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FEATURE ARTICLES

DEPARTMENTS

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Historical Advancements in Corrosion Control of Existing Conventionally Reinforced Concrete Structures in the United States: Towards a Sustainable and Viable Future

by David G. Tepke and Jose M. Mandry-Campbell

The history of durability and material provisions in codes and industry knowledge provide bases for planning and conducting structural investigations (Tepke[1]). This article explores the historical development of maintenance and corrosion control methods of existing concrete structures in the United States and touches on related topics that will likely be important in the future. For the purposes of this article, "corrosion control" applies to techniques that reduce the ingress of deleterious substances and reduce or effectively arrest corrosion. Corrosion control techniques employed both prior to and after the onset of corrosion will be considered. Specialty repair materials, contaminated concrete removal, and repair methodologies may also impact corrosion behavior and control, but are not included in the scope of this article.

This article intends to highlight the development of corrosion control for conventionally reinforced concrete and show generally what was available to practitioners at various times, as they may be encountered when investigating existing structures. It provides a brief and general overview of some of the more impactful corrosion control developments in the United States. However, some advancements elsewhere in the world are included to provide context. While several corrosion control technologies and advancements are discussed, it is not the intent of this article to be exhaustive in description or comprehensive in inclusion, nor is it the intent to promote any specific technologies or methods or comment on efficacy. Indeed, appropriate methods for corrosion control depend on a variety of factors requiring both theoretical knowledge and practical experience. As such, a specialist should be engaged to evaluate and determine appropriate strategies unique to each situation. Common variable factors to consider may include environmental conditions, structural characteristics, site access, level of future expected owner engagement, budget, safety, and desired service-life extension.

REPAIR AND SERVICE-LIFE EXTENSION ARE NOT NEW CONCEPTS

The industry's understanding of rehabilitation and service-life extension of concrete structures has considerably advanced since the latter part of the 20th century, but the general concepts of structural repair and preservation are not new. For instance, the structural condition assessment, maintenance, and repair of Rome's aqueducts and infrastructure were topics of interest to Marcus Vipsanius Agrippa (circa 63-12 BC), Sextus Julius Frontinus (circa 40-103 AD), and their contemporaries, as described in De Aquaeductu Urbis Romae (circa 97-98 AD) by Frontinus[2] (translated by Rodgers in 2003). Among the more interesting descriptions of condition, maintenance, the role of experts, and repair are:

> *"...In the same year Agrippa reconstructed the conduits of Appia, Anio, and Marcia, which were in very poor condition..." (Section 9.9)*
>
> *"...He [Agrippa] had also a personal work crew for maintaining the conduits as well as delivery-tanks and basins..." (Section 98.2)*
>
> *"...Many, sometimes large-scale, tasks are constantly arising, which should have prompt attention before extensive remedy may be required..." (Section 119.2)*
>
> *"He ought not only to consult the engineers in his own office, but also to call upon the reliable judgment and expertise of numerous others, that he may in the end determine which tasks are to be undertaken without delay and which are to be postponed... (Section 119.3)*
>
> *"Maintenance tasks arise for the following reasons: damage occurs from wear and tear, from wrongful behavior on the part of landholders, from violent storms, from faulty workmanship (which happens rather often in the case of recent works)." (Section 120)*

While these conditions are not related to corrosion of reinforcing steel, they demonstrate similar difficulties faced more than 2000 years ago in addressing repair and service-life extension. Figure 1 shows Marcus Agrippa,[3] a recent picture of the remains of historic aqueduct constructions that includes the Aqua Maria,[4] and Sextus Ilulius Frontinus.[5]

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Fig. 1: (a) Marcus Agrippa, (b) the remains of several aqueduct constructions including the Aqua Maria, and (c) Sextus Julius Frontinus (photos a and b permitted by license in references and photo c in public domain)

CORROSION OF REINFORCING STEEL, CORROSION CONTROL, AND SOCIETAL IMPACTS

Reinforcing steel in concrete is typically well protected from corrosion due to a passivation layer that develops on the steel surface as a result of the high pH of pore solution. This passivation layer can be destroyed, however, and render the steel vulnerable to corrosion in certain conditions. While there are other conditions not discussed herein that may lead to depassivation, the two most notable and frequently encountered conditions in typical structures are associated with reduction in pH from carbonation and attack from chlorides.

