

Prevention of Corrosion in Concrete Using Fly Ash Concrete Mixes

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ABSTRACT

This paper reviews the benefits of using high-volume fly ash in resisting corrosion damage in concrete structures. It considers the usefulness of current fly ash concrete technology and prevention techniques, and advances a new approach for making concrete resist the deleterious effects of corrosion.

Nationally, the use of coal combustion products (CCPs) has increased more than 50 percent in the past decade. In 2000, more than 32 million tons of coal combustion products were recycled for beneficial uses. This is more than seven times the volume of aluminum that is recycled. But even though consumption has increased rapidly, only a third of all CCPs generated in the United States are currently being used in beneficial applications. This leaves more than 76 million tons of CCPs to be disposed of annually.

The United States has recognized that its infrastructure of concrete bridges and highways is facing structural distress due to increased traffic volumes, increased axle loads and due to corrosion. In a landmark study conducted by Battelle Memorial Institute for the National Bureau of Standards, it is estimated that corrosion damage in the United States is 4.2 percent of the Gross National Product (GNP). Projecting this percentage out to recent GNP information, this amounts to about \$350 billion of corrosion damage annually. Battelle estimates that over \$139 billion (40%) of these costs could be avoided through application with existing technologies and best-known practices.

Corrosion of concrete takes place when carbon dioxide (CO₂) and chlorides penetrate concrete. As the chlorides and CO₂ penetrate concrete, the pH level of the concrete begins to drop from 12-13 to about a value of 9. In concrete construction, the 1.5 to 2 inches of concrete cover over the rebar acts as protective layer from the chlorides/CO₂ reaching the rebar. Once the threshold is reached, the concrete cover is compromised and the pH of the concrete surrounding the rebar allows for corrosion. This weakens the concrete and reduces its service life. This subsequently increases costly maintenance on repair and restoration projects for the damaged concrete structure.

There are several practical methods used to counteract problems caused by corrosion, including adequate concrete cover, better quality concrete (low permeability, no cracks), epoxy coated rebar, stainless steel reinforcement, cathodic protection, protective coatings, a corrosion inhibitors. Recent research has indicated the benefit of using fly ash in preventing corrosion damage in concrete. Reduced permeability, lower water/cement ratio, decreased drying shrinkage/cracking, and increased durability are all benefits of fly ash concrete.

INTRODUCTION

Corrosion of reinforcing steel in concrete bridges and highways has become a considerable economic and social burden for many states and safety issue to taxpayers. This premature deterioration has led to an inadequate design life of the infrastructure within the United States. The aging infrastructure is at the top of the list for the most serious problems facing the Federal Highway Administration (FHWA). The adoption of corrosion protection measures in new concrete construction has become a major focus. This includes, but is not limited to, the use of good design and construction practices, adequate concrete cover, low-permeability, corrosion inhibitors, and coated reinforcing steel. Nevertheless, the costs continue to rise faster than the repairs can be made. The direct cost today of repairing or replacing all deteriorated concrete structures is estimated to be more than \$276 billion annually or 3.1 percent of the nation's Gross National Product (GNP)¹. This is a dramatic increase from the 1975 benchmark study by Battelle-NBS², which calculated the cost of all corrosion to be \$70 billion per year, which was 4.2 percent of the nation's GNP. Today, \$121 billion per year is spent on mitigating corrosion, leaving a growing deficit of \$155 billion a year.

Further facing FHWA and the concrete construction industry is the continued environmental emphasis from the federal government and environmentalists. Concrete is an environmentally friendly and versatile material for the construction of infrastructure. Unfortunately, Portland cement, the critical component of concrete, may not be as environmentally friendly. The production of one ton of Portland cement releases about one ton of carbon dioxide (CO₂) emissions into the atmosphere. The current U.S. production of Portland cement contributes about 750 million tons of CO₂ to the greenhouse gases (GHG) in the earth's atmosphere annually. Governmental regulations on these GHG emissions are stimulating the cement industry to look at supplementary cementing materials that could be used to produce lower CO₂ emissions.

The increased interest in sustainable design and construction has created a renewed interest in Coal Combustion Products (CCPs). This trend has been accelerated by the emergence of agencies like the U.S. Green Building Council (USGBC), Leadership in Energy and Environmental Design (LEED), Coal Combustion Products Partnership (C2P2) of the USEPA, along with President Bush's Clear Skies Initiative. Their primary goal is environmentally and socially focused towards overall sustainable development. Secondly, CCPs have been found to provide the catalyst for these groups to reach their individual goals and objectives.

COAL COMBUSTION PRODUCTS (CCPs)

According to the United States Geological Survey³, CCPs rank third as the most abundant non-fuel mineral resources in the United States, its annual production is just below crushed stone, and

sand and gravel. Portland cement ranks just below that of CCPs. Concrete is said to be only second to water as the world's most consumed product. In order to produce concrete, it is necessary to use some Portland cement as a binder. The challenge is that for every ton of cement produced; about a ton of CO₂ is released into the atmosphere. CO₂ is the primary greenhouse gas attributed to the depletion of the ozone layer. By replacing one ton of cement with fly ash, an equal amount of CO₂ release into the atmosphere can be prevented.

The increased use of Portland cement is expected to continue to grow in the U.S. as in the rest of the world. Thus, we can expect increasing CO₂ emissions into the atmosphere from cement manufacturers. The agencies listed above, have brought economical and environmental pressures onto these manufacturers of cement. At this point in time, it is important to manufacture cement as environmentally friendly as possible. Furthermore, the manufacturers of cement are very much aware that for the commission of any new cement plant, the industry must show increased stewardship. One such responsible measure is the increased use and promotion of supplementary cementing materials in the production of cement and concrete.

