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Over view of cathodic protection of reinforced concrete structures by means of thermally sprayed zinc layers - a proven CP system

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Abstract

The cathodic protection (CP) of concrete structures by means of thermally sprayed zinc layers is discussed. The status of research and the existing problems in this area are reported. On the basis of literature, for CP of concrete structures with respect to anode coatings, Ti based anodes are effective but not very cost effective. Magnesium anodes are not found suitable for spraying on the surfaces of the concrete. Sprayed aluminium is not found stable in alkaline environments. Conducting polymer anodes are still needs more attention. Even though small drawbacks encountered in zinc anodes, thermal spraying of zinc on the concrete bridges and structures are feasible and found effective.

Key words: Zinc, thermal spray anodes, cathodic protection, concrete

Introduction

Cathodic protection technology is a very promizing field as a fool-proof technology for corrosion control. However cathodic protection as applied to concrete structures and bridges is a challenging task owing to the heterogeneous nature of concrete medium and also the high electrical resistivity of the concrete. Because of the cost factor, even in the US and other countries where bridge corrosion is a serious problem, cathodic protection has been adopted only in a limited number of bridges. It is necessary that, a realistic assessment and development of a cost effective and viable cathodic protection system is the need of the hour such that any construction industry can readily accept and adopt.

In the USA, the collapse of the Silver bridge into the Ohio River cost 40 lives and millions of dollars. As per the report, an estimated $2 billion was spent by US industry in 1997 for corrosion protection. Each year, the US navy spends $ 200, 000 in preventive maintenance per air-craft. It can thus be seen that, non-attention to corrosion may lead to considerable loss of money. Apart from this direct loss, losses might also take place through plant shutdowns, equipment failure, replacement of corroded items, loss of products by leakage, contamination of products, over design of plants etc., While working out the cost of corrosion in any industry all these factors are to be taken into account. Many attempts have been made in different countries to estimate the annual cost of corrosion. The following table chronologically projects the cost of corrosion in different countries.

Author	Cost of corrosion	Country	Year
Hudson	200 million pounds	UK	1940
Uhlig	US $ 6000 million	USA	1949
Vernon	600 million pounds	UK	1949

Linderborg	US$ 47-62 millions	Finland	---
Linderborg	US$ 39 millions	Sweden	---
Rajagopalan	Rs.150 crores	India	1960-61
Behrens	US$ 6000 millions	Federal Republic of Germany	1968-69
Kolotyrkin	US$ 6900 millions	USSR	1969
Rane	470millions Australian dollars	Australia	1973
Boshoku Gijutes	US $ 9200 millions	Japan	1976-77
Hadfield	600 million pounds	World	1992

In 1969, Dr.T.P.Hoar committee of UK contacted about 600 industries and major government organizations and on the basis of industry wise cost of corrosion arrived at a figure of 1335 million pounds. Out of these, building and construction industry itself contributed 250 million pounds. It is worth noting that out of 1335 million pounds nearly 310 million pounds (23%) could be saved through use of appropriate corrosion protection methods. The cost of corrosion and its control in any country, for that matter in a highly developed country such as the USA has been variously estimated as 2 to 5 % of Gross National Product. Infact, W.Brain Holts Baum, president of the National Association of Corrosion Engineers has stated as follows. "Corrosion costs $1100 for every man, woman and child in the United States. The public and Industry will continue to pay for unnecessary losses caused by corrosion until corrosion control design and maintenance procedures are implemented on a wide scale. The total annual costs of floods, hurricanes, tornadoes, fires, lightning and earth quakes are less than the costs of corrosion. Concrete structures such as bridges are vital for maintaining the life line of transport uninterrupted. Many onshore and offshore bridges are built all along the coast to transport men and materials. Other concrete structures include harbours, offshore platforms, pipelines and structures of inter-land development. Concrete bridges especially in the coastal regions are said to be in distress. The durability of concrete structures exposed to marine condition is affected even though they have been designed for a minimum life of 60 years providing a trouble free life of only about $1/5^{th}$ of the design life. To increase the trouble free life of the structures, effective additional protective measures must be undertaken at the initial stage itself. For the mitigation of corrosion of rebars in concrete structures various protective measures like coatings to steel rebars, coatings to concrete, modification of steel, corrosion inhibitors, cathodic protection of steel rebars have been reported. Each method of protection has its own merits, demerits and limitations. Proper selection of method of protection can only lead to saving of money and materials.