Carbonation progressively advances into the concrete from exposed surfaces to reduce pH through the reaction between atmospheric carbon dioxide, moisture, and calcium-bearing hydration products. Chlorides can be present within the concrete from contaminants or admixtures that were introduced during initial placement, particularly in older structures (Tepke[1]). Chlorides can also penetrate externally into the concrete over time from exposure to deicing chemicals, industrial or manufacturing chemicals, seawater (including its spray or airborne deposition), or other sources. Once present in sufficient amounts at the level of reinforcing steel, chlorides promote pitting and severe corrosion. In addition to the reduced cross-section of structural reinforcement from the corrosion process that can eventually compromise structural integrity, the conversion of steel to iron oxides and hydroxides produces expansive stresses from within the concrete that may result in cracks, delaminations, and spalls that can present tripping hazards, overhead spalling hazards, and reduced fire resistance.

Implications of reinforcing steel corrosion include potential safety hazards, costly repairs, and impacts to the environment from carbon demand associated with repairs. In severe cases, replacement may be necessary or more economical than otherwise extensive widespread repairs. The reader is referred to ACI PRC 222R[6] and ACI PRC 201.2R[7] for more complete review of mechanisms and implications of corrosion, including effects of cracking, stray currents, and specialized exposures. Figure 2 shows a schematic of the corrosion initiation process for chloride-induced corrosion and Figure 3 shows some examples of distress in structures.

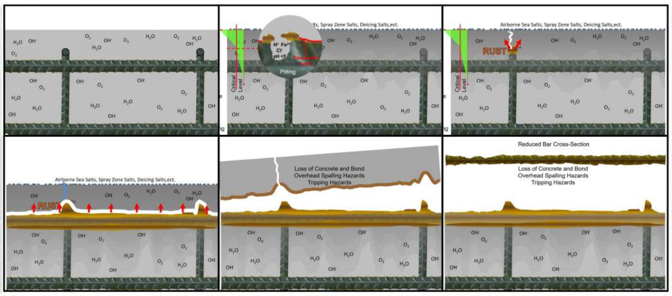

Fig. 2: Schematic of corrosion process for chloride-induced corrosion

Fig. 3: Corrosion-related distress: (a) pitting from chloride-induced corrosion (after bar cleaning), (b) corrosion products compared to bare steel, (c) corrosion-induced cracking, (d) cross-section of delamination, (e) overhead delamination and spalling hazard, (f) horizontal spalling and tripping hazard, and (g) reinforcing steel disintegration

Tuutti[8,9] proposed a two-stage service-life model for reinforcing steel corrosion caused by penetration of external contaminants (Fig. 4) that has formed the basis for many other models that have since been developed. The first phase of the model, initiation, describes the time prior to the onset of corrosion and is generally governed by the time it takes for corrosive agents to reach the steel, the properties of the steel, and the properties of the concrete, including possible presence of corrosion-inhibiting admixtures. The second phase, propagation, describes the time after the onset of corrosion towards a "limit state". The limit state represents the upper limit on acceptable corrosion, and was defined as cracking by Tuutti. The time to reach the limit state is influenced by temperature, moisture, oxygen, material properties, and the associated corrosion rate. Some newer models include a tertiary phase which depicts an exponential increase in associated costs and structural depreciation from corrosion-induced concrete damage that persists beyond the point where cracking initiates. Other models also sometimes define limit states associated with serviceability or end of safe use, etc.

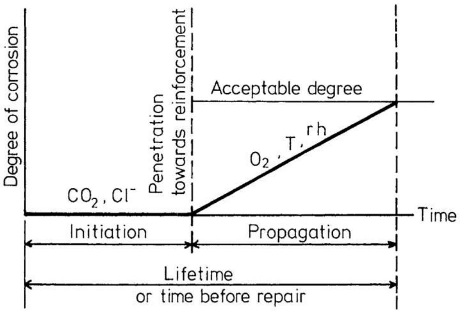

FIGURE 1. Schematic drawing of the corrosion process of steel in concrete.

