Use of Vapour Phase Corrosion Inhibitor Capsules for Long Term Protection of Repaired Reinforced Concrete Structures

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Key Words

Corrosion, corrosion inhibitor, concrete repair, historic buildings, carbonation, chloride ingress.

Abstract

A unique method for the delivery of migrating corrosion inhibitors is presented in this paper. Testing and site trials carried out showed that the inhibitor can move freely along the steel reinforcement/concrete interface and form a passivated protective coating on the steel surface. Inspection of reinforced concrete structures that were protected using this type of inhibitor several years after repair has indicated that long term protection is provided.

Introduction

It is well known that steel reinforcement within concrete is well protected from corrosion initially because of the highly alkaline nature of the cement matrix surrounding the steel which forms a passive film of cubic oxide ($\gamma - Fe_2O3$). When this environment is maintained (and in the absence of any destabilising influences such as chloride ions or carbon dioxide intrusion from the external environment or the presence of chlorides from admixtures or aggregates) no corrosion of the steel reinforcement will be expected during its design life.

As is also very well known, concrete is a material that can be misused at the time of production or placement, resulting in its durability characteristics being adversely affected, principally through increases in the water: cement ratio which greatly enhance permeability and consequently reduce durability. Poor work practices or lack of site supervision often result in a reduction of the concrete cover when steel reinforcement is inadequately braced and moves during concrete placement. Inadequate curing has a similar effect.

On many occasions, older structures were designed and built correctly but, at the time, Engineers and Concrete Technologists were unaware of the effects that chloride ions and carbon dioxide were to have on the durability of concrete.

Concrete specification today is much more focused on the durability aspects but, as mentioned earlier, things can and do go wrong at the time of production and at the time of placement.

The concrete repair industry has developed into a multi-billion dollar business. Industry and academia have worked together to ensure we understand what went wrong and how to repair the damage. This has resulted in a high degree of knowledge being generated and the development of many sophisticated solutions for concrete repair and protection.

One such development has been the in the use of corrosion inhibitors to protect steel embedded within concrete from corrosion. Corrosion inhibitors have been used for the protection of steel in process industries to great effect for over 50 years. In the 1980s, this technology began to be transferred to the protection of steel reinforcement with varying degrees of success.

This paper examines the use of one particular type of corrosion inhibitor that was patented in 1987 and was first used in the United Kingdom in a commercial application in 1992.[1] It has been used since 1987 in the repair of many concrete structures in the United Kingdom with no recorded failure. For several reasons, this technology was, until recently, only available to certain companies in the United Kingdom and was not available internationally. Consequently, many Engineers are still unaware of it.

Corrosion Inhibitors

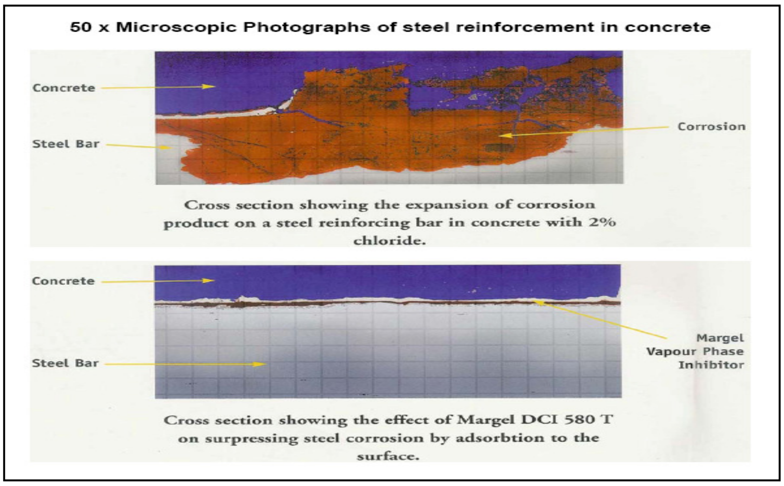
Corrosion Inhibitors for concrete fall into two main categories, integral and migratory. Integral (or cast in place) inhibitors are usually based on calcium nitrite are added as an admixture at the batch plant. Migrating (penetrating) inhibitors are based on a variety of different chemicals such as amino alcohols and pure amines. Penetrating inhibitors have usually been surface-applied liquids.