Seventy percent of all the energy in the United States is produced by the approximately 720 coal-fired power plants in about 45 states. When burning coal at these power plants, two main types of ashes are produced, coal fly ash and bottom ash. Fly ash is the very fine material carried in the flue gas, collected typically by an ESP or a baghouse, and stored in silos for use in concrete. Bottom ash is the larger/heavier particles that fall to the bottom of the boiler after combustion. An additional solid byproduct of clean coal technology processes is produced from coal containing sulfur. When this coal is burned, sulfur dioxide is produced. Scrubbers are used to collect the sulfur dioxide (by injecting a sorbent) and Flue Gas Desulfurization (FGD) material is generated. In this study, we will limit our focus to coal fly ash.

The 720 coal-fired U.S. power plants annually produce about 63 million tons of fly ash. About 31 million tons are disposed of, either onsite or in state-regulated disposal sites. Approximately 12 million tons are recycled and put to beneficial reuse in the concrete industry. Another 20 million tons are used for a range of other applications including, soil stabilization, roller compacted concrete, road base stabilization, etc. In this paper, we will focus on the use of fly ash as a mineral admixture for Portland cement concrete.

FLY ASH AS A SUPPLEMENTARY CEMENTING MATERIAL

The United States consumes over 108 million tons of cement a year, with 75 million tons being domestically produced. Roughly 25% of all cement is imported from all over the world for U.S. consumption. Currently, in the U.S., it is an accepted practice to substitute 15 to 35% cement in concrete with fly ash. The question that needs to be asked is: why are we only consuming 12 million tons of fly ash and allowing 31 million tons of fly ash to go to disposal?

The answer lies in the fact that fly ash is really not well understood by specifiers. The opportunity comes by promoting the features and benefits of fly ash to the specifiers. Specifically, addressing the engineers needs, according to specific market segment. These market segments include architectural, chemical, civil, electrical, environmental, geotechnical, highway, industrial, mechanical, mining, sanitary, structural, surveying, and transportation.

The use of fly ash (Class C and Class F) in concrete offers several significant advantages. These include:

- Reduced permeability
- Reduced water/cement ratio
- Reduced concrete segregation
- Reduced bleeding
- Increased workability/ plasticity
- Increased flexural and compressive strength
- Increases pumpability
- Reduced heat of hydration
- Cost savings to the user
- Increased sulfate resistance
- Improved freeze-thaw durability
- Reduced volume changes: dry shrinkage
- Better finishability
- Reduced expansion due to ASR
- Improved hot weather handling characteristics
- Reduced corrosion damage

Currently, concrete designers and specifiers are not designing the same as they did twenty, ten, and even two years ago. Society is demanding concrete structures last fifty, one hundred, five hundred, and even a thousand years. Wacker Drive in Chicago, Illinois was designed to last eighty to one hundred years. The Confederation Bridge located between the Northumberland Strait and Prince Edward Island and mainland Canada has a design life of one hundred years. BAPS Temple in Stafford, Texas was designed to have a service life of one thousand years. This list is growing by the day. What do all these structures have in common? Fly ash is playing a key role for the designers to build these concrete structures with a service life lasting hundreds of years. What is new about fly ash in concrete that improves the longevity of concrete structures with such long service life?

BATTELLE CORROSION STUDY²

A landmark study conducted by Battelle Memorial Institute² for the National Bureau of Standards, identified corrosion damage to reinforcing steel as the major cause for premature concrete deterioration in the United States. It is this attempt to prevent corrosion within these concrete structures that the designers of Wacker Drive, Confederation Bridge and BAPS Temple have focused on to develop structures that will last into the next century and beyond.

According to Battelle study, the cost to the taxpayer is indirectly 4.2% of the Gross National Product (GNP). Projecting this percentage out to the current 2003 GNP, corrosion is estimated to cause \$350 billion in damage annually. Battelle estimates that over \$139 billion or forty percent of these costs could be avoided through application of existing technologies and best-known practices. Being that there are concrete structures still standing today that are thousands years old, it allows for engineers to study these forgotten technologies and implement them into

today's concrete technology. The Pantheon and ancient aqueducts and Roman piers provide this opportunity for study.

THE CORROSION PROCESS

Steel corrosion in concrete structures is an electrochemical process that requires the flow of electric current and several chemical reactions. The anode and cathode can be on the same steel reinforcing bar. The anode is the location on the steel where the metal is broken down. Here is where the iron atoms lose electrons to become iron ions (Fe^{+2}). This oxidation process is referred to as the anodic reaction (See Figure 1).

