A Critical Review on Durability of Sustainable Materials and Structures

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Abstract. This paper presents a critical review of the state-of-the-art on the context of sustainable renovation of buildings and infrastructures. After a short presentation of the method and the context of the study a chronological description is used to evocate the principal fields of research and engineering practices for design of sustainable and durable materials and structures, and for evaluation of the damage state materials and structures. The new trends on the durability of materials and structures developed or reinforced in a context of increasing societal requirements in terms of sustainability are treated along with traditional mechanistic approaches such as mechanics of failure, mechanics of damage, fatigue, environmental impact on the durability including thermal, hydric and chemical interactions. In particular, some technics used for the diagnostic of historical stone buildings are cited as an example of research/engineering practice on the durability of structures and materials. The new trends on sustainable materials design and their industrial use, including the green materials, bio-resourced materials for construction and insulation of buildings, recycled materials from buildings and infrastructures are evocated in conclusion.

Keywords: Durability · Life long · Cracking · Damage · Renovation · Environmental interaction · Green materials · Recycling

1 Introduction

In the framework of ERASMUS + program KA2 – HIGHER EDUCATION STRATEGIC PARTNERSHIP entitled "Rehabilitation of the Built Environment in the Context of Smart City and Sustainable Development Concepts for Knowledge Transfer and Lifelong Learning" (RE-BUILT), this study aims to give a state of art and an analytical review of existing written resources mapping the knowledge triangle transfer on sustainable rehabilitation of built environment, more specifically in the field of durability of materials and structures. The durability of materials and structures as a research topic is at the same time an old trend and a new dynamic field of technical and scientific research. Nowadays, this old research topic is placed in the framework of sustainable development of society and is seen more and more not as a simple technical issue but also as an economic and environmental one. The main objectives of this work are to:

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1. Analyze, describe and establish where necessary the place of durability in the general framework of sustainability
2. Give an updated vision of bases of the durability of materials and structures beyond the mechanical damage and ageing of structures, stability and failure
3. Picturing the new trends on durable and sustainable materials for construction and renovation of infrastructures
4. Presenting new trends and emerging technics on monitoring, evaluation of service state of infrastructures, estimation of the life-time of infrastructures, renovation of infrastructures, preservation and restoration of historical buildings.

The methodology used for this work is a critical analysis of the abundant literature on the durability of construction materials and structures, beginning with general overview articles on each domain. Nowadays, modern approaches place the durability of materials and structures in the framework of a holistic approach to sustainability. Consequently, this review treats the problem in this framework including the sustainability of residential buildings, construction materials, new methods of monitoring and assessment of service state, design of new materials, conservation and restoration of historical buildings and life cycle assessment. The historical review of the durability is used in the first part of this study to explain the dominant material-based works in durability (durability of stones, concretes, steels, woods). While the most of this review is based on the literature analyses, two particular points: bio-sourced new materials and holistic approach in conservation and restoration of stone's historical buildings are treated more in local bases since they constitute some of the principal research themes of the authors of this document. The durability is a research and a technological field with a reach history; to establish a concise document and yet a full critical review (as much as possible), our literature research was concentrated on the scientific literature databases: Scopus, Web of Sciences, ScienceDirect as well as other peer-reviewed publications (conference/congress proceedings, open access referenced journals). In the same time, the normative materials (Eurocodes, Technical documents or guidelines) known and used by construction industry have been consulted in their online version from AFNOR (French Agency for NORmalization https://www.afnor.org/) but the English references are cited. And finally, some worldwide known websites with scientific, technical or social contents were consulted and cited here. Most of the time the English resources are selected and analyzed, even if the original works could be in other languages (few French documents are exceptions of this rule). While many aspects of durability will be discussed in details in this document, the sustainability questions are only present in its first part. A good initial point for sustainability-related literature would be these, always up-to-date, web sites https://sustainabledevelopment.un.org and http://www.fondation-2019.fr that authors suggest to the interested reader.

