Nordic Concrete Research – Publ. No. NCR 73 – ISSUE 2/ 2025 – Article 5, pp. 83-97

sciendo

Nordic Concrete Federation

ISSN online 2545-2819
ISSN print 0800-6377

DOI: 10.2478/ncr-2025-0022

Received: Sept 26, 2025
Revision received: Dec. 4, 2025
Accepted: Dec. 8, 2025

Service Life of Concrete Repairs

Roar Myrdal, PhD
Adjunct Professor, Department of Structural Engineering, NTNU
Richard Birkelands vei 1A, Trondheim, Norway
roar.myrdal@ntnu.no

Mette Rica Geiker, PhD
Professor Emerita, Department of Structural Engineering, NTNU
Richard Birkelandsvei 1A, Trondheim, Norway
mette.geiker@ntnu.no

Jan Arve Øverli, PhD
Professor, Department of Structural Engineering, NTNU
Richard Birkelandsvei 1A, Trondheim, Norway
jan.overli@ntnu.no

ABSTRACT
Effective repair and protection of concrete structures prolong their service life. This is well documented. There are various repair and protection categories ranging from mechanical repair to electrochemical repairs and surface treatments. The service life of these repairs as such is, however, less studied and documented. There are several parameters that can be used to estimate to what extent the repairs retain their protective properties over time. This paper summarises these parameters and gives a short state of the art review of published English literature over the last 35 years regarding service life of concrete repairs and protection. A call to improve the procedures linked to concrete repair is also presented.

Key words: Concrete, service life, repair, durability, limit states.

1. INTRODUCTION

Concrete repair is carried out to maintain or restore the service life of a concrete structure. The designed service life may be reduced by physical and chemical attacks caused by environmental exposure (e.g. intrusion of chloride salts from sea water) or non-conformances during construction. To counteract the governing deterioration mechanisms, various maintenance options are applied.

This paper gives a short state of the art review of the durability and service life of selected maintenance and repair methods and suggests ways to improve procedures. The focus is on the durability of the repair themselves.

According to the American Concrete Institute (ACI), the service life of a building/structure component or material is defined as the *"period of time after installation (or in the case of concrete, placement) during which all the properties exceed the minimum acceptable values when routinely maintained"* [1]. ACI distinguish between types of service life [1] as suggested by Sommerville in 1986 [2]:

> <u>Technical service life</u>
> *The time in service until a defined unacceptable state is reached, such as spalling of concrete, safety level below acceptable, or failure of elements.*
>
> <u>Functional service life</u>
> *The time in service until the structure no longer fulfils the functional requirements or becomes obsolete due to change in functional requirements.*
>
> <u>Economic service life</u>
> *The time in service until replacement of the structure (or part of it) is economically more advantageous than keeping it in service.*

Later, the term "design service life" has become widespread. The International Federation for Structural Concrete (*fib*) provides the following definition [3]:

> <u>Design service life</u>
> *The assumed period for which a structure or a part of it is to be used for its intended purpose.*

Whereas the International Organization for Standardization (ISO) has expanded this definition by incorporating anticipated maintenance [4]:

> <u>Design service life</u>
> *The assumed period for which a structure or a part of it is to be used for its intended purpose with anticipated maintenance, but without major repair being necessary.*

The service life of concrete <u>repairs</u> has not gained the same attention as the service life of concrete structures. However, more than 30 years ago the factors affecting the robustness and durability of concrete repairs were addressed from a contractor's viewpoint, with the following conclusion: "*The design and specification of concrete repairs can no longer be left to old 'rule-of-thumb' practices. The architect and engineer need to apply engineering principles in the design of repair projects with the same professionalism as they do in designing new structures*" [5].

This paper focuses on non-structural repair. First, a short overview of the main repair and protection methods used for concrete structures and the ways to observe and measure their deterioration is given. Then, a summary of what has been published on various durability parameters linked to the repair and protection methods is presented. The review shows that patch repair – especially the recipe of the repair material – has been the most studied deterioration parameter. Finally, discussions are made on where to go next to improve/develop procedures and responsibility areas related to repair actions, collection and sharing of repair data, and determination of limit states.