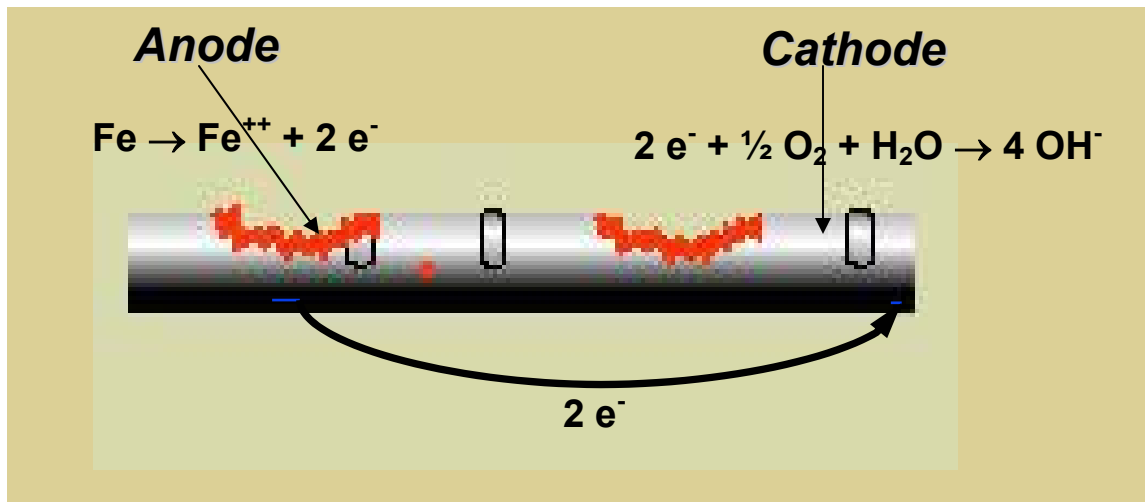


Figure 1: Typical Corrosion Cell⁴

The cathode is the location on the steel reinforcing where the metal is not being consumed. At the cathode, oxygen, in the presence of water accepts electrons to form hydroxyl ions ($\text{Fe}^{2+} + 2\text{OH}^{-} \rightarrow \text{Fe}(\text{OH})_2$). This reduction reaction (See Figure 1) is considered to be the cathodic reaction. It should be noted that water and oxygen are needed to facilitate corrosion. The electrolyte is the medium that facilitates the flow of electrons (electric current) between the anode and the cathode. Concrete, when exposed to wet-dry cycles has sufficient conductivity to serve as an electrolyte. The anodic and cathodic reactions are necessary for corrosion to occur. Furthermore, this reaction must take place simultaneously.

When Anode and Cathode are located next to each other the corrosion cell is referred to be a microcell (as shown in Figure 2). When both the anode and cathode are separated by a measurable distance, the corrosion cell is said to be a macrocell (as shown in Figure 3).

