ORIGINAL RESEARCH

Biological and microbiological factors involved in the corrosion of concrete structures and solutions to deal with the corrosion of concrete structures

Mohammad Mahdi Zakai
Bachelor's student in civil engineering, Islamic Azad University, Lahijan branch
Responsible author: Mohammad Mehdi Zakai (mohamadmehdizakai@gmail.com)

Abstract:

With the increase in the world population, especially in developing countries, housing density has increased, and sewage systems are inadequate for most of these housing units. Basically, wastewater is divided into two categories: urban and industrial, with urban wastewater containing a wide range of microbial contaminants. This problem creates a wet bed full of microorganisms and gradually causes corrosion of concrete structures and damage to the construction industry. The use of nanoparticle technology can fill the pores of the concrete surface and prevent corrosion of concrete structures and prevent the growth of fungi and microorganisms. Nanoparticles as an industry provide a new frontier for production and enable technological, health and environmental advances. We reviewed a lot of research to prevent corrosion of concrete structures and concluded that the effectiveness of nanoparticles in combating corrosion is more effective than other methods. We propose to produce plant-based nanoparticles for environmentally friendly production, and in addition to providing corrosion resistance, they are also environmentally friendly.

Keywords:
Nanoparticles, concrete structures, microorganisms, wastewater, modified cement

1. Introduction

Sewage networks are one of the public and important infrastructures of society. The development of modern sewage systems dates back to the 19th century, due to increasing concerns about public health. The first extensive modern sewage system recorded in Britain was built between 1859 and 1865 in London. In Germany, the first comprehensive sewage system was built in Hamburg in the mid-19th century. A common feature of modern sewer networks is that they are buried underground and therefore, the scale and complexity of the systems are not recognized by most people (Saucier and Herisson, 2015). Safe and cost-effective waste and wastewater collection and treatment is a key criterion for maintaining the sanitary standards expected by modern society. Especially in developing countries that are faced with housing density, the inadequacy or lack of sewage networks can lead to the spread of a wide range of infectious diseases and drinking water pollution. Microbial corrosion of concrete (MICC) has been recognized as one of the main processes for the degradation of concrete-based sewer networks worldwide, which is increasingly causing high economic costs as well as evere health and environmental concerns (Sun et al., 2015). Microbiological corrosion (MIC) is a very specific type of degradation mechanism of concrete exposed to wastewater environment. It can significantly reduce the lifespan of concrete structures, e.g. MIC of concrete is of great importance in research projects. The increasing severity of MIC problems in recent years has led to an increase in research in this field, partly due to strict government regulations regarding the nature and toxicity of industrial effluents for discharge into