2. CONCRETE REPAIR

2.1 Repair methods

The main categories of products and systems for repair and protection of concrete structures can be found in European Standard EN 1504 [6]. Based on this, the following simplified groups of repair methods can be made:

Mechanical repair
- New concrete/patch repair
- Reinforcement replacement
- Injection (filling of voids/cracks)

Electrochemical repair
- Cathodic protection
- Realkalisation
- Chloride extraction

Concrete surface treatment
- Preventive maintenance
- Treatment after repair

Examples of concrete repair are shown in Figure 1. It is quite common to combine several repair methods during a repair project. For example, prior to a chloride extraction a patch repair may be needed, and a surface treatment is often applied after the chloride extraction.

Figure 1 – Left: Spray-applied patch repair of a bridge superstructure. Photo courtesy: Norwegian Public Roads Administration. Right: Installation of anodes for cathodic protection of an offshore oil platform. Photo courtesy: Equinor.

2.2 How to assess the service life of repair and maintenance measures

The service life of the repair ends when a predetermined limit state is reached. This means that the limit state must be set before the assessment of service life of the repair can be carried out. The limit state can be determined in different ways depending on the functionality of the repair and how it protects the concrete structure. For instance, the limit state of a patch repair's ability to prevent ingress of chloride salt over time can be determined using Fick's laws in combination with chemical analysis of the patch repair at time intervals after placement.

The International Federation for Structural Concrete (*fib*) and the International Organization for Standardization (ISO) has divided the term 'limit state' for concrete structures (not the repairs) into three subgroups [3, 7, 8]:

Ultimate Limit State (ULS)
A state associated with collapse or with other similar forms of structural failure.

Serviceability Limit State (SLS)
A state that corresponds to conditions beyond which specified service requirements for a structure or structural member are no longer met.

Durability (or Condition) Limit State (DLS)
A sub-limit state of the SLS and describes the point at which durability 'failure' occurs and thereby reduces the service life of the structure.

In this paper the term 'service life' will be restricted to the age at which the repair needs to be reapplied due to loss of its functional requirements set when the repair was carried out. A review of the findings from questionnaire surveys back in 2007 estimated that almost 50 % of concrete repairs exhibit sign of failure within five years [9]. To estimate the service life of a concrete repair you need to establish a system where the following items are established:

- The damage mechanisms affecting the durability of the repair
- The rate of deterioration of the repair
- The limit state at which the repair needs to be reapplied

Once the limit state and the factors affecting the durability of the repair are set, there are several ways to assess the deterioration process and propagation. This can be divided into four groups:

1. *Visual inspection on site looking for signs of deterioration:*
   - Leaching
   - Cracks, spalling
   - Rust stains

2. *Mechanical/physical measurement on site or in laboratory to determine:*
   - Porosity/permeability of repaired area
   - Bond and possible delamination between new (patch repair) and existing concrete
   - Bond between surface coating and concrete
   - Possible freeze/thaw action

3. *Electrochemical measurement on site within and outside the repaired area to determine:*
   - Electrochemical potential and corrosion rate
   - Electrical resistivity

4. *Chemical analysis of the concrete in repaired areas to determine:*
   - Chloride content
   - pH
   - Alkali content
   - Moisture condition

3. DURABILITY PARAMETERS OF CONCRETE REPAIRS

The durability of a concrete repair can be estimated by analysing different parameters. A literature search covering this matter using Google Scholar, ResearchGate, and ScienceDirect – with search terms ‘concrete repair’, ‘durability’, and ‘service life’ – gave hundreds of papers dealing with the effect of concrete repairs on the service life of the concrete structures (from 1989 – 2025).

However, the durability and service life of the concrete repair itself are not covered in most of these studies. In the sorting of these papers and reports only approx. 30 papers were identified (see overview in Table 1). The sorting started with a screening of the abstracts and the conclusions given in each paper/report followed by a grouping of the publications according to repair method elaborated. More than half of these publications dealt with patch repair. Much fewer studies dealt with electrochemical repair, surface treatment, and crack repair (referring to the repair grouping shown in Section 2.1). The durability and service life of steel reinforcement replacement was not found in any of the papers.

