Design and specification so that 21st century reinforced concrete structures won't corrode so soon

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Summary

The durability of reinforced concrete structures is affected by a number of factors such as environmental exposure, electrochemical reactions, mechanical loading, impact damage and others. Of all of these, corrosion of the reinforcement is probably the main cause for the deterioration of steel reinforced concrete structures.

Corrosion management is becoming increasingly necessary as a result of the growing number of aging infrastructure assets (e.g. bridges, tunnels etc.) and the increased requirement for unplanned maintenance in order to keep these structures operational throughout their design life (and frequently, beyond).

A recently completed research programme by the authors investigated the long-term performance of the most common corrosion management techniques by means of in-situ and laboratory testing, and focused on full-scale bridge structures in order to collect rigorous empirical data. This was consequently analysed in order to establish improvements for the corrosion management of steel reinforced concrete structures through changes in design, specification and maintenance requirements.

This paper provides an overarching review of how the findings of this research could be applied by industry in order to enhance the durability and hence extend the service life of reinforced concrete structures.

1. Introduction

Reinforced concrete (RC) structures are widespread throughout the world and are exposed to a variety of different climate conditions. Their deterioration can be attributed to a range of different factors and can occur either due to deterioration of the concrete or the reinforcement, or both. The European Standard BS EN 1504 (1997) provides a comprehensive list of deterioration causes. Of these, corrosion of the steel reinforcement is considered the major factor for deterioration of RC structures.

Under normal circumstances, concrete provides a non-aggressive and highly alkaline environment with pH above 13, achieved during the hydration process of cement. Under these conditions, the steel remains passive and develops an oxide film which covers its surface and presents a barrier to further metal dissolution (Page & Tradeaway 1982). A wide range of factors may affect the electrochemical stability of this thin protective film. When break out of this film occurs, corrosion will initiate and propagation will be subject to concrete resistivity, humidity, chloride ingress, defects, cracks etc.

Corrosion damage to RC structures is generally attributed to chloride contamination arising from the use of de-icing salts, exposure to marine environments or casting in chlorides (Concrete Society 2000).

From all the above chloride induced deterioration is influenced in three main ways:

- Concrete and its alkalinity
- Transport of corrosion inducing species
- Reinforcement type

As such, RC structures where the concrete has high alkalinity and binding capacities, the transport of corrosion inducing species is restricted, the reinforcement is corrosion resistant, or any combination of the above, will have a contribution in increasing their durability and service life. All of the above can be addressed during the design, specification and detailing of RC structures.

2. Concrete and its alkalinity

The fact that concrete is alkaline and under these conditions steel reinforcement remains passive is well documented. However, the question arising is how well this is understood by design engineers, as well as appreciating the effects of water/cement (w/c) ratios, cement content and blended cements.

Structural engineers will dictate the choice of structural materials, sizes, quantity of reinforcement and cover and will also undertake the detailing of the structural elements. For large scale and high profile projects such as the new Forth Replacement Crossing, concrete technologists sometimes also get involved with the specification, mix design and durability of the concrete elements. However, in the majority of cases these tasks are commonly undertaken by structural engineers.

The result is that focus is primarily on: i) achieving a design compressive strength as ultimately concrete elements need to carry the structural loads and ii) achieving early strengths in order to reduce formwork striking times. However, compressive strength alone is not the sole indication of the overall quality of the concrete or of its durability. As a result, a large number of smaller scale RC structures are designed and build with a primary focus on compressive strength.

Standards such as BS EN 206 (2000) and BS 8500 (2006) provide guidance on the generic selection of designated concrete to resist certain exposure environments and stipulate minimum requirements such as cover, w/c ratio and cement content. However, one needs to be able to differentiate between the performance characteristics of the different available combinations.

For example, C40/50 concrete with a minimum design life of 100 years and an exposure class XS3 (marine tidal zone) can be made of normal Portland cement (CEM I), minimum cover of 65mm plus construction tolerance, 380 kg/m^3 of binder and a w/c ratio of 0.4. But, it may also comprise a high blend of cement with ground granulated blast furnace slag (CEM IIIA) with a minimum cover of 45mm plus construction tolerance, 380 kg/m^3 of binder and a w/c ratio of 0.35. Both concrete designs will conform to the durability requirements but in fact they will have a rather different performance (Glass et al. 2007).