sewage systems, increased temperatures, and the use of sulfate-containing detergents (Grandclerc, 2017).
Economic losses due to MIC of concrete are very high, e.g. The cost of rehabilitation in the United States was estimated at 390 billion dollars over 20 years. While in Germany and England, annual rehabilitation costs were estimated at 450 million euros and 85 million dollars, respectively. Apart from economic losses, health and environmental concerns caused by MIC have attracted more attention (Wang et al., 2020).
In general, corrosion can be defined as the loss of structural capacity over time as a result of the impact of external factors on the material. Corrosion or deterioration has many dimensions and depends on the type of structure, constituent materials, environmental conditions and operational characteristics as well as other factors. Progressive deterioration has perhaps the most extensive impact on the long-term performance of infrastructure systems. It has been observed that the loss of structural capacity over time is mainly caused by chloride ingress, which usually leads to corrosion of steel (loss of effective cross-sectional area of steel), cracking of concrete, loss of adhesive (hydrated aggregate cement paste) and is spelled (Magniont et al., 2011).
Due to the increase in housing density and the lack of sewage treatment systems, the deterioration caused by biological resources in harsh environments is significant. Biodegradation is defined as: any adverse change in the properties of a material resulting from the activities of living organisms and a process in which biological agents (i.e. living organisms) are the cause of a decrease in quality or structural value, biological deterioration or commonly known as induced deterioration. It is called from microbiological (MID) (Wei et al., 2010).
Living organisms grow on the surface of concrete and cause deterioration of concrete. Favorable environments may have high relative humidity (ie between 60% and 98%), long cycles of wetting and drying, freezing and thawing, high concentration of carbon dioxide (such as carbonation in urban atmosphere), high concentration of ions be chlorides or other salts. (e.g., marine environments) or high concentrations of sulfates and small amounts of acid (e.g., sewage pipes or waste water treatment plants) (Kocak, 2010).
Concrete structures are damaged by various physical, chemical and biological mechanisms. In fact, concrete is easily colonized by microorganisms, including bacteria, algae, and fungi. Biological degradation of concrete structures can lead to aesthetic, functional and structural problems in concrete structures. For example, Cladosporium is the dominant fungal genus associated with aesthetic degradation observed in various bridge structures (Figure 2). In another example, the presence of sulfur-oxidizing bacteria (SOB) in anoxic conditions in a French sewer network is responsible for the decrease in pH value and the loss of material from the inner walls and the reduction of the strength and density of concrete pipes. Biodegradation of concrete also endangers human health due to the release of bioaerosols of fungal spores that can cause respiratory disease. This phenomenon is known as "sick building syndrome" (SBS) (Jiang et al., 2022).
It has been estimated that structural problems related to biodeterioration cost billions of dollars per year in infrastructure maintenance, yet studies addressing this damage in concrete structures are limited. The purpose of this study is to provide an advanced survey focusing on MIC of concrete exposed to sewage environments and to investigate new methods based on nanotechnology to deal with the corrosion of concrete structures.

2. Description of the proposed method

We examined 50 articles related to concrete structures and among the available sources, we examined 27 related to the effect of biological and microbiological factors involved in the corrosion of concrete structures. In the following, we present solutions to prevent damage to concrete structures using nanotechnology.

3. Results

Investigating factors of concrete destruction by fungi

Chemical deterioration

Organic acids

One of the metabolic products of fungi are organic acids, which react with calcium to modify and improve the growth conditions of their external environment and severely cause chemical degradation of concrete. Studies show that high initial pH values of mortar stimulate the production of organic acids such as oxalic, malic, succinic and fumaric acids (De Windt et al., 2015).

Different species of fungi differ in the production of organic acids. A. niger is well known for its ability to produce a wide range of commercially important organic acids such as citric acid. Research has shown that the concentration of citric acid produced by A. niger, strain BRFM422, grown in glucose medium, increased to 2.5 g/L, however, the production of other strains under similar conditions was not detectable (Marquez-Peñaranda et al., 2016).

Portland cement contains the main elements: silicon (Si), Al, iron, calcium and a small amount of magnesium (Mg), which is usually present in the form of oxide in cement clinker Table 1. The maximum content of magnesium oxide (MgO) should not exceed 5% by mass of cementitious materials. Both organic acid hydrolysis with metal salt formation and complexation reactions are active in FID of concrete, which is the main driving mechanism of the former. In general, complexation reactions occur only when metal ions are released into solution after acidolysis. He measured the concentration of different elements after placing cement produced with different adhesives in an acidic solution containing acetic, propionic, butyric, isobutyric and lactic acids and found that the mass of Si, Al and Fe elements was released after 6 hours. to be Less than 1% of the initial mass of elements in cement samples. The stability of these elements in acidic environments is an important parameter in evaluating the chemical resistance of cement adhesives. On the other hand, calcium and magnesium salts have much higher solubility and are ranked first and second respectively in terms of dissolution rate compared to other main metal ions in cement. Reactions between calcium and most organic acids form soluble salts in concrete, which lead to calcium leaching and concrete degradation (Bertron, A et al., 2017).

Fig. 1. Typical damage of concrete elements caused by MICC in different sewage systems (Grengg et al., 2018).

Fig. 2. cases of biological degradation of concrete (Jiang et al., 2022).

