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Development of Anti-Moss and Anti-Fungal Coatings to Enhance Concrete Durability under Tropical Environmental Conditions

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Abstract Biological colonization by moss and fungi poses a significant durability challenge for concrete structures in tropical regions, where high humidity and frequent rainfall promote moisture retention and surface deterioration. This study develops and evaluates a solvent-based anti-moss and antifungal coating formulated with Special Boiling Point solvent, Mineral Turpentine, Pegasol 150, and siloxane to enhance the durability-related performance of concrete. Concrete specimens were coated after 28 days of standard curing and assessed through water spray penetration, water absorption, rapid chloride permeability testing (RCPT), microstructural characterization (SEM), phase and chemical analysis (XRD and FTIR), and one-year outdoor exposure under tropical conditions. The water spray test identified the formulation containing 7% siloxane as optimal, exhibiting complete water beading and minimal surface absorption. The coated concrete showed a denser surface morphology with reduced pore presence compared to the control, as observed by SEM. RCPT results demonstrated a 28.6% reduction in total charge passed, from 2100 Coulombs to 1500 Coulombs, corresponding to an improvement in chloride permeability classification from moderate to low. After 12 months of outdoor exposure, the coated specimens remained free of visible moss and fungal growth, whereas uncoated concrete developed pronounced biological colonization. The effectiveness of the coating is attributed to its ability to restrict moisture and ion transport through the concrete surface, thereby limiting mechanisms associated with biological growth and surface degradation. The results indicate that the developed coating provides a practical and durability-oriented protection strategy for concrete infrastructure exposed to humid and tropical environments.

Keywords Concrete Durability, Anti-Moss Coating, Anti-Fungal Materials, Siloxane, Tropical Environment

1. Introduction

Enhancing the durability and service life of concrete structures is a critical requirement for sustainable infrastructure development, particularly as modern construction increasingly faces aggressive environmental exposure and higher performance demands [1–4]. Concrete is inherently susceptible to various degradation mechanisms, including carbonation, alkali–aggregate reaction, sulfate attack, chloride ingress, and reinforcement corrosion. In addition to these well-established physical and chemical processes, biological deterioration of concrete surfaces has emerged as an important yet comparatively underexplored durability concern**,** especially in humid and tropical environments [5,6].

Biological deterioration is primarily associated with the colonization of concrete surfaces and near-surface pores by mosses, fungi, algae, and microbial biofilms. This process induces both physical and chemical alterations in the cementitious matrix. Previous studies have shown that biological growth increases surface roughness and water absorption, promotes localized porosity, and accelerates surface weathering, thereby compromising long-term durability and aesthetic quality [7-9]. Moreover, microbial metabolism generates organic acids that dissolve calcium hydroxide, reduce surface alkalinity, and destabilize hydration products such as calcium silicate hydrate (C–S–H), leading to progressive weakening of the concrete surface layer [10,11]. These effects are particularly severe in tropical regions, where persistent moisture, high relative humidity, and frequent rainfall create favorable conditions for rapid microbial proliferation [12,13].

The susceptibility of concrete to biodeterioration is strongly governed by its pore structure, moisture retention capacity, surface chemistry, and carbonation-induced pH reduction [14,15]. Accumulation of biological colonies can further modify surface morphology, reduce solar reflectivity, and intensify microstructural degradation through repeated wetting–drying cycles [16]. To mitigate these effects, various strategies have been proposed, including the incorporation of biocidal agents into cementitious matrices, the use of antimicrobial nanomaterials, and the application of surface treatments designed to limit moisture ingress and microbial adhesion [17,18].

Among these approaches, metal-oxide-based systems have attracted considerable attention due to their combined antimicrobial and durability-enhancing potential. Nanoparticles such as TiO_2, ZnO, and Ag-based materials exhibit photocatalytic activity under light exposure, generating reactive oxygen species that inhibit microbial growth and decompose organic nutrients required for moss and fungal development [19–21]. Several studies have reported significant reductions in fungal and algal colonization through nano-TiO_2 incorporation without compromising mechanical performance, while ZnO-based systems have demonstrated enhanced antifungal efficacy against common concrete-colonizing species such as Aspergillus *and* Penicillium [22,23]. In parallel, hydrophobic and siloxane-based coatings have been shown to reduce water absorption while maintaining vapor permeability, thereby limiting moisture availability for biological growth without sealing the concrete surface [24,25].

Despite these promising findings, important limitations remain in the existing literature. Many studies focus on short-term laboratory evaluations under controlled conditions, with limited consideration of long-term performance, coating penetration stability, and durability under real outdoor exposure, particularly in tropical climates where biodeterioration is most aggressive [6,13,26]. Furthermore, antimicrobial efficiency is often reported independently of key durability indicators such as permeability reduction, microstructural densification, and resistance to sustained biological recolonization. As a result, the long-term effectiveness of protective systems against biological deterioration of concrete remains insufficiently understood.

