Atmospheric Carbon Dioxide and Premature Deterioration of Steel-Reinforced Concrete Structures – A Growing Concern

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Executive Summary

Estimates of atmospheric carbon dioxide (CO_2) concentration have been increasing from a two thousand year low set in the early 1600s to record highs today. Although current concentrations may still appear small on a human scale (0.04%), they represent about a 40% increase in the chemical concentration of CO_2 in the atmosphere. It is now recognized that change to this degree can have significant consequence to materials at the molecular level.

Several decades ago, a pattern of earlier-than-anticipated deterioration of steel-reinforced concrete structures began to emerge. This pattern would later be described as a global phenomenon, a significant financial burden on society, and one of the most demanding challenges facing the construction industry.

While various causes of reinforced concrete deterioration have long been recognized, changes in concrete formulation and construction practices that were implemented in the 1960s, '70s, and 80s are now seen as contributing to reduced durability. Recently, a new causal factor was recognized – rising concentrations of atmospheric carbon dioxide that can accelerate a process known as concrete carbonation. Wang et al. (2010) and Stewart et al. (2011) found that increasing CO_2 levels will increase the rate of carbonation and the likelihood of carbonation-induced corrosion of reinforcing materials within reinforced concrete worldwide. Anticipated higher temperatures will also likely contribute to increases in concrete deterioration rates.

This report summarizes findings regarding premature deterioration of steel-reinforced concrete structures, causes, implications, and potential solutions. Links to additional information sources are provided.

Introduction

Concrete was first used extensively by the Romans who created large structures that still stand today. However, after the fall of the Roman Empire the formula for concrete was lost and use of this material didn't resurface for over a thousand years. In 1824, a bricklayer in Leeds England patented a mixture he called Portland cement. Portland cement was first exported to the U.S. in 1868 and continues to be the base formula used today (Schaeffer, 1992).

Around the mid-1800s builders, who had long recognized that concrete, while very strong in compression is quite weak in tension, began seeking solutions to a problem that limited concrete use in many applications. Eventually, the idea of reinforcing concrete with a material such as steel, that provides tensile strength, emerged.

Reinforced concrete dates back to at least 1853 when the first building, a three-story residence, was constructed in France using this technique. Over the next twenty-three years, multiple European patents for reinforced concrete were granted to early pioneers of reinforced concrete construction, primarily in France and Germany (Revealer 2011, Morgan 2015). A number of reinforced concrete buildings were constructed during this period.

In the United States concrete construction was slow to catch on. Unreinforced concrete in wall construction slowly gained popularity beginning in the mid-1850s. No doubt inspired by developments in Europe, reinforced concrete was patented in the U.S. in 1860, with the first reinforced concrete structure built domestically in 1870. Advancements in the 1880s and thereafter led to rapid acceptance of reinforced concrete construction in the U.S. in the early 20th century (Gaudette and Slaton 2007). In both Europe and the United States, steel was the reinforcement material of choice.

In the late 1950s the presence of chloride ions was identified as a major factor in steel reinforcement corrosion. It was another twenty years before the importance of carbonation in corrosion processes was understood. Only within the past ten years have increasing levels of atmospheric carbon dioxide been recognized as problematic to long-term reinforced concrete durability.

Although considerable work was done to understand the engineering aspects of reinforced concrete construction, notably less consideration was given to the durability of the new concrete-steel composite. Several decades after the introduction of reinforced concrete, corrosion of steel reinforcement materials was recognized as a problem. But another half-century would pass before the causes of corrosion were correctly identified. Understanding of durability as recently as the 1950s was based on several early 1900s studies which incorrectly identified the cause of corrosion of steel reinforcing materials as stray electrical current (Pourasee 2016). The role of chlorides in steel corrosion was also misunderstood. A belief that chlorides chemically bonded within cement, rendering them harmless to embedded steel, led to cases in which sea water and calcium chloride set-accelerators were used in concrete mixes (Broomfield 2007, Larsen 2015). These practices led to further and expensive corrosion problems.

Subsequently it was discovered that the two factors primarily responsible for corrosion of steel embedded within concrete were:

(1) the presence of chloride ions (salts) in surrounding concrete, and

(2) progressive carbonation of the covering layer of concrete with exposure to atmospheric carbon dioxide.

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The failure to understand deterioration processes throughout a long period in which many reinforced concrete structures were built resulted in a large inventory of deteriorating structures. At the time of construction these buildings were thought to be virtually indestructible.