Table 1. Average concentration of chemical components in ordinary Portland cement

Component	Average concentration (%)
SiO2	21.0
Fe2O3	2.9
Al2O3	5.0
CaO	64.2
MgO	1.7
SO3	2.6
Na2O	0.24
K2O	0.70
Equivalent alkalis	0.68
Free lime	1.2

Enzymes

Fungi secrete a percentage of extracellular enzymes that are likely also involved in fungal-induced degradation (FID). Identified hydrolytic enzymes, including proteases and lipases, secreted by Aspergillus strains isolated from old concrete buildings. Filamentous fungi, including Aspergillus, Fusarium, and Trichoderma, can secrete keratinases that react with amino acids also secreted by the fungi to produce thin needles of ettringite (Figure 3). In fresh concrete, the formation of ettringite plays a positive role by reducing the setting time and increasing the initial strength of the matrix. However, the formation of ettringite in hardened concrete may cause cracking and is therefore likely to be one of the mechanisms responsible for FID (Trzaska et al., 2017).

Mechanical destruction

In environmental conditions suitable for mushroom growth and nutrient supply, fungal hyphae adhere to the surface of porous or fissured materials and their growth is facilitated, and they penetrate into the internal materials and create new colonies that spread further and spread the fungus. They increase in the matrix. For example, in the case of impermeable organic substrates, fungal enzymes weaken the material and facilitate hyphal entry and growth.

The turgor pressure within the hyphae exerts a mechanical force on the solid material, which varies from 0.3 to 2.5 N/mm2 depending on the fungal species and the growth environment, and facilitates the extension of fungal structures such as hyphal tips and the growth process. does Fungal penetration.

Plant pathogenic fungi, including Fusarium species, with specialized penetration structures, such as appressoria, are able to generate significantly higher pressures in the range of 5-8 N/mm2. Based on our understanding of fungal behavior and interactions with concrete, it can be hypothesized that similar physical mechanisms may operate and contribute to FID of concrete. Therefore, initial chemical attack by acids and enzymes may facilitate fungal penetration and subsequent mechanical degradation, increasing porosity and cracking in concrete (Jiang et al., 2022).

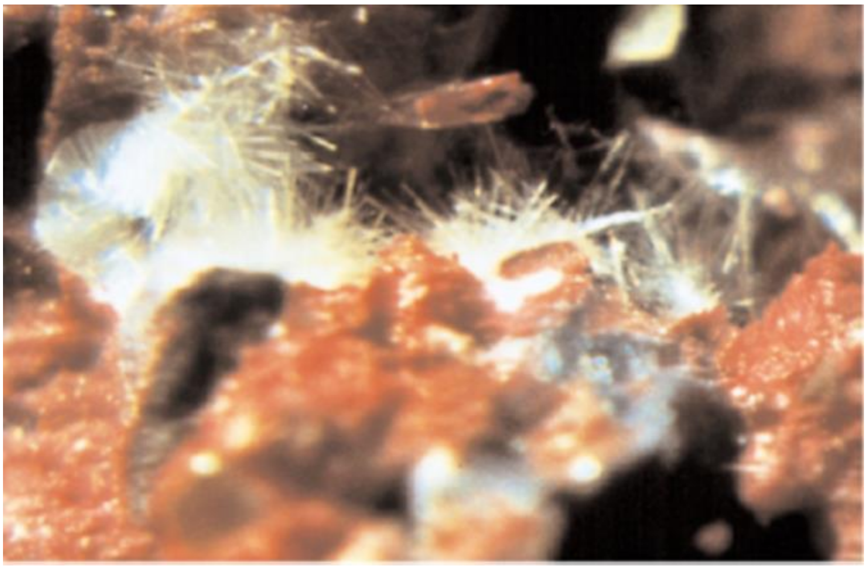

Fig. ۳. Formation of ettringite in hardened concrete (Trzaska et al., 2017).

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Table 2. The growing role of nanomaterials in corrosion control (Singh et al., 2024).

