CLIMATE-INDUCED CONSERVATION RISKS OF HISTORIC REINFORCED CONCRETE BUILDINGS: PRELIMINARY RESULTS FROM LITERATURE REVIEW

G. Boccacci [1], F. Frasca [2], B. Bartolucci[1], L. Vergelli[1], C. Bertolin [3], A. M. Siani [2]*

[1] Dept. of Earth Sciences, Sapienza University of Rome, Piazzale Aldo Moro 5, 00185 Rome, Italy – (giulia.boccacci, beatrice.bartolucci, lisa.vergelli)@uniroma1.it

[2] Dept. of Physics, Sapienza University of Rome, Piazzale Aldo Moro 5, 00185 Rome, Italy – (f.frasca, annamaria.siani)@uniroma1.it

[3] Dept. of Mechanical and Industrial Engineering, Norwegian University of Science and Technology, Richard Birkelands vei 2B, Gløshaugen, 7491 Trondheim, Norway – chiara.bertolin@ntnu.no

KEY WORDS: Conservation risks, Weathering, Massive structures, Reinforced concrete, Corrosion, Literature review.

ABSTRACT:

Environmental conditions can favour different kinds of deterioration in historic reinforced concrete structures. This preliminary results from literature review are focused on the climate-induced risks affecting reinforced concrete buildings with respect to mechanical, chemical, and biological deterioration. To this purpose, a three-step process defined by the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) flow diagram, was used leading to the inclusion of 45 documents identified via the search engines Scopus and Web of Science. The outcomes highlight that chemical and mechanical decays are the most investigated ones, being mainly triggered by salt weathering and freezing-thawing cycles. It was found that experimental and theoretical approaches are often coupled to estimate climate-induced deterioration mechanisms, also considering environmental parameters. Finally, the literature search provides some milestones which can be used to evaluate gaps and research needs in the field of climate-induced conservative risks affecting reinforced concrete structures.

1. INTRODUCTION

Historic reinforced concrete (HRC) structures built until the first half of the twentieth century include different type of buildings such as churches and museums, but also warlike buildings (i.e., bunkers, fortifications, air-raid shelters, military structures) that have their own significance. These structures have been long characterized by a lack of awareness regarding their heritage value but over the last decades, they have been invested by a new understanding as social, historical, and economic resource, leading to a rising consciousness of the importance of investigating concrete material in the built heritage for its conservation (Figenschau, 2019). Their huge dimensions and massive envelope together with their proximity to urban centres all over Europe, make them unique architectural landmarks and offer the opportunity to repurpose the original intended use, taking advantage of their monumental construction. In recent times, reinforced concrete became widely used as a building material in modern architecture, not only for the construction of buildings but also for roads, bridges, viaducts and various infrastructures, which will not be the subject of this review.

Complex, and various climate-induced degradation risks constantly threaten the durability, visual appearance and structural integrity of concrete and its metal reinforcement (Heinemann, 2013), with a great variability across countries. HRC suffers from weathering due to recurring changes of temperature and relative humidity, exposure to direct precipitation, runoff of moisture, attack of environmental agents, like acid, and salts (Li, 2022). These environmental agents can favour and accelerate degradation processes such as chloride salt attack, freezing-thawing (F-T) cycles, carbonation, alkali-silica reaction (ASR) and sulfation (Ye, 2019). They are in turn responsible for different types of damage in HRC spalling and delamination (often due to salt efflorescence formations), individual cracks, corrosion of reinforcement-rust layers, disintegration of cement matrix, and biological growth (Pardo Redondo et al., 2021). To this purpose non-destructive testing (NDT) techniques and related diagnostic studies are commonly used to determine the cause of damage and to perform repair and restoration actions aimed to enhance the service life of HRC buildings (Sharma et al., 2016).

The main goal of the current review is to depict an overview on different climate-induced degradation risks (i.e., mechanical, chemical, and biological deterioration mechanisms) affecting the damage evolution of reinforced concrete (RC) structures including historic ones, through the studies conducted since their construction and use.