An examination covering more than 200 European mechanical repair case-histories for concrete structures up to 150 years old showed that 20 % failed in 5 years, and 90 % failed in 25 years [10]. The most common cause of repair deterioration was corrosion of steel reinforcement followed by frost damage and alkali-aggregate reaction [10].

Table 1 – Identified papers and reports on the durability of concrete repair and protection published in English from 1989 to 2025.

Year	[Ref]	Type of repair and protection						Durability parameters investigated					
		General overview	Patch repair	Crack repair	Steel replacem.	Electrochem. repair	Concrete surf. treatment	Repair material recipe	Cleaning of steel	Coating of steel	Repair-substrate interphase	Degradation of surface coating	Macro-cell activity
1989	11		X						X				
1990	12		X								X		
1994	5	X	X					X			X		
1995	13						X	X				X	
1996	14	X	X					X			X		
1997	15		X					X					
2000	16	X	X					X		X			
2002	17		X										X
2002	18		X					X	X				
2004	19	X	X					X			X		
2007	10	X											
2007	9	X											
2009	20			X				X			X	X	
2011	21					X							
2014	22					X							
2014	23					X					X		
2015	24						X	X				X	
2016	25		X					X			X		X
2017	26, 27						X					X	
2017	28		X								X		
2018	29					X					X		
2018	30		X					X				X	X
2020	31	X	X					X			X		X
2020	32					X							
2021	33		X					X			X		
2021	34	X	X					X			X		
2021	35			X			X					X	
2022	36		X					X			X	X	
2022	37					X							
2023	38			X				X			X		
2024	39		X					X					
2024	40						X	X				X	
2025	41		X					X					
2025	42			X				X			X		
2025	43					X		X			X		X

3.1 Durability of patch repair

The breakdown of patch repaired areas typically appears in the form of spalling, cracking, scaling, and loss of strength [5, 14]. There are several factors affecting the durability of patch repairs, the most studied being: The repair material recipe, repair-substrate interphase, cleaning/coating of steel, and macro-cell activity.

Repair material recipe
Examined parameters related to the durability of patch repairs are often related to the recipe of the repair material. The recipe can affect the durability of the material in many ways. When it comes to parameters like porosity and permeability (e.g. related to the intrusion of chloride salts), the intrinsic repair material properties are sometimes known and can be used to estimate the durability of the material as such provided it has been prepared, placed and cured according to instructions and is without cracks. However, although concrete structures repaired with specially designed mortars (e.g. polymer-modified mortars) might lead to a lowering of permeability and a reduction of the corrosion rate of the embedded steel reinforcement [18, 36, 41], there are other factors which are more crucial to secure the durability of the repaired area. It is important to ensure that the substrate concrete and the repair material are compatible [14]. To enhance the bond strength between the cement-based repair material and the concrete substrate – and thereby prolonging the durability of the repair – the following actions have been recommended in the literature:

- Clean the contact surface of existing concrete from dust, grease and loose particles [12]
- Use of polymer-based coupling agents on substrate surface [13]
- Use of fibres in the repair materials [13]
- Use of polymer in the repair material [19]

A comparison between several patch repair materials – both proprietary and non-proprietary products – has been made to facilitate the selection of repair materials [33]. It has also been suggested that the selection of a proprietary material should be made after comparing its performance with the performance of concrete which might contain pozzolanic binders [15]. Recently it has been suggested that repair mortars made of magnesia phosphate cement exhibit relatively good durability in marine tidal zone environment due to its high resistance against seawater erosion [39].

Repair-substrate interphase
It is not only the patch repair material which is affecting the bond strength between the patch repair and the existing concrete substrate. The nature and property of the substrate will also greatly affect the bond characteristics, regardless of the patch material recipe. Based on a literature review it was found that an increase in roughness of the substrate surface can enhance the bonding strength between cement-based repair materials and concrete substrates [36]. Even an attempt has been made to develop a computer model to optimise the compatibility between material and substrate for the enhancement of the interphase [19]. Also, the substrate moisture condition at the time of patching is regarded as an important factor, but no clear consensus has been found between this parameter and bond strength [34].