Feature	Corrosion	Nanomaterials
Definition	Deterioration of metals and alloys by chemical or electrochemical reaction with the environment.	Materials with at least one dimension sized between 1 and 100 nanometers (nm). (A human hair is roughly 100,000 nm wide!)
Process	Metals tend to return to a more stable state, often oxides. This can involve the loss of electrons (oxidation) and the movement of ions in solution.	Properties of materials can change dramatically at the nanoscale. Nanoparticles can have high surface area and reactivity.
Effects	* Reduced strength and performance of structures * Leaks and failures * Safety hazards * Economic losses	* Potential environmental and health concerns are being studied * Can be used to create new materials with improved properties
Examples	Rusting of iron, tarnishing of silver	Sunscreen, stain-resistant clothing, drug delivery systems
Relationship	Nanomaterials can be used to develop new corrosion resistant coatings or improve existing ones.	Understanding corrosion processes is important for designing safe and effective nanomaterials.

Microbial colony formation on concrete

Immediately after construction of a concrete structure, concrete is usually resistant to biological attack due to its high alkalinity. Little microbial activity occurs at such a high pH. This high pH is the result of the formation of calcium hydroxide, Ca(OH)2, as a byproduct of cement hydration. Usually, water erosion and/or friction of structural elements with other materials causes roughness on the concrete surface. These conditions, in addition to the availability of moisture and nutrients, facilitate the distribution of microbes on concrete surfaces. However, the colonization of sulfur-reducing and sulfur-oxidizing bacteria on concrete is always associated with the sulfur cycle in their environment, especially in aqueous environments.

Sulfate is present in aquatic and marine environments worldwide. Anaerobic sulfur-reducing bacteria can convert sulfate to sulfide, which then combines with hydrogen to form hydrogen sulfide. Over time, the pH of the alkaline concrete surface gradually decreases with the carbonation and neutralization of hydrogen sulfide that occurs in different systems, and the volatile hydrogen sulfide is exposed to oxidation to sulfuric acid by sulfur-oxidizing bacteria (Magniont et al., 2011).

When the pH drops toward neutral, the lower pH on the concrete surface creates the conditions for microbial growth, mostly caused by neutrophilic and/or acidophilic organisms. Typically, Thiobacillus sp. (syn. Acidithiobacillus sp., including T. thioparus, T. novellus, T. neapolitanus, T. intermedius and T. thiooxidans) play a key role in colonization. When microorganisms settle on the concrete surface, they form a biofilm, which leads to the biochemical degradation of the concrete (Wei et al., 2013).

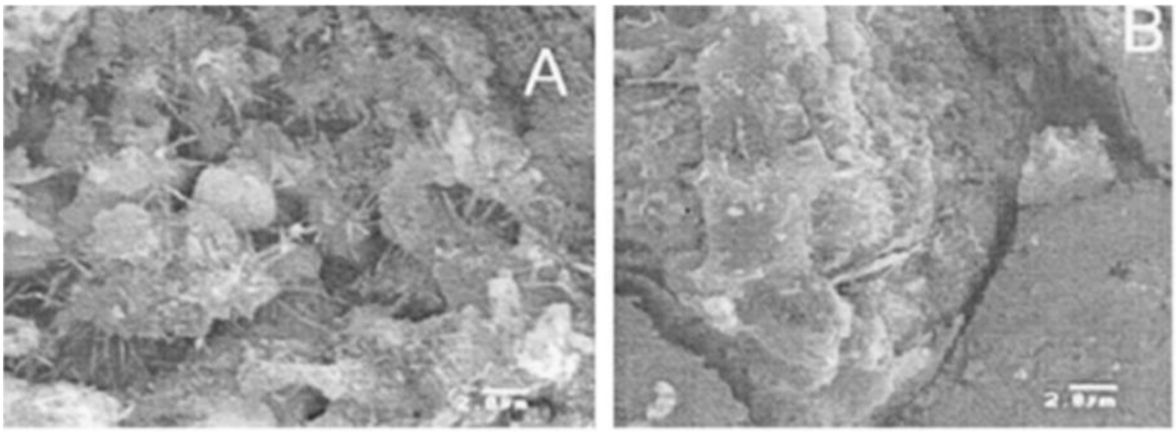

Figure 4. SEM micrographs of plain cement paste (A) and modified nano-silica (B) (Ostiguy et al., 2010).

