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Influence of Temperature Increase on the Degradation Evolution of Rendered Façades

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Abstract. *Climate change could alter the natural degradation pattern of buildings and their components. Façade claddings are directly exposed to the action of environmental agents, thus being particularly vulnerable to climate change impacts. Determining the expected degradation of the façades' external layer, according to climate parameters' projections, could be useful in the context of maintenance planning and adaptation to climate change. The present study intends to deepen the knowledge about the influence of temperature on the degradation evolution of rendered façades, considering the analysis of possible correlations between variables, based on observed and recorded climate data. It covers the degradation evolution of a sample of 26 rendered façades located in Lisbon, Portugal, based on the mean triennial degradation rate ($\Delta S_{w,mt}$) for periods of three years between 1990 and 2020. The severity of degradation index (S_w) of each façade, assessed through visual inspections in two moments in time, is used to model the individual degradation of the respective case study, necessary to calculate the sample's $\Delta S_{w,mt}$ of to each triennium. The correlation between the dependent variable $\Delta S_{w,mt}$ and the independent variable 'maximum temperature' is significant, with a Pearson correlation coefficient of approximately -0.89. The negative trend shows that the degradation of the sample tends to decelerate with the increase of maximum temperature. Therefore, the temperature warming projected for the end of the century could contribute to lessen the rate of rendered façades' degradation in the future, in Portugal or in analogous areas of the Mediterranean. The present study is part of a methodology that is being developed to quantify the impact of changes in climate parameters on the future degradation of rendered façades. Further research is necessary regarding the degradation projections, based on the climate change signal for maximum temperatures.*

Keywords: *Climate change; Façade cladding; Rendered façades; Temperature impact; Degradation evolution*

1 Introduction

Climate change's implications are expected to be wide-ranging and affect ecosystems, agriculture, health and construction (Allen et al. 2018). Consequences on the service life of buildings and components are expected, with associated costs; in this sense, climate change effects on the built environment should be properly considered at the design and maintenance planning phases (Lisø et al. 2007; Armstrong et al. 2017; Cavalagli et al. 2019; Stagrum et al.

2020). The Intergovernmental Panel on Climate Change (IPCC) acknowledges the vulnerability of buildings, components and materials to climate change-induced hazards as key uncertainty and research priority (Revi et al. 2014), in the context of adaptation. Façade claddings can be particularly susceptible to direct exposure to climate action (e.g. relative to temperature, solar radiation, humidity, precipitation, and wind) and relevant, considering their importance to the overall durability of constructions (de Brito et al. 2020; Galvão et al. 2020). External renders are relevant within this context, considering that approximately 62% of the façade claddings throughout Europe are cement renderings (Gaspar and de Brito 2011) and painted renderings is the predominant façade cladding in Southern Europe and in Portugal (Pires et al. 2015). According to the national census, the cladding of around 84% of the buildings is render (INE, 2011).

The present study focuses on the degradation evolution of rendered façades in Lisbon, Portugal, which is part of the Iberian Peninsula, Southern Europe and the Mediterranean region. The climate trends and projections for Portugal are generally in accordance with the regional ones (Christensen et al. 2013; Cramer et al. 2018; Tuel and Eltahir 2020). The country's climate is usually characterized by "moist mild winters and dry warm/hot summers" (Cardoso et al. 2019). A tendency for drying has been recorded since the mid-20th century (Carvalho et al. 2014). Projections indicate a decrease in precipitation, mainly for spring, summer and autumn (Soares et al. 2017). The mean temperature has been rising since the 1970s and the five warmest years recorded happened after the 1990s (Pereira et al. 2019). Higher maximum temperatures are expected year-round (Andrade et al. 2014), with a more significant increase in summer and autumn. Temperatures above 30 °C and heat waves are likely to happen more often and with greater intensity and length. Portugal's substantial vulnerability to climate change impacts is largely due to rising temperature and heat extremes combined with precipitation decline, which aggravates summer dryness (Cardoso et al. 2019).

The present study is part of a wider research, whose purpose is (i) to quantify the impact of several climate parameters on the degradation evolution of rendered façades, in service conditions, and (ii) to project their future degradation, based on "(i)" and on the respective climate change signal. The paper encompasses part of the study developed in (i), based on a statistical analysis of degradation variables (dependent) and climate variables (independent), concerning temperature, precipitation and wind. The one relative to maximum temperatures is the most associated to the degradation evolution of the rendered façades, thus the focus of the present paper. In addition, it is a relevant parameter in the context of the climate change signal projected for Portugal. The paper is organized according to the following stages of the methodology: degradation evolution of the case studies, in section 2, historical recorded maximum temperatures, in section 3, and statistical analysis of the respective variables, in section 4. In sections 5 and 6, the results and conclusions are presented and discussed.

