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Original Article

Evaluation of Natural and Industrial Inhibitors on the Durability of Concrete and Steel in Saline Environments

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Abstract *- In saline and marine environments, steel and the penetration of chlorides in concrete initiate and promote the rapid and progressive deterioration of structures, resulting in a loss of performance, increased maintenance needs, and a potential catastrophic failure. This has been the motivator of research in Peru to look for natural and sustainable inhibitors of a lesser ecological footprint, as the industrial inhibitors are far more detrimental, i.e., to the native plants. This research studied the relative performance of commercial vs. natural additives of steel and concrete in saline environments. In identifying optimal concentrations, plant extracts and microcapsules of avocado oil in varying concentrations were prepared. ASTM G31, G59, and C876 were the tests for corrosion measurement of the steel, and ASTM C1202 was for the chloride ion permeability. Seventeen variants were analysed with three replicates per material type. The results showed that the 75% avocado pulp coating achieved efficiencies of up to 85% on steel, similar to the industrial inhibitor. Likewise, apple and eucalyptus extracts achieved average efficiencies of over 69%, significantly reducing the likelihood of corrosion. Specifically, the 1% avocado oil microcapsule outperformed the commercial inhibitor with an efficiency of 78%, while apple and eucalyptus extracts achieved 74% and 73%, respectively, all classified as low permeability. In conclusion, natural additives, applied with appropriate formulations, can match or exceed the performance of industrial inhibitors, constituting a technical, economical, and ecological alternative for the protection of structures in marine and saline environments.*

Keywords *- Reinforced concrete, Natural inhibitors, Corrosion, Saline environments, Microencapsulation, Structural durability.*

1. Introduction

In recent decades, the premature deterioration of concrete structures exposed to marine and coastal environments has been a growing problem globally, affecting their durability and structural performance [1, 2]. In Peru, with more than 3000 km of coastline and densely populated coastal cities such as Lima, Callao, Chimbote, and Trujillo, port infrastructure, bridges, buildings, and coastal defence systems are constantly exposed to the aggressive action of chlorides and dissolved salts present in the marine environment [3, 4]. These agents penetrate the concrete, reach the steel reinforcement, and accelerate corrosion processes, causing loss of section, cracking, coating detachment, and, in critical cases, structural failure [5, 6]. According to a report by the Peruvian Association of Engineers, more than 60% of the country's bridges require urgent maintenance, and many of them show signs of cracking, corrosion, and structural wear [7]. This problem not only entails high maintenance and rehabilitation costs but also poses a significant risk to public safety and the sustainability of infrastructure investments [8]. A recent and serious case was the collapse of the Chancay vehicular bridge (km 75 of the Panamericana Norte, Lima) on 14 February 2025. The structure collapsed suddenly as a double-decker interprovincial bus and a car were passing over it, causing both vehicles to fall into the Chancay River. This accident left a tragic toll of two dead and 41 injured. Preliminary investigations indicated that the main cause was the deterioration of the central pillar due to corrosion and erosion caused by constant exposure to water, which weakened critical elements of the foundation and led to the collapse [7, 9]. Just one week later, on 21 February, another tragedy occurred in Trujillo when the metal roof of the food court at the Real Plaza shopping centre collapsed while hundreds of people were dining. The heavy structure gave way and fell on the crowd, killing six people and injuring 81 (11 of them seriously). Expert reports and photographs revealed advanced corrosion in beams and bolts, aggravated by rainwater leaks associated with Cyclone Yaku, which significantly reduced the load-bearing capacity of the roof system [10]. In response to the problem of corrosion in concrete structures, various protection and reinforcement strategies have been developed, ranging from commercial inhibitors to natural additives [11]. At the national level, products such as CHEMA Corrosion Inhibitor have proven effective in forming protective layers on reinforcement and delaying chloride penetration without affecting the mechanical properties of concrete [12]. Internationally, studies on green inhibitors derived from plant extracts have shown them to be biodegradable, non-toxic, and economically viable, offering a sustainable alternative to synthetic inhibitors [13, 14]. Similarly, research in Mexico reports that the addition of nopal mucilage improves the electrochemical resistance and impermeability of concrete [15].

Nevertheless, the use of natural methods and the additives designed to protect concrete and steel in saline environments has not been investigated to the necessary depth and breadth. More precisely, the absence of studies on the unified assessment within the Peruvian case constrains one to determine the actual performance of such products, differentiated from natural formulations and commercial alternatives, competently. This scenario defines the void this research is looking to fill.

Accordingly, the present research is guided by the following research question: Can natural additives based on apple and eucalyptus extracts and avocado-derived formulations, when applied in optimized dosages, achieve corrosion protection and chloride-penetration mitigation comparable to a commercial inhibitor under saline exposure? The working hypothesis is that properly formulated natural systems can match or exceed the performance of commercial inhibitors, and that microencapsulation may enhance performance by improving the stability and delivery of active compounds in the cementitious environment.

2. Literature Review

2.1. Plant-Derived Inhibitors Evaluated Under Saline/Marine Exposure on Carbon Steel

Research conducted in the country of Panama by members of the Faculty of Civil Engineering at the Technological University of Panama at the Experimental Engineering Centre aimed to analyse the comparative effectiveness of green inhibitors with industrial inhibitors of the minimum type. These natural compounds were put together from a mixture of 150 millilitres of deionised water with 250 grams of avocado pulp, green apple pulp, and green apple peel. Tests were done with A36 carbon steel sheets in a salinity chamber and a natural marine setting. The industrial inhibitor outperformed the rest, showing a salinity chamber efficiency of 93.42% and a marine environment efficiency of 86.29%. Among the green inhibitors, the most effective avocado pulp had efficiencies of 52.21% and 66.37% in the chamber and marine setting, respectively, followed by green apple pulp, which had efficiencies of 45.98% and 48.78% and lastly, green apple peel, which had efficiencies of 28.06% and 41.46%. These results show that, although green inhibitors do not match the performance of industrial inhibitors, they offer promising potential as a sustainable and less polluting alternative [16].

In Chile, researchers from the Institute of Chemistry at the Faculty of Sciences of the Pontifical Catholic University of Valparaíso conducted a study to evaluate the corrosion-inhibiting potential of Fuji apple peel extract (Malus domestica) on A36 carbon steel in a saline environment. The extract was obtained from 5 grams of dried peel mixed with an ethanol-water solution (1:1 v/v) at 60°C, under a solid-liquid ratio of 1:10, achieving an extraction yield of 61.04%. The total content of phenolic compounds and flavonoids was 132.44 mg GAE/g and 99.15 mg QE/g of dry extract, respectively. Concentrations of 100, 250, 500, and 1000 ppm of the extract were evaluated, applied to 0.1 M NaCl solutions. The results showed an increasing inhibitory efficiency with the concentration of the extract, reaching 88.77% by mass loss, 89.88% by Tafel polarisation curves, and 90.16% by electrochemical impedance spectroscopy (EIS) at 1000 ppm. The adsorption analysis fit the Langmuir model, and the free adsorption energy value ($\Delta G°ads$) was -15.16 kJ/mol, indicating a physisorption inhibition mechanism. These results confirmed that Fuji apple peel extract acts as an effective green inhibitor, forming an organic protective barrier on the surface of steel exposed to saline environments [17].

In Ukraine, researchers from the Department of Physical Chemistry at the National Technical University of Ukraine 'Igor Sikorsky Polytechnic Institute', in collaboration with the Institute of Chemical Technology at Dnipro University, conducted a study to evaluate the inhibitory potential of extracts obtained from industrial waste from plums, cherries, nectarines, and apples on the corrosion of carbon steel in neutral NaCl solutions. To do this, they applied the extracts at a concentration of 500 ppm and found that the inhibition efficiency increased progressively with exposure time, reaching maximum values between 94.5% and 98.6% after 48 to 50 hours, depending on the type of extract. The results demonstrated that the protection of steel is due to the formation of a protective adsorption-polymerisation film composed of chemically transformed polyphenols, such as flavanol-anthocyanin and flavanol-aldehyde adducts, which are adsorbed and polymerised on the metal surface. Electrochemical and spectroscopic analyses confirmed that the extracts act as mixed-type inhibitors, with cathodic action predominating, and that the layer formed significantly reduces the corrosion rate, thus consolidating these fruit waste extracts as an ecological and efficient alternative for the protection of steel in neutral environments [18].

2.2. Plant-Based Inhibitors Incorporated into Cementitious Systems

In Colombia, researchers from the Faculty of Engineering at the National University of Colombia conducted a study to evaluate the technical feasibility of extracts obtained from avocado seeds as corrosion inhibitors for reinforcing steel in concrete mixed with silica fume. To do this, they prepared additives from phenolic compounds extracted from both the germ and the seed coat using the Soxhlet method and filtration, and incorporated them into the concrete in different forms (liquid and solid). The proportion of silica fume used was 12% of the weight of the cement, while the natural additives were added at 0.1% of the weight of the mixture for the most representative tests.

The results showed that the samples treated with phenolic extracts from the seed germ and tegument, especially those obtained by Soxhlet, reduced the corrosion rate of steel by between 85% and 90% compared to the standard sample without additives, showing similar or superior effectiveness to commercial inhibitors, without significantly affecting the compressive strength of the concrete. In addition, the study concluded that this agro-industrial by-product represents a sustainable and low environmental impact alternative for the protection of reinforced concrete structures exposed to aggressive chloride environments [19].

2.3. Eucalyptus-Based Inhibitors: Evidence Base and Transferability to Saline Exposure

In Iran, researchers from the Department of Chemical Engineering at Golestan University conducted a study to evaluate the effectiveness of eucalyptus leaf extract (ELE) as an ecological inhibitor of mild steel corrosion in hydrochloric acid (1MHCl) solutions. The sample was made at other concentrations (200, 400, 600, and 800 ppm), and it was observed that with higher concentrations of ELE, the inhibitory efficiency increased and reached 88% at 800 ppm after 2.5 hours of exposure. The most typical results obtained with the electrochemical and weight loss methods indicated that the extract reduced the corrosion current density and the dissolution rate of the steel, and the damage and surface roughness of the examined metal were reduced much more with the SEM and AFM techniques. The conclusion was reached that the retention of the inhibitor fits the Langmuir isotherm and is an element of spontaneity, with the combination of physisorption and chemisorption constituting an effective, easily accessible, and environmentally friendly solution eucalyptus leaf extract for the preservation of steel in acid media [20].

To determine the effect of commercial eucalyptus oil on the corrosion of mild steel in a 1 M HCl solution, a study was conducted in the United Arab Emirates. The study focused on the eucalyptus oil inhibitor in the four different concentration levels of 0.25, 0.5, and 1 g/L, where it was evidenced that the inhibition efficiency reached a maximum of 95% at 1 g/L, and it was revealed that corrosion protection increased with a rise in concentration. Important findings were the corrosion current density declining significantly, and the density from 3618 to 167 micro Amperes per square centimeter, and the charge transfer resistance from 17 to 185 Ohm square centimeters increased, proving that there was a protective layer formed on the metal surface. It was determined that the adsorption of the inhibitor was consistent with the Langmuir isotherm and that unadsorbed gas molecules acted on the surface of the adsorbent, with the oil doing action. The findings from the study of steel corrosion in acidic environments proved that eucalyptus oil is affordable, readily available, and effective in protecting steel from acidic environments, where it will provide protection against corrosion of steel [21].

