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Rehabilitation of reinforced concrete by electro deposition and physicochemical process – a Review

INTRODUCTION

Cracks in concrete can be caused by various factors, such as bleeding, shrinkage, faulty construction methods, poor construction practices, thermal gradients, settlement, corrosion of reinforcement, weathering (freeze-thaw) and alkali-aggregate reaction [1]. Micro cracks in concrete can also be induced by external loadings or as a result of the interaction of the concrete with the environment. These cracks play a major role on important parameters like permeability, rate of chloride ingress, compressive strength etc., and thus affects the reinforcement corrosion protection. Normally smaller cracks are harmless according to the durability point of view than larger cracks [2].

Micro cracks, which originally exist in the concrete, may propagate and become interconnected due to an applied stress [3]. These micro cracks may form potential flow channels which provide easy access to aggressive salts and ions such as chloride ions. The importance of micro cracks on the transport properties of concrete has been highlighted recently [4].

The effect of micro cracking on permeability under uniaxial compression has been studied by several researchers [5-8]. However, there are some conflicting views pertaining to their findings. Samaha and Hover [5] reported that micro cracking in concrete at stress levels below 75% of the compressive strength did not affect the mass transport properties of concrete. The micro cracks were quantified in terms of crack length by examining a concrete slice cut from a cylinder after the compression test.

Control of crack width has been given special attention in the design of concrete structures to be adequately protected against corrosion of steel in concrete. The various codes recommend maximum crack width in the range of 0.1 to 0.3 mm depending on the aggressive nature of the environment [9]. Construction codes specify maximum tolerable crack widths in the range of 0.2 to 0.3mm.

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Furthermore, when a crack occurs in the cover concrete, the corrosion of the steel reinforcement may be accelerated because the deterioration causing factors can pass through the crack. In recent years the effect of cracking on the penetration of concrete has been the subject of numerous investigations [10-14]. All of these studies have clearly indicated that the presence of cracks could contribute to an increase in the diffusion coefficient.

Aldea et al. [15] studied the effect of cracking on water and chloride permeability of concrete. The results showed that the chloride permeability increased with the increasing crack width.

Porosity and cracks are the main factors that affect concrete quality from the point of view of protecting reinforcing steel from corrosive species [16-18]. These factors can be controlled by three major parameters: (i) a low water to binder ratio (w/b), (ii) the inclusion of supplementary cementing materials, both of which reduce the porosity and (iii) adequate curing, which will minimize any cracking [19-21].

In this paper healing of cracks other than conventional methods (such as autogenous healing and electro deposition methods) and their importance has been reviewed from the point of view of strength, permeability and corrosion.

AUTOGENOUS OR SELF HEALING OF CONCRETE

Various types of crack healing have been reported in the literature. The process can involve physicochemical process, such as ettringite formation or mechanical defects such as blocking of cracks by rust, corrosion products or exterior particles. Regardless of origin, self healing leads to the crack closing, thus improving mechanical durability and permeability properties [22].

MECHANISM OF AUTOGENOUS HEALING

Autogenous or self-healing of cracks is generally attributed to the hydration of previously unhydrated cement grains and may be aided by carbonation, the bonding material so formed containing crystals of carbonate and calcium hydroxide [23]. This process can take place only in presence of water and absence of tensile stress [24] and consists of chemical reactions of compounds exposed at the cracked surfaces. These reactions produce crystals, and the accretion of these from the opposite surfaces of a crack can re-establish the continuity of the material eventually. The essential requirement, with water, is the presence of compounds capable of further reaction. Thus, cement, hydrated or not, is the essential reactive element. Healing of cracks occurs through the carbonation of calcium hydroxide in the cement paste by carbon di oxide, which is present in the surrounding air and water. Calcium carbonate and calcium hydroxide crystals precipitate, accumulate and grow within the cracks. The crystals interlock and producing a mechanical bonding effect which is supplemented by a chemical bonding between adjacent crystals and the surfaces of the paste and the aggregate. As a result, some of the tensile strength of the concrete is restored across the cracked section and the crack may become sealed [22].

ROLE OF AUTOGENOUS HEALING IN WATER PERMEABILITY AND STRENGTH

Most studies highlighted the self-healing phenomenon by means of water permeability tests. A reduction of the flow rate through cracked concrete is the main technique used to characterize self-healing of cracks. Edvardsen [22] [performed such tests, with a single tensile crack in each. And found that leakage of water through the specimen quickly drops to a reduced level. These results show the reaction of compounds on the crack surface, followed by diffusion through the newly formed crystals. Edvardsen explains the phenomenon by the crystallization of calcium carbonate $CaCO_3$, as the main element. Another kind of experiments was performed by Jacobsen and Sellevold [25] to highlight self-healing of cracks. It consists in damaging concrete cubes by rapid freeze/thaw cycles, and then stored in water clearly showed that the deterioration was governed by the ability to take up water; the more water that leaked through the plastic foil during freeze/thaw, the larger the deterioration. Self healing may be an important factor giving concrete better frost durability in field than when submitting specimens to freeze/thaw cycles in water.