The effect of the substrate property on the durability of the repair is typically linked to the adhesion of the patch material. According to European Standard EN 1504 [6] the main feature of a patch repair system is the measurement of bond strength. This is commonly done by pull-off tests. If the test shows a failure of the bond between the repair material and the concrete substrate, this indicates that the bond strength at the interphase is lower than the strength of both the existing concrete and the repair material [14]. However, this is a destructive test method that needs a 'new local repair' of the patch repair after the measurement. As an alternative, the non-destructive technique (NDT) called Impact-echo is considered as a promising method for estimating the bond strength [28].

Cleaning/coating of steel reinforcement
The durability of patch repair of concrete structures suffering from corrosion will be affected by the condition of the steel reinforcement at the time of repair. Prior to applying the patching material, the steel rebars are normally cleaned. This can be done in several ways. Back in 1989 Vassie suggested that generally corroded steel should be grit blasted prior to patch repair, but pitted steel should be cut out and replaced [11]. Later, it was suggested that cleaning the steel surface by sand-blasting technique offers the best protection against chloride induced corrosion, followed by steel bars that are cleaned with wire brush, thereby prolonging the durability of the repair [18].

Removing chlorides from pits by cleaning is challenging. Therefore, an electrochemical technique termed Electro Active Repair (EAR) has been proposed, where direct current is applied to the steel for a short period of time to remove chlorides from corrosion products and pits [44].

Another way of preparing the rebars prior to the patch repair is to coat the steel with a material that can protect against corrosion. This is not a common process and has only been carried out occasionally. There are several types of coatings for reinforcing steel (e.g. epoxy), but the performance in corrosive environment has been questioned [16].

Macro-cell activity
The effect of patch repair on steel reinforcement corrosion has also been investigated in relation to what extent the material will form incipient anodes and macro-cell activities. When repairing a corroding steel reinforced concrete structure with a cementitious patch material, the electrochemical conditions around the steel bar will change. The original corroding area is now exposed to fresh alkaline patch repair material, but the rest of the steel bars remain in the original concrete. If the original concrete in contact with the chloride-free patch material has some chloride present, the steel in the original concrete can now form new corrosion sites. These newly formed anodic sites are known as incipient anodes and has been the reason for the failure of many patch repairs [17, 25]. To limit the development of new anodic sites, cast in sacrificial anodes have been suggested [25]. The long-term performance of these is at present unknown to the authors.

In addition to the difference in chloride content between the new cementitious patch material and the adjacent original concrete, factors like steel coatings, new cementitious binders, binders with mixed-in inhibitors and/or polymers may also create incipient anodes. This has led to an increased focus on the electrochemical incompatibility between repaired patch concrete and existing old concrete [30].

3.2 Durability of crack repair

Published data on the service life of crack repairs are scarce, but a comprehensive summary describing as many as twelve methods of crack repair, mentioning the techniques, advantages and disadvantages, and areas of application of each can be found [20]. No conclusion on service life was given other than specifying the factors affecting the service life of the crack repair.

The most studied durability parameter linked to crack repair is the repair material composition and how this affects water transport, carbonation rate, chloride ingress, and freeze-thaw resistance. Several types of materials are used to inject/fill cracks [42]:

- Epoxy resin
- Cement and microcement
- Polyurethane resin
- Hydrogel

One laboratory study compared epoxy injection with or without a surface impregnant (silane) on the surface of the filled crack and found that the carbonation rate was lowest when using epoxy injection together with a surface impregnant (silane) on the filled crack [35]. It was also found that epoxy injection gave the least freeze-thaw damage of the repaired crack [35].

There are also other materials which could be used for repairing cracks. The selection of type of material to be used depends on the surrounding environment and the type of crack (active or dormant crack). New types of materials are investigated, and it might be a potential for using alkali activated materials and geopolymer mixes as a replacement of cementitious mixes in repairing cracks in concrete [38].