2 Degradation evolution of rendered façades

2.1 Sample

The sample consists of 26 rendered façades from residential buildings, located in Lisbon, Portugal. These case studies have been subjected to visual inspections, in the context of a previous research on the service life prediction of façade claddings (Gaspar 2009; Gaspar and de Brito, 2011), with the objective of assessing the degradation condition of the external renders.

The date of each façade's fieldwork survey varies between 2005 and 2008. Since then, no maintenance actions have been implemented. New visual inspections have been performed on the claddings, in 2020 and 2021, to determine their current condition and measure the degradation evolution. The age of the case studies at the date of the reinspection ranges between 14 and 62 years. Around 69% are cement renderings, while the majority of the remaining sample is made of mixed cement and lime renderings.

2.2 Severity of degradation: S_w

The original methodology, which is the background to the present study, is based on the overall degradation condition of each rendered façade, defined by the severity of degradation index (S_w). Specific data related to the degradation of the cladding and obtained through visual inspections is necessary to calculate S_w. S_w corresponds to the ratio between the weighted area of observed construction defects and the total area of the cladded façade with the highest degradation level (Equation 1) (Silva et al. 2016).

$$S_w = \frac{\sum(A_n \times k_n \times k_{a,n})}{A \times \sum k} \quad (1)$$

S_w is the severity of degradation, in percentage;
A_n is the area affected by anomaly n, in m^2;
k_n is the multiplication factor for the anomaly n;
$k_{a,n}$ is the weighting coefficient according to the relative weight of the anomaly n;
A the total area of the constructive solution, in m^2;
k is the multiplying factor corresponding to the highest degradation condition of the area A.

The S_w value of all the case studies is then included in a model, which consists of the distribution of these values according to age, to assess the service life of the cladding. The trend reflects the degradation pattern of the respective type of cladding based on the common characteristics of the different façades in the sample, considering their behaviour in real service conditions.

2.3 Degradation evolution rate: $\Delta S_{w,\mathrm{mt}}$

Since the first inspection (Gaspar 2009; Gaspar and de Brito, 2011), 12 to 15 years have passed until the reinspection. A new methodology is developed to determine the degradation evolution of rendered façades, based on the S_w values calculated in two moments apart in time, relative to the recent and past phases of inspection. Each case study has a degradation evolution curve (Figure 1, left) fitting at least the following points: origin (0, 0), S_w at the age of the first inspection and S_w at the age of the reinspection. The resulting equation enables estimating the S_w of the external render at any age. The age of the case studies allows the analysis of the degradation evolution from 1990 to 2020.

The mean triennial degradation rate ($\Delta S_{w,\mathrm{mt}}$) measures the average evolution of S_w within three-year periods, for the whole sample that is active in each period (Equations 2 and 3). The number of active case studies per triennium depends on the respective age. Between 1990 and 2020, 10 triennial periods are considered, starting from 1990-1993. The distribution of the global $\Delta S_{w,\mathrm{mt}}$ is presented in Figure 1, right.

The results (Figure 1, right) show a negative trend. Generally, the degradation evolution of the rendered façades has slowed down since 1990.

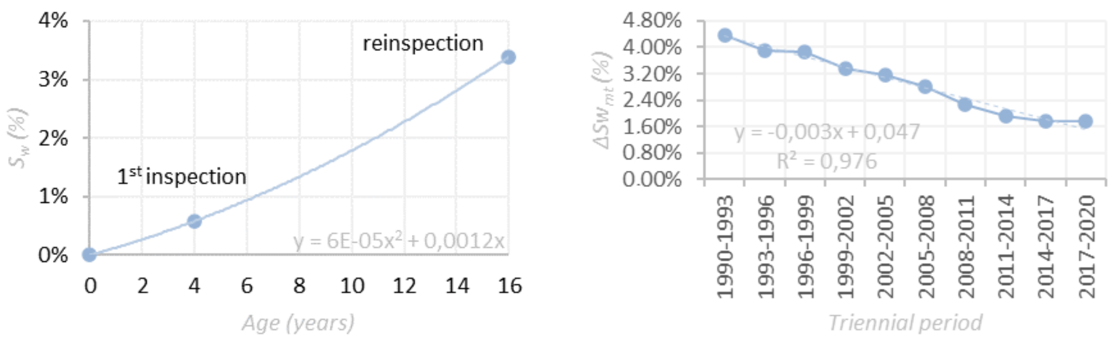

Figure 1. Distribution of the S_w resultant from the first inspection and reinspection of one case study, according to the respective age, with an order 2 polynomial trendline (left) and $\Delta S_{w,mt}$ of the whole sample for the period of 30 years until the reinspection campaign, from 1990 to 2020 (right).

