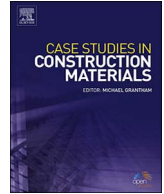




Contents lists available at ScienceDirect

Case Studies in Construction Materials

journal homepage: www.elsevier.com/locate/cscm

Case study

Long-term 20-year performance of surface coating repairs applied to façades of reinforced concrete buildings



R. Creasey, J.P. Andrews, S.O. Ekoru*, D. Kruger

Department of Civil Engineering Science, University of Johannesburg, Auckland Park 2006, South Africa

ARTICLE INFO

Keywords:

Corrosion
Carbonation
Repair coatings
Silane and siloxane
Corrosion inhibitor
Acrylic sealant
Re-alkalisation
Non-destructive tests
Visual survey

ABSTRACT

The present study was conducted to evaluate effectiveness of surface coating repairs after 20 years since their application on façade panels of two existing concrete buildings. The repairs involved coatings and electrochemical treatment systems comprising Silane and Siloxane (S/S), Amino Alcohol Corrosion Inhibitor (AACI), acrylic coating, and re-alkalisation (Re-Alk). Altogether, 11 selected façade panels were evaluated in this study. The field investigations comprised visual survey, non-destructive tests (NDT) for compressive strength using Schmidt hammer, cover depth, reinforcement bar size, Ultrasonic Pulse Velocity Test (UPV), Torrent permeability. Limited carbonation depth tests were also conducted on selected panels.

It was found that, UPV and permeability values indicated poor or very poor concrete quality in the repaired panels except for those repaired using acrylic coatings, which showed retention of good concrete quality. AACI coatings with or without S/S gave similar performance as control, implying no significantly improved protection by these repair materials.

1. Introduction

Corrosion of steel reinforcement in concrete structures is one of the most widespread problems responsible for repair and maintenance of structures in tropical countries. This attack can result from ingress of chlorides or CO₂ into concrete over a period of time. For mainland areas of tropical Africa located beyond 15 km from the seacoast, chlorides are not a major concern, leaving carbonation as the predominant deterioration mechanism responsible for reinforcement corrosion. Normal concrete has a pH of about 12.6. Under this alkaline condition, a passive iron oxide film is formed on the surface of the reinforcement steel, which protects it against atmospheric oxygen and humidity. Upon carbonation, the pH of concrete is reduced to less than 10, thus creating a significantly less alkaline environment for protection of reinforcement. Under these conditions, with sufficient oxygen and moisture, corrosion of the reinforcement initiates and leads to cracking, delamination or spalling of concrete cover. The rate at which carbonation occurs depends on the porosity and moisture condition of the concrete. The pore system of concrete is in turn influenced by the type and content of binder, water/binder ratio, curing or degree of hydration and processing factors such as compaction. Carbonation occurs optimally at a relative humidity of 50–80%, as the chemical reaction process requires the presence of water. The CO₂ concentration in the atmosphere is another important factor influencing the rate of carbonation. Worldwide, industrialization and population growth has led to persistent increase in atmospheric CO₂ levels. It is notable that average CO₂ levels exceeded 400 ppm in 2013 (<https://www.esrl.noaa.gov/gmd/ccgg/trends/full.html>). The increasingly higher CO₂ levels lead to greater carbonation progression into concrete structures.

Abbreviations: S/S, silane and siloxane; AACI, Amino Alcohol Corrosion Inhibitor; UPV, Ultrasonic Pulse Velocity

* Corresponding author.

E-mail addresses: sekolu@uj.ac.za, sekolu@gmail.com (S.O. Ekoru).

<https://doi.org/10.1016/j.cscm.2017.11.001>

Received 5 June 2017; Received in revised form 27 September 2017; Accepted 1 November 2017

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2. Steel corrosion and repair of reinforced concrete

2.1. Structural effects of reinforcement corrosion

The process of concrete repair involves diagnosis of the cause of deterioration, prescription of the appropriate repair regime or strategy and evaluation of the repair effectiveness. There are a number of repair methods that are used to control deterioration of reinforced concrete [1]. These methods are selected depending on the deterioration attack mechanism to be arrested or controlled. ICRI [2] and EN 1504 [3] give detailed techniques, procedures and material systems that may be employed to mitigate, control or remedy specific forms of deterioration including degradation due to reinforcement corrosion. As already mentioned, carbonation and chloride attack mechanisms are the two main mechanisms responsible for steel corrosion in reinforced concrete [4–8]. Studies show that there is synergy between the two mechanisms, i.e. the presence of carbonation tends to promote chloride attack partly by releasing chemically bound chlorides [9,10]. Also, at reduced pH levels resulting from carbonation, the chloride threshold for onset of corrosion is lower.

