

A Comprehensive Review of Magnesium Oxychloride Cement (MOC) and Alternative Cementitious Binders: Properties, Performance and Applications

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Citation: Yadav, N. & Meenakshi, M. (2026). A Comprehensive Review of Magnesium Oxychloride Cement (MOC) and Alternative Cementitious Binders: Properties, Performance and Applications. International Journal of Education, Modern Management, Applied Science & Social Science, 08(03(III)), 107–119. [https://doi.org/10.62823/IJEMMASSS/8.3\(III\).9487](https://doi.org/10.62823/IJEMMASSS/8.3(III).9487)

ABSTRACT

Magnesium oxychloride cement (MOC) has become increasingly popular as an environmentally friendly substitute for ordinary Portland cement (OPC), which has properties such as fast setting time, high strength at early age, low thermal conductivity, low processing energy and low carbon footprint when compared to other binders. However, due to its poor resistance to moisture, dimensional instability in wet conditions and risk of chloride attacks on reinforcing steel, wider structural applications of MOC have not yet been realized. The present paper reviews MOC hydration process, phase composition, microstructure formation with a special emphasis on the stabilization of Phase 5 ($5\text{Mg}(\text{OH})_2 \cdot \text{MgCl}_2 \cdot 8\text{H}_2\text{O}$) and Phase 3 ($3\text{Mg}(\text{OH})_2 \cdot \text{MgCl}_2 \cdot 8\text{H}_2\text{O}$), the two most important crystal phases affecting mechanical and physical properties of MOC paste. Several modification methods of MOC are reviewed, which include addition of phosphates, pozzolanic materials, fibers, polymers and carbonation assisted curing in terms of softening coefficient improvement and retaining of strength at wet state. The scope is further widened to encompass other binders, which are alternative and complementary to MOC, such as magnesium phosphate, geopolymers, calcium sulfoaluminate, and other new generation low carbon binders in terms of their energy efficiency, mechanical behavior, and environmental impacts compared with MOC. Applications for these binders are considered, ranging from traditional construction purposes, fire protection, artificial stone, waste immobilization, 3D printing elements, light weight non-structural materials, and industrial floors. The paper concludes with highlighting existing research gaps concerning the long-term durability of these binders under environmental exposure, the lack of standardized test methods, limited information on life cycle assessments, and problems with scaling of modification techniques.

Keywords: Magnesium Oxychloride Cement, Binder, calcium sulfoaluminate, ordinary Portland cement

Introduction

- **Background and Development of Magnesium Oxychloride Cement:** Magnesium oxychloride cement (MOC), popularly referred to as Sorel cement, is a magnesia cement that is non-hydraulic in nature, produced by a chemical reaction between reactive magnesium oxide (MgO) and an aqueous magnesium chloride (MgCl_2) solution. It is a part of the three-phase $\text{MgO-MgCl}_2\text{-H}_2\text{O}$ chemical system and achieves strength by precipitating and intergrowth of basic magnesium chloride hydrate phases instead of forming calcium silicate hydrates as in the case of OPC. The formation of such phases depends largely on MgO/MgCl_2 ratio, presence of moisture, MgO reactivity, and environmental conditions. Under commonly applied ambient curing conditions, Phase 5 (usually denoted as $5\text{Mg}(\text{OH})_2 \cdot \text{MgCl}_2 \cdot 8\text{H}_2\text{O}$) and Phase 3 (usually denoted as

$3\text{Mg}(\text{OH})_2 \cdot \text{MgCl}_2 \cdot 8\text{H}_2\text{O}$) are considered to be among the primary crystalline hydration products, where Phase 5 is usually linked to dense microstructure and high mechanical strength formation (Góchez et al., 2017; Guo et al., 2018; Li et al., 2020). Kinetic and phase evolution studies have additionally shown that the MOC hardening process is extremely responsive to curing conditions and Phase 5 formation kinetics (Xu et al., 2016; Zhang et al., 2017).