Figure 1
Deteriorating Steel-Reinforced Bridge Deck That Has Lost Its Concrete Cover

Source: Federal Highway Administration Research and Technology, www.fhwa.dot.gov

Beginning in the 1980s, and increasingly since then, deterioration of 20th century concrete structures (Figure 1) has been viewed with concern, as illustrated by a sampling of written observations:

Ho and Harrison (1990) – *The deterioration of reinforced concrete structures resulting from reinforcement corrosion is a worldwide concern.*

Morton and Eley (2000) – *In recent years the deterioration of 20th century reinforced concrete has become a very significant problem.*

Anisuddin and Khaleeq (2005) – *Deterioration of concrete before it has served its expected life is a global phenomenon and the situation is particularly severe in hot and arid regions of the world . . .*

Bloomfield (2007) – *The economic loss and damage caused by the corrosion of steel in concrete makes it arguably the largest single infrastructure problem facing industrialized countries*.

Talukdar and Banthia (2013) – *Although climate change will have unnoticeable effect in the near future on durability of concrete structures constructed in the year 2000, the real effects of climate change will become evident after approximately 30 years.*

Bloomfield [as quoted by Hartnett] (2014) – *When Eisenhower built the interstate* [first projects mid to late 1950s]*, we thought the bridges would last 75 years. We're replacing those bridges now*.

Gjørv (2014) – *Uncontrolled and premature deterioration of concrete structures has emerged to be one of the most demanding challenges facing the construction industry. Public agencies are spending significant and rapidly increasing proportions of their construction budgets for repairs and maintenance of existing concrete infrastructure.*

Loos (2015) – *Society is facing durability problems in many of today's concrete structures that were built during the mid-twentieth century including multiple structural failures of concrete bridges, buildings, and marine wharves.*

It is not only early to mid-20th century concrete construction practices that are of concern. Pressures to reduce both costs and construction times, combined with development of the ready-mixed concrete industry and technology improvements that allowed creation of high-strength concrete using low cement content, have resulted in less durable structures. In the 1940s, air-entrained concrete was developed, which facilitated lighter concrete structures at lower cost (Schaeffer, 1992). Use of air-entrained concrete became common in the 1960s. By 1980 it was common to formulate air-entrained concrete containing relatively little cement with a high water/cement ratio. While of high strength, such concrete was more permeable and less durable than that used earlier (Mehta and Burrows 2001). Ongoing changes in climate appear to be magnifying the effects of greater concrete permeability. The roughly 30% rise in atmospheric carbon that has occurred over the past 60 years has caused scientists to take another look at the carbonation issue. Studies to date indicate more rapid carbonation rates and greater depths of penetration, suggesting a significant problem for current and future reinforced concrete construction.

The Carbonation Issue

The Basics

Like any material, concrete deteriorates under certain conditions. From the beginning of concrete use it has been recognized that such things as freezing/thawing and wetting/drying cycles, mechanical loading, and stress-induced crack formation can adversely affect concrete over time. Deterioration can also result from design faults, improper concrete formulation, inadequate workmanship and detailing, and lack of routine maintenance. All of these factors can accelerate deterioration due to chloride exposure and carbonation (Parrott 2000, Morton 2000, Portland Cement Association 2002, Hansson et al. 2012, Loos 2015).

When steel is embedded in concrete it is initially protected from corrosion due to the fact that the surrounding concrete is strongly alkaline (pH> 12.5). Concrete, however, is porous, permitting intrusion of acidic gases such as CO_2, which progressively neutralize concrete over time (reducing pH levels to ~8). Unchecked, CO_2 intrusion will eventually eliminate the protection of embedded steel. Once protection is lost the steel becomes vulnerable to the corroding action of water and oxygen and/or chlorides. The process of CO_2 intrusion and subsequent neutralization of concrete is called *carbonation*.

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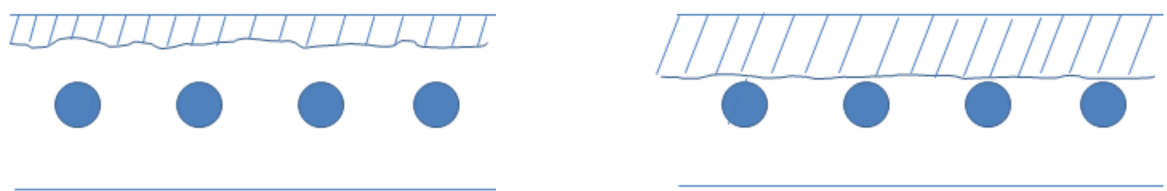
Carbonation occurs when atmospheric CO_2 penetrates concrete, reacting with cement – the binding agent in concrete – to form calcium carbonate. It occurs most rapidly at relative humidity levels of 50-70%. In well-formed, crack-free concrete, CO_2 penetrates concrete surfaces slowly, but inevitably, advancing as a more or less uniform front (Figure 2a), with the rate of penetration decreasing over time. There is no impact on corrosion until the front reaches to within about 5mm (0.2 inches) of the reinforcing steel (Yoon et al. 2007) (Figure 2b). Carbonation proceeds at a rate of up to 1.0 mm (0.04 inches) per year in high quality concrete (Portland Cement Association 2006).