The integral (or cast in place) type of corrosion inhibitors have been found to offer good performance provided that they are used at the correct dosage and the water: cement ratio of the concrete is at 0.5 or less.[2-3]

The migratory (penetrating) corrosion inhibitors have been the subject of much debate and research. It is almost impossible for the Engineer to determine if this technology is suitable or not because of the volume of published data that claim the technology works and the volume which states it does not.[4-8] It is fairly evident from the literature that, if these products can reach the steel, they do provide protection against corrosion. The issue on poor performance relates mainly to the ability of a surface applied volatile liquid to migrate thorough the concrete cover to the steel. It seems that migration does occur if the concrete matrix is sufficiently porous.[9]

A way to ensure delivery of a known quantity of the inhibitor to the steel reinforcement is to actually place the inhibitor in a high concentration close to the steel. Therefore a pure amine based inhibitor was developed in capsule form that could be inserted in a hole drilled in the concrete close to the steel.[1] By using amines of varying vapour pressures a controlled release of amine over time is achieved. By locating the capsule relatively close to the steel reinforcement, the bond line between the concrete and the steel reinforcement has the effect of "pulling" the volatile amines along the length of the steel bar as it is, in effect, the path of least resistance. The amines continue to release until the steel is coated with a passivated molecular coating on the surface of the steel.

Once in contact with the steel surface they adsorb on to the steel surface which creates a physical barrier to oxygen and water. They also ionize to create an electrochemical reaction that passivates the steel. Studies carried out by Bierrum and Partners Limited confirm this as can be seen in the photographs below.[10] These were taken after steel reinforcement was cut in a control (no chloride) concrete and a concrete to which 2% calcium chloride (by weight of cement) had been added. After 6 months, the concrete samples were split open and the corrosion observed by visual examination using a microscope.



Cross section showing the expansion of corrosion product on a steel reinforcing bar in concrete with 2% chloride.

Cross section showing the effect of Margel DCI 580 T on surpressing steel corrosion by adsorbtion to the surface.

A simple way of to see the corrosion inhibiting effect can be demonstrated through a very simple test using a nail and a corked test tube. The test specimens shown in the photographs below were prepared in September 1993 and the photographs taken after 13 years' exposure.

Both test tubes containing an amount of water had a steel nail pushed through the corks. One of the test tubes has the pure amine inhibitor added to the water. The nail in the control sample corroded and produced an expansive volume change as we see in corroded reinforcement. The protected nail had a layer of passivated surface corrosion form that protected it. The tip of the nail remained shiny, indicating an anodic effect.

In order to determine that the inhibitor could reach the steel and travel along its length, a series of tests were carried by Bierrum on specially cast concrete beams.[10] Using a headspace gas chromatography technique they determined that the corrosion inhibitor would travel along the steel reinforcement at the rate of one metre per week for the faster of the three amines in the product. This relatively fast release amine is key in providing early protection and early formation of the passivating layer.

Site Testing

In order to determine the effectiveness of the inhibitor, monitored site trials were carried in 1992 at the Central Electricity Generating Board's power station at Fawley in Hampshire, United Kingdom.

The test area was a suspended floor in the power station, subjected to frequent inundation with wash waters, therefore in a permanently saturated state.

The floor was constructed using 100mm thick reinforced concrete slabs, 1.8m x 0.6m. The slabs had longitudinal main steel, with stirrups supporting top and bottom bars. There was extensive spalling, as a result of corrosion of the reinforcement. The main areas of spalling were along longitudinal joints between panels.

Two slabs were chosen for the trial. The first had heavy longitudinal corrosion, whilst the second was one in an area not exposed to water and exhibiting no spalling or evidence of corrosion.

Measurements of corrosion were made using a device which sampled corrosion potential in the customary method using one connection to the steel and the other to a half cell on the concrete surface.

Background readings were taken from both slabs over several days, to establish their behaviour. Having obtained the base values from each slab, vapour phase corrosion inhibitor capsules were inserted and further measurements made over several months.

It was found that the dry slab maintained a steady state throughout, while the wet slab with active corrosion taking place had a potential shift which eventually provided values similar to those achieved in the dry (control) slab - indicating that the corrosion had been controlled so no further damage would occur. It would not be expected to achieve exactly the same value since saturation with water results in lower potentials.

