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The Effect of Climate Change on Weathering: Evidences from Heritage Buildings under Subtropical Conditions

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The scientific community of building physics has known for decades that weathering has a significant effect on the condition of buildings. Weathering agents such as water, carbon dioxide and oxygen, potentially accelerate the natural deterioration of buildings, leading to undesirable results, especially in cases involving buildings of special cultural importance. Climate change and its effect on weather conditions may potentially accelerate the weathering of buildings.

The purpose of this study is to examine the impact of climate change on weathering of building materials of heritage buildings under subtropical climatic conditions. As a case study, non-destructive measurements of 10 traditional buildings in Strovolos, an urban centre in Cyprus, were employed. To study the deterioration of buildings, non-destructive methods were utilized, namely infrared (IR) thermography. The deterioration was studied for different materials, different orientations, as well as for materials of different ages. Through qualitative and quantitative thermographs, the results demonstrate the significant effect of climate change on the deterioration of building materials.

Keywords: climate change, finite element, heritage buildings, numerical methods, weathering.

Introduction



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The international scientific community is increasingly concerned about the impact of climate change on structures and buildings of increased heritage interest. As early as 2005, the World Heritage Committee (WHC), started through a series of activities, to monitor the issue very closely (UNESCO, 2021). The WHC, through its ongoing activities and announcements, informs the peoples' societies and the scientific community about its findings regarding the impact of climate change on the world's cultural heritage. The impact of climate change is mainly expressed through weathering phenomena, which under galloping changing weather conditions, change the rate and intensity with which they affect the building environment. Already in areas of the world where climate change has affected to a greater extent, the phenomena of deteriorating of building materials and surface of heritage buildings, seems more important.

In the recent past, several research initiatives have been carried out to document the impact of climate change on heritage buildings. Among them is UP PeriScope (PeriScope, 2021), a research project which aims to the designing and development of an innovative, BIM-based platform for the documentation of heritage buildings. The platform is currently developed for the classification and documentation of heritage buildings in Cyprus; it is though intended to be employed in other built environments of heritage interest as well. In terms of this project, the development of a database, in which the impact of the weathering on heritage buildings is documented, is also envisioned. This database will demonstrate evidences to the platform uses on the impact of weathering on building materials and coatings applied in heritage buildings, and will allow the comparative assessment of the climate change impact on different materials under diverse conditions.

The purpose of this study is to document the impact of the weathering on the condition of building materials and surfaces of heritage buildings, through the application of a non-destructive technique (NDT), infrared (IR) thermography. Following the introductory section, a brief description on the weathering impact on heritage buildings and on the application of IR thermography to document this impact, is presented. The methods and materials employed in this study are then described. Evidences and elaboration of measurements conducted in heritage buildings in the urban center of Strovolos, on the island of Cyprus, are presented and discussed in the results section. The study concludes with its main findings, as well as with food for thought for future work and for the challenges of the field.

Introduction

Climate change has significantly affected tangible structures, especially in those regions, where the effect is more intensive. Mediterranean is characterized by an important pressure on the environment while being highly vulnerable to climate change (Giorgi and Lionello, 2008). The Mediterranean region is identified as one of the most vulnerable regions to climate change and defined as a major “hotspot” based on the results of global climate change projections. Intense environmental effects in the Mediterranean region includes a rapid change in the water cycle due to increased evaporation and lower precipitation decrease in soil water storage capacity and thus an acceleration of desertification as well as extinction of the most climate-sensitive or least mobile species and colonization by new species. The European and Mediterranean Major Hazards Agreement of 2008 declared that the vulnerability of cultural heritage sites and buildings due to climate change is evident in the heritage sites of the Europe. The agreement identified the effect of climate change on the materials used in historic buildings in Europe, proposing measures to medicate this effect. The environmental impact revolves around the atmospheric moisture changes, thermal weathering due to temperature changes in a night-day cycle, the effect of wind, desertification in heritage sites, climate and pollution acting together on structures and the biological attacks due to invasive species like termites, fungus etc (Sabbioni et al., 2008). The major effect of climate change on structures under subtropical conditions, are described below.

Cyprus is an eastern southern European island state, member of the EU. Cyprus has a subtropical climate - Mediterranean and semi-arid type, according to Köppen climate classification signs Csa and BSh¹ (Peel et al., 2007).

