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A Systematic Review on the Corrosion Behavior and Mechanisms of Steel Reinforcement in Magnesium Silicate Hydrate Cement

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Abstract. Magnesium silicate hydrate cement (MSHC) is considered a promising low-carbon alternative to ordinary Portland cement because of its lower calcination temperature and comparable mechanical performance. However, its application in reinforced concrete is limited by the corrosion risk of embedded steel, mainly associated with the relatively low alkalinity of the pore solution. This review summarizes the current understanding of the corrosion behavior and mechanisms of steel reinforcement in MSHC, with emphasis on passive film stability, chloride attack, and carbonation effects. Common evaluation methods, including electrochemical techniques and microstructural characterization, are also discussed. Existing studies indicate that although MSHC exhibits a relatively dense matrix and low chloride transport capacity, its weaker alkaline reserve reduces the stability of steel passivation compared with ordinary Portland cement. Current protection strategies mainly rely on modifying pore solution chemistry and improving interfacial conditions. Finally, key research needs are identified to support the durable application of reinforced MSHC in low-carbon construction.

Keywords: Magnesium silicate hydrate, Steel reinforcement corrosion, Carbonation, Chloride attack, Roman spectroscopy

1. Introduction

As the most widely used material, cement production has increased from 144.2 million tonnes in 1950 to 3.88 billion tonnes in 2024, making cement manufacturing the third-largest source of hard to abate emissions, following load-following electricity generation and steel production [1]. Eliminating the CO_2 emission of cement production is essential to achieve carbon neutralization. Fig.1 illustrated that the life-cycle carbon footprint of Portland cement spans several stages, including limestone calcination, high-temperature kiln fuel combustion, and transportation, with clinker production being the most carbon-intensive. Clinker, an intermediate product in cement manufacturing, releases CO_2 through both fuel combustion and the chemical decomposition of limestone [2]. Heavy reliance on clinker calcination results in exceptionally high carbon intensity.

Magnesium silicate hydrate (M-S-H) cement develops through MgO hydration to brucite, followed by reaction with dissolved silica to form M-S-H gel, which gradually becomes more

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structurally ordered and provides strength [3]. Under standard curing, compressive strength of up to 70 MPa can be achieved at 28 days [4]. Because of its comparable strength to ordinary Portland cement (OPC) and lower calcination temperature, this material has attracted increasing attention.

The durability of magnesium silicate hydrate cement (MSHC) has also been increasingly studied. Sonat et al [5]. reported that MSHC maintained mechanical performance under most exposure conditions and even showed superior strength development to OPC in $MgCl_2$ and $MgSO_4$ solutions, which shows considerable potential for application. Nevertheless, the pore solution in MSHC has a relatively low alkalinity, which may compromise the stability of the passive film on embedded steel, a factor that could limit its application in reinforced construction [6].

Existing studies on steel corrosion in MSHC have mainly concentrated on the corrosion process, its governing factors, and corresponding evaluation and mitigation approaches. These investigations have examined key aspects such as pore solution chemistry, hydration products, pore structure, chloride transport, carbonation, moisture exposure, and microstructural features [6-8]. Despite these efforts, including the incorporation of small amounts of PC, SHMP, or alkali additives to mitigate corrosion, a comprehensive understanding of the corrosion behaviour of reinforcing steel in MSHC remains unavailable. This paper therefore provides a review of the corrosion characteristics of steel reinforcement in MSHC and the mechanisms governing them.

