         | 24.98         | 24.59          | (0.39)      |
| 8     | 21.30     | 26        | 24.72         | 24.29         | 25.00         | 24.67          | (0.36)      |



**Figure 4.20.** Mass of the sodium chloride aqueous solution, absorbed by the masonry specimens.

**Table 4.27.** Mass of the sodium chloride aqueous solution, absorbed by the masonry specimens.

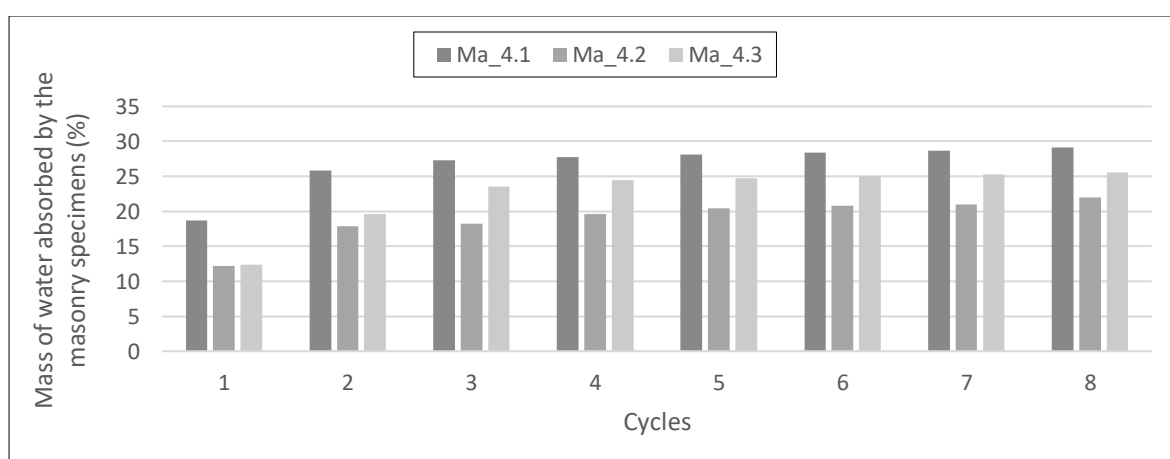
| Cycle | T<br>(°C) | RH<br>(%) | Specimens     |               |               | Average<br>(%) | Sdev<br>(%) |
|-------|-----------|-----------|---------------|---------------|---------------|----------------|-------------|
|       |           |           | Ma_1.1<br>(%) | Ma_1.2<br>(%) | Ma_1.3<br>(%) |                |             |
| 1     | 21.80     | 40        | 19.06         | 16.82         | 16.67         | 17.52          | (1.34)      |
| 2     | 21.60     | 35        | 26.38         | 24.64         | 23.50         | 24.84          | (1.45)      |
| 3     | 20.40     | 27        | 26.85         | 25.22         | 25.20         | 25.76          | (0.95)      |
| 4     | 21.20     | 39        | 27.51         | 25.75         | 25.73         | 26.33          | (1.02)      |
| 5     | 21.60     | 45        | 29.96         | 25.96         | 25.89         | 27.27          | (2.33)      |
| 6     | 21.20     | 42        | 29.98         | 26.20         | 26.09         | 27.42          | (2.21)      |
| 7     | 21.60     | 33        | 30.00         | 26.45         | 26.38         | 27.61          | (2.07)      |
| 8     | 21.30     | 26        | 30.23         | 26.72         | 26.62         | 27.86          | (2.06)      |



**Figure 4.21.** Mass of the sodium sulphate aqueous solution, absorbed by the masonry specimens.

**Table 4.28.** Mass of the sodium sulphate aqueous solution, absorbed by the masonry specimens.

| Cycle | T<br>(°C) | RH<br>(%) | Specimens     |               |               | Average<br>(%) | Sdev<br>(g) |
|-------|-----------|-----------|---------------|---------------|---------------|----------------|-------------|
|       |           |           | Ma_1.1<br>(%) | Ma_1.2<br>(%) | Ma_1.3<br>(%) |                |             |
| 1     | 21.80     | 40        | 16.10         | 13.10         | 17.11         | 15.44          | (2.08)      |
| 2     | 21.60     | 35        | 21.87         | 19.17         | 25.18         | 22.07          | (3.01)      |
| 3     | 20.40     | 27        | 25.55         | 22.10         | 26.73         | 24.79          | (2.40)      |
| 4     | 21.20     | 39        | 26.14         | 22.48         | 27.27         | 25.30          | (2.50)      |
| 5     | 21.60     | 45        | 26.06         | 22.56         | 27.14         | 25.25          | (2.39)      |
| 6     | 21.20     | 42        | 26.43         | 22.90         | 27.52         | 25.62          | (2.42)      |
| 7     | 21.60     | 33        | 26.85         | 23.11         | 27.85         | 25.94          | (2.50)      |
| 8     | 21.30     | 26        | 27.48         | 24.07         | 28.44         | 26.66          | (2.30)      |

**Figure 4.22.** Mass of the potassium nitrate aqueous solution, absorbed by the masonry specimens.**Table 4.29.** Mass of the potassium nitrate aqueous solution, absorbed by the masonry specimens.

| Cycle | T<br>(°C) | RH<br>(%) | Specimens     |               |               | Average<br>(%) | Sdev<br>(%) |
|-------|-----------|-----------|---------------|---------------|---------------|----------------|-------------|
|       |           |           | Ma_1.1<br>(%) | Ma_1.2<br>(%) | Ma_1.3<br>(%) |                |             |
| 1     | 21.80     | 40        | 16.10         | 18.73         | 12.17         | 12.33          | (14.41)     |
| 2     | 21.60     | 35        | 21.87         | 25.87         | 17.82         | 19.59          | (21.09)     |
| 3     | 20.40     | 27        | 25.55         | 27.29         | 18.25         | 23.57          | (23.04)     |
| 4     | 21.20     | 39        | 26.14         | 27.78         | 19.60         | 24.41          | (23.93)     |
| 5     | 21.60     | 45        | 26.06         | 28.07         | 20.39         | 24.77          | (24.41)     |
| 6     | 21.20     | 42        | 26.43         | 28.36         | 20.82         | 25.01          | (24.73)     |
| 7     | 21.60     | 33        | 26.85         | 18.73         | 12.17         | 12.33          | (14.41)     |
| 8     | 21.30     | 26        | 27.48         | 25.87         | 17.82         | 19.59          | (21.09)     |

#### 4.2.5 Salts distribution

Salts introduced in the specimens during the ageing treatment described in Section 3.8, caused changes in several physical properties, as proved by data analysed hereinabove. For this reason, the distribution of the salts into the specimens was also analysed, in order to relate data acquired to each other. The method used to analyse the distribution of the salts, and the results referring to the untreated specimen are described in the Section 3.6.

**Table 4.30.** Electrical conductivity of the salts aqueous solutions relating to specimens exposed to deionized water (mean test conditions: T = 21 °C, RH = 53%).

|      | <b>a: innermost<br/>(<math>\mu\text{S}/\text{cm}</math>)</b> | <b>b: middle<br/>(<math>\mu\text{S}/\text{cm}</math>)</b> | <b>c: outermost<br/>(<math>\mu\text{S}/\text{cm}</math>)</b> |
|------|--------------------------------------------------------------|-----------------------------------------------------------|--------------------------------------------------------------|
| 1Br  | 88                                                           | 71                                                        | 67                                                           |
| 1Mo  | 288                                                          | 242                                                       | 246                                                          |
| 2Br  | 76                                                           | 71                                                        | 73                                                           |
| 2Mo  | 205                                                          | 192                                                       | 184                                                          |
| 3 Br | 229                                                          | 218                                                       | 188                                                          |
| 3 Mo | 89                                                           | 65                                                        | 65                                                           |

Measures conducted according to the standard: EN 11087:2003. Conductivity of deionized water:  $5\mu\text{S}/\text{cm}$ .

Table 4.30 shows the results referring to one among the specimens exposed to deionized water. Data reveal that the ratio between the average values referring to mortar and bricks is between 2.64 in the middle, and 3.43 on the top. This means that soluble ions are more copious in mortar than in bricks, in accordance with the results referring to the untreated specimens. Reading data horizontally, they prove that the gradient is similar for mortar and for bricks, since the ratio between the values referring to the outermost and the innermost samples range from 0.82 to 0.90 in the first case, and from 0.73 to 0.96 in the second. On the contrary, reading data vertically, not meaningful changes occur.

Table 4.31 shows the results referring to one among the specimens exposed to sodium chloride aqueous solution. Data reveal that the ratio between the average values referring to mortar and bricks is between 1.61 in the middle, and 1.73 on the top. This means that soluble ions are more copious in mortar than in bricks, in accordance with the results referring to the untreated specimens, but in this case the difference is less strong. Reading data horizontally, they prove that the gradient is more evident for bricks than for mortar,

since the ratio between the values referring to the outermost and the innermost samples range from 0.61 to 1.10 in the first case, and is 0.48 in the second. On the contrary, reading data vertically, they prove that a positive gradient exists from below upward. The ratio between the values referring to the lowest and the uppermost samples range from 0.62 to 1.05 in the first case, and from 0.58 and 0.83 in the second.

**Table 4.31.** Electrical conductivity of the salts aqueous solutions relating to specimens exposed to NaCl aqueous solution (mean test conditions: T = 22 °C, RH = 54%).

|      | <b>a: innermost<br/>(<math>\mu\text{S}/\text{cm}</math>)</b> | <b>b: middle<br/>(<math>\mu\text{S}/\text{cm}</math>)</b> | <b>c: outermost<br/>(<math>\mu\text{S}/\text{cm}</math>)</b> |
|------|--------------------------------------------------------------|-----------------------------------------------------------|--------------------------------------------------------------|
| 1Br  | 250                                                          | 211                                                       | 152                                                          |
| 1Mo  | 487                                                          | 356                                                       | 233                                                          |
| 2Br  | 171                                                          | 201                                                       | 188                                                          |
| 2Mo  | 450                                                          | 238                                                       | 215                                                          |
| 3 Br | 403                                                          | 206                                                       | 192                                                          |
| 3 Mo | 154                                                          | 159                                                       | 160                                                          |

Measures conducted according to the standard: EN 11087:2003. Conductivity of deionized water: 9 $\mu\text{S}/\text{cm}$ .

**Table 4.32.** Electrical conductivity of the salts aqueous solutions relating to specimens exposed to  $\text{Na}_2\text{SO}_4$  aqueous solution (mean test conditions: T = 20 °C, RH = 55%).

|      | <b>a: innermost<br/>(<math>\mu\text{S}/\text{cm}</math>)</b> | <b>b: middle<br/>(<math>\mu\text{S}/\text{cm}</math>)</b> | <b>c: outermost<br/>(<math>\mu\text{S}/\text{cm}</math>)</b> |
|------|--------------------------------------------------------------|-----------------------------------------------------------|--------------------------------------------------------------|
| 1Br  | 90                                                           | 91                                                        | 85                                                           |
| 1Mo  | 255                                                          | 218                                                       | 68                                                           |
| 2Br  | 81                                                           | 69                                                        | 66                                                           |
| 2Mo  | 291                                                          | 180                                                       | 65                                                           |
| 3 Br | 260                                                          | 220                                                       | 78                                                           |
| 3 Mo | 77                                                           | 58                                                        | 56                                                           |

Measures conducted according to the standard: EN 11087:2003. Conductivity of deionized water: 7 $\mu\text{S}/\text{cm}$ .

Table 4.32 shows the results referring to one among the specimens exposed to sodium sulphate aqueous solution. Data reveal that the ratio between the average values referring to mortar and bricks is between 2.03, on the top, and 2.93 on the bottom. This means that soluble ions are more copious in mortar than in bricks, in accordance with the results referring to the untreated specimens. Reading data horizontally, they prove that the gradient is more evident for bricks than for mortar, since the ratio between the values referring to the outermost and the innermost samples range from 0.73 to 0.94 in the first

case, and from 0.22 to 0.30 in the second. On the contrary, reading data vertically, a clear gradient exists neither in bricks nor in mortar.

**Table 4.33.** Electrical conductivity of the salts aqueous solutions relating to specimens exposed to  $\text{KNO}_3$  aqueous solution (mean test conditions:  $T = 24\text{ }^\circ\text{C}$ ,  $\text{RH} = 52\%$ ).

|      | <b>a: innermost<br/>(<math>\mu\text{S}/\text{cm}</math>)</b> | <b>b: middle<br/>(<math>\mu\text{S}/\text{cm}</math>)</b> | <b>c: outermost<br/>(<math>\mu\text{S}/\text{cm}</math>)</b> |
|------|--------------------------------------------------------------|-----------------------------------------------------------|--------------------------------------------------------------|
| 1Br  | 205                                                          | 203                                                       | 164                                                          |
| 1Mo  | 464                                                          | 384                                                       | 143                                                          |
| 2Br  | 156                                                          | 161                                                       | 151                                                          |
| 2Mo  | 614                                                          | 602                                                       | 228                                                          |
| 3 Br | 620                                                          | 597                                                       | 246                                                          |
| 3 Mo | 141                                                          | 129                                                       | 123                                                          |

Measures conducted according to the standard: EN 11087:2003. Conductivity of deionized water:  $2\mu\text{S}/\text{cm}$ .

Table 4.33 shows the results referring to one among the specimens exposed to potassium nitrate aqueous solution. Data reveal that the ratio between the average values referring to mortar and bricks is between 1.73 on the top, and 3.72 on the bottom. This means that soluble ions are more copious in mortar than in bricks, in accordance with the results referring to the untreated specimens but, in this case, values are less uniform. Reading data horizontally, they prove that the gradient is more evident for bricks than for mortar, since the ratio between the values referring to the outermost and the innermost samples ranges from 0.80 to 0.97 in the first case, and from 0.31 to 0.40 in the second. On the contrary, reading data vertically, a clear gradient exists neither in bricks nor in mortar.

Comparing these results with those relating to the untreated masonry specimens, other interesting results emerge. Overall, the conductivity is higher in the first than in the second case, proving the effect of the salts. The ratio between the average value referring to bricks and mortar taken from untreated specimens and specimens exposed to sodium chloride aqueous solution, is 2.80 and 1.38, respectively. Similarly, the ratio between the average value referring to bricks and mortar taken from untreated specimens and specimens exposed to sodium sulphate aqueous solution, is 1.14 and 0.81, respectively. Finally, the ratio between the average value referring to bricks and mortar taken from untreated specimens and specimens exposed to potassium nitrate aqueous solution, is 2.44 and 1.98, respectively. These comparisons prove that overall, the effect of the salts is more evident

in bricks than in mortar, and that it is more serious in those specimens exposed to sodium chloride and potassium nitrate aqueous solutions, since these two salts are more soluble than the potassium nitrate (Section 2.4.1).

Comparing the acquired data with those in literature, no uniform evidences occur. For instance, the results are not consistent with those derived from the study of Falchi et al. (2018), dealing with the moisture distribution in venetian masonries. Several graphs are provided in the research, showing the distribution of the salts in the wall, in relation to the height and the depth of the measuring points. Curves proved that the percentage of the salts is higher in the surface than in the inner part of the wall. This study takes into account all the kind of salts, without distinguish the ion species. On the contrary in the study conducted by Biscontin (2001), several graphs show the distribution of both the total salts soluble and some ion species, individually. In this case, data revealed that the percentage of the total salts and the Na<sup>+</sup> and K<sup>+</sup> ions increased within 5 cm from the external surface, consistently with the results of the measurements conducted in this research. However, it must be kept in mind that the results coming from the researches quoted hereinabove refer to real case studies, while in this study the reference is to masonry specimens made in laboratory.

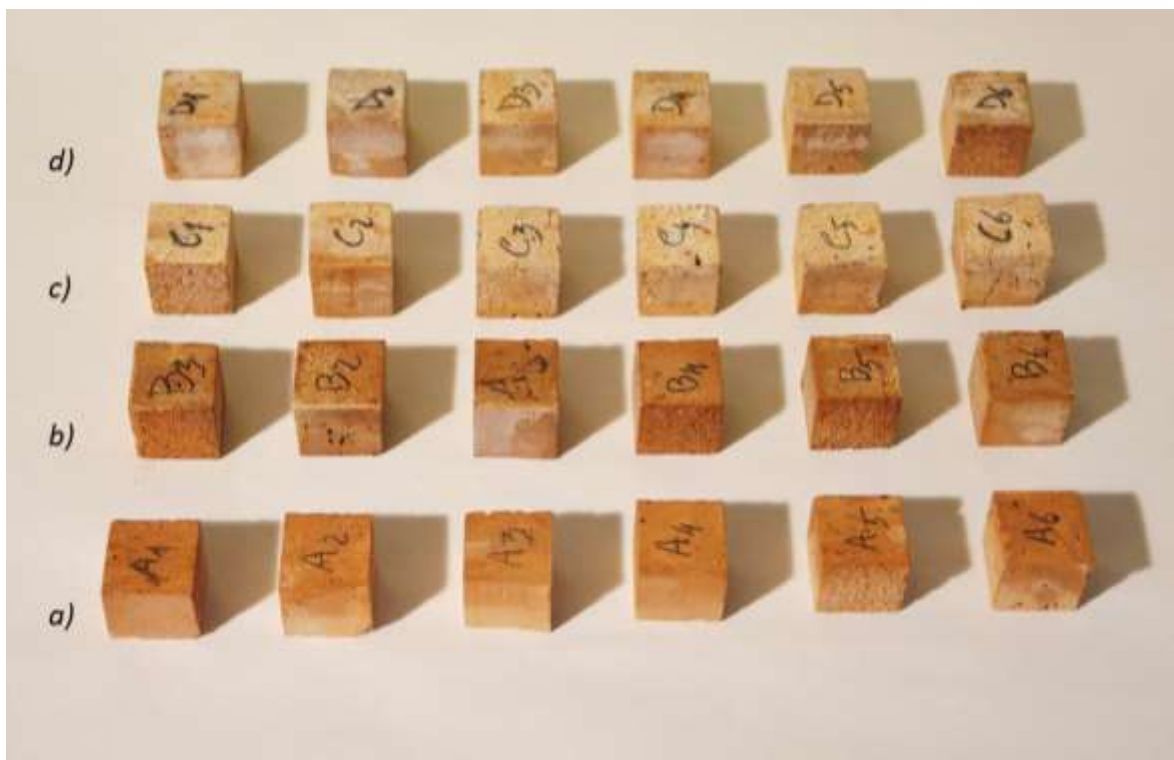
#### **4.3 Study of the effects of the ageing treatment on the construction materials**

Data referring to masonry specimens show that soluble salts and temperature changes, cause a meaningful worsening of the compressive strength and also a variation of the stiffness and the unit weight.

The results of the mechanical test conducted on the masonry specimens refer to a kind of masonry which was selected among several possible (Section 3.2). As it was stated in the Section 3.10, the purpose of the last part of this research is to understand if it is possible to extend the results to other kind of masonry, starting from the data referring to bricks and mortar specimens. For this reason, next to the masonry specimens, even brick and mortar specimens underwent the same ageing treatment and were characterised from the mechanical point of view.

#### 4.3.1 Visual inspection

Figures 4.23 and 4.24 show the aspect of the bricks and mortar specimens respectively, at the end of the ageing treatment. Specimens exposed to deionized water show only a more saturated colour respect to the untreated specimens. As regard the specimens exposed to sodium chloride aqueous solution, the saturation of the colour is more evident, especially for the mortar specimens. Moreover, efflorescences are more visible in bricks than in mortar specimens. As regard the specimens exposed to sodium sulphate aqueous solution, serious cracks are visible. One among the brick specimens is also deformed because of the effect of the salts which pull from the interior of the pore of the specimens, causing mechanical stresses. As regard the specimens exposed to potassium nitrate aqueous solution, colour change and efflorescences were recorded.



**Figure 4.23.** Brick specimens after the ageing treatment: a) specimens exposed to deionized water; b) specimens exposed to sodium chloride aqueous solution; c) specimens exposed to sodium sulphate aqueous solution; d) specimens exposed to potassium nitrate aqueous solution.



**Figure 4.24.** Mortar specimens after the ageing treatment: a) specimens exposed to deionized water; b) specimens exposed to sodium chloride aqueous solution; c) specimens exposed to sodium sulphate aqueous solution; d) specimens exposed to potassium nitrate aqueous solution.

#### 4.3.2 Unit weight

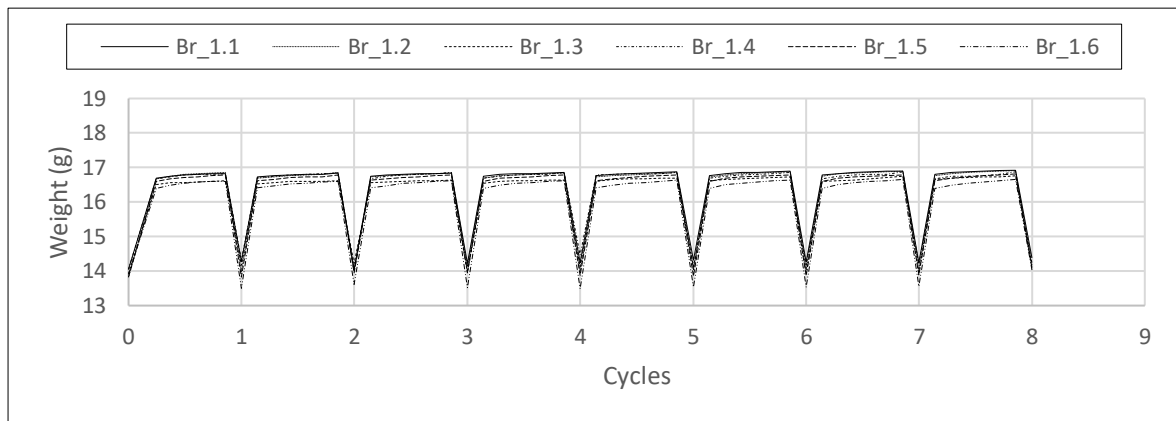
The values of the unit weight were determined during all the cycles of the ageing treatment, in order to evaluate how this parameter changed over time, according to the environmental conditions which the specimens were exposed to.