Atmospheric Moisture, Salt Crystallization and Rising Damp

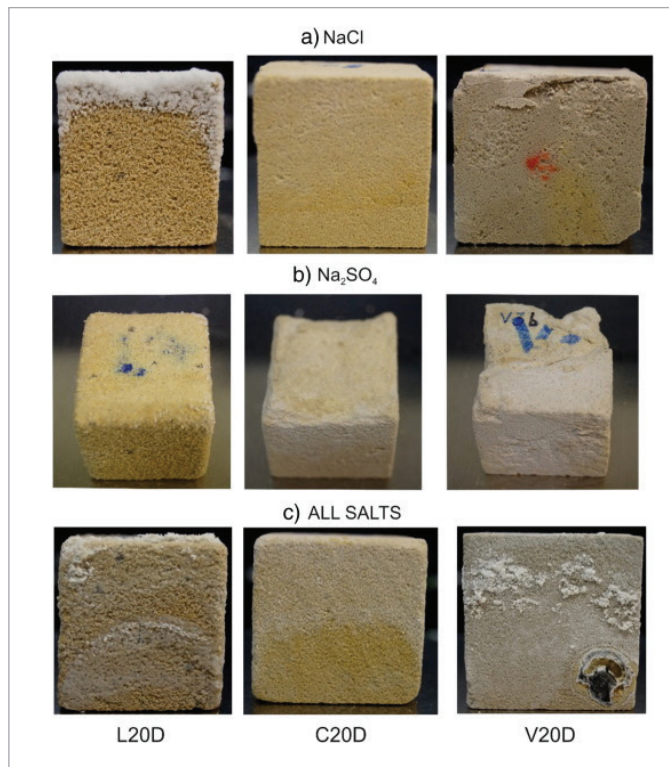
The changes in atmospheric moisture can be the result of intense rainfall, changes in water table levels and subsequently to soil chemistry and of the humidity cycles themselves. The variations of the relative humidity in buildings can cause increased time of dampness of the materials throughout the day which in turn, can lead to loss of surface material, microbial growth of organic and loss

The Effect of Climate Change on the Deterioration of Building Materials

1 Csa: Mediterranean hot summer climates, BSh: Hot semi-arid climate

Fig. 1

Sample photographs from the experiment conducted by Menendez et al. on different kind of stones with 3 different weathering mediums a) sodium chloride, b) sodium sulphate and c) salt mixture at room temperature and low relative humidity. The formation of salts, delaminations and discolouring is visible on the specimen's surface (source: Menendez et al., 2016)



of strength due to crack formation. Another direct effect of the relative humidity is the crystallization and dissolution of salts in standing structures, archaeology sites, wall paintings, frescos and other decorated surfaces as higher level of moisture can relate to prolonged periods of dampness of materials which results in discolouring of facades. Reduction of the moisture content of the environment can lead to faster evaporation times, which in turn, accelerates the salt crystallization (Sabbioni et al, 2008).

Another environmental factor affecting salt crystallization is the increased temperature (Fig. 1). Higher temperatures can result to higher amounts

of evaporation, resulting in the white cotton like formation of salts on the surface. In repeated cycles of this process, the surface of the porous limestone eventually delaminates and a honeycomb structure is developed in the worst-case scenario or at the best, the surface discolors with oxide stains (Menéndez and Petráňová, 2016) (Pan et al., 2019).

Temperature Fluctuations

The thermal load that buildings undergo throughout the day, due to temperature fluctuations are in some cases extreme. For the subtropical environment of Cyprus, this is especially true for the summer season, which is evident that in recent years the temperatures have risen and the lows and highs in a summer day can vary greatly (Xystouris et al., 2020). Also, through climate modeling over the last decade, it's been demonstrated that the temperature has risen by 1 to 3 C° and it's estimated that by the end of the century, the yearly period of high temperatures (excess of 38 C°), i.e. the summer season, will last an additional 2 months, resembling the conditions in cities like Cairo and Bahrain (Exizidou et al., 2017). These temperature fluctuations of cooler nights (25 C°) and warmer days showcase a magnitude of difference of around 15 C°, that can lead to an excessive rate of deterioration of facades due to the higher thermal stresses developed in the materials (Christoudias et al, 2012). This is more evident in the buildings visited with orientations facing the direction of the sun for prolonged periods of time (Panteli et al., 2018). Through the field experience gained and observations made during the in-situ visits by the authors, the facades of the buildings with direct sunlight exposure or partially exposed surfaces have a higher crack occurrence both in the quantity of crack formation and severity in comparison to facades that are protected from direct sunlight either due to orientation or partial shading provided by adjacent buildings, trees or roof canopies.