The paper is structured into three sections: following the introduction, the second section (i.e., Methodology) describes the search strategy based on the three-step process that led to the screening of the documents analysed in this review. The third section (i.e., Results and Discussion) highlights the temporal and geographical distribution, subject areas of the research, main research approaches used in literature and their findings. Discussion on the outcomes is here provided. Then, the last section (i.e., Conclusions) evaluates the aspects mentioned above and identifies knowledge gaps and research needs in the field of climate-induced conservative risks affecting reinforced concrete buildings.

2. METHODOLOGY

A first step of the literature review included an exploratory survey to pinpoint the most common climate-induced degradation processes affecting reinforced concrete buildings to extrapolate appropriate keywords for conducting the systematic literature review that was performed using a three-step process following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) flow diagram (Page et al. 2021). The PRISMA has allowed to organize the collection and identification of relevant scientific records to be included in the analysis and review processes. The methodology conducted for the research topic is summarized in Figure 1.

* Corresponding author

2.1 Exploratory survey for keywords detection

The exploratory survey was carried out in order to detect useful keyword combinations to be subsequently used in the PRISMA literature review. This survey was conducted through the Scopus database (Elsevier, The Netherlands) by searching useful documents for the definition of the degradation mechanisms caused by environmental agents which can threaten the preservation of HRC structures. The research was performed with 4 keyword combinations using the Boolean operator "AND": (1) "weathering" AND "reinforced concrete" AND "building"; (2) "weathering" AND "reinforced concrete" AND "review"; (3) "decay" AND "reinforced concrete" AND "building"; (4) "decay" AND "reinforced concrete" AND "review". The publications thus obtained were filtered, in order to obtain a total of 23 documents which were the most inherent to the topic of climate-induced degradation mechanisms on reinforced concrete structures. Consultation of these documents allowed the most frequently used terminology in this field to be determined, and thus enabled the identification of the most effective keyword combinations to be used in order to conduct the literature review.

2.2 PRISMA: Identification step

The PRISMA method includes the following three-step process: 1) Identification, 2) Screening and 3) Inclusion.
The identification of the proper literature was conducted using the two databases of Scopus and Web of Science involving the combinations of the optimal detected keywords. In Scopus, the search was performed for the fields "Article title, Abstract and Keyword". Similarly, in Web of Science the search field "Topic" was selected, meaning Title, Abstract, Author keywords and Keyword plus. This search included all documents in the databases through the end of February 2023. The combination of search words was organized in 7 search strings where the terms have been connected using the Boolean operators "AND" and "OR". The keyword combinations used are reported in Table 1. The search initially yielded to a total of 1776 records; successively, the group was further reduced by excluding those documents that (i) where not journal articles or conference articles or book contributions, (ii) were not available online (iii) were not written in English. After that, 242 duplicates were removed, bringing the total to 920 documents.

Research	Keyword combinations
1	carbonation AND reinforced concrete AND building
2	chloride attack AND reinforced concrete AND building
3	(sulphate OR sulfate) AND Reinforced concrete AND building
4	corrosion AND salt weathering AND reinforced concrete
5	alkali-silica reaction AND reinforced concrete AND building
6	(thermal effect OR thermal expansion) AND reinforced concrete AND building
7	(freeze-thaw OR froze weathering) AND reinforced concrete AND building

Table 1. Search strings of keyword combinations used in the PRISMA Identification step.

2.3 PRISMA: Screening and Inclusion steps

Second phase of screening step included the reading of title and abstract in 920 documents.

Articles "out of topic" were excluded as they dealt with the following topics:

- Type of concretes containing fibres as reinforcement (i.e., steel fiber-reinforced concrete (SFRC), glass fiber-reinforced concrete (GFRC), polypropylene fiber-reinforced concrete (PFRC), carbon fiber-reinforced concrete (CFRC), nylon fiber-reinforced concrete (NFRC), etc.).
- Concrete infrastructures others than buildings (aqueducts, viaducts, bridges, railway, highway, nuclear power reactor facilities, missile launch structures).
- Very modern concrete structures (<20 years, built with very modern type of concretes).
- Restoration/repairing methodologies such as those implemented for corrosion resistance enhancement (i.e., use of corrosion inhibitors, recycled plastics, recycled aggregate concrete, anti-carbonation surface coatings, mineral additive, hydrophobic concrete coatings, etc.).
- Post-repair evaluations, both superficial and structural (i.e., resistance evaluation of repaired/treated concrete to decay mechanisms).
- Fire/earthquakes damaged structures performance evaluation (i.e., occurrence of multiple hazards in extreme conditions and extreme scenarios).
- Effect of thermal insulation (energy efficiency of a concrete building).
- Papers particularly focused on the effectiveness of specific techniques or development of new techniques for reinforced concrete structures condition monitoring.