As regard the bricks and mortar specimens exposed to deionized water, the variation of the weight during the ageing treatment is shown in Figure 4.25 and 4.26 respectively, while Figure 4.27 and 4.28 show the maximum and minimum values of the weight measured for each cycle. They are averaged over the three specimens and related to the respective mean values over the last seven cycles (dashed line and continuous line), and to the mean value before the start of the ageing treatment (dashed-dot line).

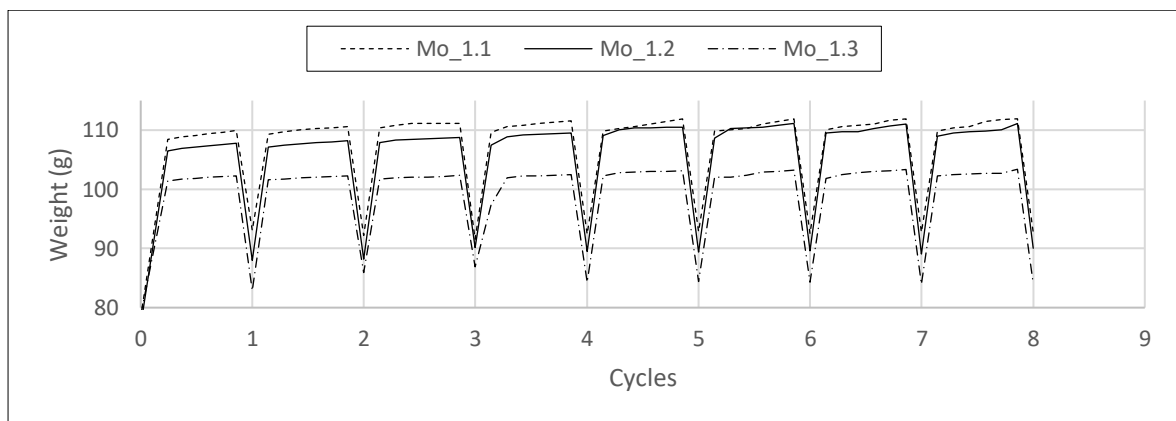
The weight of the brick specimens increased by 18.53% (from 14.14 g to 16.75 g) during the first ageing cycle, and it further increased by 1.38% during the following (from 16.75 g to 16.89 g). The mean minimum and maximum values of the weight were 14.04 g and 16.81 g, respectively, corresponding to a decrease/increase of -0.71% and 18.88% from the initial weight (14.14 g). The standard deviation was 0.05 g and 0.09 g respectively. The two values of the weight are the thresholds within which the weight of the treated brick specimens varied. The maximum value is very similar to that obtained from the absorption test at atmospheric pressure (16.79 g), while the minimum is lower than the initial value (14.14 g), but higher than the weight of the dried specimen (13.93 g).

A similar analysis of the results can be done for the mortar specimens. Their weight increased by 35.10% (from 78.9 g to 106.6 g) during the first ageing cycle, and it further increased by 2.63% during the following (from 106.6 g to 109.4 g). The mean minimum and maximum values of the weight were 88.9 g and 108.5 g, respectively, corresponding to an increase of 12.74% and 37.58% from the initial weight (78.9 g). The standard deviation was 0.27 g and 0.67 g respectively. The two values of the weight are the thresholds within which the weight of the treated brick specimens varied. The maximum value is very similar to that obtained from the absorption test at atmospheric pressure (108.9 g). The minimum value is 13.90% higher than this relating to dried specimens.

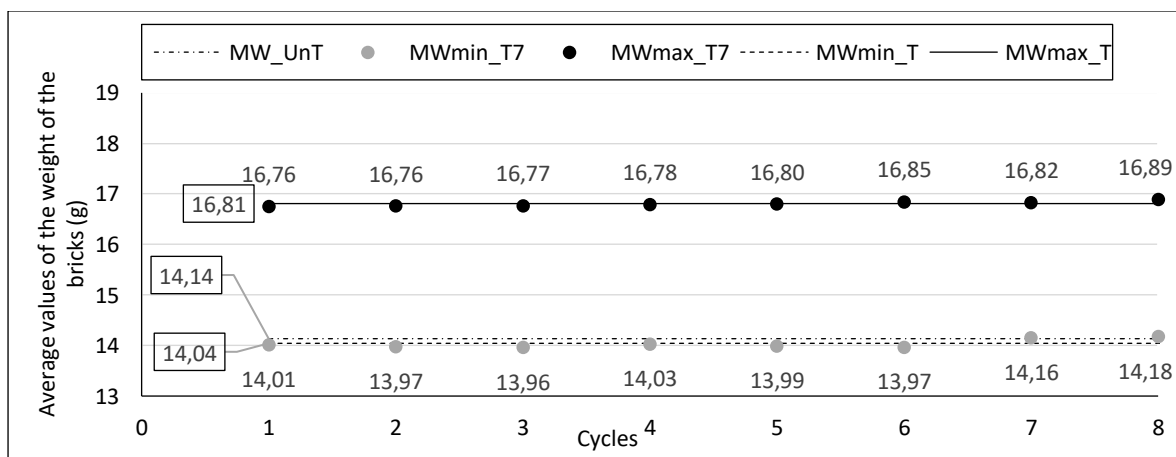
Figures 4.29 and 4.30 show the increase in the mass of water absorbed by the brick and mortar specimens during all cycles. The mean value, determined from all the specimens, increased from 20.20% to 21.20% for the former, and from 36.66% to 40.24% for the latter. It is interesting to note that the weight increase of the mortar specimens is two times greater than that of the brick specimens. Comparing these results to those relating to masonry specimens (from 17.71% to 24.75%, Section 4.2.2), it seems that bricks have a higher influence than mortar.



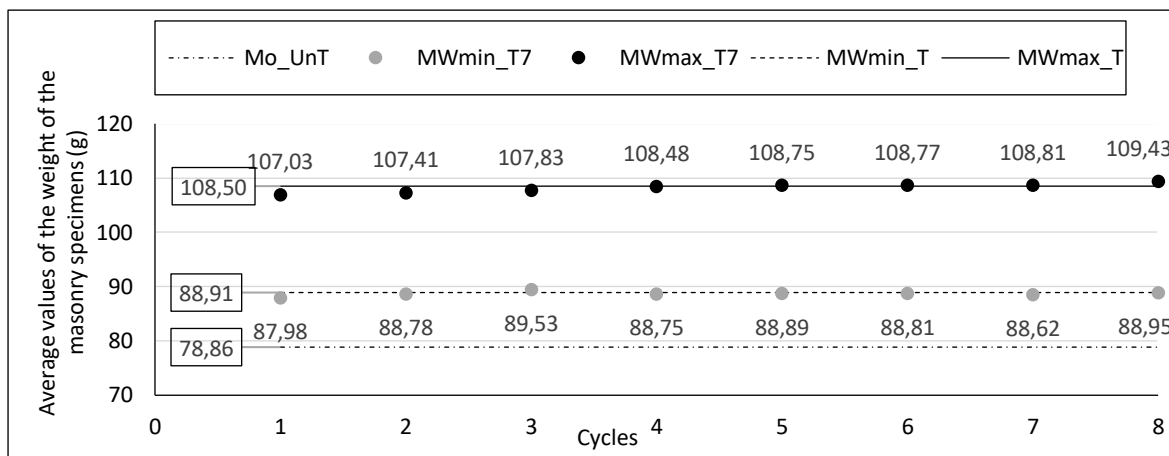
**Figure 4.25.** Variation of the weight during the ageing treatment (brick specimens exposed to deionized water).



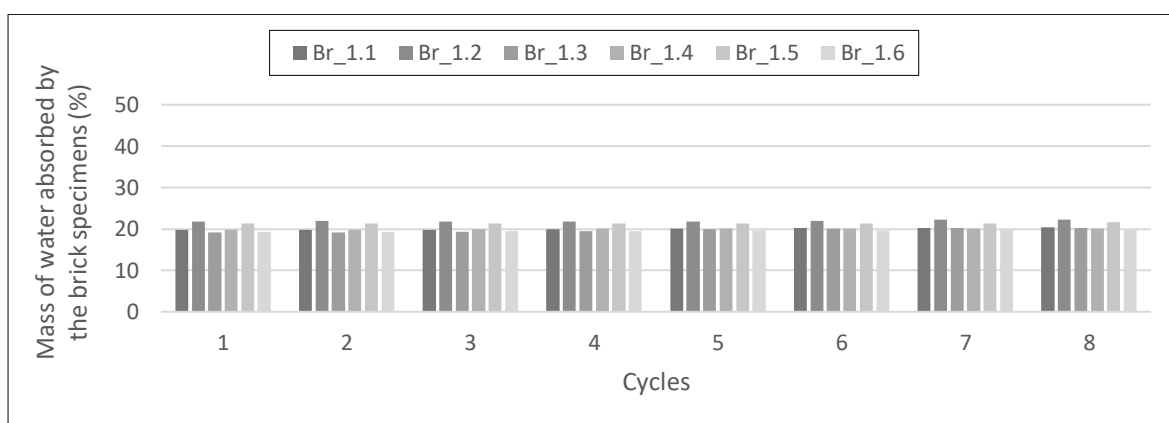
**Figure 4.26.** Variation of the weight during the ageing treatment (mortar specimens exposed to deionized water).



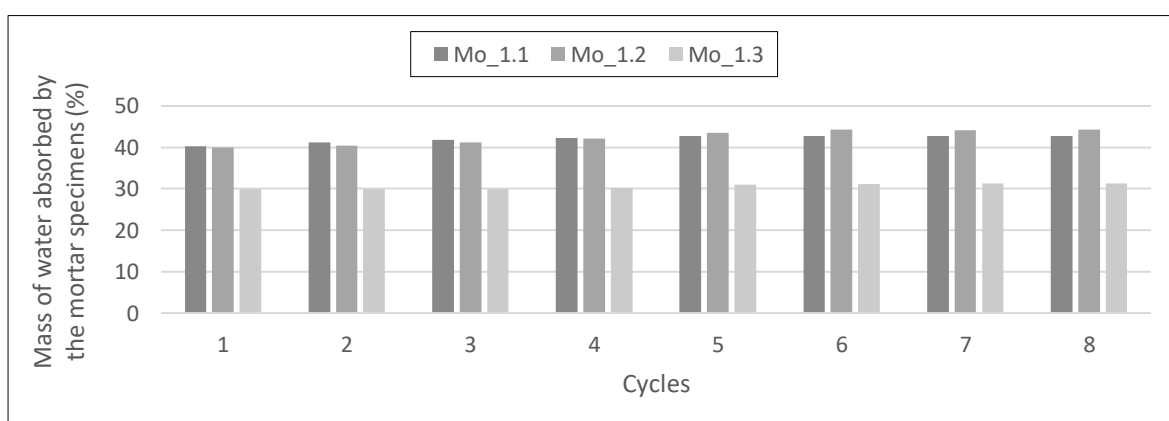
**Figure 4.27.** Average values of the weight over each cycle (brick specimens exposed to deionized water).



**Figure 4.28.** Average values of the weight over each cycle (mortar specimens exposed to deionized water).



**Figure 4.29** Mass of the denoised water absorbed by the brick specimens during the ageing treatment.



**Figure 4.30.** Mass of the denoised water absorbed by the mortar specimens during the ageing treatment.

Tables 4.34 and 4.35 show the weight values of untreated and treated brick and mortar specimens, respectively. For the treated specimens, seven weight values are reported: one for each step (i.e. 24 hour treatment) of the ageing treatment. The values were calculated as the arithmetic mean among the three specimens, averaged across the last seven cycles. Starting from these data, the unit weight of the untreated and treated specimens was determined.

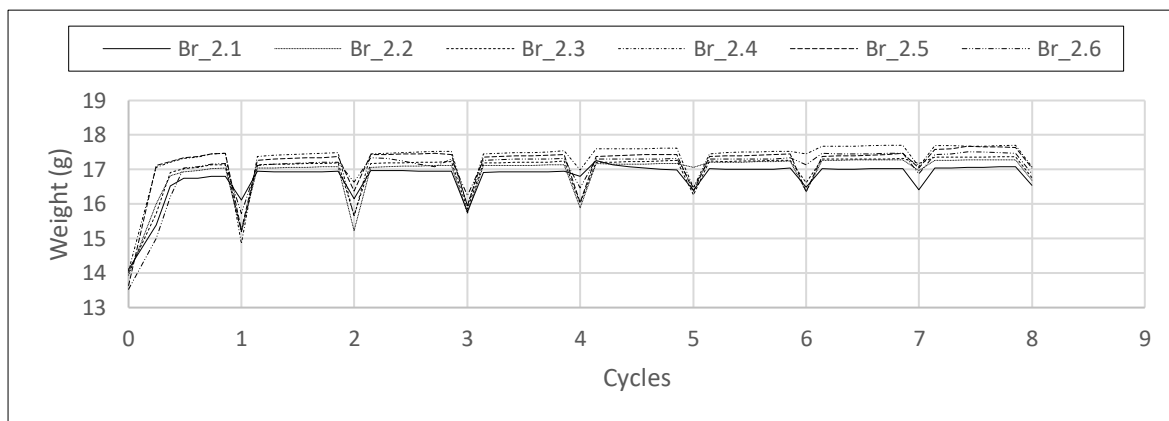
Brick and mortar specimens exposed to salts aqueous solutions showed a behaviour which is qualitatively similar to that relating to specimens exposed to deionized water. The results referring to the specimens exposed to sodium chloride aqueous solution are summarised in Figures 4.31 – 4.36 and in Tables 4.36 - 4.37; the results referring to the specimens exposed to sodium sulphate aqueous solution are summarised in Figures 4.37 – 4.42 and in Tables 4.38 - 4.39; the results referring to the specimens exposed to potassium nitrate aqueous solution are summarised in Figures 4.43 – 4.48 and in Tables 4.40 - 4.41.

**Table 4.34.** Variation of the weight during one cycle (brick specimens exposed to deionized water).

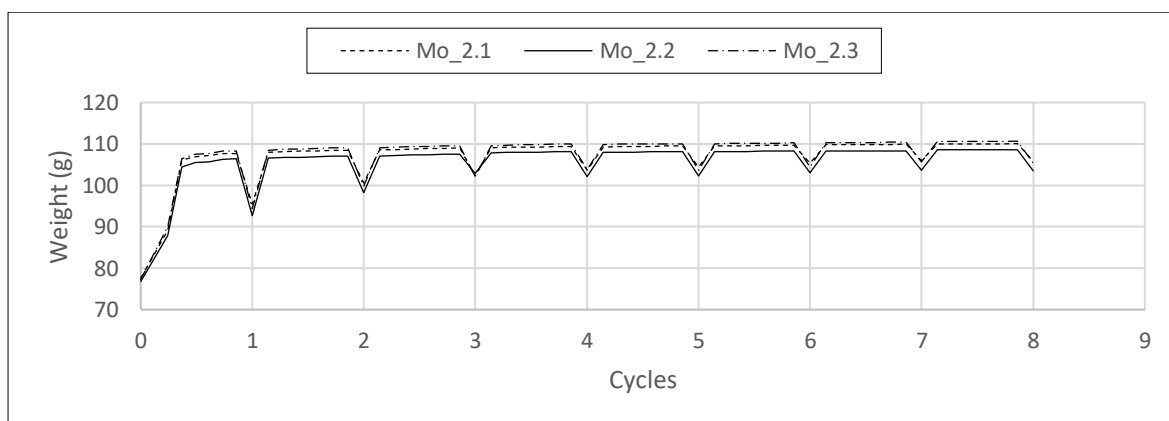
| Conditions |        | Weight            |          | Water content |       | Unit weight (g) |
|------------|--------|-------------------|----------|---------------|-------|-----------------|
|            |        | Average value (g) | Sdev (g) | (g)           | (%)   |                 |
| Untreated  |        | 14.14             | (0.11)   | 0             | 0     | 1767            |
| Treated    | Step 1 | 14.18             | (0.12)   | 0.05          | 0.33  | 1773            |
|            | Step 2 | 16.66             | (0.15)   | 2.53          | 17.89 | 2083            |
|            | Step 3 | 16.71             | (0.14)   | 2.57          | 18.19 | 2088            |
|            | Step 4 | 16.75             | (0.13)   | 2.61          | 18.50 | 2094            |
|            | Step 5 | 16.80             | (0.11)   | 2.66          | 18.82 | 2099            |
|            | Step 6 | 16.84             | (0.10)   | 2.71          | 19.14 | 2105            |
|            | Step 7 | 16.89             | (0.09)   | 2.75          | 19.46 | 2111            |

**Table 4.35.** Variation of the weight during one cycle (mortar specimens exposed to deionized water).

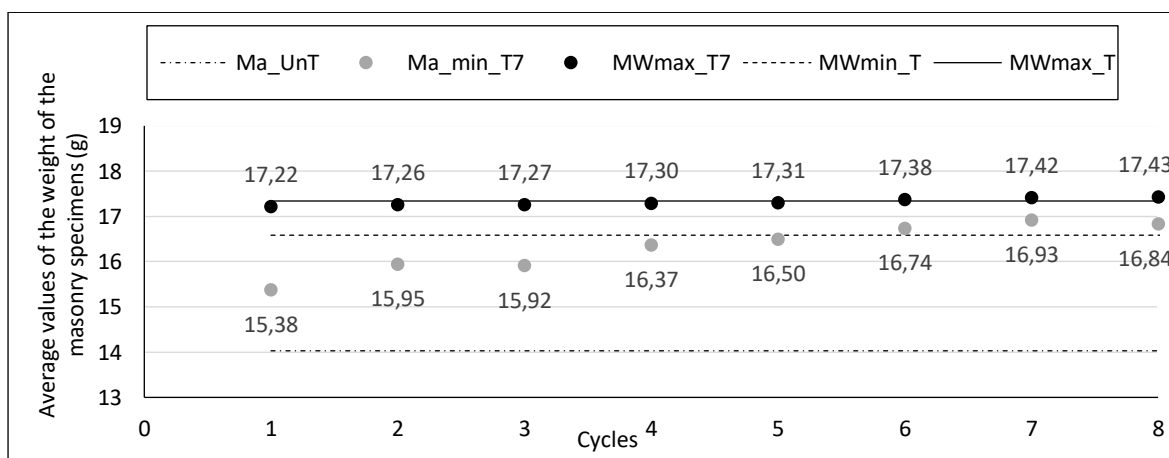
| Conditions |        | Weight            |          | Water content |       | Unit weight (g) |
|------------|--------|-------------------|----------|---------------|-------|-----------------|
|            |        | Average value (g) | Sdev (g) | (g)           | (%)   |                 |
| Untreated  |        | 78.9              | (0.82)   | 0             | 0     | 1232            |
| Treated    | Step 1 | 88.9              | (4.43)   | 10.09         | 12.79 | 1390            |
|            | Step 2 | 106.4             | (3.73)   | 27.57         | 34.96 | 1663            |
|            | Step 3 | 107.1             | (3.97)   | 28.29         | 35.87 | 1674            |
|            | Step 4 | 107.7             | (4.37)   | 28.81         | 36.53 | 1682            |
|            | Step 5 | 108.4             | (4.94)   | 29.50         | 37.40 | 1693            |
|            | Step 6 | 108.7             | (4.80)   | 29.88         | 37.89 | 1699            |
|            | Step 7 | 109.4             | (4.68)   | 30.57         | 38.76 | 1710            |



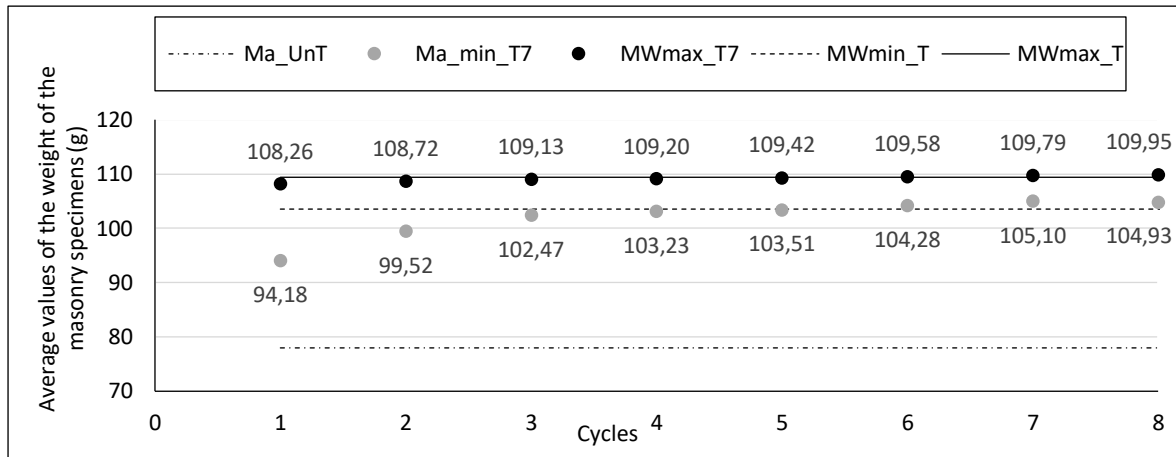
**Figure 4.31.** Variation of the weight during the ageing treatment (brick specimens exposed to sodium chloride aqueous solution).



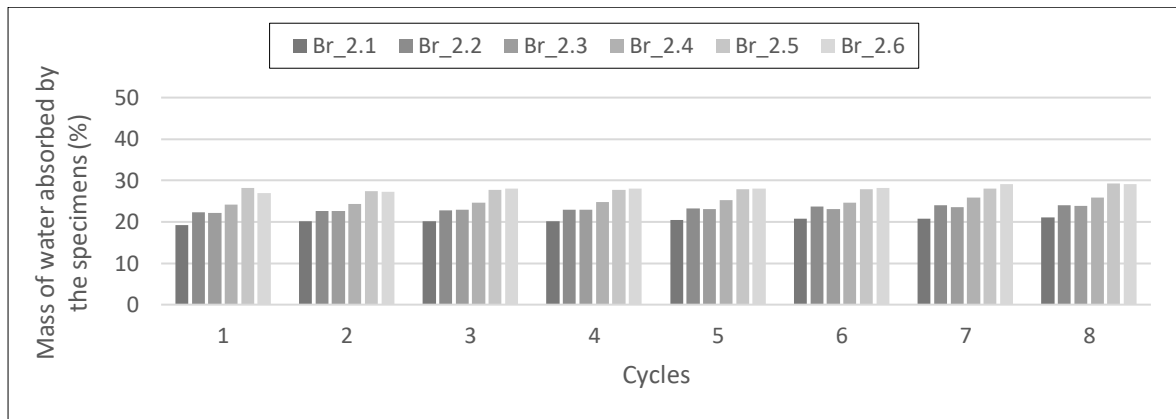
**Figure 4.32.** Variation of the weight during the ageing treatment (mortar specimens exposed to sodium chloride aqueous solution).