2.4. Critical Synthesis and Positioning of the Present Study

The corrosion damages the reinforcing steels and the structure itself, thus raising the protective methods and the sustainable solutions to avoid severe decay of reinforcing steels and improve the impermeability of the concrete. Even though natural additives have been applied to other materials used in construction, like commercial concrete and other plants, the steel and concrete, and their pliability, remain the core of this nature-supplemented construction. For this reason, the incorporation of avocado pulp directly on steel, and microencapsulated avocado oil on concrete, and the addition of apple and eucalyptus leaf extracts in both systems, remain to be evaluated comparatively and systematically in the same experimental designs.

In this context, the study examines the performance of apple and eucalyptus leaf extracts, avocado pulp, and microencapsulated avocado oil in comparison with a commercial corrosion inhibitor, taking into account their use on reinforcing steel and within concrete. The materials were assessed using ASTM G31, G59, C876, and C1202 test methods, which made it possible to observe differences in corrosion response and chloride penetration under comparable conditions. Rather than focusing on a single formulation, the work explores several dosage levels in order to identify practical ranges with consistent protective effects. The results are intended to provide technical guidance for the use of natural inhibitors in structures exposed to high salinity and humidity, particularly in coastal areas of Peru, where durability remains a persistent concern.

3. Materials and Methods

This section describes the materials and experimental procedures used to evaluate the corrosion protection of reinforced concrete exposed to saline environments using natural and commercial inhibitors. Apple and eucalyptus extracts, avocado pulp, and microencapsulated avocado oil were evaluated as natural alternatives, while Per Iron Protec and Chema Corrosion Inhibitor were used as commercial references. The performance was assessed separately for reinforcing steel and concrete using standardised ASTM G31, G59, C876, and C1202 test methods.

3.1. Natural Inhibitors

Plant-derived corrosion inhibitors made from agricultural waste and other natural agents are low-impact and increase the renewability and biodegradability of corrosion inhibition materials. They are a good alternative to chemical inhibitors. They are much less impactful than synthetic materials and are therefore a preferred choice. They have a lot of organic materials that have an affinity for corroded metals and form protective films that seal off corroded places and lower corrosion rates. They work well and are useful because they have a lot of functional protective compounds that bind and restabilize the metals underneath them to provide corrosion control. They provide a lot of chemical protection from aggressive corrosion agents. Recently, they have begun to assess the technical usability of corrosion inhibitors and their extraction optimization and combination with other materials to increase their industrial usability and corrosion control [22-24].

3.1.1. Apple Inhibitor

For its various health benefits, the apple (Malus domestica) is an exceptionally healthy fruit option and a leading source of numerous bioactive substances, including quercetin, epicatechin, ascorbic acid, and tartaric acid, which are among a range of vitamins and minerals, as well as flavonoids, polyphenols, and pectins. An apple\, impacts and contributes positively, and is recognised for containing powerful antimicrobial and antioxidant properties. Furthermore, some of these compounds have been recognised for serving as a green inhibitor of metal corrosion in acidic media. Apples, therefore, have the potential to be an alternative to conventional synthetic inhibitors in an economically viable and ecologically safe manner. This can be applied in a multitude of technology and environmental protection initiatives [25-27]. This is summarized in Table 1, where, in addition to antioxidant power, the corrosion-inhibiting potential of apple extracts is also presented. The apple oxidant, which is polyphenols and flavonoid-rich, is primarily responsible for the high oxidant activity, captures free radicals, and protects the metal surfaces. Also, Electrochemical measurements of the apple extracts show an outstanding corrosion inhibition of over 85%. This is an excellent indicator that the apple exhibits a corrosion-inhibiting potential for producing an anti-corrosive metal surface in acid media.

Table 1. Properties of apples

Property	Description
Total polyphenol content	4.0 mg GAE/mL (gallic acid equivalent) [26, 27].
Total flavonoid content	1.5 mg QE/mL (quercetin equivalent) [26, 27].
Antioxidant activity (DPPH)	85% free radical inhibition (IC_{50}: 90 µg/mL) [25, 26].
Main antioxidant compounds	Quercetin, epicatechin, ascorbic acid, tartaric acid [25, 26].
Effective inhibitor concentration	5.0 g/L [25, 26].
Inhibitor type	Mixed (anodic and cathodic) [25, 26].

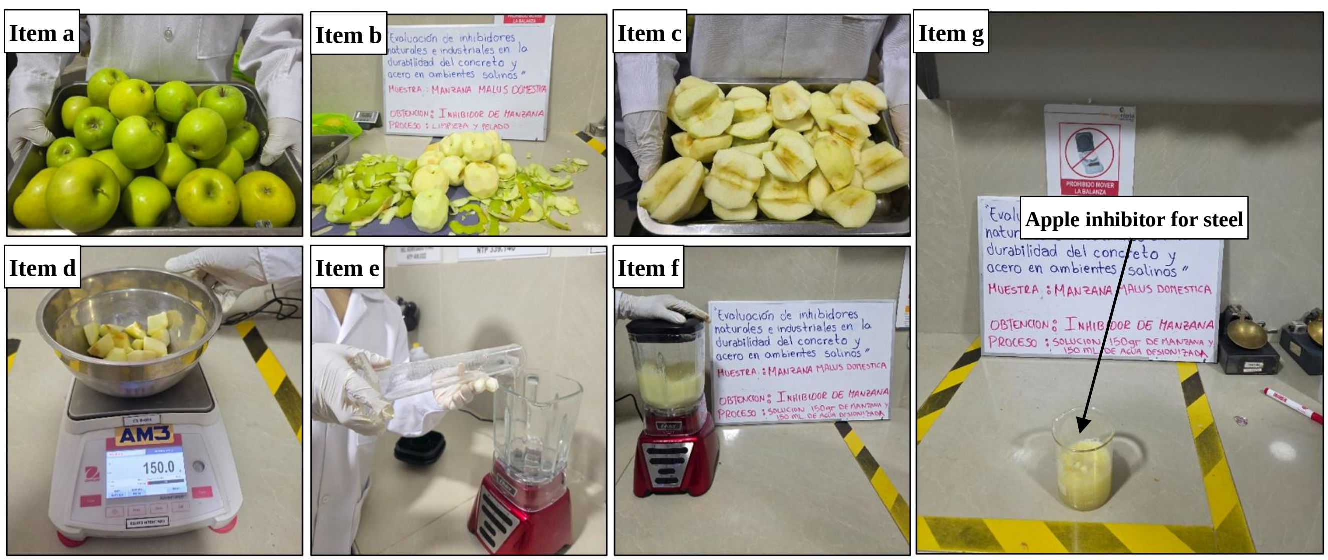

Fig. 1 Apple inhibitor for steel

According to an experimental study conducted in Panama, the application of green apple extracts on A36 carbon steel sheets demonstrated the ability to mitigate corrosion in marine environments and in salinity chambers. In this reference study, the extract was prepared by hand using 250 grams of fresh green apple pulp mixed with 150 millilitres of deionised water, obtaining a homogeneous paste by industrial blending, which was applied directly to the metal surface for corrosion testing [16].

Based on this methodology, in the present research, paste extracts were prepared with varying amounts of pulp (150 g, 200 g, 250 g, 300 g, and 350 g) while keeping the volume of deionised water constant (150 mL) in order to validate and analyse the effect of extract concentration on inhibitory efficiency.

Obtaining the Apple Inhibitor

Figure 1 shows the procedure used to obtain the green apple paste extract used as a natural corrosion inhibitor. The process was carried out in seven phases: (a) selection and cleaning of the raw material, where green apples in good condition, free of bruises or damage, were chosen and carefully washed to remove surface dirt and residues that could alter the composition of the extract; (b) hygienic peeling of the apples, manually removing the skin and stalk with clean utensils, in order to work only with the pulp, which contains the active compounds of interest; (c) internal inspection and cutting of the pulp, dividing the apples into medium-sized pieces and removing the core and seeds to ensure uniformity in the texture and quality of the mixture; (d) weighing the pulp on a calibrated scale, obtaining batches of 150 g, 200 g, 250 g, 300 g and 350 g of fresh pulp, which allowed different concentrations of the extract to be established while maintaining the same proportion of diluent; (e) measurement of deionised water in a graduated cylinder, measuring a constant volume of 150 mL for each batch, in order to ensure that the only variable under study was the amount of pulp; (f) blending and homogenisation of the mixture in industrial equipment, combining the pulp and deionised water until a uniform paste with a homogeneous consistency was achieved, free of visible lumps, suitable for experimental application; and (g) obtaining the final extract, which was transferred to beakers labelled with the corresponding concentration and used in the corrosion tests.

3.1.2. Eucalyptus Leaf Inhibitor

Eucalyptus leaf extract (Eucalyptus camaldulensis) is a plant-based substance obtained from aqueous extraction processes of its leaves, rich in bioactive compounds such as polyphenols, flavonoids, and terpenoids. These compounds give the extract important antioxidant and antimicrobial properties, as they participate in the neutralisation of free radicals and the inhibition of bacterial growth.

In addition, eucalyptus extract is widely recognised as a natural reducing and stabilising agent in the green synthesis of nanoparticles, due to the presence of hydroxyl and carboxyl functional groups. This antioxidant and reducing capacity, together with its antimicrobial efficacy, position eucalyptus leaf extract as a sustainable and efficient alternative for applications in environmental remediation and material protection technologies, offering ecological advantages over synthetic products and facilitating the development of green and economical methods [28-30]. These properties are shown in Table 2.

Table 2. Properties of eucalyptus leaf extract

Property	Description
Total polyphenol content	196.5 mg/100g MS [28, 29].
Antioxidant activity (DPPH)	43% free radical inhibition [29].
Main bioactive compounds	Polyphenols, flavonoids, terpenoids, -OH and -COOH groups [29, 30].
Bacterial inhibition zone (E. coli)	19.3 ± 0.5 mm [29, 30].
Bacterial inhibition zone (S. aureus)	15.7 ± 1.4 mm [28, 29].
Arsenic removal efficiency (as a reducing agent in Fe_2O_3 NPs)	99.2% removal [30].
Role in corrosion inhibition	Reducing and stabilising agent in green synthesis; formation of protective film on steel [30].

According to the properties described in Table 2 and the literature review, eucalyptus leaf extract stands out for its high content of phenolic compounds, flavonoids, and terpenoids, as well as containing functional groups such as hydroxyls and carboxyls. According to the experimental results, the greatest protection against accelerated corrosion of reinforcing steel in reinforced concrete was obtained using a concentration of 40% by weight of eucalyptus extract relative to the distilled water used to prepare the coating mixture, showing a significant reduction in rust formation, a decrease in crack width and an improvement in the structural performance of the elements analysed [31]. Therefore, to validate its effectiveness, eucalyptus leaf extract was prepared based on concentrations of 20%, 30%, 40%, 50% and 60%.

Obtaining the Eucalyptus Inhibitor

Figure 2 shows the procedure used to obtain the paste extract from eucalyptus leaves. The process was carried out in five stages: (a) stems with fresh eucalyptus leaves were collected and selected, ensuring that they were free of pests, spots or visible damage, and stored in clean metal trays for controlled handling; (b) the eucalyptus leaves were cleaned and sorted, removing dust and surface debris by washing them in running water and then air-drying them, ensuring that they were in suitable condition for the preparation of the inhibitor; (c) the clean leaves were weighed on a digital scale, establishing different batches in order to prepare extracts at varying concentrations of 20%, 30%, 40%, 50% and 60% in relation to the distilled water used; (d) The leaves were placed in the blender jug together with the corresponding volume of distilled water, taking care to maintain the exact proportion in each test in order to control the concentration variable. (e) The plant material was blended and homogenised until a uniform mixture of intense green colour and pasty consistency was obtained; and finally, the final extract was obtained, which was transferred to beakers labelled with the respective concentration, to be subsequently used in the corresponding tests.