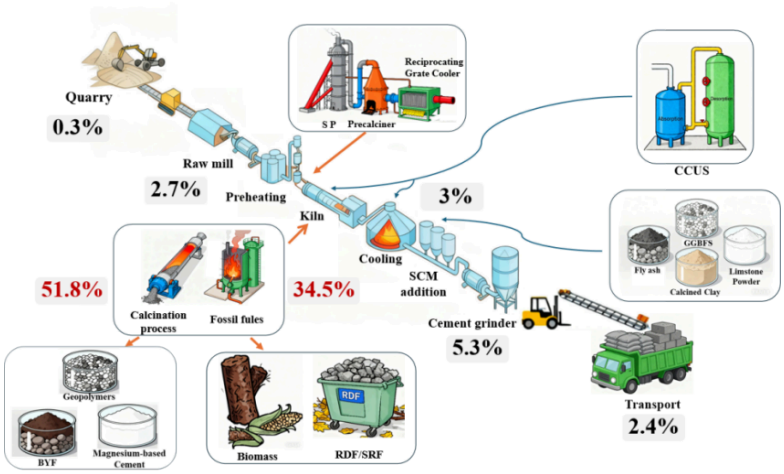

Figure 1. CO_2 emissions and mitigation strategies in cement production

This review examines the corrosion behaviour of reinforcing steel in MSHC, with emphasis on the underlying mechanisms. Section 2 discusses the principal corrosion mechanisms and the factors governing them, including pore solution alkalinity, hydration products, chloride ingress, and carbonation. Section 3 summarizes the main techniques used to assess corrosion. Section 4 reviews corrosion performance under different exposure scenarios and evaluates the effectiveness of currently available protection strategies. Section 5 concludes the review by summarizing the key findings and identifying priorities for future research. The review is intended to provide a scientific basis for the safe and durable use of MSHC in low-carbon reinforced concrete.

2. Corrosion mechanisms of steel reinforcement in Magnesium Silicate Hydrate Cement

2.1. Formation and stability of passive films

The durability of steel reinforcement in OPC primarily depends on whether a stable passive film can form on its surface. The pore solution pH of OPC is typically above 12.5, so steel can more readily

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enter a passive state under normal conditions. Compared to MSHC is usually only around 9.5-10.5, which is lower than the highly alkaline environment required for the formation of a stable passive film [3,4]. Bharati et al. [7] showed that in studies of MgO and MgO-SiO_2 suspensions, that unmodified Mg-based systems exhibited more negative OCP, indicating that stable passivation was more difficult to achieve in such systems. Mi et al. [8] further found that when a small amount of PC was incorporated into Mg-based systems, the pore solution pH could increase to above 12, enabling the re-establishment of passivation. Therefore, low-alkalinity pore solution is the primary factor limiting the formation and long-term stability of passive films on steel reinforcement in MSHC, and it also provides the basis for subsequent chloride induced attack, carbonation induced depassivation, and corrosion propagation [6,8].

In addition to pore solution alkalinity, the composition of hydration products directly affects the passivation behavior of steel reinforcement. OPC mainly produces C-S-H gel and $Ca(OH)_2$ during hydration, and $Ca(OH)_2$ can continuously provide a high alkaline reserve. By contrast, MSHC mainly forms M-S-H gel, often accompanied by varying degrees of residual brucite, resulting in an overall low-alkalinity hydration system that hardly provide a strongly passivating environment as persistently as OPC [3,4]. Studies have shown that hydration products in the M-S-H system not only alter pore solution chemistry, but also affect the formation pathway and composition of passive films on steel surfaces. Mi et al. [8] reported that the passive film formed on steel in Mg-based blended cement systems contained not only Fe_3O_4 but also $Mg(OH)_2$-related components, indicating that the Mg-based hydration environment directly contributed to passive film formation. Bharati et al. [7] further reported that the addition of SHMP improved the workability of the MSHC, increased the pore solution pH, and promoted a more favorable hydration and interfacial environment for steel passivation, resulting in the formation of a more protective passive film. These results indicate that hydration products, pore solution chemistry, and passive film structure are closely coupled in MSHC. The stability of steel passivation therefore depends not only on pH, but also on the overall hydration product system and its evolution.

2.2. Corrosion deterioration mechanisms

Localized depassivation of reinforcing steel may be induced either by the accumulation of chloride ions at the steel interface or by a decline in pore solution alkalinity associated with carbon dioxide ingress. In chloride-containing environments, corrosion initiation is primarily controlled by the transport of Cl^- through the matrix and its subsequent build-up at the steel surface [9,10]. When a critical chloride level is reached, the steel is no longer able to remain passive, and corrosion tends to initiate in the form of pitting [11]. Although MSHC usually has a denser matrix and a lower chloride diffusion coefficient than OPC [12], the comparatively lower pH of its pore solution is less conducive to maintaining passive film stability.

