Material Sensors for the Surface Recession of Calcareous Stones: Understanding Present and Future Decay

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Summary

The study proposes material sensors to assess the rate of the surface recession of calcareous stones through atmospheric weathering. The sensors, made of highly polished alabaster and Carrara marble, were exposed outdoors for up to 10 months. The analytical methods employed involve gravimetry, gloss measurements, and microscopy. For alabaster sensors, the results show a good reliability for gravimetry, but lesser for gloss; this sensor material might prove more relevant for sheltered exposure. In turn, the marble sensors yield very promising results for gloss measurements, but less with gravimetry; longer exposure times might change this. Microscopy proves suitable for both types of sensors, with emphasis on the surface profile and roughness obtained by digital microscopy. The trial exposure confirms that material sensors can help understand exposure and microclimatic conditions affecting the preservation of heritage assets.

Keywords: *calcareous stone, surface recession, material sensor, gloss measurement, digital microscopy, field exposure*

Introduction

Calcareous stones, including porous and compact limestones and marbles, are common and significant heritage materials. They have been extensively used in sculpture and architecture across various regions and historical periods. Certain calcareous stones were primarily used regionally, while others journeyed vast distances, as early as antiquity. Important heritage landmarks such as the Parthenon in Athens, Michelangelo's David, the Taj Mahal in Agra, and gothic churches such as St. Stephen's Cathedral in Vienna are constructed from stones belonging to this material group.

These are chemically vulnerable materials due to the solubility of calcium carbonate in water and acids. Consequently, monuments constructed from these stones have always been subject to intensive maintenance and repair, a practice continuing to present times. As part of preventive conservation strategies, some heritage assets are sheltered or relocated to indoor environments. Various types of coatings have been developed to protect calcareous surfaces against material loss. However, within the framework of minimal intervention, determining which monuments require protective treatment and which not poses a significant challenge for conservators.

To support the decision-making process regarding conservation measures, it is essential to assess the rate of material decay. Various methods have been developed to measure or calculate surface recession for specific stones or monuments. These methods vary in approach, ranging from theoretical mathematical calculations and dose-response functions to gravimetric measurements or analyses of runoff water. However, the actual situation with a particular monument may differ from the values derived from these methods. In this paper, we present one potential approach to address this challenge.

The Surface Recession of Calcareous Stones

The surface recession of calcareous stones is mostly explained by three different but interconnected mechanisms.

The so-called "karst effect" explains the dissolution of calcite in unpolluted rain. Calcium carbonate is slightly soluble in water (0,014 g/l) but much more in weak acids. In reality, rainwater is never pure but rather slightly acidic due to the absorption of carbon dioxide from the atmosphere. As a result, clean rainwater typically has a pH of 5.6 and can dissolve up to four times more calcium carbonate than water with pH 7.[1] Hence, calcareous surfaces, whether in the landscape or on monuments, undergo dissolution with each rain event. In rain exposed areas on monuments the dissolved calcium carbonate is mostly washed away; this results in surface recession – material is removed from the surface.

With polluting agents in the air, different deterioration mechanisms become more important. The so-called 'acid rain' (wet deposition) is produced by the dissolution of different acidic pollutants in rainwater on its way through the atmosphere, the pH falls as low as 4 (acid fog reaching sometimes a pH of 2).[2] A different mechanism, known as dry deposition, involves pollutants accumulating first on and within the surface of a material, only to be dissolved later by precipitation. This mechanism is mostly relevant in dry phases and in direct vicinity of pollution sources.[3] With both deposition scenarios, if the pollutant is SO_2, as was commonly the case in the past, sulphation occurs. Depending on the exposure and the substrate involved, a crust forms (only in rain-protected areas), and/or deep sulphation of the stone material occurs.[4]

Due to the decreasing levels of SO_2 in the air (at least in Europe), the future recession of calcareous stone can mainly be attributed to the so-called "karst effect." The increasing amount of CO_2 in the air, coupled with shifts in climate due to climate change, is expected to further exacerbate material loss due to the "karst effect," especially in northern and central Europe. This and other shifts in heritage climatology were addressed in the NOAH'S ARK Project (2004 – 2007).[5] The findings regarding surface recession of compact calcareous stones were published in 2009:

> The most marked change in recession rates across the period is the general increase throughout Europe, particularly noticeable in high rainfall areas, e.g. mountain areas of central Europe, Scandinavia and Scotland. The change can be of

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[1] Michael STEIGER, Elena A. CAROLA, and Katja STERFLINGER, "Weathering and Deterioration," in *Stone in Architecture: Properties, Durability*, ed. Siegfried Siegesmund and Rolf Snethlage, 4. ed. (Berlin, Heidelberg: Springer Berlin Heidelberg; Springer, 2011), 258–59.

[2] *Ibid.*, 259.

[3] Dario CAMUFFO, *Microclimate for Cultural Heritage: Conservation, Restoration, and Maintenance of Indoor and Outdoor Monuments*, 3rd ed. (San Diego: Elsevier Science & Technology, 2019), https://ebookcentral.proquest.com/lib/kxp/detail.action?docID=5799303, 125–30.

[4] *Ibid.*, 129.

[5] NOAHS ARK, Funded by the EU, FP6-2002-SSP-1, Grant agreement ID: 501837,

> more than 6 µm year-1 in regions where the recession was around 20 µm year-1 in 1961-1990, which is a 30% increase.[6]

So, it can be argued that with the increasing concentrations of CO_2 in the air, the surface recession of calcareous materials due to the "karst effect" will rise. This is attributed to higher levels of CO_2 dissolved in rainwater, resulting in lower pH levels and in rising solubility of calcium carbonate in rainwater. Additionally, climate change and with it the change in temperature and distribution of precipitation through the year influence the surface recession. Longer exposure periods above 0°C result in increased time spent at temperatures critical for surface recession due to the "karst effect," as calcium carbonate can only dissolve in liquid water.

However, in reality, surface recession is highly dependent on the specific calcareous substrate involved and its physical properties, such as porosity, capillarity, microstructure, and relevant mineral impurities. Additionally, factors such as the exposure and/or the relevant microclimatic effects also significantly influence the rate of surface recession. To better understand these for a particular monument, this paper suggests the use of material sensors.

Material Sensors

Material sensors are not a new idea in conservation. The best-known sensors used in the field aim to assess the suitability of materials for the use in museum storages or showcases; these are known as Oddy tests.[7] Many materials release gaseous compounds when they degrade, which can harm or endanger museum objects. In the Oddy test, a set of metal coupons (thin sheets) is exposed in an atmosphere alongside the material being evaluated. Any emerging corrosion indicates the presence of harmful gases.

Similarly, in stone conservation, some studies have attempted to use lithic materials to estimate the harmfulness of a particular environment and/or exposure. However, most of these studies are focused on sulphation[8] or on the combined effects of weathering in general.[9]

The present study aims to systematize the use of material sensors to enhance the understanding of surface recession of calcareous stones, within a dynamic outdoor environment. This approach aims at examining particular monuments always in their specific position and exposure conditions in contrast to the phenomenon of surface recession in general.

Methodology

In preliminary tests and studies, various stones were evaluated for their potential as material sensors to measure surface recession in calcareous stones. These included compact limestone from Vratsa, Bulgaria, marble from Carrara, Italy, and three different types of alabaster.[10] Different surface finishes, such as hand-polished and machine-polished, were examined, along with various analytical methods for assessing material loss, including gloss measurements, gravimetry, and optical and 3D digital microscopy.

The preliminary studies began with laboratory tests, followed by a short-term outdoor exposure period of 3[11] and 6 months in a rural area of Lower Austria (a reclining angle of 45° facing NNW). Insights gained from analyses of the sensors (using gloss measurements, gravimetry, and microscopy) were utilized to further refine and develop the methodology.