This step led to exclude 795 documents. The remaining documents were further screened by removing those documents which did not focus on the weathering action due to wind, UV radiation or recurring changes of temperature and relative humidity. Consequently, 80 publications were discarded, while 45 publications were finally selected for inclusion; among them, 40 journal articles, 4 conference papers and 1 book contribution.

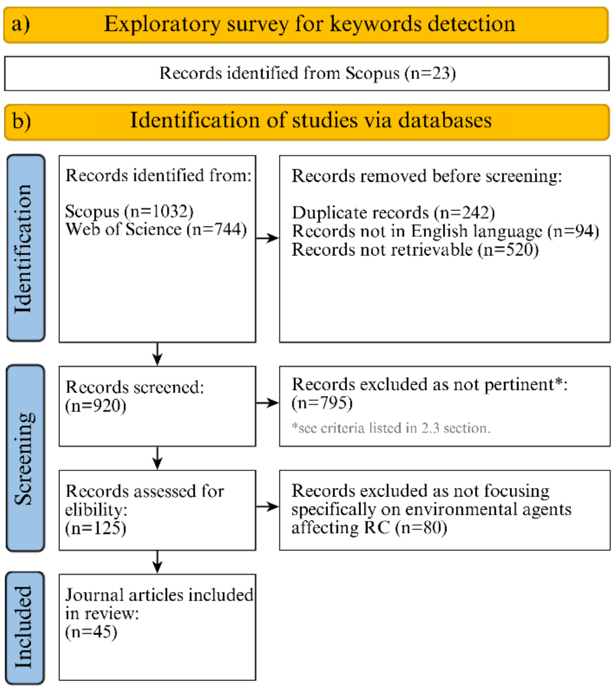

Figure 1. Prisma flow diagram for systematic reviews (b) showing the number of documents selected after each step.

The exploratory survey for identifying the optimal keywords (a) is previous and out of the Prisma process.

3. RESULTS AND DISCUSSION

3.1 Temporal and geographical distribution

Figure 2 shows the temporal evolution of the studies conducted on the climate-induced mechanism affecting RC buildings. It can be noticed that the interest on this is topic tends to increase only in recent years, although the number of research works is still not high.

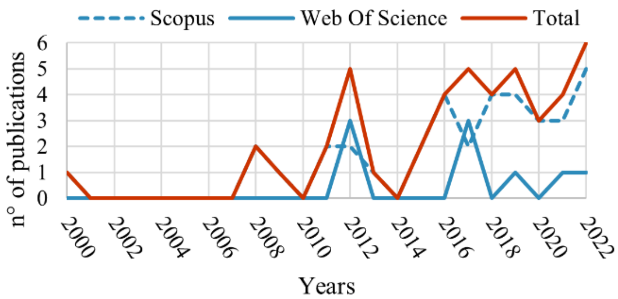

Figure 2. Distribution of documents by year of publication.

By looking at the first authors' affiliation of the papers it was found that 47% of the research works were conducted in the Asian continent, 22% in Europe, 18% in North America followed by Africa, South America and Oceania. In fact, Chinese research groups had the highest number of publications on the subject (12 papers), followed by France (6 papers) and Canada (5 papers).

3.2 Subject areas of the research

In Figure 3 the expertise of both the first and last authors of each document are reported, demonstrating that the field was poorly characterized by interdisciplinarity among researchers. In fact, the authors were mainly involved in Engineering studies (82%), then in Material Science studies (17%) and only 1% of researchers were involved in Earth and Planetary Science studies.