To address these gaps, the present study develops and evaluates a bio-resistant concrete coating with anti-moss and antifungal properties**,** formulated using a solvent-based siloxane system comprising Special Boiling Point solvent, Mineral Turpentine, Pegasol 150, siloxane, and deionized water as a co-solvent. The coating is designed to form a homogeneous thin film with high penetration capability and sustained antimicrobial performance. Its effectiveness is assessed through biological inhibition, microstructural characterization, and durability-related properties of concrete, including resistance to moisture ingress and environmental exposure. The findings aim to contribute to the development of durable and sustainable protective coatings for concrete infrastructure in tropical environments.

2. Material and Methods

2.1. Materials

2.1.1. Special Boiling Point

Special Boiling Point (SBP) solvent is a refined hydrocarbon solvent with a controlled boiling range, typically between 100–140 ℃, used to optimize the evaporation rate and film formation in surface coatings. In anti-fungal and anti-algae concrete coatings, SBP acts as a carrier medium that ensures uniform dispersion of siloxane and organic additives. Its moderate volatility helps balance surface wetting and penetration into the concrete pores, improving adhesion and water repellency [21]. SBP also facilitates the formation of a compact hydrophobic film without leaving oily residues.

2.1.2. Mineral Turpentine

Mineral turpentine (white spirit) is a petroleum-derived aliphatic solvent used to adjust viscosity and enhance film formation in coating formulations. In this system, it functions as a diluent and co-solvent that aids the homogeneous dispersion of active siloxane compounds and organic agents. Its slow evaporation rate extends the open time of coating application, allowing better surface coverage and deeper pore penetration. Additionally, mineral turpentine reduces surface tension, enabling more efficient waterproofing and alkali resistance [22].

2.1.3. Pegasol 150

Pegasol 150 is a high-boiling-point glycol ether (commonly 150 ℃ range) that functions as a co-solvent and stabilizer in coating formulations. Its key role is to improve miscibility between polar (siloxane) and non-polar (hydrocarbon) components, ensuring a stable emulsion. Pegasol 150 enhances coating film uniformity, reduces surface defects, and improves UV stability and fungal resistance by facilitating slow solvent evaporation. It also contributes to maintaining the elasticity of the coating layer after curing, preventing microcracks during thermal expansion or shrinkage [23].

2.1.4. Siloxane

Siloxane is the principal active hydrophobic agent in the formulation. It forms a Si–O–Si polymeric network upon curing, creating a breathable yet water-repellent surface layer that blocks moisture ingress while allowing vapor diffusion. The presence of siloxane significantly improves durability, self-cleaning ability, and resistance to algae and fungal growth. This effect is attributed to its low surface energy and chemical stability under UV and alkaline environments. Siloxane-based coatings are widely recognized for extending the service life of concrete structures and reducing biological colonization [24,25].

The anti-moss and antifungal coating used in this study is a proprietary formulation developed by the authors, consisting of a combination of Special Boiling Point solvent, Mineral Turpentine, Pegasol 150, and Siloxane. This co-solvent system is designed to produce a homogeneous thin film with high penetration ability and sustained antimicrobial activity.

Control Concrete (CC) and Anti-Moss and Anti-Fungus Concrete Coating (MFC) are the codes for the samples. Concrete specimens were prepared using standard cast concrete (Canstin concrete), shaped into prismatic blocks with dimensions of 100 × 100 × 100 mm. The concrete mix was designed according to conventional practice to achieve the target compressive strength suitable for structural applications.

2.2. Methods

2.2.1. Mix Design and Preliminary Evaluation

In the first stage, four different Job Mix Formulation (JMF) were prepared, as presented in Table 1. Each formulation (A–D) was prepared with varying siloxane contents to evaluate its influence on water repellency and surface permeability. All mixtures were thoroughly blended until homogeneous before application to the concrete specimens.

Table 1. Job Mix Formulations for Anti-Moss and Anti-Fungal Coating

Property	**Weight (in %)**			
	A	**B**	**C**	**D**
Special Boiling Point	54	52	50	48
Mineral Turpentine	20	20	20	20
Pegasol 150	25	25	25	25
Siloxane	1	3	5	7

After 28 days of curing, all coated mortar samples were subjected to a water spray penetration test to evaluate their surface absorbency. The formulation that exhibited the lowest water absorption was selected as the optimal coating material for subsequent testing and characterization.

2.2.2. Preparation of Concrete Specimens

In the second stage, concrete specimens were produced using a design compressive strength of 25 MPa. Two specimen geometries were prepared: Rectangular panels with dimensions of 300 mm × 300 mm × 50 mm, and Canstein-type blocks with dimensions of 600 mm × 160 mm × 280 mm, as illustrated in Figure 1. All specimens were cured under standard conditions for 28 days before further testing and coating application.

2.2.3. Coating Application

In the third stage, coating was applied to the concrete surfaces at an age of 7 days. Two categories of specimens were prepared: CC (Control Concrete): specimens without coating application. MFC (Anti-Moss and Anti-Fungus Concrete Coating): specimens coated with the selected anti-moss and anti-fungal formulation (selected JMF). The coating was applied evenly using a brush method in two layers with an interval of 12 hours between applications to ensure proper film formation, as illustrated in Figure 2.

In the fourth stage, after 28 days of curing, the following tests were conducted on both CC and MFC specimens.