3.3 Durability of electrochemical repair

Among the electrochemical repair methods (cathodic protection, chloride extraction, and realkalisation), only cathodic protection is a permanent action that needs to function for many years. The two other methods are only temporary actions lasting from weeks to months, and therefore not associated with durability issues as such. It is the effect of the repair action on the durability of the concrete structure that matters in this case, and not the durability of the components and systems used to repair.

Typical parameters affecting the durability of realkalised and chloride extracted concrete are level of impressed current and duration [21, 23, 37], and possible development of cracks due to excessive current density [32]. Findings also show that electrochemical repair might alter the pore sizes and pore distributions in the cement paste [32, 45]. Therefore, the durability and service life of the concrete structure after chloride extraction or realkalisation can be prolonged by applying a concrete surface protection which may delay further carbonation and ingress of chloride salts (see Section 3.4).

Cathodic protection systems can be either ‘self-driven’ (galvanic coupling between sacrificial anodes of a less noble metal and the steel reinforcement) or powered by an impressed current. Factors affecting the durability of the latter are mainly linked to the materials used to set up the anode (anode mesh, ribbons, rods, conductive coatings, embedding mortar) and the electrical equipment (current supply, wiring, reference electrode, datalogger).

Systems for impressed current cathodic protection are generally durable over many years provided maintenance is carried out on a regular basis. However, some failures may occur mainly related to defective details such as local current leakage or poor electrical isolation [22]. In 2018, Polder et al. [29] prepared an overview of 30 years' experience with cathodic protection of steel in concrete in The Netherlands and concluded that cathodic protection has become a fully accepted method of securing durability and safety of steel reinforced concrete structures.

A recent examination of the long-term performance of a cathodic protected coastal concrete bridge in Norway [43] showed that the anode embedding mortar in the vicinity of the anode ribbons had been neutralised (pH=7) and went through a phase change resulting in a risk of damage of the overlay mortar. Therefore, the following recommendations were given [43]:

- Use of mesh anodes instead of ribbon anodes.
- Mortars for embedding the anodes should have similar electrical resistivity as the undelaying concrete.

3.4 Durability of concrete surface treatment

There are three main categories of surface treatments used for protection of concrete structures according to the European Standard EN 1504 [6]:

- Hydrophobic impregnation
    - *Water repellent surface (no surface film, and no filling of pores)*
    - *Typical materials: Silanes and siloxanes*
- Impregnation
    - *Reduction of surface porosity (filling of pores)*
    - *Typical materials: Sodium silicates ('water glass')*
- Coating
    - *Protective layer/film on the surface (no filling of pores)*
    - *Typical materials: Resins (epoxy, acrylic, polyurethane) and cementitious coatings*

They are all subjected to aging and weathering (e.g. temperature variations and precipitation). Studies on the durability of these materials are dealing with the breakdown of the material. A laboratory study carried out more than 30 years ago on concrete structures exposed to chloride concluded that methyl methacrylate coatings provided the best long-term protection against chloride intrusion in the tidal zone compared to polyurethane and epoxy coatings, and that epoxy coating was the least good in the atmospheric and immersed zones [13]. In 2017 a comprehensive review of the performance of different types of surface treatments were made with the conclusion that due to limited research on the durability of surface treatment, it is very difficult to predict the service life of surface treated concrete [26, 27]. As part of this review the service life of concrete surface treatments was predicted based on the calculated reduction in resistance against chloride intrusion in natural environment involving both ultraviolet radiating and wetting/drying cycling, and it was concluded that silane-based treatments have a substantial longer service life than resin-based coatings [27].

An important durability parameter linked to the service life of hydrophobic silane treatment is the effective depth of silane penetration. A recent study on this parameter has concluded that "*there is a lack of more effective treatment methods to improve the effective penetration depth and integrity of silane molecular hydrophobic film*" [40].