Status report

After extensive research and testing, the Federal Highway Administration, USA issued the policy statement that the only rehabilitation technique that has proven to stop corrosion in salt contaminated bridge decks, regardless of the chloride content of the concrete is cathodic protection [1].

According to Hull, out of 5,00,000 bridge decks in the USA, 3,00,000 are candidates for cathodic protection [2]. Throughout the 1970’s a variety of bridge deck cathodic protection designs was initiated, using different types of anodes such as conductive coke asphalt overlays, platinum wire, graphite fibre anodes and slot anodes surrounded by conductive polymer materials etc.[3]. During the early 1980’s systems using anodes that covered the entire concrete surface were introduced [4-7]. The use of conductive materials such as metallizing (Zn), conductive coatings, mesh or network of conductive polymer cable became known during 1980-1981 [8]. The Ontario Ministry of Transportation, Canada had applied cathodic protection to about 40 structures till 1990 [9]. In 1989, 287 cathodic protection systems on bridge decks and substructures had been in operation in the US and Canada. In the year 1991, 11 bridge systems were reported under operation [10]. Germany’s first cathodic protection system for a chloride contaminated reinforced concrete structure was installed in 1986 as a pilot project. The system was switched off after 15 years because of traffic related reconstruction. In 2001, Mietz et. al. from BAM, Germany made an investigation of the conductive polymer/copper ore anode and reported that irreversible changes had substantially decreased the polymers conductivity limiting its functionality [11].

The following criteria have been compared for their reliability:

a. E- Logi test
b. 100 mV potential decay
c. 300 mV potential shift
d. –770 mV vs. CSE instantoff potential
e. –850 mV vs. CSE instantoff potential

Obviously the current required shifting the potential to –770 mV/ -850 mV has been found to be much higher. 100 mV potential decay was initially reported to be a reliable criterion but subsequently has been found to give underprotection. Though E-Logi criterion has scientific basis, experimentation is somewhat complicated.

Electrical resistivity of the concrete has been found to be one of the factors influencing the potential shift. In this respect, use of conductive polymer anode was found to be highly advantageous. Conventional shot-crete overlay system has been found to perform satisfactorily when compared to conductive paint system.

In the case of sub-structures wide variations in current requirements were observed in low tide and high tide cycles. One of the significant findings has been the effect of migration of chlorides towards the surface. This migrating chloride could cause disbondment of the conductive coating and ultimately lead to failure of cathodic protection. These studies indicated that impressed current cathodic protection system based on conductive mastic or conductive concrete may not be effective in marine substructure environments. Conductive rubber anodes have also been experimentally used in the USA for marine substructure protection. Various investigations have shown that the protection current density may lie in the range of 10-20 mA/m^2 of concrete surface area. Internal graphite anodes mounted in drilled holes inside the concrete structures have been found to be quite useful. For effective monitoring of the cathodic protection embeddable reference electrodes have been developed and used.

Stratfull had evaluated the various cathodic protection criteria on a salvaged section of the bridge deck that was removed from the Gleebe Road over crossing on the George Washington Memorial Parkway [12].

Eight experimental cathodic protection systems with 8 different types of anodes were installed on piers of the Burlington Bay Skyway by the Research and Development Branch of the Ontario Ministry of Transportation and Communication during the year 1982–83 [13]. Kessler and Langley evaluated a cathodic protection system using conductive coatings and conductive concrete in two deteriorated reinforced concrete bridge structures [14].

