Performance evaluation of patch repairs on historic concrete structures (PEPS): a bibliographic review of patch repair durability.

Jean Ducasse-Lapeyrusse[1,2,3*], *Elisabeth* Marie-Victoire[1,3], *Myriam* Bouichou[1,3], *Ana Paula* Arato Goncalves[4], *Simeon* Wilkie[4], *Susan* Macdonald[4], *Nicki* Lauder[5], *David* Farrell[6], *Paul* Gaudette[7], *Ann* Harrer[8]

[1]Laboratoire de Recherche des Monuments Historiques (LRMH), Ministère de la Culture, 29 rue de Paris, 77420 Champs-sur-Marne, France
[2]Comue Paris Est Sup, 6-8 avenue Blaise-Pascal Cité Descartes, 77455 Marne-la-Vallée, France
[3]Sorbonne Universités, Centre de Recherche sur la Conservation (CRC, UAR 3224), Museum national d'Histoire naturelle, Ministère de la Culture, CNRS; CP21, 36 rue Geoffroy-Saint-Hilaire, 75005 Paris, France
[4]Getty Conservation Institute, 1200 Getty Center Drive, Suite 700, Los Angeles, CA, 91356, USA
[5]Historic England, The Engine House, Fire Fly Avenue, Swindon, SN2 2EH
[6]Rowan Technologies Ltd, 1 Barnfield, Urmston, Manchester, M41 9EW9DX England
[7]Wiss, Janney, Elstner Associates, Chicago, Illinois, United States
[8]Wiss, Janney, Elstner Associates, Los Angeles, California, United States

Abstract. Concrete repair and, more specifically, patch repair, is a complex process, which still presents challenges and results in durability issues. Durability of a patch repair is affected by many factors occurring throughout the repair process, such as diagnosis of the existing structure, design of the repair material, surface preparation, workmanship, loading, and exposure conditions [1]. Each phenomenon should be individually understood, but, for an efficient and durable repair, a holistic approach is advisable as every parameter is likely to affect several other variables in a different way [2]. This topic is abundant in the scientific literature related to contemporary concrete structures, but few are dedicated to historic concrete. All the considerations for modern buildings are relevant for concrete heritage, but additional specific requirements must be considered in order to preserve its cultural significance. The purpose of this bibliographic study is to highlight the key factors for evaluating the performance of concrete patch repair in the peculiar context of cultural heritage. Particular focus is put on compatibility issues between the repair system and the original historic material.

1 Introduction

Concrete is the most widely used construction material in the world. It enabled the creation of a large number of iconic buildings and civil engineering structures during the 19th and 20th centuries, some of which are protected as historic monuments [3]. Historic concrete structures bear witness to the technological evolution of the material and to the exploration by engineers, architects, and builders of the plastic and structural possibilities of concrete, especially regarding reinforced concrete [4].

As the main pathology of reinforced concrete is the corrosion of steel reinforcement, resulting in delamination and spalling, the most common repair technique is patching. The patch repair process begins with the removal of loose and damaged concrete that is cracked, spalled, delaminated, carbonated or contaminated with pollutants. Repair usually involves cleaning of the steel and, in some cases, the application of a protective coating to the steel. The replacement of the defective concrete is made with repair material that re-establishes the original form of the member [5].

A study of 230 conventional reinforced concrete structures in Europe [1,6,7] revealed that approximately 50% of the assessed patch repairs resulted in failure, sometimes within five years very quickly and with a maximum lifetime of around 10 years. For historic monuments, the deterioration processes result in dramatic loss of original material and consequent additional restoration costs. From an economic, environmental and heritage point of view, the long-term performance of patch repairs and the preservation of the cultural significance of the original fabric is a challenge clearly identified [8].