- Mixture of fast curing, high early age strength, high adhesion properties, wear resistance and flame resistant, in addition to relatively low alkalinity, has been responsible for allowing MOC to have niche applications that do not suit OPC. These are industrial flooring, grinding wheels, decorative stones, flame resistant products, thermal insulation products, wood-cement composites, among others. The low energy requirement to process MOC in comparison with the OPC clinker has also generated considerable interest in its use as a low energy binder.
 - **Need for Alternative Cementitious Materials:** Development of alternate cementitious binders has gained momentum due to high energy consumption and greenhouse gas emissions linked to OPC production. This means that more effort is being focused on the development of binders whose function is to lower the amount of clinker without compromising the mechanical and durability aspects. MgO cementitious systems constitute an important category of alternative binders due to the fact that reactive MgO can be made from comparatively low temperatures of calcination; however, this advantage is dependent on the source of MgO, calcination process, transport and MgCl_2 production (Kastiukas et al., 2019a & 2019b).
 - According to life cycle assessment (LCA), the environmental footprint of MOC cannot thus be generalized from its relatively low calcination temperature. The manufacturing process and reactivity of MgO have been found to play a crucial role in its embodied energy and environmental footprint (Kastiukas et al., 2019a & 2019b). However, optimization of the calcination of $\text{Mg}(\text{OH})_2$ has proved effective in cutting down energy requirements and generating very reactive MgO for MOC production (Kastiukas et al., 2019b). Moreover, MOC can use industrial and mineral by-products such as pulverized fuel ash and incinerated sewage sludge ash. These additions can affect phases formed, porosity, dimensional stability, and water resistance while at the same time valorizing the waste (He et al., 2017a & 2017b).
- Low-carbon cementitious materials in general include geopolymers/alkali-activated binders, calcium sulfoaluminate (CSA) cement, and magnesium phosphate cements (MPC). While these different types of binders exhibit very different chemical reactions and hydration behavior, they all have the common goal of offering alternative binders for applications which would otherwise use Portland cement. Geopolymerization is based on the dissolution and polycondensation of aluminosilicates, while CSA cement relies mainly on the formation of sulfated hydrates such as ettringite in order to achieve strength gain. MPCs form as a result of the acid–base reaction between reactive MgO and phosphate compounds, and are known for quick hardening and early strength development (Haque and Chen, 2019; Ranjbar et al., 2020; Singh and Middendorf, 2020; Tao et al., 2023). As such, when comparing these binders, not only strength but durability, environmental impact, and processability have to be considered.
- **Advantages and Limitations of MOC:** MOC comprises of rapid strength gain, good wear and fire resistance, low thermal conductivity, relatively low alkalinity, and filler compatibility. However, long-term water exposure may lead to instability of the oxychloride phases, leading to formation of $\text{Mg}(\text{OH})_2$ and chloride leaching. The performance of MOC is dependent on the properties of the composition, magnesium oxide activity, porosity, curing process, and exposure conditions. The free chloride ions and relatively low alkalinity are another point of concern for conventional reinforcement (Gong et al., 2020a; Qiao et al., 2019).

Advantages	Limitations
Rapid setting and hardening	Poor water resistance
High early mechanical strength	Decomposition of Phase 3 and Phase 5 in Water
Good abrasion resistance	Strength loss after prolonged water exposure
Fire and heat resistance	Possible expansion due to residual MgO hydration
Relatively low thermal conductivity	Chloride-related durability concerns
Relatively low alkalinity	Sensitivity to mixture composition and curing
Compatibility with various fillers/ additives	Limited suitability for continuously wet environments
Potential for waste-material incorporation	Additive modification may increase formulation complexity

- **Gaps in Existing Reviews and Rationale for the Present Review:** Existing reviews cover MOC production, hydration, phase formation, modification, and water resistance are also discussed, although comparison between additives is hard owing to variations in MgO reactivity, amount used, curing and durability practices. Issues like waste valorization, carbonation, and additive manufacturing must also be considered within a unified performance-based approach. A mechanisms-focused review would, therefore, be quite helpful in establishing the connection between composition, phases formation, microstructure, durability, environmental effect, and application.
- **Objectives and Structure of the Review:** This review will attempt to present the knowledge on MOC hydration and structure-property relationships; evaluate chemical, mineral, polymeric, fiber, waste-derived, and carbonation-assisted modification; consider sustainability and durability; and outline major research gaps and directions for future research.

Fundamentals of Magnesium Oxychloride Cement (MOC)