Glass et al. (1997) demonstrated that variations in the mix due to the use of blended cements affects the overall alkalinity and as a consequence the chloride threshold for corrosion initiation. In addition, recent research by the authors (Christodoulou et al. 2010), which investigated the corrosion risk following the interruption of the protective effects delivered by electrochemical treatments which are commonly used to repair, refurbish and rehabilitate corrosion-induced deterioration on RC structures, also confirmed that the development of a sufficient buffer of alkalinity will hinder corrosion initiation.

On balance, improvements are needed on codifying research findings which highlight the link between durability and alkalinity of the concrete while at the same time continue educating engineers on the relationships between concrete technology, durability and corrosion.

3. Transport mechanism

Concrete is a naturally porous material. The size and distribution of pores in concrete varies and depends on the constituent materials, quality of compaction, the materials used in the mix design, the water-to-cement ratio, the degree of hydration, and curing (Concrete Society 2008). Some of these pores will be interconnected to form a network of pore space that can be penetrated by water, gas or ions.

The relevant transport mechanisms for potential ingress include (Kropp and Hilsdorf 1995):

- diffusion of free molecules or ions due to a concentration difference;
- permeation of gases or liquids through water saturated specimens due to hydraulic pressure difference; and
- capillary suction of liquids due to surface tension acting in capillaries.

Whilst, these mechanisms act together under natural environmental exposure conditions, capillary suction tends to be the dominant mechanism (Kropp and Hilsdorf 1995, Ungricht 2004).

Current practice for predicting the rate of ingress of corrosion inducing species into RC is based on the error function solution to Fick’s secondary law of diffusion (Concrete Society 2004). However, in practice this is further complicated by the effects of capillary absorption, surface concentration of chlorides, cover zone variations in consistency and time-dependant effects.

The presence of cracks and joints is often overlooked. Their relationship with corrosion risk is well documented (Concrete Society 2000). Their occurrence is not uncommon and in fact structural design codes (BSI 2005) take them into account. However, durability analysis has limitations on this particular topic. A recent research project by the authors (Christodoulou et al. 2013) also highlighted the significance of cracks and joints on the performance and durability of repairs on RC structures.

Laboratory testing of the mix design has the potential to identify potential issues with the durability of the chosen concrete which can therefore be addressed prior to construction. Indeed, large scale projects usually invest in laboratory testing of concrete mix designs in order to demonstrate durability and in certain cases such requirements are part of the specification too. However, this type of testing is not generally required by design codes and questions remain with regards to the choice and suitability of the testing principles (i.e. permeability, capillary suction, initial surface absorption, chloride migration etc.).

Overall, it is apparent that a gap exists in current codes, industry practice and potential in-situ performance. Improvements are needed into prescribing the properties of concrete governing the transport of corrosion inducing species in order to improve durability.

4. Reinforcement

Reinforcement induced deterioration is the single biggest contributor factor for the degradation of RC elements. As such, it is no surprise that in general repair, refurbishment and rehabilitation techniques usually involve electrochemical treatments in order to arrest active corrosion and provide long-term corrosion prevention (Concrete Society 2004). As far as new structures are concerned, epoxy coated reinforcement has been frequently used, followed by galvanised reinforcement, stainless steel and non-metallic reinforcement.

All of these alternatives to plain carbon steel aim to provide an overall increase in corrosion resistance. However, there are inherent drawbacks with each one of them that the designer needs to consider. Epoxy coated reinforcement is not traditionally used within the UK and Europe, whereas it remains popular in the Middle East and America. The epoxy coating is responsible for corrosion resistance but any damage to it during handling, installation and construction can potentially have a greater long-term detrimental effect. Galvanised and stainless steel offer enhanced corrosion resistance, but carry higher capital costs.

Where the environmental exposure is expected to be severe, repairs and disruption would be costly, and a long design life is required, it is prudent to consider these alternative reinforcing materials for the areas in the highest corrosion risk. Recent research has actually demonstrated that duplex steel 1.4362 and austenitic 1.4401 steel remain passive in environments with high chloride concentration (Serdar et al. 2013).

Structures utilising non-metallic reinforcement such as carbon fibre are currently scarce in the UK and globally. Structural design codes do not cover them fully, designers lack experience and their associated long-term benefits and drawbacks are still the subject of significant research. This suggests the prerequisite ongoing need for additional research and education. Overall, the choice of construction materials ought to be driven through durability, whole life cycle and risk analysis.

5. Concluding remarks

All of the above highlight the limitations of current design codes. Durability is mainly assessed based on concrete mix design and cover. Advice with regards to the use of alternative (i.e. non-corroding) reinforcing materials remains scarce. In addition, the critical chloride threshold for corrosion initiation remains subjective and varies as a result of the variance of the concrete itself.