The goal of the PEPS project '*Performance Evaluation of Patch Repairs on Historic Concrete Structures*' is to evaluate the performance of patch repairs on exposed concrete in historic structures and buildings in order to better understand the key design and specification parameters and application methods required for a successful conservation approach [9]. This project started in 2018 bringing together three institutions from three countries: the Getty Conservation Institute (GCI) from the United States, Historic England (HE) from the United Kingdom and the Laboratory of Research on Historical

* Corresponding author: jean.ducasse-lapeyrusse@culture.gouv.fr

Monuments (LRMH) from France. Expert consultants from Rowan Technologies (England) and Wiss, Janney, Elstner Associates (USA) have also joined the project team. Previous publications [8,9] can give additional information about the PEPS project.

This bibliographic review continues the first step in the reflection about the patch repair durability in the specific context of culturally significant concrete structures. The understanding of all of the aspects of the durability of a patch repair helps to identify the parameters and the material properties to be assessed for a relevant performance evaluation of patch repairs on historic concrete structures.

2 Patch Repair Durability: A Holistic Approach

For an efficient and durable repair, a holistic approach is advisable. The phenomena affecting the durability of patch repairs must be considered as a whole, not only as a collection of parts. There is interdependence between several parameters that must be considered simultaneously, as each parameter may affect the other variables in different ways. [2]. The durability of a patch repair is affected by many factors throughout the repair process, from the conception of the repair procedure to the external influences during the service life. [7] (Fig. 1). The conception of a durable intervention is based on the documentation and on the validity of the diagnosis of the existing structure, which allow an appropriate design and selection of an intervention approach, with well-defined performance requirements. The processes should involve all the relevant stakeholders for each phase, the owner, asset managers, technical consultants, engineers, repair specialists, material suppliers, etc.

The implementation includes factors related to workmanship and to the conditions in which the implementation took place: the surface preparation, the application method, the movement and vibration during works, the ambient conditions during works, the supervision of the works' execution, the curing and bond.

The properties of the repair material and the properties and condition of the original substrate must be compatible.

Finally, the external influences such as the loading conditions and the service and exposure conditions affect the durability of the intervention.

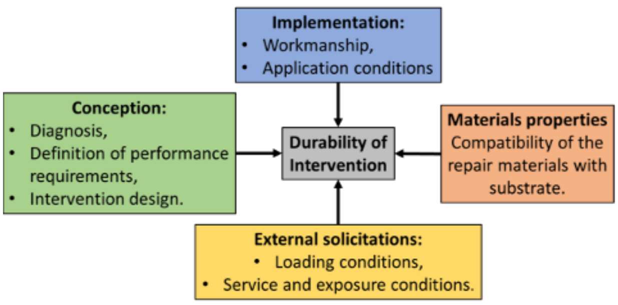

Fig. 1. Factors potentially affecting the durability of an intervention, adapted from [7].

Compatibility of the patch repair material with the original substrate appears to be a major issue [10–13]. ‘Compatibility’ is not the same as similarity in properties. For example, some authors [11,12] highlight that bad concrete should not be repaired with a similar one. Also, making a new concrete with properties similar to the original one (weathered, carbonated, exposed to different conditions, pollutants, with a particular loading history, etc.) is practically impossible.

Compatibility is defined as: “a balance of physical, chemical and electrochemical properties and dimensions between a repair material and the existing substrate that will ensure that the repair can withstand all the stresses induced by volume changes and chemical and electrochemical effects without distress and deterioration over a designated period of time.” [14]. Several parameters should be evaluated to achieve a compatible repair, considerations include dimensional, mechanical, physical, chemical, electrochemical, and aesthetical aspects [10].

2.1 Dimensional compatibility

Dimensional compatibility appears for some authors to be the most important consideration for repairs [2,13,15]. The following material properties influence dimensional compatibility between repair and substrate materials:

- Drying shrinkage of the repair material;
- Thermal expansion or contraction differences;
- Differences in the modulus of elasticity;
- Creep properties;
- Tensile strength and tensile strain capacity;
- Relative fatigue performance.