Liu et al. [26] also carried out experiments to study the influences of cement particles diameter distribution and constitute on self-healing performance of concrete. Waterproof concrete structures cracked and leaked gently at the beginning, but after a period of time, it was found that the cracks closed completely and did not leak at all [27]. Wieland and Michaela [28] studied that an autogenous healing would take place in water under pressure when up to certain width of the crack.

RECOVERY OF STRENGTH ON CRACK HEALING

Deterioration and healing are measured through the evolutions of the compressive strength and the resonance frequencies giving the dynamic modulus of elasticity. Freeze/thaw cycles lead to a decrease of both resonance frequencies and compressive strengths, and self-healing gives a substantial recovery of the frequency but only a small recovery of the compressive strength [25]. It was shown that the recovery was associated with a self-healing process where micro cracks were locally filled up by newly formed hydration products. These products, mainly of CSH-type, were able to bridge several cracks with widths smaller than approximately 5 μm.

Cracks not only influence the service durability of concrete structure, but also are harmful for the structure safety. However, not all initial micro cracks develop into harmful cracks or unstable cracks. Since earlier researchers discovered that cracked specimens under compressive testing at 28 days healed autogenously after had been stored outdoors for 8 years. Wagner [26] investigated the cracks in seal-coated cement-mortar linings in water pipe and fittings would self-heal by chemical reaction when totally immersed in potable water. Hannant and Keer [27] studied self-healing process of micro cracks in concrete. Gray [28] examined the self-healing of interfacial bond between steel fibers and mortar matrix.

ROLE OF TEMPERATURE AND CRACK WIDTH ON SELF HEALING

Reinhardt and Jooss [29] established self-healing behavior of cracked concrete as a function of temperature and crack width and they found that the average crack width measured at the surface showed the fastest self-healing. Smaller cracks do heal faster than greater ones and a higher temperature favours a faster self-healing process.

ROLE OF CHLORIDE INGRESS ON SELF HEALING OF CRACKED CONCRETE

Increased chloride transfer in concrete due to load induced cracking was observed by Samaha and Hover and by Locoge et al. [30-31]. Fidjestal and Nilsen[32], discussed possible reduction of chloride ingress and corrosion rate in cracked concrete due to crack-healing. However, none of them compared systematically chloride transport in concrete with "fresh" and "healed" cracks. Dry [33] developed and investigated various systems for self-repair of cracks: so-called smart materials with hollow fibres containing repairing chemicals. When released at cracking of the concrete, these chemicals were able to give the repaired crack better mechanical properties and permeability than the sound material.

CRACK HEALING OF REINFORCED CONCRETE BY ELECTRO DEPOSITION

There are many repair methods available such as epoxy injection, polymer impregnation routing and sealing, grouting, overlays and surface treatment etc. One of the techniques in dealing with crack is by electro deposition method. Electro deposition refers to the precipitation of material on the surface of an electrode by electrolysis [34]. The electro deposition method has been developed by several researchers in the past 10 years and applied to marine structures. Their results suggested that the use of the electro deposition method on concrete is highly satisfactory but very limited literature is available, however on this topic [35].

One of the techniques of dealing with crack repair is the electrochemical method. Investigations proved that it was possible to close the cracks in reinforced concrete by applying an electric current, especially under special environments where other traditional repair systems are inefficient.

APPLICATION OF ELECTRIC CURRENT

Direct current was applied by a power supply between the embedded reinforcing steel and a titanium mesh anode immersed in the solution and located at the bottom of the container (Fig.1). The embedded steel was connected to the negative terminal of the potentiostat and the external anode was connected to the positive terminal. The potentiostat used as power supply was adjusted to deliver a current density (0.5 A/m^2) to the concrete surface for 8 weeks. This current density is relatively low, so the generation of OH^- and the potential for alkali–aggregate reaction are not expected [36]. If the current density is low, the treatment is longer.