Fig. 4: Corrosion initiation and propagation model presented as Figure 1 in Tuutti (reproduced with permission from the American Concrete Institute)

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The corrosion initiation phase can be prolonged through surface-applied protective coatings or treatments that effectively retard the ingress of deleterious species and moisture, and inhibit or delay initiation. Once corrosion begins (propagation phase), short-term or long-term electrochemical mitigation techniques can abate or drastically slow down the rate of corrosion in most situations. Electrochemical chloride extraction (ECE) and realkalization are acute electrochemical techniques applied for short periods that remove chlorides from the vicinity of the steel or increase concrete alkalinity, respectively. Cathodic protection (CP) is an electrochemical technique that depresses the potential of the steel, equilibrates potential differences along the steel surfaces, forces cathodic reactions, and modifies the concrete environment near the steel over an extended period to arrest corrosion using more moderate protection current densities. Galvanic cathodic protection (GCP) is accomplished through connecting embedded steel to anodes made of more active metals at higher natural energy states (such as zinc, aluminum, or their alloys). The more active metals protect the steel through the inherent generation of protective current when dissimilar metals are connected in an electrolyte. The more active metal is sacrificially consumed as it protects the steel. Impressed current cathodic protection (ICCP) uses anodes, typically inert or practically so, and an external power supply to generate and maintain protective current. Both CP techniques may also be used prior to corrosion initiation as a preventative approach, sometimes termed cathodic prevention. GCP is sometimes used in this manner as part of concrete repairs to reduce the "halo effect" or "incipient anode effect" (Fig. 5) which are phrases used to describe the propensity for corrosion to begin in contaminated existing concrete adjacent to new patch repairs.

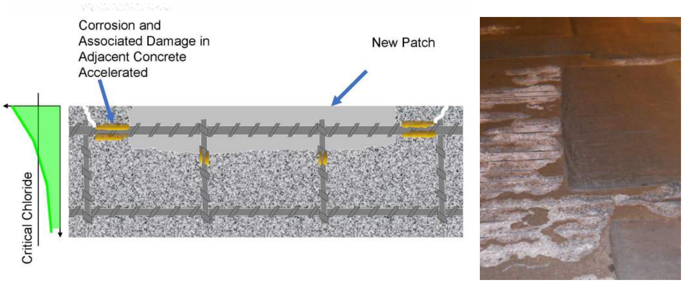

Fig. 5: (a) Schematic and (b) example of incipient anode effect after the repair of concrete

Protective coatings may additionally be used during propagation phase to limit moisture, but this is generally a temporary approach and only substantially effective when combined with other methods that arrest corrosion, particularly in aggressive conditions. Additional information on corrosion control measures, and associated benefits and limitations, can be found in ACI PRC 222R,[6] NACE SP0390,[10] NACE SP0187,[11] and NACE SP0112.[12]

In a study that considered data representative of the years 2010-2011, Angst[13] estimated that the direct costs associated with corrosion control, prevention, and repair for concrete structures in the United States was approximately US $50 billion. With inflation and the continual aging of infrastructure, this number likely exceeds US $70 billion today. While this sum alone is cause for concern, the societal impacts of concrete corrosion add even more context to the importance of proactive control. Indirect inconveniences associated with frequent repair and replacement construction, potential safety hazards in areas of severely corrosive conditions, and global warming potential from carbon-generating repairs and replacements of structures can all be decreased with the continued development and practical adoption of proactive control techniques.

EXAMPLES OF SOME MAJOR ADVANCEMENTS IN CORROSION CONTROL IN THE 20TH AND 21ST CENTURIES

General Publications and Initiatives Associated with Corrosion Control

The first ACI Committee 201 report in 1962[14] included a section on corrosion of reinforcement in concrete that briefly mentioned cathodic protection and provided some discussion on coatings for corrosion control. However, the report also indicated:

> *"Several methods of stopping or retarding further corrosion have been suggested and tried experimentally. None of these methods has been demonstrated to be completely adequate or economical." (ACI 201[14] pg. 1801)*

Tuutti reported on his service-life model in 1980[8] and the first ACI 222 committee report on corrosion of metals in concrete was published in 1985.[15] The International Association of Concrete Repair Specialists was formed in 1988 (later named International Concrete Repair Institute in 1993) with the following stated purpose:[16]

> *"To improve the quality of concrete restoration, repair, and protection through education of, and communication among, the members and those who use its services."*

