Eco-Friendly Corrosion Inhibition and Strength Improvement of Concrete Using Agricultural Waste–Derived Mango Leaf Extract

Dharmaraj Rajalinggam[1*], *Mohan Raj Robin* Rajan[1], *Selvapriya* Velusamy[2], *Ragavi* Tamilventhan[1], *Bavadharani* Sivaraj[1], and *Logeshwaran* Alagarsamy[1]

[1]Department of Civil Engineering, KPR Institute of Engineering and Technology, Coimbatore, TN, India.
[2]Department of Civil Engineering, PSG Institute of Technology and Applied Research, Coimbatore, TN, India.

Abstract. Embedded steel reinforcement corrosion has been a significant source of reinforcement loss in reinforced concrete (RC) constructions and is specifically prevalent in chloride containing and chemically aggressive environments. Traditional corrosion inhibitors albeit effective are normally synthetic and costly and pose health threats to the environment. The paper examines the use of mango leaf extract as a by-product of agriculture waste that contains polyphenols and tannin as sustainable and eco-friendly corrosion inhibitor in M25-grade concrete. It was used as extract at 0, 1, 2, and 3 percent doses and its effect on the compressive strength, split tensile, flexural and durability (loss of weight in the presence of chemicals) was observed after 7, 14 and 28 days. Results show that, 1-2% extract significantly increases mechanical performance, whereby the maximum compressive strength (34.2 N/mm^2), split tensile strength (3.10 N/mm^2), and flexural strength (6.1 N/mm^2) are recorded at 2 percent dosage. Durability results showed reduced weight loss, indicating improved resistance to aggressive environmental conditions. The results show that mango leaf extract could serve as a cost-effective and sustainable alternative to conventional chemical inhibitors, adding to the longevity and durability of RC structures and contributing to the principles of the circular economy.

1 Introduction

The most actively employed construction material globally is concrete, which is the basis of contemporary infrastructure because of the compressive strength, versatility in designs, and cost-effectiveness. In the majority of structural practice, concrete is reinforced with steel to create RC systems that can sustain compressive and tensile stress. Nevertheless, the performance and durability of the RC structures in the long-run is severely influenced by the corrosion of embedded steel reinforcement, especially when used in hostile environments,

*Corresponding author: dharmaraj.r@kpriet.ac.in

including marine environments, industrial environments, de-icing salts and high-moisture or sulfate-rich environments[1,2].

Reinforcement corrosion starts when the protective passive coating around the steel is destroyed either because of chloride ingress, carbonation or chemical attack. Upon breaking down of this passive film, there will be occurrence of electrochemical reactions and corrosion products will form which are larger in volume compared to the original steel [3].

This volumetric expansion causes tensile stress in the concrete around it leading to cracking, spalling, delamination, loss of bond between steel and concrete, loss of cross-sectional area of steel and structural degradation at the end. All of these have an impact on the shortening of service life, higher maintenance costs, and structural safety being compromised [4].

In order to reduce the reinforcement corrosion, a range of preventive actions has been followed which include surface coating, cathodic protection system, addition of mineral, and chemical corrosion inhibitors. The most appealing of these methods are the corrosion inhibitors because they are easy to add to the concrete mixes and can postpone the corrosion processes without any significant change in the construction process [5].

Nevertheless, the traditional corrosion inhibitors like calcium nitrite, inorganic salts, and organic amines have been linked to high prices, environmental issues as well as possible health hazards. Synthetic inhibitors are also many, toxic, most likely to leech, and add to the embodied carbon of the construction materials, which reduces their sustainability [6].

To address these issues, there has been a growing interest in research towards the utilization of natural plant extracts and agricultural wastes-based materials as green corrosion inhibitors. These substances are phytotoxic and biodegradable, non-toxic, abundant and contain numerous phytochemical compounds including tannins, flavonoids, polyphenols and alkaloids. These substances are antioxidants, chelators and film formers, and this property is likely to allow them to adsorb on steel surfaces and prevent the corrosion of electrochemical reactions [7–9].