4. SUMMARY AND THE WAY FORWARD

4.1 Summary of today's experience

The durability of concrete repairs has gained some attention over the last years as outlined in the previous paragraphs. Most of the studies referred to are focusing on the repair technique, and especially on the repair material (e.g. a patch repair mortar, or a concrete surface treatment/coating). It is seen (Table 1) that out of 17 papers and reports on patch repair as many as 14 are focusing on the impact of the repair material recipe on the durability and service life of the repair. Only nine of those papers are focusing on the repair-substrate interphase, a parameter regarded very important to build good interfacial bonding. Likewise, the papers dealing with crack repair focus mostly on the repair material type/recipe, less on the repair-substrate interface, and only sometimes on the sealing of the crack using an overlay and surface treatment.

As previously mentioned (Section 3.3), the only electrochemical technique potentially affected by long-term durability issues is cathodic protection. One statistical study in the Netherlands in 2014 found that there was a 50 % probability that repair of parts of the system was needed at an age of 15 years after installation [22]. These are systems comprising several elements, some related to the electrical components, others to the anode material part. However, overall good working lives have been documented for many cathodic protection systems based on long-term field experience [22].

Studies on the degradation of surface treatments are mainly focused on the composition of the material and its gradual loss of ability to withstand water permeation and chloride diffusion. Surprisingly little has been reported on the effect of the coating-substrate interphase.

4.2 The way forward

The above-mentioned findings clearly show that there is a need for more knowledge on the service life of concrete repairs. Almost always there are multiple factors involved in the degradation of a concrete repair, and it is important that such research comprises the whole set of factors involved in the estimation of the service life of a given repair case. Without compiling these factors, the forecasting of the service life of the repair is hard to make. Unfortunately, many papers tend to describe only one or two durability parameters, and not the whole system. We need to develop better procedures and systems related to concrete repair; some proposals being:

<u>Definition of limit state</u>
A limit state must be defined before assessing the service life of the concrete repair. This should be predetermined before the repair work starts.

<u>Responsibility areas</u>
It is essential to make better guidelines and systems showing all the various responsibility areas linked to concrete repair. This includes all decision making and executing operations involved. The design process includes the importance of selecting the optimal repair strategy, time for intervention, and limit state determining re-repair, considering both functionality and sustainability in general. The execution involves many operations. E.g., for patch repair this includes removal of old concrete, cleaning and pre-treatment of the concrete surface prior to the repair (roughness, moisture, use of primer), new concrete recipe, which patching technique to be used (e.g. spraying), potential surface treatment of the final repair, etc. All these factors have

impact on the service life of the repair, and partners like the owner, consultants, contractors, and material suppliers will give important inputs.

Reporting and sharing of repair data
There is a need to establish a common system for collecting, reporting and sharing data for concrete repair operations which includes design, execution and follow-up. This should also contain a set of criteria for how the repair works and its expected service life. The establishment of an open international database that collects all these data would be highly welcomed.

ACKNOWLEDGEMENT

The authors gratefully acknowledge Excon – Green Management of Structures for Infrastructure (Research Council of Norway project number 340843) for its funding support. Inputs from partners participating in work package Excon H5 on repair and lifetime assessment are also highly appreciated.

REFERENCES

1. ACI PRC-546-23: "Concrete Repair—Guide", ISBN: 9781641952385, 2023, pp 59.
2. Sommerville G: "Design Life of Structures". *The Structural Engineer*, Vol 64, 1986, Issue 2.
3. fib (Fédération International du Béton): "Model Code for Service Life Design". *Bulletin* 34, 2006, Lausanne, Switzerland.
4. ISO 16204: "Durability - Service life design of concrete structures", 2012, p. 2.
5. Emmons P H & Vaysburd A M: "Factors affecting the durability of concrete repair: the contractor's viewpoint". *Construction and Building Materials*, Vol. 8, 1994, pp. 5-16.
6. EN 1504: "Products and systems for the repair and protection of concrete structures". https://www.en-standard.eu/.
7. ISO 2394: "General principles on reliability for structures", 2015, pp. 23-24.
8. Alexander M & Beushausen H: "Durability, service life prediction, and modelling for reinforced concrete structures – review and critique". *Cement and Concrete Research*, Vol. 122, 2019, pp. 17-29.
9. Matthews S: "CONREPNET: Performance-based approach to the remediation of reinforced concrete structures: Achieving durable repaired concrete structures". *Journal of Building Appraisal*, Vol. 3, No. 1, 2007, pp 6-20.
10. Tilly G: "The Durability of Repaired Concrete Structures". *Proceedings*, IABSE Symposium Report 93 (22), 2007, pp. 1-8.
11. Vassie P R: "The Influence of Steel Condition on the effectiveness of repairs to reinforced concrete". *Construction & Building Materials*, Vol. 3 No. 4, 1989, pp. 201-207.
12. Silfwerbrand J: "Improving Concrete Bond in Repaired Bridge Decks". *Concrete International*, Vol. 12, No. 9, 1990, pp. 61-66.
13. Zemajtis J & Weyers R E: "Service Life Evaluation of Concrete Surface Coatings". *Transportation Research Record* 1490, Management and Maintenance of Bridge Structures, National Academy Press Washington D.C. 1995, pp. 67-74.