Kessler and Powers have evaluated the performance of conductive rubber anodes to protect steel reinforced concrete piles in marine environments [15].

Tellamanti have conducted long-term tests on mixed metal oxide titanium anode expanded net and examined the chemical changes in concrete around the anode surface during the functioning of the protection system [16]. Of all the embeddable reference electrodes studied, silver electrode showed better stability.

Brain Hope and John Poland studied the effect of rectifiers on the hydrogen generation [17]. The studies revealed that when the cathodic protection is applied using commercial rectifier (unfiltered circuit) hydrogen was produced when polarized potentials were more negative than –940 mV vs. CSE.

Hannah Schell and David Manning have evaluated the performance of metal oxide titanium mesh anode on Freeman's Bridge deck, Ontario [18]. After 9 months of cathodic protection the physical condition of the deck surface was examined and no delamination of the overlay had occurred in areas where the anodes were installed.

Robert Brown and John Tinnea have discussed the problems in designing the cathodic protection of reinforced concrete structures and suggested suitable recommendations to obtain the designed life of a cathodic protection system with minimum maintenance problems [19].

Funahasi and Bushman evaluated the influence of temperature and chloride content on the amount of polarization shift required to protect the reinforcing steel in concrete [20].

Kurt Nielsen et. al. have evaluated the performance of internal anodes mounted in drilled holes inside the structures [21]. The anode consisted of graphite backfill material, which was injected into 12 mm dia. drilled holes. This type of anode had the following advantages:- no additional weight, fast and easy mounting, reduced problems with short circuits and applicable where hot protection is required.

SHRP had conducted a survey on cathodic protection systems installed in various interstate highway bridges in the US and Canada [22]. Survey mainly consisted of corrosion current density used, type of anode, measurement of decay potential, chloride content and visual observations. Out of 287 cathodic protection installed bridges, 49 bridges were surveyed for the efficiency of cathodic protection after 7 to 15 years of system installation. Six types of anodes had been used. In bridge deck, the most commonly used anodes were conductive asphalt with silicon iron anode, slotted carbon filled conductive polymer anode, conductive cable anode and expanded titanium mesh anode. In substructures, the anodes used were conductive carbon paints and flame/arc sprayed coating. Of the 151 zones inspected, only 18 zones were deemed to have failed by the criteria used by the inspection team.

An intermittent impressed current cathodic protection technique using photo voltaic energy has been evaluated for its ability to protect bridge concrete piles [23].

A sacrificial magnesium anode installed on an underground reinforced concrete structures was found to meet the established cathodic protection criteria [24]. The problems encountered while using thermal spray anodes of zinc or titanium have been discussed in detail [25]. Titanium based mesh anode for CP of concrete structures was reported [26].