- **Chemistry and Constituents of MOC:** MOC is made from MgO, MgCl₂ solution, and water. The reactivity of MgO depends on calcination temperature, particle size, surface area, purity, and crystallite size. Magnesium chloride concentration and ratios of MgO/MgCl₂ and H₂O/MgCl₂ affect dissolution, nucleation, phase formation, and setting process. Water affects workability and ion transport, while too much water may increase the capillary porosity and permeability (Guo et al., 2018; Li et al., 2020).
- **The MgO-MgCl₂-H₂O System and MOC Phase Formation:** Hydration process of MOC is dependent on its composition and temperature. Phases 3 and 5 are main phases of MOC that are used for ambient curing process; usually, Phase 5 is associated with high strength due to interlocked crystal structure. But the strength cannot be determined by just Phase 5 content; other factors include crystal structure, intergrowth, pore structure, residual MgO, and amorphous phases. Variations in the ratios of H₂O/MgCl₂ and temperature affect greatly the phase formation and strength (Ye et al., 2018; Zhang et al., 2016).
- **Hydration and Hardening Mechanism:** The hardening process is a result of MgO dissolution and hydration that leads to ionic interaction, precipitation and growth of crystals, and microstructure densification. Phase 3 and Phase 5 grow to create a strong interconnected matrix. Thus, mechanical properties depend on the reaction products' phase composition and interfacial interactions with porosity (Góchez et al., 2017; Guo et al., 2018).

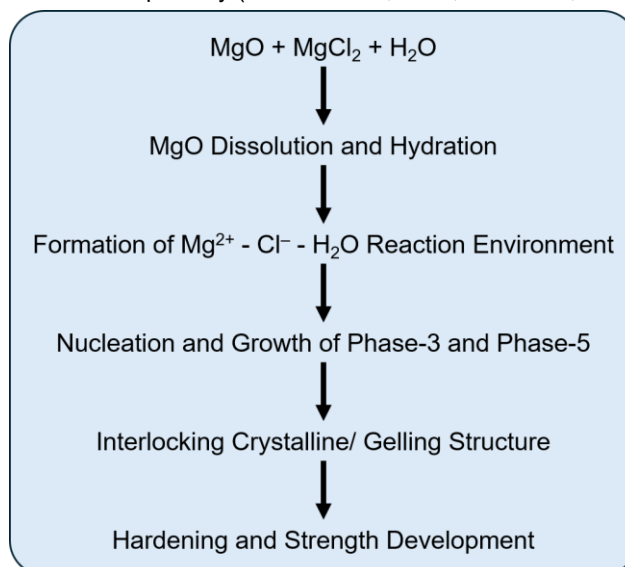


Figure 1: A simplified conceptual sequence of MOC hydration and hardening mechanism

- **Stability of MOC Hydration Products:** Water may cause MOC hydrate decomposition by way of destabilization leading to phase transition, chloride leaching, microstructure change, and

degradation in strength. This is the reason why dry-cured high strength may not mean wet durability. Modifications such as phosphate-based, organic acid-based, ash, glass, and silica have been studied for enhancing phase stability and resistance to water, yet the impact on setting, strength, and porosity depends on the dosage (He et al., 2018; Chen et al., 2019; Li et al., 2020).

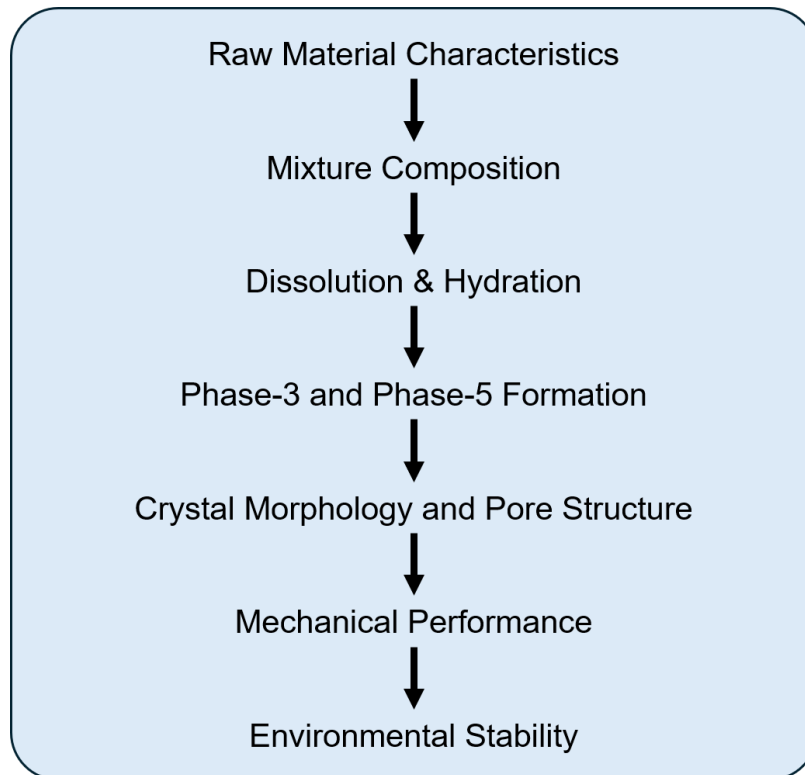


Figure 2: Fundamental structure–property relationship of MOC.