14. Cusson D & Mailvaganam N: "Durability of Repair Materials". *Concrete International: Design and Construction*, Vol. 18, No. 3, 1996, pp. 34-38.
15. Cabrera J G & Al-Hasan A S: "Performance properties of concrete repair materials". *Construction and Building Materials*, Vol. 11, Nos 5-6, 1997, pp. 283-290.
16. Vaysburd A M & Emmons P H: "How to make today's repairs durable for tomorrow - corrosion protection in concrete repair". *Construction and Building Materials*, Vol. 14, 2000, pp. 189-197.
17. Pruckner F & Gjørv O E: "Patch Repair and Macrocell Activity in Concrete Structures". *ACI Materials Journal*, March-April 2002, pp. 143-148.
18. Al-Dulaijan S U, Al-Zahrani M M, Saricimen H, Maslehuddin M, Shameem M & Abbasi T A: "Effect of rebar cleanliness and repair materials on reinforcement corrosion and flexural strength of repaired concrete beams". *Cement and Concrete Composites*, Vol. 24, No. 1, 2002, pp. 139-149.
19. Czarnecki L: "Repair Systems, Searching Towards Compatibility Measures". *Proceedings*, Int. RILEM TC 193-RLS Workshop on Bonded Concrete Overlays, Stockholm, Sweden, 2004, pp 5-11.
20. Issa C A: "Methods of crack repair in concrete structures". Failure, Distress and Repair of Concrete Structures. Woodhead Publishing Series in Civil and Structural Engineering, 2009, pp. 169-193.
21. Sahal M, Tong Y Y, Merino B S, Bouteiller V, Marie-Victoire E & Joiret S: "Durability of impressed current realkalisation treatment applied on reinforced concrete slabs after 5 years". *Proceedings*, 12th International Conference on Durability of Building Materials and Components, France, April 2011, France, pp. 1505-1513.
22. Polder R, Leegwater G, Worm D & Courage W: "Service life and life cycle cost modelling of cathodic protection systems for concrete structures". *Cement & Concrete Composites*, Vol. 47, 2014, pp. 69–74.
23. Redaelli E & Bertolini L: "Durability aspects of electrochemical realkalisation treatment". *Proceedings*, Concrete Solutions 2014, CRC Press, pp. 215-220.
24. Li G, Yang B, Guo C, Du J & Wu X: "Time dependence and service life prediction of chloride resistance of concrete coatings". *Construction and Building Materials*, Vol. 83, 2015, pp. 19–25.
25. Eldho C A, Jones S, Nanayakkara O & Xia J: "Performance of Concrete Patch Repairs: From a Durability Point of View". *Proceedings*, 5th International Conference on Durability of Concrete Structures, 2016, pp. 66-72.
26. Pan X, Shi Z, Shi C, Ling T-C & Li N: "A review on surface treatment for concrete - Part 1: Types and mechanisms". *Construction and Building Materials*, Vol. 132, 2017, pp. 578-590.
27. Pan X, Shi Z, Shi C, Ling T-C & Li N: "A review on surface treatment for concrete - Part 2: Performance". *Construction and Building Materials*, Vol. 133, 2017, pp. 81-90.
28. Garbracz A, Piotrowski T, Courard L & Kwasniewski L: "On the evaluation of interface quality in concrete repair system by means of impact-echo signal analysis". *Construction and Building Materials*, Vol. 134, 2017, pp. 311–323.