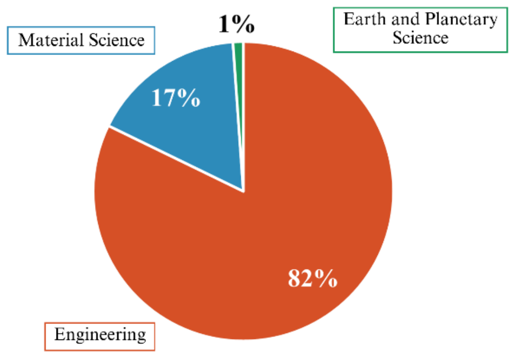

Figure 3. Percentage of subject areas of expertise of first and last authors representing their research field and cultural background.

The subject areas of the journals in which this type of research was published, were mainly related to the field of "Civil Engineering", "Material Science" and "Construction and Building Technology", being *Construction and Building Materials*, *Engineering Structures*, *Structure* and *Cement and Concrete Research* (all by Elsevier) the four journals with the highest number of published documents for each (considering all the 45 records).

3.3 Type of research approach in the publications

All the 45 records were analysed in terms of the type of research approach they used. Figure 4 reports the number of publications according to the type of research approach. It can be noticed that most of the documents presented a "mixed" approach (n=21) both theoretical and experimental (e.g., formulation/review of prediction models for reinforced-concrete deterioration processes and subsequent experimental verification). In 10 cases out of 21 the experimental verification was conducted thanks to data already available in the published literature; in the remaining 11 cases the models were instead validated based on new data acquired in the same investigation. In this latter instance, 5 records performed laboratory tests on samples extracted from existing buildings (real cases), 3 records performed laboratory tests on experimental materials (i.e., reinforced concrete specimens specially created) and 3 records reported data from *in situ* monitoring on real cases. In some documents (8 cases) the approach was defined to be "absolute" i.e., exclusively theoretical, while it was exclusively experimental in 15 cases. When only experimental, the documents can be divided into those conducting in laboratory tests (n=11) and those carrying out *in situ* monitoring (n=1), while 3 records reported them both. Going into more details, laboratory tests were performed on samples extracted from real buildings in 5 cases and in the remaining 9 cases they were performed on experimental materials specifically created. Finally, only one document was found to have a review approach.

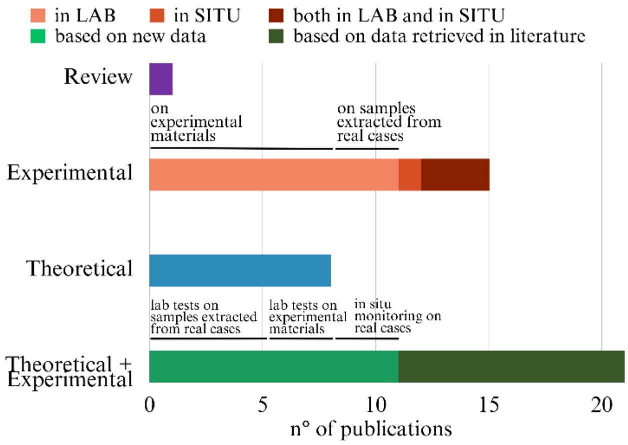

Figure 4. Number of publications according to the type of research approach.

3.3.1 Experimental approach: Experimental approach was carried out through laboratory tests on samples (directly acquired from real case-studies as well as experimentally created), and through *in situ* monitoring to obtain information on the current state of the aging structure or on its levels of decay. Analysis conducted in laboratories on reinforced concrete samples can be approximately divided into four main categories named "Chemical", "Mechanical", "Physical" and "Electrochemical" according to their working principle.

Figure 5 reports the percentage of the type of analysis (almost completely destructive) carried out in the revised articles that performed lab experimental testing. Chemical tests resulted to be the most frequently used, being the phenolphthalein indicator method for carbonation depth assessment the most exploited one, followed by mechanical analysis mainly consisting in compressive strength measurements and static loading tests, and by physical (i.e., Mercury Intrusion Porosimetry MIP , Scanning Electron Microscope SEM, Thermogravimetric Analysis TGA, Powder X-Ray Diffraction XRD, bulk X-Ray powder diffraction

XRPD, Raman Spectroscopy and Differential Thermal Analysis DTA) and electrochemical (i.e., half-cell potential measurements and corrosion rate measurements through potentiostat) tests.