As a result, the exposure protocol implemented in this study and discussed here was designed. Samples of Carrara marble and a white homogeneous alabaster with a size of 4×4×1 cm were produced; the front was polished to the highest degree possible. The rear-side was protected by a thin glass plate glued to the sample, the four lateral sides

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[6] Alessandra BONAZZA et al., "Mapping the Impact of Climate Change on Surface Recession of Carbonate Buildings in Europe," *The Science of the Total Environment* 407, no. 6 (2009): 2047, doi:10.1016/j.scitotenv.2008.10.067.

[7] L. R. GREEN and D. THICKETT, "Testing Materials for Use in the Storage and Display of Antiquities: A Revised Methodology," *Studies in Conservation* 40, no. 3 (1995): 145, doi:10.2307/1506472.

[8] R. A. LEFEVRE et al., "Modelling of the Calcareous Stone Sulphation in Polluted Atmosphere After Exposure in the Field," *Geological Society, London, Special Publications*, 2007.

[9] Thomas BIDNER et al., "Stone as Sensor Material for Weathering," in *Understanding and Managing of Stone Decay: SWAPNET 2001*, ed. Richard Prikryl, Heather A. Viles (The Karolinum Press, 2002).

[10] The inclusion of alabaster, despite its chemical differences to calcareous stones, aimed to explore the potential for a rapid sensor. Such a sensor would be valuable in scenarios where time is limited and quick decision-making assistance is needed. A typical case would be the conservation of a single sculpture, where a decision is required regarding whether to apply a protective coating at the end of the conservation treatment. The sensors could be installed at the beginning of the project and analysed towards the end. Alabaster's higher solubility could ideally aid the decision-making process even after exposure for a couple of months.

[11] Marija MILCHIN, Johannes WEBER, and Gabiela KRIST, "Sensor Materials for the Deterioration of Carbonates in a Changing Outdoor Environment," *IIC News in Coservation*, no. 97 (2023).

by an aluminium tape.[12] The same tape also covered the upper 10 millimetres of the front in order to create a sheltered surface that can be directly compared to the unsheltered and therefore weathered surface (Fig.1).

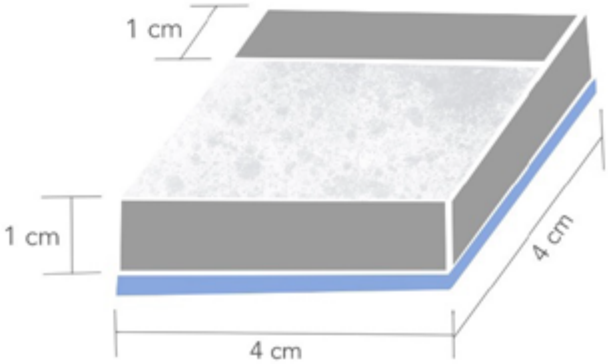

Fig. 1: The design of the material sensors (blue: glassplate; grey: aluminium tape)

The samples were weighed before exposure (with and without aluminium tape). The gloss before exposure was measured with a multi gloss meter[13] on all samples in three angles (20°, 60°, and 85°) at at least three positions. Prior to measurement, the potential dependence of gloss values on measurement direction was assessed. No differences were detected for Carrara and alabaster. The samples were then exposed (start of the exposure 01.04.2023) on a rack with a reclining angle of 45° facing NNW in a rural area in Lower Austria[14] at a height of approximately 4m, unsheltered by roof or trees.

After time periods of 1, 2, 7, 9, and 10 months, samples were collected and analysed. The gravimetric measurements were repeated both with and without aluminium tape. The tape was removed mechanically; any adhesive residues were removed with acetone. The gloss was measured as previously described. Microscopic analyses were conducted using both a 3D digital microscope [15] and an optical microscope[16] with incident light. The 3D digital microscope employed in this study has the capability to detect surface relief via a light beam, allowing for the indirect measurement of surface roughness. This feature was implemented with the exposed samples. The previously mentioned sheltered upper portion of the sample was compared to the exposed and weathered portion. To ensure precise measurement, one sample section was carbon-sputtered, which is typically used in SEM analysis, resulting in an opaque surface and improved accuracy.[17] Line roughness measurements were conducted on weathered and sheltered areas of the sensors, allowing for surface recession assessment from the profile. The extreme washout on the border between sheltered and unsheltered regions was disregarded in the analysis.[18]