Fig. 2 Eucalyptus inhibitor for steel

Table 3. Properties of persea americana

Property	Description
Total phenolic compound content	Rich in polyphenols, flavonoids, and tannins [32].
Antioxidant activity (DPPH)	Proven; free radical formation inhibited (protective effect) [32].
Inhibitory efficiency (NaCl 3.5%)	17.97% in corrosion rate, 32.92% in surface resistance [32, 33].
Inhibitory efficiency (HCl 1M)	Up to 93.2% at 30 ppm (ethanolic extract, gravimetric and electrochemical test) [32, 33].
Protective film formation	Confirmed by SEM, AFM, and FTIR; reduction in roughness and corrosion [33, 34].
Type of inhibition	Mixed (anodic and cathodic); physical and chemical adsorption [34].

3.1.3. Avocado Inhibitor

Avocado (Persea americana), in addition to its recognised importance as a food source, has established itself as a natural source of bioactive compounds with corrosion-inhibiting potential in reinforcing steel embedded in concrete. Extracts prepared from the pulp, peel, and especially the seed of the fruit are rich in polyphenols, flavonoids, and tannins, which promote the formation of protective films on the surface of the steel, acting by adsorption mechanisms and as a physical barrier against the entry of aggressive agents. Electrochemical methods and accelerated concrete testing have confirmed that these properties lower the corrosion rate and raise the surface resistance of the reinforcement in saline and acidic conditions. The application of avocado extracts as a green inhibitor is a cost-effective and eco-friendly substitute for synthetic inhibitors that enhances the longevity of reinforced concrete structures and mitigates the negative environmental effects of standard steel protection [32-34].

Polyphenols, flavonoids, and tannins in avocado create remarkable properties that aid in the Steel Corrosion Avocado Protection phenomenon due to the protective barriers formed and the corrosive process inhibitors, as seen in Table 3. Corrosion Protection Steel Avocado Pulp Coatings have been recognized in the literature review as a protective coating for reinforcing steel in the Corrosion Protection Steel Avocado Pulp Coatings scholarly articles. The most recent studies produced a compound consisting of 80% homogenized avocado pulp and 20% distilled water, which was created to maintain a sterile medium and a stable coating [32]. To validate avocado s inhibitory nature, a mixture of homogenized avocado pulp was prepared with distilled water in the ratios of 70, 75, 80, 85, and 90% pulp out of the total mixture. Each mixture was measured accurately to the respective ratios of distilled water for the purpose of surveying the efficiency of the natural coating.

Obtaining the Avocado Inhibitor

The process of obtaining avocado paste extract, which is used as a natural corrosion inhibitor coating, is shown in Figure 3. Four-step processes were involved. Stage A involved fruit selecting and receiving, in which avocados at the intermediate ripeness stage, fresh-looking, and without surface blemishes, were put into clean metallic trays. Stage b involved fruit opening and separating by carefully extracting the skin and seed in order to leave pulp as the only available mass. Stage c involved pulp cleaning and conditioning. This consists of the removal of skin and unwanted fibers and contamination in order to keep the pulp homogeneous, void of any skin and unwanted fibers, and to ensure that the pulp is indeed. Stage d involved the pulp being blended and homogenized in a blender where a ratio of fresh pulp and distilled water was used (70%, 75%, 80%, 85% and 90% pulp in relation to the total volume of the mixture) until a uniform, creamy paste with a characteristic green colour was obtained; Finally, the extract was obtained and stored in beakers, which were properly labelled with the mixture ratio used.

Fig. 3 Obtaining the Avocado inhibitor

3.2. ASTM A615 Grade 60 Reinforcing Bar

A reinforcing bar is a steel material formed by hot rolling and designed with high-bond ribs that significantly improve its bond with reinforced concrete. In Peru, it is widely used under the ASTM A615 Grade 60 / NTP 341.031 standard, with a design that ensures a minimum yield strength of 420 MPa (4,280 kg/cm²) and a tensile strength of at least 620 MPa (6,320 kg/cm²), guaranteeing ductility and structural safety [35, 36]. In conventional buildings such as homes, buildings, bridges, and industrial works, this steel is the most widely used due to its balance between price, availability, and technical performance, both seismic and structural. In these projects, the 5/8" bar diameter is one of the most commonly used, as it provides an excellent ratio between strength and ease of handling on site, adapting to different types of structural elements such as columns, beams, and plates [36]. That is why 5/8" ASTM A615 Grade 60 corrugated iron was used for this research, as shown in Figure 4.

Fig. 4 ASTM A615 Grade 60 5/8" corrugated iron

3.2.1. PER IRON PROTEC additive

Per Iron Protec 1k additive was used to protect the reinforcing steel from corrosion in environments with high humidity and aggressive agents. This product is a cementitious mortar composed of cementitious binders, powdered polymers, and corrosion inhibitors, specifically formulated to be applied to concrete reinforcement and prevent the formation of rust. The preparation consisted of mixing the product with clean water in a ratio of 1 litre per 5 kilograms of powder, thus obtaining a homogeneous, lump-free paste. It was applied in two successive layers: the first acting as an anti-corrosive coating and the second applied 24 hours later, ensuring a total thickness of 2 mm [37], as shown in Figure 5. This additive was chosen due to its local availability in the study area and served as a reference for comparing its performance with the natural additives proposed in the research.

Fig. 5 Application of the Per Iron Protec 1k additive

3.3. Concrete with Strength f'c = 350 kg/cm²

Concrete is a heterogeneous composite material consisting mainly of a combination of Portland cement, coarse and fine aggregates, water, and, in many cases, additives. This composition allows its microstructure and mechanical properties to be modified, adjusting its strength, durability, and workability according to project requirements. Depending on its mix design and the use of additives, concrete can be used in a wide variety of structural applications, ensuring adequate performance even in aggressive environmental conditions [38]. In this study, the concrete mix was designed to achieve a compressive strength of 350 kg/cm² at 28 days, in accordance with the provisions of Standard E.060 'Reinforced Concrete' of the National Building Regulations [39]. This lowest required strength concerns the service life and protection of the reinforcement from the action of chlorides and from corrosion, and meets the particular conditions for concretes and structures subjected to aggressive environments like marine environments.

3.3.1. Mix Design

For the study, the aggregates were from quarries within the Huancayo. Fine aggregate was the coarse sand from the Mito quarry located in Orcotuna, whereas the coarse aggregate was the ¾ inch crushed stone from the Ataura quarry in Jauja. Regarding the water condition of the materials, it was found that the fine aggregate had 1.40% and 1.60% of absorption and moisture content, respectively, whereas the coarse aggregate had 1.83% and 0.48% of absorption and moisture content, respectively. These values were used to calculate the moisture content of the concrete mix design to control the effective water in the batch to maintain moisture equilibrium and strength. The mix design used is provided in Table 4.

Table 1. Concrete mix design F'c=350 kg/cm2

Property	Value
F'c (kg/cm²)	350
a/c	0.35
Coarse Aggregate Size	¾"
Cement (Kg)	594
Fine Aggregate (Kg)	824
Coarse Aggregate (Kg)	683
Water (L)	208
Corrected Water (L)	215

Figure 6 shows the initial trials aimed at establishing the basic attributes of the concrete. In the figure, parts a and b present slump and temperature tests that were completed according to the incumbent legislation. These tests were performed for the base mixture and the altered versions containing the natural and artificial additives for the purpose of ensuring comparability of results and confirming that the requisite workability criteria were met.

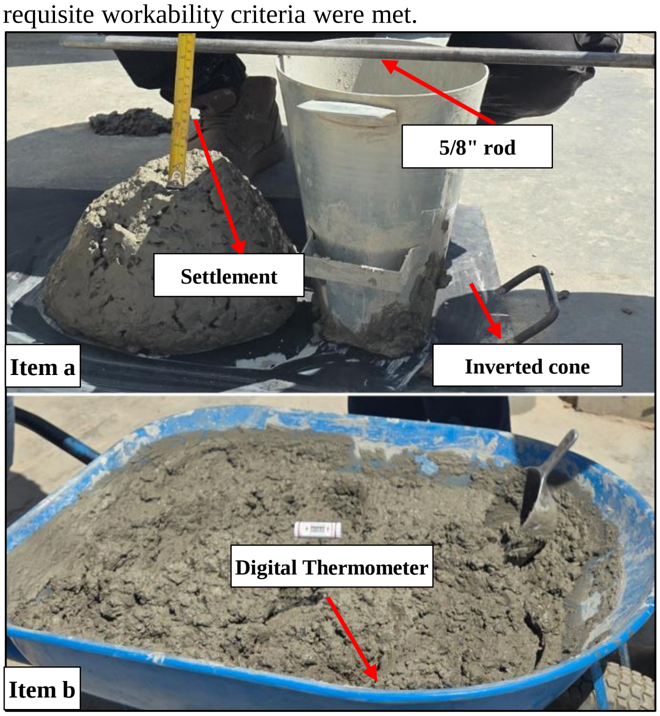

Fig. 1 Slump and temperature of concrete

3.4. Natural Concrete Additives

The incorporation of natural additives into concrete was intended to analyse their effect on the setting process, workability, and mechanical performance of the material. Apple and eucalyptus extracts were used, prepared using controlled methods to ensure their purity and stability.

3.4.1. Obtaining the Apple Additive

A study from India showed that replacing small portions of water with apple juice in cement mixtures had no negative consequences in terms of mechanical strength, but did, to a minor degree, help with cement setting. This efficiency plateaued with 15% of the weight of the cement, which corresponded to the case with water and apple extract [39]. In order to validate and expand on these results in the present study, additional percentages of 10%, 12.5%, 15%, 17.5% and 20% of the mixing water volume were evaluated, keeping the water/cement ratio constant. To obtain this additive and apply it, the steps are detailed in section (2.1.1.1. Obtaining the Apple Inhibitor, from item a) to item d).

From there, two additional steps were carried out, as detailed in Figure 7: (a) extraction of the juice using an extractor, into which the chopped pulp was introduced to obtain a liquid with the organoleptic characteristics of the fruit; and (b) filtering the juice obtained using a fine mesh to separate solids, fibres and pulp residues, thus ensuring a clearer and more stable solution for use; and finally (c) storing the filtered juice in a graduated beaker, labelled with the corresponding volume and concentration, to be subsequently incorporated into the concrete mixtures.

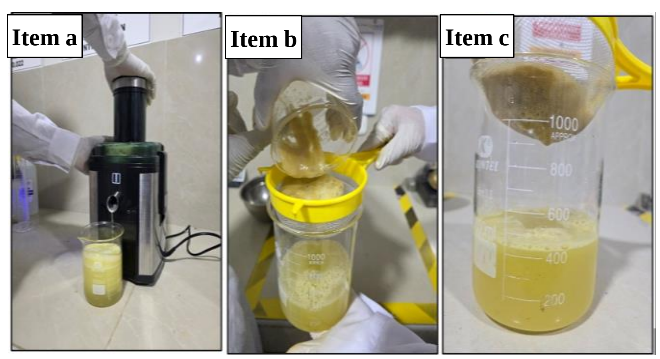

Fig. 7 Obtaining the apple additive for concrete

3.4.2. Obtaining the Eucalyptus Additive

In the case of eucalyptus leaf extract, a previous study was used as a reference, which identified an optimal dose of 5% relative to the weight of the cement, capable of maintaining and even improving the physical and mechanical properties of the concrete [40].