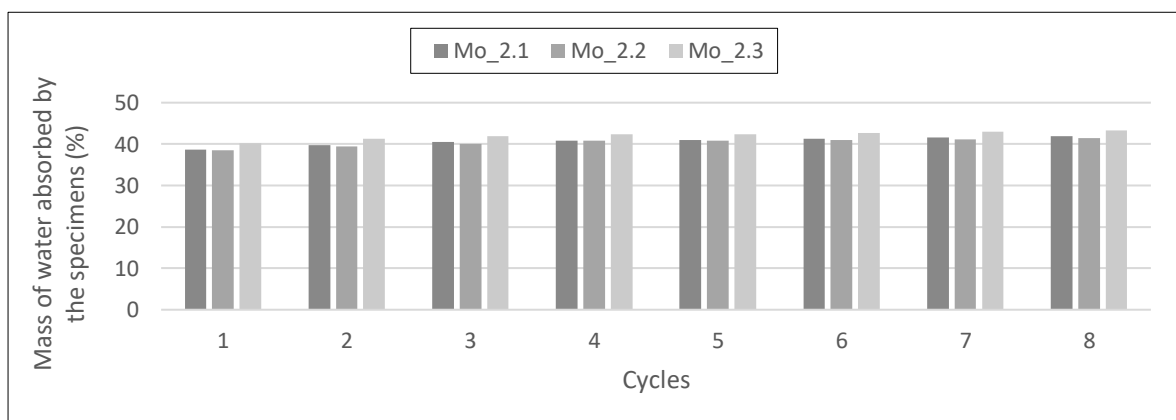
**Figure 4.33.** Average values of the weight over each cycle (brick specimens exposed to sodium chloride aqueous solution).



**Figure 4.34.** Average values of the weight over each cycle (mortar specimens exposed to sodium chloride aqueous solution).



**Figure 4.35.** Mass of the sodium chloride aqueous solution absorbed by the brick specimens during the ageing treatment.



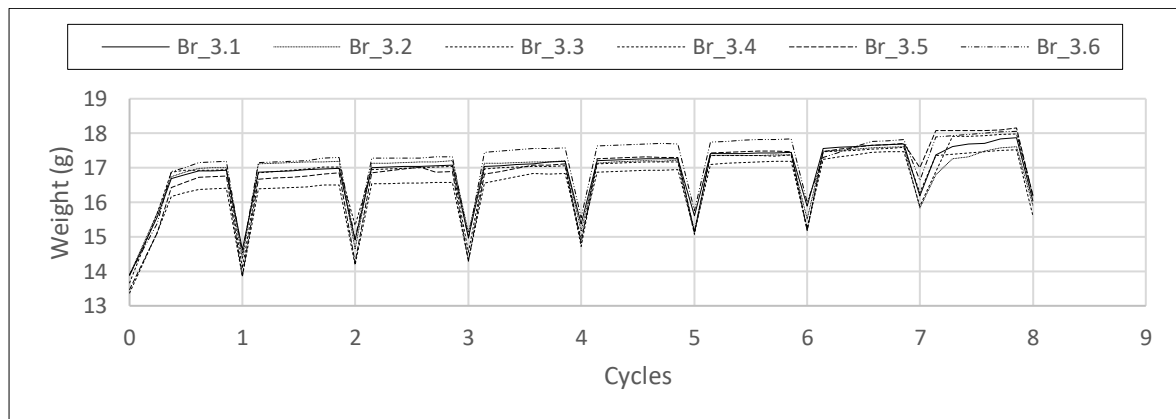
**Figure 4.36.** Mass of the sodium chloride aqueous solution absorbed by the mortar specimens during the ageing treatment.

**Table 4.36.** Variation of the weight during one cycle (brick specimens exposed to sodium chloride aqueous solution).

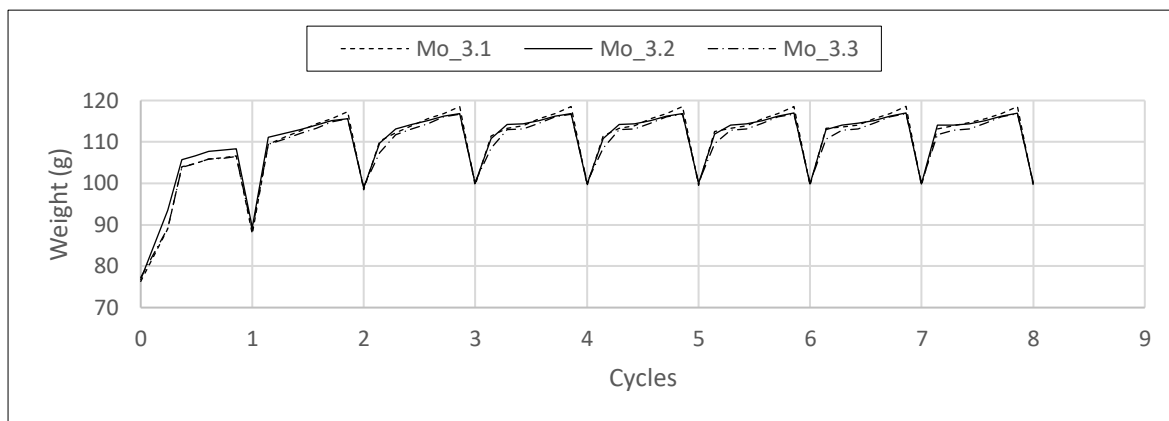
| Conditions |        | Weight               |             | Water content |       | Unit weight<br>(g) |
|------------|--------|----------------------|-------------|---------------|-------|--------------------|
|            |        | Average value<br>(g) | Sdev<br>(g) | (g)           | (%)   |                    |
| Untreated  |        | 14.03                | (0.27)      | 0             | 0     | 1754               |
| Treated    | Step 1 | 16.84                | (0.20)      | 2.81          | 20.00 | 2104               |
|            | Step 2 | 17.25                | (0.25)      | 3.22          | 22.94 | 2156               |
|            | Step 3 | 17.26                | (0.24)      | 3.23          | 23.01 | 2157               |
|            | Step 4 | 17.42                | (0.24)      | 3.39          | 24.16 | 2177               |
|            | Step 5 | 17.42                | (0.24)      | 3.39          | 24.19 | 2178               |
|            | Step 6 | 17.43                | (0.24)      | 3.40          | 24.23 | 2179               |
|            | Step 7 | 17.43                | (0.24)      | 3.40          | 24.24 | 2179               |

**Table 4.37.** Variation of the weight during one cycle (mortar specimens exposed to sodium chloride aqueous solution).

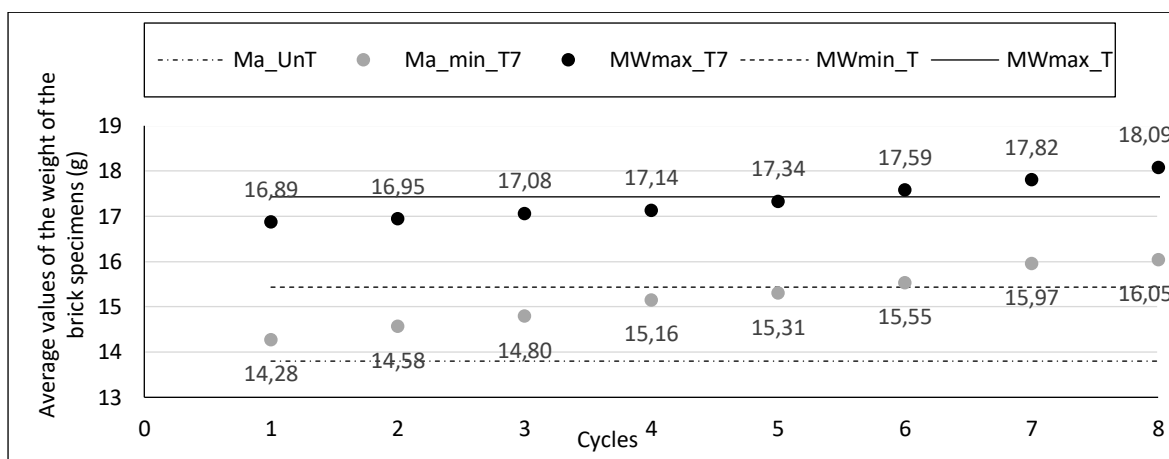
| Conditions |        | Weight               |             | Water content |       | Unit weight<br>(g) |
|------------|--------|----------------------|-------------|---------------|-------|--------------------|
|            |        | Average value<br>(g) | Sdev<br>(g) | (g)           | (%)   |                    |
| Untreated  |        | 78.0                 | (0.70)      | 0             | 0     | 1218               |
| Treated    | Step 1 | 104.                 | (1.20)      | 26.94         | 34.55 | 1639               |
|            | Step 2 | 107.4                | (1.08)      | 29.44         | 37.75 | 1679               |
|            | Step 3 | 109.9                | (1.01)      | 31.94         | 40.96 | 1718               |
|            | Step 4 | 109.9                | (1.01)      | 31.95         | 40.97 | 1718               |
|            | Step 5 | 109.9                | (1.01)      | 31.95         | 40.97 | 1718               |
|            | Step 6 | 109.9                | (1.01)      | 31.96         | 40.98 | 1718               |
|            | Step 7 | 109.9                | (1.02)      | 31.96         | 40.99 | 1718               |



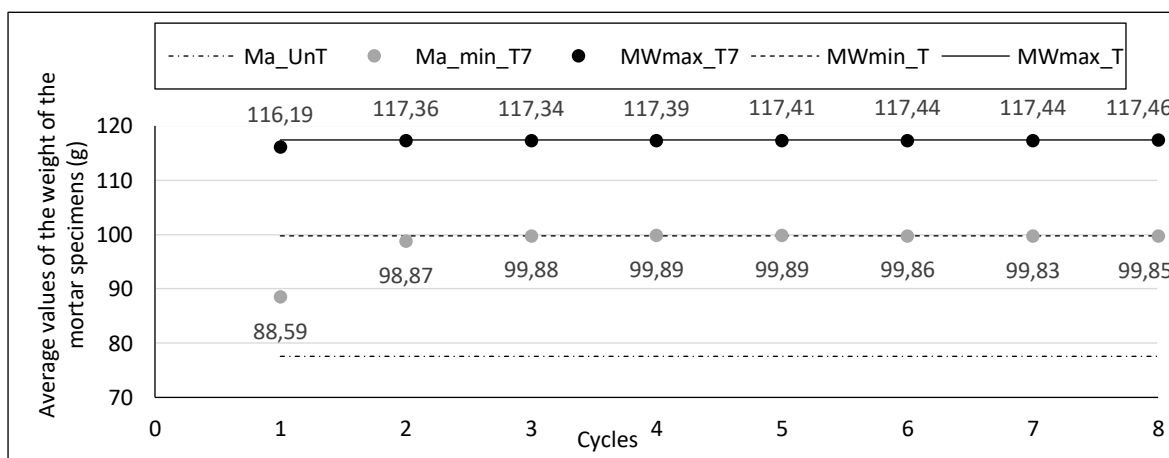
**Figure 4.37.** Variation of the weight during the ageing treatment (brick specimens exposed to sodium sulphate aqueous solution).



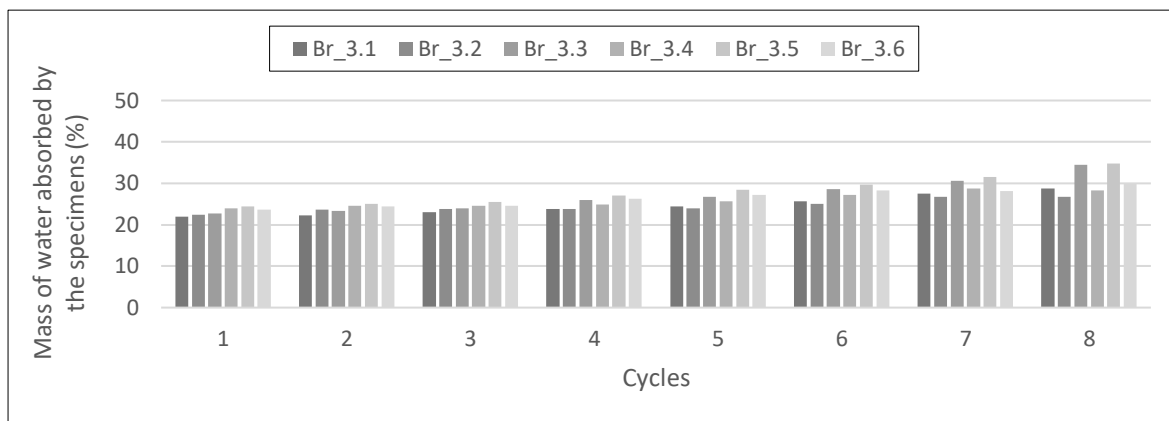
**Figure 4.38.** Variation of the weight during the ageing treatment (mortar specimens exposed to sodium sulphate aqueous solution).



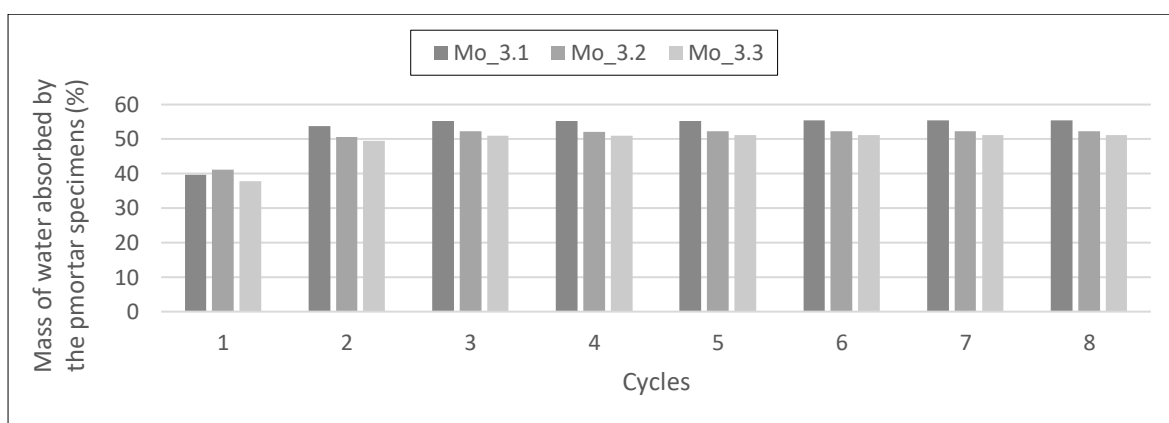
**Figure 4.39.** Average values of the weight over each cycle (brick specimens exposed to sodium sulphate aqueous solution).



**Figure 4.40.** Average values of the weight over each cycle (mortar specimens exposed to sodium sulphate aqueous solution).



**Figure 4.41.** Mass of the sodium sulphate aqueous solution absorbed by the brick specimens during the ageing treatment.



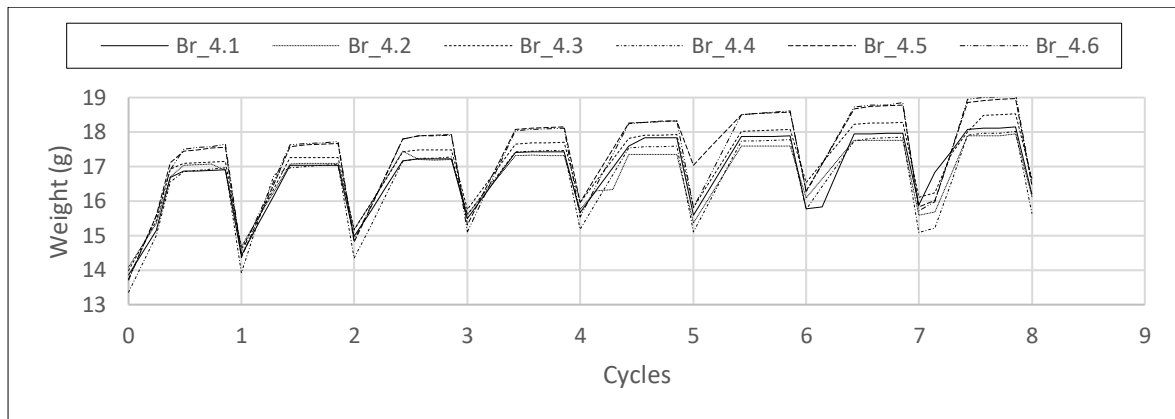
**Figure 4.42.** Mass of the sodium sulphate aqueous solution absorbed by the brick specimens during the ageing treatment.

**Table 4.38.** Variation of the weight during one cycle (brick specimens exposed to sodium sulphate aqueous solution).

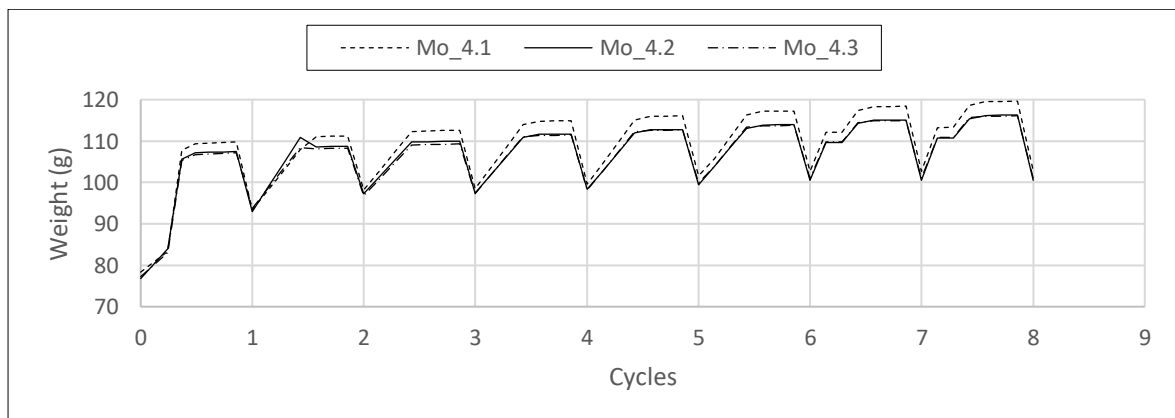
| Conditions |        | Weight            |          | Water content |       | Unit weight (g) |
|------------|--------|-------------------|----------|---------------|-------|-----------------|
|            |        | Average value (g) | Sdev (g) | (g)           | (%)   |                 |
| Untreated  |        | 13.80             | (0.25)   | 0             | 0     | 1725            |
| Treated    | Step 1 | 16.05             | (0.15)   | 2.25          | 16.30 | 2006            |
|            | Step 2 | 17.92             | (0.31)   | 4.12          | 29.83 | 2240            |
|            | Step 3 | 18.04             | (0.39)   | 4.24          | 30.72 | 2255            |
|            | Step 4 | 18.07             | (0.38)   | 4.27          | 30.92 | 2258            |
|            | Step 5 | 18.07             | (0.38)   | 4.27          | 30.94 | 2259            |
|            | Step 6 | 18.08             | (0.38)   | 4.28          | 30.99 | 2260            |
|            | Step 7 | 18.09             | (0.38)   | 4.29          | 31.06 | 2261            |

**Table 4.39.** Variation of the weight during one cycle (mortar specimens exposed to sodium sulphate aqueous solution).

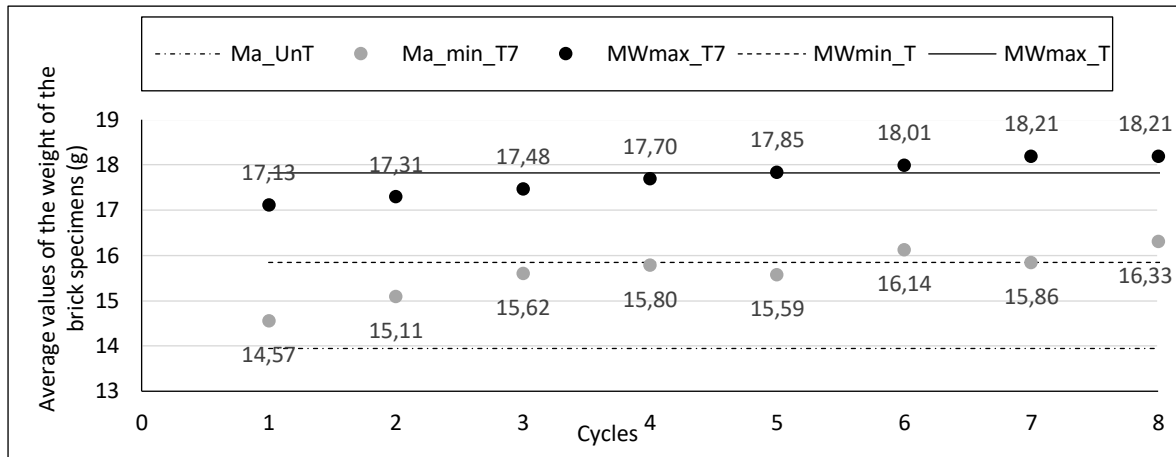
| Conditions | Weight            |          | Water content |       | Unit weight (g) |
|------------|-------------------|----------|---------------|-------|-----------------|
|            | Average value (g) | Sdev (g) | (g)           | (%)   |                 |
| Untreated  | 77.6              | (0.76)   | 0             | 0     | 1212            |
| Treated    |                   |          |               |       |                 |
| Step 1     | 99.9              | (0.34)   | 22.28         | 28.73 | 1560            |
| Step 2     | 113.4             | (0.67)   | 35.84         | 46.20 | 1772            |
| Step 3     | 113.8             | (0.75)   | 36.20         | 46.68 | 1778            |
| Step 4     | 114.6             | (1.29)   | 36.99         | 47.69 | 1790            |
| Step 5     | 115.2             | (0.64)   | 37.66         | 48.56 | 1800            |
| Step 6     | 116.4             | (0.42)   | 38.81         | 50.03 | 1818            |
| Step 7     | 117.5             | (0.98)   | 39.89         | 51.43 | 1835            |



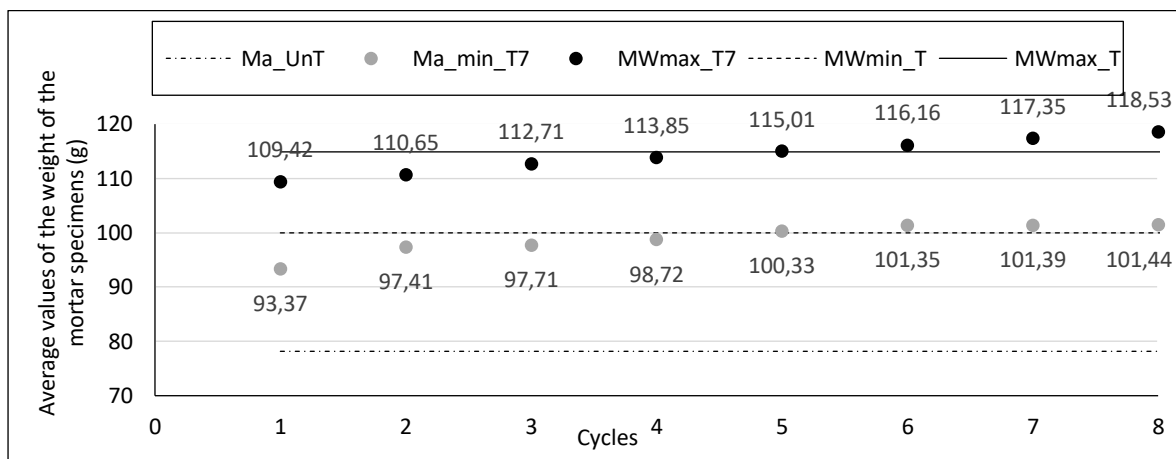
**Figure 4.43.** Variation of the weight during the ageing treatment (brick specimens exposed to potassium nitrate aqueous solution).