$$\Delta Sw, mt = \frac{\sum_{i=1}^{n}(\Delta Sw, t)}{n} \qquad (2)$$

$\Delta S_{w,mt}$ is the mean triennial degradation rate of the active case studies in the selected triennial period, in percentage;
$\Delta S_{w,t}$ is the triennial degradation rate of an individual case study, in percentage;
n is the number of active case studies for the selected triennial period.

$$\Delta Sw, t = Sw, 2t - Sw, 1t \qquad (3)$$

$\Delta S_{w,t}$ is the triennial degradation rate of an individual case study, in percentage;
$S_{w,2t}$ is the S_w of an individual case study at the most recent year of the selected triennial period, in percentage;
$S_{w,1t}$ is the S_w of an individual case study at the oldest year of the selected triennial period, in percentage.

3 Climate action: Maximum temperature

The historical observed climate data is sourced in the European Climate Assessment and Dataset (ECAD) website (https://www.ecad.eu/) and recorded at the Lisbon's weather station Instituto Geofísico D. Luís. The climate index that concerns maximum temperatures is the mean of daily maximum temperature (TX) (Equation 4).

The historical TX is presented according to the same triennial periods (Figure 2) as $\Delta S_{w,mt}$. The trend is positive, which indicates a tendency for maximum temperatures to increase in the future, in accordance with the climate change signal by the end of the 21st century (Cardoso et al. 2019).

According to ECAD, if TX_{ij} is the maximum temperature at day i of period j, then mean values in period j are given by: (4)

$$TXj = \sum_{i-1}^{I} TXij/I$$

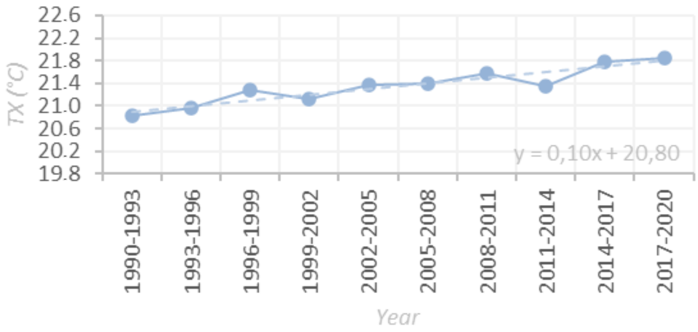

Figure 2. Triennial distribution of historical climate data from the variables TX over the period between 1990 and 2020, with the respective trendline (source Instituto Geofísico D. Luís, Lisbon).

4 Statistical analysis: Pearson correlation coefficient and simple linear regression

The Pearson correlation coefficient (r) measures the linear association between two variables. The strength of the correlation is more significant the closer the r value is to the extremities of its reference scale, which ranges between –1 and 1. Values higher than 0.7 conventionally indicate a strong correlation (Schober et al. 2018). The r resultant from the analysis of the dependent variable $\Delta S_{w,\mathrm{mt}}$ and independent one TX is -0.89, approximately, which indicates a significant correlation.

The scatterplot of both variables is also revealing of their association strength, as the closer the distribution is to a straight line, the stronger the correlation is (Sedgwick 2012). The dispersion of the data in the SLR model of $\Delta S_{w,\mathrm{mt}}$ and TX (Figure 3) is approximately linear. The coefficient of determination (R^2) measures the dependent variable's proportion of variance explained by the independent variable in the model (Zhang 2017). The highest R^2 is 1, which indicates a perfect fit (Chicco et al. 2021) and the higher the R^2, the more robust the model is and the more capable of describing the data (Di Bucchianico 2008). The R^2 of the model (Figure 3) is 0.79, approximately, meaning that the capacity of TX to predict the $\Delta S_{w,\mathrm{mt}}$ is significant.