Need for Additive Modifications of Magnesium Oxychloride Cement (MOC)

MOC has a unique blend of fast setting rate, high strength at an early age, high abrasion resistance, thermal fire resistance, low thermal conductivity, and low alkalinity. Nonetheless, the widespread use of MOC in the construction industry has been hindered due to the instability of its hydration products when exposed to continuous moisture. This is because Phase 3 $[3\text{Mg}(\text{OH})_2 \cdot \text{MgCl}_2 \cdot 8\text{H}_2\text{O}]$ and Phase 5 $[5\text{Mg}(\text{OH})_2 \cdot \text{MgCl}_2 \cdot 8\text{H}_2\text{O}]$, which are the main bearing strength phases of MOC, are likely to transform/decompose when in an aqueous environment. Therefore, modification of MOC through additives is not only meant to increase the initial strength but also to improve the stability of phases, moisture resistance, dimensional stability, microstructure integrity, and mechanical performance of MOC (Ahmad et al., 2024a; Li et al., 2020).

- **Poor Water Resistance as the Principal Limitation:** Water sensitivity is the key issue of MOC. It may lead to the destruction of oxychloride hydrates, precipitation of $\text{Mg}(\text{OH})_2$, leaching of soluble species, and changes in porosity, resulting in loss of mechanical and dimensional stability. It depends on phase composition, reactivity of MgO , mixing ratio, curing, porosity, and conditions of exposure (Ahmad et al., 2024a; Li et al., 2020).
- **Instability of Strength-Carrying Hydration Phases:** Phase 5 provides a significant contribution to the interconnection of the strength-carrying structure, while water sensitivity may destroy such a network. Hence, the successful modification should maintain structural stability during exploitation, not merely provide high initial strength. Phosphate and sulfate-based modifications may enhance the water resistance, but high dosages can result in strength decrease or different thermal properties (Li et al., 2016).

- **Residual Strength Instead of Initial Strength:** Besides the initial strength, the evaluation of durability should include residual strength and softening coefficient. Phase composition, volume stability, pore structure, and microstructure after water exposure can serve as indicators of modification efficiency. Studies employing phosphoric/tartaric acids, fly ash, and mixed modifiers prove the importance of both strength and durability optimization (Chen et al., 2019; Gong et al., 2020b).

Therefore, the primary aim of MOC modification is to optimize the performance rather than maximizing its strength. The goal of a good addition system would be to enhance the water resistance and strength retention capabilities without compromising on setting characteristics, dimensional stability, thermal properties, processability, and environment-friendliness. It is this mechanistic understanding that lays the foundation for the critical analysis of various phosphate-based, sulfate-based, mineral-based, polymer-based, fiber-based, waste-based, and composite modification approaches discussed below.

Classification of Additives Used in Magnesium Oxychloride Cement (MOC)

Additive modification represents another critical approach for modifying the characteristics of MOC, including its water repellency, phase stability, mechanical strength, structure, and durability. The efficiency of the modifier is determined by its chemistry, size, reactivity, solubility, amount, and interaction with the $\text{MgO-MgCl}_2\text{-H}_2\text{O}$ system. Modifiers can engage in reactions of hydration and secondary reactions, or operate mainly through physical filling, pore refinement, hydrophobization, interfacial modification, and reinforcement. Therefore, the reaction between MOC and an additive is normally determined by multiple mechanisms. Inorganic modifiers, supplementary cementitious materials, polymers, fibers, and composite modifiers have been recently recognized as key approaches to improve MOC properties (Ahmad et al., 2024a; Hamada et al., 2025).

For the purpose of comprehensive analysis, modifiers used in MOC systems may be divided into: (i) phosphate-containing, (ii) sulfate-containing, (iii) silica- and silicate-containing, (iv) mineral and supplementary cementitious materials, (v) industrial wastes-based, (vi) polymeric and organic, (vii) fiber-containing, and (viii) compound and multi-component additives.