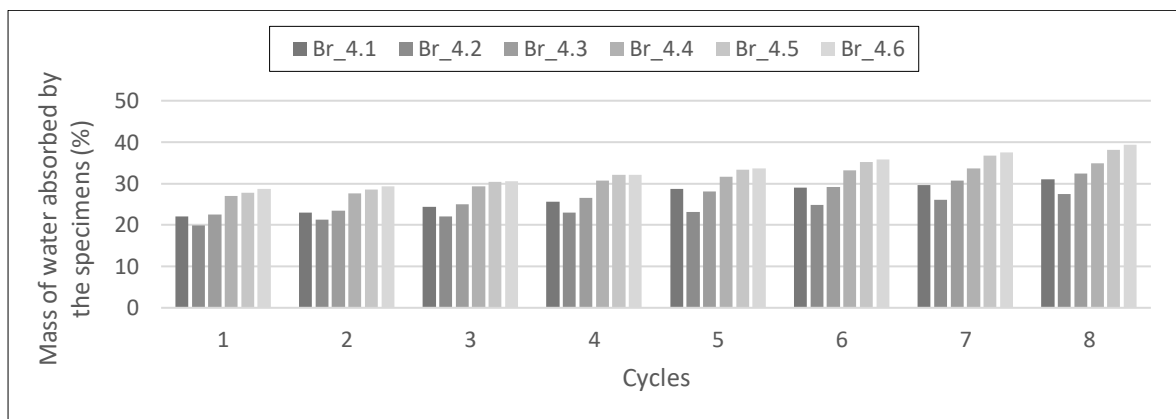
**Figure 4.44.** Variation of the weight during the ageing treatment (mortar specimens exposed to potassium nitrate aqueous solution).



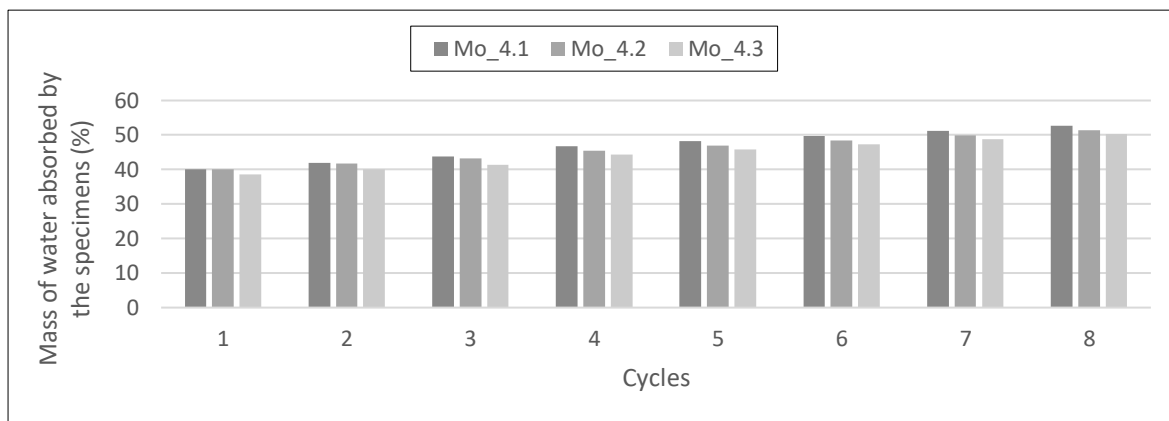
**Figure 4.45.** Average values of the weight over each cycle (brick specimens exposed to potassium nitrate aqueous solution).



**Figure 4.46.** Average values of the weight over each cycle (mortar specimens exposed to potassium nitrate aqueous solution).



**Figure 4.47.** Mass of the potassium nitrate aqueous solution absorbed by the brick specimens during the ageing treatment.



**Figure 4.48.** Mass of the potassium nitrate aqueous solution absorbed by the mortar specimens during the ageing treatment.

**Table 4.40.** Variation of the weight during one cycle (brick specimens exposed to potassium nitrate aqueous solution).

| Conditions |        | Weight            |          | Water content |       | Unit weight (g) |
|------------|--------|-------------------|----------|---------------|-------|-----------------|
|            |        | Average value (g) | Sdev (g) | (g)           | (%)   |                 |
| Untreated  |        | 13.95             | (0.26)   | 0             | 0     | 1743            |
| Treated    | Step 1 | 16.33             | (0.28)   | 2.38          | 17.08 | 2041            |
|            | Step 2 | 16.25             | (0.57)   | 2.31          | 16.55 | 2032            |
|            | Step 3 | 17.20             | (0.36)   | 3.26          | 23.36 | 2150            |
|            | Step 4 | 17.99             | (0.09)   | 4.04          | 28.98 | 2248            |
|            | Step 5 | 18.16             | (0.30)   | 4.22          | 30.25 | 2270            |
|            | Step 6 | 18.17             | (0.31)   | 4.23          | 30.32 | 2272            |
|            | Step 7 | 18.21             | (0.29)   | 4.26          | 30.58 | 2276            |

**Table 4.41.** Variation of the weight during one cycle (mortar specimens exposed to potassium nitrate solution).

| Conditions |        | Weight            |          | Water content |       | Unit weight (g) |
|------------|--------|-------------------|----------|---------------|-------|-----------------|
|            |        | Average value (g) | Sdev (g) | (g)           | (%)   |                 |
| Untreated  |        | 78.2              | (0.77)   | 0             | 0     | 1221            |
| Treated    | Step 1 | 101.4             | (1.17)   | 23.26         | 29.76 | 1585            |
|            | Step 2 | 112.7             | (1.45)   | 34.56         | 44.21 | 1761            |
|            | Step 3 | 112.8             | (1.46)   | 34.61         | 44.27 | 1762            |
|            | Step 4 | 117.7             | (1.80)   | 39.56         | 50.61 | 1840            |
|            | Step 5 | 118.4             | (2.01)   | 40.28         | 51.53 | 1851            |
|            | Step 6 | 118.5             | (2.03)   | 40.32         | 51.57 | 1851            |
|            | Step 7 | 118.5             | (1.99)   | 40.36         | 51.62 | 1852            |

From an overall point of view, the following considerations can be done on the basis of the data referring to the specimens exposed to salts aqueous solutions.

During the first aging cycle, the weight of the brick specimens exposed to sodium chloride, sodium sulphate and potassium nitrate aqueous solutions increased by 22.53% (from 14.03 g to 17.19 g), 21.59% (from 13.80 g to 16.78 g) and 21.79% (from 13.95 g to 16.99 g), respectively. During the following ageing cycles, the weight of the brick specimens further increased by 1.40% (from 17.19 g to 17.43 g), by 7.80% (from 16.79 g to 18.09 g) and by 7.18% (from 16.99 g to 18.21 g), respectively. The last two values are higher than those relating to brick specimens exposed to deionized water.

Moreover, as regard the brick specimens exposed to sodium chloride aqueous solution, the mean minimum and maximum values of the weight were 16.58 g and 17.34 g, respectively, corresponding to an increase of 18.17% and 23.59% from the initial weight (14.03 g). As regard the brick specimens exposed to sodium sulphate aqueous solution, they were 15.43 g and 17.43 g, corresponding to an increase of 11.81% and 26.30% from the initial weight (13.80 g). Finally, as regard the brick specimens exposed to potassium nitrate aqueous solution, they were 15.85 g and 17.82 g, corresponding to an increase of 13.62% and 27.74% from the initial weight (13.95 g). In all cases, the two values of the weight are the thresholds within which the weight of the treated brick specimens varied.

Similarly, during the first aging cycle, the weight of the mortar specimens exposed to sodium chloride, sodium sulphate and potassium nitrate aqueous solutions increased by 37.82% (from 78.0 g to 107.5 g), 38.01% (from 77.6 g to 107.1 g) and 38.23% (from 78.2 g to 108.1 g), respectively. During the following ageing cycles, the weight of the brick specimens further increased by 2.23% (from 107.5 g to 109.9 g), by 9.71% (from 107.1 g to 117.5 g) and by 9.62% (from 108.1 g to 118.5 g), respectively. These values are similar to those related to mortar specimens exposed to deionized water.

Moreover, as regard the mortar specimens exposed to sodium chloride aqueous solution, the mean minimum and maximum values of the weight were 103.5 g and 109.4 g, respectively, corresponding to an increase of 32.78% and 40.29% from the initial weight (78.0 g). As regard the brick specimens exposed to sodium sulphate aqueous solution, they were 99.7 g and 117.4 g, corresponding to an increase of 28.60% and 51.38% from the

initial weight (77.6 g). Finally, as regard the brick specimens exposed to potassium nitrate aqueous solution, they were 99.9 g and 114.9 g, corresponding to an increase of 27.90% and 46.97% from the initial weight (78.2 g). In all cases, the two values of the weight are the thresholds within which the weight of the treated brick specimens varied.

#### 4.3.3 Compressive strength and stiffness

After the ageing treatment, the brick and mortar specimens underwent mechanical test to evaluate their compressive strength and their stiffness, according to the method described in the Section 3.7.3. The stress-strain curves relating to all the specimens are contained in the *Attachment 6* and in the *Attachment 7*, respectively.

Tables 4.42 – 4.45 and 4.46 – 4.49 summarise data acquired, relating to brick and mortar specimens, respectively. Data refer to the weight the specimens had when the test was performed, and to their water content, in turn.

**Table 4.42.** Mechanical properties of the brick specimens exposed to deionized water  
(mean test conditions: T = 23.4 °C RH = 60%).

| Specimen | Weight<br>(g) | H <sub>2</sub> O content<br>(%) | $\sigma_{\max}$<br>(N/mm <sup>2</sup> ) | E<br>(N/mm <sup>2</sup> ) |
|----------|---------------|---------------------------------|-----------------------------------------|---------------------------|
| Br_1.1   | 16.96         | 20.71                           | 44.44                                   | 2727                      |
| Br_1.2   | 16.96         | 22.63                           | 45.98                                   | 4293                      |
| Br_1.3   | 16.76         | 20.32                           | 40.88                                   | 3644                      |
| Br_1.4   | 16.95         | 20.64                           | 48.73                                   | 1193                      |
| Br_1.5   | 16.91         | 22.29                           | 41.03                                   | 2880                      |
| Br_1.6   | 16.78         | 20.60                           | 37.82                                   | 3442                      |
| Average  | 16.89         | 21.20                           | 43.15                                   | 3030                      |
| Sdev     | (0.09)        | (0.99)                          | (5.61)                                  | (1170)                    |

**Table 4.43.** Mechanical properties of the brick specimens exposed to sodium chloride aqueous solution (mean test conditions: T = 23.4 °C RH = 60%).

| Specimen | Weight<br>(g) | H <sub>2</sub> O content<br>(%) | $\sigma_{\max}$<br>(N/mm <sup>2</sup> ) | E<br>(N/mm <sup>2</sup> ) |
|----------|---------------|---------------------------------|-----------------------------------------|---------------------------|
| Br_2.1   | 17.08         | 21.05                           | 35.93                                   | 2690                      |
| Br_2.2   | 17.28         | 23.96                           | 29.21                                   | 4154                      |
| Br_2.3   | 17.37         | 23.89                           | 35.61                                   | 3359                      |
| Br_2.4   | 17.70         | 25.85                           | 27.39                                   | 2357                      |
| Br_2.5   | 17.68         | 29.62                           | 24.77                                   | 2747                      |
| Br_2.6   | 17.48         | 29.16                           | 34.07                                   | 2280                      |
| Average  | 17.43         | 25.59                           | 31.16                                   | 2931                      |
| Sdev     | (0.24)        | (3.32)                          | (3.92)                                  | (204)                     |

**Table 4.44.** Mechanical properties of the brick specimens exposed to sodium sulphate aqueous solution (mean test conditions: T = 23.4 °C RH = 60%).

| Specimen | Weight<br>(g) | H <sub>2</sub> O content<br>(%) | $\sigma_{\max}$<br>(N/mm <sup>2</sup> ) | E<br>(N/mm <sup>2</sup> ) |
|----------|---------------|---------------------------------|-----------------------------------------|---------------------------|
| Br_3.1   | 17.73         | 27.74                           | 17.31                                   | 1998                      |
| Br_3.2   | 18.04         | 29.78                           | 15.97                                   | 1350                      |
| Br_3.3   | 18.49         | 38.29                           | 14.98                                   | 2593                      |
| Br_3.4   | 17.81         | 30.36                           | 11.99                                   | 954                       |
| Br_3.5   | 18.40         | 36.59                           | 11.45                                   | 1151                      |
| Br_3.6   | 18.35         | 31.93                           | 18.03                                   | 1258                      |
| Average  | 18.14         | 32.45                           | 14.96                                   | 1551                      |
| Sdev     | (0.32)        | (4.13)                          | (2.72)                                  | (621)                     |

**Table 4.45.** Mechanical properties of the brick specimens exposed to potassium nitrate aqueous solution (mean test conditions: T = 23.4 °C RH = 60%).

| Specimen | Weight<br>(g) | H <sub>2</sub> O content<br>(%) | $\sigma_{\max}$<br>(N/mm <sup>2</sup> ) | E<br>(N/mm <sup>2</sup> ) |
|----------|---------------|---------------------------------|-----------------------------------------|---------------------------|
| Br_4.1   | 18.15         | 30.95                           | 40.57                                   | 2840                      |
| Br_4.2   | 17.95         | 27.40                           | 35.44                                   | 3849                      |
| Br_4.3   | 18.53         | 32.45                           | 44.51                                   | 2753                      |
| Br_4.4   | 18.02         | 34.89                           | 38.33                                   | 2222                      |
| Br_4.5   | 18.97         | 38.10                           | 44.13                                   | 2056                      |
| Br_4.6   | 19.11         | 39.32                           | 40.42                                   | 2048                      |
| Average  | 18.45         | 33.85                           | 40.57                                   | 2628                      |
| Sdev     | (0.50)        | (4.50)                          | (3.45)                                  | (690)                     |

**Table 4.46.** Mechanical properties of the mortar specimens exposed to deionized water  
(mean test conditions: T = 23.4 °C RH = 60%).

| Specimen | Weight<br>(g) | H <sub>2</sub> O content<br>(%) | $\sigma_{\max}$<br>(N/mm <sup>2</sup> ) | E<br>(N/mm <sup>2</sup> ) |
|----------|---------------|---------------------------------|-----------------------------------------|---------------------------|
| Mo_1.1   | 112.1         | 43.00                           | 2.16                                    | 84.5                      |
| Mo_1.2   | 112.2         | 45.62                           | 1.89                                    | 51.3                      |
| Mo_1.3   | 104.0         | 32.10                           | 2.36                                    | 44.6                      |
| Average  | 109.4         | 40.24                           | 2.14                                    | 60.1                      |
| Sdev     | (4.7)         | (7.17)                          | (0.24)                                  | (21.3)                    |

**Table 4.47.** Mechanical properties of the mortar specimens exposed to sodium chloride aqueous  
solution (mean test conditions: T = 23.4 °C RH = 60%).

| Specimen | Weight<br>(g) | H <sub>2</sub> O content<br>(%) | $\sigma_{\max}$<br>(N/mm <sup>2</sup> ) | E<br>(N/mm <sup>2</sup> ) |
|----------|---------------|---------------------------------|-----------------------------------------|---------------------------|
| Mo_2.1   | 110.2         | 41.99                           | 1.37                                    | 93.4                      |
| Mo_2.2   | 108.8         | 42.42                           | 1.49                                    | 149.6                     |
| Mo_2.3   | 110.8         | 42.84                           | 1.39                                    | 87.1                      |
| Average  | 110.0         | 42.42                           | 1.42                                    | 110.0                     |
| Sdev     | (1)           | (0.43)                          | (0.06)                                  | (34.4)                    |

**Table 4.48.** Mechanical properties of the mortar specimens exposed to sodium sulphate aqueous  
solution (mean test conditions: T = 23.4 °C RH = 60%).

| Specimen | Weight<br>(g) | H <sub>2</sub> O content<br>(%) | $\sigma_{\max}$<br>(N/mm <sup>2</sup> ) | E<br>(N/mm <sup>2</sup> ) |
|----------|---------------|---------------------------------|-----------------------------------------|---------------------------|
| Mo_3.1   | 118.6         | 55.41                           | 1.58                                    | 92.8                      |
| Mo_3.2   | 117.0         | 50.17                           | 1.57                                    | 46.6                      |
| Mo_3.3   | 116.8         | 52.86                           | 1.61                                    | 41.2                      |
| Average  | 117.4         | 52.81                           | 1.59                                    | 60.2                      |
| Sdev     | (1)           | (2.62)                          | (0.02)                                  | (28.3)                    |

**Table 4.49.** Mechanical properties of the mortar specimens exposed to potassium nitrate  
aqueous solution (mean test conditions: T = 23.4 °C RH = 60%).

| Specimen | Weight<br>(g) | H <sub>2</sub> O content<br>(%) | $\sigma_{\max}$<br>(N/mm <sup>2</sup> ) | E<br>(N/mm <sup>2</sup> ) |
|----------|---------------|---------------------------------|-----------------------------------------|---------------------------|
| Mo_4.1   | 120.8         | 54.20                           | 1.96                                    | 66.8                      |
| Mo_4.2   | 117.5         | 52.99                           | 1.78                                    | 102.1                     |
| Mo_4.3   | 117.3         | 51.78                           | 2.08                                    | 77.2                      |
| Average  | 118.5         | 52.99                           | 1.94                                    | 82.1                      |
| Sdev     | (2)           | (1.21)                          | (0.15)                                  | (18.1)                    |

Table 4.50 shows data relating to all kind of the treated brick specimens, compared to data referring to the untreated specimens (Section 3.5).

**Table 4.50.** Comparison among the mechanical properties of all the brick specimens which underwent the ageing treatment in laboratory and the untreated specimens.

| Untreated                                |                           | H <sub>2</sub> O                         |                           | NaCl                                     |                           | Na <sub>2</sub> SO <sub>4</sub>          |                           | KNO <sub>3</sub>                         |                           |       |       |
|------------------------------------------|---------------------------|------------------------------------------|---------------------------|------------------------------------------|---------------------------|------------------------------------------|---------------------------|------------------------------------------|---------------------------|-------|-------|
| σ <sub>max</sub><br>(N/mm <sup>2</sup> ) | E<br>(N/mm <sup>2</sup> ) | σ <sub>max</sub><br>(N/mm <sup>2</sup> ) | E<br>(N/mm <sup>2</sup> ) | σ <sub>max</sub><br>(N/mm <sup>2</sup> ) | E<br>(N/mm <sup>2</sup> ) | σ <sub>max</sub><br>(N/mm <sup>2</sup> ) | E<br>(N/mm <sup>2</sup> ) | σ <sub>max</sub><br>(N/mm <sup>2</sup> ) | E<br>(N/mm <sup>2</sup> ) |       |       |
| 53.44                                    | 3566                      | 48.73                                    | 1193                      |                                          |                           |                                          |                           | 44.51                                    | 2753                      |       |       |
| 52.55                                    | 4053                      |                                          |                           |                                          |                           |                                          |                           |                                          |                           |       |       |
| 51.67                                    | 3656                      |                                          |                           |                                          |                           |                                          |                           |                                          |                           |       |       |
| 48.09                                    | 3179                      |                                          |                           |                                          |                           |                                          |                           |                                          |                           |       |       |
| 44.31                                    | 3830                      |                                          |                           |                                          |                           |                                          |                           |                                          |                           | 45.98 | 4294  |
|                                          |                           |                                          |                           |                                          |                           |                                          |                           |                                          |                           | 44.44 | 2727  |
|                                          |                           |                                          |                           |                                          |                           |                                          |                           |                                          |                           | 41.03 | 2880  |
|                                          |                           |                                          |                           |                                          |                           |                                          |                           |                                          |                           | 40.88 | 3644  |
| 30.33                                    | 1440                      |                                          |                           |                                          |                           |                                          |                           |                                          |                           | 37.82 | 3442  |
|                                          |                           |                                          |                           |                                          |                           |                                          |                           |                                          |                           |       | 35.93 |
|                                          |                           | 35.61                                    | 3359                      |                                          |                           |                                          |                           |                                          |                           |       |       |
|                                          |                           | 34.07                                    | 2280                      |                                          |                           |                                          |                           |                                          |                           |       |       |
|                                          |                           | 29.21                                    | 4154                      |                                          |                           |                                          |                           |                                          |                           |       |       |
|                                          |                           | 27.39                                    | 2357                      |                                          |                           |                                          |                           |                                          |                           |       |       |
|                                          |                           | 24.77                                    | 2747                      |                                          |                           |                                          |                           |                                          |                           |       |       |
|                                          |                           |                                          |                           | 18.03                                    | 1258                      |                                          |                           |                                          |                           |       |       |
|                                          |                           |                                          |                           | 17.31                                    | 1998                      |                                          |                           |                                          |                           |       |       |
|                                          |                           |                                          |                           | 15.97                                    | 1350                      |                                          |                           |                                          |                           |       |       |
|                                          |                           |                                          |                           | 14.98                                    | 2593                      |                                          |                           |                                          |                           |       |       |
|                                          |                           |                                          |                           | 11.99                                    | 954                       |                                          |                           |                                          |                           |       |       |
|                                          |                           |                                          |                           | 11.45                                    | 1151                      |                                          |                           |                                          |                           |       |       |

As regard the brick specimens exposed to the sodium chloride aqueous solution, the average value of the compressive strength and that of the modulus of elasticity are 33.31% and 10.83% lower than those referring to the untreated specimens.