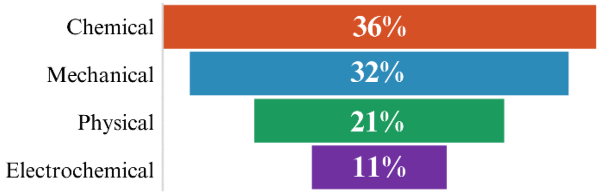

Figure 5. Percentage of the type of analysis (chemical, physical, mechanical, or electrochemical) carried out in the papers conducting experimental approaches.

It is worth noticing that among the laboratory experiments only in 13 cases both RC samples extracted from real cases and those specifically created, were subjected to pre- or ongoing experimental settings. Examples of pre- or ongoing conditioning consisted in samples' acclimatisation at some temperature (T) and relative humidity (RH) conditions in climate chamber (Hussain et al. 2011, Yuan et al. 2012), accelerated carbonation in carbonate chamber (He et al. 2022, Cheng et al. 2021, Elsalamawy et al. 2019, Ghantous et al. 2017), raining-drying cycles simulations in custom rain chamber (Ghantous et al. 2017), wetting-drying cycles simulations with artificial seawater in curing pool (Hussain et al. 2011) and freezing-thawing cycles simulations in temperature-controlled chamber (Wang et al. 2019, Ma et al. 2016, Diao et al. 2011, Sha et al. 2012).

A minor number of documents employed an experimental approach by performing *in situ* monitoring directly on different zones of RC real buildings across different countries. Table 2 shows the parameters monitored through NDT techniques (semi-destructive only in few cases), and the surveyed/tested zones in RC buildings (bibliographic references are also reported). Monitored variables were both material and environmental related factors detected by different types of probes located mainly in proximity of contaminated RC zones (i.e., surfaces affected by delamination and spalling or visible rebar corrosion). Outdoor exposed walls appeared to be the most monitored areas together with outdoor columns followed by façades and balconies that were monitored just in one instance. In some cases, comparisons were made between outdoor and indoor walls (Crevello et al., 2019) or between outdoor exposed walls and outdoor protected walls (Hadja et al. 2017) to study the different effects on the structural properties of the buildings. Environmental factors (such as air temperature, seawater temperature, relative humidity, amount of wind-driven rain, amount of direct solar radiation) were directly monitored only in 3 cases out of 9, while in other 2 documents investigations were carried out by using climate data coming from other sources (as explained in the bottom of Table 2). The case-studies were represented mainly by residential or public buildings and in only 2 cases by "historical" and "historic" buildings respectively (Marie-Victoire et al. 2012, Crevello et al, 2019). Locations of case-studies were various (China, United States, Finland, Portugal, France, Mexico and Algeria) with different types of climates ranging from tropical to subarctic. It is interesting to note that, among the reasons generally reported as driving this type of investigation, there were the desire to perform durability and serviceability assessments, as well as to estimate remaining service lives of buildings. Secondarily, the minimization of maintenance costs for RC structures placed in contaminated environments, was also a driving motivation.

Ref	Monitored parameters	Monitored zones
Gu et al. 2022	Cover thickness Carbonation depth Corrosion condition Cracking condition	Outdoor columns
Crevello et al. 2019	Relative humidity Temperature Corrosion rate	Outdoor and indoor walls
Köliö et al. 2017	Relative humidity Temperature Amount of wind-driven rain Amount of direct solar radiation	Façades and balconies
Marie-Victoire et al. 2012	Corrosion rate Resistivity Polarization resistance	Outdoor walls
Castro et al. 2000	Resistivity	Outdoor columns
Iskander et al. 2012	Expansion joint displacement Temperature	Outdoor walls
Bastidas-Arteaga et al. 2022	Air temperature Relative humidity Pressure	*Other
Hadja et al. 2017	Compressive strength	Outdoor protected wall and outdoor exposed wall
Nguyen et al. 2017	Air temperature Seawater temperature Relative humidity	*Other

**Investigations carried out using climate data not directly collected in proximity of RC structures. First case: ERA5-LAND reanalysis (with a spatial resolution of about 9 km). Second case: by Mèteo France weather station (from instrumented sites located inland and, on the seashore).*

Table 2. Monitored parameters and monitored zones in the real case-studies analysed by the selected documents dealing with experimental approach carried out through *in situ* monitoring (the corresponding bibliographic reference is reported in the first column).