In order to corroborate and expand on these results, this study evaluated addition ratios of 3%, 4%, 5%, 6% and 7%, analysing their influence on the workability, mechanical strength, and durability of concrete against chloride penetration. To obtain this additive and apply it, the steps detailed in section (2.1.2.1. Obtaining the eucalyptus inhibitor) were followed, and two additional steps detailed in Figure 8 were then carried out: (a) filtering the liquefied extract, in which the vegetable paste was poured onto a fine mesh sieve and subjected to manual pressure with a metal spatula, with the aim of separating the liquid fraction rich in soluble compounds (phenols, flavonoids, and terpenoids) from the solid fibrous part; and (b) collection of the filtered extract in a 1000 mL graduated beaker, obtaining a dark green, homogeneous solution free of coarse particles, suitable for use as an inhibitor additive in concrete mixtures.

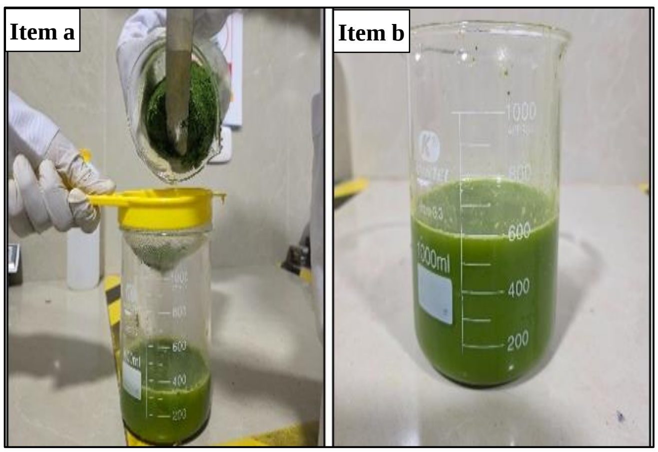

Fig. 8 Obtaining the eucalyptus additive for concrete

Amounts of Apple and Eucalyptus Additives

Table 5 shows the amounts of additives used in the study, which were defined according to the previously established mixture design. These values ensured the correct dosage of the components, guaranteeing both experimental consistency and the possibility of making subsequent comparisons between the different treatments applied.

Table 5. Amount of liquid additives in the mixture

Apple Additive		Eucalyptus Leaf Additive	
Dose (%)	**Amount (L)**	**Dose (%)**	**Amount (L)**
10%	65.88	3%	19.76
12.50%	82.34	4%	26.35
15%	98.81	5%	32.94
17.50%	115.28	6%	39.53
20%	131.75	7%	46.11

3.4.3. Microencapsulation of Avocado Oil

Active ingredients for cement additives are microencapsulated in a matrix of gelatin, alginates, resins, and other polymers. This technique both sequesters the additive from the environment and allows for a slower release of the inhibitors, leading to controlled release of the additive from its coat [41].

Previous research has shown that microencapsulation of avocado oil improves its stability, preservation, and industrial applicability, so this technology was adopted in this study to enhance its properties and expand its use [42, 43]. Given the limited information on its application as an additive in concrete, used vegetable oil was taken as a reference, whose optimal incorporation percentage is 1.5% by weight of cement, improving workability and compressive strength without negatively affecting other mechanical properties [44]. To validate and compare results, additions of 0.5%, 1%, 1.5%, 2% and 2.5% relative to the weight of the cement were tested.

Preparation of Avocado Oil Microcapsules

In this research, avocado oil was obtained through a cooking process [45] and microencapsulated through complex coacervation with unflavoured gelatin and sodium alginate [42]. Figure 9 shows the procedure for obtaining avocado oil microcapsules, which was carried out in eight stages: (a) the avocado pulp was prepared by cutting the fruit into small pieces, followed by manual pressing and subsequent placement in a frying pan; (b) the pulp was cooked in a pan over medium heat (80 °C) under constant stirring, with the aim of evaporating the water content and promoting the release of oil, obtaining a paste-like mass of intense green colour with visible oily areas on the surface; (c) the cooked material was filtered by applying manual pressure through a fine metal mesh to separate the liquid from the residual fibres; (d) the collected oil was stored in graduated beakers, yielding a characteristic yellowish-green extract; (e) the polymer wall was prepared with a gelatin:sodium alginate ratio of 3:1. Thirty grams of gelatin and 10 grams of sodium alginate were used, dissolved separately in distilled water in proportions equivalent to 53.3 ml of water per gram of gelatin (at 50 °C) and 17.8 ml of water per gram of alginate (at 20 °C), values that were detailed in Table 6 but with actual quantities; (f) Dissolution and emulsification were carried out by stirring the gelatin rapidly for 15 minutes until completely dissolved, while the alginate was hydrated with gentle stirring for the same amount of time, avoiding lumps.

The avocado oil was added to the hot gelatin solution and homogenised for 3 minutes, forming a fine emulsion; the amount added was 33 ml, calculated with a core: wall ratio of 1:1.3. Keeping the emulsion at 50 °C and stirring constantly, the alginate solution was gradually added; (g) the pH was adjusted with glacial acetic acid to a value of 4.0 as measured by a pH meter, which induced the formation of coacervate around the oil droplets; and (h) cooling and stabilisation were carried out by gradually reducing the mixture to 10 °C and refrigerating it at 4 °C for 12 hours in the dark.

Subsequently, the coacervate was separated, frozen at -80 °C for 24 hours, and subjected to freeze-drying at -40 °C for 72 hours. Finally, the dry material was ground and sieved through a No. 20 mesh, obtaining a fine, stable microencapsulated powder ready for application in concrete.

Fig. 9 Microencapsulation of avocado oil

Table 6 details the quantities of avocado oil, total microencapsulated oil, gelatin, sodium alginate, and distilled water volumes used for each dosage level considered for 1 m³ of concrete. These ratios were defined in correlation to the levels of incorporation specified in the experimental design to achieve a homogeneous mixture and proper distribution of every additive in the concrete matrix. The chosen mixes enable a systematic comparison to evaluate the influence of microencapsulated avocado oil as a functional additive contributor to the cementitious system with respect to the mechanical and durability performance of concrete.

Table 6. Quantities of Avocado oil microcapsules

% Avocado Oil	Oil (L)	Gelatin (kg)	Alginate (kg)	Microencapsulated (kg)
0.50%	3.29	3.21	1.070	4.282
1%	6.59	6.42	2.141	8.564
1.50%	9.88	9.63	3.211	12.846
2%	13.18	12.85	4.282	17.128
2.50%	16.47	16.06	5.352	21.409

Fig. 10 Application of the corrosion inhibitor scheme in concrete

3.5. Industrial Additive for Concrete Chema Inhibitor

Chloride ingress in reinforced concrete structures in a marine environment is one of the main causes of rapid corrosion of the steel reinforcement [46]. To mitigate this problem, Chema Corrosion Inhibitor was used in this study as a commercial benchmark additive. This product is said to create a protective barrier at the steel surface through a chemical reaction with the metal, which slows down the entry of aggressive ions. The inhibitor was added to the concrete mix at a rate of 8 L/m³ of fresh concrete, as recommended by the manufacturer, to achieve an adequate throughout distribution in the concrete [12], as shown in Figure 10. This additive was selected because of its easy availability in the study area and was also used as a commercial reference to compare its effectiveness with the natural additives evaluated in the research.

3.6. Tests Performed

This section presents the tests performed to evaluate the protection of reinforced concrete against saline environments, using both additives and coatings of natural and commercial origin. The tests included determining the corrosion resistance of steel using standardised tests (ASTM G31, ASTM G59, and ASTM C876), as well as evaluating the permeability of chloride ions in concrete according to ASTM C1202. Table 7 summarises the experimental variants evaluated for the steel and concrete tests. For apple extracts, paste mixtures were prepared with different pulp concentrations, keeping the volume of deionised water constant at 150 mL, in order to analyse the effect of concentration on inhibitory efficiency. In the case of eucalyptus leaf extract, the percentages correspond to the proportion of extract relative to the total volume of distilled water used as a solvent. Finally, the avocado microcapsules were incorporated into the concrete in proportions relative to the weight of the cement in each mixture.

Table 7. Ensayos realizados

Material	Variants evaluated	Nº	Standard
STEEL	No additive (standard)	3	ASTM G31, G59, C876
	With an industrial additive	3	
	Apple extract 150g	3	
	Apple extract 200g	3	
	Apple extract 250g	3	
	Apple extract 300g	3	
	Apple extract 350g	3	
	Eucalyptus leaf extract 20%	3	
	Eucalyptus leaf extract 30%	3	
	Eucalyptus leaf extract 40%	3	
	Eucalyptus leaf extract 50%	3	
	Eucalyptus leaf extract 60%	3	
	Avocado additive 70%	3	
	Avocado additive 75%	3	
	Avocado additive 80%	3	
	Avocado additive 85%	3	
	Avocado additive 90%	3	
CONCRETE	No additive (standard)	3	ASTM C1202
	With an industrial additive	3	
	Apple extract 10%	3	
	Apple extract 12.5%	3	
	Apple extract 15%	3	
	Apple extract 17.5%	3	
	Apple extract 20%	3	
	Eucalyptus leaf extract 3%	3	
	Eucalyptus leaf extract 4%	3	
	Eucalyptus leaf extract 5%	3	
	Eucalyptus leaf extract 6%	3	
	Eucalyptus leaf extract 7%	3	
	Avocado microcapsule 0.5%	3	
	Avocado microcapsule 1%	3	
	Avocado microcapsule 1.5%	3	
	Avocado microcapsule 2%	3	
	Avocado microcapsule 2.5%	3	

3.6.1. Mass Loss Test after Immersion in Saline Solution ASTM G31

This testing protocol determines the corrosion resistance of metals through mass loss after the sample is dipped into a saline solution. A primary aim is to determine the corrosion loss rate of the given metal shown in equation 1. The mass loss is a direct measure of the corrosion resistance of the metal in the corrosive environment. The technique is documented by ASTM G3 [47], and theoretical mass loss data in scientific literature. The process involves cutting a metal sample to a given dimension and immersing it in a corrosive liquid to measure mass loss and the corrosion loss rate as the difference in the sample weights before and after the experiment. The technique is reported and well documented in the scientific and engineering community to measure the corrosion loss and protective measures of different materials and protective coatings, drained samples to provide primary ground materials and systems to devise corrosion protective systems [48-50].

$$CR = \frac{K \cdot W}{A \cdot T \cdot D} \quad (1)$$

The corrosion rate is represented as (CR) which is in mm/year, (W) represents the mass loss in grams, (A) is the surface area in cm² of the corroded metal, (T) is the time in hours (24), (D) is the metal's density in g/cm³ (7.85), and (K) is the conversion constant (87.6 x 103).

ASTM G31 Test Procedure

Figure 11 shows the procedure followed for the preparation, coating, and exposure of the steel samples used in the evaluation of corrosion inhibitors, which was carried out in six main phases: (a) sample preparation: corrugated steel bars with a nominal diameter of 5/8" (19 mm) were selected, which were carefully cut to a length of 20 cm, deburred at their ends, and marked with an identification code in an area not exposed to the corrosive medium; (b) cleaning and initial weighing: the bars were washed with detergent, rinsed with water, dried completely, and finally, their initial weight was recorded using a high-precision analytical balance; (c) preparation and application of coatings: natural and industrial inhibitors were applied to each clean and dry sample by immersion, ensuring uniform coverage, and left to dry at room temperature for 19 hours before exposure; (d) Immersion in the corrosive solution: a 3% sodium chloride (NaCl) solution was prepared in distilled water, with which the test container was filled, placing the coated bars in it without touching each other, remaining submerged for 72 hours at 23 °C; (e) final measurement and reporting: the bars were removed with plastic tweezers, rinsed with plenty of distilled water, and each bar was weighed on the analytical balance to record the final weight of the steel after exposure.