- **Phosphate-Based Additives:** Phosphate-based chemical modifiers are one of the most widely studied additives used in MOC. The examples of such additives include phosphoric acid, soluble phosphate salts, potassium dihydrogen phosphate (KH_2PO_4), ammonium phosphates, and other similar compounds containing phosphates. They act by modifying the hydration medium and phase formation in MOC. The phosphates may react with the magnesium-containing substances, affect the formation of the oxychloride phases, and contribute to the formation of secondary magnesium-phosphate-containing products.
- Phosphate modification of MOC is usually linked to the improvement of its water resistance and mechanical strength after the immersion process. It was found by Chen et al. that phosphoric acid promoted the formation of Phase 5 and changed the pore structure, which enhanced the water resistance (Chen et al., 2019). Nevertheless, the effectiveness of this modification is dosage-dependent; excessive amounts of phosphates inhibit the hydration of MgO and negatively affect its strength and thermal stability.
- **Sulfate-Based Additives:** Compounds such as FeSO_4 and MgSO_4 fall into the category of chemical modifiers containing sulfate ions. The sulfate ions may modify the ionic environment of the $\text{MgO-MgCl}_2\text{-H}_2\text{O}$ system and affect hydration kinetics, crystal formation, phase composition and microstructure.
- Experimental studies have proved that addition of sulfate is able to enhance water resistance due to changes in hydration products and crystal structure. It is necessary to mention that modification by sulfates does not always lead to improvement in properties. For instance, FeSO_4 and KH_2PO_4 can increase water resistance and decrease mechanical strength and thermal stability depending on concentration (Li et al., 2016). Thus, sulfates should be regarded as phase and hydration modifiers with controlled dose not to damage mechanical characteristics of MOC.
- **Silica and Silicate Additives:** Silica and silicate additives give reactive silicon and play an essential role in modification of MOC microstructure and water resistance. They include silica fume, nano-silica, colloidal silica, sodium silicate and others.

Their effect is based on both the chemical and physical processes. Reactive silica is capable of reacting with magnesium-bearing minerals and creating amorphous or partially crystallized magnesium-silicate-bearing phases. At the same time, nano-silica serves as the filler, providing the nucleating effect and enhancing packing and minimizing capillary porosity. According to Guo et al., silica fume and mixed silica fume/fly ash systems are capable of significantly improving the waterproofing properties via pore refinement, particle filling, and Mg-Cl-Si-H gel formation (Guo et al., 2021). The use of nano-silica is able to influence the hydration rate and microstructure formation due to high specific surface area. However, the use of excessive amounts of fine particles increases the amount of water required and leads to agglomeration.

- **Mineral and Supplementary Cementitious Materials:** Mineral additives and supplementary cementitious materials (SCMs) such as fly ash, slag, metakaolin, calcined clay, high silica minerals and other finely divided inorganic materials may work by both physical and chemical actions simultaneously.
- The finely divided particles can increase the density of packing and reduce the connectivity of pores, and reactive silicon and aluminum oxides can react chemically with MgO and other components of MOC. He et al. showed that pulverized fuel ash (PFA) and incinerated sewage sludge ash (ISSA) were capable of reacting with MgO to form magnesium aluminosilicates that would form an inseparable part of Phase 5 matrix (He et al., 2020).
- The efficiency of SCMs is greatly affected by the chemical composition, amount of amorphous phase, particle size and reactivity. An excess of the additives may lead to depletion of reactive MgO fraction, and thus formation of MOC phases that provide strength to the system may be impaired. Thus, SCMs should be considered as multifunctional additives, but not inert fillers.
- **Industrial Waste-Derived Additives:** Waste-derived materials have received attention due to their dual role in improving properties and recycling wastes. These include PFA, ISSA, waste glass powder, metallurgical wastes, and other Si-, Al-, Ca-, or Fe-rich industrial wastes.
- Fine particles from these materials could serve as fillers, whereas their reactive components could react further forming amorphous products. The inclusion of PFA and ISSA in MOC showed that the presence of waste-derived aluminosilicate phases helped in densifying the matrix and improving its water resistance (He et al., 2020). There is also a recent study on using metastatite as another reactive mineral to replace or modify the conventional reactive minerals in MOC, which has shown better mechanical and water resistance properties of the MOC (Venkatesh & Shanmugasundaram, 2024).
- However, composition variability, soluble salts, impurities, and hazardous constituents can impact the performance and environmental impact of these materials. Therefore, performance evaluation of waste-derived additives should consider their composition, leaching behavior, and environmental stability.
- **Polymeric and Organic Additives:** Polymeric and organic modifiers represent another approach of modification in which hydrophobic properties, film formation, pore plugging, elasticity, and surface bonding are more significant than direct MOC crystal chemistry modification. Such additives are PVA, acrylics, latexes, epoxy resins, polymer dispersions, organic acids, and natural organic modifiers.
- The application of polymer film is able to partially plug capillary pores and limit water movement in relation to moisture-susceptible oxychloride phases. Moreover, it can increase particle binding and influence the fracture characteristics. According to the recent literature review, polymer emulsions and hybrid polymer materials are promising modifications for MOC durability improvement (Hamada et al., 2025).
- Nevertheless, the introduction of such modifiers will also influence the process of setting, hydration, rheology, and porosity of the material. Therefore, selection of the modifier type, its dosage, dispersion and compatibility with the MOC matrix are critical.
- **Fiber-Based Additives:** Fiber-based additives mainly help to overcome the fracture properties and mechanical weaknesses of MOC without changing the hydration chemistry of the MOC binder.