Figure 2
Progressive Carbonation from Exposed Surfaces



a. Carbonation is Underway, but Depth Not Close To Reinforcing Steel

b. Carbonation Depth Nearing Corrosion Risk to Reinforcing Steel

The total life span of a steel-reinforced concrete structure is defined by the period of time prior to removal of the alkaline protection of reinforcing steel, through either chloride exposure or carbonation, and by the rate of corrosion of steel reinforcement once the protective layer is lost (Pacheco and Polder 2010). Corrosion reduces the strength of the steel and can lead to cracking. The cracking can occur because oxides are formed as the steel begins to corrode and these oxides occupy a much greater volume than the original steel. This growth in volume causes stresses to develop that can lead to cracking of the concrete cover and further accelerated deterioration.

Duration of the protective layer largely defines the longevity of a steel-reinforced concrete structure. Consequently, one consideration in design of concrete structures is the depth to which reinforcing steel is buried in the concrete matrix, often defined as the thickness of the concrete covering. Modeling is used to estimate rates of penetration and to determine the thickness of concrete cover needed to provide a high probability of attaining a given design life. For instance, when modeling indicates an average rate of CO_2 intrusion of 0.5 mm (0.02 in.)/year, a minimum concrete cover of 37.5 mm (roughly 1 ½ inches) is prescribed to attain a 75 year design life, assuming that surfaces remain crack free.

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Carbonation and Increasing Levels of Atmospheric CO_2

Loos (2015) recently observed that while other forms of concrete deterioration, such as chloride penetration, have received more attention, carbonation is becoming of increasing concern due to the increase of CO_2 in the atmosphere. Consequently, scientists worldwide have begun to focus on the potential for greater carbonation-induced concrete deterioration as the CO_2 concentration increases. The early consensus is that rising CO_2 levels pose a significant problem.

Wang et al. (2010) and Stewart et al. (2011) found that the increasing CO_2 levels will increase the likelihood of carbonation-induced corrosion in reinforced concrete worldwide, and that higher temperatures would likely increase deterioration rates. For several regions of Australia, risks of carbonation-induced damage were predicted to increase by over 400% by 2100, and in two of Australia's cities – Sydney and Darwin – damage to 20-40% of all concrete infrastructure by 2100 was projected. Wang and colleagues (2010) concluded that carbonation can have a considerable negative impact on durability, especially for above ground structures and those exposed to high CO_2 concentrations.

Other studies concluded that global climate change will affect CO_2 intrusion rates and result in significantly greater ultimate carbonation depths over the long term (Talukdar and Banthia 2012, 2013; Wang et al. 2012; Bastidas-Arteaga et al. 2013; Peng and Stewart 2014; Saha and Eckelman 2014). Temperature increases are likely to increase steel corrosion rates (Stewart et al. 2011). The Talukdar/Banthia 2013 study employed modeling of rising atmospheric CO_2 levels and changing climate conditions and concluded that there would likely be little near-term effect on concrete structures built in the year 2000, but that future construction would need to take into account the likelihood of premature deterioration in the design stage. Worst case scenarios indicated reduction of serviceable lifespans of 15-20 years for structures built in 2030, with evidence of damage within 40-45 years of construction. The Bastidas-Arteaga study (2013) indicated that climate change might reduce the time to failure of reinforced concrete structures by up to 31%.

Worst case scenarios indicated reduction of serviceable lifespans of 15-20 years for structures built in 2030, with evidence of damage within 40-45 years of construction.

Saha and Eckelman (2014), noting that 57 percent of Boston's 1,700 concrete buildings were built in the 1960s, predicted that at existing rates of decay coupled with anticipated warming of climate, 60 percent of the city's buildings will face structural deterioration by 2050. They further indicated that carbonation and chlorination intrusion in current concrete construction projects will likely exceed current code-recommended concrete cover thicknesses within 65 and 40 years, respectively, time periods well within normal building life expectations.