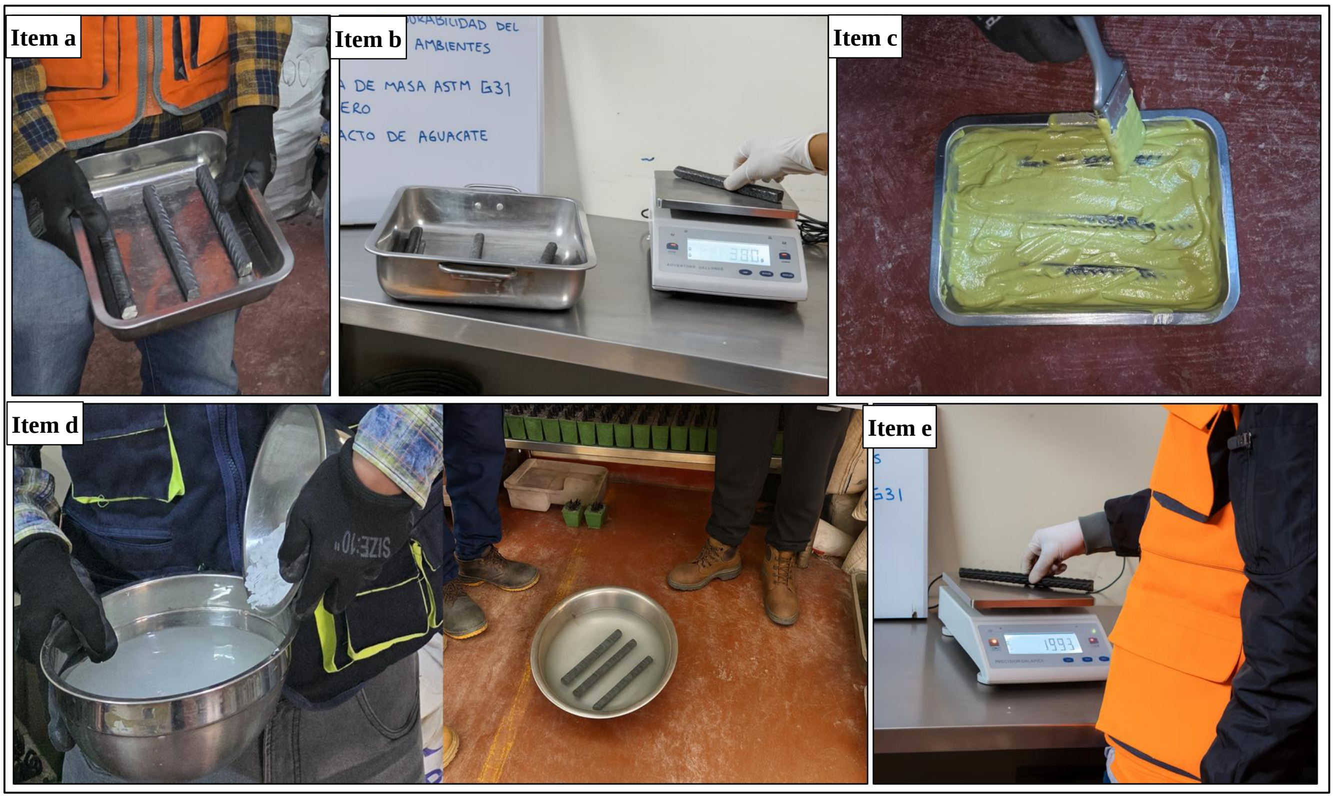

Fig. 11 ASTM G31 test procedure

3.6.2. ASTM G59 Electrochemical Corrosion Rate Measurement Test

This test is a standardized electrochemical technique used to evaluate the corrosion rate of metallic materials embedded in concrete, especially in simulated chloride environments, by measuring the corrosion current density (Icorr). According to ASTM G59 [51], the methodology consists of applying a slight potential variation around the corrosion potential of the embedded steel, using an electrochemical cell consisting of a working electrode (the steel bar to be evaluated), an auxiliary electrode, and a $Cu/CuSO_4$ reference electrode.

Using the slope from the range close to the corrosion potential gives the value of polarization resistance, which is directly linked to the instantaneous corrosion rate, which does not require the specimen to be destroyed. This method has gained popularity among researchers seeking to quantify corrosion resistance for various steels, offering a measurable standard for toughness in corrosive environments [52, 53]. The corrosion rate can be calculated using the corrosion rate equation 2.

$$CR(mpy) = 0.129 \cdot C \qquad (2)$$

Where the value CR(mpy) is the corrosion rate in mils per year, (C) is the corrosion current density in μA/cm², the constant 0.129 was adopted in the equation for converting corrosion current density to corrosion rate, in accordance with ASTM G102 [54].

ASTM G59 Test Procedure

Figure 12 shows the procedure followed for the electrochemical testing of steel bars with natural and industrial coatings, carried out in five main phases: (a) selection and preparation of samples, 5/8" diameter corrugated steel bars cut into 10 cm segments were used, which were sanded to remove rust and dirt, washed with water and left to dry, with both ends covered with resin and only 5 cm exposed in the central area; (b) preparation and application of coatings: apple and eucalyptus extracts, an avocado pulp-based additive, and the reference industrial additive were prepared and applied with a brush to the exposed area of the bars, left to air dry for one hour, and then dried in an oven at 40°C for two hours to promote adhesion, at 40 °C for two hours to promote adhesion, then stored under protected conditions until testing; (c) preparation of the corrosive solution: a 3.5% w/w NaCl solution was prepared in distilled water, using 200 mL per electrochemical cell, ensuring its homogeneity and maintaining a constant temperature of 25 °C; (d) assembly of the equipment: the corrosion test was carried out in a three-electrode electrochemical cell, in which the coated bar functioned as the working electrode, the reference electrode was Ag/AgCl, and the counter electrode was platinum, all connected to an ACM's Instruments potentiostat [55], coupled to a computerized data acquisition system with specialized software for real-time monitoring; before starting the measurement, the Open-Circuit Potential (OCP) was allowed to stabilize for 30 minutes; and (e) measurement and analysis, where the Linear Polarization Resistance test (LPR) test was performed by applying a ±20 mV sweep with respect to the OCP at a speed of 1 mV/s, recording the current response as a function of the applied potential. The procedure was repeated three times per variant to ensure reproducibility, and finally, the resistance and corrosion rate of each coating were calculated, which allowed for a comparison of their effectiveness against an uncoated bar.

Fig. 12 ASTM G59 test procedure

3.6.3. Corrosion Potential Test of Steel Embedded in Concrete using the ASTM C876 Half-Cell Technique

The half-cell potential test, described in ASTM C876 [55], s a widely used non-destructive electrochemical technique for evaluating the probability of corrosion in steel reinforcing bars embedded in concrete. It consists of measuring the difference in electrical potential between the steel and a copper/copper sulfate ($Cu/CuSO_4$) reference electrode placed on the surface of the concrete, without requiring damage or removal of the reinforcement. The estimated corrosion risks, corrosion process monitoring, and maintenance planning. Predicting the corrosion risk and the estimated corrosion risks allows for corrosion risk monitoring and maintenance planning. This risk assessment and methodology are engaged in monitoring the In-Place structural assessment. Most especially, the structures where environmental aggressiveness and exposure to chlorides are present. The assessment is standardized and metric provided, and the methodology is universal. The methodology excels in its meritorious qualities. It is systematic, inexpensive, and diagnostic to determine the reinforcement preservation. Also, it is in a great state of preservation [56-58]. According to ASTM C876, the half-cell potential values presented in Table 8 are classified into three categories: high, zero, and low probability of corrosion. According to this criterion, potentials more positive than -0.20 V indicate a low probability of corrosion (<10%), while those more negative than -0.35 V correspond to a high probability of corrosion (>90%). This interpretation, based on the standard, allows the identification of variants that provide greater protection to reinforcing steel against corrosion in aggressive conditions [55].

Table 2. ASTM C876 potential values [55]

Half-cell potential (V vs. CSE)	Probability of active corrosion in reinforcing steel
More positive than -0.20 V	Low probability (<10%)
Between -0.20 V and -0.35 V	Zone of uncertainty (cannot be determined with certainty)
More negative than -0.35 V	High probability (>90%)

ASTM C876 Test Procedure

Figure 13 shows the procedure followed for evaluating the corrosion potential of steel embedded in concrete using the half-cell technique (ASTM C876), which was carried out in four main phases: (a) preparation of the coatings and steel: 5/8" diameter corrugated steel bars were cleaned with a wire brush and clean cloths to remove rust, dirt, and surface grease, after which they were immersed in the solutions corresponding to each coating variant, ensuring a uniform layer in the area that would be embedded in the concrete; Subsequently, they were left to dry at room temperature for 24 hours before molding. (b) Preparation of concrete specimens: cylinders 100 mm in diameter and 200 mm in height were made using plastic molds lubricated with release agent, in which the coated bars were positioned vertically in the center, ensuring minimum coating and alignment using centering devices. and then poured the structural concrete (f'c = 350 kg/cm^2) in two layers, compacting with a metal rod and rubber combo; the samples were demolded after 24 hours and transferred to a wet curing chamber at 20 °C for 28 days; (c) Preparation of the measurement system: the concrete surface was cleaned with a damp cloth and the upper end of the steel was left exposed for electrical connection, using a high-impedance digital voltmeter (≥ 10 MΩ), a $Cu/CuSO_4$ reference electrode, and cables with alligator clips, after verifying the polarization of the reference electrode. (d) Measurement of the half-cell potential: the negative terminal of the voltmeter was connected to the exposed steel and the positive terminal to the reference electrode, which was placed on the moistened concrete surface, recording the values under controlled environmental conditions.

Fig. 13 ASTM C876 test procedure

3.6.4. ASTM C1202 ASTM C1202 Electrical Current Passage Test

The internationally recognized ASTM C1202 standard establishes the procedure for evaluating the permeability of concrete to chloride ion penetration using an electrical current passage test, known as the Rapid Chloride Permeability Test (RCPT) [59]. This method applies a constant voltage across a cylindrical concrete specimen and records the total electrical charge that passes through it over a fixed time. The measured charge is then used as an indirect indicator of the specimen's resistance to chloride ingress. Because it is simple to reproduce and provides a consistent basis for comparison, this test is commonly adopted in laboratory research to compare mixtures, assess new cementitious systems, and verify the performance of ion-migration test setups, including studies that develop or calibrate migration equipment and those that contrast electrochemical approaches for durability assessment [60-62]. The ASTM C1202 standard allows the resistance of concrete to chloride ion penetration to be evaluated by measuring the electrical charge transferred in a six-hour test. A lower charge value indicates greater impermeability and, therefore, better concrete performance in aggressive environments, which helps to extend the service life of reinforced concrete structures exposed to corrosion risks, as can be seen in Table 9 [59].