Mechanisms of Deterioration of Building Materials

According to the resource library of National Geographic (National Geographic, 2021), weathering is the natural phenomenon that describes the breaking down or dissolving of rocks and minerals

on the surface of the Earth. The main agents of weathering are considered to be water and ice, acids, salts, plants, animals, and changes in temperature. The latter parameter is directly related to climate change, to this end the effects of the greenhouse effect also impact on weathering.

The main mechanisms that outline weathering and lead to building material deterioration due to weathering are the following:

- _ Wet and dry expansion
- _ Frost induced weathering
- _ Salt crystallisation
- _ Biological degradation
- _ Chemical Weathering
- _ Mechanical Weathering
- _ Thermal Expansion
- _ Deterioration

All deterioration mechanisms are directly or indirectly water based. Upon absorbing water, building materials become saturated (Fig. 2). The presence of an incompressible medium like water in the pores of a material causes internal stresses which exert pressure against its bonds; this effect results to tension strains within the material. In cases that the tension capacity of materials is exceeded, cracking along the weaker sections of the material is caused (Schaffer, 2015). The effect is similar in freezing conditions, causing the absorbed water to frost and expand. The thaw-frost cycles can result to exfoliation, dislocations and milling of building elements and of their surface (Clim et al, 2016).



Fig. 2

Deterioration at the base of an adobe wall (left) and characteristic fissure on the upper part of an adobe wall caused by the action of rainwater (right) (Illampas et al., 2009). Each separate render layer spalled off was caused by freezing temperatures in a lean lime render saturated with water (Balksten et al., 2021)

Salt crystallization (Fig. 3) in limestone occurs when the absorbed water by the pores of a building material begins to evaporate. During the evaporation stage, the ions of building materials are pulled out of the porous and crystallize on the surface of the material. This effect is extended within the pores of the material as well. The effect results to the building material breaking up and smoothing out of its edges. While the pores of the material crystallize, they become oversaturated and internal stresses result to cracks (Angeli et al., 2007).

Biological degradation (Fig. 4) refers to the development of microorganisms and fungus at the mortar joints and the building material themselves. The microorganisms lead to the development of plantations that with the root develop-



Fig. 3

Salt Crystallization-Weathering of Stone (Gupta, 2013)

Fig. 4

Visible microbial growth



Fig. 5

Hadrian's Arch at the Acropolis, Athens, 2005, marble blackened and corroding from acid rain (Marcok, 2015)



Fig. 6

Formation of Vertical cracks due to thermal expansion. Distinct characterization of thermal cracks is the thicker crack on one side that slims out further along



ment due to the water cause the internal stresses to develop and destroy the bond between mortar-stone (Clim et al., 2016).

Chemical deterioration of building elements refers to the chemical reactions that erode the stone facade of buildings due to processes like dissolution, hydrolysis and oxidation. The chemical reaction in this case, alters the composition of stones or acts at the surface level of the stone. This form of weathering is mainly attributed to air pollution, since the main chemical attackers are acid gasses, like carbon dioxide or acid sulphur. The acid gasses end up on the surface of heritage buildings through rain precipitation or winds, resulting to a black crust on the surface of the stones. Acids can further penetrate in building elements and result in their deterioration (Fig. 5) (Gupta, 2013).

Weathering due to thermal expansion in buildings occurs regularly under sub-tropical environmental conditions. In terms of weathering mechanisms, along with rising damp, thermal expansion is one of the most important factors when it comes to accelerated weathering or normal pace ageing of a heritage building. The internal strain caused by thermal fluctuations in the building's materials during a day-night cycle can result to crack formation and propagation in buildings as shown in Fig. 6. The crack formations can lead to deterioration of the building element, by allowing water seepage during rainwater runoff and microbial growth in the cracks. Another result of thermal expansion in stones is the enlargement of the pores, which in return can be saturated with water due to minor cracks caused by the thermal cycle (Luque et al., 2010).

The weathering mechanisms discussed, are all in one way or another, affected by environmental conditions. The water concentration in the pores of building elements is directly controlled by the ambient temperature and the relative humidity. Under high temperatures and low relative humidity, water will evaporate faster, and thus propagating the salt crystallisation on the surface of the stones. On the other hand, a high temperature moist environment can help the growth of micro bacterial organisms and lead to biological growths in the building elements and development of fungus.