3.3.2 Theoretical approach: Among the 45 articles here included, some used exclusively a theoretical approach (*n*=8), while others used a mixed approach (*n*=21). The latter one mainly consisted in the formulation (or revision or updating) of predictive models for the estimation of the onset and progression of degradation mechanisms, and their subsequent validation through experimentally collected data.

In the present review, models were considered and evaluated only when including environmental factors possibly influencing reinforced concrete deterioration. The main environmental parameters that, in addition to the material ones (such as concrete permeability, water/cement ratio in concrete, degree of cement hydration, etc.), were mostly considered in the formulation of predictive models were temperature and relative humidity (both together and individually), contribution of solar radiation, atmospheric CO_2 concentration and precipitation. Figure 6 summarizes the information regarding the main categories of predictive models found in the revised documents. 39% of cases dealt with carbonation-induced deterioration models above all for the estimation of carbonation depth (Chen et al. 2021, Gopal et al. 2020, Elsalamawy et al. 2019, Mizzi et al. 2018, Li et al. 2018, Bastidas-Arteaga et al. 2022), but also carbonation diffusion coefficient (Liu et al. 2022, Peng et al. 2016, Gorga et al. 2018), and carbonation rate (Ekolu et al. 2020, Hwang et al. 2020). Chloride-induced deterioration models followed with 18%, again including prediction models dealing with both chloride ingress (Bastidas-Arteaga et al. 2016, Nguyen et al. 2017) and chloride diffusion (Shen et al. 2019, Damrongwiriyanupap et al. 2015, Alsheet et al. 2018). Alkali silica reaction (ASR) -induced deterioration models were explored in 11% of cases (Gorga et al. 2022, Vo et al. 2021, Gorga et al. 2018), as well as corrosion initiation (Gu et al. 2022, Hussain et al. 2011) and corrosion rate (Saura-Gómez et al. 2022) prediction models. Finally, others less frequent theoretical approaches (one per each document), attempted to perform mathematical formulation and calculation models for service life assessment (Köliö et al. 2017), climate load (Yuan et al. 2012), temperature change effect (Reem et al. 2017), apparent coefficient of concrete thermal expansion (Iskander et al. 2012), multi-chemo-physics model for the triple coupling of ASR, steel corrosion and freeze-thaw cycles (Gong et al. 2019) and for short-term stiffness in concrete subjected to freeze-thaw cycles (Sha et al. 2012).

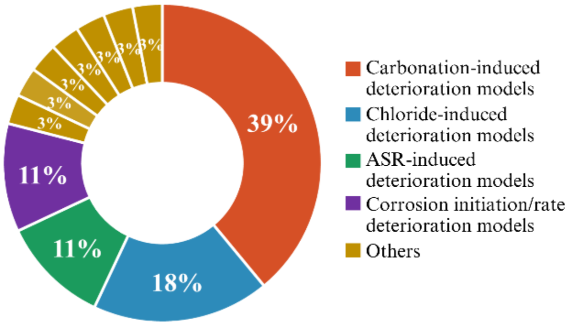

Figure 6. Percentage of type of prediction models formulated, updated, or revised in the selected documents.