Table 3. ASTM C1202 test values [59]

Electrical charge (Coulombs)	Chloride permeability classification
> 4000	Very high
2000 - 4000	High
1000 - 2000	Moderate
100 - 1000	Low
< 100	Very Low

ASTM C1202 Test Procedure

Figure 14 shows the procedure followed for testing chloride ion permeability using the ASTM C1202 electrical testing technique, which was carried out in five main phases: (a) sample preparation, concrete cylinders 100 mm in diameter and 200 mm in height were made, incorporating apple and eucalyptus extracts, avocado oil microcapsules, and a reference industrial additive, in proportions defined with respect to the weight of the cement; after molding, the specimens remained in their molds for 24 h and were then cured in water for 28 days; (b) cutting and preparation of discs, the cured cylinders were demolded and cut transversely with a concrete disc cutter, obtaining discs 50 mm thick and 100 mm in diameter with parallel and flat surfaces; (c) saturation of the samples: the discs were placed in a vacuum chamber at -90 kPa for 18 hours, completely submerged in deionized water, and then kept submerged at atmospheric pressure for an additional hour, ensuring complete saturation of the pores; (d) Test setup: each disc was placed in the ASTM C1202 cell between two sealed compartments, filling one side with 200 mL of 0.3 N NaCl solution (anode) and the other with 200 mL of 0.3 N NaOH (cathode), connecting the corresponding electrodes to the positive and negative poles of the power supply; (e) application of potential and data recording: the power supply was adjusted to apply 60 V DC across the sample, recording the electric current every 30 minutes for 6 h, verifying that the system temperature remained between 20 and 25 °C.

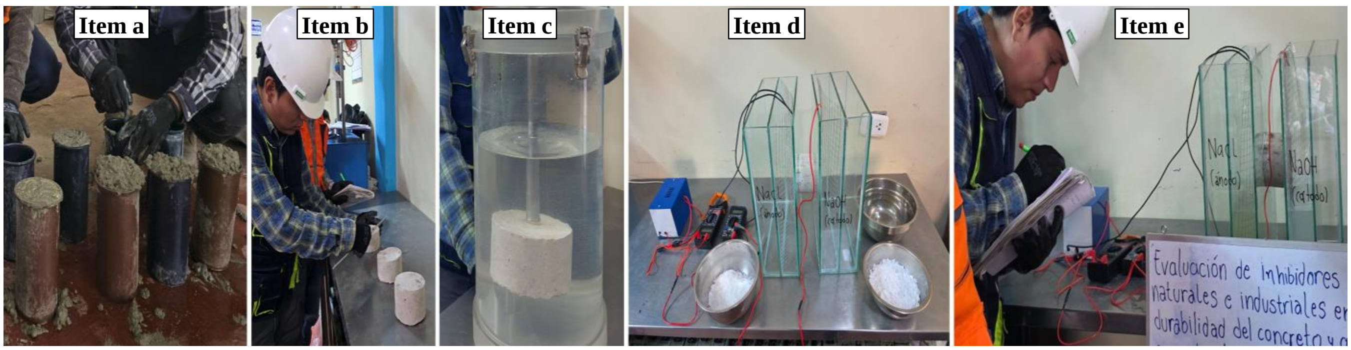

Fig. 14 ASTM C1202 test procedure

4. Results

This section presents the results of the evaluation of natural and commercial additives applied to steel and concrete exposed to saline conditions. The tests carried out made it possible to analyze the behavior against corrosion and chloride penetration, as well as to compare the relative effectiveness of each treatment. The results showed significant differences in the performance of the additives, which made it possible to identify those with the greatest potential for protection and durability in aggressive environments.

4.1. Mass Loss Test After Immersion in Saline Solution ASTM G31

The results obtained from the gravimetric weight loss test conducted on 5/8" corrugated steel bars exposed for 24 hours in a salt spray chamber are presented in Table 10. In general, the corrosion behaviour of the specimens showed clear differences depending on the treatment applied. The control samples, which did not include any type of additive, exhibited the highest corrosion rate, confirming the severe effect of the saline environment in the absence of protective mechanisms.

On the other hand, the specimens treated with the industrial inhibitor showed a markedly lower corrosion rate, reaching a minimum value of 0.000000006 mg/cm²·h and an inhibition efficiency of 90.67%. This result confirms the high effectiveness of the commercial product in forming a stable protective layer on the steel surface under accelerated corrosion conditions. In contrast, the samples treated with apple extract showed a progressive increase in inhibition efficiency as the dosage increased, reaching a maximum value of 82.67% at 300 g. However, at higher concentrations, a decrease in efficiency was observed, which may be associated with the formation of less uniform or unstable protective films. Similarly, the eucalyptus leaf extract exhibited concentration-dependent behaviour.

The best performance was obtained with the 40% extract, which achieved an inhibition efficiency of 78.67%. Both lower and higher concentrations resulted in reduced protection, indicating that an optimal balance is required between extract concentration and surface adsorption. In the case of the avocado-based additive, high inhibition efficiencies were recorded across all evaluated dosages. The 75% formulation showed the highest efficiency (85.33%), followed by the 80% and 85% formulations, which maintained satisfactory protective performance. Finally, in all cases where inhibitors were applied, the treated steel bars retained a greater final mass compared to the control samples, reflecting lower material loss due to corrosion. Overall, the results demonstrate that both natural extracts and the avocado-derived additive are capable of reducing corrosion under saline exposure, although the industrial inhibitor remained the most effective solution within the experimental conditions evaluated.

Table 10. ASTM G31 test

Variant evaluated	Total, surface area (cm²)	Initial mass (g)	Final mass (g)	Corrosion rate (mg/cm²·h)	Inhibition efficiency (%)
No additive (standard)	54.29	155.20	155.1925	0.000000064	0.00%
With an industrial additive	54.29	155.20	155.1993	0.000000006	90.67%
Apple extract 150g	54.29	155.20	155.1972	0.000000024	62.67%
Apple extract 200g	54.29	155.20	155.1975	0.000000021	66.67%
Apple extract 250g	54.29	155.20	155.1978	0.000000019	70.67%
Apple extract 300g	54.29	155.20	155.1987	0.000000011	82.67%
Apple extract 350g	54.29	155.20	155.1969	0.000000027	58.67%
Eucalyptus leaf extract 20%	54.29	155.20	155.1963	0.000000032	50.67%
Eucalyptus leaf extract 30%	54.29	155.20	155.1966	0.000000029	54.67%
Eucalyptus leaf extract 40%	54.29	155.20	155.1984	0.000000014	78.67%
Eucalyptus leaf extract 50%	54.29	155.20	155.1965	0.000000030	53.33%
Eucalyptus leaf extract 60%	54.29	155.20	155.1957	0.000000037	42.67%
Avocado additive 70%	54.29	155.20	155.1977	0.000000020	69.33%
Avocado additive 75%	54.29	155.20	155.1989	0.000000009	85.33%
Avocado additive 80%	54.29	155.20	155.1984	0.000000014	78.67%
Avocado additive 85%	54.29	155.20	155.1981	0.000000016	74.67%
Avocado additive 90%	54.29	155.20	155.1971	0.000000025	61.33%

Figure 15 compares the inhibition efficiencies obtained with the different treatments. The commercial inhibitor produced the highest value, reaching 90.67%. Among the natural alternatives, the avocado-based additive at 75% showed the closest performance, with an efficiency of 85.33%. The apple extract at 300 g ranked next, with an inhibition efficiency of 82.67%, remaining clearly below the industrial reference. Finally, the 40% eucalyptus leaf extract had the highest value at 78.67%, 12 points behind the industrial additive. This hierarchy of results shows that, although the industrial additive remains the most effective, the 75% avocado additive and the 300 g apple extract are highly competitive natural alternatives, while the eucalyptus extract offers moderate but still significant performance compared to the standard.

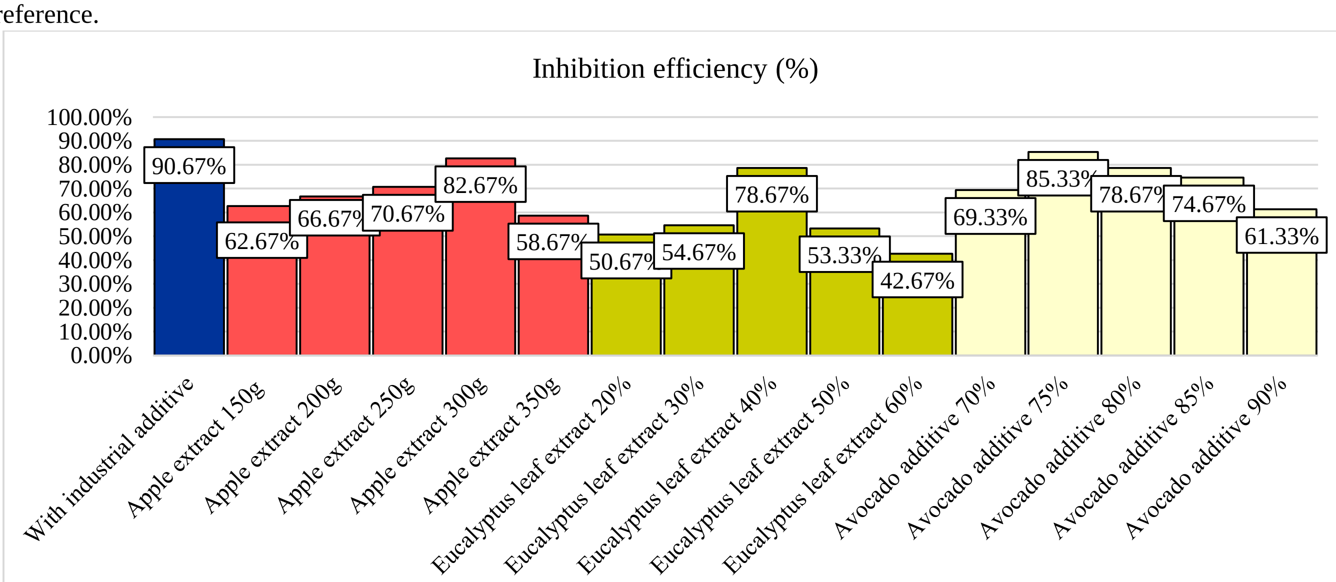

Fig. 15 ASTM G31 inhibition efficiency (%)

4.2. ASTM G59 Electrochemical Corrosion Rate Measurement Test

The results obtained from the electrochemical corrosion rate measurement test, performed in accordance with ASTM G59, on 5/8" ASTM A615 Grade 60 corrugated steel bars exposed in direct contact with saline solution are presented below. Table 11 shows that the absence of an inhibitor generated the highest degree of corrosion, reflected in a high current density (35.40 µA/cm²), low polarisation resistance (1.28 Ω·cm²), and maximum corrosion rate (4.57 mpy), confirming the total exposure of the steel to the aggressive environment. The industrial additive achieved the highest efficiency (80.68%) due to the formation of a stable and continuous protective film that limited the transport of corrosive ions. Among the natural inhibitors, the best performance was achieved by the 75% avocado additive, with 77.68%, whose effectiveness is associated with fatty compounds and antioxidants that generate an adherent hydrophobic layer on the steel. The 300 g apple extract achieved an inhibition efficiency of 72.20%, while the 40% eucalyptus leaf extract reached 69.83%. In both cases, the protective effect is associated with the interaction of organic compounds with the steel surface. When the extract concentration exceeded the optimal level, a reduction in efficiency was observed due to the formation of non-uniform surface layers that reduced the effectiveness of corrosion protection.