Regardless of the type of attack mechanism, the resulting structural effects of steel corrosion in concrete are the same, i.e. cracking, spalling, delamination and loss of steel area, which cause damage to mechanical properties and ultimately reduce the service lifespan of affected structural elements [11,12]. The growth of expansive corrosion products is responsible for the time-based degradation [13–15].

In columns, loss of steel area following spalling and delamination effects of corrosion, increases steel stress and reduces column load bearing capacity. Sharif et al. [16] conducted patch repair with and without simultaneous applied loading and found that the load distribution between the repair and substrate concrete was mostly dependent on relative difference in elastic moduli of the two materials. A repair material of similar elastic modulus as substrate promotes equal sharing of applied loads. Generally, it is essential to conduct repairs while existing applied loads are being relieved through external supports or propping, for example. Tapan and Aboutaha [17] evaluated the effects of concrete cover and loss of steel in bridge columns by plotting the moment-load interaction diagrams. They found that corrosion of tension reinforcement leads to significant reduction in column capacity, while corrosion of reinforcement on the compression side of columns majorly reduced effective depth. In beams, Yu et al., 2015 [18] found that loss of steel area in tension reinforcement due to corrosion, reduced ductility and moment capacity of the beam with a failure resulting from rupture of tension steel while the control beam was over-reinforced and failed by concrete crushing in the compression zone. Lachemi et al. [19] found that about 5% mass loss in steel due to corrosion, significantly increased deflection from 5 to 8 mm to 12–15 mm. Also, there was reduction in load carrying capacity as mass loss was increased to 15–20%. Ballim and Reid [20] reported an increase of 40–70% in deflection for 6% mass loss of steel. Wang et al. [21] reported that a loss of more than 10% area of stirrups majorly affected shear resistance capacity of beams. Various experimental models have been proposed for prediction of service life in corrosion-affected concrete structures [6,11,22–26].

Typically, patch repairs are conducted to remedy corrosion-induced and other surface defects prior to application of protective surface coatings [27–29]. However, durability of repairs is known to be a major challenge in the industry, as repairs often tend to fail earlier than expected, consequently creating another premature cycle of repairs. One common problem in patch repair is the formation of incipient anodes surrounding the new patch. It is generally accepted that the presence of anodic sites is a form of cathodic protection on the adjacent non-corroding sections of steel, i.e. cathodes. The removal of these anodic sites through patch repair, eliminates this protection on cathodic regions. Upon loss of this protection, these previously cathodic regions that are in the chloride-contaminated or carbonated substrate concrete adjacent to the repair, turn into anodes [30–32].

2.2. Surface coatings

Repair coating systems create a physical barrier to seal-off the surface thus inhibiting ingress of CO₂, moisture and/or oxygen into reinforced concrete, in turn restricting the corrosion process. The coatings discussed in this paper do not include those applied directly onto the steel surface [33]. Hydrophobic surface coatings create a drying action by repulsion of water molecules during wetting cycles. Coatings are considered effective in protecting concrete surfaces that are free of cracks and surface defects. Pan et al. [34] conducted a survey of literature on various surface coatings including acrylic coating, silanes, siloxanes, epoxy coating, polyurethane coating, nano-SiO₂ and sodium silicate. They reported that concrete strength and other mechanical properties are generally not highly affected by surface coatings [34,35], but fire resistance and durability can be significantly impacted, depending on the type of coating [36]. Silicate-based coatings are reported to improve fire resistance while abrasion resistance performance by various treatments were reported to improve in the order of sodium silicate >> ethyl silicate >> nano-silica. Polymer coatings significantly reduce drying shrinkage by forming an air-tight surface seal which prevents moisture removal from concrete into the atmosphere. Some coatings that have been reported to reduce water absorption include epoxy coatings, silane with applied acrylic coating on top, methyl methacrylate, two coats of alkyl alkoxy silane and oligomeric siloxane. For resistance to chloride ingress, polymer coatings, polyurethane and acrylic coatings are considered to be most effective [34,37]. The effectiveness of various surface coatings in reducing carbonation progression is also reported in the literature [34]. It has been shown that silane/siloxane coatings are less effective compared to other coating types, producing about 20% reduction in carbonation depth. These coatings are known to be effective in reducing moisture penetration. Silicate-based coatings provide better performance with calcium silicate, ethyl silicate and sodium silicate respectively giving 23–54%, 40–80% and 60–90% reduction in carbonation. However, sodium silicate does not provide good long-term performance unlike ethyl silicate which is generally effective in the long-term. Acrylic coatings provide the best anti-carbonation performance with almost 100% prevention of carbonation progression. Surface coatings tend to degrade over

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