Results

Gravimetry

The differences in weight measured before and after exposure were, as expected, much more relevant for the alabaster than for the marble samples. This discrepancy is explained by the higher solubility of calcium sulphate in comparison with calcium carbonate.[19] While the alabaster samples showed a loss of more than 1 g (1.14 g) over a surface of approx. 12 cm2 in 10 months,[20] for the marble samples a maximum loss of only 0.03 g for the same surface and period of time could be measured. The gradual loss noted for the alabaster samples shows that gravimetric measurements are reliable for this kind of sensor. Over longer exposure periods, it is anticipated that the loss of material for alabaster will continue at a similar rate.

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[12] Tesa® Aluminium Tape, is a tape from aluminium foil (100 µm) with acrylate as glue, suitable for repairs indoors and outdoors (stable in temperature range of -40°C until +160°C).

[13] BYK®, micro-TRI-gloss

[14] Sattelbach in Lower Austria (48.0297938, 16.13777273).

[15] Kayence, VHX-7000.

[16] Olympus BX 40.

[17] In preliminary studies, it was observed that surface roughness measurements, which are conducted with a light beam in the 3D digital microscope, encountered issues with semi-transparent crystals, a common occurrence with marble and alabaster. Consequently, a solution was required to cover the surface and render it opaque, while minimizing interference with the surface relief.

[18] It is hypothesized that the significant washout observed in this area was triggered by the prolonged presence of water drops due to their adhesion to the sticky tape. Therefore, this effect was considered atypical of the actual exposure conditions but rather typical of the design of the exposure setup.

[19] Calcium sulphate has approx. 20 times higher solubility in pure water than calcium carbonate.

[20] Calculated with a density for alabaster of about 2.3 g/cm^3 this results in an average surface recession of about 0.5 mm/year.

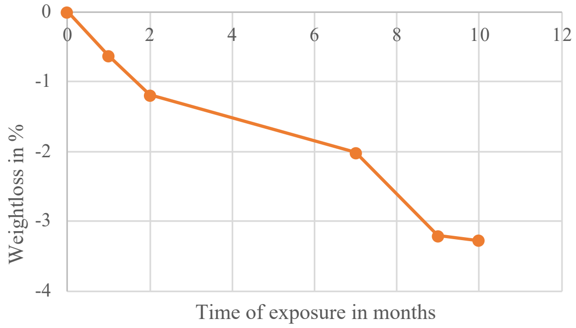

Diagram 1. Weight loss in % of total weight, alabaster samples

The values obtained for the marble samples on the other hand are so low that the results are not significant or reliable, in part due to the error range of the scale used.[21] Gravimetric measurements for the marble sensors might become more relevant for longer exposure periods (several years).

Gloss Measurements

The gloss measurements showed very promising results within the first months of exposure for both alabaster and marble. After the full exposure period, all results from gloss measurements were subjected to statistical analysis to evaluate their significance individually and in relation to each other, considering different exposure times.[22]

The weathered alabaster samples show significant differences compared to both the initial experiment's baseline and the values observed after one month. However, after two months of exposure the comparison with values from longer exposures becomes insignificant e.g. the gloss at 60° after two months of exposure (M=1.77; SD=0.06) is not significantly different to the gloss at 60° after nine months of exposure (M=1.96; SD=0.11; t(2)= -3.46; p=ns; Cohen's d = 0.10). The loss of gloss occurs so rapidly that after two months only few gloss units remain, making any later measurement unreliable, and providing no further information on decay. However, alabaster may prove useful for rapid-sensors or for indoor or sheltered exposure, particularly for assessing the impact of condensate on stone surfaces. This topic needs further investigation in the future.

