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Magnesium Phosphate Cement for Rapid Repair: Hydration Mechanisms, Early-Age Strength Development, and Application Perspectives

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Abstract. Magnesium phosphate cement (MPC) is a rapid-hardening cementitious material with high early-age strength and good bonding performance, making it attractive for emergency and rapid repair applications. This review summarizes the hydration mechanisms, early-age strength development, and engineering applications of MPC. The setting and hardening of MPC are mainly governed by phosphate dissolution, MgO dissolution, ion interactions, and the rapid precipitation of struvite-type hydrates. The resulting interlocking crystal network provides the structural basis for rapid strength development. Key factors affecting early-age performance include MgO reactivity, M/P ratio, water-to-binder ratio, retarder dosage, and curing conditions, which interact strongly and should be optimized together. MPC has been successfully applied in pavements, bridge decks, airport runways, railway facilities, and other localized repairs requiring short closure periods. However, short working time, concentrated heat release, early-age water sensitivity, and relatively high material cost still limit wider application. Future research should focus on multi-objective mix design, durability, low-cost raw materials, and standardized reopening criteria.

Keywords: Magnesium phosphate cement, Rapid repair, Hydration mechanism, Early-age strength, Engineering application

1. Introduction

Localized damage to transportation infrastructure, such as pavement potholes, bridge deck spalling, airport runway damage, and railway component defects, can threaten structural durability and operational safety and often requires repair within short closure windows. Rapid repair materials must therefore develop sufficient strength within hours while maintaining workable setting time, reliable bonding, and dimensional stability. Although Portland cement (PC) offers mature technology and reliable long-term performance, its slow hydration limits its use in emergency repair. Rapid-hardening cements, accelerators, and polymer modification can improve early strength but may compromise workability, shrinkage, or long-term behavior. Thus, rapid repair materials should be designed to balance construction time, early load-bearing capacity, and service performance rather than simply maximize setting speed or early strength. Magnesium phosphate cement (MPC) is

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a rapid-hardening binder produced by the acid-base reaction between MgO and soluble phosphates. Its rapid precipitation of magnesium phosphate hydrates gives MPC fast setting, high early-age strength, low shrinkage, and good interfacial bonding [1-4]. Optimized formulations can reach about 28 MPa at 1h and over 40 MPa at 3h [1], highlighting its potential for rapid repair. However, MPC performance depends strongly on raw materials, mix design, and curing, while short working time, heat release, limited early water resistance, and relatively high cost still restrict wider application. This review focuses on the hydration mechanisms, early-age strength development, and rapid-repair applications of MPC. Section 2 discusses its hydration process, Section 3 analyzes the main factors affecting early strength, Section 4 summarizes engineering applications and performance perspectives, and Section 5 presents the main conclusions.

2. Hydration mechanisms of magnesium phosphate cement (MPC)

2.1. Raw materials of MPC

Calcined MgO is the main basic component of MPC and is commonly produced by thermal decomposition of magnesite or magnesium hydroxide ($Mg(OH)_2$) [5-7]:

$$MgCO_3 \rightarrow MgO + CO_2 \quad (1)$$

$$Mg(OH)_2 \rightarrow MgO + H_2O \quad (2)$$

As shown in Fig.1, phosphate salts are the main acidic component of MPC [8-11]. Ammonium dihydrogen phosphate (ADP) reacts rapidly with MgO to form $NH_4MgPO_4 \cdot 6H_2O$, but ammonia release during mixing and hardening may cause environmental and health concerns. Potassium dihydrogen phosphate (KDP) forms $KMgPO_4 \cdot 6H_2O$ without ammonia release and is therefore widely used in modern MKPC systems. Dipotassium hydrogen phosphate (K_2HPO_4), with weaker acidity, can increase the initial pH and slow early reactions, although its reaction products are more complex.