[illegible]

compressive strength of the former is 5.15% lower than that of the latter, while the modulus of elasticity is 54.17% lower.

As regard the mortar specimens exposed to the sodium chloride aqueous solution, the average value of the compressive strength is 37.10% lower, while that of the modulus of elasticity is 14.07% higher than those referring to the untreated specimens.

As regard the mortar specimens exposed to the sodium sulphate aqueous solution, the average value of the compressive strength and that of the modulus of elasticity are 29.56% and 25.95% lower than those referring to the untreated specimens.

As regard the mortar specimens exposed to the potassium nitrate aqueous solution, the average value of the compressive strength and that of the modulus of elasticity are 13.88% and 60.17% lower than those referring to the untreated specimens.

From an overall point of view, the mechanical features of the specimens exposed to the ageing treatment are worse than those referring to the untreated specimens. Results are comparable from the point of view of the compressive strength, while as regard the modulus of elasticity the variability is high. This could be due to the method used to measure deformation or to the non-standardization of the specimens, which were handmade.

As regard the compressive strength, comparing data relating to brick, mortar and masonry specimens, it emerges that a qualitative relationship exists between the kind of salts aqueous solution used for the ageing treatment and the decrease in the values of the mechanical parameters. The specimens exposed to sodium chloride or sodium sulphate aqueous solutions show the worst performance. On the contrary the specimens exposed to potassium nitrate aqueous solutions show a better performance, even if worse than that of specimens exposed to deionized water. No great differences occur between specimens untreated and exposed to deionized water. It is interesting to underline that as regard the mortar specimens, the lowest values of the compressive strength occur in those exposed to sodium chloride, while as regard the brick specimens, they occur in those exposed to sodium sulphate.

As regard the relationship between the values referring to the masonry, bricks and mortar specimens some consideration can be done. Firstly, comparing the stress-strain curves of

all kind of specimens, it emerges that those relating to the masonry stay between those relating to the constitutive materials, consistently with theoretical and experimental data widely spread in literature (Como, 2013; Drysdal et al. 1994).

Scientific literature provides also several formulas to derive the maximum compressive strength of the masonry, starting from data referring to the constitute materials. For instance, the following formula is provided by the Eurocode 6 (EN 1996 1-1, 2013):

$$f_k = k f_b^{0.7} f_m^{0.3} \quad (4.1)$$

where:  $f_k$  is the characteristic strength of the masonry;  $f_b$  is the normalised mean compressive strength of the masonry unit in the direction of the applied action (product between the compressive strength of the brick, the conditioning factor and the shear factor; the latter were set 1 and 0.77 respectively);  $f_m$  is the compressive strength of the mortar;  $k = 0.55$  is a constant obtained from the Table 3.3 of the Eurocode 6.

In this case, the formula 4.1 was applied considering not the characteristic values of the strength, but the raw data, deriving from the experimental measures. It emerges that the maximum strength of the untreated masonry specimens ranges from 5.75 N/mm<sup>2</sup> and 8.98 N/mm<sup>2</sup>. In this case, the mean value of the  $f_k$  calculated through the formula 4.1 is 7.94 N/mm<sup>2</sup> (Sdev 0.99). This is 8.5% lower than the mean value referring to the experimental data.

Similarly, the mean values of the  $f_k$  referring to the treated specimens, exposed to deionized water or sodium chloride, sodium sulphate, potassium nitrate aqueous solutions, are 7.41 N/mm<sup>2</sup> (Sdev 0.48), 5.21 N/mm<sup>2</sup> (Sdev 0.51), 3.22 N/mm<sup>2</sup> (Sdev 0.38), 6.89 N/mm<sup>2</sup> (Sdev 0.40), respectively. Comparing this data with those collected in Table 4.25, it emerges that they are lower than the mean value referring to the experimental data. The best correspondence occurs for specimens exposed to deionized water where the ratio between the mean values is 0.12. On the contrary, the worst correspondence occurs for specimens exposed to sodium sulphate water solution where the ratio between the mean values is 0.54.

Even for the modulus of elasticity, several theoretical formulas exist in literature. Drysdale et al. (1994) proposed a formula widely used (Lourenco and Pina-Henriques, 2006; Binda, 1988) which links the modulus of elasticity of the masonry to these of the constitutive materials:

$$E_{Ma} = \frac{1}{\frac{\delta}{E_{Br}} + \frac{1-\delta}{E_{Mo}}} \quad (4.2)$$

where:  $E_{Ma}$ ,  $E_{Br}$  and  $E_{Mo}$  are the Moduli of elasticity of the masonry, the brick and the mortar, respectively;  $\delta$  is given by:  $\delta = t_{Br} / (t_{Br} + t_{Mo})$ , being  $t_{Br}$  and  $t_{Mo}$  the height of brick and mortar joints, respectively.

Even in this case the formula 4.2 was applied considering not the characteristic values of the strength, but the raw data, deriving from the experimental measures. It emerges that the modulus of elasticity of the untreated masonry specimens ranges from 117.4 N/mm<sup>2</sup> and 522.2 N/mm<sup>2</sup>. The mean value is 334.5 (Sdev 158.35), twice the corresponding value deriving from the experimental measures.

Similarly, the mean values of the modulus of elasticity referring to the treated specimens, exposed to deionized water or sodium chloride, sodium sulphate, potassium nitrate aqueous solutions, are 101.3 N/mm<sup>2</sup> (Sdev 75.60), 155.2 N/mm<sup>2</sup> (Sdev 58.65), 105.2 N/mm<sup>2</sup> (Sdev 86.77), 114.6 N/mm<sup>2</sup> (Sdev 37.02), respectively. Comparing this data with those collected in Table 4.25, it emerges that they are lower than the mean value referring to the experimental data, except for that referring to the specimens exposed to the sodium chloride aqueous solutions.

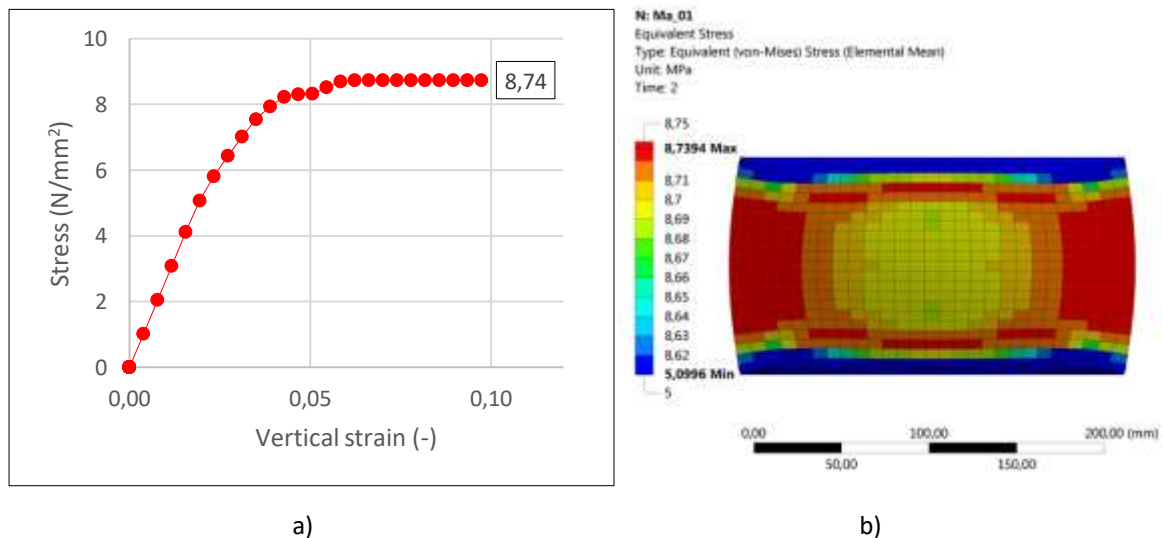
#### 4.4 Results of the Finite Element Analysis

In the previous sections, the mechanical results referring to the masonry specimens and to their construction materials were presented and analysed. Data referring to the untreated and treated specimens were compared and the decrease in the mechanical features was obtained.

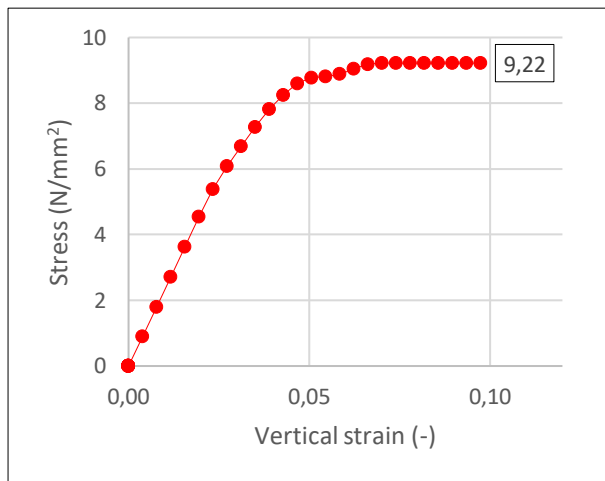
The aim of this part of the research is to extend the results referring to the masonry specimens used to conduct the experiment, to other kind of brickworks. This study was conducted through a Finite Element Analysis approach, as it was described in the Section 3.10.

The masonry specimens belonging to the same group, were modelled with a macro and a micro approach. In the former, a homogeneous material was assigned to a virtual prism, while in the latter, bricks and mortar were modelled separately and a different material was assigned to each part.

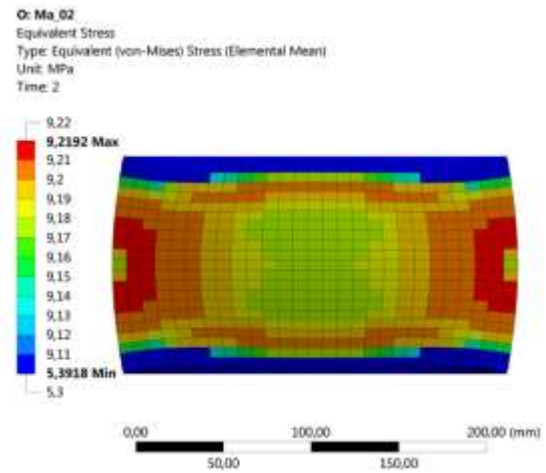
The experimental stress-strain curves obtained through the mechanical test, referring both to the masonry specimens and to the construction materials, were very different from each other. For this reason, they were not averaged but used to define several variants of the same material, in the same conditions. Figures 4.49 – 4.51 show the virtual curves, and the stress distribution, referring to the untreated masonry specimens. The structural analysis reproduces the experimental results faithfully. The stress distribution is consistent with the crack path of the specimens, showed in the photographs which are in the *Attachment 2*.



**Figure 4.49.** a) stress-strain curves; b) stress path (on the right) of the masonry specimen Ma\_01 (untreated), obtained with FEA.

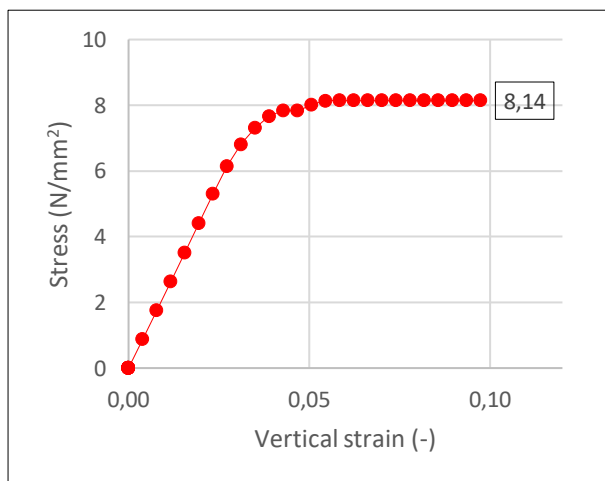


a)

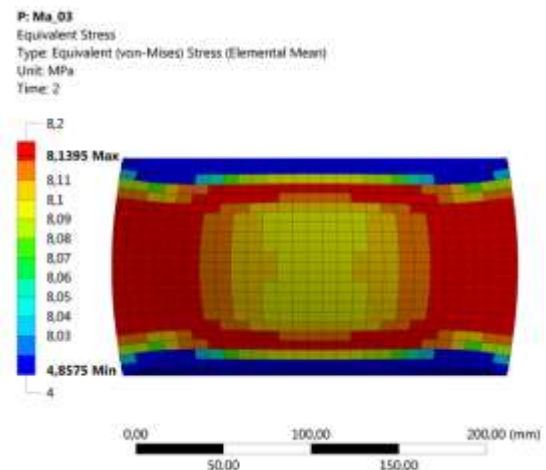


b)

**Figure 4.50.** a) stress-strain curves; b) stress path (on the right) of the masonry specimen Ma\_02 (untreated), obtained with FEA.

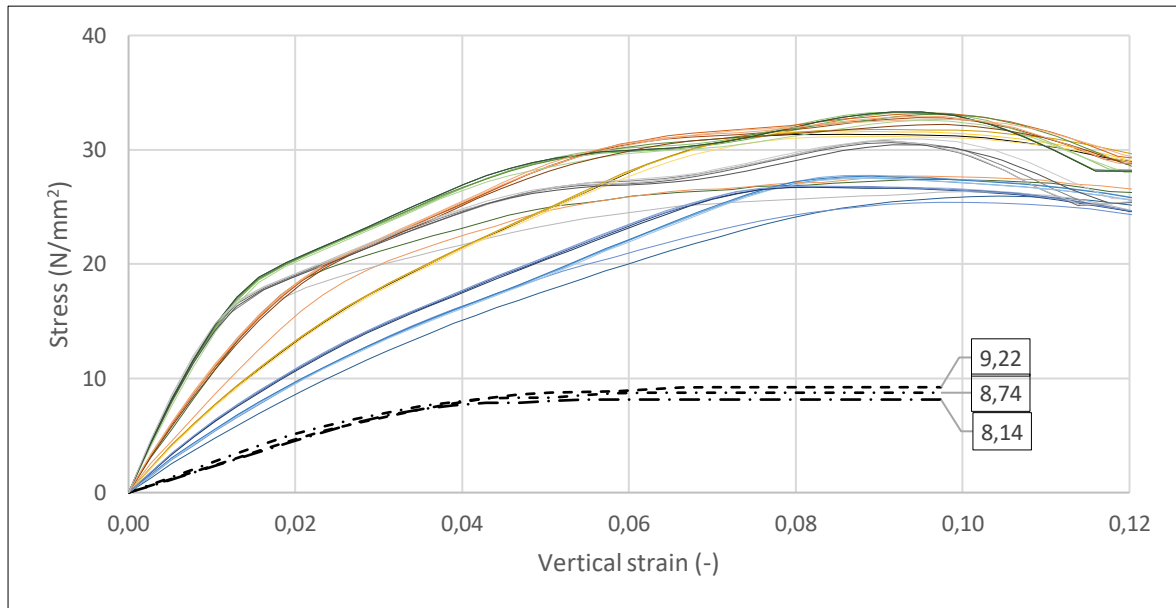


a)



b)

**Figure 4.51.** a) stress-strain curves; b) stress path (on the right) of the masonry specimen Ma\_03 (untreated), obtained with FEA.



**Figure 4.52.** Comparison among the stress-strain curves of the untreated masonry specimen obtained with FEA conducted with a micro element approach (solid lines), and a macro element approach (dash and dash-dot lines) compared with those obtained with FEA conducted with a micro element approach.

**Table 4.52.** Comparison of the results of the FEA of the untreated masonry specimens, conducted with a micro element approach.

| Specimen  | Weight<br>(g) | $\sigma_{max}$<br>(N/mm <sup>2</sup> ) | E<br>(N/mm <sup>2</sup> ) | Specimen  | Weight<br>(g) | $\sigma_{max}$<br>(N/mm <sup>2</sup> ) | E<br>(N/mm <sup>2</sup> ) |
|-----------|---------------|----------------------------------------|---------------------------|-----------|---------------|----------------------------------------|---------------------------|
| (Ma)_0.1  | 5137          | 31.28                                  | 761                       | (Ma)_0.19 | 5124          | 31.69                                  | 769                       |
| (Ma)_0.2  | 5137          | 27.31                                  | 530                       | (Ma)_0.20 | 5124          | 27.34                                  | 534                       |
| (Ma)_0.3  | 5137          | 33.00                                  | 1510                      | (Ma)_0.21 | 5124          | 33.08                                  | 1540                      |
| (Ma)_0.4  | 5137          | 26.45                                  | 626                       | (Ma)_0.22 | 5124          | 26.60                                  | 632                       |
| (Ma)_0.5  | 5154          | 32.79                                  | 1146                      | (Ma)_0.23 | 5142          | 32.67                                  | 1164                      |
| (Ma)_0.6  | 5154          | 29.76                                  | 1691                      | (Ma)_0.24 | 5142          | 30.70                                  | 1615                      |
| (Ma)_0.7  | 5137          | 27.54                                  | 623                       | (Ma)_0.25 | 5172          | 31.05                                  | 747                       |
| (Ma)_0.8  | 5137          | 25.77                                  | 460                       | (Ma)_0.26 | 5172          | 27.16                                  | 523                       |
| (Ma)_0.9  | 5137          | 27.41                                  | 1060                      | (Ma)_0.27 | 5172          | 32.53                                  | 1461                      |
| (Ma)_0.10 | 5137          | 25.40                                  | 517                       | (Ma)_0.28 | 5172          | 26.54                                  | 617                       |
| (Ma)_0.11 | 5154          | 27.67                                  | 842                       | (Ma)_0.29 | 5189          | 32.22                                  | 1116                      |
| (Ma)_0.12 | 5154          | 26.28                                  | 1101                      | (Ma)_0.30 | 5189          | 30.13                                  | 1531                      |
| (Ma)_0.13 | 5168          | 31.44                                  | 763                       | (Ma)_0.31 | 5114          | 31.27                                  | 774                       |
| (Ma)_0.14 | 5168          | 27.41                                  | 531                       | (Ma)_0.32 | 5114          | 33.99                                  | 1562                      |
| (Ma)_0.15 | 5168          | 33.13                                  | 1521                      | (Ma)_0.33 | 5114          | 32.99                                  | 1562                      |
| (Ma)_0.16 | 5168          | 26.72                                  | 628                       | (Ma)_0.34 | 5114          | 26.54                                  | 636                       |
| (Ma)_0.17 | 5185          | 33.19                                  | 1152                      | (Ma)_0.35 | 5131          | 32.91                                  | 1177                      |
| (Ma)_0.18 | 5185          | 30.28                                  | 1644                      | (Ma)_0.36 | 5131          | 27.75                                  | 1638                      |

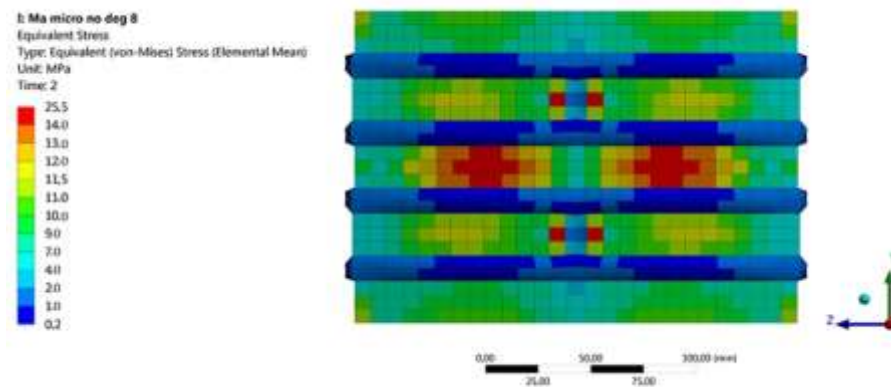
Figure 4.52 shows all the stress-strain curves referring to the untreated specimens derived from the FEA conducted with a macro element and a micro element approach. As regard the latter, overall, 36 curves were obtained combining data referring to masonry and brick specimens, according to the criterion described in Section 3.10 and shown in Figure 3.36. In Table 4.52 the weight, the equivalent modulus of elasticity and the stress value referring to the same value of the strain, that is 0.1, are collected. The equivalent modulus of elasticity refers to the first part of the curves, that is between 0 and  $6 \pm 1 \text{ N/mm}^2$ .

As regard the weight, the values are very similar each to the other. The average value is 5147 g (Sdev 22 g), 4.80% higher than that referring to the real masonry specimens, recorded in Table 3.19. The geometric virtual models do not fit perfectly to the real ones, nor the ratio between the bricks and the mortar parts can be perfectly determined. This aspect can explain the reason of the difference occurred in the weight.