3.4 Climate-induced deterioration on RC buildings in the publications

From the analysis of the 45 articles included in this literature review, it emerged that the type of most investigated decay by the authors (from the point of view of climate-induced deterioration processes) was that of chemical degradation (69% of occurrences) followed by the mechanical one (31%). Biological degradation was not addressed in any document. It is important to bear in mind that one document may have explored both chemical and mechanical decay, and that one specific climate-induced deterioration process (such as salts weathering), could have led to both chemical and mechanical pathological manifestations in RC material. Figure 7 reports the percentage of most investigated climate-induced mechanisms causing chemical (orange line) and mechanical (blue line) decay on RC buildings, according to the revised literature. It is clearly visible how both chemical and mechanical decays were reported to be mainly triggered by salts weathering processes (85% and 29% respectively). In fact, soluble salts such as chloride, carbonate, sulphate and phosphate from groundwater, damp soil or sea can be transported in solution through the pores and capillaries of concrete; moisture evaporation causes salts to crystallize and exert pressure on the surrounding concrete causing cracks initiation. At the same time, their attacks are major situations where reinforcement corrosion can occur (Chemrouk, 2015). Freezing-thawing cycles represent a threat especially for mechanical deterioration (24%) as the frozen of pore solution creates internal pressure in pores and led to mechanical damage of concrete; but also, in less cases for the chemical one (6%) because generation of new cracks into the material provides new penetration path for water and salts into concrete (Wang et al., 2019). Chemical degradation is found to be explored in the documents also by studying drying-wetting cycles (4% of cases), and rainwater erosion and thermal effect in very few cases (both 2% of cases). Immediately following the salts weathering and freezing-thawing cycles, the two climate-induced mechanisms most responsible for the mechanical damage in RC were the thermal effect and the alkali silica reaction (both 19% of cases). The former in fact being represented by daily and seasonal fluctuations in temperature as well as by direct heating from the sun, can cause overall structural deformation, displacements, and stresses in concrete elements (Reem et al., 2017). The latter is an endogenous chemical reaction between “unstable” silica mineral forms within the aggregates and the alkali hydroxides dissolved in the concrete pore solution. The reaction generates a secondary product, the alkali silica gel that induces expansive pressures within the reacting aggregate material and the adjacent cement paste. Generated stresses can cause microcracking and reduction of the mechanical material properties (Gorga et al., 2018). Moreover, rainwater erosion and drying-wetting cycles were reported to cause mechanical decay in few cases (both 5%). As salts weathering was found to be the climate-induced degradation mechanism most responsible for both chemical and mechanical decays, different type of salts attacks can be distinguished. Those performed by carbonates, chlorides, sulphates, or phosphate were more studied in the revised literature in relation to RC building damage.

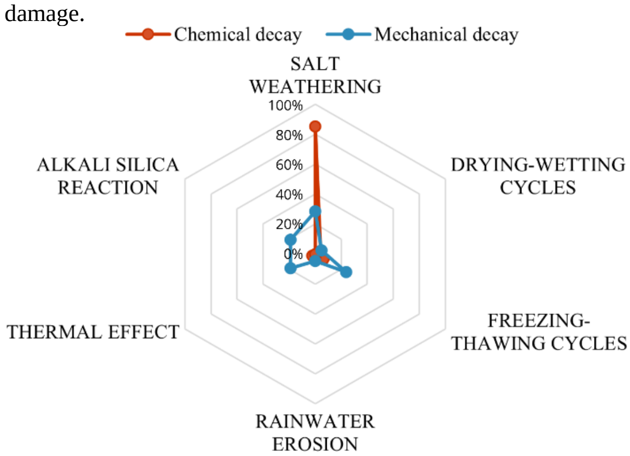

Figure 7. Percentage of most investigated climate-induced mechanisms causing chemical and mechanical decay on reinforced concrete buildings.

3.5 Conservative risks under changing climate

Global changes in terms of carbon dioxide concentration, temperature, and humidity associated to the ongoing climate change, could potentially led to the intensification (and acceleration) in the degradation processes of building materials, affecting their durability and service life. It is worth noticing that only 6 records out of 45, considered future climate change scenarios in the evaluation of climate-induced damage mechanisms on RC buildings. The above-mentioned documents were published in recent years, specifically in 2016 (*n*=2), 2017 (*n*=1), 2018 (*n*=1), 2021 (*n*=1) and 2022 (*n*=1), reflecting a growing interest of the scientific community in integrating climate change mitigation and adaptation measures in the field of conservation. Only one record focused on the assessment of the costs and benefits of one type of climate adaptation measure for existing RC buildings subjected to chloride ingress and climate change (Bastidas-Arteaga et al. 2016). The remaining 5 documents instead, investigated the potential future impacts of climate change on the durability and damage risks on RC structures.