Application of Non-destructive Techniques for Defining Weathering Effects in Building Materials

IR thermography as a Non Destructive Testing method can prove to be an ally in the fight against weathering of heritage buildings. It can help as an early sign of deterioration through a building's facade and act as a proactive mitigation tool. The IR thermography can help establish the sub surface condition of an element through capturing the thermal variations through surface thermal pattern variations, i.e. changes in temperature over space and time. The variations in thermal patterns can point to discontinuities of the material, moisture, crack formations or any other defects that might be present in the subsurface (Bisegna et al., 2013).

The NDT method of IR Thermography regarded by many as the go to method for building diagnostics as it is a cost effective way since it's more affordable than most techniques used in the field. It is also safer to use for the buildings as it's a non contact way for analysing surface debonding, delaminations etc. The main advantage of IR thermography is the ability to conduct real time tests through the digital images produce, without the destruction of the element and able to find deformations that with naked eye would be impossible to detect. Another important advantage of the technique, is that it can help identify weak spots in a buildings envelope and minimise the cost of maintenance or repairs to the specific area, while at the same time with this, the cost for living minimises as well as the energy efficiency can be bettered. The main disadvantages of the method is that is referred to as a "boundary technique", which means that the thermal camera is limited to a solid structure and can only capture images up to a limited depth of material. The final con point is the fact that in order to interpret and understand the thermal images, it involves an experienced test user with good intuition and judgment at identifying discolorations of the images and connects that to a defect (Kylili et al, 2014). This fact was decisive for the authors to use thermographs in conjunction to digital imaging in order to demonstrate and explain the damages discussed in this paper. By careful elaboration of the deviation in thermal radiation and thus temperature, issues not visible in the digital imaging can be found. The chosen thermographs along with the corresponding digital image makes the weathering mechanisms almost self-explanatory and easily understood, which for the purpose of this report is more relevant, since the focus is not on the technique, but on the weathering effect in heritage buildings under subtropical conditions. Furthermore, the report includes only a fraction of the thermal imaging conducted in regards to the raw quantity of thermographs taken during the in situ visits, which makes it impossible to include all thermographs.

In the context of this work, the effect of climate change on the degradation of heritage buildings' construction materials was conducted. Measurements were carried out in 10 buildings in the traditional core of Strovolos (Nicosia) as noted in Table 1. The research also involved 8 buildings in the historic core of the city of Limassol for which at this moment the data are still being processed. The measurement campaign took place between February 2020 and July 2021. The Plan drawings are in North orientation facing upwards while in the case of plots containing a sort of complex, abbreviations B.A., B.B, B.C. were used to differentiate between the main building which is Building A, i.e. B.A and moving down the alphabet based on the purpose of the building. The highlighted facade is the main entrance facade of the building in each case.

For the procedure, the NDT method of IR thermography was employed. The equipment used for the thermographs is a FLIR E50 thermal camera. The Procedures described in the standard CYS EN 16714-1:2016 were followed.

The effect of weathering due to climate change was examined for porous limestone from Mammari and Yerolakos region (Press and Information office, 2015) and locally produced adobe brick. Generally, the construction method for the time period of the studied buildings sees the complete

Materials and Methods

use of Porous Limestone for the facade that faces the street and has the main entrance to the building, while for the rest of the facades porous limestone has been used as a foundation up to the window sill, and from there upwards the structure is built with adobe brick. The composition of the Adobe bricks consists of Clay (local soil mixed with water) and straw, as fibres for added strength (Castrillo et al., 2016). Masonry plasters consisted of a lime-based mortar for the exterior side of the walls and gypsum-based mortar for the interior side of the walls.

Table 1
List of studied buildings

Build- ing ID	Latitude	Longitude	Construc- tion Period	Photograph	Orientation(N)
Plot 337	35° 8'49.65"N	33°20'24.85"E	<1945		
Plot 217	35° 9'3.38"N	33°20'35.71"E	<1945		
Plot 547	35° 8'59.83"N	33°20'37.69"E	<1945		
Plot 230	35° 8'45.66"N	33°20'25.09"E	<1945		
Plot 317	35° 8'43.28"N	33°20'25.52"E	<1945		
Plot 566	35° 08'53.7"N	33°20'25.4"E	<1945		

Build- ing ID	Latitude	Longitude	Construc- tion Period	Photograph	Orientation(N)
Plot 215	35° 09'03.6"N	33°20'34.2"E	<1945		
Plot 71	35° 09'10.2"N	33°20'30.7"E	<1945		
Plot 290	35° 8'58.98"N	33°20'26.1"E	<1945		
Plot 131	35° 8'58.22"N	33°20'22.8"E	<1945		

In this part of the report, the various IR thermographs will be discussed in regards to the damages found during in situ visits. The analysis involves a discussion about the damage recorded as well as the root of the problem and any external factors making the problems even worse. The damages observed during the in situ visits were previously discussed and are the rising damp, thermal expansion, chemical weathering i.e. carbon dioxide deposition and microbial growth on building elements.