Curves are very different from each other. Their initial slopes, corresponding to the modulus of elasticity, range from  $459 \text{ N/mm}^2$  (curve (Ma)\_0.8) to  $1691 \text{ N/mm}^2$  (curve (Ma)\_0.6). Those values are very higher than those determined experimentally, recorded in Table 3.19; the ratio between the former and the latter ranges from 2.66 to 9.81. Comparing these results with data referring to bricks and mortar, recorded in Tables 3.18 and 3.17 respectively, it emerges that in the masonry specimens used for the experimental measures, the modulus of elasticity is strongly affected by that of the mortar, which average value is  $231.7 \text{ N/mm}^2$ , while in the virtual masonry specimens the modulus of elasticity is affected by that of the bricks, which average value is  $3287 \text{ N/mm}^2$ .

As regard the stress, values referring to the same strain prove that it ranges from  $25.40 \text{ N/mm}^2$  (curve Ma\_0.10) to  $33.99 \text{ N/mm}^2$  (curve Ma\_0.32).

According to the results, among the curves referring to the micro models, curve (Ma)\_0.8 is the most similar to those referring to the macro models and to the experimental tests, in turn. The stress path of the specimen (Ma)\_0.8 is shown in Figure 4.53.



**Figure 4.53.** Stress path in the virtual masonry specimen ((Ma)<sub>0.8</sub>).

From a qualitative point of view, the stress path is consistent with the results of the experimental tests. In fact, mortar joints are confirmed to be the weakest elements, where the stress values are not up to 2 N/mm<sup>2</sup>, while bricks are the most resistant elements, where the stress values reach 14 N/mm<sup>2</sup>. Furthermore, Figure 4.53 shows that the stress in the bricks increases more in the central part of the specimen than in the uppermost and the lowest planes. This result is consistent with the barrel effect which was also verified during the crushing test.

Despite these results, the Finite Element Analysis is not able to return the behavior of the specimen faithfully, in its entirety, as it is proved by the numbers. Based on these results, the simulation was not extended to the treated specimens, as it was scheduled in the Section 3.10. Before doing that, further considerations and studies must be done with regards to the implementation of the data.

## CHAPTER 5

### Conclusions

In the Chapter 4, the partial results were discussed and some consideration were given. Here, an overall assessment of the whole research project will be done, and the main results achieved will be pointed out.

The ageing treatment designed for the purpose of this research produced some results on the specimens which were measured successfully.

The first meaningful result consists on the evaluation of the variation of the unit weight of the masonry specimens, due to the presence of the water absorbed by capillarity. Data proved that the difference between the unit weight of the untreated and the treated specimens is significant, since in the second case the increase is about 24%, regardless of the conditions to which the specimens underwent. Moreover, considering the results referring to the construction materials, the increase reached the 30% in the case of the bricks and the 50%, in the case of the mortar. This demonstrated the critical influence of the bond pattern characterizing the masonry specimens.

Another important result consists on the worsening of the mechanical performances of the brick, mortar and masonry specimens. As regard the specimens exposed to deionized water, the worsening is quite inexistent, despite they underwent the dry/wet cycles. On the contrary, as regard the specimens exposed to salts aqueous solutions it is significant. The comparison among data referring to the masonry specimens exposed outside and to those referring to the specimens undergoing the ageing treatment in the laboratory, confirmed that the worsening is due mainly to the presence of the salts.

On the basis of this consideration, the environmental conditions to which the specimens underwent may seem to be a minor matter. However, it must be pointed out that a fundamental difference existed between the specimens inside the laboratory and those outside. In fact, the former were exposed only to a severe thermal variation ( $\Delta T = 60\text{ }^{\circ}\text{C}$ , over 24 hours, for 8 times), and no other source of damage, while the latter were exposed to a less severe thermal variation ( $\Delta T = 20\text{ }^{\circ}\text{C}$ , over 24 hours) but also to several other sources of damage, among which the rain, the solar radiation and the biological infestation. So, from the mechanical point of view, the effects produced by the severe thermal variation in the specimens inside the laboratory are comparable to those produced by the weathering events in the specimens exposed outside. Further studies should be conducted on masonry specimens exposed to the same treatment but simulating also the effect of the other source of damage to confirm or deny this hypothetical explanation.

Finally, another meaningful outcome derived from the Finite Element Analysis which was conducted in order to try to extend the result of the experimental measures to other kind of brickworks. Regardless the conditions to which the specimens underwent during the ageing treatment, the decrease in the compressive strength of the masonry specimen is consistent with that of its constitutive materials. On the basis of these results it seemed that the behaviour of the masonry could be easily described starting from that of its components. However, the Finite Element Analysis proved that is not possible. These results discouraged to extend the approach also to the treated specimens. Further studies should be conducted to find a way to make the analytical results consistent with the experimental ones.

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## Chapter 4

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## ATTACHMENTS

**Attachment 1:** List of the most common brickwork typologies

**Attachment 2:** stress-strain curves of the untreated bricks, mortar and masonry specimens and some photographs of the last ones

**Attachment 3:** Design of the weather station through Arduino

**Attachment 4:** stress-strain curves of the masonry specimens exposed outside

**Attachment 5:** stress-strain curves of the masonry specimens treated in the laboratory

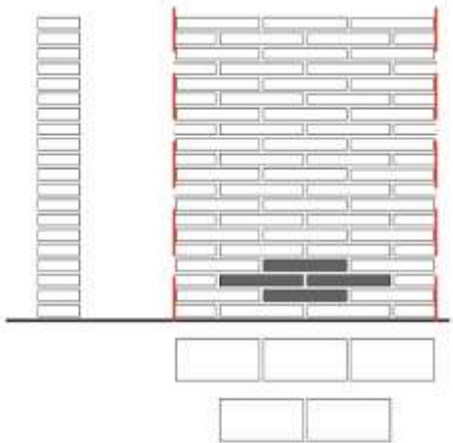
**Attachment 6:** stress-strain curves of the brick specimens treated in the laboratory

**Attachment 7:** stress-strain curves of the mortar specimens treated in the laboratory

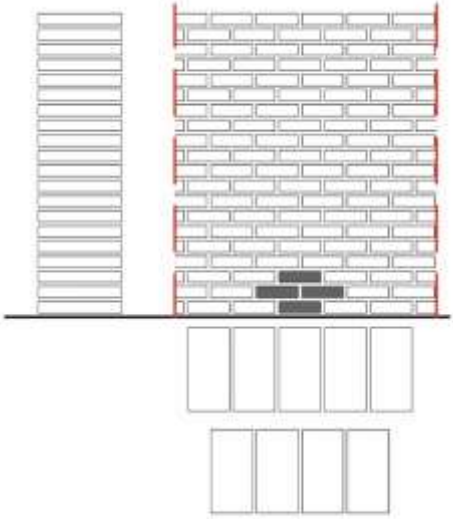
**Attachment 8:** Papers published during the PhD program period

**Attachment 1: List of the most common brickwork typologies**

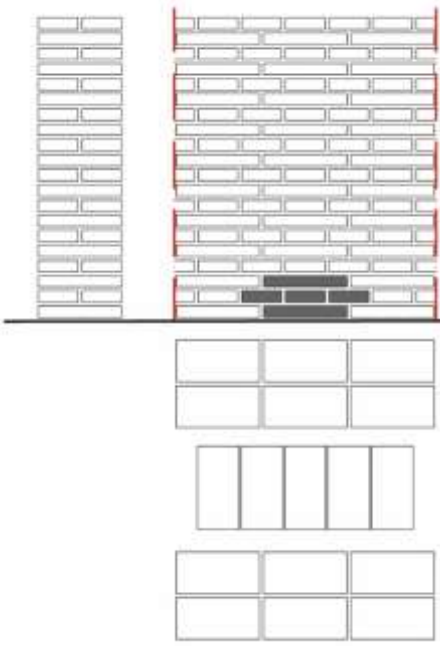
**1. Stretcher or running bond.**

| Scheme                                                                            | Description                                                                                                                                                                                      |
|-----------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|  | <p>This is the simplest arrangement. All bricks are stretchers, with vertical joints staggered of one head. Half bricks are used to create the wall corners or to complete vertical borders.</p> |

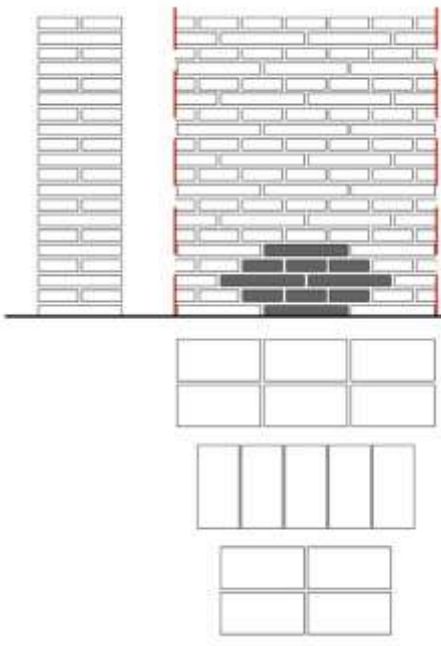
## 2. Header bond.

| Scheme                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  | Description                                                                                                                                                                                                                                                              |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|  <p>The diagram illustrates the Header bond brickwork. The top part is a side elevation showing a wall where every brick is laid as a header. The vertical joints of each course are perfectly aligned with those of the courses above and below. The wall's edges are finished with alternating courses of full bricks and three-quarter bricks. Below the elevation is a plan view of the same section, showing the rectangular layout of the bricks from above.</p> | <p>In this kind of bond, all the bricks are laid as headers on the faces, and vertical joints of each course are centred in relation to the upper and lower ones. The borders of the wall can be made up by alternating couple of entire and three – quarter bricks.</p> |

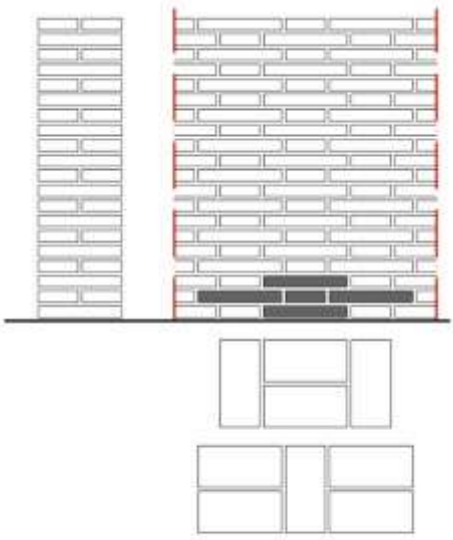
### 3. English bond.

| Scheme                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             | Description                                                                                                                                                                                                                                                                                 |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|  <p>The diagram illustrates the English bond brickwork. The top part is a side elevation showing a wall with alternating courses of stretchers and headers. The stretchers are laid in horizontal courses, and the headers are laid in vertical courses. The vertical joints between the stretchers in one course are centered on the headers in the course below. The bottom part is a plan view showing the layout of the bricks in a corner. It consists of four rows of bricks: the first and third rows have three bricks each, and the second and fourth rows have four bricks each. The bricks are laid in a staggered pattern, with the headers in the second and fourth rows centered on the stretchers in the first and third rows.</p> | <p>In this kind of bond courses of stretches and header bricks are alternated. The vertical joins between the stretchers bricks are centred on the headers bricks in the course below. Depending on the thickness of the wall, half and three-quarter bricks need to build the corners.</p> |

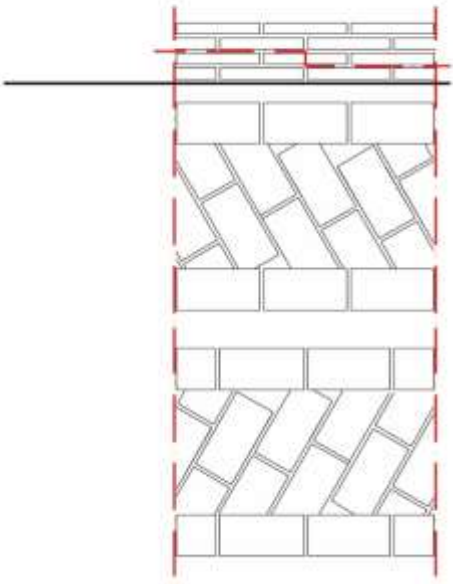
#### 4. English cross bond.

| Scheme                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          | Description                                                                                                                                                                                                                                                                                               |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|  <p>The diagram illustrates the English cross bond brickwork. The top part is a side elevation showing two vertical stretches of brickwork. The left stretch is a standard English bond, alternating between courses of all headers and all stretchers. The right stretch is a cross bond, where the vertical joints of one stretch are staggered relative to the other. Below the elevation is a plan view showing the layout of bricks in a corner, with headers and stretchers arranged to show the cross bond pattern.</p> | <p>This kind of bond is similar to the English bond one but in this case the vertical joints of two consecutive stretches courses are not aligned but staggered of one head. Also in this situation, depending on the thickness of the wall, half and three-quarter bricks need to build the corners.</p> |

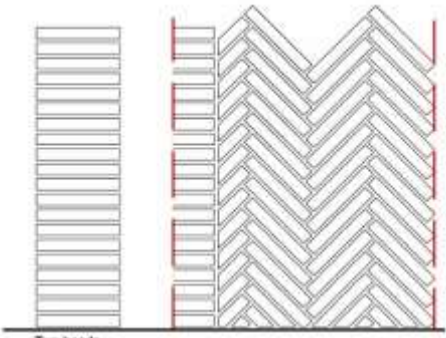
## 5. Flemish bond.

| Scheme                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          | Description                                                                                                                                                                       |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|  <p>The diagram illustrates the Flemish bond brickwork. The top part shows a side elevation of a brick wall. On the left, a single vertical column of bricks is shown. To its right, a larger section of the wall is shown, with red lines indicating the vertical joints between bricks. The bricks are arranged in a pattern where headers and stretchers alternate in each course. The bottom part of the diagram shows a plan view of the brickwork, with two rows of bricks. The first row consists of three bricks: a header, a stretcher, and a header. The second row consists of three bricks: a stretcher, a header, and a stretcher. This plan view demonstrates how the bricks are laid out in a grid pattern.</p> | <p>In this kind of bond headers and stretchers bricks are alternated in each course, so that all the headers bricks are centred on the stretchers bricks of the course below.</p> |

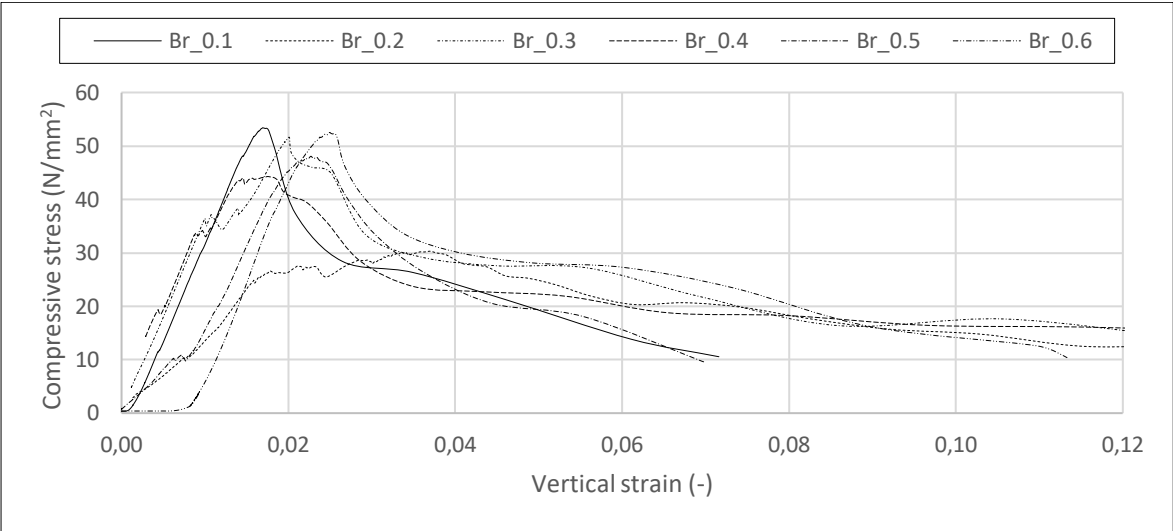
## 6. diagonal bond.

| Scheme                                                                             | Description                                                                                                                                                                                                                                                                                                                                                                                                                                                          |
|------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|  | <p>In this kind of bond two header courses and two diagonal courses are alternated. These are obtained by arranging bricks with an angle of 45 or better than 60 degrees with the length of the wall. In this way, any correspondence of vertical joints is avoided, and the walls result well united. This arrangement has the drawback of requiring a lot of cut bricks not only in correspondence of corner or borders, but along all the length of the wall.</p> |

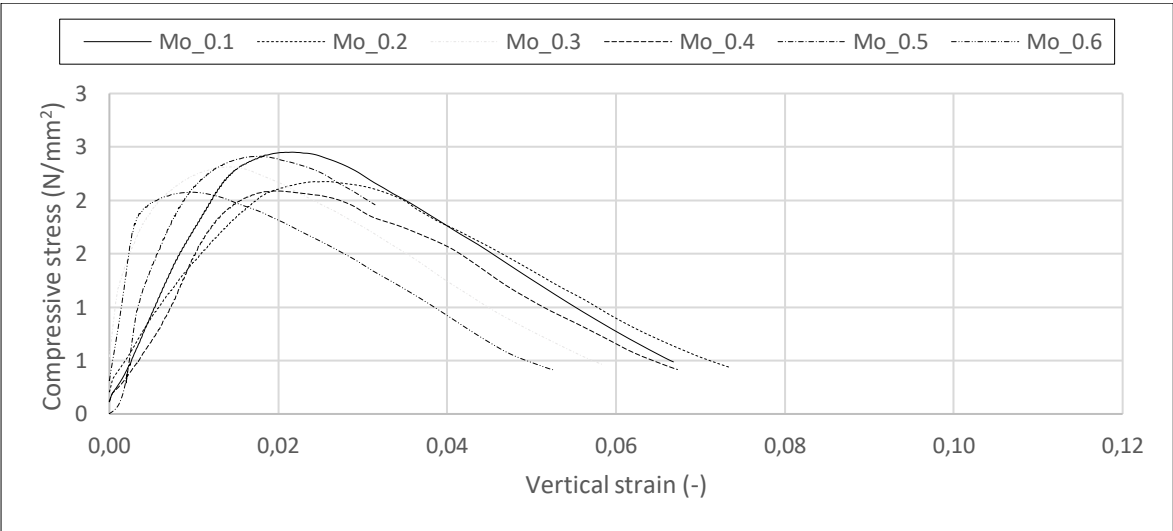
## 7. Herring bone bond.

| Scheme                                                                                             | Description                                                                                                                                                                                                                                                                                                                      |
|----------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|  <p>Two heads</p> | <p>In this kind of bond, the bricks are laid in course inclined at 45°, in relation to the vertical plane, in two directions from the centre. This arrangement allows a great union among the units but make difficult the realizations of the corners and the borders of the walls because it requires a lot of cut bricks.</p> |

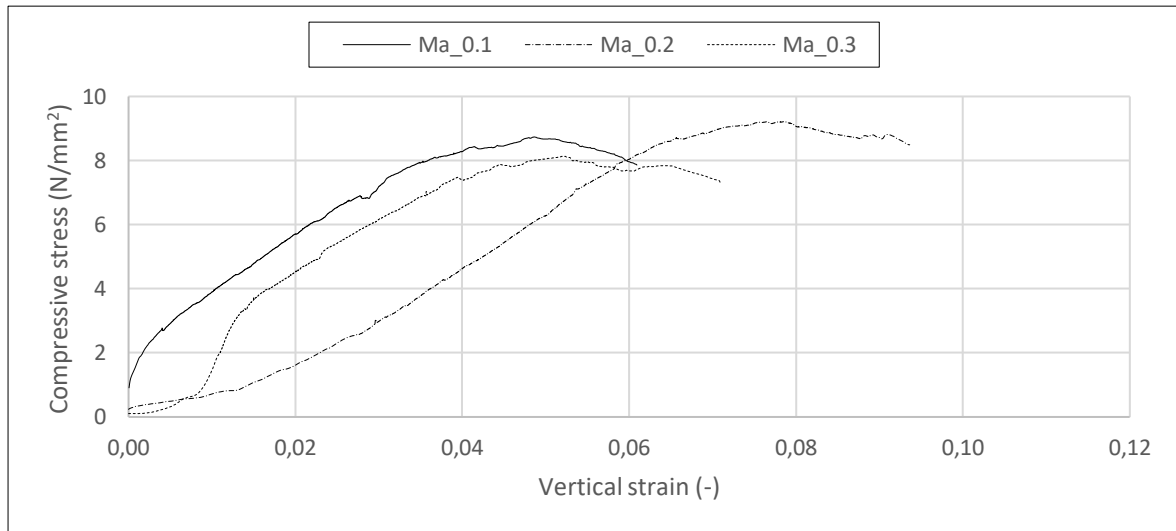
**Attachment 2: Stress-strain curves of the untreated bricks, mortar and masonry specimens and some photographs of the last ones**



**Figure A.2.1.** Stress-strain curves of the untreated brick specimens.



**Figure A.2.2.** Stress-strain curves of the untreated mortar specimens.



**Figure A.2.3.** Stress-strain curves of the untreated masonry specimens.



a)



b)



c)



d)



e)



f)

**Figure A.2.4.** Photographs of the masonry specimen Ma\_0.2 taken during the compressive test:  
a) 0.00 N/mm<sup>2</sup>; b) 4.76 N/mm<sup>2</sup>; c) 5.95 N/mm<sup>2</sup>; d) 7.14 N/mm<sup>2</sup>; e) 8.33 N/mm<sup>2</sup>; f) 8.74 N/mm<sup>2</sup>.

### **Attachment 3: Design and construction of the weather station through Arduino**

*“Arduino is an open-source electronics platform based on easy-to-use hardware and software”* (<https://www.arduino.cc/en/guide/introduction>). It consists on a microcontroller, that is a physical programmable circuit board, and an Integrated Development Environment (IDE) software which runs in the computer and is used to write and upload computer code to the physical board (<https://learn.sparkfun.com/tutorials/what-is-an-arduino/all>).

During last years, the Arduino platform has become quite popular with people interested in the development of prototypes, and simple professional and educational projects.

Sensors are one of the strengths of Arduino platform. They allow to record data from the environment, which are processed by the microcontroller according to the instructions provided by the user through the code which is implemented on it. The code allows also to answer the external input, so the system is an interactive one. A lot of sensors have been developed during last years, so the applications of the Arduino platform are potentially unlimited.