- Examples of fibers being used include PVA, polypropylene, glass, carbon, basalt, cellulose, and many more.
- Their main mode of action lies in crack bridging and stress transfer mechanisms. The use of fibers in MOC limits crack formation and can enhance tensile and flexural strength, toughness, ductility, and the cracked condition behavior of MOC. The success of fiber-reinforcement in MOC lies in factors such as fiber length, aspect ratio, volume fraction, surface characteristics, fiber dispersion, and fiber-matrix interfacial adhesion. Recent MOC studies have focused on fiber-reinforced MOC to enhance tensile ductility and structural performance (Ahmad et al., 2024; Hamada et al., 2025).
- Too much addition of fibers will impair workability and lead to increased porosity. Hence, the combination of fiber with chemical or mineral additives is very attractive.
- **Compound and Multi-Component Additives:** Compounds or multiple-component systems use a combination of two or more additives with complementary roles. This becomes more critical today, since one particular additive might enhance a certain property but simultaneously hinder another. In some cases, phosphates are able to influence phase stability, silicate-containing additives lead to secondary gel formation and better pore structure development, and polymers limit water entry into the system. The same goes for the use of mineral additives together with fiber reinforcement, resulting in enhanced matrix densification and increased cracking resistance.
- The latest studies show that the right combinations of the mentioned additives may yield synergistic effects in terms of better water resistance, strength retention, microstructure, and durability (Hamada et al., 2025; Huang et al., 2021). At the same time, however, the interaction between several additives may significantly alter hydration behavior. Thus, compound systems need to be formulated on the basis of mechanism, rather than trial and error.
- **Functional Classification and Overall Perspective:** The principal functional roles of MOC additives can be summarized as follows:

Sr. No.	Additive Class	Dominant Mechanisms	Principal Targeted Properties
1	Phosphate-based	Mg–P interaction, phase/hydration modification	Water resistance, phase stability
2	Sulfate-based	Ionic and phase modification	Hydration control, durability
3	Silica/silicate-based	Secondary gel formation, pore filling, nucleation	Strength, densification, water resistance
4	Mineral/SCMs	Filler effect, secondary reaction, pore refinement	Strength, pore refinement, durability
5	Industrial waste-derived	Reactive phases, filler effect, gel formation	Water resistance, sustainability, strength
6	Polymer/organic	Film formation, pore blocking, interfacial modification	Water resistance, flexural behavior, toughness
7	Fiber-based	Crack bridging and stress transfer	Tensile/flexural strength, toughness
8	Compound/multi-component	Synergistic mechanisms	Balanced overall performance

None of these classifications is mutually exclusive. A waste material, for example, could be both an SCM and a source of reactive silica while polymer-treated fibers could serve both to protect the interface and reinforce the matrix. Classification, hence, should take into account either the main component or the function of the additive rather than the exclusive presence of a certain mechanism, just like in the classification provided in the supplied draft.

As such, one can state that modification of MOC with additives takes place via the following interrelated mechanisms: chemical modification of hydration and phase formation, physical modification of pore structure and matrix density, as well as reinforcing and protecting effects on the hardened product. Hence, the best formulations are those that optimize both phase stability, water resistance, mechanical characteristics and durability of the MOC.

Effect of Additives on Magnesium Oxychloride Cement (MOC)