2 Durability Versus Sustainability, Place of Durability in Sustainable Development

While the word "durability" is simple to use, the concept of durability is often more difficult to define [1, 10], and different authors might not mean the same thing when using the same word. Misused sometimes in everyday language as a synonym to the "sustainability" the durability concept is limited to only the longevity of a given product, its ability to remain functional (without excessive maintenance), under normal conditions of use, i.e. the conditions it has been designed for.

When dealing with sustainability two approaches are distinguished: "the weak sustainability" postulates the full substitutability of natural capital whereas the strong conception demonstrates that this substitutability should be severely limited due to the existence of critical elements that natural capital provides for human existence and well-being" [1, 2]. It is clear however that, whatever weak or strong sustainability is adopted, it involves three aspects: economic, social and environmental. It promotes an approach of social development at present such that any of these three dimensions is not compromised for the next generations. Since 1990, Daly [6] defined the criterion for an economic or material flux to be considered as sustainable:

- The consumption rate of renewable resources should not exceed the rate of regeneration of these same resources
- The consumption rate of non-renewable resources should not exceed the rate of developing renewable resources that could substitute these resources
- The rate of pollution issued by the use of any resources should not exceed the capacity of the nature to assimilate this pollution.

This vision of sustainable development implies in particular that the longevity (durability) of materials and structures should match these economic and environmental exigencies. The way this matching could be done, the tools and methods for evaluation of the ability of an infrastructure to satisfy the objectives it is constructed for, the technics to protect or to extend the life of structures, to renovate them are some central topics on durability.

The main topic on durability in Civil Engineering has been, for longtime, design and selection of durable constructive materials (i.e. constructive materials that could assure mechanical stability of civil engineering structures). With time, and because of recent economic challenges, the domain of interest of durability in civil engineering has continuously enlarged and enriched including nowadays various fields such as building physics and hygrothermal behavior of construction materials, durability approach for historical and old buildings, service life prediction methodologies based on big-data analyses. [122, 123]. There is not only a natural extension of the topics covered by the durability but also a shift of the principal domain of research. At least two major societal facts have conditioned this shifting:

Firstly, the increasing pressure from civil society to minimize the anthropic impact on nature. Having long-life materials or structures is not anymore sufficient, the mechanical stability of infrastructure is not anymore the only, neither the principal criterion of limit design approach and life service prediction of structures. Well-being, thermal comfort, air quality, health impact become major criteria for building design in the top of mechanical stability [11, 12]. Consequently, the life of a building is not anymore equivalent to its mechanical life and durability science is now opened to the physics of buildings and complex thermo-hydro-mechanical coupled processes that it is governed by.

Secondly, the massive development of numerical technologies (ongoing numerical revolution) leads to cloud-connected databases and relevant numerical technics for their treatment. In particular, BIM technology and Artificial Intelligence appear today as unavoidable and very powerful tools in analyzing complex situations in diagnostic, monitoring and renovation [13–15]. An important feature on recent developments in the field that has been possible due to the extensive use of numerical tools is the interoperability among technical concepts of durability and other concepts of sustainability: specific tools are developed to give the durability its place in general framework of sustainability including in the assessment of performance of materials and/or structures also the capacity to be recycled and the possibility of resource renovation [5, 14, 16].