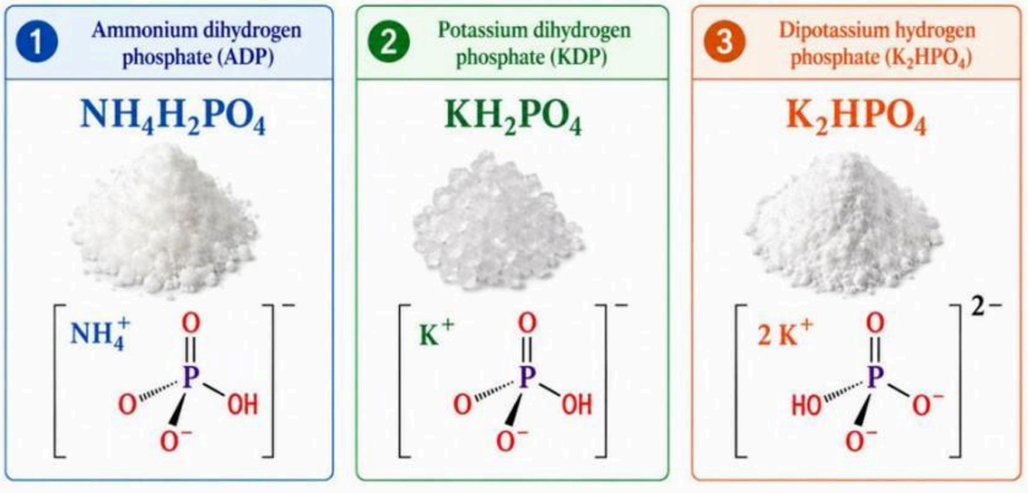

Figure 1. Main phosphate salts in MPC

Because MgO reacts rapidly with phosphate, retarders are commonly added to extend the working time of MPC. Borax ($Na_2B_4O_7 \cdot 10H_2O$) is widely used and is believed to retard hydration by

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complexing Mg^{2+} and forming a temporary boron-containing layer on MgO particles, thereby slowing MgO dissolution and K-struvite nucleation [12]. Typical dosages are about 5-10% of MgO mass, although the optimum value depends on MgO reactivity, M/P ratio, temperature, and water content.

For MPC repair mortars and concretes, aggregates and mineral fillers also affect performance. Fine aggregate can reduce binder demand, limit dimensional changes, and improve wear resistance, although excessive sand may weaken paste coating and early bonding. Coarse aggregate improves dimensional stability and helps control heat rise in thicker repairs but increases mixing and compaction difficulty. Mineral additions such as fly ash, slag, and calcined clay may refine the pore structure through filler effects and, in some cases, participate in hydration reactions.

2.2. Acid-base reaction and main hydration products of MPC

The hydration of MPC begins with the dissolution of phosphate salts. Taking KDP as an example, KH_2PO_4 dissolves in water to release K^+ and acidic phosphate species, resulting in an initially acidic pore solution. Under these conditions, MgO dissolves through proton attack according to the reaction $MgO + 2H^+ \rightarrow Mg^{2+} + H_2O$. As Mg^{2+} is continuously released into the pore solution, acid-base equilibria and complexation reactions occur between hydrated magnesium ions and phosphate species, including $H_2PO_4^-$, HPO_4^{2-}, and PO_4^{3-}.

When the activities of Mg^{2+}, K^+, and phosphate species reach supersaturation, K-struvite begins to nucleate and grow rapidly. The overall reaction of KDP-based MKPC can be expressed as [13, 14]:

$$MgO(s) + KH_2PO_4(aq) + 5H_2O(l) \rightarrow KMgPO_4 \cdot 6H_2O(s) \quad (3)$$