The application of vegetable inhibitors is consistent with the sustainability goals in the world, waste valorization, and the principles of a circular economy in the construction business [10,11]. Mango leaves (Mangifera indica) are one of the agricultural wastes that have received attention due to its richness in tannins and polyphenolic compounds, most of them usually discarded. The past research has reported that mango leaf extract and such plant-based additives can affect the cement hydration, densification of the matrix, and concrete mechanical performance [12,13].

Along with possible corrosion resistance, such extracts can add to decreased permeability and other properties related to durability. Nevertheless, there is still a limited number of studies on mango leaf extract in concrete that involve experiments, even concerning the simultaneous assessment of mechanical strength and durability measures of the material in regulated laboratory settings. Hence, this research project examines how mango leaf extract, which is a natural and environmentally friendly additive, influences the mechanical and structural behavior of the M25 grade concrete.

The extract was added on different proportions (0, 1, 2 and 3 percent of cement by weight) and its impact was measured based on the compressive strength, split tensile strength, flexural strength and durability analysis based on the weight loss analysis under the conditions of chemical exposure [14,15]. The research will offer a preliminary experimental evaluation of mango leaf extract as a sustainable concrete admixture as well as determine the optimum dose of the extract and guidelines to be followed in future long-term and mechanistic research.

2 Materials and methods

2.1 Materials

The materials to be used in this investigation were the ones picked to give consistent and reliable performance to the M25-grade concrete. Ordinary Portland cement (OPC) of grade 53, which meets the criteria of the IS 12269 was the main binding material. The cement had good fineness, good setting qualities, and soundness to provide concrete of structural grade. The fine aggregate was natural river sand and it falls under Zone II as per IS 383:2016. The sand was also clean, no silt and other unpleasant materials were present and it guaranteed the right workability and bonding within the concrete matrix.

The coarse aggregate was crushed granite that had a nominal size of maximum 20 mm and a specific gravity of 2.75. It exhibited angularity and low flakiness of particles, both of which provided sufficient interlocking qualities and mechanical stability. Both mixing and curing activities were carried out using potable water that was free of oils, organic matter, acidic impurities among others as suggested in the IS 456:2000. The Properties of materials used are presented in Table 1.

Table 1. Properties of materials

Material	Property	Value
Cement (OPC 53)	Specific gravity	3.15
	Initial setting time	30 min
	Final setting time	600 min
Fine aggregate	Zone	II
	Specific gravity	2.65
Coarse aggregate	Max size	20 mm
	Specific gravity	2.75
Mango leaf extract	pH	6.8
	Density	0.3 g/cm³
	Viscosity	1.8 cP
	Solvent used	Ethanol

The corrosion inhibitor that was applied in this research was the mango leaf extract which was taken using the mature mango leaves that were bought locally. The leaves were first washed to get rid of dirt and dust, and the second step was shade drying of the leaves to retain phytochemical compounds and to avoid degradation of the leaf under heat. They were dried and broken into a fine powder so that they can be extracted easily.

The ethanol was used to extract the powdered leaves; the mixture was heated at 65-70 °C followed by continuous stirring. The extract obtained was a concentrated organic extract containing tannins, polyphenols and flavonoids, which have the corrosion-inhibitory capacity. The extract had a pH of 6.8, viscosity of 1.8cp and a density of 0.3 g/cm^3. It was added to the mixing water in the following concentrations namely 1, 2 and 3 percent of cement weight as well as to a control mixture with no extract. These dosages have been chosen to test the optimum as well as threshold levels of mechanical and durability improvement.

2.2 Methods

The concrete mix design was in line with the recommendations of IS 10262:2019 to produce M25 grade of concrete with the target mean strength of 31.6 MPa. All mixtures were kept with a constant water cement ratio of 0.45 to allow uniformity. Four mixes were made (a control mix 0% inhibitor, and three mixes containing 1, 2 and 3 percent mango leaf extract). The mixing water was mixed with the extraction solution then added to the dry materials. A mechanical drum mixer was used for mixing the materials, where the cement, sand and coarse aggregates were mixed together during the drying process that took two minutes.