	N	Gloss in GU, Mean	Std. Deviation	Std. Error Mean
before exposure	15	90.4800	1.32568	0.34229
1 month exposure	3	1.2333	0.05774	0.03333
2 months exposure	3	1.7667	0.05774	0.03333
7 months exposure	3	1.8333	0.05774	0.03333
9 months exposure	3	1.9667	0.11547	0.06667
10 months exposure	3	2.1000	0.000000a	0.00000

[a]. t cannot be computed because the standard deviation is 0.

Table 1. Gloss measurements 60°, alabaster sensors

The statistical analysis of the results for marble, both as a single sample and when paired with different exposure times, gave significant results. One of the least significant combinations was the gloss measured at 60° before (M=104.87; SD=1.55) and after one month of exposure at 60° (M=75.67; SD=1.76). Even here a high level of significance was achieved (t(2)=12.34; p<0.01; Cohen's d=4.07), thus demonstrating the compatibility of marble sensors with gloss measurements.

	N	Gloss in GU, Mean	Std. Deviation	Std. Error Mean
before exposure	15	104.87	1.552	0.401
1 month exposure	3	75.6667	1.76163	1.01708
2 months exposure	3	33.8667	0.97125	0.56075
7 months exposure	3	58.1667	1.73877	1.00388
9 months exposure	3	51.9000	1.93132	1.11505
10 months exposure	3	35.6000	5.38609	3.10966

Table 2. Gloss measurements (60°), marble sensors

The results exhibit greater consistency and demonstrate greater potential with marble than with alabaster, revealing a gradual decrease in gloss values across all three angles. However, the 60° angle appears to be the best choice since the expected values cover a wide range of gloss units (0 - 120 GU). Additionally, some gloss meters only measure at a 60° angle. Therefore, maintaining a 60° angle as a minimum requirement for all measurements allows for better accessibility of the method for users, especially for conservator-restorers.

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[21] Sartorius®, BP 2100S, d=0,01g.

[22] The statistical analyses were conducted by Jana Korunovska.

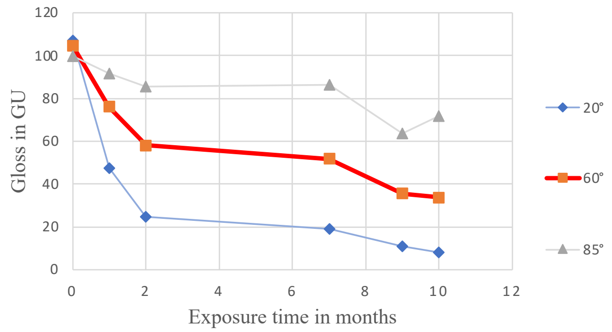

Diagram 2. Gloss loss in GU, marble samples (20°, 60°, and 85°)

The results suggest that similar measurements could also be beneficial for longer exposures (i.e., several years) and are both easy and cost-effective to employ. It can also be anticipated that the same measurements will be reliable for compact polishable limestones. However, further exposures and measurements are necessary to establish a correlation between the decrease in gloss and the rate of surface recession.

Microscopy

Microscopically, differences in the surface relief between the protected and exposed areas were examined. Using a 3D microscope, line roughness was measured; i.e. for the 10-month exposed marble, the protected areas exhibited very low roughness values: Ra=0.06µm, Rz=0.42µm (Fig. 2), whereas the exposed areas showed much higher roughness: Ra=5.50µm, Rz=30.94µm (Fig. 3).