For ADP-based MAPC, the principal reaction is:

$$MgO(s) + NH_4H_2PO_4(aq) + 5H_2O(l) \rightarrow NH_4MgPO_4 \cdot 6H_2O(s) \quad (4)$$

struvite and struvite commonly form needle-, rod-, or plate-like crystals. These crystals nucleate around MgO particles and in the pore solution, then grow and interlock to form a continuous solid network. This transition converts the paste from a flowable state into a load-bearing skeleton, producing rapid setting and early strength gain. Continued dissolution and precipitation further fill intercrystalline spaces and densify the pore structure. Thus, MPC strength depends not only on the amount of hydration products, but also on crystal morphology and network connectivity. Hardened MPC usually contains phases other than K-struvite. A low M/P ratio may leave residual soluble phosphates, whereas a high M/P ratio or low MgO reactivity can result in unreacted periclase, which may later hydrate to $Mg(OH)_2$. Other secondary phases, including amorphous magnesium phosphates, newberyite, and bobierrite, may also form depending on composition and pH [14, 15]. Residual MgO can act as a microfiller, but excessive amounts may create weak regions through later hydration, interfacial deterioration, or volume change.

3. Early-age strength development of magnesium phosphate cement

3.1. Characteristics of early strength gain

The early-age performance of rapid repair materials should be linked to the required reopening time. Strength within 1-3 h determines whether traffic can be restored quickly, while later strength reflects

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early service stability. Optimized MPC systems have been reported to reach about 28 MPa at 1 h and over 40 MPa at 3 h [1]. Their 1 d, 3 d, and 7 d strengths can reach about 68%, 77%, and 88% of the 28 d value, compared with 39%, 57%, and 73% for PC. However, compressive strength alone is insufficient for repair applications; flexural strength, interfacial bonding, and fatigue resistance should also be considered.

3.2. Influence of material parameters on early strength

3.2.1. Calcination temperature and reactivity of MgO

The calcination regime of MgO strongly affects the early-age performance of MPC. According to calcination temperature, MgO is generally classified as light-burned (700-1000 °C), hard-burned (1000-1500 °C), and dead-burned (1500-2000 °C), which is shown in Fig.2. Light-burned MgO has a high specific surface area and more lattice defects, allowing rapid Mg^{2+} release and promoting K-struvite formation, but excessive reactivity may cause flash setting and loss of workability. With increasing calcination temperature, sintering and grain growth reduce MgO reactivity, delay K-struvite formation, and generally lower early-age strength [5-7]. Hard-burned MgO therefore shows moderate reactivity, whereas dead-burned MgO has the densest structure and lowest reactivity. Holding time and cooling rate also affect MgO reactivity by altering decomposition, sintering, and lattice defects. Thus, MgO selection should balance reactivity, early strength, and constructability.

(a) 700 °C MgO; *(b) 1100 °C MgO;* *(c) 1500 °C MgO.*

Figure 2. The powders of different types of MgO

3.2.2. Magnesia-to-phosphate molar ratio

The M/P ratio strongly influences the reaction and strength development of MPC. Although the theoretical stoichiometric ratio for K-struvite formation is 1, practical mixtures commonly use M/P values of about 2-8 [15, 16]. A low M/P ratio may limit K-struvite formation and leave residual soluble phosphates, reducing water stability. Increasing M/P generally promotes phosphate fixation and crystal-network formation, but an excessive ratio leaves more unreacted MgO and reduces the proportion of effective binding phases. Therefore, an optimum M/P range exists, and its appropriate value depends on MgO reactivity, water-to-binder ratio, and retarder dosage.

3.2.3. Water-to-binder ratio

The water-to-binder ratio strongly affects the reaction and pore structure of MPC. A lower ratio increases ionic concentration, promotes K-struvite precipitation, and reduces capillary porosity, which generally benefits early strength. However, insufficient water can hinder KDP dissolution and reduce paste workability. In contrast, a higher ratio improves flowability but dilutes Mg^{2+} and phosphate species, delays precipitation, and increases porosity. Typical MPC water-to-binder ratios

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range from 0.15 to 0.30, with 0.15-0.20 commonly used [10, 11]. The water-to-binder ratio also interacts with M/P; thus, these two parameters should be optimized together rather than independently.