Table 11. ASTM G59 test

Variant evaluated	Corrosion Current Density (μA/cm²)	Polarisation resistance (Ω·cm²)	Corrosion rate (mpy)	Inhibitor efficiency (%)
No additive (standard)	35.40	1.28	4.57	0.00%
With an industrial additive	6.84	5.95	0.88	80.68%
Apple extract 150g	22.86	2.42	2.95	35.42%
Apple extract 200g	14.96	3.18	1.93	57.74%
Apple extract 250g	11.93	4.10	1.54	66.30%
Apple extract 300g	9.84	4.84	1.27	72.20%
Apple extract 350g	12.28	4.09	1.58	65.31%
Eucalyptus leaf extract 20%	25.31	2.07	3.26	28.50%
Eucalyptus leaf extract 30%	21.37	2.82	2.76	39.63%
Eucalyptus leaf extract 40%	10.68	4.32	1.38	69.83%
Eucalyptus leaf extract 50%	12.46	4.05	1.61	64.80%
Eucalyptus leaf extract 60%	16.24	2.91	2.09	54.12%
Avocado additive 70%	13.86	3.65	1.79	60.85%
Avocado additive 75%	7.90	5.69	1.02	77.68%
Avocado additive 80%	11.26	4.25	1.45	68.19%
Avocado additive 85%	12.91	3.89	1.67	63.53%
Avocado additive 90%	14.62	3.40	1.89	58.70%

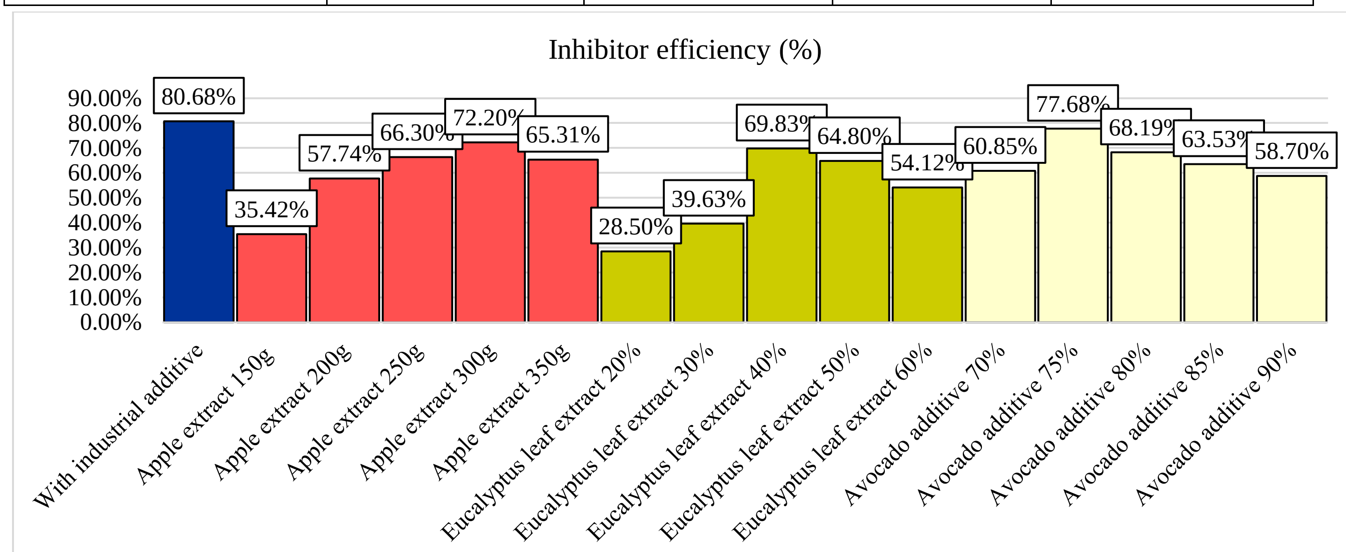

Fig. 16 Inhibition efficiency ASTM G59 (%)

Figure 16 shows the industrial additive with an efficiency of 80.68%, while the 75% avocado additive reached 77.68%. The 300 g apple extract registered 72.20%, corresponding to 89.4% of the industrial additive's performance, while the 40% eucalyptus leaf extract obtained 69.83%, equivalent to 86.6%. The order of effectiveness was: first, the 75% avocado additive, followed by the 300 g apple extract, and, in third place, the 40% eucalyptus extract. The differences observed indicate that the most efficient natural formulations remain within a margin of efficacy reduction of less than 14%, making them competitive options compared to the industrial product in corrosion protection applications.

4.3. Corrosion Potential Test of Steel Embedded in Concrete using the Half-Cell Technique, ASTM C876

The results obtained in the corrosion potential test of steel embedded in concrete, carried out in accordance with ASTM C876, are presented below. 5/8" corrugated steel bars coated with different natural additives, an industrial additive, and a standard without an additive were evaluated using the half-cell technique with a $Cu/CuSO_4$ electrode to determine the probability of corrosion under conditions of exposure to saline solution. Table 12 shows that the sample without an additive had the most negative potential (-0.410 V vs $Cu/CuSO_4$), classified according to ASTM C876 as having a high probability of corrosion (>90%), confirming the total absence of protection. The industrial additive performed best, reaching a potential of -0.179 V, corresponding to a low probability of corrosion (<10%) and an efficiency of 56.34%, due to the formation of a stable protective film that limits electrochemical activity on the steel surface. The avocado additive with 75% addition obtained a potential of -0.191 V (low probability of corrosion) and an efficiency of 53.41%. Similarly, the 300 g apple extract obtained (-0.194 V; 52.68%) and the 40% eucalyptus leaf extract obtained (-0.199 V; 51.46%), both classified as having a low probability of corrosion. Finally, it was observed that concentrations above the optimum showed negative potentials and lower efficiencies, which evidenced a loss of inhibitory protective capacity.

Table 12. ASTM C876 test results

Variant evaluated	Potential (V vs $Cu/CuSO_4$)	ASTM C876 Interpretation	Inhibitor efficiency (%)
No additive (standard)	-0.410	High probability of corrosion (>90%)	0.00%
With an industrial additive	-0.179	Low probability of corrosion (<10%)	56.34%
Apple extract 150g	-0.368	High probability of corrosion (>90%)	10.24%
Apple extract 200g	-0.321	High probability of corrosion (>90%)	21.71%
Apple extract 250g	-0.197	Low probability of corrosion (<10%)	51.95%
Apple extract 300g	-0.194	Low probability of corrosion (<10%)	52.68%
Apple extract 350g	-0.208	Uncertain area	49.27%
Eucalyptus leaf extract 20%	-0.371	High probability of corrosion (>90%)	9.51%
Eucalyptus leaf extract 30%	-0.263	Uncertain area	35.85%
Eucalyptus leaf extract 40%	-0.199	Low probability of corrosion (<10%)	51.46%
Eucalyptus leaf extract 50%	-0.218	Uncertain area	46.83%
Eucalyptus leaf extract 60%	-0.353	High probability of corrosion (>90%)	13.90%
Avocado additive 70%	-0.198	Low probability of corrosion (<10%)	51.71%
Avocado additive 75%	-0.191	Low probability of corrosion (<10%)	53.41%
Avocado additive 80%	-0.204	Uncertain area	50.24%
Avocado additive 85%	-0.341	Uncertain area	16.83%
Avocado additive 90%	-0.368	High probability of corrosion (>90%)	10.24%

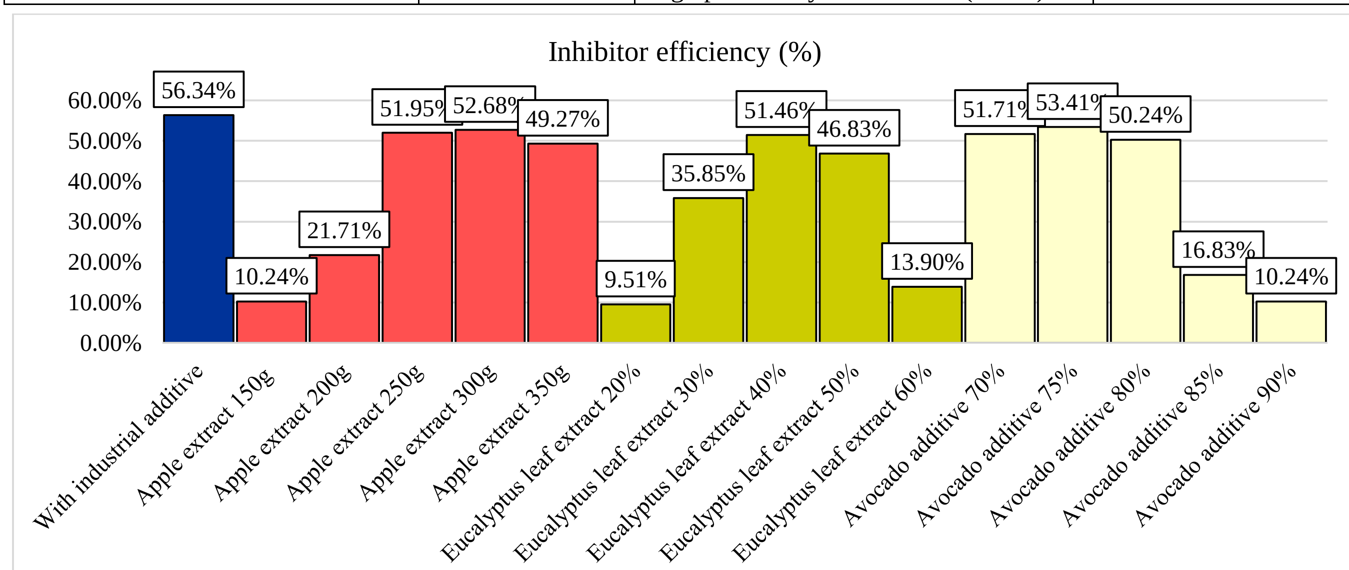

Fig. 17 ASTM C876 inhibitor efficiency (%)

Figure 17 shows that the industrial additive reached an efficiency of 56.34%. The 75% avocado-based additive followed closely with 53.41%, corresponding to a difference of 2.93 percentage points. The apple extract at 300 g recorded 52.68%, while the 250 g apple extract and the 40% eucalyptus leaf extract showed similar values of 51.95% and 51.46%, respectively. Based on these results, the effectiveness ranking was led by the 75% avocado additive, followed by the 300 g and 250 g apple extracts, and finally the 40% eucalyptus extract. Overall, the differences with respect to the industrial additive remained below 4.9 percentage points.

4.4. ASTM C1202 Electrical Current Pass Test

Table 13 presents the charge passed values, ASTM C1202 permeability classification, and inhibition efficiency for the evaluated mixtures. The reference concrete without additives showed high chloride permeability, with a transferred charge of 3627 C. In contrast, the industrial additive produced the greatest reduction in permeability, reaching 912 C and an efficiency of 74.86%, which corresponds to low permeability according to ASTM C1202. Among the apple extract mixtures, the 17.5% dosage showed the best performance, with a charge of 941 C and an efficiency of 74.06%, followed by the 15% dosage (984 C, 72.87%) and the 20% dosage (1143 C, 68.49%). The lower doses (10% and 12.5%) showed moderate efficiencies, below 50%. In the case of eucalyptus leaves, the 5% dose stood out with 981C, and 72.95% efficiency (low permeability), followed by 6% (68.98%) and 7% (67.52%), while doses below 4% had efficiencies below 61%. Avocado microencapsulation exhibited the best overall results, especially at 1% (789C, 78.25% efficiency) and 0.5% (76.81%), both with low permeability ratings; higher doses showed a slight decrease in efficiency but remained above 62%.