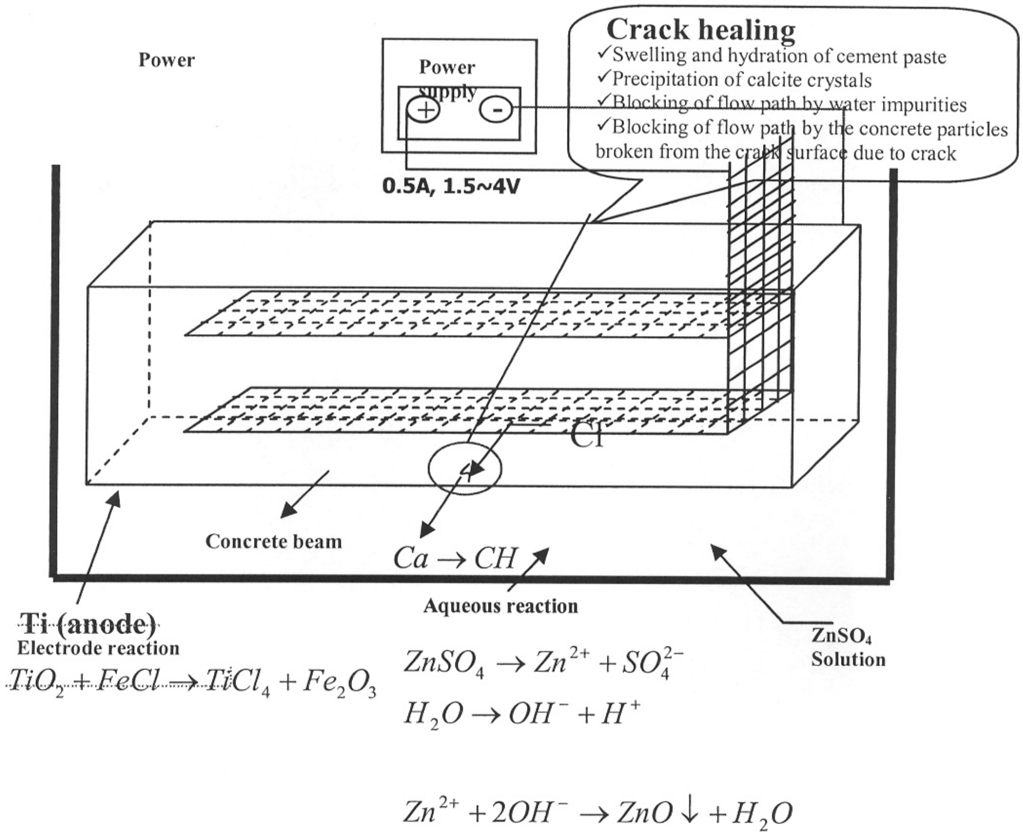

Fig.1: Application of electro deposition under laboratory conditions

The electro deposition method of rehabilitation is to fill the crack in concrete and to coat the concrete surface by electrodeposits of chemical compounds such as $CaCO_3$ and $Mg(OH)_2$. The CO_3^{2-} ions present in the seawater form $CaCO_3$ but not $MgCO_3$ because $Mg(OH)_2$ is less soluble than $MgCO_3$. In the case of

Ca^{2+} the contrary is the case and therefore $CaCO_3$ is formed. These layers of inorganic compounds are known to provide a physical barrier, and reduce the flux of gas or solution inside the concrete. This can be accomplished by feeding a weak direct current between the reinforced steel (the cathode) in concrete structure and an electrode (the anode) located under seawater. Ryo and Otsuki [35] carried out few experiments (Fig.2) on the electro deposition method for rehabilitation of cracked reinforced concrete beams of size 15×15×125 cm, immersed in a $ZnSO_4$ solution and applied with a constant current for 8 weeks and the results indicate that electrodeposits formed on the concrete surface (Fig.3) were able to close the concrete cracks and to decrease the concrete permeability. In addition, the investigation shows that the application of electro deposition have effects on the desalination of concrete and re-passivity of the reinforcing steel in concrete.

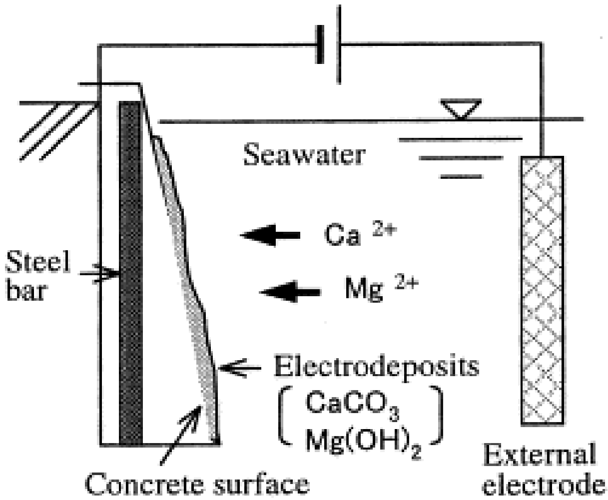

Fig. 2: Application of electro deposition in marine structure [35]

Ryo and Otsuki [37] evaluated the external solutions of the electro deposition to show the effectiveness of this method as a means of rehabilitation and protection of cracked mortar specimens. They have chosen the electrolytes based on the stability of the solution, i.e., not strongly acidic and the solution should be electrolytic. Within these parameters, eight types of electrolyte solutions ($MgCl_2$, $ZnSO_4$, $AgNO_3$,$CuCl_2$,$Mg(NO_3)_2$,$CuSO_4$,$Ca(OH)_2$, $NaHCO_3$) were selected, current applied was found to be (0.25 A/m^2 and 0.5 A/m^2). The concentration of each solution taken was 0.1 mol/L and they concluded that the $MgCl_2$ and the $ZnSO_4$ solutions are most effective for the purpose of precipitating the deposition product inside and outside cracks in mortars [35].