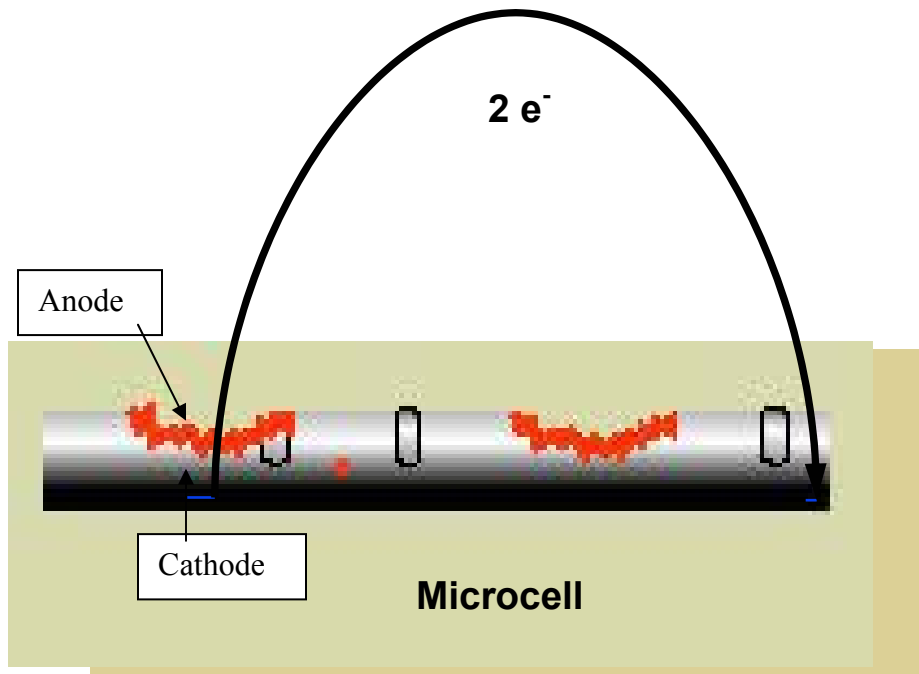


Figure 2: Corrosion Microcell⁴

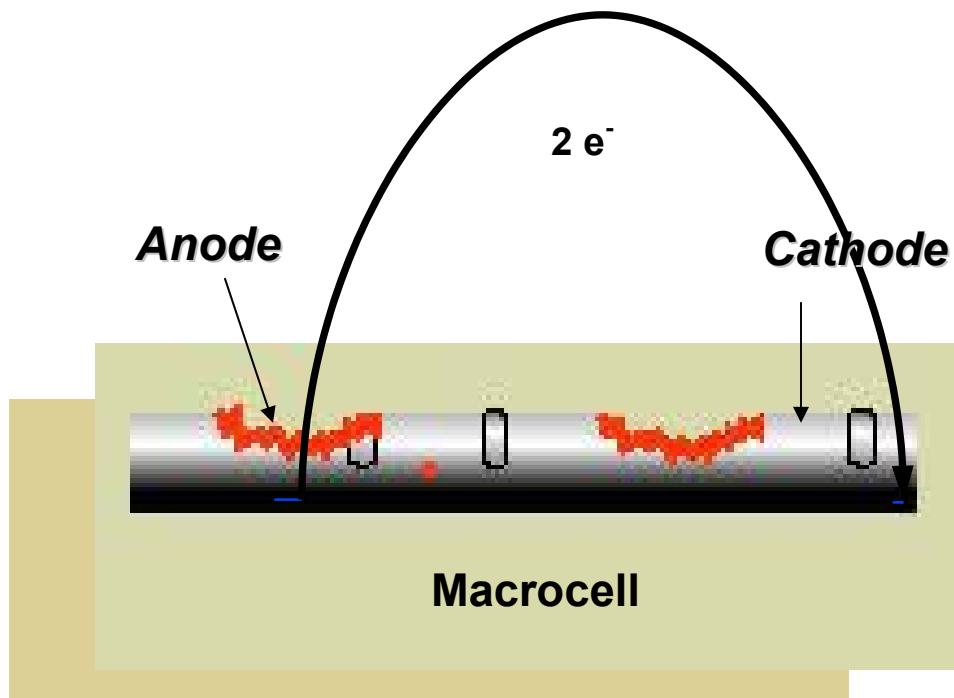


Figure 3: Corrosion Macrocell⁴

Passivation of Steel in Concrete

Concrete is an alkaline environment with a pH between 12 and 13. Due to this environment, a passivating layer of iron oxide is formed around the steel. This protects reinforcing steel initially from corrosion in concrete as shown in Figure 4.

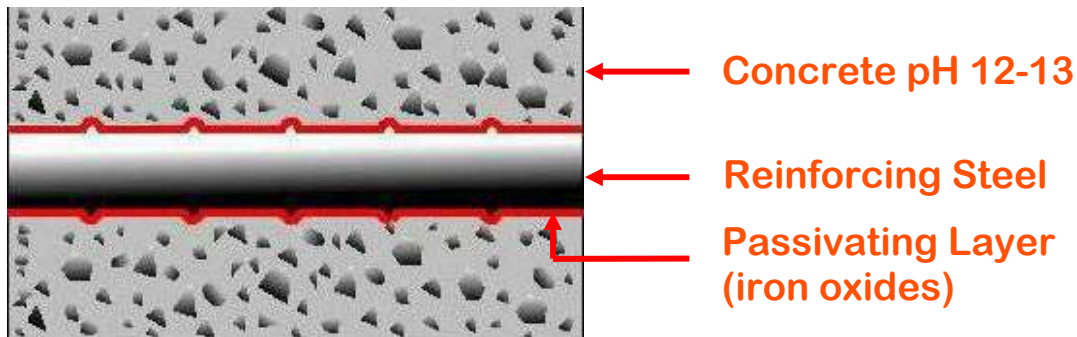


Figure 4: Passivating Layer of Iron Oxide⁴

Corrosion Model

Corrosion of reinforcing steel takes place when carbon dioxide (CO_2) and chlorides penetrate concrete. As the chlorides and CO_2 penetrate concrete and dissolve in the pore solution, carbonic acid is formed. This acid reacts with the alkali in the cement to form carbonates and to lower the pH level of the concrete (See Figure 5). In concrete construction, the 1.5 to 2 inches of concrete cover over the rebar acts as protective layer from the chlorides/ CO_2 reaching the rebar.

Once the threshold is reached (See Figure 6), the concrete cover is compromised and the pH of the concrete surrounding the rebar allows for corrosion. When the alkalinity begins to drop from 12-13 to about a value of 9, the steel becomes depassivated. In the presence of water and oxygen, corrosion is initiated. Rust forms on the steel (See Figure 7) and expands in volume three to six times that of the original steel. This increase in volume change increases the stresses in the concrete resulting in cracks, delaminations and spalls. Concrete is brittle, and will crack and break with as little as one-hundredth-of-an-inch increase in the diameter of the reinforcement bar. This further accelerates the corrosion process by opening larger pathways for water, oxygen, chlorides and CO_2 to penetrate into concrete. This weakens the concrete and reduces its service life, subsequently increasing costly maintenance until total replacement is needed.