Cathodic Protection of reinforced concrete structures

Cathodic protection of reinforced concrete has been developed by a combination of trial and error, fundamental research, applied research and transfer of technology from related fields. These developments have been underway for 35 years and have been progressed by civil engineers, concrete technologists, corrosion scientists and cathodic protection engineers. In the U.K. in 1993 the investment in repairs to reinforced concrete structures incorporating cathodic protection has grown from a minimal £100,000 p.a. to some £20 million p.a. [27] In Japan, concrete structures exposed to marine environments are deteriorating due to corrosion of reinforcement. Since this deterioration advances rapidly and seriously, effective corrosion protection must be considered for both new construction and damage-repair. Cathodic protection is expected to be a practical corrosion protection system for all concrete structures in marine environments. The developmental criteria for cathodic protection on concrete structures and the examining of over-protection problem on prestressed-concrete structures are two points were considered for the establishment of high reliability for cathodic protection of concrete structures [28]. In Italy, the current and potential distributions measured on concrete slabs and simulated by computer modeling are discussed in relation with the application of cathodic protection to new reinforced structures as a corrosion preventive method [29]. In Canada, the laboratory program undertaken to investigate the practicality and safety of applying cathodic protection to prestressed concrete structures has been described [30]. In Australia, corrosion and spalling of reinforced concrete columns particularly in tidal seawater zones is a major concern. A greater emphasis is being given to the maintenance and preservation of existing structures rather than the expensive alternative of replacement. A newly developed technique of applying cathodic protection to steel reinforced concrete comprise of conductive tape and mixed metal oxide coated titanium mesh anode (CAT) system. Protection is provided with an even current distribution over the surface via the conductive tape. A major advantage of the CAT system is that it does not require the use of specialized equipment and that installation time is minimal. Two trials performed on road bridges in Victoria and Queensland, Australia are described in detail. The CAT systems were installed to protect the tidal zones and above. Polarization effects and the possibility of current "dumping" in submerged zones were investigated [31]. The impressed current cathodic protection on reinforced concrete shown that the cathodic area is initially made very alkaline immediately after switch-on and the anodic area becomes acidic in nature. This acidic area spreads out from the anodic electrode towards the cathodic area. It is found that this alkalinity is produced at the cathodically impressed rebar as the impressed current (a) uses up the dissolved oxygen; (b) requires the hydroxyl ions to carry the ionic current; (c) produces hydrogen. In conclusion, for cathodic protection to work effectively there must be a way for oxygen to diffuse to the cathodic area, so that it takes part in the cathodic reaction. The anodic area becomes acidic and the alkaline OH^- ions are moved away from the rebar as a requirement for continuous current flow [32]. Pietro Pedeferri described the developments in cathodic protection for aerial concrete structures and the operating conditions as far as potential and current are concerned and the problems regarding throwing power, the possibility to reach a condition of protection without running the risk of hydrogen embrittlement in the case of prestressed structures are discussed. Examples of cathodic protection and cathodic prevention design, execution, operation and monitoring are given [33]. After nineties, cathodic protection of steel in concrete is reported by several authors [34-56]. The utility of conducting polymer composites and conductive coatings for cathodic protection is reported [57-60].

Cathodic protection of concrete structures by thermally sprayed zinc coatings [61-68]

Caltrans came to the fore again by developing thermal sprayed zinc applied to bridge substructures. This system was somewhat more durable than conductive coatings, without the requirement for a perfectly dry surface. The use of arc sprayed zinc on the 10,000 m^2 substructure of the Yaquina Bay bridge in Oregon in 1992 is one of the largest single substructure CP projects undertaken in the USA. The Strategic Highway Research Program (SHRP) undertook an extensive survey of the CP systems on North American bridges in 1988-89. They found 840,000 m^2 of concrete surface under cathodic protection on the US and Canadian interstate highway system.

The following main conclusions can be drawn:

- at the moment experiences from about 20 bridges exist; the oldest system is about 15 years in service. In all reports the thermally sprayed zinc layers are described to operate satisfactorily.
- for CP systems with zinc layers the same protection criteria are valid (minimum potential under wet conditions or minimum value for depolarisation after switching off the current during a certain period of time for dry conditions)
- the anodes have shown physical integrity during 4.5 years of testing (no delamination) in the aggressive conditions of Florida
- laboratory investigations have shown that after 2 years of testing current densities were in the range of 11 mA/m^2. In areas with severe corrosion the 100 mV criterion for depolarisation was achieved within 4 hours
- pre-tests with an organic coating onto the zinc layer have shown that the polarisation behaviour was not significantly affected