Carbonation also plays an important role in the durability of steel reinforcement in MSHC. In OPC-based concrete, CO_2 ingress consumes $Ca(OH)_2$ and decalcifies C-S-H, which lowers the alkalinity of the pore solution and destabilizes the passive film on the steel surface [13,14]. In MSHC, however, the effect of carbonation is more complicated. On the one hand, carbonation depletes the OH^- reserve in the system and reduces the alkalinity around the steel, making passive film maintenance more difficult. On the other hand, the resulting carbonation products may partially fill pores and densify the matrix, thereby restricting transport processes [15]. It has been reported that, under accelerated carbonation, reactive magnesium cement (RMC) can develop higher strength through the formation of HMCs. Even so, its protection of embedded steel remains markedly inferior to that provided by OPC. The RMC system is characterized by a relatively low OH^-

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concentration in the pore solution, and its carbonation depth can exceed 10 mm after 7 days, whereas OPC shows a carbonation depth of only about 3 mm and the steel remains passive [15]. These findings suggest that the strength gain associated with carbonation curing in magnesium-based binders remains insufficient to offset their limited resistance to carbonation-induced corrosion, which mainly stems from the relatively low pH of the pore solution. However, corrosion behaviour of steel in MSHC under carbonation has received limited attention, and the underlying mechanisms have yet to be fully clarified.

3. Evaluation methods for steel corrosion in Magnesium Silicate Hydrate Cement (MSHC)

3.1. Electrochemical methods for evaluating corrosion behavior

Electrochemical methods are currently the most commonly used and the most direct techniques for evaluating the corrosion behavior of steel reinforcement in cement. Open-circuit potential (OCP) can be used to rapidly determine the electrochemical state of steel: when the potential is generally more negative, the steel is more likely to be in an active corrosion state, whereas a shift toward more positive values often suggests that the passive film is forming or stabilizing [6]. Polarization-based methods are suited for quantitative electrochemical characterization [16]. Linear polarization resistance (LPR) is commonly used to estimate corrosion rate, Tafel polarization can be used to analyze anodic and cathodic reaction characteristics, and electrochemical impedance spectroscopy (EIS) can distinguish bulk resistance, interfacial charge-transfer resistance, and film characteristics, making a key method for studying passive film stability on steel in MSHC [17,18]. Previous studies have employed OCP and EIS to characterize the establishment of passive films on steel rebars in MSHC [6]. LPR and Tafel polarization measurements have also been used to systematically evaluate the corrosion resistance of steel in MSHC under ambient conditions and cyclic chloride exposure [7]. These studies indicate that electrochemical methods can provide real-time and continuous monitoring of the transition of steel from the passive state to the corroding state. This capability makes them effective tools for assessing steel corrosion in MSHC systems.

3.2. Microstructural characterization of corrosion products

The microstructural characterization of corrosion products mainly serves to answer two questions: what products form on the steel surface, and how these products are distributed on the steel surface and within the interfacial region. Current studies mainly focus on two types of surface layers: relatively stable passive films with protective functions, and corrosion product layers formed after corrosion develops. In terms of characterization methods, Raman spectroscopy is suitable for identifying the composition of oxides or corrosion products on the steel surface [15], X-ray photoelectron spectroscopy (XPS) can analyze the chemical states of elements in the film, low-kV backscattered electron imaging (BSE) can be used to observe interfacial morphology and film continuity, and X-ray diffraction (XRD) can assist in identifying crystalline corrosion products. When internal three-dimensional distribution is of interest, X-ray computed tomography (XCT) can also be used to visualize the spatial characteristics of cracks, pores, and corrosion damage. Existing studies have characterized the passive film formed on steel reinforcement in MSHC using Raman spectroscopy, XPS, and BSE. In addition, XRD and scanning electron microscopy (SEM) can be used to analyze the phase composition and microstructural morphology of corrosion products after chloride exposure [6,7]. From the perspective of methodological development, machine learning and deep learning approaches can also be integrated with microscopic images, XCT data, or

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spectroscopic data to enable automatic identification of corrosion product types and localization of their distribution, thereby improving the efficiency of large-scale image analysis. Although these methods have not yet been widely applied to the study of steel corrosion in MSHC, they are expected to become important auxiliary tools for microstructural characterization in future research.