Furthermore, it leads to the major question of what constitutes *major* and *routine* maintenance of RC, and at which point in time repairs need to be undertaken. This is readily available for more stand-alone proprietary products such as bridge bearings or street lamps but not for highly variable and continuous materials such as concrete. To answer this question, it is very common to examine the design *intent*. In most cases this tends to be quite vague as the requirement is for the structure to carry a specific design load over its specified design life. Operations and maintenance requirements will rarely stipulate time intervals for major maintenance and repair of non-proprietary elements such as concrete.

This gap in the current knowledge of major infrastructure maintenance inherently affects the reliability of durability and whole life cycle analysis and has led to the current and on-going demand for repair, refurbishment and rehabilitation, and in a number of occasions even to litigation. Utilising lessons learnt from corrosion and asset management of our current infrastructure will promote enhanced durability, as well as extend both service life and choice of materials through a more educated understanding of their properties.

While we remain highly critical of our current corrosion and asset management practice, there is also a need to recognise the significant research findings and improvements within civil and materials engineering. Nowadays, structures are subjected to far greater stresses and loads, even when compared to a century ago. In addition, modern infrastructure has become significantly leaner, encouraging a higher utilisation of materials. This can also be demonstrated through a historical review of design loads and safety factors. On balance, it is acknowledged that modern infrastructure has moved towards addressing our current and reasonably foreseeable social, economic and civilisation needs while sustaining our finite resources and the environment.

In conclusion, the following items ought to be taken under consideration during design, specification and detailing so that 21st Century structures won't corrode so soon:

- Invest in further education of engineers with regards to material properties and corrosion management;
- Durability analysis and consideration becoming a core requirement for every new structure;
- Improve current understanding of major maintenance requirements for non-proprietary products, such as concrete, and incorporate it into whole life cycle analysis;
- Utilise the alkalinity of the concrete mix as the primary corrosion resistance measure;
- Exploit material developments to control the transport of corrosion inducing species;
- Use of alternative reinforcing materials for areas of high corrosion risk and/or structural safety;

References

British Standards Institution 1997, BS EN 1504-9:1997, *Products and systems for the protection and repair of concrete structures – Definitions, requirements, quality control and evaluation of conformity: Part 9. General principles for the use of* products and systems, London: BSI.

British Standards Institution 2000, BS EN 206-1:2000, *Concrete – Part 1: Specification, performance, production and conformity*, London: BSI.

British Standards Institution 2006, BS 8500:2006, *Concrete – Complimentary British Standard to BS EN 206*, London: BSI.

Christodoulou C., Austin S., Goodier C., Webb J., and Glass G. 2013, Diagnosing the cause of incipient anodes in repaired reinforced concrete structures, *Corrosion Science*, 69, pp. 123 – 129.

Christodoulou C., Glass G., Webb J., Austin S. and Goodier C. 2010, Assessing the long term benefits of Impressed Current Cathodic Protection, *Corrosion Science*, 52, pp. 2671 – 2679.

Concrete Society 2000, Technical Report 54, *Diagnosis of deterioration in concrete structures*, Surrey, UK.

Concrete Society 2004, Technical Report 61, *Enhancing reinforced concrete durability: Guidance on selecting measures for minimising the risk of corrosion of reinforcement in concrete*, Surrey, UK.

Concrete Society 2008, Technical Report 31, *Permeability testing of site concrete,* Surrey, UK.

Glass G.K. and Buenfeld N. 1997, The presentation of chloride threshold level for corrosion of steel in concrete, Corrosion Science, 39, pp. 1001 – 1013.

Glass G.K. Reddy B. And Clark L.A. 2007, Towards rendering steel-reinforced concrete immune to chloride-induced corrosion, *Proceedings of the Institution of Civil Engineers, Construction Materials,* Paper 700014.

Kropp J. and Hilsdorf H.K., RILEM Report 12, *Performance criteria for concrete durability*, Taylor and Francis, Oxford, UK, 1995.

Page C.L. and Tradeaway K.W.J. 1982, Aspects of the electrochemistry of steel in concrete, *Nature*, 297, No. 5862, pp. 109-115.

Serdar M., Zulj L.V. and Bjegovic D. 2013, Long-term corrosion behaviour of stainless reinforcing steel in mortar exposed to chloride environment, *Corrosion Science*, 69, pp. 149 – 157.

Ungricht H., Wasserhaushalt und Chlorideintrag in Beton – Einfulls der Exposition und der Betonzusammensetzung, Ph. D. Thesis (In German), Universities of Zurich and Basel, 2004.