Li (2009), referring to increasing rates of concrete deterioration from all causes, summarized the situation this way:

> *Although infrastructure deterioration might not be as dramatic as damage from fires or earthquakes, the magnitude of this problem in terms of structural life cycle, economic, social, and environmental impacts under service loading conditions dwarfs those associated with failures under severe loading conditions. The economic impacts are associated with the high cost of maintaining, repairing or replacing deteriorating structures, which is exceedingly burdensome on building owners, departments of transportation, the insurance industry and society.*

The Saha/Eckelman study, as well as a number of others (Stewart et al. 2011, Nanukuttan and Basheer 2012, Gjørv 2014) point to the likelihood of rising repair costs for concrete structures due to increasing effects of carbonation and the need for damage mitigation measures in future construction projects. Changes in design specifications and possibly in construction practices will likely be needed. Wang et al. (2010) propose that practices to reduce deterioration should be considered at four stages: material design, structural design, building construction, and operation.

Potential Solutions

The most comprehensive solution to the problem of increasing carbonation rates in reinforced concrete would be to stabilize, or slow the rate of increase in, concentrations of atmospheric CO_2. However, given that under current policies, further increases in CO_2 levels are all but certain, other solutions must be sought.

Repair

One approach to rising rates of deterioration is to simply monitor and repair as needed. The anticipated repair costs can also be factored into life cycle cost analyses at the building design stage. However, a number of studies have found that repairs are often short-lived. Morton and Eley (2000), for instance, reported that repairs are generally not guaranteed for more than 20 years, and effective measures to restore a deteriorating structure often require treatment of an entire building, rather than selected areas where damage is visible. Broomfield cited an analysis of 230 repaired reinforced concrete structures which found that 20%, 60%, and 90% of repairs failed within 5 10, and 25 years, respectively (Larsen 2015).

Prevention

One preventive strategy is to increase the thickness of the concrete cover (Wang 2010). This approach was recommended by Saha and Eckelman (2014); they indicated that increasing the cover thickness by only 3 to 12 mm ($^1/_8$ to ½-inch) would be sufficient to avoid predicted increases in deterioration rates. In fact, the chair of the American Concrete Institute's standards setting committee was recently quoted as saying that he expects his committee to recommend an increase in concrete cover thickness in the near future (Hartnett 2014). But such a strategy has a price – both in terms of construction costs and initial environmental impacts. Saha and Eckelman (2014) estimate a 2-4 percent increase in building costs associated with the increases in concrete cover which they proposed. Because production of cement is highly energy intensive, a somewhat greater increase would likely occur in environmental performance measures including fossil energy consumption and global warming potential.

Treatment

Another strategy, which dates back to the 1980s (Ho and Harrison 1990), involves treating of concrete surfaces with special coatings to limit permeability. A number of coating products are currently on the market, with current use primarily on older buildings. Effective use of these materials requires periodic reapplication.

Formulation

Another approach is to change concrete formulation. Recognition that high water-cement ratios lead to greater capillary porosity has led to development of water reducing agents that allow use of much less water in the concrete mix. It is also been shown that incorporation of supplementary materials such as fly ash and blast furnace slag can reduce permeability and reduce crack formation. Use of curing agents other than water has also been shown to have promise in improving concrete durability (Oregon State University 2016).

Changing the Reinforcing Materials

Yet another strategy is to treat or change the reinforcing materials to reduce corrosion potential. Numerous materials are currently being evaluated to determine long term performance, including epoxy coating of reinforcing steel, stainless steel, galvanized steel, various steel alloys, use of metals other than steel, carbon fiber reinforcement of the cement matrix, and incorporation of corrosion inhibitors within cement (Portland Cement Association 2006, Hansson et al. 2012). Epoxy coating of steel is currently practiced in highly corrosive environments such as bridge decks exposed to deicing salts and structures in marine environments (Virmani 2007).

The Bottom Line

Premature deterioration of steel-reinforced concrete structures – especially those located in hot, humid, marine environments, or those periodically exposed to deicing salt – has become an issue in recent decades. Structures built in the first half of the 20th century were constructed prior to understanding of major contributing factors to steel reinforcement deterioration with the result that many such structures have required extensive repair or demolition. Later, pressure to complete construction more quickly resulted in another cohort of lower durability structures. Now there is a new concern related to a changing climate: increasing levels of atmospheric carbon dioxide, combined with higher average temperatures, appear to pose a threat to longevity of reinforced concrete structures of all kinds, in large part because of increasing carbonation rates and depth of carbonation penetration.

A number of strategies for reducing deterioration rates are in use or under development. These include increases in the thicknesses of concrete cover, use of permeability-reducing coatings, changes in concrete formulations, and treatment or replacement of reinforcing materials to reduce corrosion potential. All of these strategies are likely to increase costs of construction and preventive maintenance and associated environmental impacts, but if successful will extend useful life and reduce future costs of repair.

Heightened awareness of the premature deterioration problem in steel-reinforced concrete structures is needed throughout the building sector, with near-term consideration given to possible prevention strategies. It is important that such consideration include assessment of life cycle costs and environmental impacts linked to each option for change.

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