3 Advanced Durability on the Frame of Sustainability: Brief Historical Review of Fundamentals of Durability and Recent Trends

While the estimation of the duration of the life of structures has always been a question raised from constructors and users of all times from the very beginning of the history of humanity (when the man moves from occasional shelters and caverns towards permanent habitations), The answer has progressively evolved and modernized. During historical times, this answer was given in terms of techniques and construction materials that procured to buildings (castles, religious construction, artworks) and infrastructures (mainly bridges and roads) the longest life possible. Some of the most famous constructions that went through history are here witnesses of human genius to capitalize the experience cumulated by generations even though a scientific response of the whole problem is yet to be found. In the earlier works, the durability of structures (and materials constituting these structures) was posed as a simple question of the lifetime of a damaged structure before its (mechanical) failure. A damaged structure/material in this context was just a structure/material with (mechanical) degraded properties as compared to the properties of a healthy state of this same structure/material [25, 26]. The origins of durability science are closely linked to those of failure mechanics whose bases were founded with studies on crack growth and failure of structures performed in the early 20th century, by Inglis and the theories for crack propagation by Griffith and Irwin [30, 31, 33]. Moving away from classical mechanical design approach considering that the failure of a structure comes as soon as the applied stress is higher than limit stress identified in the laboratory, these works introduced an energetical approach establishing the conditions for which a defect in a material could lead to unstable crack propagation in brittle materials. The stress intensity factor (SIF) and the critical stress intensity (K_{IC}, known also as an intrinsic property of a material called toughness or tenacity) become tools for life length estimation and risk failure assessment of structures.

The crack propagation researches on brittle materials were gradually adopted, adapted and extended to other classes of materials (ductile, heterogenous, fibrous, composite materials), in various loading conditions (various modes of crack propagation, modes I, II, and III as well as mixed modes) including, in fine, the effect of the structure (characteristic length of the structure) on the rate of crack growth [31]. The phenomenon of subcritical crack growth, extensively studied from the middle of the last century, with the works of Paris, Atkinson and many other researchers makes it possible to understand and explain the failure of structures under loads lower than critical ones, when these loads are maintained for some periods of times [34, 35]. Fatigue, crack evolution, and failure due to cyclic loadings even under lower stresses as compared to yield stress of materials, were studied almost at the same time than the subcritical crack growth. The well-known theory of fatigue developed by Paris [36] and various other models/theories developed since then have definitely transformed the design approach not only on the mechanical industry but above all, the approach design of civil structures. Remarkably, research works in the field have demonstrated the notable impact of environmental conditions on the rate of crack propagation constituting the bridges with new research domains: thermo poromechanics, multiphysics coupling, design of composite materials, nanomaterials, additives, and so on (see Sect. 4).

The intensive use of man-manufactured materials in constructions such as various metallic materials (steel and aluminium for example just to mention the most widespread among them), concretes, composite materials and so on, brought the question of the durability of materials and structures in the domain of material conception and reuse: how to design the structure and microstructure of material in order to fulfil specific requirements in terms not only of the mechanical stability of structures but also, more and more in terms of comfort, economy, ecological footprint and reuse. In the practice of civil infrastructures and building design the limit design approach includes norms for both Serviceability Limit State (SLS) and Ultimate Limit State (ULS) [37, 42]. It was widely accepted that the long-term behavior of structures is closely related to the time-dependent behavior of materials constituting the structure (they could manifest a brittle or a viscous behavior depending on the micro-mechanisms governing at microstructure level), their interaction with the environment and the conditions of use. For years now, the studies in durability are mostly material-driven: worldwide scientific and technological networks deal with the durability of concrete [39], steel [56], stones [55].

Nowadays, the durability of materials and structures is an everyday-evolution-perimeter field of scientific research and engineering applications with complex interactions to many other scientific and technical disciplines such that it could be, first of all, defined as a multidisciplinary activity. Among modern trends on durability, one could point out the most dynamic ones that shape the nowadays image of scientific and technological research and covers the whole life of a structure from its design to its recycling:

– Design of green, high performant, locally adapted, recycled, bio-sourced, low carbon new materials as a response to the rarefication of raw materials, climate change and social worldwide promotion. From the durability point of view, these materials reveal a double challenge: in one hand, that of technics for the assessment of the durability of these non-conventional materials and, on the other hand, that of long-term compatibility of these materials with traditional materials co-used in construction. [7, 10–12, 19–21, 53, 54]
– Developing of modern technics for continuously, in the field, monitoring of materials and structures state evolution, for durability assessment and maintenance of buildings,

expert systems for structural, thermal, hygrothermal and aeraulic evaluation, numerical technics for restoration and retrofitting including artificial intelligence (AI) [10, 11, 20, 44, 48, 50–52].