Within this research project, Arduino was used to made a simple weather station. Firstly, the hardware was made using an Arduino mega 2560 board, to which the following sensors were connected:

- A DHT22 temperature and humidity sensor;
- A rain sensor, composed of a rain detection plate with a comparator who manages intelligence;
- An internal Real Time Clock (RTC).

The weather station was supplied by solar energy, so a solar charged shield was also connected to the main board, to which a solar panel (6 V, 3.5 W) and a LI-ion battery (4200 mA) were connected in turn.

The weather station installed in the experimental field is shown in Figure 3.29, in the text, while a detail of its parts is shown in figure A.3.1. The board and the wiring were put inside a waterproof electrical junction box. Cables connected to the solar shield and to the rain

detection plate get out from a pipe, while the temperature and humidity sensor was inside another pipe. In this way the sensor could recorder the external parameters but it was protected from weather. Despite this, the sensors revealed to be very delicate, so the temperature and humidity sensors were changed every month, while the rain sensor was changed only twice over a year.

The code was written in the open source Arduino software (IDE). It is reproduced hereafter. The code set up in such a way that data were recorded every 15 minutes for one year.

Data recorded are reproduced in the Figures 4.1 – 4.3 in the text.



**Figure A.3.1.** the weather station made with the Arduino components.

Code:

### Arduino Code

```
#include <Wire.h>
#include "ds3231.h"
#include <SPI.h>
#include <SD.h>
#include "cactus_io_DHT22.h"

#define BUFF_MAX 128
#define DHT22_PIN 2 // what pin on the arduino is the DHT22 data line connected to

uint8_t time[8];
char recv[BUFF_MAX];
unsigned int recv_size = 0;
unsigned long prev, interval = 3000;

void parse_cmd(char *cmd, int cmdsize);

const int chipSelect = 4; //LASCIARE 4

File myFile;

DHT22 dht(DHT22_PIN);

void setup()
{
    //CLOCK
    Serial.begin(9600);
    Wire.begin();
    DS3231_init(DS3231_INTCN);
    memset(recv, 0, BUFF_MAX);
    Serial.println("GET time");

    Serial.println("setting time");
    parse_cmd("T501716212062018", 16);

    //SD
    Serial.begin(9600);
    Serial.print("Initializing SD card...");
    pinMode(53, OUTPUT);

    if (!SD.begin(chipSelect)) {
        Serial.println("initialization failed!");
        return;
    }
    Serial.println("initialization done.");

    // open the file. note that only one file can be open at a time,
    // so you have to close this one before opening another.
    myFile = SD.open("test.txt", FILE_WRITE);
```

```

//TEMPERATURE
Serial.begin(9600);
Serial.println("DHT22 RH-T Sensor initialised");

Serial.println("Date - RH - T");

}

void loop() {
  // put your main code here, to run repeatedly:


//CLOCK
char in;
char buff[BUFF_MAX];
unsigned long now = millis();
struct ts t;

// show time once in a while
if ((now - prev > interval) && (Serial.available() <= 0)) {
  DS3231_get(&t);

// there is a compile time option in the library to include unixtime support
#ifdef CONFIG_UNIXTIME
  snprintf(buff, BUFF_MAX, "%d.%02d.%02d %02d:%02d:%02d %ld", t.year,
    t.mon, t.mday, t.hour, t.min, t.sec, t.unixtime);
#else
  snprintf(buff, BUFF_MAX, "%d.%02d.%02d %02d:%02d:%02d", t.year,
    t.mon, t.mday, t.hour, t.min, t.sec);
#endif

  Serial.print(buff); Serial.print(" \ "); //l'ho cambiato da println a print così non va a capo il \ serve
  per separare i campi
  prev = now;
}

if (Serial.available() > 0) {
  in = Serial.read();

  if ((in == 10 || in == 13) && (recv_size > 0)) {
    parse_cmd(recv, recv_size);
    recv_size = 0;
    recv[0] = 0;
  } else if (in < 48 || in > 122) {; // ignore ~[0-9A-Za-z]
  } else if (recv_size > BUFF_MAX - 2) { // drop lines that are too long
    // drop
    recv_size = 0;
    recv[0] = 0;
  } else if (recv_size < BUFF_MAX - 2) {
    recv[recv_size] = in;
    recv[recv_size + 1] = 0;
    recv_size += 1;
  }
}

```

```

    }

    delay(0); //

//TEMPERATURE
// Reading temperature or humidity takes about 250 milliseconds!
// Sensor readings may also be up to 2 seconds 'old' (its a very slow sensor)
dht.readHumidity();
dht.readTemperature();

// Check if any reads failed and exit early (to try again).
if (isnan(dht.humidity) || isnan(dht.temperature_C)) {
    Serial.println("DHT sensor read failure!");
    return;
}

Serial.print(dht.humidity); Serial.print(" %\t\t");
Serial.print(dht.temperature_C); Serial.println(" *C\t"); //ho cambiato da print a println

myFile = SD.open("test.txt", FILE_WRITE);
myFile.print(buff); myFile.print (" ");
myFile.print(dht.humidity); myFile.print (" ");
myFile.print(dht.temperature_C); myFile.println (" ");
myFile.close();

delay(9000);

}

void parse_cmd(char *cmd, int cmdsize)
{
    uint8_t i;
    uint8_t reg_val;
    char buff[BUFF_MAX];
    struct ts t;

    //snprintf(buff, BUFF_MAX, "cmd was '%s' %d\n", cmd, cmdsize);
    //Serial.print(buff);

    //TssmmhhWDDMMYYYY aka set time
    if (cmd[0] == 84 && cmdsize == 16) {
        //T355720619112011
        t.sec = inp2toi(cmd, 1);
        t.min = inp2toi(cmd, 3);
        t.hour = inp2toi(cmd, 5);
        t.wday = cmd[7] - 48;
        t.mday = inp2toi(cmd, 8);
        t.mon = inp2toi(cmd, 10);
        t.year = inp2toi(cmd, 12) * 100 + inp2toi(cmd, 14);
        DS3231_set(t);
    }
}

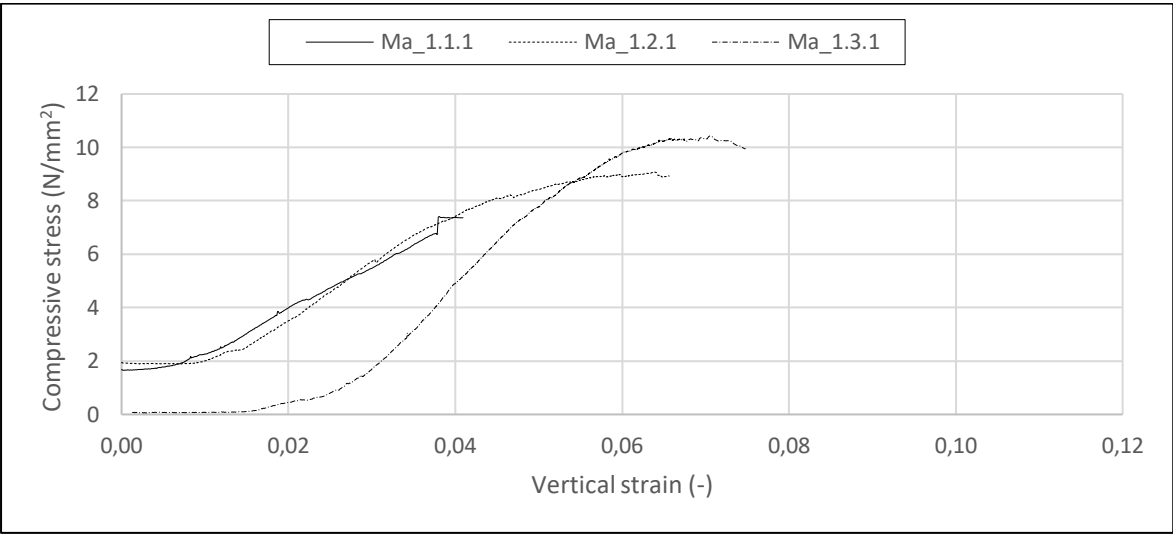
```

```

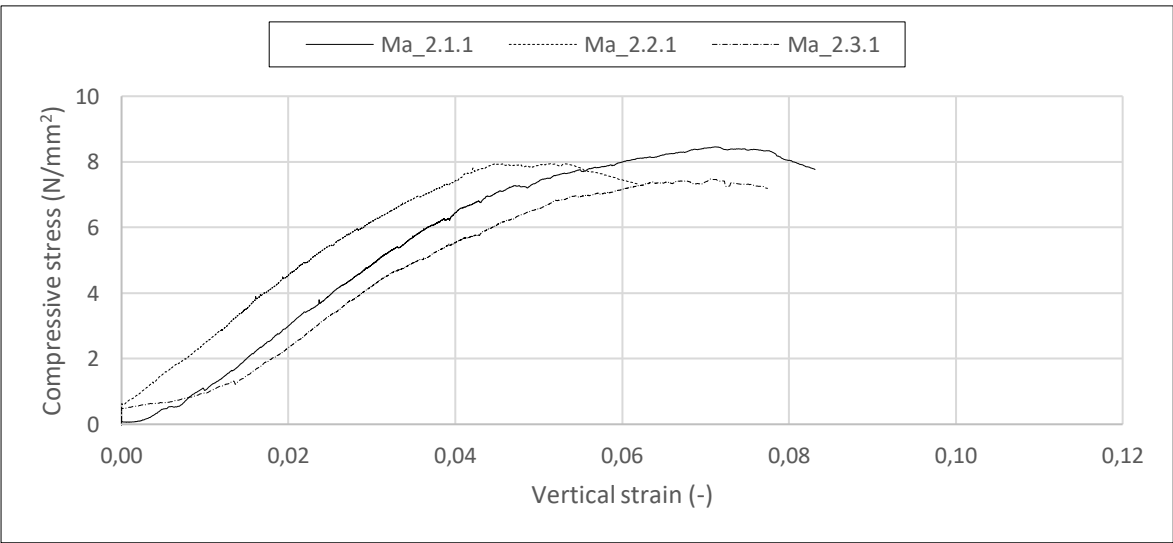
    Serial.println("OK");
} else if (cmd[0] == 49 && cmdsize == 1) { // "1" get al.arm 1
    DS3231_get_a1(&buff[0], 59);
    Serial.println(buff);
} else if (cmd[0] == 50 && cmdsize == 1) { // "2" get al.arm 1
    DS3231_get_a2(&buff[0], 59);
    Serial.println(buff);
} else if (cmd[0] == 51 && cmdsize == 1) { // "3" get aging register
    Serial.print("aging reg is ");
    Serial.println(DS3231_get_aging(), DEC);
} else if (cmd[0] == 65 && cmdsize == 9) { // "A" set al.arm 1
    DS3231_set_creg(DS3231_INTCN | DS3231_A1IE);
    //ASSMMHHDD
    for (i = 0; i < 4; i++) {
        time[i] = (cmd[2 * i + 1] - 48) * 10 + cmd[2 * i + 2] - 48; // ss, mm, hh, dd
    }
    uint8_t flags[5] = { 0, 0, 0, 0, 0 };
    DS3231_set_a1(time[0], time[1], time[2], time[3], flags);
    DS3231_get_a1(&buff[0], 59);
    Serial.println(buff);
} else if (cmd[0] == 66 && cmdsize == 7) { // "B" Set al.arm 2
    DS3231_set_creg(DS3231_INTCN | DS3231_A2IE);
    //BMMHHDD
    for (i = 0; i < 4; i++) {
        time[i] = (cmd[2 * i + 1] - 48) * 10 + cmd[2 * i + 2] - 48; // mm, hh, dd
    }
    uint8_t flags[5] = { 0, 0, 0, 0, 0 };
    DS3231_set_a2(time[0], time[1], time[2], flags);
    DS3231_get_a2(&buff[0], 59);
    Serial.println(buff);
} else if (cmd[0] == 67 && cmdsize == 1) { // "C" - get temperature register
    Serial.print("temperature reg is ");
    Serial.println(DS3231_get_treg(), DEC);
} else if (cmd[0] == 68 && cmdsize == 1) { // "D" - reset status register alarm flags
    reg_val = DS3231_get_sreg();
    reg_val &= B11111100;
    DS3231_set_sreg(reg_val);
} else if (cmd[0] == 70 && cmdsize == 1) { // "F" - custom fct
    reg_val = DS3231_get_addr(0x5);
    Serial.print("orig ");
    Serial.print(reg_val, DEC);
    Serial.print("month is ");
    Serial.println(bcdtodec(reg_val & 0x1F), DEC);
} else if (cmd[0] == 71 && cmdsize == 1) { // "G" - set aging status register
    DS3231_set_aging(0);
} else if (cmd[0] == 83 && cmdsize == 1) { // "S" - get status register
    Serial.print("status reg is ");
    Serial.println(DS3231_get_sreg(), DEC);
} else {
    Serial.print("unknown command prefix ");
    Serial.println(cmd[0]);
    Serial.println(cmd[0], DEC);
}
}
}

```

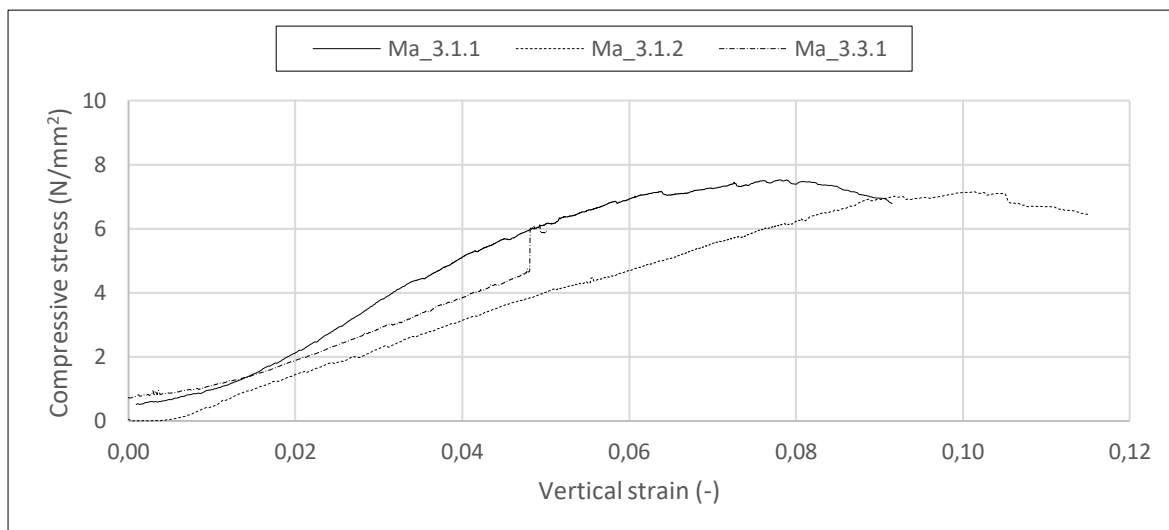
**Attachment 4: Stress-strain curves of the masonry specimens exposed outside**



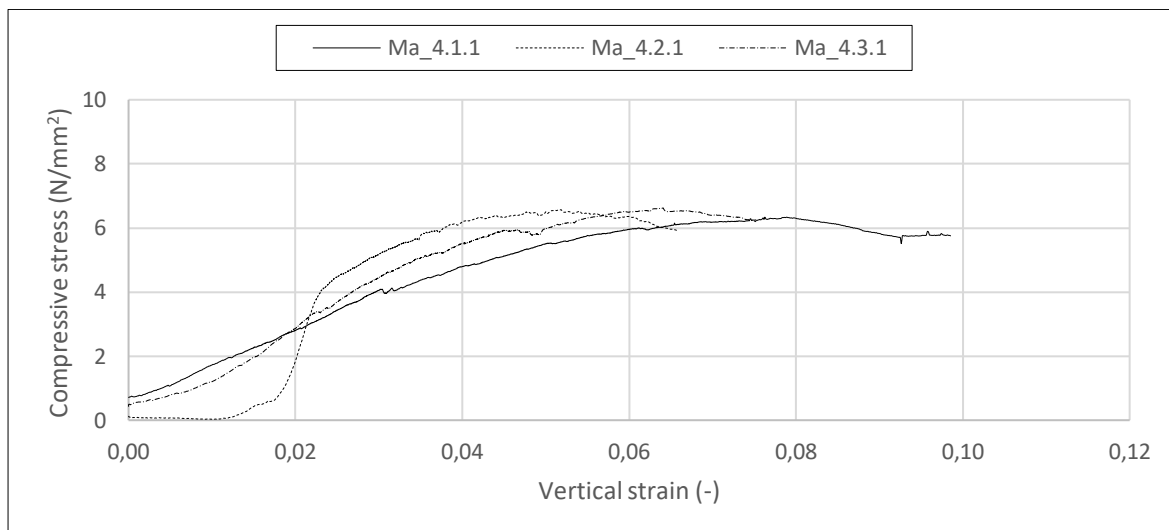
**Figure A.4.1.** Stress-strain curves of the masonry specimens exposed to water.



**Figure A.4.2.** Stress-strain curves of the masonry specimens exposed to sodium chloride aqueous solution.



**Figure A.4.3.** Stress-strain curves of the masonry specimens exposed to sodium sulphate water solution.



**Figure A.4.1** Stress-strain curves of the masonry specimens exposed to potassium nitrate aqueous solution.

Attachment 5: Stress-strain curves of the masonry specimens treated in the laboratory

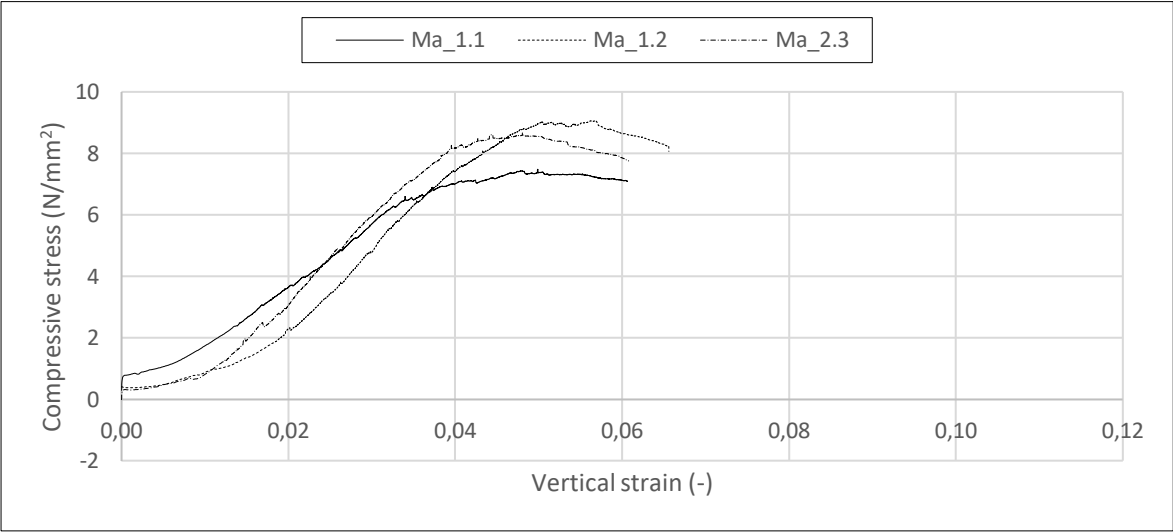


Figure A.5.1. Stress-strain curves of the masonry specimens exposed to deionized water.