The extract of the mango leaf was then gradually added to the water and mixing was done until a homogenous workable concrete was prepared. Molds of different sizes were placed based on the test requirements and fresh concrete was placed. Compressive strength was tested using cube molds 150 × 150 × 150 mm, split tensile strength was checked using cylindrical molds 150 mm × 300 mm, and flexural strength was checked using beam molds 100 × 100 × 500 mm. The three layers were filled into each of the molds, and the layers were compacted with the help of a table vibrator in order to remove entrapped air and assure that the consolidation process has taken place correctly.

The specimens were demolded after 24 hours of setting and put in a curing tank with water that was at 27 ± 2 C. Curing of the specimens was done on a 7, 14, and 28 days to determine the strength increase with time. Mechanical testing was done as per the pertinent Indian Standards. Tests were conducted on compressive strength through a compression test machine (CTM) of 2000 KN compression test machine (IS 516:1959) at a steady rate. Split tensile strength was measured as the cylindrical specimens were subjected to the diametral compression according to the IS 5816:1999.

Flexural strength was determined by two-point loading technique as indicated in the IS 516 and the value of modulus of rupture was estimated from the specimen geometry and load at failure. The durability test was conducted by weight-loss test in order to test the resistance of concrete to chemical attack. At the end of the curing period, the specimens were dried and weighed to obtain the initial mass. After that, they were placed in a chemically hostile environment that resembled severe exposure to the environment. The specimens were dried, cleaned after a given exposure period then reweighed. Deterioration was quantified as a percentage weight loss whereby the smaller the weight loss the greater the durability and the protective performance because of the mango leaf extract.

3 Result and discussion

3.1 Compressive Strength

The outcome of compressive strength tests makes it clear that the addition of mango leaf extract improved the performance of the M25-grade concrete in all the curing ages. The lowest values were registered by the control mix, whereas the ones with the extract registered higher values at the 7, 14, and 28 days. Out of the treated mixes, the dosage of 2% showed the best compressive strength with 34.2 MPa at 28 days as opposed to 32 MPa in the control. This can be explained by the bioactive compounds present in the extract that probably acted in enhancing the densification of the microstructure, minimized the number of voids and enhanced the cement paste-aggregate bonding. A slight decline at the 3% dose is an indication that a high organic content could disrupt the hydration process or lead to a small change in efficiency of compaction. The compressive strength results in Fig. 1, in general, suggest that

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the use of the extract produces a positive effect within an optimal dosage of 2 percent, which is the most effective one.