– Holistic approaches in design, maintenance, restoration, reuse of materials for buildings and infrastructures. While infrastructures and buildings are seen as essential for mankind, they have an impact and contribute to environmental degradation, including air, water and land pollution, localized health issues and resources depletion [57]. The durability in constructions becomes a part of the global problem that should be resolved as a whole in the framework of sustainable buildings and infrastructures. These approaches express a design philosophy that strives to enhance effective resource efficiency, and reduce negative impacts on human wellbeing and dignity, in a cost-effective manner [57–59].

4 Environmental Impact on Durability of Materials and Structures

The concept of loads, used in a normative way in structural design, expresses the (mechanical) interaction of a structure with its environment. Various norms and standards have been established in various parts of the world to harmonize the quantification of this interaction (Eurocodes, ASTM, and so on). Following these approaches, the environmental impact and its evolution in time are established following some consensual guides governing all design processes of structures and eventually their evolution state. For example, wind and/or snow loads are counted in engineering European practice using the guidelines of Eurocodes [37, 42], through so-called characteristic values. However, the impact of the environment on the durability of materials and structures is much more complex and determinant than the mechanical impact given in these standardization codes and guidelines. From a theoretical point of view, poromechanics theory developed since the middle of last century and most of the last decades, gives a solid framework to treat these interactions [26–28, 60, 61]. Without going into details of the theory, some outstanding outcomes and consequences are discussed hereafter. The most distinguished feature of this theory is the mutual impact on the overall response of a material, of its solid matrix, fluid that fills its porous space and the state of each phases constituting the material. The fluids filling the pore space and solid matrix interact with each other mechanically, thermally, chemically, leading to an evolution of the material and structure, eventually to its ageing, and definitely impact its durability.

Within the range of temperatures to which construction materials, buildings and civil engineering infrastructures are exposed (much lower than the fusion temperature of materials), the impact of *thermal conditions* of the environment on the durability is manifested, at least, in three ways:

Firstly, through the strains/stresses generated from the variation of temperature. In the simplest form, the free thermal strains are related linearly to the variation of the temperature through the thermal expansion coefficient [60, 61, 65]. Where the thermal strains are partially or fully obstructed, stresses are generated, whose amplitude depends also on mechanical properties of the material.

– Secondly, in long time when a structure is submitted to fluctuations of temperature due to environmental thermal changes - convection, diffusion, radiation - because of the mechanism of thermal expansion cited before, the local stresses at least up to some depth of the surface, are also susceptible to fluctuate. These fluctuations could lead to the decay and failure of the materials and structures through a mechanism of thermal fatigue [26, 27, 62, 64–66]

– Thirdly, the temperature could significantly impact the creep rate of all materials, especially the construction materials. The most known mechanism through which this impact performs represents the decrease of activation energy of slip lines where the temperature increases (known as Arrhenius law), leading to higher creep rates [41, 66]. In the same way, the temperature increase leads to modification of the rate of critical and subcritical crack growth, impacting directly the life duration of a given structure.

The impact of temperature in the case of porous media (most of the geomaterials used in constructions – stone, concrete, wood, and so on) is a more complex phenomenon, some aspects are treated later on this document.