2.2.4. Water Spray Penetration Test

The water spray penetration test was conducted to assess the effectiveness of the coating in preventing water ingress. After 28 days of curing, the concrete specimens were exposed to a continuous water spray for 30 minutes under a pressure of approximately 0.3 MPa. The surface condition was then observed to determine the degree of water absorption and visible penetration marks. The formulation exhibiting the lowest visible water absorption was selected for subsequent analysis.

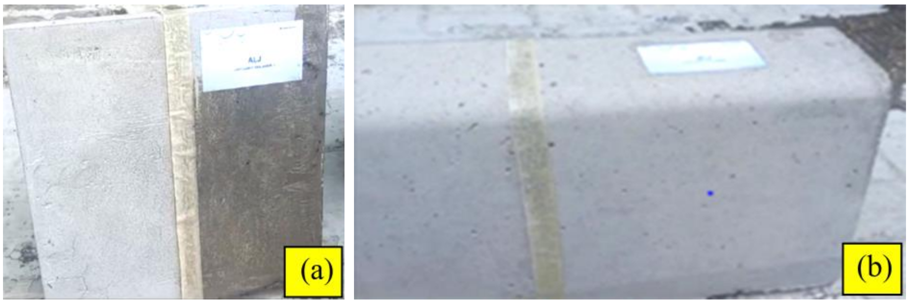


Figure 1. Two specimen geometries: (a) Rectangular panels and (b) Canstein-type blocks

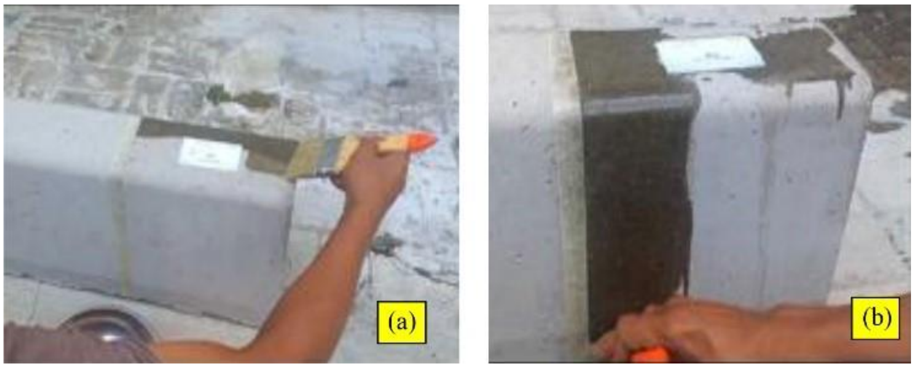


Figure 2. Cross-directional coating application: (a) horizontal first layer and (b) vertical second layer for uniform coverage

2.2.5. X-Ray Fluorescence (XRF)

XRF was conducted in accordance with ASTM C1365 using X-ray fluorescence (XRF) analysis with a PANalytical Epsilon 1 spectrometer equipped with a 50 kV Ag radiation source, which was performed to determine the elemental oxide composition of the concrete samples. The test identifies and quantifies major oxides such as SiO_2, CaO, Al_2O_3, Fe_2O_3, and MgO, which influence the hydration products and microstructural properties of cementitious materials. Changes in oxide ratios, particularly the CaO/SiO_2 ratio, indicate variations in the formation of calcium–silicate–hydrate (C–S–H) and other secondary phases that affect durability, alkalinity, and biological resistance.

2.2.6. Scanning Electron Microscopy (SEM)

SEM was conducted in accordance with ASTM E1508 using a JEOL JSM-6510LV microscope (JEOL Ltd., Akishima, Tokyo, Japan) to examine the surface morphology and microstructural characteristics of the concrete specimens. The analysis provides high-resolution images that reveal the distribution of hydration products, pore structure, and the interface between coating and substrate. A denser and more compact microstructure indicates improved hydration and reduced porosity, contributing to enhanced durability and biological resistance.

2.2.7. Fourier Transform Infrared Spectroscopy

FTIR was conducted following ASTM E1252 using an FTIR spectrometer (Shimadzu IR Prestige-21, Japan) to identify the functional groups and chemical bonds present in the concrete matrix. The analysis detects characteristic vibrations of Si–O, Ca–O, and O–H groups, which correspond to hydration products such as C–S–H and $Ca(OH)_2$. Shifts or intensity changes in these bands indicate chemical interactions between the coating and the cement matrix, confirming the formation of additional silicate or carbonate phases that enhance durability and biological resistance.

2.2.8. Rapid Chloride Permeability Test

The RCPT was conducted following ASTM C1202, using a standard RCPT test apparatus to evaluate the chloride ion penetration resistance of concrete specimens. This electrochemical test measures the total charge (in coulombs) passed through a concrete disk when subjected to a constant voltage, indicating its permeability. Lower charge values correspond to reduced ionic transport and denser microstructure, signifying improved durability and resistance to chloride-induced corrosion.

2.2.9. Outdoor Exposure and Visual Observation

In the fifth stage, long-term observation was carried out by placing both rectangular and canstein specimens in an outdoor environment for 12 months under natural exposure to sunlight and rainfall (Figure 1). Compressive strength testing was not included in this study, as the coating system was designed to enhance surface durability and resistance to biological colonization rather than to modify the bulk mechanical properties of hardened concrete.