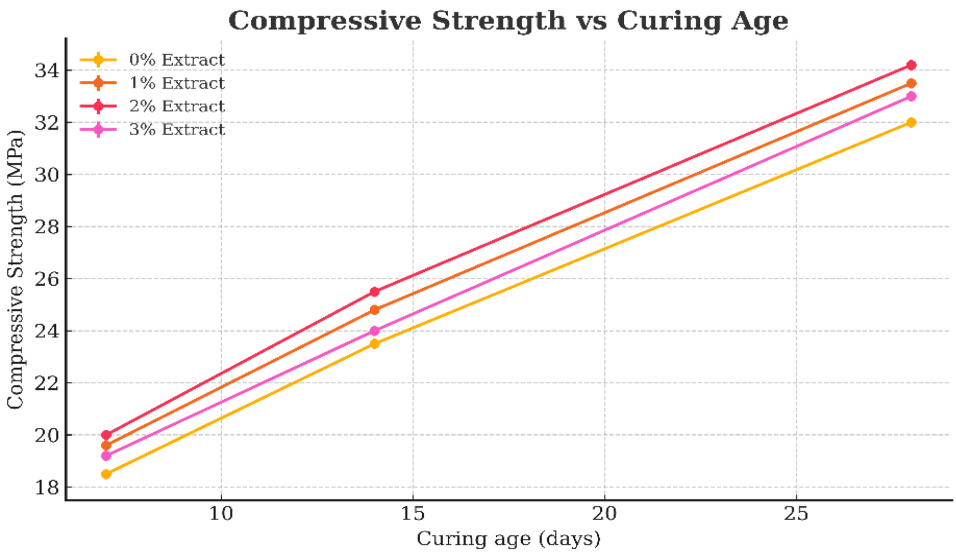

Fig. 1. Compressive strength graph

3.2 Split Tensile Strength

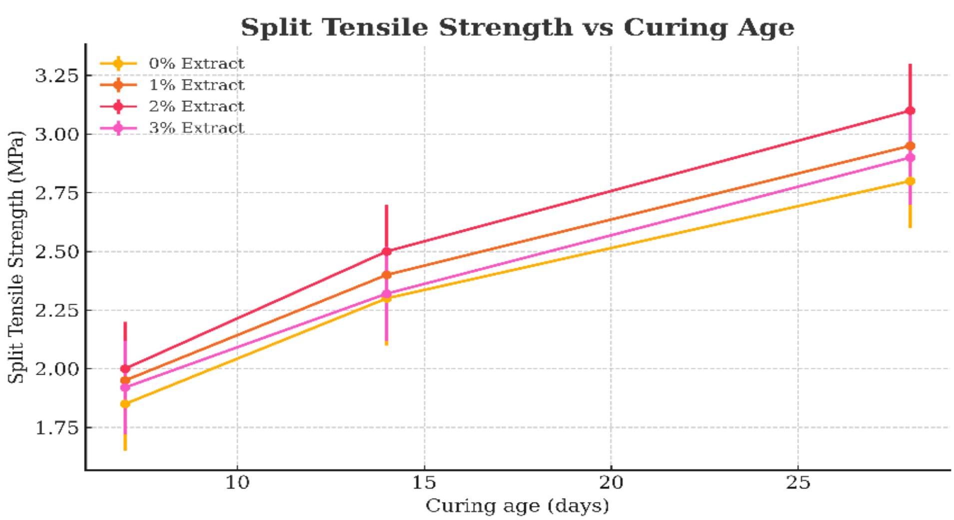

Fig. 2. Split tensile strength graph

The results shown in Fig. 2 indicate that the split tensile strength was in the same trend as compressive strength and extract-modified mixes had better tensile resistance than the control. The 2% mango leaf extract mix once more showed the best strengths in all the curing ages, showing better results in tensile stress resisting. It was found that the 2 percent mixture was 3.10 MPa at the 28 days, which was higher than the control value of 2.80 MPa. The improvement indicates that the extract was useful in enhancing bonding between aggregates and the cement matrix in order to redistribute tensile stresses of a more uniform form. This tendency could be explained by the fact that natural tannins and polyphenols could exist and suppress the formation of microcracks in the early hydration period and enhance internal cohesion. The fact that it is slightly lower at 3 percent dosage supports the conclusion that there is an optimal level that is passed and above which, too much organic material can have an adverse effect on hydration or matrix structure.

3.3 Flexural Strength

Flexural strength of the concrete beams also exhibited some improvement, whereby mango leaf extract was added. The 2% dosage once more gave the greatest flexural performance at all the curing ages with a flexural performance of 6.1 MPa at 28 days as compared to the control that had 5.6 MPa. This is especially because flexural strength is susceptible to crack formation and propagation, and the findings shown in Fig. 3 indicate that the extract increased the tension resistance to bending in the concrete. This increase is probably related to better particle packing, less connectivity of pores, and enhanced ability of bridging cracks as a result of a denser matrix. The steady enhancement of compressive, tensile, and flexural strengths supports the positive influence of the extract addition, and the minimal decrease at the dosage of 3 percent once more supports the necessity to adhere to the optimum concentrations.