Hygro - (and more often *hygrothermal*) impact on the durability of materials and structures is known for a very long time. However, the complexity of the problem is such that, nowadays makes the field a domain of intensive research. The impact of nonreactive wetting fluids, saturating the pore space of a material, could be taken into account through the effective stress concept, even if the definition of this concept itself is yet an open question [60, 62–64]. Yet, the mechanisms of hygrothermal impact on the durability of materials and structures are more complexes and multiple:

– When the wetting fluid (most of the time water) fills only part of the pore space, then a capillary meniscus is formed governing the equilibrium of fluid pressure in the pores. Since, in the framework of perfect gases, the capillary pressure (capillary pressure is the difference between the air pressure and fluid pressure) is linked to relative humidity (Kelvin's law), the evolution of the humidity in the environment where the structure is located leads also to the evolution of the "effective stress" (much the same as when the temperature fluctuates). It should be noted that these effective stress fluctuations are produced on the top of all other dead and live loads and could significantly shift the equilibrium point of the structure (equal to the working point for a system that works stably). Then a fatigue mechanism is geared up affecting the durability of the structures [26, 28, 35, 38, 62–64].
– A second way through which hygrothermal state would impact the durability of a material (and the durability of a structure) is the modification of its physical and mechanical properties: a significant decrease of the strength and Young's modulus when the humidity increases is reported by many studies in a great number of porous materials. In some stones, for example, the strength is decreased by 40% in range of in-field humidity variations [45, 62, 64, 65, 69]. The impact of the humidity in the subcritical crack growth rate was also indicated since the very first works [34, 36]
– A third way through which the hygrothermal state of a material and structure would impact its durability is the creation of favorable conditions for chemical and biological activity on/into the structure. In fact, some ranges of humidity are very favorable to the birth and developing of various kinds of dissolution/precipitation mechanisms or

even growth of (micro)organisms and generally biological activity, either in the pores of the material or on its surface [50, 68]

When the question of the impact of environmental conditions on the durability of materials and structures is discussed, the very first factor that gets valuable insight is *the chemical interactions of the structure with its environment*. These factors are activated or not in terms of environmental conditions AND the constituents of the material. Without being exhaustive on this point, some typical chemical interactions that play a crucial role in the durability of materials are shortly commented here:

– Oxidation-reduction reactions: the main concern of these interactions is the oxidation of steel components of structures. The corrosion could dramatically affect the durability of steel, reinforced concrete, pretension cables, mixt structures and so on [26, 56, 71]. The oxidation has at least two consequences on the durability of the structures that suffered because of it: the corrosion products replacing the initial steel have an almost nil strength, so that from some levels of oxidation the stability of the structure is put in question; the products of oxidation have a specific volume higher (from 2 to 3 times) as compared to the volume of the steel itself – such that a spalling of concrete would happen around corroded rod of reinforced concrete structures. The other types of metallic structures (aluminium, stainless steels) are also concerned by this kind of chemical interaction, even if the rate of oxidation is lower than normal steels. While all possible precautions on protection of these structures from corrosion are taken in the design phase of the structures (for example, by coating the elements with non-oxidant material, or by creation of an electric potential preventing oxidation) the technics of assessment of the oxidation state and repairing of these structures are also a topic of perpetual development [46, 56, 71]. In normal conditions, the alkalinity of concrete (pH around 13) prevents the steel from corrosion. However, at lower pH levels, steel attains a high corrosion potential. The development of active corrosion in reinforced concrete results from two mechanisms: chloride diffusion in concrete and carbonation of concrete. The common feature of these two mechanisms is the diffusion of external agents through the pores. Both mechanisms are of great concerns, especially for maritime and off-shore structures.
– The dissolution, mineralogic transformations, and crystallization of new minerals in the pores of materials constituting structures: this physicochemical process is enhanced by the fluid saturating the pores of materials that have a high dissolvable potential (limestones, for example). The anions (positive ions) of dissolved material could combine with cations dissolved in the saturating fluid to eventually create some new minerals. In the case of limestones for example, the Ca++ anions are combined with SO_4^- that could come from the polluted atmosphere enriched with SO_2 [55, 61, 70]. Crystallization of new minerals in the one hand modifies the mechanical properties of the structure, and on the other hand, could sometimes be associated with so-called crystallization pressure, thought to be responsible for crack initiation from pores when crystallization takes place.