The first version of the ACI 546 Concrete Repair Guide was published in 1996.[17] NACE RP0187 Design Considerations for Corrosion Control of Reinforcing Steel in Concrete was published in 1987[11] and included discussion on preventative measures, cathodic protection and monitoring, and NACE RP0390 Maintenance & Rehabilitation Considerations for Corrosion Control of Existing Steel-Reinforced Concrete Structures was published in 1990.[10] Vision 2020: "A Vision for the Concrete Repair, Protection and Strengthening Industry" was established in 2003 with one of the goals being to establish testing protocol for evaluating corrosion mitigation techniques in existing structures.[18] ACI 562 Concrete Repair Code was first published in 2013[19] (updated 2016, 2019, and 2021), has been adopted as permissible in several jurisdictions, and will be referenced as a permissible approach for repair of concrete structures in the 2024 International Existing Building Code. M-82 protocol for

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evaluating corrosion control technologies in repairs, was published by the Bureau of Reclamation in 2014.[18]

Figure 6 represents a timeline of some key advancements for the purpose of giving the reader a general understanding of progress. It is not meant to be comprehensive in nature. The following sections provide a brief description of some of the advancements.

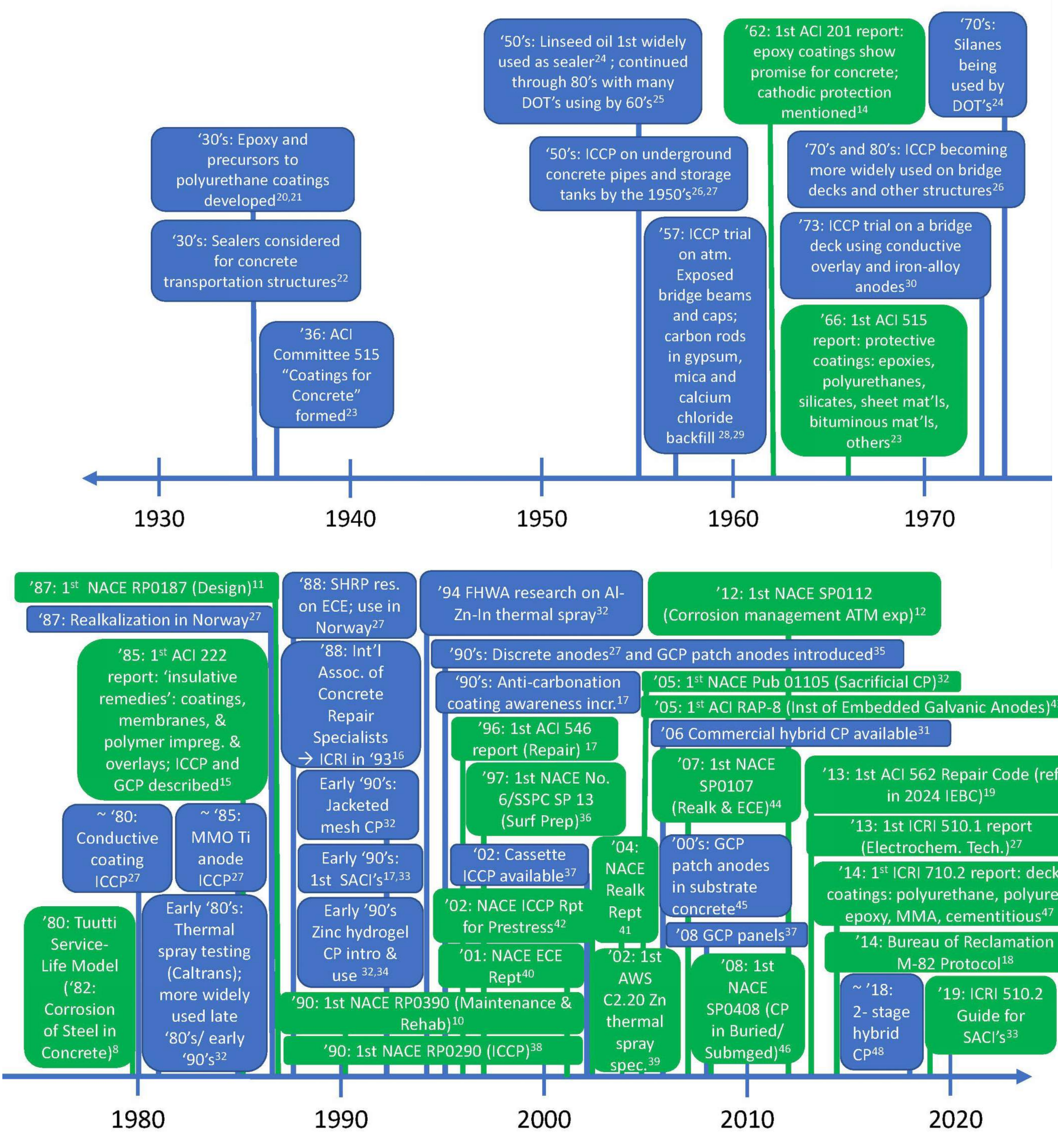

Fig. 6: Timeline with some key documents (green) and advancements (blue) [10,11,14-17,19-48] (note that this chart represents only some of the advancements, and is not meant to be all-inclusive)

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Protective Coatings

Initial chemistry formulations for epoxy coatings[20] and polyisocyanate precursors to polyurethane coatings[21] were developed in the 1930s. ACI Committee 515 was formed in 1936[23] "to prepare recommended practices for the application of coatings to concrete surfaces for the purpose of decoration, dampproofing, and waterproofing, and to protect concrete against deleterious agents by externally applied materials, whether coatings, linings, chemical-resistant masonry, or chemical treatments by liquids or gases." The first ACI 201 committee report in 1962[14] included statements cautioning against the use of protective coatings to arrest ongoing corrosion, but discussed the likely benefit of protective coatings:

> *"The judicious application of waterproof coatings may serve to prolong the useful life of a structure but their indiscriminate use may increase the level of moisture within the concrete and thus accelerate corrosion. None of them offer permanent protection." (pg. 1801)*
>
> *"Epoxy resin paints, although recently developed, show considerable promise as protective coatings for concrete." (pg. 1813)*