Many materials change in volume due to shrinkage, changes in moisture and temperature or local swelling (iron oxides due to steel corrosion, ettringite formation, etc.). The restrained volume changes of repair materials, caused by the restraint from the bond to the existing substrate, causes stresses and possible cracking (within the repair material or the substrate) or debonding if they exceed their strengths [15,16].

Dimensional compatibility can be defined as the ability of the repaired area to withstand volume changes without loss of bond or delamination [13], while simultaneously avoiding creating cracks in the repair or substrate. It also includes the ability of the repaired area to carry its share of the applied load without distress [13]. For a non-structural patch repair, the dimensional compatibility requirements are not met by selecting repair material with properties similar to the substrate ones. The dimensional compatibility is related to the “extensibility of material” [15]. It is the appropriate combination of low elastic modulus, high creep, low shrinkage, and high tensile strength, the interaction of which leads to reduced cracking [16]. A low modulus of elasticity induces a low tensile stress for a given magnitude of shrinkage. A high creep allows a higher amount of stress relaxation. A high tensile strength allows a high tensile stress in the material without cracking.

For structural repairs, the creep and the modulus of elasticity of the repair material must allow an appropriate load distribution between the substrate and the repair.
The properties involved in the dimensional compatibility depend on the composition of the materials, the application, the curing, and the external conditions during the work and during the service life of the structures (especially temperature and humidity).

2.2 Bond Strength

Correlated to the dimensional compatibility considerations, the bond between the repair material and the substrate is critical to guarantee the durability of the repair. More important than achieving maximum adhesion is reaching monolithic behavior, which ensures an even distribution of stresses. The interface between the repair material and the substrate is subjected to considerable stresses caused by volume changes, freeze-thaw cycles, force of gravity, impact or vibrations, etc. [15]. Two origins of the mechanism of adhesion have to be considered: specific adhesion and mechanical interlocking [17]. The parameters affecting the degree and durability of bond are [15]:

- Properties of the substrate concrete and surface;
- Absorption and roughness of the substrate;
- Properties of repair material;
- Adequacy of adherence of the repair material in both uncured and cured states;
- Environmental conditions.

The substrate preparation during the implementation work has primary influence on the porosity and mechanical properties of the repair material and on the quality of the interface between the original concrete substrate and the repair [11,15,18]. The related substrate parameters involved are superficial tension, roughness, porosity, capillarity, saturation level, mechanical characteristics, microcracks, chemical composition of the interstitial water, impurities, etc. [19,20]. Many of these parameters are influenced by the environment, temperature and the relative moisture, but also by the curing conditions, the implementation work and the human factor – for example, the pressure applied on the repair material during a manual application [19,20].

The selection of a technique to remove the original damaged concrete, to clean the surface and to achieve the appropriate roughness of concrete without excessive microcracking is essential [11, 33, 37].

In addition, specific consideration must be given to the transition zone – the thin layer of the repair material in contact with the substrate whose characteristics differ from the bulk repair material. Bonding agents can improve adhesion, and polymers in cementitious materials may improve the bond characteristics on structures subjected to extensive temperature cycles [15,21]. But it should be noted that bonding agents can also affect the transport properties of the transition zone [22].

2.3 Permeability issues

The transport of fluids (liquids or gases with potential aggressive agents) through the repair material depends on the porous network including macro and microcracks. Various phenomena govern fluid transport through porous media such as capillary, diffusion, and osmotic actions. The location of the repair in the structure, the chemical environment, temperature, moisture and stresses all need to be considered. Furthermore, compression or tension of the materials can induce reversible changes in the size of pores [15].

A low intrinsic permeability is often recommended for the repair materials [2] but cracking is a much more predominant parameter affecting water and gas transport in the repair system. In some cases, a repair material with a low permeability can be harmful. With an impermeable repair material, frost or salt crystallization pressures can create large stresses – particularly at the bond interface. Repeated cycles of crystallization lead to severe deterioration [23]. This type of failure is common in structures like dams [13].