Specifically, Talukdar et al. (2016) proposed an updated empirical model to predict the diffusion coefficient of carbon dioxide in concrete under changing climate in buildings located in United States, based upon two *representative concentration pathways* (RCPs) scenarios (RCP 4.5 and RCP 8.5) proposed by the Intergovernmental Panel on Climate Change (IPCC, 2013) fifth assessment. Climate change impacts on the durability and damage risks on reinforced concrete structures located in Chinese cities were investigated by Peng et al. (2016), and then by Chen et al. (2021) both of whom considered RCP 2.6 and RCP 8.5 representing high and low carbon emission scenarios respectively. These kinds of investigations were carried out on European case-studies too, by Mizzi et al. (2018) who explored the effects of future climate projections (RCP 2.6 and 8.5) on RC structures in Malta; and by Bastidas-Arteaga et al. (2022) who proposed an approach for multi-region assessment of carbonation in RC buildings under changing climate in three different Portuguese regions under three emission scenarios (i.e., RCP 2.6 – RCP 4.5 – RCP 8.5).

4. CONCLUSIONS

Preliminary results from literature review describe the state of knowledge of climate-induced deterioration mechanisms affecting the conservation of reinforced concrete buildings. Based on the outcomes of this review we can trace the main findings and what is still missing and less addressed. The main conclusions can be drawn as follows:

4.1 Types of approach in investigating climate-induced risks on RC buildings

The type of approach in investigating climate-induced risks on RC buildings was found to be "mixed" between experimental and theoretical in most of the cases.

- When experimental, chemical analysis (especially phenolphthalein indicator method for carbonation depth assessment) resulted to be the most frequent test used in the laboratory to evaluate RC samples (both mock-ups and specimens directly extracted from real-case studies), followed by mechanical analysis (especially compressive strength measurements). Moreover, pre- and ongoing conditioning of samples was mainly performed through the use of climate chambers, carbonation chambers and curing pools. No *in situ* indoor monitoring was conducted by any of the studies here included, to assess the existing risk affecting the inner part of RC building envelopes. *In situ* monitoring were mainly performed on outdoor walls and columns and only in few cases comparisons were made with more protected zones. Motivations driving this type of research were the desire to perform durability and serviceability assessment as well as that of minimizing maintenance costs.
- When theoretical, the approach mainly consisted in the formulation and revision of carbonation-induced deterioration models, followed by chloride-induced deterioration models, and subsequent by experimental verification both through the acquisition of new experimental data and/or of data already available in literature. Major environmental parameters considered in the formulation of prediction models, in addition to the material ones, were temperature, relative humidity, solar radiation and precipitation.

4.2 Types of climate-induced investigated decays affecting RC buildings

Chemical followed by mechanical climate-induced decays were found to be the most investigated in relation to RC buildings (while biological decay was not addressed by any document), and mainly triggered by the climate-induced mechanism of salts weathering, followed by freezing-thawing cycles. Generally, the exploration of coupling effects between different type of climate-induced deterioration process is found to be very important.
Finally, historic reinforced concrete buildings were poorly monitored and, conversely, the case-studies concerned almost exclusively public or residential buildings. Moreover, a growing body of literature is investigating conservative risks also considering different future climate change scenarios, to enhance risk awareness related to RC buildings' preservation under changing climate and to propose possible adaptation actions to extend their service life.

Further works in this area should be addressed to:

- Investigate historic buildings in the framework of built heritage. In fact – for new/recent buildings – the effectiveness of these experimental and theoretical approaches in concrete durability and decay assessment has widely been demonstrated and such knowledge could be applied to HRC too.
- Expand databases of suitable in-situ data (both outdoors and indoors) so that a reasonable and comprehensive evaluation of laboratory test-based deterioration models and their accuracy, can be validated.
- Fill the gap highlighted in past years, about the lack of experimental data for chloride penetration into concrete.
- Continue performing both experimental and theoretical research (i.e., more advanced prediction models) on the impact of different synergistic deterioration mechanisms on RC buildings to assess their durability and need of maintenance.
- Study the long-term effect of climate change on reinforced-concrete durability in different countries and climate zones, also considering several adaptation strategies to achieve long-term conservation of HRC structures.

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