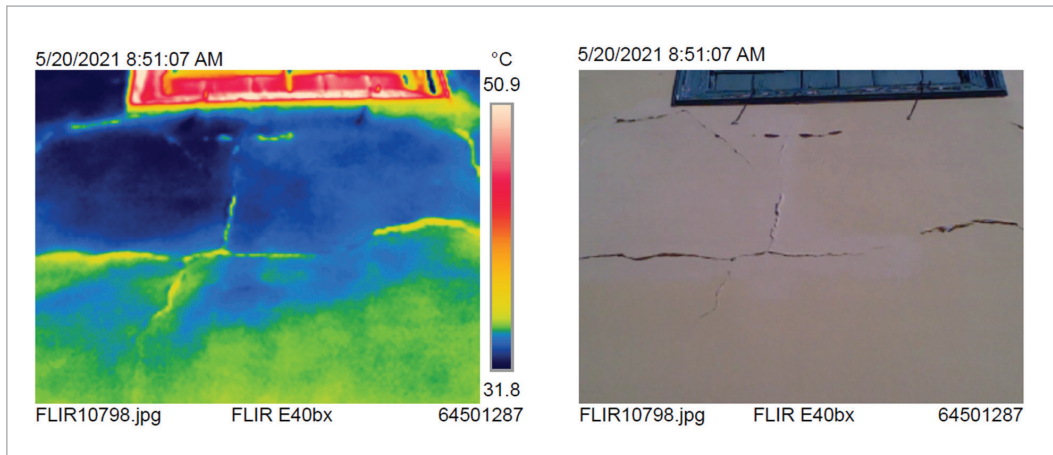
Thermal Expansion Thermographs

The thermograph presented in Fig. 7 is from Building 6-Plot 566 and was taken in February of 2021. It shows extensive crack formation below the window at the second floor level. The cracking is directly related to thermal expansion of the materials and this is a result of prolonged sun exposure and repeated temperature fluctuations. The orientation of the wall is South East, which translates to sun exposure from sunrise until midday with a total exposure everyday roughly for 7

Results and Discussion

Fig. 7

Thermal Expansion-
The masonry exhibits
extensive cracking



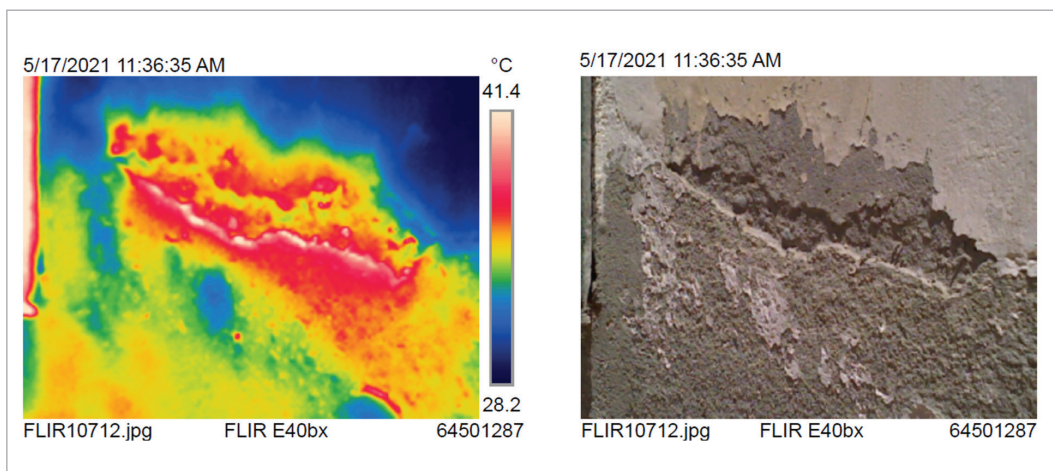
hours during the summer season and 5 hours during the winter. This prolonged exposure means that the higher temperature reached for this masonry during peak exposure is very different from the lowest temperature that will drop to during the night time which causes the materials to experience thermal strains, resulting in crack formations.