While thermo-hydro-chemical interactions of the structure with the surrounding environment are cited here separately, in reality, they take place at the same time and in many cases by amplifying the impact of each other. For example, in a saturated porous medium, temperatures below the freezing temperature could lead to cracking of the material, up to its complete failure, by a combination of retraction of material (due to negative variation of the temperature) and crystallization pressure generated by the formation of ice. Likewise, the high temperature could enhance the diffusion in porous media (because of the reduction of the superficial tension of fluids) leading to the acceleration of the oxidation process in concrete as described above. These multiphysics coupled phenomena call for appropriate multiphysics approaches for characterization of their impact [26, 27, 38, 39, 44, 51, 60, 66].

5 Stonework Structures Durability: Assessment of State of Historical Buildings, Monitoring, Maintenance and Restoration

Historical buildings (in many cases stonework structures and masonry) are the object of interest not only from cultural heritage and economic point of views but also from the scientific and technical point of views, especially for durability studies [28, 45, 55, 72, 74]. Many of the technics cited hereafter could be used for other types of structures.

The first step of the stonework diagnosis is the state of structure report, which aims at detecting and documenting the state of degradations [68, 70, 75]. Are qualified as degradations all alterations which, from some historical and sociological criteria, are not tolerated and considered to be a damage to the material or its appearance.

So, not all changes in terms of aspect and/or properties imply degradation. The development of a patina, for example, generates a surface hardening, a local decrease in water transport properties, and usually a slight color change. However, these induced changes are rather beneficial to the durability of the masonry and could be considered as roughly uniform for all stone. Hence, patina may not be considered as degradation although it is actually an alteration. Likewise, alterations that are exclusively aesthetic, such as soiling or certain biological colonization, may also not be considered as degradations. The state report shall denominate these alterations and their extent, so as to detect a progression by comparison between two different temporal states. For this comparison to be reliable, it is essential that each report hold the same rigor. Various technics for characterization and quantification of degradations could be used the most frequently used in practice are briefly commented here.

5.1 Visual Observations of Degradations

This inspection is currently unavoidable because the criteria for the classification of stone degradations, documented and classified in an illustrated glossary ICOMOS [55], are based exclusively on the appearance of the surface of the stone. This inspection requires a close to surface view, and observations from several angles which could be an operational problem for masonry in elevation, above moats, or masks. Nowadays, the use of drones makes it easier to observe hard-to-access facings at a low cost. Still, several overflights should be undertaken not only to detect degradations through photos but also to have photos from various angles in order to specify the nature and intensity of those degradations.

5.2 Photographic Survey

The photographic survey remains today the most common and the simplest solution be applied to document the state of degradation of masonry facings. In order to produce metric mappings, i.e. on which reliable quantitative measurements can be made, the mapping medium must be free from any distortion or perspective effects. Such a mapping medium cannot, therefore, be simple photos and should be treated using various technics such as for 3D models or ortho projections [70, 87].

Ortho projections are produced by projecting a 3D model onto a primitive surface such as a reference plane or cylindrical surface. They, therefore, correspond to an orthographic view (to be opposed to a perspective view), that is to say, that every point of the resulting image comes from a ray perpendicular to the observed surface, much the same as architect plans or elevations, but it reflects the appearance of the surface as a photograph or a laser scanner can appreciate it. It can be realized by terrestrial or aerial photography, or a laser scanning survey, or a combination of both, generally supplemented by a topographic survey and geolocate data and provides a scale if no laser survey is performed. The resulting ortho projection can then serve as cartographic support for informing the health status of the masonry walls. The use of primitive surfaces to store conservation data into a collaborative interface represents the first attempt to create an HBIM (Heritage Building Information Modeling) [85, 86].