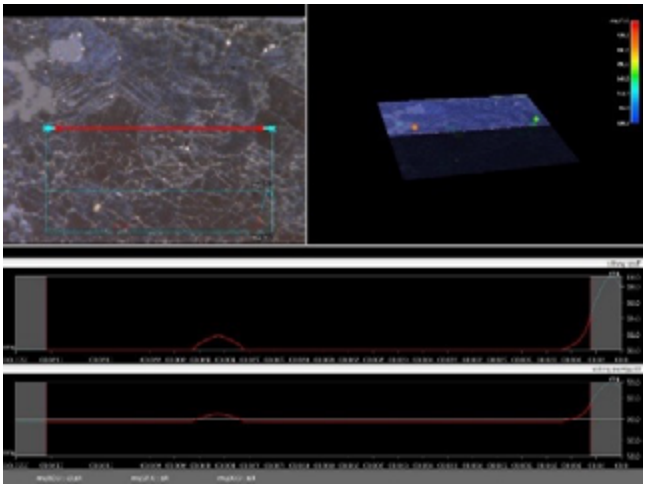

Fig. 2. Roughness measurement, protected area, MV- 10-months exposed marble sensor

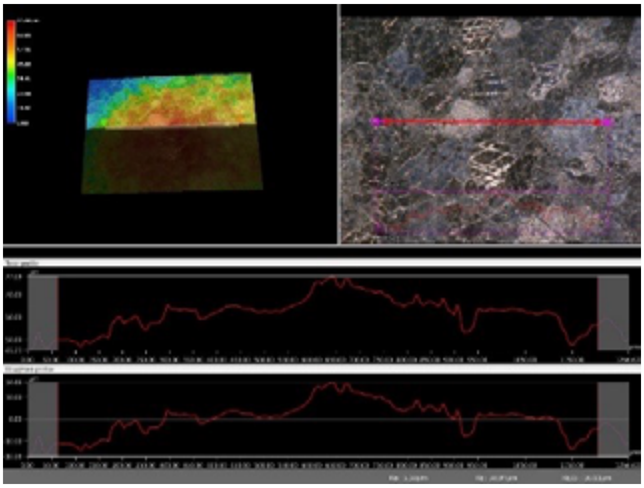

Fig. 3. Roughness measurement, exposed area, MV- 10-months exposed marble sensor

Additionally, the structure and morphology of the surface were analysed using the 3D microscope. By direct comparison of the protected and unprotected surfaces, surface recession could be directly measured using line measurements. As anticipated, the alabaster samples exhibited a higher rate of surface recession compared to the marble samples.

Figures 4 and 5 depict the analyses of the alabaster sensor after 10 months of exposure. The washout along the border between the protected and exposed areas is noticeable in the blue region. As evident from the profile in Figure 5, subtracting this effect is relatively straightforward, facilitating the calculation of surface recession. In this case, the surface recession for the alabaster over 10 months amounts to approximately 360 µm.

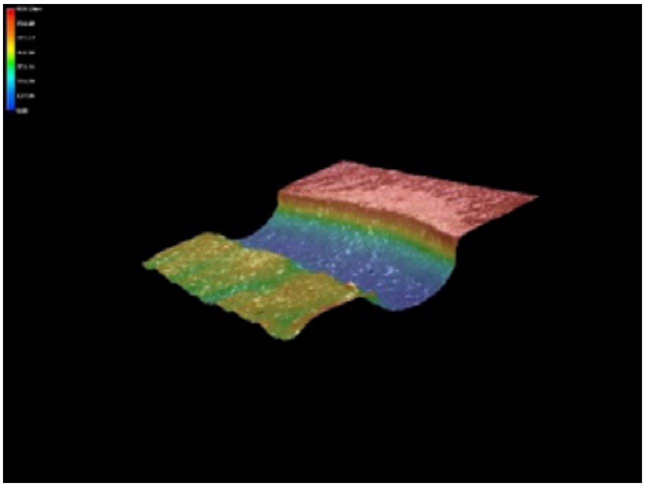

Fig. 4. 3D relief of the surface of AV (10-months exposed alabaster sensor), protected area, wash out and exposed area