Rising Damp

Rising Damp is the first and most occurring damage in all the in situ visits conducted. Rising damp is proven to be one of the main reasons of heritage buildings been crippled and damaged. In Fig. 8 rising damp is been observed in the masonry element which caused the plaster to develop internal stresses due to an incompressible medium like water which in returned, lead to crack formation. The surface layer of paint delaminates due to evaporation cycles of the water, which draws ions out of the masonry and into the surface of the plaster, which causes salt crystallisation. The surface of the plaster seems to be in a honey comb state due to the repeated cycles of water evaporation and salt crystallisation. In Fig. 9 the cycle is at a different pace from Fig. 8, the surface paint has delaminated and detached from the plaster underneath developing the “hills” and “valleys” on the surface of the asbestos based paint. Both thermographs are from Building 1- Plot 337 and are from a Southwest orientation taken in October of 2020.

Fig. 8

Rising Damp
damage



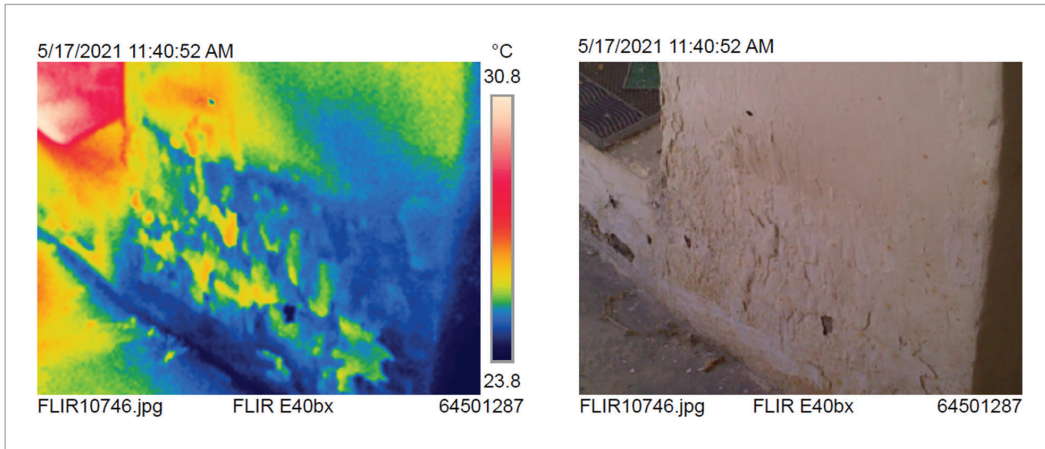


Fig. 9
Rising Damp-Salt
Crystallisation

Microbial and Plant Growth

The following Fig. 10 and Fig.11 are from Building 4- Plot 230 and are North and West facing respectively and the in-situ visits were in November of 2020. The thermograph depicts the micro-