3. Results and Discussion

3.1. Water Spray Penetration Test

Based on the water spray penetration test, formulation JMF D (7% siloxane) in Table 2 was identified as the optimal coating composition, demonstrating the highest hydrophobicity and lowest surface absorption, and was therefore selected for subsequent durability and microstructural analyses (XRF, XRD, SEM, FTIR, and RCPT).

3.2. X-Ray Fluorescence (XRF)

The XRF analysis results (Table 3) indicate that the MFC sample exhibits significant changes in Figure 1. SEM micrographs of (a) control concrete (CC) and (b) coated concrete with the anti-moss and antifungal formulation (CFM) are presented, along with a comparison of their major oxide compositions relative to CC. The CaO content increased from 35.25% to 45.12%, while SiO_2 decreased from 54.72% to 42.87%. In addition, MgO showed an increase from 0.56% to 1.11%, and SO_3 rose from 0.99% to 1.72%, whereas Fe_2O_3 remained relatively stable.

The increase in CaO and MgO contents suggests the enhanced formation of calcium silicate hydrate (C–S–H) and magnesium silicate hydrate (M–S–H) phases, which contribute to improved microstructural densification and resistance to water and microbial penetration. According to H. Qu et al. [27], a higher CaO/SiO_2 ratio in the concrete matrix elevates the surface alkalinity, thereby creating an environment unfavorable to moss and fungal growth [28].

Furthermore, the rise in SO_3 concentration in MFC indicates the possible formation of sulfate-based compounds that may impart antimicrobial properties [29]. The stability of Fe_2O_3 content between both samples implies that the MFC treatment does not significantly alter the ferritic phase. However, as reported by Jafarpisheh et al. [23], minor increases in Fe content can act as a photochemical catalyst, enhancing antifungal activity, particularly in materials containing TiO_2-based pigments that exhibit photocatalytic self-cleaning behavior.

3.3. X-Ray Diffraction (XRD) Analysis

The XRD patterns presented in Figure 3, show that the control concrete (CC) contains distinct diffraction peaks corresponding to Fe_2O_3 (hematite) and minor phases of K_2O/Al_2O_3. These peaks confirm that CC possesses a relatively stable crystalline structure, yet still contains microscopic pores and amorphous phases that remain vulnerable to water ingress and biological colonization. This pattern aligns with the observations of Noeiaghaei et al. [5], who reported that untreated concrete surfaces, despite being dominated by C–S–H phases, often exhibit insufficient microstructural compactness, thereby facilitating moisture retention and microbial growth.

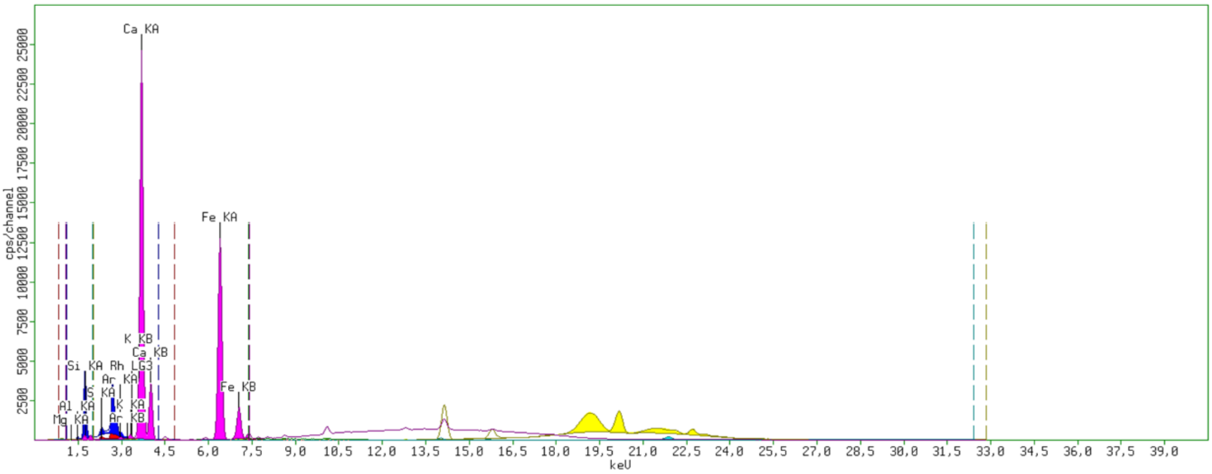
As further emphasized by Cheng et al. [30], a high content of $Ca(OH)_2$ at the concrete surface increases alkalinity, which initially suppresses biological activity; however, under prolonged humid conditions, carbonation can produce a surface carbonate layer that inadvertently promotes moss growth.