With respect to the principle of water reduction of the concrete in order to reduce the corrosion rate of the reinforcement, current research results have shown that the corrosion rate can be decreased to a negligible level in the case that the chloride contamination is not too high. Initial problems with the adhesion of zinc on concrete have been solved by modifications of process engineering parameters of the spraying (distance, angle) and a pretratement of the surface (blasting, heating). Tests and already existing practical applications have shown that sprayed zinc layers adhere very well at dry blasted surfaces. Further investigations have shown that an increased surface temperature (60 – 150 °C) during spraying significantly increases the adhesion. Investigations on the thermal influence of the melt droplets which hit the concrete surface do not exist. Metallographic examinations of the interface zinc/concrete do not indicate temperature related changes of the microstructure in the concrete or the cement phase. In this project such processes or changes (induced by zinc dissolution) at the interface zinc/concrete should be also investigated. Use of sprayed zinc anode for cathodic protection in concrete structures has ben attempted only recently. As such, the performance data is available only for a limited period. Even though the sprayed zinc has been experimented both as sacrificial and impressed current systems, the latter appears to be more effective. Arc spray process has been widely used in experimental studies. It has been found that the coating thickness is to be limited to 20 mils (0.5 mm) to avoid disbondment. At the time of spraying the concrete surface should be kept dry and warm and grit blasted at low air pressure, so as not to expose to coarse aggregates. Under impressed current system, 100 mV polarisation decay has been adopted to evaluate the effectiveness of the system and it has been found that all the portions have not satisfactorily fullfilled this criterion. In one experiment 80 % area had passed this criterion, while in another experiement only 18 % area had passed. Laboratory experiments have shown that the organic coating system over zinc spray can be beneficial from the point of view of a reduction in current requirements.

This review reveals that lot more developmental work needs to be carried out to make cathodic protection of concrete structures economically viable.

Existing problem in chloride contaminated concrete

For the rehabilitation of chloride-contaminated concrete structures with high chloride contents in principle the following strategies are possible:

- conventional mechanical removal of all chlordie-contaminated concrete and replacing by new repair mortar or concrete. If not all chloride-contaminated concrete is removed, this kind of patch repair has a high risk of forming new incipient anodes in vicinity to the new repair and hence the rehabilitation is only temporary. Furthermore, if the chloride content is high also in deeper areas the removal of that concrete can cause serious problems.
- due to disadvantages of the patch repair, cathodic protection systems for atmospherically exposed reinforced concrete structures have been developed and they show satisfactory results in practical application.
- the measures for drying out of the concrete by means of water-tight surface protection coatings can suppress the corrosion risks. But these processes take considerable time.

With a temporary cathodic protection system sufficient protection during such drying out processes could be possibly achieved. Experiences from different practical applications have shown that thermally sprayed zinc coatings on concrete surfaces are effective galvanic anodes to ensure cathodic protection of depassivated reinforcing steel over a limited period of time. Such anode systems are cheap, easy to apply and do not need maintenance. The idea of the combination with a surface protection overlay is that the reinforcing steel can be protected over the remaining service life of the structures.

Frequenly asked questions on thermal spray zinc coatings on concrete

- is the bond between sprayed zinc layer and concrete as well as between zinc and surface protection overlay sufficient and durable?
- is the galvanic current between zinc as sacrificial anode and the reinforcing steel sufficient to protect the steel?

- are there any limits with respect to maximum chloride levels
- long term performance of the anode
- suitable backfill material between anode and concrete
- protection criteria to be established
- studies on the anode and cathode terminals
- suitable additional protective surface coating to zinc

Future work on the above unsolved questions will lead a fool-proof technology and a proven system for protecting reinforcements in bridges and structures.

Conclusions

On the basis literatures studied the following broad conclusions have been made on cathodic protection with respect surface coatings on concrete.

1. Ti based anodes are effective for cathodic protection but not very cost effective anodes.
2. Magnesium and magnesium alloy anodes are not found suitable for spraying on the surfaces of concrete.
3. Aluminium spraying is found to be not stable in alkaline environments.
4. Conducting polymer anodes are still needs more attention.
5. Even though small drawbacks encountered in zinc anodes, thermal spraying of zinc on the concrete bridges and structures are feasible and found effective.

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