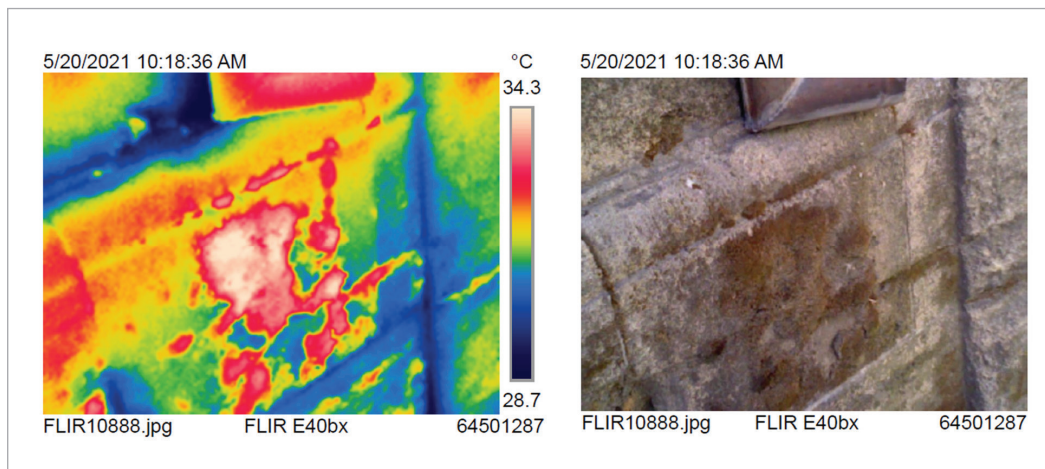


Fig. 10
Fungi growth on surface
of Stone

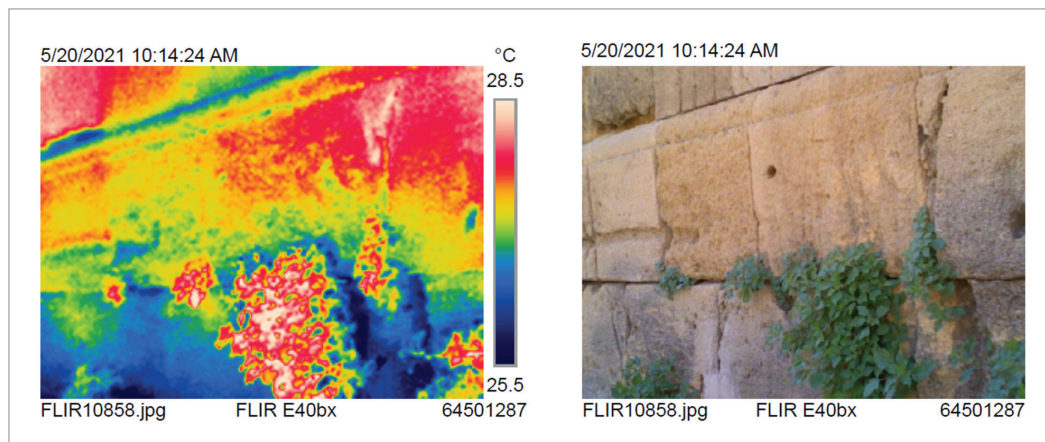


Fig. 11
Plant Growth in gaps
between the Stones of the
Masonry

bial growth that follows the rising damp in masonry elements. Due to high relative humidity and warm environmental conditions, as well as the presence of moisture in building elements, fungus develops and grows on the surface of building shells. Depending on the type of fungi, they can be toxic and cause health problems to occupants after a prolonged exposure to their toxins. Plant growth in building elements can find root in cracks, voids or gaps in the mortar between stones. The plant development is based on wind transportation of the seeds or by adjacent plants to the walls themselves. The growth of the plants causes the mortar to delaminate and detach from the stones with the growth of the root system of the plantation that puts the bonds of the mortar under stress at the micro scale level.

Chemical Weathering of Masonry Walls

The carbon dioxide deposition on building elements is a weathering mechanism requiring the chemical reaction of the two mediums, carbon dioxide and the building material (silica based materials). Carbon Dioxide is deposited mainly through two environmental mechanisms, primarily through rain washing the carbon dioxide out of the atmosphere and onto the building shells and secondly through wind gusts. The presence of Carbon Dioxide on buildings is observed through the accumulation of a blackened crust (Fig. 12 and Fig. 13) on building elements and is evident from the in situ visits; the accumulation tends to happen on horizontal surfaces, which is easier for the carbon dioxide to stick to. A deteriorated, deformed surface is left behind after the chemical bonding of carbon with silica materials takes place. The thermographs are from building 3-Plot 547 and the in situ visits were in November of 2020.