Table 2. Water spray penetration test of Job Mix Formula

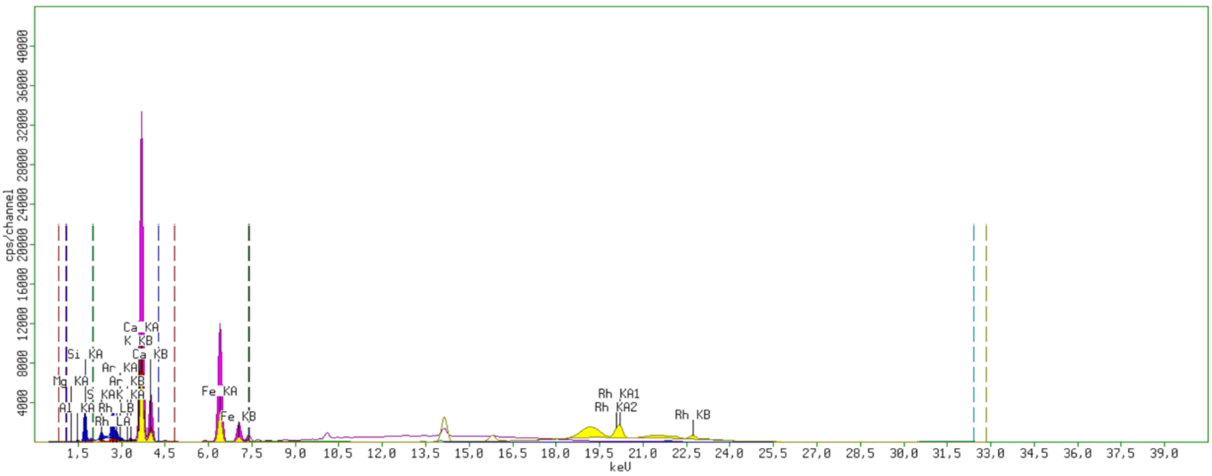
Coating Formulation	Siloxane Content (%)	Visual Observation after Water Spray	Relative Absorption (qualitative)	Performance
A	1	Surface darkened rapidly; visible wet areas	High	Poor
B	3	Slightly reduced darkening; localized wet zones	Moderate	Fair
C	5	Minimal surface darkening; partial beading	Low	Excellent
D	7	No visible absorption; full water beading	Very Low	Excellent

Table 3. X-ray Fluorescence result of CC and MFC

Oxides	Control Concrete in %	Anti-Moss and Anti-Fungus Concrete Coating (MFC) in%
MgO	0.56	1.11
Al_2O_3	4.87	5.57
SiO_2	54.72	42.87
SO_3	0.99	1.72
K_2O	0.59	0.56
CaO	35.25	45.12
Fe_2O_3	3.01	3.03



(a)



(b)

Figure 3. X-ray diffraction (XRD) patterns of (a) control concrete (CC) and (b) Anti-Moss and Anti-Fungus Concrete Coating

In contrast, the MFC sample exhibits the formation of semi-crystalline phases such as $ZnTiO_3$ and $CaTiO_3$, consistent with findings by Jaramillo-Fierro et al. [31] and Liu et al. [32], who demonstrated that these compounds play a crucial role in enhancing self-cleaning behavior and bio-colonization resistance of concrete surfaces. Moreover, the emergence of photocatalytically active phases suggests the ability of the coated surface to degrade organic substances through mild oxidative reactions under UV exposure, thereby suppressing moss and fungal growth [33,34].

The reduced intensity of the Fe_2O_3 diffraction peak in MFC indicates that the coating process yields a more homogeneous surface and minimizes oxidation reactions within the aggregates. This phenomenon implies that the MFC layer functions not only as a physical barrier against moisture penetration but also as a chemical modifier that enhances the surface phase stability and strengthens resistance to biological degradation.

3.4. Scanning Electron Microscopy (SEM) Analysis

The microstructural features of the control concrete (CC) and the Anti-Moss and Anti-Fungus Concrete Coating (MFC) are presented in Figure 4. The SEM images of the CC specimens (Figures 4a and 4c) show a heterogeneous microstructure characterized by the presence of microcracks**,** open pores**,** and loosely bonded hydration products**.** These features indicate a relatively porous matrix that facilitates moisture penetration and provides favorable conditions for biological colonization, as commonly reported for conventional cementitious materials [35-37].

In contrast, the SEM images of the MFC specimens (Figures 4b and 4d) reveal a denser matrix with reduced pores and fine particles distributed over the surface. The compact morphology suggests improved surface continuity and reduced pathways for moisture ingress compared to the uncoated concrete. Such microstructural refinement is consistent with the matrix densification effect reported in previous studies on coated and modified cementitious systems [29].

The reduced pore presence and more compact surface observed in the MFC specimens are relevant from a civil engineering perspective, as they are directly associated with lower permeability and improved resistance to environmental exposure. These observations support the durability-related performance discussed in subsequent sections, without relying on speculative interpretation beyond the experimental evidence [24,30,38].

3.5. Fourier Transform Infrared Spectroscopy (FTIR)

The FTIR spectra of the control concrete (CC) and the Anti-Moss and Anti-Fungus Concrete Coating (MFC) samples are presented in Figure 5. In the CC specimen, broad absorption bands at approximately 3443 cm^{-1} and 1637 cm^{-1} are attributed to O–H stretching and H–O–H bending vibrations, respectively, indicating the presence of free and physically bound water within the hydrated cement matrix. These bands are commonly associated with C–S–H gel and calcium hydroxide in conventional Portland cement systems. A prominent band near 1030 cm^{-1} corresponds to asymmetric Si–O–Si stretching, confirming the dominance of silicate-based hydration products. In addition, weak carbonate bands at around 1420 cm^{-1} and 713 cm^{-1} indicate partial surface carbonation caused by exposure to atmospheric CO_2 [28].