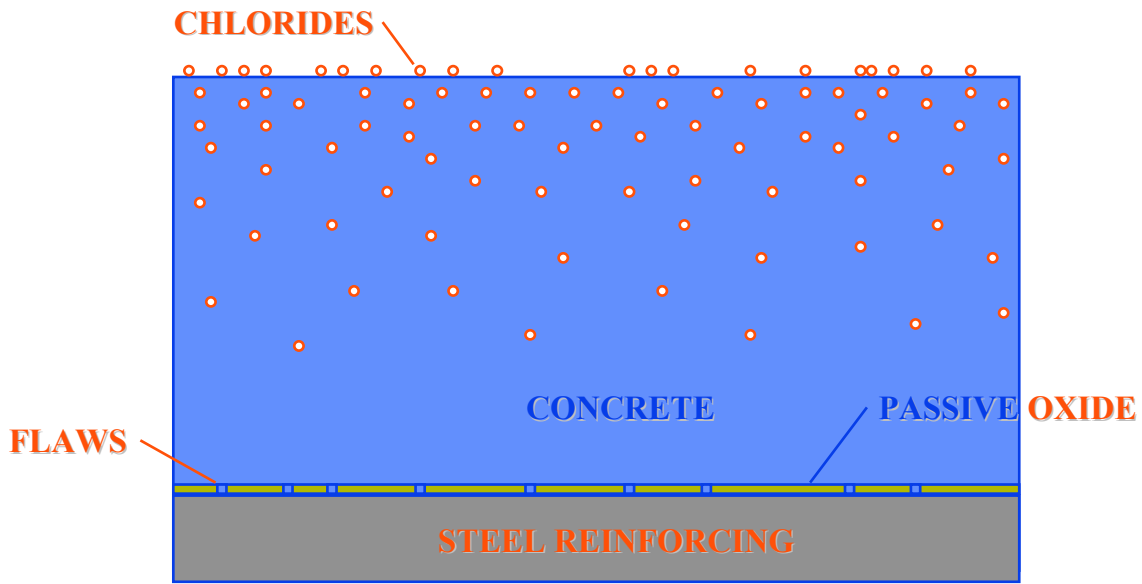


Figure 5: Corrosion Model - Chlorides/CO₂ Penetrate Concrete

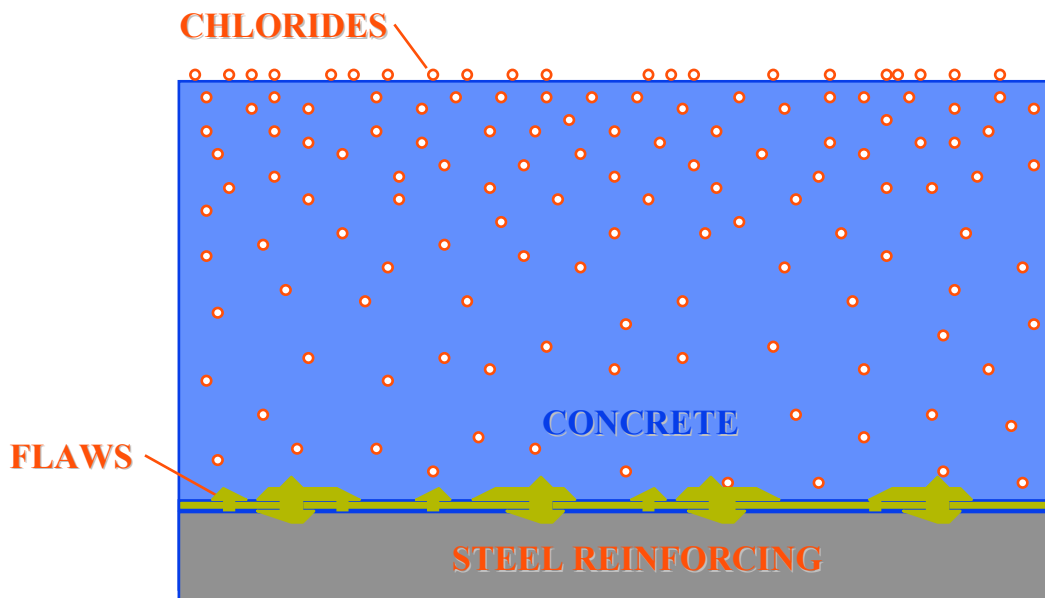


Figure 6: Corrosion Model – Threshold is reached

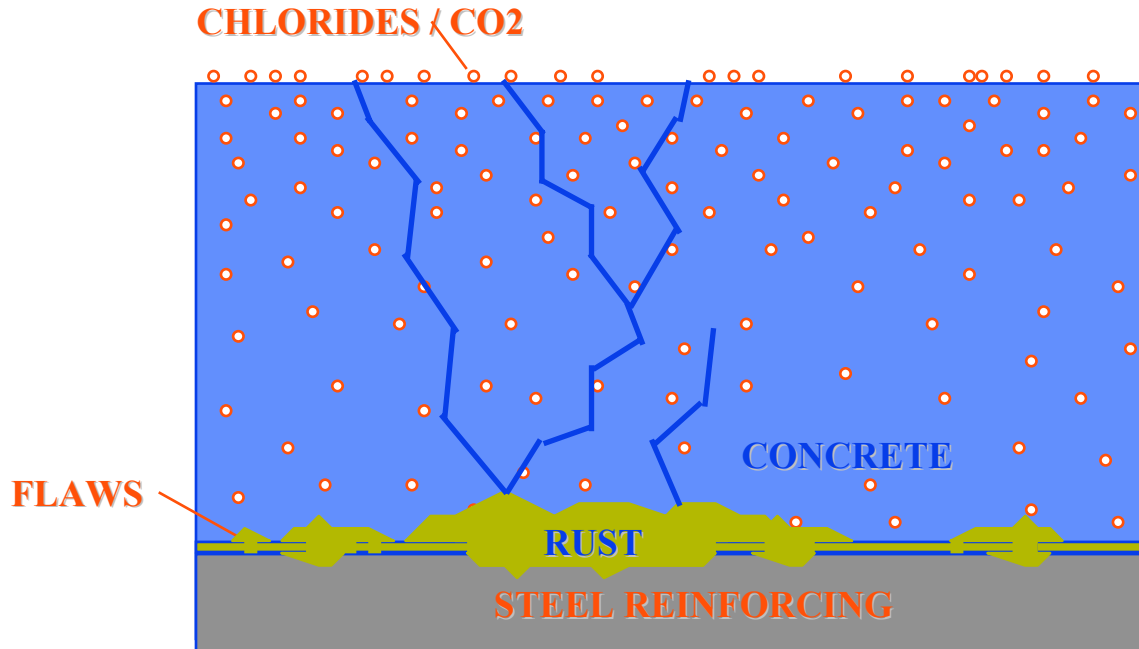


Figure 7: Corrosion Model – Significant Corrosion Damage

Corrosion Controlling Phenomenon

There are three principal phenomena that control corrosion-induced deterioration of reinforcement in concrete. They are chloride diffusion, corrosion, and deterioration rates. Chloride diffusion rate is the rate at which chlorides ions diffuse through the surface of the concrete cover. Corrosion rate is the rate at which the corrosion process progresses after depassivation of the steel has occurred. Deterioration rate will determine the length of time before repair or replacement of the deteriorated concrete structure is required.