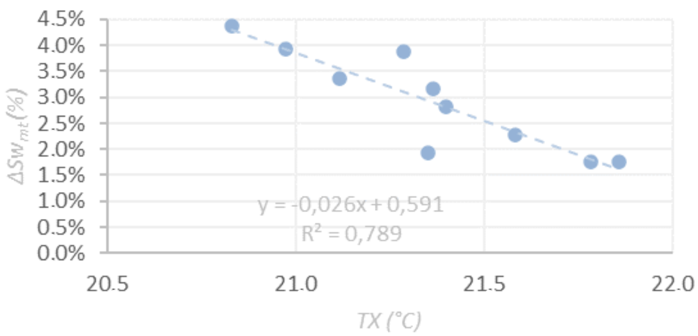

Figure 3. Distribution of the global $\Delta S_{w,\mathrm{mt}}$ according to TX for the triennial periods between 1990 and 2020.

5 Results and discussion

The triennial periods characterized by higher values of TX are associated to less degradation evolution (Figure 3) of the rendered façades, located in Lisbon, Portugal. This suggests that the degradation of rendered façades will tend to decelerate with the future increase in maximum temperatures, indicated by the positive historical trend (Figure 2) and the local projections for the end of the 21st century (Cardoso et al. 2019). The influence of temperature in triggering defects in façade claddings is often associated to fluctuations of temperature and moisture or rain, which affect the hygrothermal behaviour of the materials (Charisi et al 2018; Socoloski et al. 2023). According to the results of the statistical analysis including all the climate variables, part of the wider research where the present study fits, the rise of TX is associated with the decline in the number of wet days between 1990 and 2020. This suggests that precipitation tends to decrease with the increase in maximum temperatures. Renderings will probably be wet less frequently and during shorter periods, due to both more intense temperatures and less precipitation. This can be positive for the durability of renderings, considering that (i) water is one of the main agents causing defects in this type of coating (Almeida et al. 2021) and (ii) moisture, whose main source is wind driven rain, is a significant cause of several types of defects in painted renderings, whether by staining, cracking or loss of adhesion (Socoloski et al. 2023).

The periods in which TX reaches higher levels might be favourable to the coatings' drying, contributing to shorten moister cycles. Therefore, the degradation by staining, which is the most frequent in the case studies, could decline. Superficial moisture on the rendering contributes to the adherence and accumulation of particles and living organisms necessary to the development of dirt stains and biological growth (Pereira et al. 2018). Long wet periods and slow drying contributes not only to the accumulation of dirt and growth of biological organisms, but also to efflorescence (Pereira et al. 2020). Therefore, drier renderings are likely to be less affected by all of these types of stains. In the case of efflorescence, because the dissolution of salts in water is mandatory for this mechanism of degradation to develop (Lubelli et al. 2006).

Theoretically, an increase in temperature could be favourable to several mechanisms of degradation causing cracks and loss of adhesion defects in external renders, as high temperatures could promote: (i) expansion of the rendering and gradients within it (Nenevê et al. 2022), (ii) thermal-induced movements that affect specific building components with consequences to the coating (Gaspar and de Brito 2005; Pereira et al. 2020), (iii) dimensional variations, deformations and stresses of a hygrothermal nature (Varas et al. 2008; Silva et al. 2016; Sandak et al. 2019), (iv) rapid evaporation of water with dissolved salts and subsequent cryptoflorescence, if the water does not reach the surface fast enough so the salts are deposited over it (Kourkoulis 2007; Jia et al. 2019), (v) alkali-aggregate reaction speed and expansion (De Grazia et al. 2021) and (vi) carbonation rate and depth (Drouet et al. 2019). However, a harmful effect of high temperature frequently implies the prior existence of water in the render or the combined action of temperature and water (Barrelas et al. 2023). Therefore, the evolution of degradation due to cracking and loss of adhesion phenomena might be hindered in the context of temperature warming, due to the general expected decrease in precipitation.

6 Conclusions

The $\Delta S_{w,\mathrm{mt}}$ trend is negative, reflecting the deceleration of the rendered façades' degradation evolution since 1990. The capacity of TX to predict $\Delta S_{w,\mathrm{mt}}$ is significant, as is the correlation between variables. The projected increase in maximum temperatures is likely to contribute to slow down the degradation of rendered façades in the future. The combined action of temperature rise with precipitation decline might be relevant to the development of degradation mechanisms causing stains, cracks and loss of adhesion defects. The conclusions of the present research could apply at a regional level, to the areas of the Mediterranean region or Southern Europe where climate trends and projections coincide with those for Portugal. Further research is necessary to project quantitatively the degradation of rendered façades, based on the results of the present study and on the climate change signal for maximum temperatures.

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