In contrast, the MFC specimens exhibit a noticeable reduction in the intensity of O–H-related bands, suggesting decreased surface moisture retention. The Si–O–Si stretching band becomes sharper and more defined, indicating a more polymerized and compact silicate network at the concrete surface. Weak absorption features observed in the 700–900 cm^{-1} region are associated with metal–oxygen vibrations, which are consistent with the presence of oxide-containing phases detected by complementary XRD analysis. From a durability perspective, these spectral changes indicate improved surface compactness and chemical stability, which contribute to reduced moisture ingress and enhanced resistance to environmental exposure.

The MFC spectrum shows reduced O–H band intensity and sharper Si–O–Si peaks, suggesting enhanced silicate polymerization and a denser hydration network. The appearance of weak bands between 700–900 cm^{-1} is attributed to Ti–O and Zn–O vibrations, indicating the formation of $ZnTiO_3$/$CaTiO_3$ photocatalytic phases that contribute to self-cleaning and antimicrobial behavior. These changes confirm that MFC exhibits improved microstructural compactness and chemical resistance.

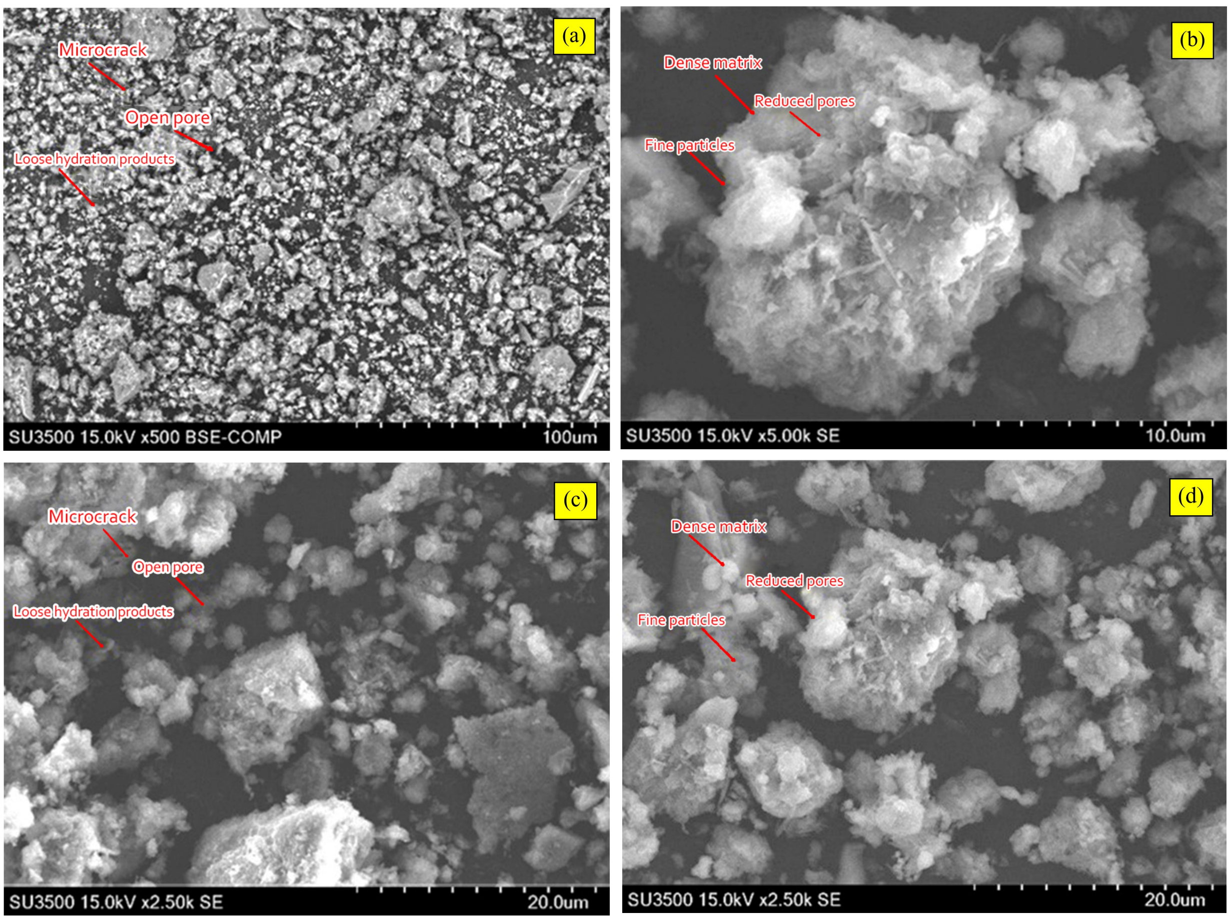
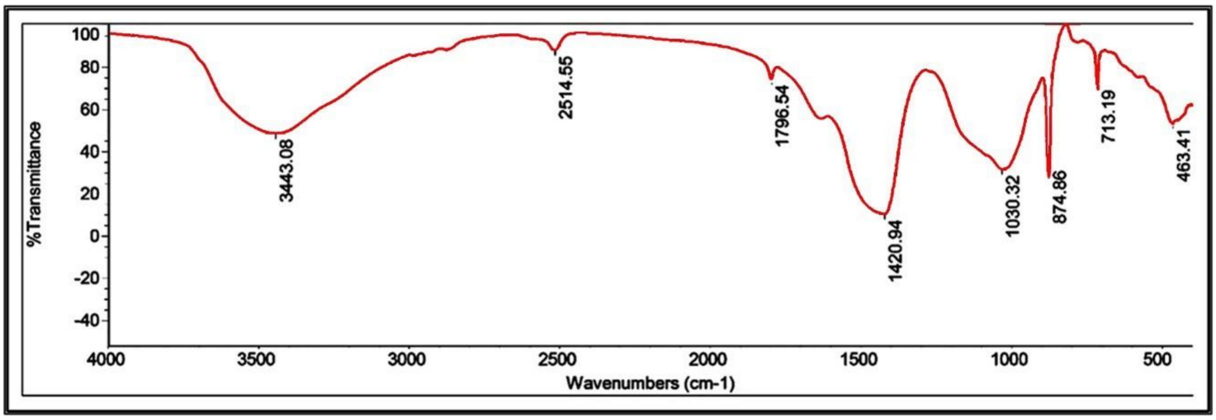
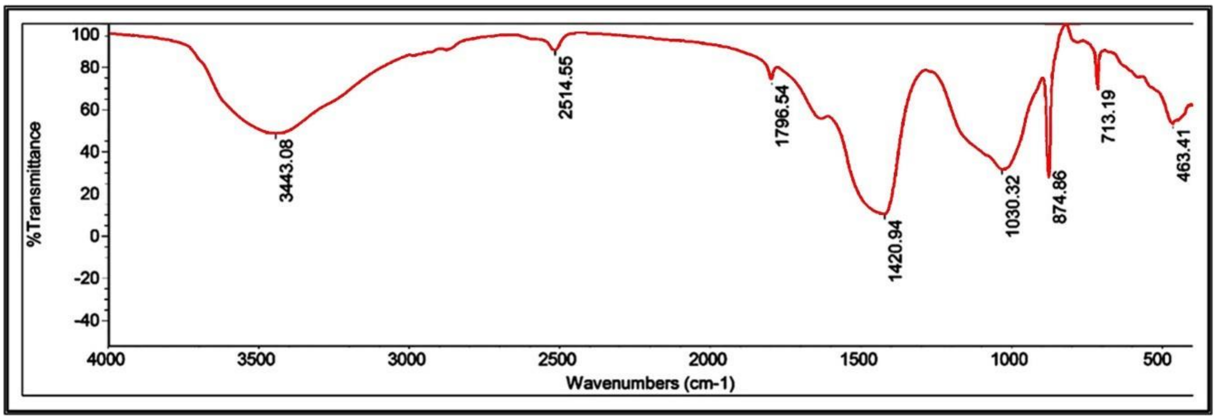