Some authors [24] recommend repair material with similar moisture diffusivity and mechanical properties for a substrate concrete with a high diffusion resistance. For substrate concrete with high permeability, highly adhesive patch repair material should be used [24]. In some circumstances, at the interface beneath the repair region, the stress can largely be affected by the moisture diffusion resistance [24].

2.4 Chemical compatibility

Chemical compatibility must be considered for the selection of the repair material but it is an aspect seldom reported in the literature [15]. For these authors [15,23], chemical incompatibility is a contributing factor to certain major causes of repair failures and is likely occurring more often than is realized. Alkali-aggregate reaction, sulfate attack, reinforcement corrosion due to high chloride content or low pH are examples of damaging mechanisms which could be related to chemical incompatibility.

The following parameters of the repair material and the substrate should be considered to prevent any pathological reaction: reactive aggregates, alkali content, tricalcium aluminate (C_3A) content, sulfate and chloride content [23]. The presence of soluble salts should also be taken into account to avoid salt scaling.

2.5 Electrochemical consideration

A short time after concrete patch repairs (a few months to a year); further corrosion deterioration can sometimes be observed in the chloride contaminated substrate concrete around the patches. This phenomenon is called incipient anode or ring anode formation [25] and is the reason for the failure of many patch repairs [26]. For some authors, the incipient anode effect is the consequence of the electrochemical incompatibility between the patch material and the concrete substrate [5,15,26].

Repair materials differ from the substrate concrete in terms of chloride content, oxygen availability, pH, or permeability properties [15,25,26]. This creates two different environments around the steel bar in the repair and in the substrate concrete. The part of the steel bar with the least electrochemical potential will serve as the anode, while the part with the higher electrochemical potential acts as the cathode. The electron transfer takes place between these locations, resulting in the formation of macrocells and corrosion at the anode could occur.

In addition, the repair intervention with the removal of the damaged area and its replacement with sound material could affect the electro-potential of the reinforcement bars all around the patch. The removal of the damaged area, initially the anodic zone, removes the "cathodic protection" of the reinforcing bars around the repair [4, 64], as a result the rebars surrounded by original undamaged concrete could become the anodes.

Several authors [5,25–28] highlight the importance of chloride content and carbonation of the substrate. The reinforcement steel in a substrate with a high chloride content or carbonated may start to corrode after the loss of the cathodic protection.

A basic rule is that reducing transport processes should reduce the electrochemical incompatibility [15]. However, this aspect of compatibility is subjected to numerous parameters involving environmental conditions and other types of compatibility such as dimensional, chemical or in relation to permeability.

Permeability is a factor to consider in the macrocell corrosion process. On one hand, a low permeability material can trap or create a new macro anode due to chloride ion gradients and oxygen ion deficiency [15]. On the other hand, a low-permeability repair material, with a higher electrolytic resistance, should reduce the cathodic contribution of the patch to the surrounding substrate by limiting the availability of oxygen, inhibiting the transport of hydroxyl ions [15]. The availability of oxygen in the patch has an influence on the ring-anode corrosion [5]. During periods of oxygen deprivation, the limiting current density is low and the damaging effect is less severe but the ring anode can still be observed [5].

Theoretically, in a chloride-free environment, the application of a repair patch that has similar permeability to the substrate should reduce the potential difference [29]. However, a low-quality repair patch (for example with high porosity or low mechanical strength) designed to match the substrate concrete can be vulnerable to carbonation attack and chloride ion penetration. Chloride penetration through the interface between the parent original concrete and the repair material, or damage to the steel/original concrete interface during preparation of the repair area may be the main reasons for the incipient anode corrosion [25].

Like permeability, the concrete resistivity is a major factor that influences the magnitude of the macrocell corrosion [30]. A patch with high resistivity should diminish the incipient anode effect [5,26] as the material offers a high resistance to the rate of flow of the ions between the anode and cathode areas. If the resistivity of the substrate is low, the incipient anode effect is likely to occur irrespective of the patch quality [5,26].