- Additives exert their impact on MOC through four primary mechanisms: hydration and phase control, formation of by-products, pore structure alteration, and reinforcement or hydrophobic stabilization. It is determined by dosage, particle properties, curing conditions, and additives interaction with the base material.
- Influence of Chemical Additives on Hydration and Phase Formation: Phosphate-based additives may affect hydration kinetics and stabilize strength-forming phases. Advantages should be considered with potential drawbacks such as retardation, change in the setting time, and strength decrease at high concentrations (Huang et al., 2021, 2024).
- Influence of Siliceous and Pozzolan Additives: Silica fume, nano-silica, fly ash, and rice husk ash may provide both particle filling and formation of by-products. It has been shown that RHA can form amorphous Mg-Cl-Si-H gel and densify the matrix (Nie et al., 2022).
- **Effect of Gypsum and Sulfate-Containing Additives:** Gypsum and sulfates may enhance water resistance and volume stability but would result in delayed set time and reduced early strength. Use of waste gypsum has exhibited great promise in terms of improvement in retention of strength after immersion in water (Ma et al., 2022).
- Effect of Waste-Derived and Supplementary Materials: Waste ashes, RHA, gypsum, and many others can serve as fillers, sources of reactive silica and aluminosilicates or secondary phase-forming materials. Their advantages largely depend on their composition and quality control measures (Nie et al., 2022).
- Effect of Hydrophobic and Organic Additives: Hydrophobic materials restrict water penetration and have a refining effect on pore structures. Modification using stearic acid has been observed to lead to a finer structure along with greater hydrophobicity while polymers affect moisture transport and bonding at interfaces (Xu et al., 2023).
- Effect of Fibers on Mechanical Behavior: Fibers mainly influence fracture behavior and not the reaction mechanism. A combination of fibers increases tensile strength and strain tolerance while excessive content decreases flowability (Ahmad et al., 2024b).
- **Effect of Hybrid Additive Systems:** The combination of chemical, mineral, polymeric, and fiber additives will help overcome several deficiencies at once. Advantages have been noted such as an improvement in terms of water resistance, strength retention, and mechanical properties, but an increase in the complexity of the system makes it harder to control mechanisms and processes (Huang et al., 2021; Hamada et al., 2025).
- Overall Effect of Additive Modification: In general, additives affect MOC by means of four interrelated channels: (i) controlling hydration and phase formation, (ii) secondary reactions product formation, (iii) pore structure modification/refinement, and (iv) strengthening or hydrophobizing the hardened matrix. It should be noted that the desirable effect is not the highest compressive strength but the optimal balance of strength, phase stability, water resistance, dimensional stability, toughness, and durability.

Sustainability and Environmental Considerations

- **Resource Efficiency and Waste Valorization:** Additives made from wastes could be used in addition to saving virgin resources by altering the properties of MOC. These additives could be, for instance, fly ash, RHA, wood wastes, FGD gypsum, and others. Their environmental benefit will depend on their processing, transportation, and preparation demands (He et al., 2022; Nie et al., 2022).
- Energy Consumption and Carbon Footprint: MOC may need processing of MgO at low temperatures in comparison with Portland cement clinker, but it does not necessarily mean lower environmental impacts. MgO and MgCl₂ production, fuel use, transportation, and other aspects influence life cycle results significantly (Kastiukas et al., 2019b; Ruan et al., 2016).
- Carbonation and CO₂ Absorption: The phases of Mg-bearing MOC could absorb CO₂ and form magnesite, hydromagnesite, chlorartinite, and other mineral compounds. Some studies have shown that long-term testing of MOC boards had CO₂ absorption effects, whereas high CO₂ content could stimulate carbonation. The overall CO₂ absorption effect

needs to be estimated together with production and transportation emissions (Power et al., 2017; Jankovský et al., 2020)

- **Life-Cycle and Performance-Based Assessment:** Comparisons that make sense need to cover global warming potential, energy/resource use, water, waste diversion, transport, carbonation, durability, and end-of-life. Functional units based on equivalent engineering service are better than comparisons based solely on mass (Aslani & Hachem-Vermette, 2022).

Challenges and Research Gap

While there have been many improvements in relation to magnesium oxychloride cement (MOC), there are still some scientific and technical issues that hinder the wider use of this material in practical engineering applications. Performance of additives is highly dependent on MOC composition, MgO reactivity, additive dose, curing procedure, and test method, which makes comparison among various publications difficult.

Standardization and reproducibility issues are important. Additives doses are expressed on the basis of different references, namely as weight percent of MgO, as a percent of total binder, as substitution ratio, and as concentration of solution. As a result, similar doses can differ greatly. Future studies must provide details about composition of the mixes, MgO reactivity, particle size distribution, additive properties, and curing conditions..

Another significant deficiency relates to the concurrent optimization of mechanical strength, water resistance, dimensional stability, and the process of hardening itself. An additive increasing resistance to the effects of water may not optimize the mechanical strength at the beginning, and excessive mineral or chemical treatment may even harm the other characteristics. Experiments conducted on silica fume-fly ash and gypsum prove that additives do not have the same effect in all formulations and cannot be considered universal solutions. Thus, future research should pursue a multiple optimization objective rather than determine the optimum content based on one property alone.