Since ortho projection does not allow to observe the 3rd dimension and because some degradations could evolve in-depth at the same time or independently to their extension on the surface, it may be relevant to store and use locally the raw 3D model obtained from laser scanning or the one used to perform orthophotography to spatially compare different temporal states.

5.3 Non-destructive Characterization

The only observation of the external aspect of a masonry facing is not enough to ensure the reliability of a health diagnosis, and characterization of structures state by nondestructive technics is nowadays a common practice [77], [78]. These technics complete the purely external visual control by quantifying mechanical and physical properties of the subsurface. They allow in particular to appreciate the extent of desquamation beyond its limits visible to the naked eye.

These technics could be as simple as the "knock test", consisting to evaluate the state of stone using the different sounds produced when ones knock to its surface, to more sophisticated ones [82].

Among the more inexpensive technics, the application of which requires direct access to the surface tested, are the electrical resistivity profiling and the hardness test. The electrical surface resistivity measurement by tip is generally used in a comparative manner within the same material to differentiate the wet areas from dry ones [83, 84]. The hardness tester estimates the local hardness of stone and makes it possible to evaluate its state relative to other measured points [79]. If an analogue material calibration in the laboratory has been previously performed, this test can become quantitative. Compared to the concrete hardness test, the lower rebound energy allows it to be used on softer materials but also limits its study area to a much lower depth. Although considered as non-destructive, the test may, to some extents, damage the surface appearance. Because stones and mortars generally exhibit a decrease in hardness as moisture increases, variations in electrical resistivity and hardness measurements as a function of moisture changes may exhibit some degree of correlation.

Portable spectrometry analyzes powders from a stone placed on a dedicated strip to identify and quantify certain chemical elements [82]. Nowadays, the test could be performed using a smartphone equipped with the *ad hoc* accessory. Although the collection of the powder to be tested can be considered as destructive, the small quantities of powder required for a test make it possible to put into perspective and often to classify this technique among the non-destructive control.

Karsten's tube measures the water flow time through the surface of a tested stone [81]. This measurement, which requires direct access to the surface tested, is therefore well correlated with the transport properties of the stone.

The microdriller, which consists in measuring the drill resistance of a drill according to the depth, makes it possible to generate a resistance profile of the tested material in situ. Thus, this drilling test is to be placed in the control rather nondestructive than really nondestructive. However, the hole generated by the drill (diameter between 3 and 5 mm and max length 5 cm) is small enough to be plugged by a thin mortar which must allow to recover the initial surface appearance. This test makes it possible to reveal induration profiles [80] or, conversely, damaged areas, provided that the piercing device can be perfectly maintained and produce noise-free measurments.

Infrared thermography (IR) is based on the measurement of infrared radiation emitted by an observed surface. This radiation depends mainly on the temperature of the object, which allows this technique to generate a temperature map of the observed area. It is then possible, using obtained temperature map, to highlight areas of thermal heterogeneity such as thermal bridges, or damaged parts of a structure that for some reasons manifest a thermal difference [76]. For the same environmental conditions, stones of different thermal properties also have distinct surface temperatures so the IR thermography could help to distinguish stones of different nature on a façade.

6 Sustainable Materials for Construction and Renovation of Infrastructures and Buildings

The renovation of buildings and infrastructures is a process conditioned by many technic and socio-economic factors. The choice of materials to be used in the restauration of historical buildings is mostly guided by historical, ethical and cultural considerations. However, in the renovation of urban buildings, this choice, certainly constrained by socio-economic considerations, is strongly impacted by technical considerations. As an example, all urban renovations today are subject of strict requests on energetical performance increase as well as on grey energy reduction [87]. In France, a third of the housing stock is concerned by this thermal renovation [88]. One of the objectives of the Energy Transition Act is to renovate 500,000 homes per year by 2050. Consequently, the regulations provide a framework for improving energy efficiency, determine the performance to be respected during insulation work, and encourage the use of materials and equipment that respect the comfort and health of the occupant.