Mechanism and process of microbial degradation

One of the most destructive factors that lead to the rapid deterioration of concrete pipelines in sewage is H2S, which also attacks concrete floors in animal housing buildings and in sewage and sewage treatment plants. Existing sulfur-oxidizing bacteria convert moisture-soluble H2S to sulfuric acid (H2SO4), commonly known as biogenic sulfuric acid, which is believed to be responsible for biodegradation. This release of biogenic acid decomposes cementitious materials in concrete, resulting in the production of gypsum (CaSO4 with various hydration states) and possibly ettringite (3CaO•Al2O3•CaSO4•12H2O•O2O•O31), which have a wide range of properties.

Gypsum can act as a protective layer for concrete, just as primary corrosion protects metals (such as an oxide layer on aluminum). If this protective coating of plaster is removed, the concrete surface can be exposed to acid attack and accelerate damage to the surface. In addition, the mixture of gypsum and calcium aluminates in concrete causes the production of ettringite, which increases the internal pressures due to its relatively large volume and leads to cracks.

Corrosion of concrete is washed away by the flow of sewage, and this accelerates the process of concrete corrosion, and new surfaces of concrete are exposed to sewage and microorganisms, and accelerates the process of removing concrete layers.

Microorganisms can penetrate the concrete texture even if there are no pores in the concrete. The most common mechanism of their entry is through microcracks or through concrete capillaries.

Laboratory analysis of concrete samples has shown that many microorganisms such as fungi (yeasts, cladosporium, mycelium, hyphae, etc.), bacteria (actinomycetes, thiobacillus, etc.), algae (the most popular algae diatoms) and even protozoa are found in the concrete matrix.
The higher the porosity of the concrete, the higher the wear level of the concrete and the depth of the protective concrete cover on the reinforcement. More diffusion and less concrete cover can facilitate other deterioration processes such as reinforcement corrosion (Kaushal et al., 2020).

Ways to deal with biological deterioration of concrete

Control of biodeterioration processes should begin with measures that prevent favorable growth conditions for harmful microorganisms. The use of water repellants or stabilizers for concrete and stone should be done according to the type of concrete structure and existing conditions.
Protection of concrete structures against microbial degradation can be enhanced by treatment with biocides or the addition of protective coatings such as water repellents. Changing the composition of the concrete mix changes variables such as alkalinity and silica fume, as well as modification of polymers.
Corrosion rate has an inverse relationship with alkalinity, and silica reacts with Ca(OH)2 in the presence of water and forms cement compounds consisting of calcium silicate hydrate. Silica fume concrete improves strength performance and durability characteristics. Researchers have reported that the use of polymer modified concrete and mortar can improve the durability of concrete sewer pipes.
Biocides are another way to reduce the harmful effects of microbes on concrete. In a study, different biocide formulations containing class F fly ash, silica soot, zinc oxide, copper slag, ammonium chloride, sodium bromide and cetyl-methylammonium bromide were investigated as concrete compounds with germicidal properties. They studied concrete mixtures containing 10% ZnO (both in the field and in the laboratory) and concluded that the mixture was comparable to proprietary commercial biocides (Wu et al., 2020).
None of the mentioned solutions have a stable effect in preventing the deterioration of concrete structures. Our goal is to provide an effective and economical solution, at the same time compatible with the environment, to deal with concrete corrosion.

Nanotechnology is a way to deal with the corrosion of concrete structures!

Nanoparticles are very small materials (between 1 and 100 nm) that have unique physical and chemical properties. For this reason, researchers have been encouraged to use these materials in various fields such as drug delivery, construction industry, and as chemical and biological sensors (Rastogi et al. 2019).
Inhibition of concrete corrosion is one of the important fields of study. It is obvious that corrosion is harmful to the durability of reinforced concrete structures in terms of greatly reducing the useful life, especially for structures that are exposed to wet environments and conditions for the growth of microorganisms. Such damage results in significant repair costs that far exceed the original construction cost, where severe decay conditions often result in complete failure of the structure. Typically, the highly alkaline pH (range 12.5 to 13.5) of concrete structures causes a passive layer to form on the exterior of the steel, thereby reducing susceptibility to further corrosion (Heikal et al., 2015).
In the pores of high-alkali concrete, a thin, stable oxide layer formed on the surface of the steel renders it passive against corrosion. The presence of a sufficient concentration of chloride ions (Cl) destroys this protective layer and corrosion occurs. Therefore, the risk of chloride-induced corrosion is exacerbated by the free migration of chlorine through the cement paste.
When the corrosion process begins, the corrosion products (iron oxides and hydroxides) are usually deposited in the confined space of the concrete around the

steel. Deposition of such residues in the limited space that creates expansion stresses leads to cracking and flaking of the concrete coating (Singh et al., 2015).