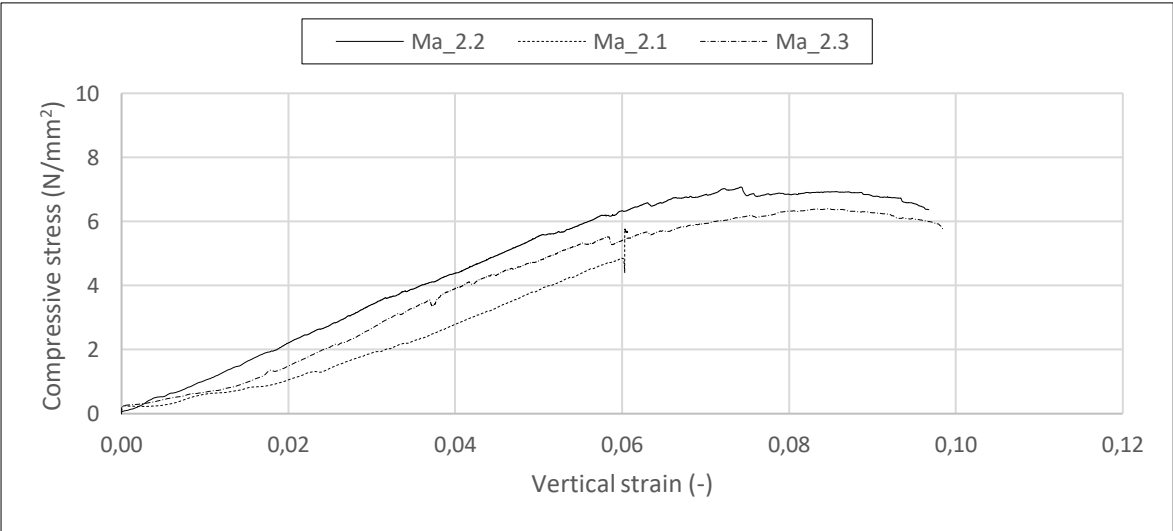
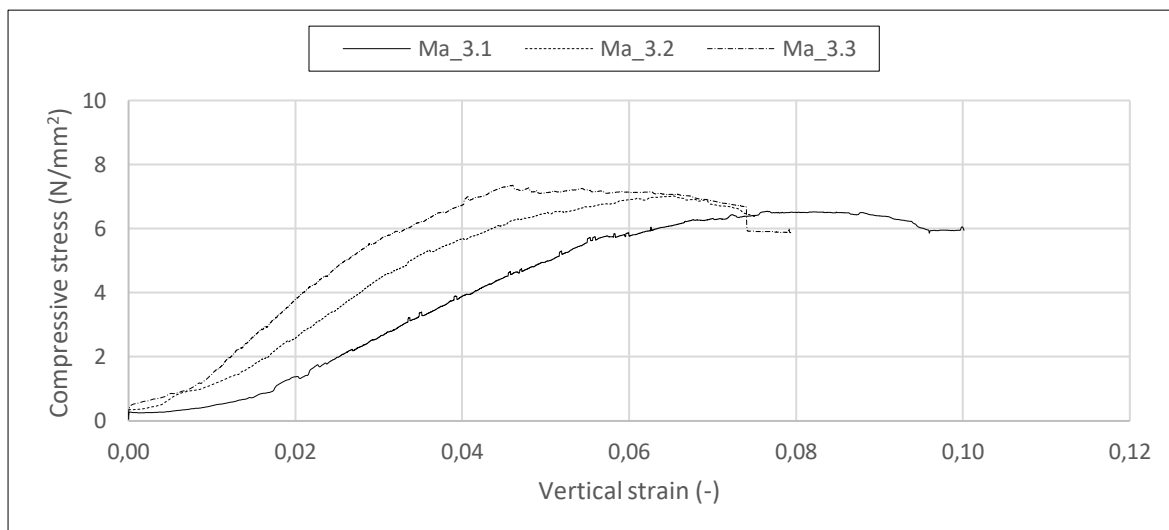
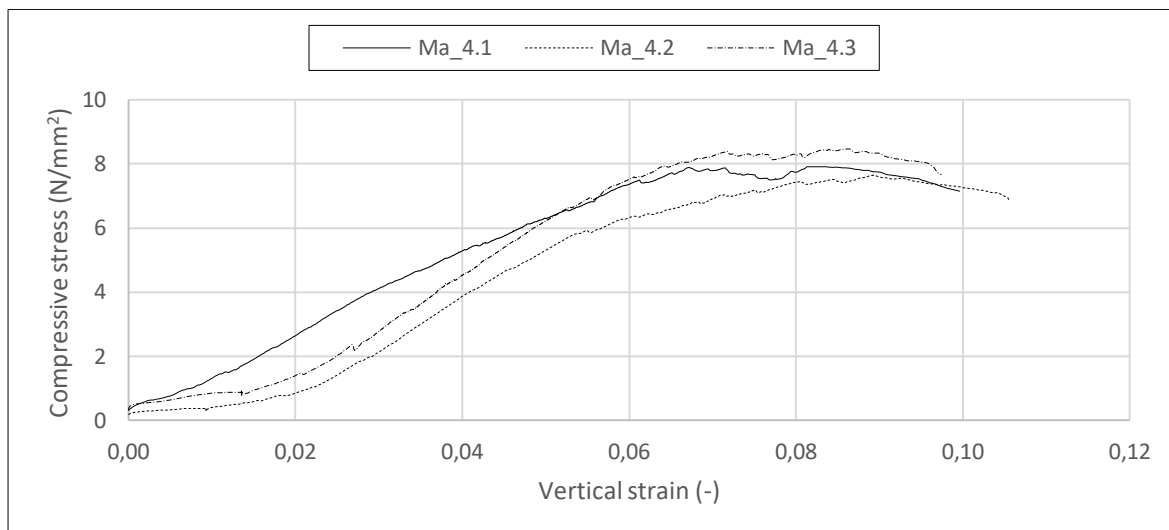


Figure A.5.2. Stress-strain curves of the masonry specimens exposed to sodium chloride aqueous solution.

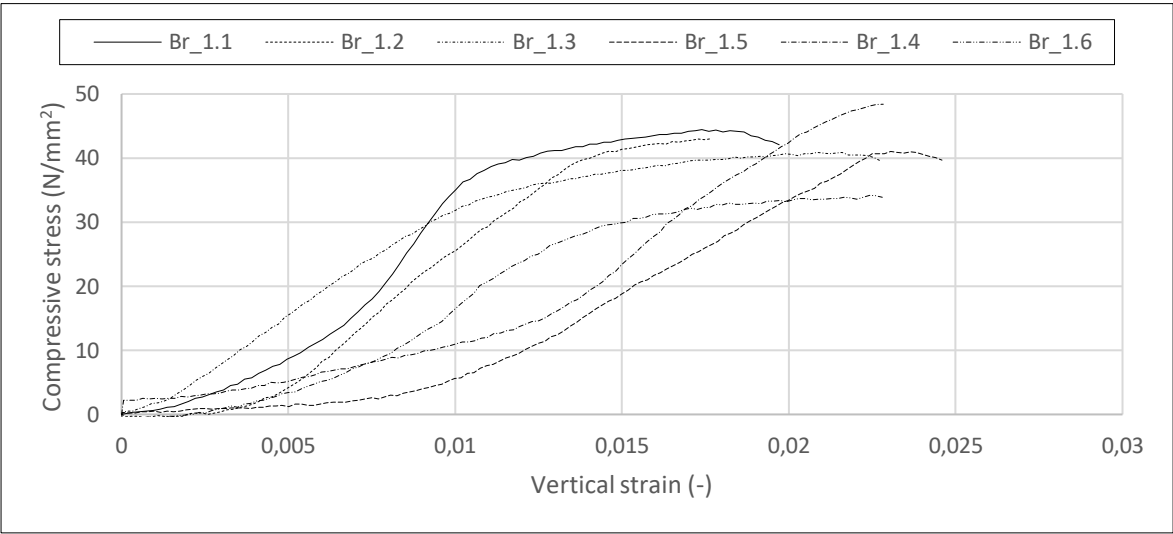


**Figure A.5.3.** Stress-strain curves of the masonry specimens exposed to sodium sulphate aqueous solution.

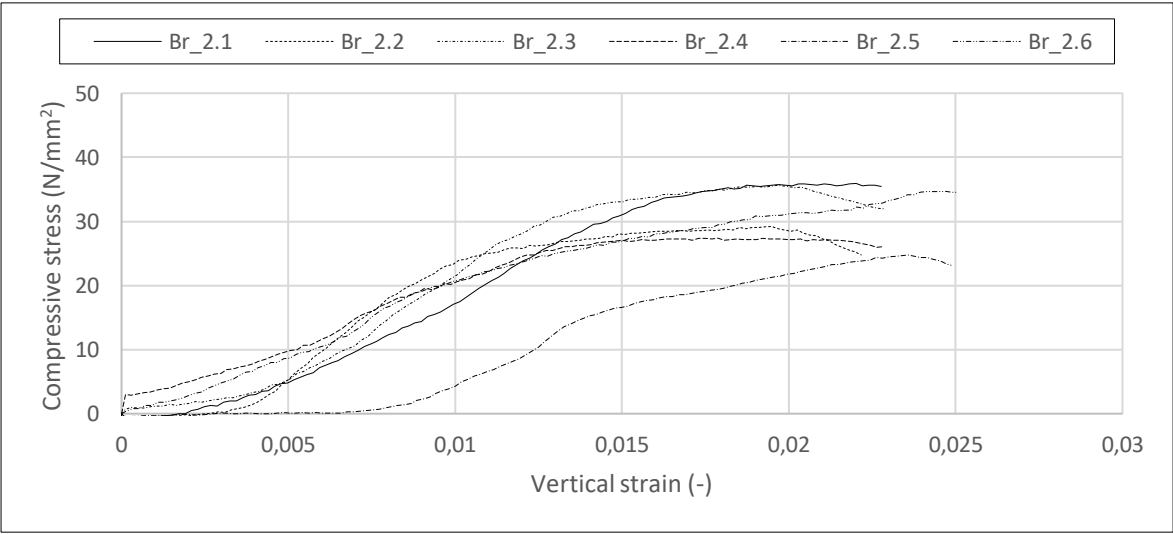


**Figure A.5.4.** Stress-strain curves of the masonry specimens exposed to potassium nitrate aqueous solution.

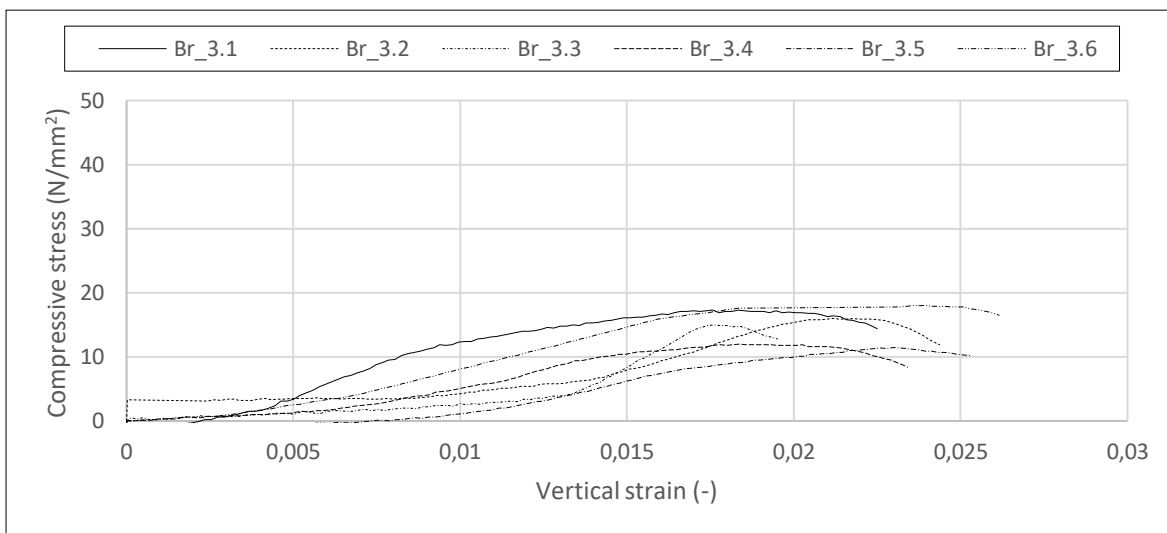
**Attachment 6: Stress-strain curves of the brick specimens treated in the laboratory**



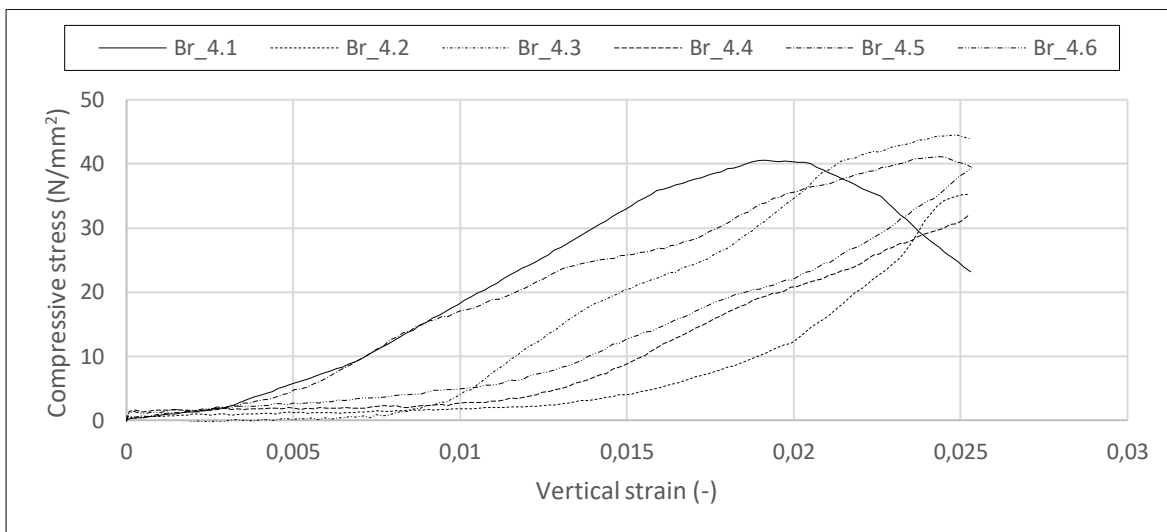
**Figure A.6.1.** Stress-strain curves of the brick specimens exposed to deionized water.



**Figure A.6.2.** Stress-strain curves of the brick specimens exposed to sodium chloride aqueous solution.

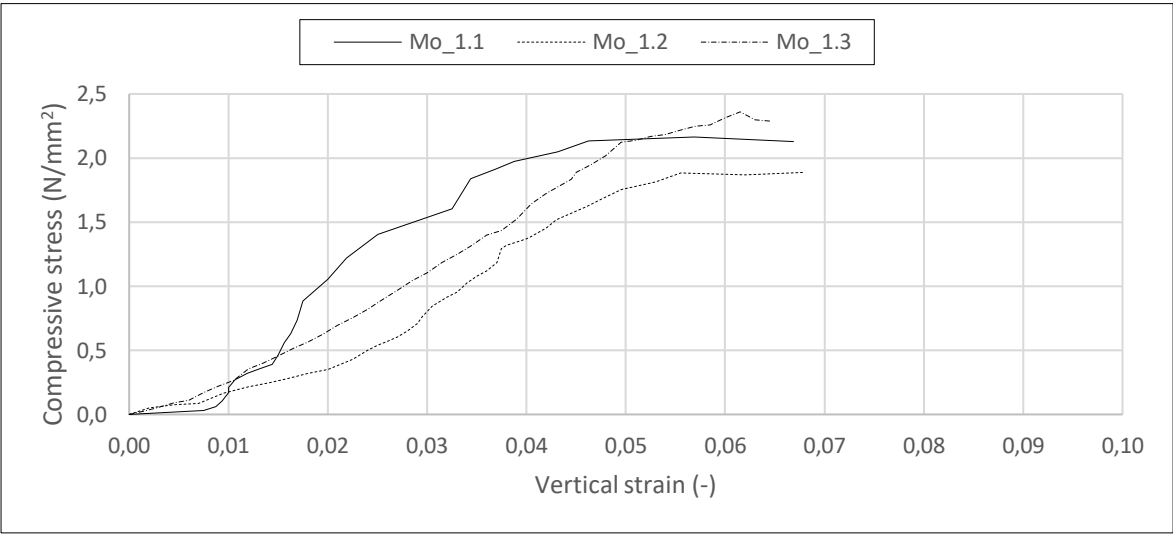


**Figure A.6.3.** Stress-strain curves of the brick specimens exposed to sodium sulphate aqueous solution.

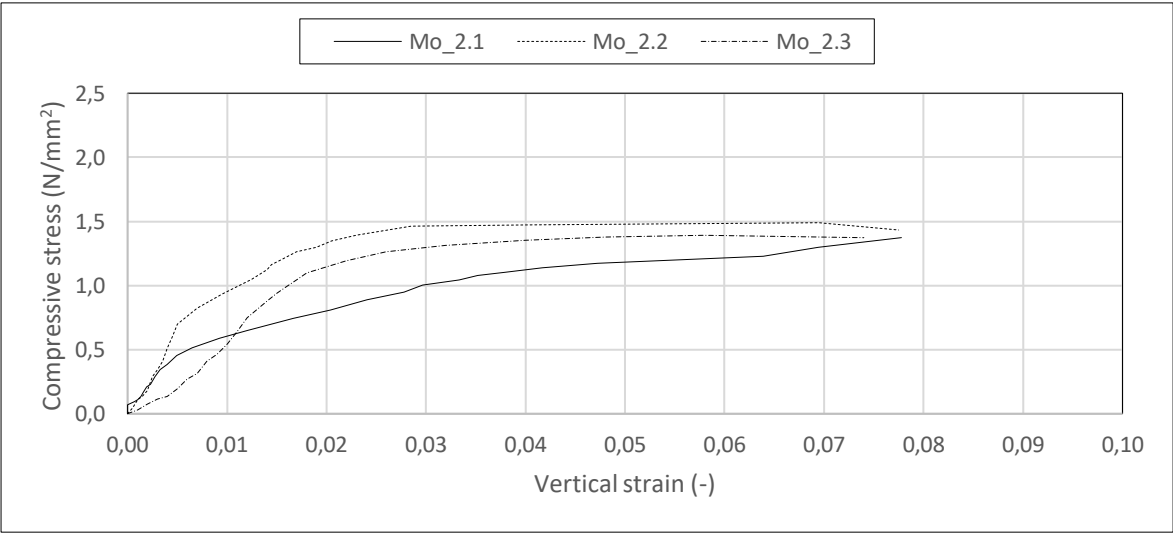


**Figure A.6.4.** Stress-strain curves of the brick specimens exposed to potassium nitrate aqueous solution.

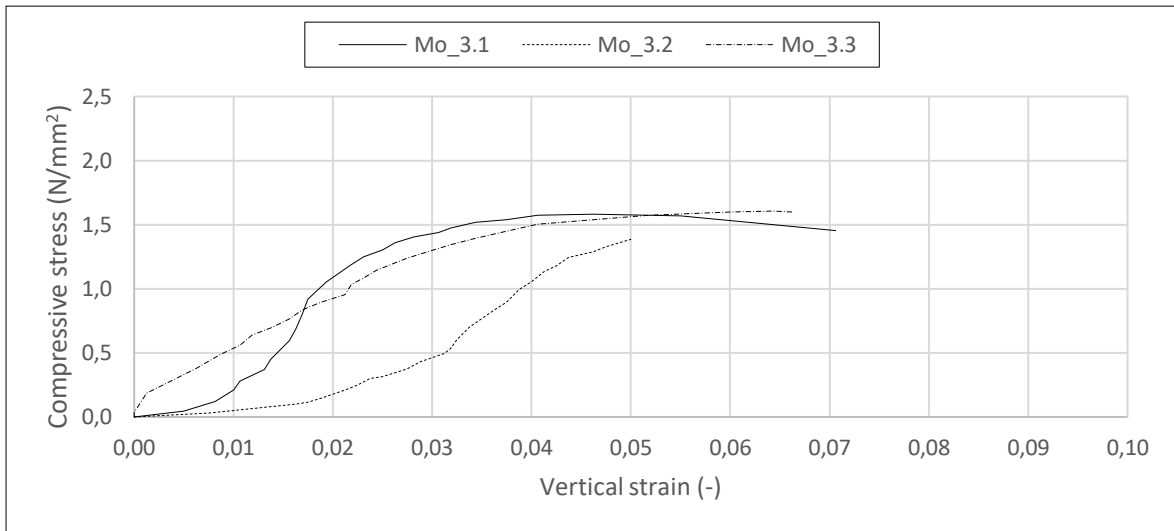
**Attachment 7: Stress-strain curves of the mortar specimens treated in the laboratory**



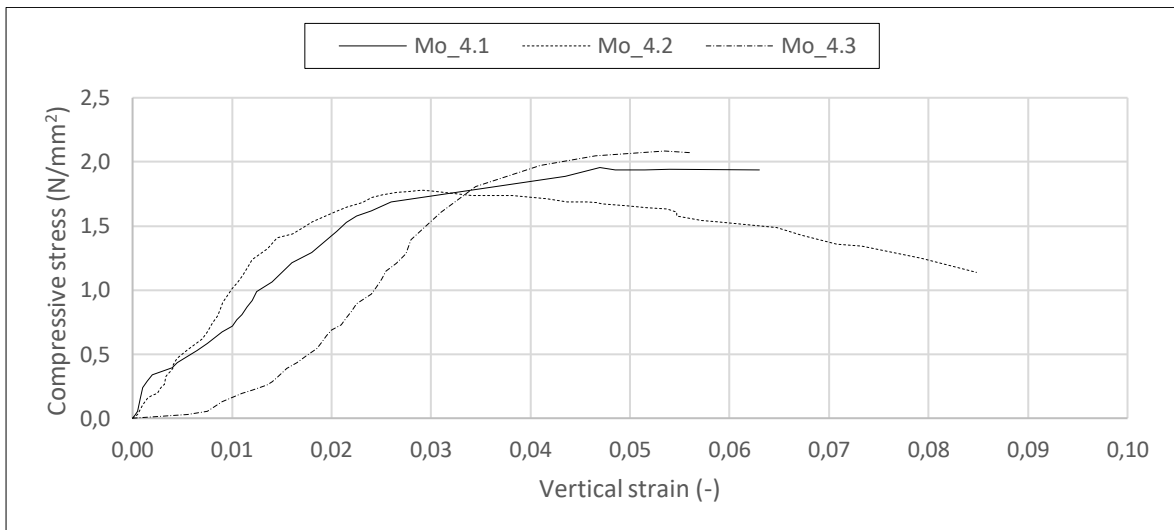
**Figure A.7.1.** Stress-strain curves of the masonry specimens exposed to deionized water.



**Figure A.7.2.** Stress-strain curves of the brick specimens exposed to sodium chloride aqueous solution.



**Figure A.7.3.** Stress-strain curves of the brick specimens exposed to sodium sulphate aqueous solution.



**Figure A.7.4.** Stress-strain curves of the brick specimens exposed to potassium nitrate aqueous solution.

## Attachment 8: Papers published during the PhD program period

The research conducted within the PhD program produced several results. Some of these were recently published in the international journal *Heritage*, and the paper was also selected as the cover for the March 2020 issue.

In addition to the aforementioned paper, dealing with a theme which is inherent to the main field of the research, two other papers were also published in the context of the PhD course, dealing with the use of the FEA in the field of cultural heritage.

Moreover, some documents were written for the STORM project, since it financed the PhD research. The major contribution was given for the production of the document hereinbelow:

STORM Consortium (2017). D1.4. *Quick damage assessment methods*, in: Project STORM – Safeguarding cultural heritage through Technical and Organisational Resources Management (<http://www.storm-project.eu/>).

Finally, within the last three years, a monography and a conference paper were also published, dealing with a theme which was studied outside the framework of the PhD program.

Papers published in the international journals are listed below and the full articles are also attached. The reader can note that in all the publications the PhD student is the first or the only one author.

- Giacccone, D., Santamaria, U., & Corradi, M. (2020). An Experimental Study on the Effect of Water on Historic Brickwork Masonry. *Heritage*, 3(1), 29-46.  
<https://doi.org/10.3390/heritage3010003>.
- Giacccone, D., Fanelli, P., & Santamaria, U. (2020). Influence of the geometric model on the structural analysis of architectural heritage. *Journal of Cultural Heritage*. (in press).  
<https://doi.org/10.1016/j.culher.2019.12.001>.
- Giacccone, D. (2020). The peristyle of the Temple of Apollo at Syracuse: Historical hypotheses of reconstruction revisited through a finite element analysis. *Digital Applications in Archaeology and Cultural Heritage*, 16, e00138.  
<https://doi.org/10.1016/j.daach.2020.e00138>.