Figure 4. SEM micrographs of (a,c) control concrete (CC) showing microcracks, open pores, and loose hydration products, and (b,d) Anti-Moss and Anti-Fungus Concrete Coating (MFC) exhibiting a denser matrix with reduced pores and fine particles



(a)



(b)

Figure 5. FTIR spectra of CC and CFM samples, indicating stronger Si–O–Si bonding and the emergence of Ti–O and Zn–O peaks associated with $ZnTiO_3$ and $CaTiO_3$ phases

3.6. Rapid Chloride Permeability Test (RCPT)

The results of the Rapid Chloride Permeability Test (Fig. 6) revealed a significant reduction in the total charge, passed from 2100 ℃ for the uncoated (control) specimen classified as Moderate (borderline Low–Moderate) to 1500 ℃ after the application of the anti-moss and anti-fungal coating, which corresponds to a Low permeability category according to ASTM C1202.

The results showed a decrease of approximately 28.6% in total charge, a decrease in the total charge passed (2100 Coulombs to 1500 Coulombs), and an increase in the chloride permeability classification from moderate to low, indicating a substantial improvement in the concrete's resistance to chloride ion penetration [30,31,39].

3.7 Result of Outdoor Exposure and Visual Observation

In Figure 7, after observing typical tropical conditions, such as temperature and relative humidity, for 12 months with exposure to sunlight and natural rainfall, the Anti-Moss and Anti-Mold Coating provided a preventative effect by forming a biofilm layer that serves as a substrate for moss and mold growth. Similar observations were reported by Mohammed et al. [40], Hodul et al. [41], Adebanjo et al. [42], and Mu et al. [43], who demonstrated that hydrophobic silane/siloxane coatings significantly suppress microbial colonization on concrete surfaces in humid and warm climates.

3.8. Discussion

Biological colonization on untreated concrete surfaces is closely associated with moisture availability, pore structure, and surface chemistry, which govern transport mechanisms and durability performance under humid environments. The control concrete exhibited visible moss and fungal growth after outdoor exposure, accompanied by higher water absorption and a more porous near-surface morphology. Previous studies have demonstrated that such conditions promote moisture retention and accelerate surface degradation through physical weathering and chemical interactions with cement hydration products [5–9,11], hydrophobicity and full water beading, confirming effective pore-blocking.