The results of researchers' work show that corrosion is responsible for a significant reduction in flexibility, strength and cross-sectional area of steel reinforcement. Consequently, the continuous deterioration of such mechanical properties can negatively affect the safety and long-term performance of reinforced concrete structures. To overcome such drawbacks, various protection strategies have been proposed that allow to slow down, delay or stop the corrosion process. These strategies include epoxy coatings, galvanized steel rebars, the use of stainless steel reinforcing bars, the use of low-permeability concrete as surface concrete treatment, cathodic protection systems, as well as the use of glass fibers and silica fume. The goal of all these approaches is to increase the useful life of concrete structures. However, most methods that are strategized to protect steel reinforcement in concrete provide insufficient protection due to the complex nature of the corrosion mechanism (Singh et al., 2016).

Nanotechnology can produce products with many unique properties that can improve current building materials: lighter and stronger structural composites, low-maintenance coatings, better cementitious materials, lower heat transfer rates, fire resistance and insulation, better sound absorption from Sound absorbers and reflections. Better Glass Since particle size is a critical factor, the properties of materials at the nanoscale differ from those at larger scales. Below the limit, physical phenomena begin to behave differently: gravity becomes negligible electrostatic forces, and quantum effects begin to dominate. At the same time, the ratio of surface atoms to interior atoms increases and creates the so-called "nano effect" (Khandve, 2014).

Nanoparticles can resist corrosion by increasing reactivity. Consequently, we can use this property to create innovative corrosion inhibitors or coatings. Paints or coatings can strategically incorporate nanoparticles to act as a barrier against corrosive agents.

Their high surface area allows them to effectively create a physical barrier between the material and its environment. In addition, some nanoparticles can act as "sacrificial agents" and preferentially eat themselves to protect the underlying material. Another promising avenue for nanotechnology is the development of self-healing materials. Imagine a bridge or pipeline that can automatically repair itself by detecting the onset of corrosion.Table 2 shows the growing role of nanomaterials in corrosion control (Singh et al., 2024).

Nano particles in building materials

Concrete

Concrete is one of the most important construction materials used. The primary components of concrete used in today's constructions include Portland cement base adhesives, water, and coarse and fine aggregates. Binders are made from grinding Portland clinker with some calcium sulfate and can also contain fine mineral powders such as pozzolan (usually volcanic ash), limestone, granulated blast furnace slag, and fly ash (usually from coal-fired power plants). To modify the properties of concrete for the concrete structure industry, chemical additives, such as air entraining agents and superplasticizers, are added in small amounts. It is important to develop these changes in the contract because the durability and serviceability of concrete structures and surfaces are constantly being tested under different weather conditions. Durability of concrete depends on the bonding interfaces between voids, aggregates and cement paste. Therefore, nanomaterials with properties such as durability and strength are of particular importance in the production of concrete, and studies show their positive and significant impact on concrete strength.

In conventional concrete, silica ($SiO2$) is present as part of a standard mix. However, in recent studies, it was found that the use of