Chloride Diffusion: The main factor influencing chloride diffusion in concrete is permeability. Concrete permeability can be reduced by reducing the water-cement ratio of concrete, adding pozzolanic materials to concrete, adding polymer modifiers to concrete, and suitable aggregate gradation.

Corrosion Rate: In general, the concentration of chloride ions in concrete, next to the steel, needs to be more than $(1.2 \text{ lb/yd}^3)^5$. This will initiate the depassivation of the steel and initiate corrosion. Factors influencing the corrosion rate of steel in concrete are:

- Availability of water and oxygen
- Ratio of steel surface area at the anode to that at the cathode
- Amount of chloride ions in the porewater
- Resistivity of the concrete
- Temperature
- Relative humidity (both internal and external)
- Concrete microstructure

The availability of oxygen is directly related to the rate of diffusion through the concrete. The denser the concrete, the slower the rate of diffusion. When concrete is totally submerged in water, the rate of diffusion is also slowed down. This is because the oxygen must diffuse through the porewater to get to the steel. When concrete is dry, oxygen can freely move through the pore structure of the concrete. Continuous wetting and drying will also accelerate the corrosion process.

Deterioration Rate: Very little research has been done in the area. The focus has been on the depth of concrete cover of the steel and the permeability of concrete. High-strength concrete generally has low water-cement ratio, low porosity, and a relatively high modulus of elasticity. The high-strength concrete with a higher modulus of elasticity is less forgiving than concrete with a lower modulus. Concretes with lower modulus may deflect without cracking, while the higher modulus ones may fracture. On the other hand, high-strength concrete generally has a lower permeability therefore taking longer for the chlorides to accumulate at the steel. The key to long-term durability of reinforced concrete structures is the use of Portland cement high fly ash concrete with low permeability and adequate concrete cover.

COST OF CORROSION

In 2002 a study was presented to the U.S. Federal Highway Administration (FHWA)⁶ outlining the cost of corrosion. The study titled “Corrosion Costs and Preventive Strategies in the United States” focused on identifying the cost of corrosion by specific industry sectors (See Figure 8) and establishing control methods to minimize the problem.

Results of the study showed the total annual estimated direct cost of corrosion for 1998 to be \$276 billion – 3.1% of the nation’s Gross Domestic Product (GDP). Extrapolated into 2003, it is \$350 billion. The report revealed that although corrosion management has improved over the past several decades, the U.S. must find better methods to control corrosion.

Corrosion experts have spent the last decade focusing on new construction, specifically on materials and design. Today, much of our infrastructure is reaching the end of its design life. The emphasis has shifted to maintaining and extending the service life of these concrete structures.

Of the nearly 600,000 bridges, there are roughly 235,000 conventional reinforced concrete bridges, and 108,000 prestressed concrete bridges operating in the U.S.¹ They support nearly 270 million residents and 7 million business establishments. It is estimated that 15% are structurally deficient because of corroded steel and steel reinforcement. The Status of the Nation’s Highway Bridges: Highway Bridge Replacement and Rehabilitation Program and National Bridge Inventory, Thirteenth Report to the United States Congress¹, estimated that 80,000 bridges on the federal system and 103,000 bridges of the federal system were deficient in some way. While there was a decrease in the number of bridges in need of repair or replacement, the costs increased by 12% during the same period. Assuming that the total transportation sector is responsible for 21.5% of the corrosion, it can be calculated, that the cost will be about \$75,250,000. The direct corrosion cost associated with bridges is 37% or \$27,842,500 annually in 2003. The indirect costs or those incurred by users are estimated to be tenfold (example, wear and tear on the automobiles, increased gasoline, delays in product transport, missed

appointments, and other inconveniences that result in lost revenue.) This indirect cost that is due to corrosion of bridges, burdens our society roughly \$278,425,000 annually.