The numerous factors that can affect this complex electrochemical mechanism make it difficult to identify the original cause of the incipient anode corrosion in the field.

2.6 Aesthetic compatibility

Matching the color, finish, and texture of existing concrete is an important requirement for historic monuments when these characteristics contribute value to its cultural significance. Proper surface preparation should be used to reduce the visibility of the repair and have neat boundary lines (double saw cut or coring the corners [31]). The perimeter of damaged areas might have to be adapted, sometimes expanded; either to disguise the joint between old and new in a less prominent spot or the depth might have to be increased to be able to use the correct coarse aggregate size. Technically, a modification of the geometry of the patch repair to a more regular shape can be advisable to reduce stresses around corners of the patch [32].

Patch repair materials should be customized to match the original concrete substrate. Concrete repair can be specifically formulated to achieve similar color, based on the characterization of the original cement paste and aggregates. And the repair application technique can be developed specifically to achieve similar surface texture to the original, whether it is polished, with exposed aggregates, etc. Trials and mockups should be made, cured, and dried to inform final development of repair material and to serve as control for the subsequent work. Sufficient curing time is essential, as the concrete continues to fade and change color over time. Matching the color of the new repair and the existing concrete substrate can be a challenge, especially since the old and the new material can weather differently, resulting in color shifts which can be visible on sites [4]. Additionally, aesthetic evolution can be variable between different faces of the structure, with different exposure conditions. Achieving similar texture can also lead to a specific work schedule, for example, when a bush hammered finish is to be replicated, a minimum curing of the repair concrete is required (preferably 28 days or more) before bush hammering.

3 Specific Considerations for Culturally Significant Concrete Structures

As with contemporary concrete constructions, repairs on concrete structures with cultural significance require a holistic approach with similar durability considerations but pose additional concerns that should guide every step of the intervention [33].

More specifically, historic monuments require studies and documentation to understand the place, context and their cultural significance [4,34,35]. Understanding significance, identifying the properties of the historic concrete relevant for construction history and heritage values is essential to developing appropriate conservation strategies [36]. All these preliminary phases should guide the repair process to balance standard concrete repair methods with conservation requirements [4]. These investigations can give additional information regarding composition, characteristics of the concrete, and the way the material was made [4].

The materials or techniques used in historic concrete could add complexity to the conservation project. Some of the techniques and materials were experimental with unproven performance records and could lead to deterioration issues [37]. Some of the materials used, such as asbestos, are now known to be hazardous. In addition, the properties of historic concrete are not always similar to the properties of contemporary concrete [32] which could make it difficult to achieve compatibility with current repair materials and techniques developed for contemporary concrete [36].

The additional concerns that affect concrete repairs on culturally significant structures are the subject of recently published documents offering guiding principles specific to the conservation of concrete heritage [4,35]. These documents align with broader conservation concepts adopted internationally by organizations like ICOMOS [34,38–40], and in European standards [41,42]. They aim to reveal and retain the cultural significance of these monuments by adopting criteria such as retention of authenticity by minimizing loss of original material, and minimizing future risk by adopting compatibility, reversibility or retreatability in interventions.

3.1 Retention of Authenticity

Authenticity appears as an essential qualifying factor concerning value of a cultural heritage [43]. The concept of authenticity depends on the nature of the cultural heritage, its cultural context, and its evolution through time. It may include form and design, materials and substance, use and function, traditions and techniques, location and setting, spirit and feeling, and other factors [43].

In the context of concrete repair of historic monuments, the intervention must respect the design concept, techniques and the original material to preserve the aesthetic and historical value of the structure [38,39]. Consequently, these repairs have a larger focus on aesthetic and minimizing loss of original material.

Concrete repair intervention must integrate harmoniously with the whole through aesthetic compatibility between repair and original surface [35]. This is necessary to maintain the visual integrity of the architectural element, thereby retaining its aesthetic value.