Finally, long-term durability has been studied poorly. Most papers concentrate on early age features or only relatively short immersion time, whereas the practical application of MOC requires studying its behavior in water for a longer period and in various environmental conditions.

Further work is needed on the nature of mechanisms of additive-MOC interactions. Information can be provided by conventional methods such as XRD, FTIR, SEM/EDS, and thermal analysis, but it may be hard to determine reactions taking place at the interface and amorphous phases generated. More sophisticated methods, including advanced quantitative phase analysis, spectroscopy, microscopy, and three-dimensional microstructure investigation need to be utilized in order to correlate additive chemistry, reaction route, phase formation, pore structure, and performance.

Gaps in knowledge include scale-up and reproducibility in the case of waste-based additives where composition changes according to source and processing, compatibility with modified MOC and reinforcement systems, and last but not least sustainability in terms of full life cycle assessment of the additive processing, transportation, MgO preparation, curing and carbonation, service life, and disposal rather than the assumption that incorporation of waste automatically decreases impact.

Overall, future studies should move from additive screening to performance and mechanism-driven design, validated by tests and life cycle analysis.

Future Research Perspectives

- Future research and development of magnesium oxychloride cement (MOC) must move beyond empirical additive screening towards mechanism- and performance-based materials development. The performance of an additive depends on its chemistry, dosage, nature of MgO, curing conditions, phase transformation, microstructure, and exposure conditions. Therefore, future research must develop predictive models that relate additive properties and process parameters to performance, durability, dimensional stability, and environmental impact of MOC.
- **Mechanism-Based Additive Design and Optimization:** Additives should be chosen based on their roles, including phase stabilizers, pore refiners, hydrophobicity enhancers, reinforcements, or waste additives. Multi-objective design of experiments can help in establishing effective dosage range and counteract detrimental effects.

- **Advanced Characterization and Additive-MOC Interactions:** Future research must use advanced characterization techniques in addition to traditional techniques to differentiate between reaction, fillers, phase stabilizers, and pore refinement.
- **Long-Term Durability and Controlled Curing:** The testing must go further than temporary immersion periods to cover wet-dry cycling, thermal variation, carbonation, chloride exposure, and multi-loading. Testing of air, humidity-controlled, and CO₂ curing must be conducted along with additive modification
- **Multifunctional and Waste-Derived Systems:** Hybrid systems need to be evaluated for their synergistic, additive, or antagonistic impact. Characterization of chemical composition, mineralogy, particle size, reactivity, impurities, and processing requirements is required before any performance and sustainability claims can be made about waste materials.
- **Predictive Modelling, Standardization, and Scale-Up:** Statistical and machine learning-based models might establish relations between MgO reactivity, MgCl₂ concentration, additive nature/dosage, curing and environmental exposure histories, and the resulting strength, durability, phases and microstructures. Standardized testing and inter-laboratory validations are needed before prediction and scaling can become possible.
- **Sustainability and Application-Specific Development:** In the future MOCs have to consider not only technical aspects but also their life cycle assessment, and develop for specific applications, such as boards, panels, flooring, repair materials, precast products and composites reinforced with them. This development process can be outlined as follows: raw-material characterization → additives selection → dosage and curing optimization → microstructure and phase characterization → durability testing → LCA → scale-up → application-specific formulation.

Conclusion

Magnesium oxychloride cement (MOC) can be considered an interesting technical option of cementitious binders with unique features such as fast hardening, good mechanical behavior, heat resistance, and even sustainability. This literature review confirms that the MOC behavior depends on a number of factors including properties of magnesium oxide, chemical features of magnesium chloride, the amount of water, phases formed, curing conditions, and microstructure developed. The main drawback of MOC is low moisture resistance. However, it is not the only possible problem since additives, supplementary materials, polymer and fiber reinforcement, and carbonation proved to be effective in overcoming the problem of water resistance, but they may cause trade-offs between strength, setting time, workability, durability, cost, and sustainability.

Thus, future work must focus on formulating systems based not on material improvement but on mechanism-based and performance-based formulations. Characterization of standardized materials, dosing of materials, durability testing, long-term exposure testing, microstructural/phase characterization, and inter-laboratory comparison are critical steps needed for meaningful comparisons between MOC systems. At the same time, pilot-scale synthesis, reinforcement compatibility, formulation with specific applications, and life-cycle analysis must become part of future studies. In general, the transition of MOC from development at the laboratory scale to engineering applications must involve optimization of all these aspects simultaneously.

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