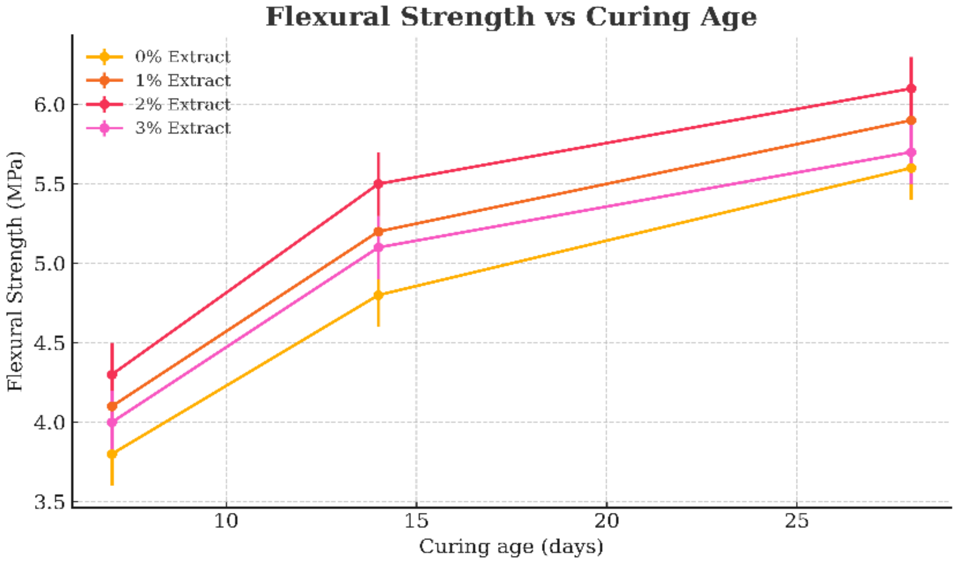

Fig. 3. Flexural strength graph

3.4 Durability (Weight Loss Analysis)

The durability test showed that the mango leaf extract significantly enhanced the resistance of concrete to chemical attack. The control specimens had the most weight loss in the exposure which implied more deterioration and degradation of material. However, the mixes of the 1 percent and 2 percent extract exhibited lesser weight loss with the 2 percent mix performing optimally. This slowing down of decay indicates that the extract helped in producing a less permeable matrix that restricts the infiltration of harmful ions and water. The protective layers and refined pore structures might also have been developed by the bioactive compounds that were found in the extract, and this helps in slowing down degradation. The 3-percentage dosage again resulted in a slight drop in performance, and this might be indicative of possible increments in the pore volume or disruption of hydration at higher organic concentrations. The findings shown in Fig. 4 support the idea that an optimal dosage of mango leaf extract has a potential to significantly increase the durability of concrete.

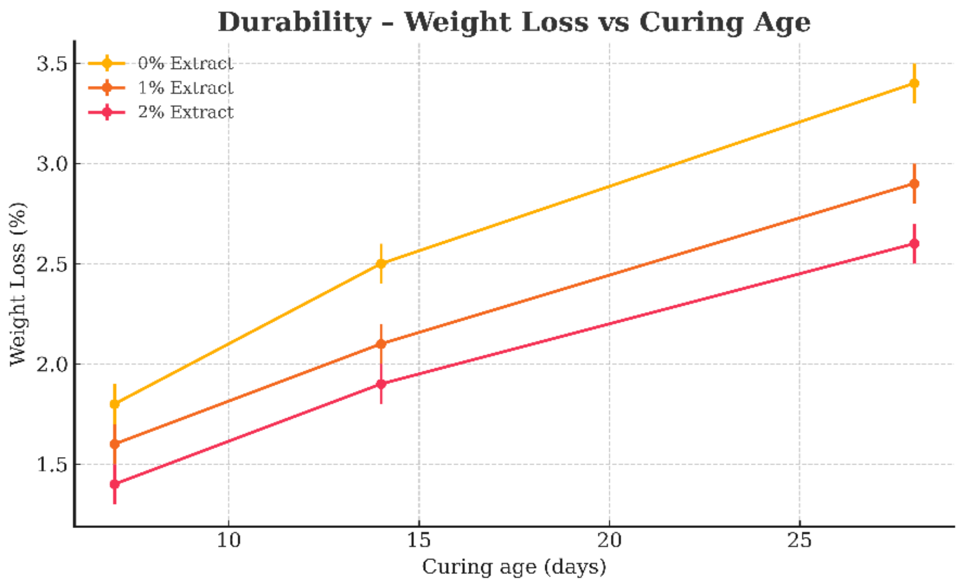

Fig. 4. Durability / Weight loss graph

3.5 Predictive Interpretation and Performance Analysis

The overall results indicate that mango leaf extract improves both the mechanical and durability properties of concrete when used in appropriate proportions. This steady growth in the 1 percent and the 2 percent doses shows that the bioactive compounds found in the extract are actively involved in the hydration process of cement. These compounds seem to favor the growth of a finer and more uniform microstructure which is manifested in the progressive strength improvements and decrease in the degradation of the treated mixes. The linear increase in compressive, tensile, and flexural strengths until the optimum dosage of 2 percent indicates that there is predictability in the quality improvement of concrete with a moderate level of extract dosage.