Preservation of the original material is also imperative [4,34]. Interventions on structure with heritage significance must be limited to necessary actions to ensure safety and durability with the least harm to heritage values [39]. Imperfections and alterations can be a part of the history of the structure and contribute to the heritage value. Therefore, they should be maintained as long as the safety requirements are not compromised [39].

In keeping concrete repairs to a minimum, as for all other considerations, a long-term view must prevail [36]. An initially invasive technique could be preferable if it can result in a more durable solution providing a better long-term preservation by avoiding additional future repairs.

3.2 Minimizing Risk through Compatibility, and Reversibility or Retreatability

Due to the irreplaceable nature of culturally significant structures, all measures should be taken to minimize risk by using materials and techniques that are compatible to the original and by designing solutions that are reversible, if possible. Preference for reversible solutions aims at allowing future replacement with more suitable measures, if new knowledge is acquired [39]. Where reversibility is unfeasible or compromises quality of the solution, interventions should aim at retreatability [4,39].

The selection of compatible repair materials and methods should be guided by investigation, testing, and analysis of results to ensure durable repairs that preserve the concrete's significance.

The choice between "traditional" and "innovative" techniques should be considered taking into account the specificity of each case [39]. The least invasive and the most compatible techniques with heritage values should be selected [39] with consideration to safety and durability requirements. Characteristics and information on the performance of repair materials and techniques are necessary to understand the long-term effects of the adopted repair materials and methods [4,35,39].

All the recommendations related to conservation work on a culturally significant structure demand documentation of the project and outcome. At the end of the intervention, recommendations for the ongoing care of the structure including managing use, maintenance and environmental conditions should be provided to the owner and the site manager.

3.3 Specificity of Patch Repairs in Historic Concretes

Patch repair of historic concrete monuments is a common technique, however, it can sometimes conflict with conservation goals previously presented.

Concrete repair is an irreversible intervention as it requires removal of deteriorated original material and retreatability is also a challenge because redoing repairs requires further removal of original material to achieve appropriate surface preparation.

In addition, some of the recommendations for a durable patch repair can be in opposition to the principle of minimum intervention, such as removing all the chloride contaminated or carbonated substrate. Such requirements from guides or standards relevant to ordinary concrete should not be strictly applied to historic structures without discernment.

Nevertheless, patch repair allows for a localized intervention limited to the deteriorated areas and, when properly done, can be a long-lasting solution that avoids advancement of deterioration and potential loss of the architectural element or structure. Moreover, patch repairs can fulfill the goal of preserving aesthetic value of forms, color and texture of the original material. The iterative process of conducting trials and creating mock-ups is essential to develop a good aesthetic match. The principles of aesthetic compatibility mentioned above are fully applicable. Monitoring the intervention is fundamental to define and calibrate the development of repair materials. In conservation, testing repair and treatment materials is crucial [4,44].

Another conflict relates to the preservation of authenticity which gives preference to the use of repair materials as close as possible to the original material. However, this consideration could be in contradiction with the goals of durability and compatibility for concrete repair. The original material despite its cultural significance could be a contributing factor in the deterioration mechanism affecting the structure. Compatibility with an original weak material and potentially contaminated by sulfate or chloride, minimum intervention and achieving a durable patch repair is a difficult combination. For example, the compatibility of the repair material with a sulfate polluted historic concrete, due to environmental pollution, might lead to changes in the concrete design compared to the original one in order to have a sulfate-resistant material.

The dilemma between compatibility and authenticity can be illustrated by the use of fiber or modified-cementitious repair materials. While deviating from the composition of the original concrete, these materials may sometimes be used to achieve a more durable repair.

4 Conclusion

Patch repair is a widely used technique to address the effects of reinforcement corrosion on both ordinary and culturally significant reinforced concrete structures. The holistic approach recommended to achieve successful and durable repairs is similar in both cases, and only deviates in that culturally significant structures have added requirements that increase the complexity of the process.