In 1998 Geomaterials Limited (now part of Sandberg LLP) were commissioned to determine that the inhibitor was present in panels treated at Wynford House in London.[11] A few days after insertion of the corrosion inhibitor capsules, concrete cores were taken at 20mm, 50mm, 130mm and 200mm from the point where the capsule had been inserted. As the amine vapour is alkaline they were able to determine using indicator solutions applied soon after extraction of the core if an alkaline environment had been created at the concrete steel interface. The test confirmed that the corrosion inhibitor had travelled the full length of the core. Cores taken from an adjacent, untreated, panel were tested and no reaction with the indicator solution occurred.

Case Histories

In the 1930s, reinforced concrete was adopted as the material of choice for many residential and commercial buildings in the UK, and in London in particular. Concrete was strong, cost effective and could be easily cast to produce sections not easy to create in other materials (such as stone and steel). This led to the creation of many of what are considered today to be iconic structures. By introducing calcium chloride, the early strength development of concrete could be accelerated thereby reducing construction time. It was not until the mid to late 1970s that Engineers began to understand the effect this had on the durability of concrete structures. In addition, the relationship between water: cement ratio and curing on durability and, in particular, in controlling carbonation, was not understood in the early years, so specifications were based on compressive strength attainment with no regard for durability.

Isokon Building

The Isokon building in Lawn Road, Hampstead, London, is a concrete block of 34 flats designed by the architect Wells Coates. They were built between 1933 and 1934 as an experiment in communal living. Most of the flats had very small kitchens as there was a large communal kitchen for the preparation of meals, connected to the residential floors via a food lift system. Services, including laundry and shoe-shining, were provided on site.

The communal kitchen was converted into the Isobar restaurant in 1937. In 1969, the Isobar was converted into flats and, in 1972, the building was sold to Camden Council and gradually deteriorated until the 1990s, when it was abandoned and lay derelict for several years. In 2003, the building was completely refurbished. Vapour phase corrosion inhibitor capsules were placed throughout the structure in order to provide long term protection to the reinforcement. Seven years after the concrete repairs were carried out, the building is still in excellent condition with no signs of corrosion-induced damage to the structure.

The building has been granted Grade I listed status, placing it amongst the most architecturally-significant historical buildings in the UK.

Highpoint 1 & 2

The Highpoint apartments, so-called because of their location on a hill above Hampstead, London, are one of the best examples of early International Style architecture in the capital. Located at the corner of a landscaped area along North Road, they were built in two phases, Highpoint I in 1935 and Highpoint II finished in 1938.

Highpoint I incorporated many innovative features and was technically very advanced for the time. The concrete walls were built using a system of removable platforms that eliminated the need for scaffolding, making the walls and floors monolithic. This construction system was chosen instead of the normal concrete frame method to avoid problems with pour joints, to reduce the possibility of structural cracks and because it was less expensive. While the system was common in civil engineering, this was the first time it was applied to building construction.

Shortly after Highpoint I was finished, the developer purchased the neighbouring land to the south. The plan was to build more middle class housing as a continuation of Highpoint I. Public reaction to Highpoint I, however, resulted in design changes to the second building. It insisted that any future buildings had to preserve the architectural character of the neighbourhood. After a lengthy review and negotiation process, during which many different designs were considered, the building size was limited to one-fifth the size of the original. This reduction of the number of apartments, coupled with the cost (which had doubled) resulted in a strategy to design luxury apartments instead of lower-cost flats. The original design of 57 flats was thus reduced to 12 maisonettes.

In 2005, refurbishment of the external concrete elements was required. Patch repairs were carried out with a proprietary concrete repair system. As is well documented, patch repairs can promote and accelerate corrosion in areas adjacent to the patch repair, particularly in carbonated concrete (referred to as the anodic ring effect). For this reason, vapour phase corrosion inhibitor capsules were inserted throughout the structure, providing long term protection to the unrepaired areas. A recent site inspection confirmed that the structure was in good condition with no signs of any of the patch repairs failing.

Conclusion

While the use of surface applied vapour phase migration (penetration) corrosion inhibitors remains the subject of debate as to whether they work or not, the development of technology to produce solid timed release capsules that are placed close to the reinforcing steel has been shown to be an effective delivery mechanism that does provide long term protection against corrosion in reinforced concrete.

One of the major benefits of this type of system is that it can be used to protect concrete without too much disruption to the structure, making it very suitable for use where minimum disturbance to the populace and damage to the structure are important factors.

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