4. Comparison of corrosive about materials and protection strategies

4.1. Influence of different conditions on steel corrosion of OPC and MSHC

Compared with OPC, the corrosion protection afforded by MSHC is more strongly governed by the conditions at the steel interface. The highly alkaline pore solution generally allows the formation and long term maintenance of a stable passive film on the steel surface in OPC. By contrast, in MSHC, the lower pore solution alkalinity places steel closer to the depassivation threshold and increases its sensitivity to aggressive external exposure. Steel passivation in MSHC therefore depends on a much narrower range of interfacial conditions than in OPC.

The distinction between OPC and MSHC becomes more pronounced under chloride exposure. The MSHC cover layer exhibits a relatively low chloride migration capacity, with a chloride migration coefficient markedly lower than that of PC. Meng et al. [6] reported that the chloride migration coefficient of the MSHC mixtures was 2.1×10^{-12} m^2/s, compared with 11.5×10^{-12} m^2/s for their OPC counterparts, indicating the markedly superior resistance of the M-S-H matrix to chloride transport. This result suggests that the M-S-H matrix can effectively retard Cl^- ingress from a transport perspective. However, once chloride ions accumulate locally at the steel interface beyond the critical threshold, passive film breakdown is promoted under the relatively low-pH conditions of this system. The same study further showed that, after cyclic chloride immersion, the corrosion rate in MSHC reached 7.1 μA/cm², exceeding that measured in OPC. These findings indicate that the corrosion response of magnesium silicate hydrate cement is governed primarily by the limited stability of the passive state after chloride accumulation at the steel interface.

Electrochemical measurements further reveal the different corrosion responses of MSHC and OPC. At 56 d, the total impedance of MSHC was approximately four times that of OPC. Under cyclic chloride exposure, however, the half cell potential of MSHC frequently dropped below -500 mV after wetting cycles, indicating a high probability of corrosion. In contrast, OPC remained above −150 mV after drying cycles, corresponding to a much lower corrosion risk [6]. These results show that OPC can still retain a certain degree of passivation after aggressive exposure because of its higher alkaline reserve, whereas the electrochemical stability of MSHC is more readily disturbed by environmental fluctuations.

The main indicators of steel corrosion in OPC and MSHC are summarized in Table 1. The protective performance of OPC is mainly derived from the high alkalinity of the pore solution and the stability of the passive film. Compared with OPC, protection relies more heavily on the dense pore structure and the barrier effect of the cover layer in MSHC. Accordingly, corrosion protection in OPC is dominated primarily by chemical passivation, whereas that in MSHC depends more on resistance to external ingress.

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Table 1. Key indicators of steel corrosion in OPC and MSHC

Indicators	OPC	MSHC
pH	12.5-13.5	8-12
Chloride migration coefficient (m^2/s)	11.5×10^{-12}	2.1×10^{-12}
Carbonation depth (mm at 7d)	3	10

4.2. Applicability of different protection strategies

Current protection strategies for steel corrosion in MSHC mainly focus on three aspects: increasing alkalinity, and improving interfacial film formation. The first approach is the incorporation of small amounts of OPC. Existing studies have shown that about 2% OPC can already increase pore solution alkalinity and promote steel passivation; if the dosage is further increased to 20%, corrosion resistance under carbonation conditions becomes more stable, and this strategy is therefore suitable for structural components with higher durability requirements [8,15].

The second approach is the use of SHMP or small amounts of alkali additives. SHMP not only improves the workability of MSHC, but also raises pH and promotes the formation of a more favorable passive film. Small amounts of NaOH/KOH can also enhance passivation [7]. Such methods are more suitable at the material design stage.

Overall, current studies show that effective corrosion protection in MSHC relies on establishing a pore solution and interfacial environment capable of sustaining stable passivation of steel. Although the specific routes differ, OPC incorporation, SHMP addition, and minor alkali modification all improve corrosion resistance through their influence on alkalinity, hydration chemistry, and passive film formation. OPC contributes more directly to passivation stability, especially under carbonation exposure. Existing results show that corrosion control in MSHC is jointly influenced by matrix chemistry, hydration evolution, and the stability of the steel surface film. Understanding these coupled effects is important for the development of MSHC systems with improved durability.