Table 13. ASTM C1202 test results

Variant evaluated	Charge transferred (Coulombs)	ASTM C1202 classification	Inhibitor efficiency (%)
No additive (standard)	3627	High	0.00%
With an industrial additive	912	Low	74.86%
Apple extract 10%	1941	Moderate	46.48%
Apple extract 12.5%	1823	Moderate	49.74%
Apple extract 15%	984	Low	72.87%
Apple extract 17.5%	941	Low	74.06%
Apple extract 20%	1143	Moderate	68.49%
Eucalyptus leaf extract 3%	1924	Moderate	46.95%
Eucalyptus leaf extract 4%	1425	Moderate	60.71%
Eucalyptus leaf extract 5%	981	Low	72.95%
Eucalyptus leaf extract 6%	1125	Moderate	68.98%
Eucalyptus leaf extract 7%	1178	Moderate	67.52%
Avocado microcapsule 0.5%	841	Low	76.81%
Avocado microcapsule 1%	789	Low	78.25%
Avocado microcapsule 1.5%	924	Low	74.52%
Avocado microcapsule 2%	1031	Low	71.57%
Avocado microcapsule 2.5%	1359	Low	62.53%

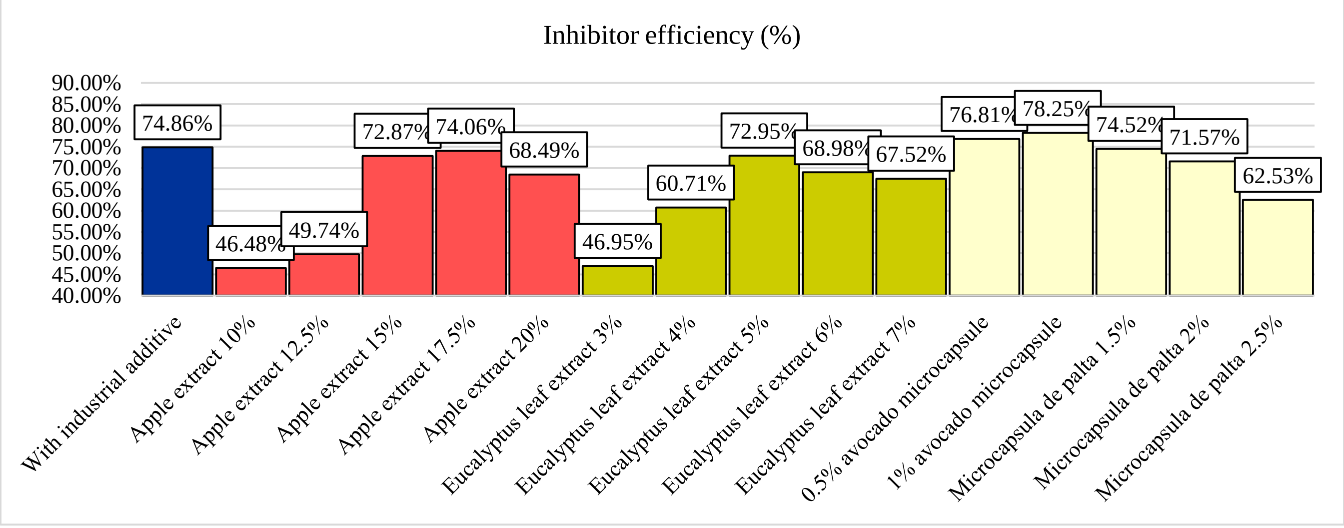

Fig. 18 ASTM C1202 inhibitor efficiency (%)

Figure 18 shows that microencapsulation of avocado at 1% and 0.5% outperformed the industrial additive, with differences of 3.39% and 1.95%, respectively. The 17.5% apple extract, 1.5% avocado microcapsule, 15% apple extract, 5% eucalyptus leaf extract, and 2% avocado microcapsule also achieved values close to the industrial additive, with margins of less than 3% difference. In contrast, the rest of the formulations showed significantly lower efficiencies, in some cases below 50% of that obtained with the industrial additive, showing that only certain doses of natural additives can match its performance.

4.5. Optimal Additive Doses

The results shown in Table 14 allowed us to identify the optimal doses of natural additives that offered the best performance against corrosion in steel and against chloride penetration in concrete. In the case of steel, evaluated using ASTM G31, ASTM G59, and ASTM C876 tests, the 75% avocado additive dosage showed the highest inhibitory efficiency, reaching values close to the industrial additive, followed by the 300 g apple extract and the 40% eucalyptus leaf extract. In concrete, analysed using the ASTM C1202 test, the 1% avocado microcapsule recorded the lowest transferred load, with a low permeability rating, while the 17.5% apple extract and 5% eucalyptus leaf extract also showed outstanding performance. These results showed that, in both steel and concrete, the effectiveness of natural inhibitors depended heavily on the dose applied, with optimal concentrations beyond which efficiency decreased due to destabilisation of the protective film or increased permeability.

Table 14. Optimal doses of natural additives

Material evaluated	Natural additive	Optimal dose	Regarding	Main essay	Efficiency (%)	ASTM classification
Steel	Avocado additive	75%	Percentage of pulp in relation to the mixture of avocado + distilled water	ASTM G31 / G59 / C876	85.33 / 77.68 / 53.41	Low probability of corrosion
	Apple extract	300 g	Pulp mass with 150 mL of fixed deionised water	ASTM G31 / G59 / C876	82.67 / 72.20 / 52.68	Low probability of corrosion
	Eucalyptus extract	40%	Percentage of extract relative to the volume of distilled water	ASTM G31 / G59 / C876	78.67 / 69.83 / 51.46	Low probability of corrosion
Concreto	Apple extract	17.50%	Percentage of cement weight (replacement) of water	ASTM C1202	74.06	Low permeability
	Eucalyptus extract	5%	Percentage of cement weight (replacement) of water	ASTM C1202	72.95	Low permeability
	Avocado microcapsule	1%	Percentage by weight of cement (added to mixture)	ASTM C1202	75.3	Low permeability

5. Discussion

According to research conducted by a team from the Faculty of Civil Engineering at the Technological University of Panama, the application of green inhibitors based on avocado and green apple pulp on A36 carbon steel exposed to marine environments and in a salinity chamber showed that avocado was the most efficient natural inhibitor, with inhibition percentages of up to 66.37% in prolonged exposure, although it did not reach the performance of the industrial minium inhibitor, which exceeded 90% [16]. In the present investigation, the 75% avocado pulp coating achieved higher efficiencies (85.33% in ASTM G31, 77.68% in ASTM G59, and a low probability of corrosion in ASTM C876), reducing the difference with the industrial product to less than 3 percentage points. Furthermore, by incorporating 1% microencapsulated avocado oil into concrete, it was possible to outperform the commercial additive in the ASTM C1202 test, with an efficiency of 78.25% and a low permeability rating. This shows that, although both studies agree that avocado is the most promising green inhibitor, improvements in dosage and application techniques, such as microencapsulation, make it possible to optimise its performance to match or exceed that of traditional inhibitors.

According to research conducted by researchers from the Department of Chemical Engineering at Golestan University in Iran, Eucalyptus Leaf Extract (ELE) applied to mild steel in a 1 M HCl medium achieved a maximum inhibition efficiency of 88% at a concentration of 800 ppm, acting as a mixed inhibitor and forming stable protective layers through combined physisorption and chemisorption mechanisms [20]. In the present research, although a different and more aggressive medium, such as the saline environment, was used, eucalyptus extract achieved competitive efficiencies in steel and concrete, with values close to 79% in ASTM G31 and low permeability ratings in ASTM C1202 for its optimal doses. These results, together with the performance of other natural additives such as avocado and apple, show that the effectiveness of green inhibitors is not limited to controlled acidic environments, but can be adapted and maintain high performance in real marine conditions, thus offering a technical and sustainable alternative to industrial inhibitors.

According to research conducted at the Catholic University of Colombia, Persea americana extract applied in saline media reduced the corrosion rate of steel by 74%, attributing this effect to the high concentration of tannins and phenolic compounds present in the Pulp [32]. In this research, the use of 75% avocado pulp as a coating achieved efficiencies of up to 85.33% (ASTM G31) and 77.68% (ASTM G59), with a low probability of corrosion (ASTM C876), representing a significant improvement over the aforementioned study. Furthermore, by using microencapsulated avocado oil in concrete, 78.25% efficiency was obtained in ASTM C1202, surpassing the industrial additive. This confirms that avocado not only maintains its effectiveness as a green inhibitor in steel, but also, through optimisation of dosage and application techniques, can match or surpass commercial products even in highly aggressive marine conditions.

6. Conclusion

Firstly, the research showed that the differentiated application of natural solutions for steel and concrete coatings for reinforcement and additions to the mixture is an effective strategy for improving the durability of structures exposed to marine and saline environments. The tests carried out showed that, through the correct selection of dosage and application technique, it is possible to reduce steel corrosion and concrete permeability significantly, achieving performance comparable to and even superior to that of industrial inhibitors. This comprehensive approach makes it possible to take advantage of locally available plant resources, optimise performance against aggressive agents, and expand sustainable technical alternatives in the design and maintenance of infrastructure in areas of high environmental aggressiveness.

Secondly, apple extract showed acceptable performance, although with limitations compared to the other inhibitors. In steel, the optimal dose of 300 g with 150 mL of deionised water achieved an average efficiency of 69.18% considering the three tests (ASTM G31, G59, and C876), reflecting its ability to reduce corrosion through the action of polyphenols and flavonoids, although with lower stability under sustained chloride conditions. Specifically, the 17.5% water replacement dose recorded an efficiency of 74.06% in ASTM C1202, classified as low permeability and comparable to the industrial additive. However, its effect was linked more to the reduction of permeability than to a true passivating action on the steel, which limits its robustness in more aggressive scenarios.

Thirdly, eucalyptus extract showed intermediate performance compared to the other inhibitors. In steel, the optimal dose of 40% aqueous extract achieved an average efficiency of 66.65% in ASTM tests, which showed the formation of a less stable protective film that was more sensitive to concentration variations when attacked by chlorides. Specifically, the best response was obtained with 5% relative to the weight of cement, with an efficiency of 72.95% in ASTM C1202, classified as low permeability. However, the dosage range was very narrow, which reduced its reliability under severe conditions. Consequently, although eucalyptus can be considered a viable green option, its application is more suitable as a complement in moderately exposed structures than as the main inhibitor in marine environments.

Fourthly, avocado proved to be the most effective and reliable natural inhibitor against corrosion. In steel, the optimal dose of 75% homogenised pulp achieved an average efficiency of 72.14% in ASTM tests, with values very close to those of industrial additives and classified as having a low probability of corrosion. This superior performance was explained by the formation of a more stable and adhesive hydrophobic film thanks to the tannins and fatty compounds present in the pulp. Specifically, the best response was obtained with 1% microencapsulated avocado oil by weight of cement, achieving the lowest transferred load (789 C) and an efficiency of 78.25% in ASTM C1202, even surpassing the commercial product. Microencapsulation was key, as it ensured the controlled release of the active compounds and improved the durability of the protective effect. Overall, avocado showed a more robust range of efficacy than apple and eucalyptus, confirming it as the most viable alternative for reinforced concrete structures in marine and highly aggressive areas.

Finally, the results establish a solid technical basis for the implementation of natural additives differentiated according to the material to be protected: optimised coatings for steel and controlled additions for concrete. This strategy not only offers technical benefits in terms of durability and corrosion resistance, but also promotes environmental sustainability and the valorisation of locally available plant resources. As a recommendation, its application is particularly relevant in structures exposed to marine influence and highly aggressive conditions, such as bridges located on the coastline, piers and artisanal fishing landings, breakwaters, river defences, foundations of buildings near the coast, water reservoirs, irrigation canals and reinforced concrete structures in ports and breakwaters, where protection against corrosion and chloride ingress is essential to prolong the useful life of the infrastructure.

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