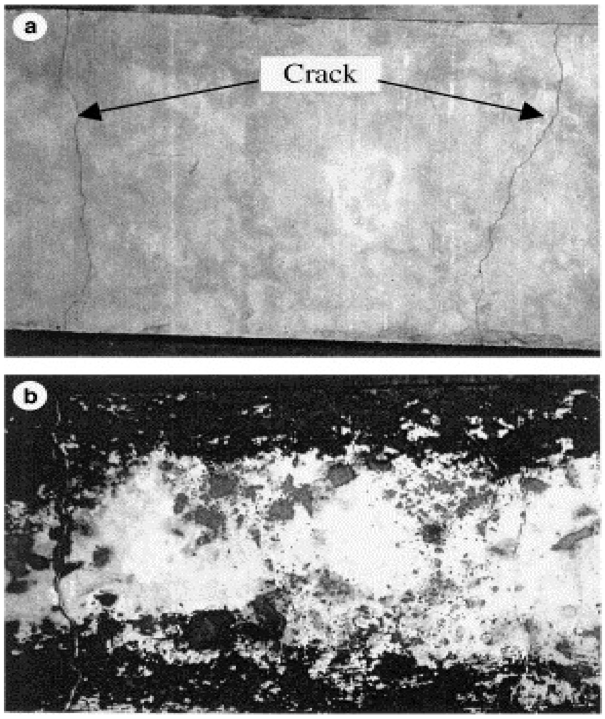

Fig. 3. Appearance of deposits on the concrete surface: (a) before charging; (b) 4 weeks after charging [35].

Ryou and Monteiro [38] studied the electro deposition as a rehabilitation method of reinforced concrete both under laboratory and field conditions. Field investigations were performed on a 35-year old structure that had been damaged by corrosion to assess the feasibility of using this technique in field conditions. The field results indicated that the electrodeposits formed on the concrete surface closed the cracks in the concrete. In addition, the application of electro deposition had beneficial effects on the electrochemical property of the reinforcing steel in concrete.

CLOSURE OF CONCRETE CRACKS

The concept of electro migration can be applied to the concrete, because concrete is a porous material having an electrolyte in the form of pore solution. The electro deposition process has been shown to rehabilitate marine concrete structures by using sea water as the electrolyte. It is observed that electro deposition developed on the concrete surface and along the crack. The chemical reactions in the solution are represented in Fig.3 [39]. The results indicate that electrodeposits formed on the concrete surface are capable closing the concrete cracks and that the electro deposition method is effective on the repassivity of the reinforcing steel in concrete. In addition, the investigations show that the deposition product can improve the microstructure of the mortar surface [37].

CONCLUSIONS

The present paper reviewed the self healing and electro deposition method of crack healing in concrete. From the reported literature the following conclusions were drawn:

- The electrochemical technique was used to rehabilitate cracked reinforced concrete both in laboratory and under field conditions.
- This closes concrete cracks and improves the concrete water-tightness and mechanical properties by precipitating deposition materials on the surface of the concrete.
- Deposition materials were precipitated on the concrete surface and in the cracks by applying an electrical charge between the embedded steel in the concrete and a titanium mesh anode immersed in the electrolyte solution.
- The amount of crack closure during the test period showed the development of electro-depositing. The cracks in the test specimens were closed almost perfectly at the end of the test period. The filling depth of the cracks varied according to the crack width.
- The electrodeposits on the concrete surface helped to decrease the concrete permeability.
- In addition, the investigations show that the deposition product can improve the microstructure of the mortar surface.
- The self-healing ratio of concrete increases with the increasing of damage degree when the damage degree is lower than the threshold. If the damage degree is higher than the threshold, the self-healing ratio decreases with the increase of damage degree.
- The threshold level depends on materials. The threshold for normal strength concrete is higher than that for high strength concrete.
- It has been shown that the decrease of the flow rate depends on crack width and temperature. Smaller cracks do heal faster than greater ones and a higher temperature favours a faster self-healing process.
- Internal cracking reduced the compressive strength and increased the chloride penetration rate.

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