Just a few years later in 1966, ACI Committee 515[23] published "Guide for the Protection of Concrete Against Chemical Attack by Means of Coatings and Other Corrosion Resistant Materials" that described a wide range of chemicals that attack concrete and steel, as well as recommendations for protective coatings for use on concrete, including epoxies, polyurethanes, silicates, sheet materials, hot-applied bituminous materials, and others.

The use of sealers was considered in the 1930s for transportation structures.[22] Linseed oil was used between the 1950s and 1980s,[24] and was commonly being used by departments of transportation (DOT's) by the late 1960s.[25] Alkyl alkoxysilanes were first proposed as a concrete sealer in Germany in 1969[49] and silanes were being used by US DOT's by the 1970s.[24] A considerable amount of research and investigation was conducted in this period on sealer materials, including those of oil and rubber, resins, petroleum products, silicones, and others.[50]

The first ACI 222 committee report in 1985[15] discussed the use of "insulative remedies" to "isolate reinforced concrete from a corrosive environment". These insulative remedies included surface coatings, membranes, polymer impregnation, and polymer overlays. The 1985 report cautioned that once corrosion is active, coatings do not stop corrosion but may provide some mitigating effects.

Developments into the 1990s and beyond included increased awareness for the use of anti-carbonation coatings for reducing associated penetration.[17] NACE No. 6/SSPC-SP 13, *"Surface Preparation for Concrete"*, was first published in 1997[36] (since updated multiple times). ICRI 710.2[47] was first published in 2014 to provide guidance on horizontal waterproofing including polyurethane, epoxy, polyurea, cementitious, and methyl methacrylate coatings. Environmental and health issues, such as lead and volatile organic contents, have influenced coating technologies as regulations have been imposed on limits in application and in disposal.

Additional discussion on coatings or applications for corrosion control can be found in ACI PRC 222R,[6] ACI PRC 546.3R,[51] ACI PRC 515.2R[52] and ICRI 710.2.[47] Figure 7 shows some examples of protective coatings on concrete structures.

Fig. 7: (a) Cementitious and (b) polyurethane deck coatings

Surface-Applied Corrosion Inhibitors

Corrosion-inhibiting admixtures for new concrete were first commercially available in the late 1970s.[53] Surface-applied corrosion inhibitors (SACIs) for use on existing structures were first introduced in the early 1990s[17,33] with much research being conducted in the years and decades that followed. A number of technologies have since been proposed or made commercially available.[6, 33] ICRI 510.233, a guide discussing technologies, evaluation and use, was published in 2019. ACI PRC 222R-196 and ACI PRC 546R-1617 provide information and recommendations regarding SACIs; reference to use is not included in the current version of NACE SP039010.