In another aspect, the construction and renovation of public infrastructures is also concerned by the smart choice of materials since this sector, a big consumer of raw materials already, will increase its consumption of materials to 100 billion tonnes by 2030 [90]. Meanwhile, the access to non-renewable raw materials has become increasingly limited, calling for urgent solutions and new alternatives. Among the best sustainable alternatives, recycling of industrial waste and by-products (slag, foundry sand, etc.), materials from deconstruction in the building sector, or agricultural co-products, are already developed worldwide to various extents.

In France, for example, a "Low Carbon Building Renovation" label was introduced in the first half of 2018 [91] aiming to reduce CO2 emissions by half compared to the original building taking into account the carbon storage capacities of constructions [80].

Consequently, there has been growing interest in the development of eco-materials for the energy rehabilitation of old buildings [21]. Numerous works in the literature have been performed on materials with low environmental impact by using different vegetal aggregates and binders [8, 19, 20, 93–95]. Various types of natural fibres are used, depending on the biomass production and climate of regions and countries in the world. An increasing range of plant by-products properties are being studied in order to obtain a wide variety of aggregates for vegetal concrete purposes. Reviews of the availability of vegetal aggregates have been reported in countries such as Spain [96], France [97], UK [98] and more globally in the world [99], as creating local industries with materials made with crude earth raw earth or crude oil and vegetal aggregates is an objective in many different parts of the world [100, 101]. Other advanced research has shown that it is possible to produce high performance natural fiber composite based on clay matrix [102], cement [103, 104] and lime or polymer matrix capable of meeting any engineering demand in terms of strength and energy absorption capability [106, 107]. The choice of the binder type in this application is of great importance and complexity. The binder must comply with an easy mixing, a perfect coating of fibers, a correct molding and a final composite with good mechanical properties. A number of authors agree that hydraulic binder can produce unacceptable results in the case of hemp-based composite [108, 109]. However, other results show that mixtures with higher ratio of cement have higher compressive strength [110]. Several investigations have been performed to study the effect of humidity and temperature on the one hand on thermal conductivity [112] and on the other hand on equilibrium moisture content [113] of coating plaster used for straw bales construction. The results indicate that the thermal conductivity of the coating plaster decreases with increasing fibre content.

In the context of building insulation, other researchers have been interested in evaluating the developed materials with in-situ tests under environmental climatic changes in order to ensure effective implementation in the real case [113–116], or by using accelerated aging conditions in the laboratory [11, 104, 118, 119]. It is also important to study the implementation of rehabilitation that makes possible the preservation of the building identity and its history [7, 120, 121].

Despite the growing interest in this type of materials and the recognition of their thermal, water and comfort performance [21], their use remains hampered by the absence of a normative framework and implementation rules specific to these materials to move towards a control of their use and their durability. For some materials/technics (hemp block for example) several technical recommendations [22, 23], implementation guides and technical data sheets are already in use in the artisanal and industrial practice. The situation is however more disparate for other bio-resourced materials with a level of integration quite different for one material to another or even from one country to another.

7 Conclusion

The durability of materials and structures is still nowadays a dynamic field of scientific and technical research and of permanent industrial innovation. The sustainability as a societal approach has however greatly modified and extended the principal fields of application of these researches. In the design of new materials and structures or in renovation of existing ones the criteria of evaluation of durability of materials end structures are not any more exclusively mechanical. While traditional topics such as fracture mechanics, time dependent behavior, interaction of materials and structures with environmental factors such as temperature, humidity, chemical reactive agents, are in continuous development and take advantages from numerical progress, new trends occupied nowadays the center of durability research and technological progress: design of new green sustainable materials, multicriteria assessment of their durability, reducing of raw materials in use and replacing with recycled and renewable ones. The technics for assessment of state of structures evolve too and include along with traditional technics of diagnostics new nondestructive technics that are called to be reinforced and developed in the future.

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