Fig. 12

Carbon Dioxide accumulating on the stone column

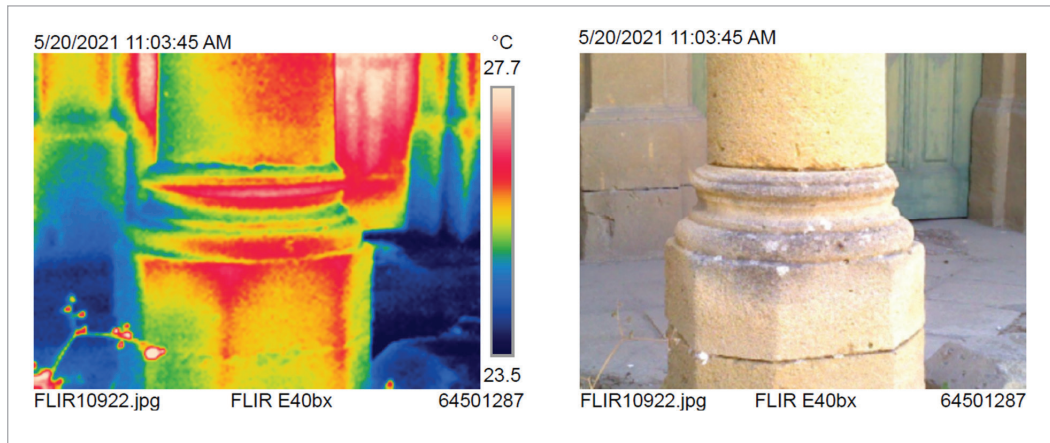
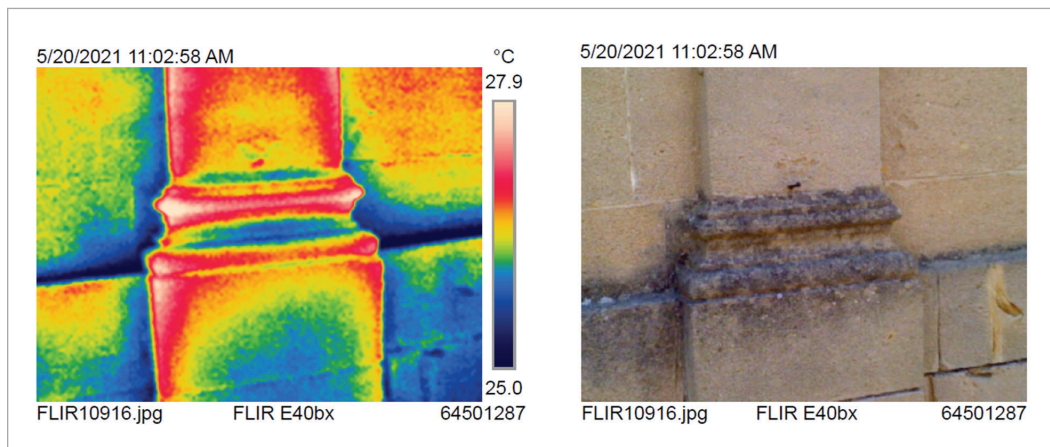


Fig. 13

Accumulation of Carbon Dioxide at the change of thickness in the material



The climate is widely discussed in recent years in regards to its impact on buildings. Numerous studies have been published, discussing the various weathering mechanisms that act upon exposed building materials. In this study in situ measurements were employed to classify the weathering mechanisms under subtropical conditions, based on the frequency of observation. This study revealed that the leading cause for wear and tear in building facades was rising damp from the soil and absorption of water, either through rainwater run offs that are absorbed through cracks in the building's facades or through high relative humidity in the atmosphere. The evaporation cycles may draw out the ions from stones, resulting to salt crystallization on the surface of the material. As more and more cycles may occur, this may result to deformation of the element. The second most commonly occurring and damaging weathering mechanism observed was found to be the thermal expansion of material and facades. Day-night cycles under subtropical conditions may result to significant surface temperature alteration of facades due to solar exposure, based on the orientation of a building. During the spring and autumn, high changes of surface temperature are observed, exceeding 50 °C in some cases, reaching 55-60 °C during midday and being reduced to 10-15 °C during night. Over the past few years this temperature fluctuations seem to increase due to climate change effects (Christoudias et al., 2012). Crack formation due to thermal expansion may lead to water penetrating the surface, resulting to a combination of stresses within a wall rising due to water absorption but also due to thermal load.

The third most common mechanism was found to be the deposition of carbon dioxide on buildings. This was observed through the blackened and discoloured facades of the buildings. While this affects the quality of the materials due to the chemical reaction between carbon dioxide and silica-based materials like limestone and lime plaster, it might be argued that buildings in general might be helping in the removal of carbon dioxide from the atmosphere and help alleviate some of the carbon introduced to the atmosphere in the construction and the operational phase of the building. The severity of carbon deposition was not found to be as of great importance as the first two mechanisms, as it can be easily handled.

The fourth most occurring weathering mechanism was found to be the microbial and plant growth, which causes delamination in the surfaces of the facades or breakage of the bonds between the different materials. The occurrence of plant growths requires certain conditions to occur like high moisture content within the masonry and some kind of point of entry for the seeds to be planted like a crack or a void in the mortar joints between the stones. Microbial growth, like fungi, also requires appropriate conditions on the surface of the wall and a window of prolonged shading during the day so that the surface does not dry out fast and the fungi can develop. Because of the conditions of occurrence, microbial and plant growth is not as common as the previously mentioned weathering mechanisms, and it's not as destructive as well since they can be mitigated through various chemical sprays.

While the four main weathering mechanisms have been identified in this field research, the connection of occurrence and the acceleration or deceleration of the weathering of a building to the climate change at this point cannot be established. While climate change does have a connection to all four weathering mechanisms, the fact remains that in order to correlate climate change to the weathering of buildings, a longer period of observations need to be undertaken.

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Conclusions

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