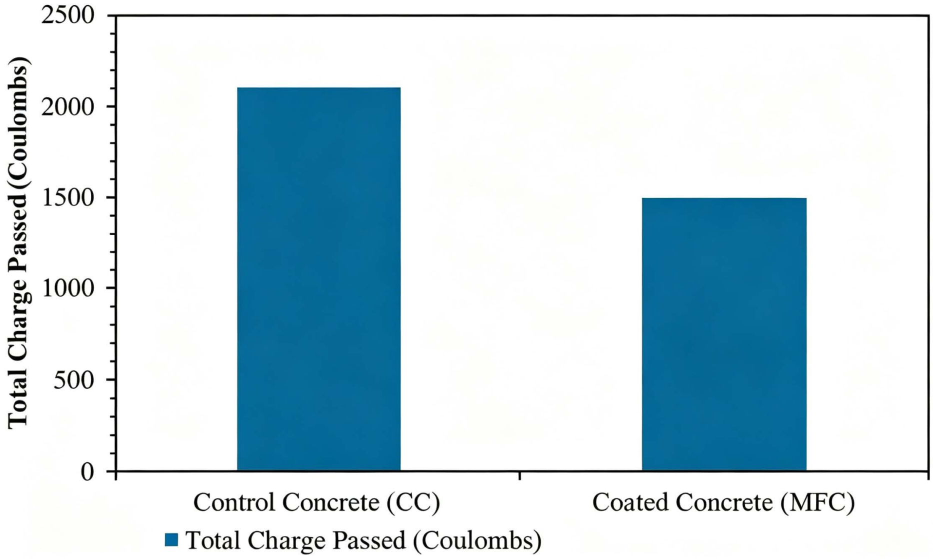


Figure 6. Results of the Rapid Chloride Permeability Test (RCPT) for CC and MFC specimens after 28 days of curing

Figure 7. Visual appearance of concrete specimens after one year of outdoor exposure: (a) uncoated control concrete (CC) with visible moss and fungal growth, and (b) coated concrete (MFC) showing no biological contamination

The coated concrete (MFC) showed a marked reduction in biological colonization, which correlates with measurable improvements in durability-related parameters rather than aesthetic effects alone. The application of the coating significantly reduced water absorption and chloride ion permeability, indicating restricted moisture and ion transport through the surface zone. From a civil engineering perspective, these parameters are widely recognized as key durability indicators, as reduced permeability limits environmental ingress and mitigates degradation under aggressive exposure conditions [15–18,24,25].

Microstructural characterization further supports these findings. SEM analysis revealed a denser and more homogeneous surface morphology for the coated specimens, with fewer open pores and microcracks compared to the uncoated concrete. XRD and FTIR analyses confirmed the formation of semi-crystalline phases such as $ZnTiO_3$ and $CaTiO_3$, along with enhanced Si–O–Si bonding, indicating improved surface stability and pore-blocking effects [17–20,22,23]. These microstructural modifications are consistent with previous reports on metal-oxide-based systems and siloxane treatments that enhance resistance to moisture penetration and biological activity [19–21,24]. This finding is consistent with previous studies on silane-based composite coatings, which improve surface protection through enhanced bonding and functional nanoparticle dispersion [44].

Importantly, the reduction in moss and fungal growth should be interpreted primarily in terms of durability preservation. Biological inhibition limits surface moisture accumulation and biofilm formation, which are known to intensify concrete deterioration through repeated wetting–drying cycles and localized chemical attack [6,11,13]. Therefore, the engineering relevance of reduced biological colonization lies in its indirect contribution to controlling moisture transport and surface degradation mechanisms rather than visual appearance alone.

The discussion is deliberately restricted to experimentally observed physical, microstructural, and durability-related parameters supported by testing and established literature. While no direct prediction of service life extension is made, the combined reductions in water absorption, permeability, and biological colonization demonstrate enhanced resistance to environmental degradation mechanisms relevant to concrete structures exposed to humid and tropical conditions [6,11,13].

4. Conclusions

This study evaluated the effectiveness of a solvent-based siloxane coating in mitigating biological colonization and improving durability-related performance of concrete under tropical environmental conditions. The results confirm that untreated concrete is highly susceptible to moss and fungal growth, which is associated with increased moisture retention, higher porosity, and enhanced transport of water and aggressive agents, leading to surface degradation mechanisms relevant to long-term durability.

The application of the coating significantly reduced biological colonization while simultaneously improving key engineering durability indicators, including water absorption and chloride ion permeability. These results indicate restricted moisture and ion transport through the near-surface zone, which is critical for limiting environmental ingress and degradation under humid exposure conditions. Microstructural analyses further revealed a denser and more homogeneous surface morphology, supported by the formation of semi-crystalline phases such as $ZnTiO_3$ and $CaTiO_3$ and enhanced Si–O–Si bonding, contributing to pore-blocking and surface stabilization effects.

The reduction in biological growth is significant primarily due to its indirect role in controlling moisture accumulation and surface deterioration rather than aesthetic improvement alone. Although no direct service life prediction is made, the observed improvements in physical, microstructural, and durability-related parameters demonstrate enhanced resistance to environmental degradation mechanisms relevant to concrete infrastructure in humid and tropical climates.

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