29. Polder R & Peelen W: "Cathodic protection of steel in concrete – experience and overview of 30 years application". *Proceedings*, ICCRRR 2018, 6 pp.
30. Ali M S, Leyne E, Saifuzzaman M & Mirza M S: "An experimental study of electrochemical incompatibility between repaired patch concrete and existing old concrete". *Construction and Building Materials*, Vol. 174, 2018, pp. 159–172.
31. Czarnecki L, Geryło R & Kuczynski K: "Concrete Repair Durability". *Materials*, 2020, Vol. 13, 4535; doi:10.3390/ma13204535.
32. Zhu P, Zhang J & Qu W: "Long-term effects of electrochemical realkalization on carbonated concrete". *Frontiers of Structural and Civil Engineering*, Vol. 14. No. 1, 2020, pp. 127-137.
33. Shi W & Shafei B: "Bond characteristics between conventional concrete and six high-performance patching materials". *Construction and Building Materials*, Vol. 308, 2021, 124898, 12 pp.
34. Baloch W L, Siad H, Lachemi M & Sahmaran M: "A review on the durability of concrete-to-concrete bond in recent rehabilitated structures". *Journal of Building Engineering*, Vol. 44, 2021, 103315, 18 pp.
35. Kim T-K & Park J-S: "Experimental Evaluation of the Durability of Concrete Repair Materials". *Applied Sciences*, Vol. 11, 2021, 18 pp.
36. Song Xu, Song Xi, Liu H, Huang H, Anvarovna K G, Ugli N A D, Huang Y, Hu J, Wei J & Yu Q: "Cement-Based Repair Materials and the Interface with Concrete Substrates: Characterization, Evaluation and Improvement". *Polymers*, Vol. 14, 2022, 1485, 25 pp.
37. Bouteiller V, Tissier Y, Marie-Victoire E, Chaussadent T & Joiret S: "The application of electrochemical chloride extraction to reinforced concrete – A review". Construction and *Building Materials*, Vol. 351, 2022, 128931, 21 pp.
38. ElKhatib L W, Elkordi A & Khatib J: "Methods and Surface Materials Repair for Concrete Structures – A Review". *BAU Journal - Science and Technology*, Vol. 4, No. 2, 2023, 21 pp.
39. He Y, Li Y, Jia J, Xu Q & He K: "Effect of seawater dry-wet cycling on the durability of concrete repair materials". *Journal of Sustainable Cement-Based Materials*, Vol. 13, No. 3, 2024, pp. 402-415.
40. Zewei D, Xiaodong & Ming Z: "Research progress of silane impregnation and its effectiveness in coastal concrete structures: A review". *Journal of Building Engineering*, Vol. 91, 2024, 109550, 14 pp.
41. Cui Z, Li Y, Bao Q, Chen Y, Xu Q, He Y & Wu F: "The impact of multi-marine intertidal service on the durability of concrete repair materials". *Case Studies in Construction Materials*, Vol. 22, 2025, 04358, 14 pp.
42. Berkowski P & Dmochowski G: "Examination of the influence of material and design parameters on the development of cracks due to the action of an elevated groundwater table". *Proceedings*, MATEC Web of Conferences 409 Concrete Solutions 2025, 05005 (2025), 7 pp.
43. Geiker M, Danner T, Polder R, Antonsen R & Hornbostel K: "Long term phase changes in cathodically protected marine reinforced concrete bridge". *Materials and Structures*, Vol. 58:168, 2025, 15 pp.

44. Polder R B & Geiker M R: "Electro active repair of concrete: Innovation for increased repair durability". *Proceedings*, 5th International Symposium on Life-Cycle Engineering, IALCCE, 2017, pp. 1594-1601.
45. Siegwart M, Lyness J F & McFarland B J: "Change of pore size in concrete due to electrochemical chloride extraction and possible implications for the migration of ions". *Cement and Concrete Research*, Vol. 33, 2003, pp. 1211-1221.