As a major cause of repair failure, the corrosion process is widely studied in the context of patch repairs [25–30,45–52]. The electrochemical phenomena involved are addressed through the mechanism of incipient anode formation. This complex topic includes other compatibility aspects such as permeability and chemical compatibility with the influence of chlorides, carbonation and pH. Permeability itself is affected by the cracking behavior and then by dimensional compatibility and application conditions.

Chemical compatibility issues that can affect patch repairs (alkali-aggregate reaction, sulfate attack, etc.) are described in detail for the broader concrete deterioration context. General considerations about these chemical attacks and reactions could be transposed to patch repair recommendations.

Permeability is generally a subject of concern but only as an influencing parameter for electrochemical compatibility. It is not a common characteristic evaluated during the repair design and the material selection. Often, the more impermeable repair material is considered preferable whether it is compatible with the substrate or not. This could be due to cracking being a much more important factor for transfer mechanisms.

Cracking and debonding are at the intersection of several issues. Dimensional incompatibility, chemical incompatibility, reinforcement corrosion, inappropriate workmanship or application conditions results in cracking in the repair material or in the substrate or debonding of the repair. In return, cracks and debonding affect permeability and contribute to aesthetic incompatibility. A diagram summarizes the interdependence of these different parameters in Fig. 2.

One limitation of the holistic approach is, by definition, the number of parameters to consider and the quantity of properties to determinate. For ordinary concrete structures, some authors [16] propose quantifiable requirements for several repair material properties. Standards and guides recommend a global performance-based approach and present lists of characteristics to consider according to the principle and the method chosen for the repair ([1], EN 1504 series 1 to 10 [53], ACI guides [54,55], etc.).

While aesthetic compatibility is usually not a factor of primary importance for common concrete, it is essential for concrete heritage. However, cultural heritage goals for patch repair are not limited to the aesthetic factor. The main objective in conservation of concrete heritage is to preserve its cultural significance. This concept is presented in recent documents that give specific guidance for conservation of cultural heritage in concrete [4,35] in accordance with broader conservation principles for historic monuments. This objective should influence all the steps in the repair process. In addition, criteria such as retention of authenticity by minimizing loss of original material, and minimizing future risk by adopting compatibility, reversibility or retreatability in interventions make an intricate puzzle to solve in order to fulfill all the requirements for a successful patch repair.

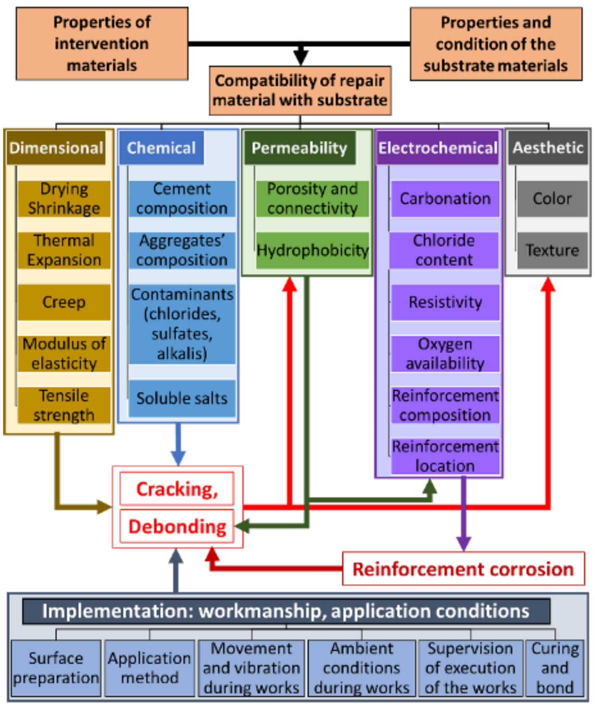

Fig. 2. Diagram of interaction between the different compatibility aspects and the workmanship and the application conditions.

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