nano-silica (NS) in concrete and cement paste improved particle packing in both materials.
Due to its small particle size, NS acts as a nanofiller for calcium silicate hydrate (Ca-Si-H) particles in cement and acts as a strong binding agent, thereby increasing cohesion between cement and aggregate. to give The rate of hydration of cement is also increased, which effectively reduces the setting time, the sleeping period and increases the initial strength. Nano silica also reduces the porosity of concrete and reduces the ability of water and other elements to penetrate into concrete, which prevents the potential of concrete degradation and makes it impossible for most living organisms to penetrate into concrete.
Figure 3 under the scanning electron microscope (SEM) shows a plain cement paste and a cement paste modified with nano-silica. Another nanoparticle used in concrete is nano-titania (TiO_2), which is abundantly produced due to its anti-corrosion, stability and photocatalytic properties. The photocatalytic activity of TiO_2 is due to the high surface area of the particles. Therefore, when concrete is added to the concrete, it becomes self-cleaning, self-disinfecting, and cleaning the environment. In the presence of light, TiO_2 breaks down organic contaminants and soil on the concrete surface into harmless water and CO_2. The products of the catalytic reaction are then easily removed by simple washing or rain (Mohajerani et al., 2019).
According to the research conducted in 2018 by Asaad et al., silver nanoparticles had a positive and significant effect in preventing corrosion, which is described below:
Silver nanoparticles (AgNPs) of oil palm (Elaeis guineensis/EG) leaf extract doped (EG/AgNPs) were prepared as a new, non-toxic and environmentally friendly corrosion inhibitor. which were included in the cement composite and were investigated against the corrosion of reinforcing steel in natural sea water. Standard corrosion monitoring techniques including linear polarization resistance (LPR), potentiodynamic polarization, half-cell potential (HCP) and electrical resistance were used to screen the corrosion inhibition potential of EG/AgNPs-activated steel concretes after weekly exposure to wet and dry cycles. became. In addition, the microstructural, morphological, thermal and elemental properties of such concrete were determined in 365 days of exposure. The microstructure of EG/AgNPs inhibiting powder, concrete before and after treatment (powder and small pieces) as well as the surface of steel reinforcement were analyzed. Incorporation of 5% green EG/AgNPs inhibitor in steel reinforced concrete increased the corrosion resistance, where a thin protective barrier was formed on the reinforced steel surface. This improvement is due to the formation of excess calcium silicate hydrate gel (C-S-H) in the concrete and thus blocking the pores of the concrete. The maximum inhibition efficiency was recorded as 94.74%. These EG/AgNPs have been found to have a green color for optimal corrosion inhibitor treatment to achieve durable concrete structures (Asaad et al., 2018).

4. Discussion and conclusion

Nanoparticle technology is used in a wide range of biological, non-biological and industrial processes. The small size, large surface-to-volume ratio, and unique mechanical, electromagnetic, optical, and biochemical properties of nanoparticles make them useful for limitless applications. Among many metal nanoparticles, silver nanoparticles combined with plant extracts as corrosion inhibitors are less toxic, cheap and environmentally friendly than other chemical compounds. Silver nanoparticles are useful due to their good electrical conductivity, chemical flexibility, catalytic and antibacterial properties.

Nanoscale materials have various applications in biological and non-biological fields. As such, many industries have embraced the advancements that nanoparticles can provide and are advancing industry-specific products. This is seen in a wide range of applications, through the field of construction with recycled materials enriched with nanoparticles with similar mechanical properties such as fresh materials, drug delivery and antibacterial properties in clothing. In a causal relationship, the amount of demand and supply has increased to match the trend of using nanoscale materials and has greatly increased the production rate compared to previous years.

As the emergence of nanoparticles occurred rapidly, regulations related to health, safety, and environmental considerations of production, product use, and end-of-life disposal were difficult to keep out of industry. It is important to consider the long-term effects that the nanoparticle industry may have. This has been demonstrated in studies showing the toxicity of substances previously thought to be non-toxic to mammals. It is related to the small size and formation of particles that alter the interaction with biological systems.

The production and use of nanoparticles requires monitoring and regulation prior to widespread introduction to avoid any harmful consequences that may not have emerged as viable commercial production due to the relative youth of nanoparticles. We reviewed a lot of research and concluded that nanoparticles are both more practical and more accessible. The important issue related to nanoparticles is, can we produce environmentally friendly nanoparticles that are both safe for buildings and do not pass through biological membranes? This question provides an idea for designing environmentally friendly nanoparticles. Nanoparticles produced with plant extracts and organs. This is a new idea in the construction industry and fighting the corrosion of concrete structures in dealing with microorganisms.

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