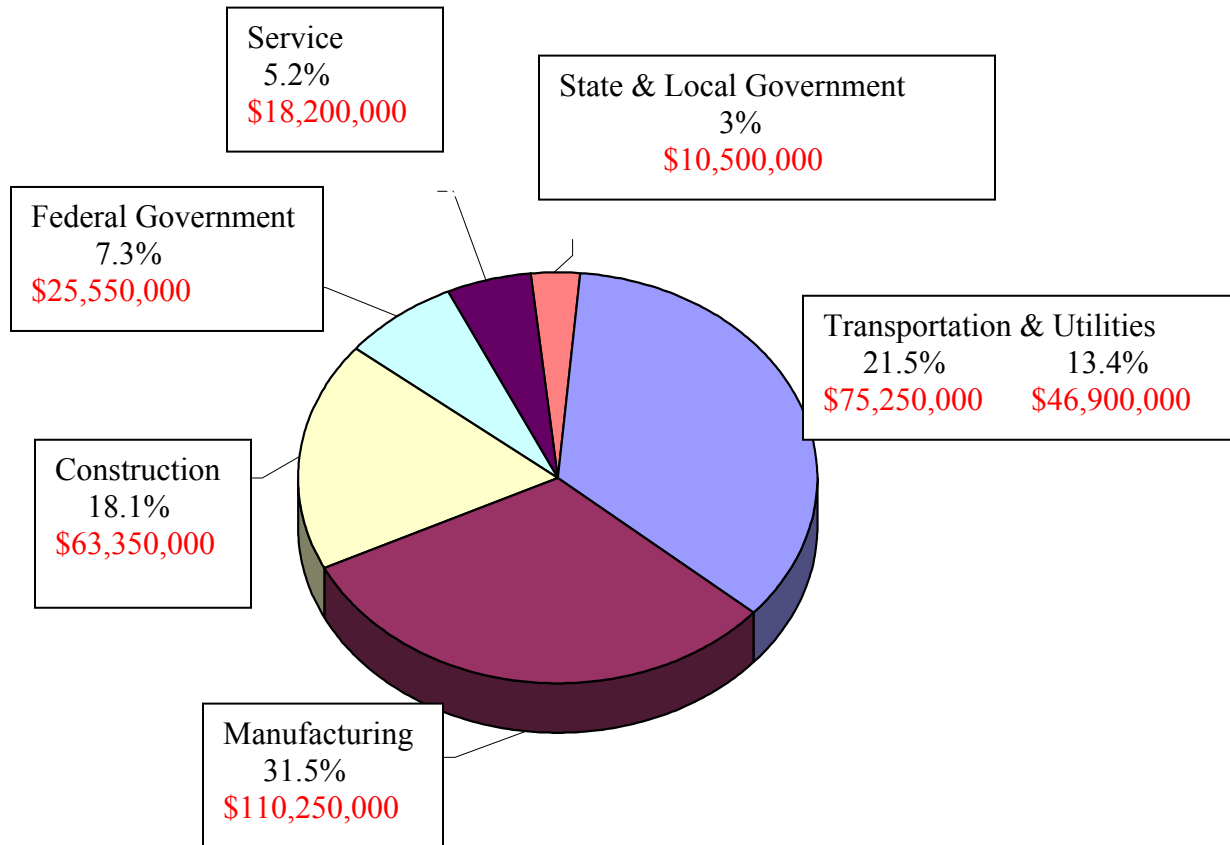


Figure 8: Corrosion Damage in the US – Breakout of Industry Segments¹

MEASURES FOR PREVENTING CORROSION OF CONCRETE

Most corrosion-protection measures utilize the basic principle to prevent the CO₂ and chloride ions from reacting with the steel surface and also to increase the time needed for the chloride ions to penetrate through the concrete cover. Although these measures do not stop corrosion from eventually initiating, they do increase the service life of reinforced concrete by slowing the corrosion process. The materials include admixtures, sealers, and membranes, overlays, and coatings on steel reinforcing. The use of fly ash as a mineral admixture to concrete, for the prevention of corrosion, is presented below.

Fly Ash for Corrosion Mitigation

Mineral admixtures can be used to enhance the corrosion-control potential of concrete by reducing permeability. Fly ash is one of the most common admixtures used in concrete but rarely

thought of to mitigate corrosion. Normally, designers focus at maintaining the alkaline pH of 12 – 13 in concrete to sustain the steel in a non-corrosive environment. Because lower pH fly ash replaces cement, the primary source of the alkalinity in concrete, many designers have avoided its use. In a well-hydrated concrete mix, the Portland cement may contain up to 15 – 40 percent calcium hydroxide by weight of cement. This is usually adequate to maintain the pH at 12 – 13. Because fly ash improves the density of concrete along with other beneficial factors, it more than compensates for the slightly lower pH.

During the cement hydration process, 15 to 40 percent of the cement does not hydrate. This unhydrated cement or calcium hydroxide (CH) is detrimental to concrete because it aides in the premature deterioration of concrete. Chemically, calcium hydroxide will react with sulfates, alkali silica and CO₂ to deteriorate concrete. Thus, the goal of the designer of the concrete mix is to chemically change this calcium hydroxide and maximize CSH (Calcium Silicate Hydroxide) while maintaining the pH.

If we examine a simple 25% replacement, one would be removing a very small portion of the calcium hydroxide. For example, 100 lbs of cement on the average would produce 30 lbs of calcium hydroxide. If we replaced 25 % fly ash from the 100 lbs. of cement, we would end up with 22.5 lbs of calcium hydroxide. This scenario figures the ash contributing zero percent calcium to the mix.

The pozzolanic reaction in fly ash converts the CH into more of the CSH – thus leading to reduced permeability. With the use of fly ash, the ingress of moisture, oxygen, chlorides, and aggressive chemicals are slowed significantly - thus improving durability and serviceability. It should be noted that after twenty years of curing, it is not uncommon to see fly ash concrete have a chloride diffusion coefficient 100 times less than a control Portland cement concrete. Thus, fly ash can improve durability such as alkali attack, sulfate attack, chloride ingress, CO₂ and corrosion.

The Ohio State University is collaborating with ISG Resources in researching the use of high-volume fly ash for increased durability and lowered corrosion potential of structural concrete. Two methods are under investigation: 1. Fly ash replacement for cement in conjunction with fly ash addition for fine aggregate. 2. Fly ash replacement for cement.

Fly ash Replacement for cement in Conjunction with fly ash addition for fine Aggregate

Chloride permeability results of control (no fly ash) and high volume fly ash mixes at 28 days of curing are presented in Table 1. It can be seen that the samples with no fly ash had the highest chloride permeability while concrete samples with fly ash had much lower permeability values. As the amount of fly ash replacing cement increased, the chloride permeability rapidly reduced.

Results of unconfined compressive strength tests of control and fly ash concrete samples are presented in Table 2. After 28 days of curing, all the fly ash sampled had strengths well in excess of the no fly ash concrete sample. As the replacement of cement by fly ash increased, the strengths increased rapidly.