Figure 8 shows the application of a commercially marketed SACI at a parking structure.

Fig. 8: Application of surface-applied corrosion inhibitor to parking garage surface at test area showing sectioned installation for ensuring adequate coverage rates

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Electrochemical Techniques

Sir Humprey Davy reported on the protection of copper sheathing from seawater with iron during his work funded by the British Navy in 1824;[54] however, widespread use to protect steel in concrete would not come until more than 100 years later. By the 1950s, ICCP was being used on underground prestressed concrete water pipelines and storage tanks.[26,27] The first use of ICCP in atmospherically exposed concrete in the United States might be that reported by Stratfull.[28,29] This included the use of carbon rods in gypsum, mica, and calcium chloride backfill in a trial system on bridge beams and pile caps that started in 1957. Stratfull[30] reported experimental application of ICCP on a bridge deck for Caltrans in 1973 with an electrically conductive asphalt concrete overlay using coke aggregate and iron alloy anodes. Conductive coatings with primary anode wires were introduced around 1980 and MMO (mixed metal oxide) coated titanium anodes were introduced around 1985.[27]

Thermal spray GCP was tested by Caltrans in the early 1980s and became more widely used in the late 1980s and early 1990s.[32] FHWA research was conducted on Al-Zn-In alloys for thermal spray in the 1990s[32] and the first AWS standard specification for zinc thermal spray was published in 2002.[39]

Other advancements in the 1980s include research and introduction of ECE and realkalization.[27,40,41] Discrete ICCP anodes and patch repair galvanic anodes were introduced in the 1990s with a number of patents on galvanic systems being filed in the 1990s and 2000s.[27,34,35,45] Hydrogel systems,[32] cassette systems,[37] and panel systems[37] were also among the technologies introduced in the 1990s or 2000s. Commercial hybrid ICCP/GCP and self-performing 2-stage systems were introduced after the turn of the 21st century.[31,49]

The first ACI 222 committee report in 1985[15] provided discussion and comparison of GCP and ICCP in concrete. This guide was updated 1996, 2001, and 2019. A number of NACE and ICRI guide documents and publications were introduced for the first time in the 1990s and 2000s, including NACE documents on corrosion in different environments, design for corrosion control, maintenance and rehabilitation, ICCP, GCP, and prestressed concrete.[10,11,12,32,38,40,41,42,44,46] A field guide to installation of embedded galvanic anodes was published as ACI RAP-8 in 200543. The reader is referred to Figure 6 and references[26, 27] for additional historical context, and references[6,38,44,46,55] for additional technical information. Figure 9 shows some examples of cathodic protection on existing structures.

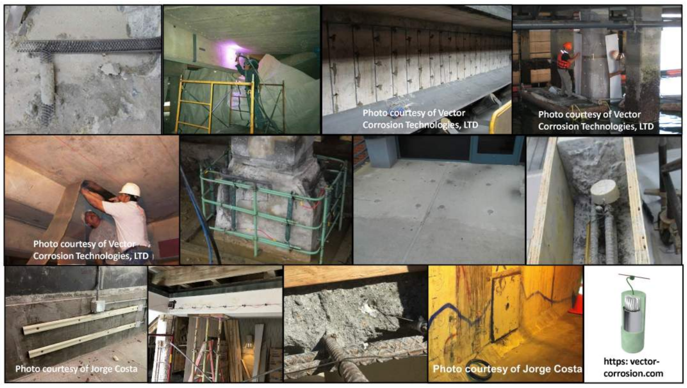

Fig. 9: Cathodic protection systems: (a) MMO-Ti mesh ICCP, (b) thermal spray, (c) discrete anodes, (d) jacketed mesh system, (e) zinc hydrogel sheeting, (f) discrete zinc anodes inside repair, (g) discrete zinc anodes, (h) patch galvanic anode, (i) cassette ICCP system, (j) hybrid ICCP/GCP system with zinc anodes, (k) zinc anodes outside patch area, (l) zinc galvanic panel, and (m) 2-stage ICCP/GCP anode

FUTURE CONSIDERATIONS

Sustainability

Meeting the needs of today's society in an economically viable manner without sacrificing the environment of today or the future requires deliberate consideration of design and construction of new structures, as well as proactive preventative maintenance of existing structures. Embodied carbon and global warming potential of construction and construction materials must be coupled with service-life expectancy of structures to estimate the realistic long-term impact on the environment. Certainly, recent focus has been placed on decreasing environmental impact of new concrete structures through the development and implementation of initiatives such as the integration of alternative cements, use of portland-limestone cements, more judicious use of supplemental waste materials in concrete, codification for use of FRP reinforcement in concrete structures, codification of sustainability for concrete structures, and development of a durability code to extend the life of new structures.