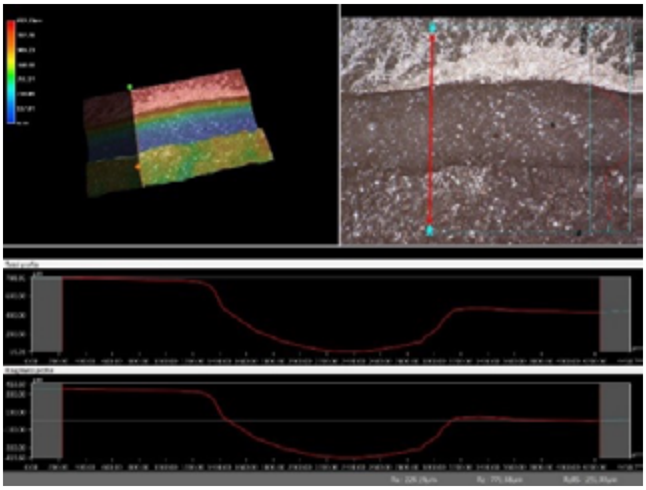

Fig. 5. Surface profile, protected area, wash out and exposed area, AV (10-months exposed alabaster sensor)

The microscopy results indicate that sheltering an area in close proximity to the exposed surface is highly beneficial, particularly when combined with analyses with the digital 3D microscope.

Discussion

The results show that material sensors have the potential to help understand the rate of deterioration for a specific position and exposure of a monument with focus on the surface recession of calcareous stones.

For the exposure of alabaster sensors, gravimetry proved to give usable results, whereas gloss measurements are of relevance only for the first couple of months in the exposed outdoor environment. Microscopy provides very clear and accessible results both in terms of surface roughness and surface recession. However, it is recommended wherever possible to use sensors with the same or similar composition as the monument asset. Therefore, alabaster sensors should rather not be the first choice for monitoring monuments made of calcareous stones in outdoor environments, unless as a rapid sensor for very short (accelerated) exposure times or under indoor or sheltered conditions. The same could aid in understanding the effect of potential condensation events on surface decay. Nevertheless, this area requires further research and should be explored in future studies.

The marble sensors show a very useful pattern of surface recession which can be best analysed with a combination of gloss measurements and 3D digital microscopy. Especially, the inexpensive and straightforward gloss measurements offer promising prospects for future use. They are easily implemented and appear to provide a high level of confidence in understanding the rate of surface recession. The gravimetric measurements may hold greater interest with longer exposures. However, it is advisable to track weight changes at every exposure duration to ensure comprehensive monitoring. To establish a robust correlation between the loss of gloss and the amount of material loss, further measurements are required in future studies. For improved correlation, it is recommended to retain the Carrara sensor throughout all exposures. Additionally, it is advisable to expose the calcareous material from which the assessed monument is made. If the original material is not available or accessible, lithic material very similar to the original should be exposed instead. Combining the Carrara sensor with one made from a lithotype of the monument's heritage material can facilitate relevant results for the monument asset and at the same time allow for comparability between different sites.

Conclusions

This trial confirms that using material sensors can help us better understand the decay rate of monuments or heritage assets. Gravimetry, gloss measurements, and surface microscopy prove valuable in comprehending the real conditions on-site. However, there are currently no standardized values available to aid decision-making regarding protection or preventive conservation measures. The establishment of such a protocol is imperative and will require numerous future measurements. The investigation of the influence of seasonal variations and climatic parameters on individual results has not yet been studied. This aspect constitutes an area of future research.

Outlook

This study will enter the next phase in the framework of the EU founded Project STECCI,[23] in which material sensors will be exposed on 10 different sites[24] and analysed after 1 and 2 years. In order to establish a correlation with the already existing data, each sensor set will include a polished sample of Carrara marble. More importantly, each set will accommodate two samples from the stone from which the monument involved is made (a polished one and one

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[23] STECCI - Stone monument ensembles and the climate change impact (Project number: 101094822, HORIZON-CL2-2022-HERITAGE-01), Funded by the EU, https://steccihorizoneu.com/.

[24] The locations are in six different countries: Austria, Bosnia and Herzegovina, Croatia, Germany, France and Malta.

with a rough surface for analyses of bio colonisation and possible soiling), and last but not least, as a connecting reference stone, a compact lime stone from the island of Brač, the so-called Veselje Unito, with two samples pro set, analogue to the local stone, will be exposed. The samples will be exposed on a rack with a reclining angle of 45°. The polished samples will be analysed following the methodology already stated in this paper. The two samples with rough surfaces will mostly be analysed microscopically. The precise methodology is in the development phase and will be published elsewhere in future.