5. Conclusion

This work reviewed the corrosion behavior of steel reinforcement in magnesium silicate hydrate cement, the following main conclusions can be drawn:

(1) Steel corrosion in MSHC is mainly controlled by the relatively low alkalinity of the pore solution. Although MSHC generally has a dense pore structure and high bulk resistance, this physical barrier effect cannot fully compensate for its weaker chemical passivation capacity.

(2) Existing studies have mainly assessed corrosion by electrochemical methods, supported by pore solution analysis and microstructural characterization. These methods have improved understanding of passive film breakdown and corrosion progression, but the link between interfacial environmental variation and electrochemical response remains insufficiently understood.

(3) Current methods to improve MSHC durability mainly involve increasing pore solution alkalinity. Small additions of organic phosphorus compounds, SHMP, and alkaline additives show promise, but their long term effectiveness remains unclear.

References

[1] Davis S J, et al. Net-zero emissions energy systems [J]. Science, 2018, 360 (6396): eaas9793.

DOI: 10.54254/2755-2721/2026.33068

[2] Liao S, et al. China's provincial process CO_2 emissions from cement production during 1993-2019 [J]. Scientific Data, 2022, 9 (1): 165.
[3] Sreenivasan H, et al. A critical review of magnesium silicate hydrate (M-S-H) phases for binder applications [J]. Cement and Concrete Research, 2024, 178.
[4] Zhang T, Cheeseman C R, Vandeperre L J. Development of low pH cement systems forming magnesium silicate hydrate (M-S-H) [J]. Cement and Concrete Research, 2011, 41 (4): 439-442.
[5] Sonat C, Teo W W, Unluer C. Performance and microstructure of MgO-SiO_2 concrete under different environments [J]. Construction and Building Materials, 2018, 184: 549-564.
[6] Meng D, Yang E H, Qian S. Corrosion behavior of steel reinforcement in magnesium silicate hydrate (M-S-H) concrete [J]. Cement and Concrete Research, 2025, 193.
[7] Bharati, Engelberg D, Unluer C. Characterisation of passive layer on steel immersed in MgO-SiO_2 binder suspension solution [J]. Corrosion Science, 2025, 255.
[8] Mi T, Yang E H, Unluer C. Passivation of reinforcing steel in reactive MgO cement blended with Portland cement [J]. Cement and Concrete Composites, 2023, 143.
[9] Zhang B, et al. Unmasking chloride attack on the passive film of metals [J]. Nature Communications, 2018, 9 (1): 2559.
[10] Ghods P, et al. Angle-resolved XPS study of carbon steel passivity and chloride-induced depassivation in simulated concrete pore solution [J]. Corrosion Science, 2012, 58: 159-167.
[11] Angst U, et al. Critical chloride content in reinforced concrete — A review [J]. Cement and Concrete Research, 2009, 39 (12): 1122-1138.
[12] Zhang T, et al. Chloride Ion Penetration Resistance and Pore Structure of Magnesium Silicate Hydrate (M-S-H) Mortars [C]//. Atlantis Press, 2018.
[13] Morandeau A, Thiéry M, Dangla P. Investigation of the carbonation mechanism of CH and C-S-H in terms of kinetics, microstructure changes and moisture properties [J]. Cement and Concrete Research, 2014, 56: 153-170.
[14] Šavija B, Luković M. Carbonation of cement paste: Understanding, challenges, and opportunities [J]. Construction and Building Materials, 2016, 117: 285-301.
[15] Mi T, Yang E H, Unluer C. Corrosion resistance of steel reinforcement in carbonated reactive magnesia cement-based mixes with different Portland cement contents [J]. Cement and Concrete Composites, 2024, 152.
[16] Zaki A, et al. Non-Destructive Evaluation for Corrosion Monitoring in Concrete: A Review and Capability of Acoustic Emission Technique [J]. Sensors, 2015, 15 (8): 19069-19010.
[17] Kim J, Park K T, Kwon T H. Influencing Factors of Steel States in Concrete Based on Electrochemical Impedance Spectroscopic Measurements [J]. Applied Sciences, 2022, 12 (24).
[18] Chang Z T, Cherry B, Maroszeky M. Polarisation behaviour of steel bar samples in concrete in seawater. Part 2: A polarisation model for corrosion evaluation of steel in concrete [J]. Corrosion Science, 2008, 50 (11): 3078-3086.