A white paper by ICRI Committee 160[56] highlighted some of the key aspects of sustainability with respect to repairs, corrosion control, and influence of service-life extension. Corrosion control provides a sustainable option for existing reinforced concrete structures by increasing service-life and decreasing the frequency of environmentally costly repair or replacement. Within the past 30 years, standard methods have been developed which have broadened the use of corrosion control in repair and preventative maintenance. There is potential for further investigation into the economic and environmental impacts of service-life consideration and corrosion control.[57]

Safety

Safety of existing structures in coastal environments and those exposed to deicing chemicals or other corrosive conditions recently has been of increased focus. References[58-61] provide discussion on structural safety and expected future initiatives, including impact from corrosion.

Technology

The prospective future of concrete repair and corrosion control offers promise in moving toward a more sustainable future. The process of evaluating existing structures will likely advance with new technologies that assist in determining the feasibility, cost-effectiveness, longevity, and general quality of repair. However, many structures are not evaluated

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or considered for comprehensive maintenance until well after corrosion and damage initiate, limiting options for assessments and service-life extension techniques for the design professional. Repairing a structure with extensive deterioration generally requires added conservatism. Thus, timeliness of evaluation is a key factor in maximizing benefits of corrosion control.

There has been recent interest in the use of machine learning for better predicting concrete properties and corrosion.[62,63] Development of these principles may be able to assist in predicting the critical time for evaluation of a structure. If a reasonably large database of different structures and deterioration mechanisms is created, and dependable methods and techniques are used for generating information, machine learning technology may offer the potential to help better predict the corrosion initiation (or other distress mechanism) more accurately in new or existing structures. This data could be used to form a maintenance plan during design of a structure or as a guide for evaluation strategies. Pacheco and Tepke[64] provide discussion on best practices for corrosion monitoring, but certainly, monitoring and control systems for structural health monitoring and corrosion control will continue to advance.

A number of questions may come to mind regarding the future research needs and practices of corrosion control.

Sustainability

- How will alternative cements impact corrosion and corrosion control in the future?
- How will alternative reinforcing materials, such as corrosion-resistant steel and fiber-reinforced polymer (FRP) reinforcement, impact need and implementation of corrosion control?
- How will the industry accurately represent carbon demand and global warming potential as they relate to sustainability initiatives for service-life implications, repairs, replacements, and forecasted material use in the future? What research or information is needed?
- How will sustainability initiatives or material regulations impact corrosion control?
- How will sustainability standards for new structures (such as being developed by ACI Committee 323) impact corrosion control?
- How will new initiatives for durability code (such as being developed by ACI Committee 321) and maintenance influence service-life and implementation of corrosion control?
- How will relative cost differences associated with structural replacements, structural repair, corrosion control, and preventative maintenance influence societal norms for addressing existing structures?

Safety

- How will adoption of ACI 562 Repair Code impact repairs and corrosion control?
- How will safety regulations impact corrosion control?
- How will aging structures impact demand for corrosion control?

Technology and Technology Transfer

- How will Artificial Intelligence and machine learning impact the industry?
- How will monitoring corrosion and corrosion control advance?
- What is the best way to promote training for professionals and tradesmen implementing corrosion control?
- How will recent advancements and trends such as use of specialty concretes, corrosion inhibitors, and other materials in new construction impact corrosion control?
- What new technologies will be developed for corrosion control and how will newer technologies perform? How will new technologies associated with surface treatments, cathodic protection, specialty repair materials, evaluation, and monitoring perform?

CLOSING

Significant progress was made with respect to technologies and industry guidance for corrosion control of existing concrete structures in the 20th century. Topics and initiatives associated with building safety, economical implementation, sustainability, and further technological advancements are expected to impact research and application in the near future. The authors have attempted to provide some historical basis and perhaps some thoughts on where the industry may be going.

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