The project consortium hopes that this set-up will allow for comparable information on surface recession, bio-colonization, and soiling between different sites and monuments. All sites consist of calcareous materials and are placed in different geographical and climatical regions of Europe. Together with data from weather stations and climate modelling, this should help make decisions about conservation concepts (preventive and interventive), maintenance, and care in the future.

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Sažetak

Materijalni senzori za površinsko udubljivanje vapnenačkog kamena: razumijevanje sadašnjeg i budućeg propadanja

U radu se predlažu materijalni senzori za utvrđivanje udubljivanja površina na vapnenačkim vrstama kamena i metodologija njihova korištenja. Senzori koji su korišteni u radu načinjeni su od homogenog alabastera i kararskog mramora. Lica senzora polirana su, a sve ostale strane i gornjih deset milimetara lica izolirani su kako bi se ograničilo propadanje njihove nezaštićene, prednje strane. Priređeni senzori izloženi su na otvorenom, u Donjoj Austriji, u različitim vremenskim razdobljima (od jednog do deset mjeseci), na nosačima okrenutim u smjeru sjever-sjeverozapad i postavljenim pod kutom od 45°.

Promjene nastale zbog propadanja analizirane su nakon izlaganja pomoću gravimetrije, mjerenjem sjaja i pod mikroskopom (digitalna 3D i optička mikroskopija), a napravljena je i usporedba s početnim izmjerama.

Rezultati su pokazali zadovoljavajuću pouzdanost kada je riječ o senzorima od alabastera i gravimetrijskim mjerenjima, a nešto manju pouzdanost pri mjerenju sjaja. To senzore od alabastera čini zanimljivijim u kratkoročnim izlaganjima (brzi senzori) ili u zaklonjenim položajima i izlaganjima u zatvorenom, za što će biti potrebna daljnja istraživanja.

Mramorni senzori daju vrlo pouzdane i relevantne rezultate pri mjerenju sjaja, a manje pouzdane kada je riječ o gravimetrijskim mjerenjima. Za bolje je rezultate gravimetrije za mramorne senzore potrebno dulje vrijeme izlaganja. To se posebno odnosi na razdoblja dulja od dviju godina, što bi moglo biti područje istraživanja u budućnosti.

Mikroskopija je podobna i za alabaster i za mramor. Tu su posebno relevantni profil površine i izmjere njezine hrapavosti, a to je moguće postići digitalnim mikroskopom.

Ovo testno izlaganje potvrđuje da materijalni senzori mogu značajno poboljšati razumijevanje izloženosti i mikroklimatskih uvjeta koji pogađaju spomenike i druga baštinska kulturna dobra. Gravimetrija, mjerenje sjaja i mikroskopija pokazali su se vrijednim za razumijevanje stvarnog stanja *in situ*. Ipak, trenutno se ne raspolaže standardiziranim vrijednostima koje bi pomagale u donošenju odluka, a odnose se na zaštitne ili preventivne konzervacijske mjere. U tom je smislu imperativ ustanovljavanje protokola za brojna buduća mjerenja. Za poboljšanje korelacije preporučuje se zadržati senzore od kararskog mramora pri svim izlaganjima. Usto, savjetuje se izlagati materijal od kojega je određeni spomenik sačinjen. Ako izvorni materijal nije dostupan, umjesto njega treba izložiti kameni materijal koji je vrlo sličan originalu. Kombiniranjem senzora od kararskog kamena sa senzorom načinjenim od litotipa povijesnog materijala spomenika može se olakšati dobivanje relevantnih rezultata za spomenike kojima se pristupilo i istovremeno omogućiti usporedivost različitih lokacija.

Ključne riječi: *vapnenački kamen, udubljivanje površine, materijalni senzor, mjerenje, digitalna mikroskopija, terenska izloženost*