It can be inferred that the concrete containing 2% mango leaf extract is likely to exhibit improved long-term durability under aggressive environmental conditions. The fact that the extract reduces the permeability and refines the pore network indicates reduced rate of chloride ingress and sulfate penetration, which are two major causes of corrosion in the reinforcement of the steel. This means that extract-treated concrete could be used to construct structures which would have slower degradation rates, increased service life, and would need less maintenance. Also, the lesser weight loss on chemical assault denotes enhanced resistance not only to corrosion, but also to general environmental degradation. The tendencies observed indicate that an organic layer may be developed in the matrix semi-protectively that may act in a similar fashion as standard corrosion inhibitors but in a more sustainable fashion. The minor decrease in activity at 3% extract dosage also provides a significant predictive result. High organic content may adversely affect the hydration process and increase porosity, resulting in slight decreases of strength and durability. Therefore, for practical applications a dosage of approximately 2% is recommended to achieve optimal performance.

Overall, the analysis trends illustrate a definite positive correlation between the controlled extract dosage and performance improvement of concrete. The findings of all the test categories were consistent, and this indicates that mango leaf extract can be effectively used as a reliable and environmentally-friendly performance enhancer in concrete after being optimized at the 2 percent level. This gives it a chance to be used not only in traditional structural concrete but also in infrastructure projects that are oriented on a long-term sustainability in terms of which durability and environmental compatibility should be the major concern.

4 Conclusion

This study demonstrates that the addition of mango leaf extract positively affects the mechanical strength and durability performance of M25 grade concrete at the right dosage. Concrete mixtures with 2% mango leaf extract showed better compressive, split tensile, and flexural strengths and less weight loss due to chemical exposure than control mixes. These findings suggest that moderate inclusion of the extract leads to higher performance of concrete. It is possible to explain the noted improvements by the fact that the mango leaf extract contains bioactive organic compounds that may enhance the effectiveness of the matrix cohesion and permeability. The suggested effect on microstructural densification and resistivity to corrosion is however indicative in nature as well as founded on performance patterns as opposed to actual electrochemical or microstructural data. It is also noted that excess dosage of the extract that was above the optimal level (3 percent) led to a slight decrease in performance and thus the need to optimize dosage and the fact that too much organic content will disrupt cement hydration and development of the matrix. Overall, the obtained results indicate that the mango leaf extract has a potential to become a promising sustainable and plant-based concrete admixture, which is able to improve strength and durability measures in the short term. However, laboratory testing to a maximum of 28 days only have been taken and long-term durability tests, electrochemical corrosion tests, and microstructural tests are needed to entirely determine its efficiency as a corrosion-inhibiting agent in reinforced concrete applications.

5 Future scope and recommendations

The promising outcomes of this study present several directions of the future research. To begin with, long-term durability tests such as chloride penetration, carbonation depth, freeze thaw resistance, and accelerated corrosion tests should be done to confirm the predictive performance trend of this study. Additional research is required on the mango leaf extract in combination with various cementitious mixtures such as fly ash, slag or silica fume, to improve its suitability as a green admixture. It is highly suggested to conduct microstructural studies based on XRD, FTIR, SEM, and TGA to get a more profound understanding of the chemical processes by which the extract alters the hydration and pore structure.

The future research can also address the question of the scalability of extract production and its economic viability and its possible variability, depending on the maturity of the leaf, the extraction process or the nature of the solvent. Research on the extract with commercial superplasticizers, retarders and corrosion inhibitors would assist in knowing whether the extract is flexible in the actual construction setting. Also, it would be interesting to test its performance in conditions of real-time field exposure in reinforced concrete and use this evidence as valuable evidence at the structural level of implementation.

This study suggests that the 2% mango leaf extract dosage is the best way to improve the mechanical and durability properties. This natural plant-based additive can become a sustainable and low-cost solution in enhancing the performance and livelihood of concrete structures, should further validation be made.

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