This portion of research at The Ohio State University was stimulated by Washington State’s DOT projects on fly ash overlays as an alternative to silica fume or latex-modified overlays. The interest for this alternative approach was stimulated by the sensitivity of the existing mixes to weather, temperature and pouring schedule. The goal for Washington State DOT was: to provide an air-entrained fly ash mix that could be field placed at an 1 1/4 to 1 1/2 thickness, would develop a 3000 psi compressive strength in 4 days and achieve 150 day rapid-chloride permeability of 750 coulombs or less.

Mix proportions were developed by the local ready mix producer who selected 611 pounds of Type II cement and 275 pounds of Class F fly ash as the mix to meet the specifications. Admixtures included: air-entraining agent, retarder and a superplasticizer. This combination was selected from a round of tests performed in their lab.

Current WDOT specifications allowed for fly ash to constitute a maximum 25% of the total cementitious material and differed from the high volume mix in three aspects: 1). Water reducer was used instead of superplasticizer. 2). 3/4 –inch coarse aggregate was used instead of the 3/8-inch material. 3). Water-reducer dosage per hundred pounds of cement remained constant, and w/cm was varied to achieve the desired 4-inch slump.

Results showed high volume fly ash mixes could improve the concrete strength and permeability while providing workability superior to that of the original overlay mixers. Further improvements indicated lower dosages of water reducer and superplasticizer combinations were not needed to provide adequate workability at the low w/cm ratio. On recent deck overlay projects, mid-range water reducer (dosage based on cement weight only) and an air entrainment are being used.

MIX	COULOMB	COULOMB RANGE	CHLORIDE PERM.	TYPICAL OF
658 / 0	4509	> 4000	HIGH	W/C > 0.6 PCC
658 / 75	2404	2000 - 4000	MODERATE	W/C 0.4 - 0.5 PCC
530 / 130	1497	1000 - 2000	LOW	W/C < 0.4 PCC
530 / 260	797	100 - 1000	VERY LOW	SILICA FUME
611 / 275	639	100 - 1000	VERY LOW	SILICA FUME

Table 1: Chloride Permeability for Fly Ash Concrete Mixes

CEMENT #	658	658	530	530	611
FLY ASH #	0	75	130	260	275
W/(C+P)	0.41	0.37	0.38	0.33	0.28
AIR%	6.6	6.2	5.9	5.4	4.7
COMP – 3 DAY	NONE	NONE	NONE	NONE	NONE
7 DAY	4765	4675	4295	4325	NONE
14 DAY	5480	5630	5185	5330	8015
28 DAY	6140	6580	6020	6315	8995
148 – 157 DAY	6730	7420	7360	8390	11995
300 DAY	6800	7780	8070/6900	8950	12430

Table 2: Unconfined Compressive Strength for Fly Ash Concrete Mixes

Fly ash replacement for Cement

Longer-term chloride ion permeability tests were carried out on samples of concrete containing 0, 15, 30, and 50% Class F fly ash replacing cement. These tests conducted at The Ohio State University are summarized in Table 3. The chloride ion permeability of the fly ash mixes was significantly lower than that of the no fly ash mix. The permeability reduced with increase in percent fly ash. Increase in curing time from 6 months to 1 year led to about 4.75% reduction in the permeability of the no fly ash mix, while the permeability of the fly ash mixes reduced 30% to 40% over the same time period. Even at one year of curing, the no fly ash concrete sample had moderate chloride ion penetrability while all the fly ash concrete samples had very low penetrability values. The high-volume fly ash mixes would be the most durable concrete mixes for preventing corrosion in reinforced concrete structures.

	Chloride Ion Permeability (Coulombs)	
	6-Month Curing Time	1-Year Curing Time
0% Fly Ash Mix (Control)	3,580 (Moderate)	3,410 (Moderate)
15% Fly Ash Mix	1,160 (Low)	720 (Very Low)
30% Fly Ash Mix	550 (Very Low)	390 (Very Low)
50% Fly Ash Mix	530 (Very Low)	300 (Very Low)

Table 3: Chloride Ion Permeability for Fly Ash Concrete Mixes at 6 and 12 Months of Curing

CONCLUSIONS

Corrosion remediation and prevention in the United States continues to burden the budgets of state Departments of Transportation, Federal Highway Administration. Government regulations, environmentalist and society further complicate the situation by requiring lower CO₂ sustainable design and longer service life of its infrastructure. Fly ash through its synergies with CO₂, sustainable design, and natural pozzolanic reaction with cement can provide the benefits necessary to appeal to these groups and the designers.

The pozzolanic reaction of fly ash in concrete converts calcium hydroxide into Calcium Silicate Hydroxide, while maintaining the pH, leading to reduced permeability. With the use of fly ash, the ingress of moisture, oxygen, chlorides, carbon dioxide, and aggressive chemicals are slowed significantly - thus improving durability and serviceability.

The chloride ion permeability of the fly ash concrete mixes are significantly lower than that of no fly ash mixes. The permeability reduces with increase in percent fly ash. Increase in curing time from 6 month to 1 year curing led to a slight reduction (4.75%) in the permeability of the no fly ash mix, while the permeability of the fly ash concrete mixes reduced 30% to 40%. Clearly, the high-volume fly ash concrete mixes, with low chloride ion permeability values, are desirable in concrete technology to prevent the deleterious effect of corrosion in reinforced concrete structures.

The increased interest in sustainable design and construction has created a renewed interest in fly ash and other coal combustion products. This trend has been accelerated by the emergence of agencies like the U.S. Green Building Council (USGBC), Leadership in Energy and Environmental Design (LEED), and Coal Combustion Products Partnership (C2P2) of the USEPA. Their primary goal is environmentally and socially focused towards overall sustainable development.

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