3.2.4. Retarders

Retarders strongly affect the early-age behavior of MPC. An appropriate borax dosage slows MgO dissolution, extends working time, and reduces flash setting, while having only a limited effect on 1 d strength [12]. Excessive borax, however, delays supersaturation, reduces early hydration-product formation, and increases porosity, leading to lower early strength. Thus, retarder performance should be evaluated not only by setting time, but also by flow retention, temperature rise, and 1-3 h strength.

3.2.5. Curing regimes

The curing regime strongly affects hydration-product stability and strength development in MPC. Appropriate moisture helps sustain further reaction, whereas early water immersion may dissolve K-struvite, promote phosphate leaching, and increase pore connectivity [17, 18]. Therefore, sealed, high-humidity, and immersion curing should be distinguished. MPC generally shows relatively low drying shrinkage, although residual MgO hydration and dissolution–reprecipitation may still cause volume changes. Temperature also influences reaction kinetics: higher temperatures accelerate KDP dissolution, MgO reaction, and crystal nucleation but shorten working time and intensify heat release, while lower temperatures delay strength development. Thus, curing conditions should be selected according to the intended service environment.

4. Rapid repair applications and performance perspectives

4.1. Application scenarios of MPC-based repair materials

MPC is particularly suitable for rapid repair because it can develop load-bearing capacity within hours rather than days. Its rapid setting, high early-age strength, low shrinkage, and good interfacial compatibility help shorten closure times and reduce traffic or production interruptions [3, 4]. Typical applications include pavement potholes, bridge deck spalling, expansion-joint regions, airport runways, and railway facilities. Its rapid reaction and early heat release also provide some potential for low-temperature repair.

MPC can also be used for local strengthening, anchoring, void filling, and rapid restoration of industrial foundations. However, long-term water exposure, large-volume placement, and prolonged construction may increase concerns related to water stability, heat release, and short working time. Thus, MPC is best suited to localized repairs requiring short closure periods and rapid return to service.

4.2. Bonding performance with existing concrete

MPC generally bonds well with existing concrete because magnesium phosphate hydrates can penetrate surface irregularities and form mechanical interlocking [2-4]. However, reliable bonding still requires proper substrate preparation. Loose particles, oil, standing water, or unsuitable moisture conditions can weaken the interface, so the old concrete should be roughened, cleaned, and moisture-controlled before repair. Because MPC sets rapidly, placement, compaction, and finishing

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should be completed promptly, while retempering and excessive delays between layers should be avoided. Bond quality can be verified by pull-off or splitting bond tests.

4.3. Limitations and future work of MPC

Despite its rapid setting, high early-age strength, and good bonding, MPC is limited by short working time, flash setting, and concentrated heat release. These issues can reduce fluidity and create thermal stress in thick repairs. Water stability is another concern, as early exposure may dissolve K-struvite, promote phosphate leaching, and reduce strength [17, 18]. Thus, mix design should balance reaction rate, workability, early strength, and water resistance.

Future research should emphasize multi-objective optimization rather than strength alone. Low-temperature-calcined MgO, low-grade magnesium sources, and industrial by-products may reduce cost and environmental impact [6, 19, 20]. Standardized raw-material characterization, durability evaluation, and reopening criteria are also needed to support reliable engineering application.

5. Conclusion

This review summarizes the hydration mechanisms, early-age strength development, and rapid-repair applications of magnesium phosphate cement (MPC). The main conclusions are as follows:

(1) MPC hardens through phosphate dissolution, MgO dissolution, ion interaction, and rapid precipitation of struvite-type hydrates. In KDP-based MKPC, K-struvite ($KMgPO_4 \cdot 6H_2O$) forms a continuous interlocking crystal network, which provides the main structural basis for rapid setting and early strength development.

(2) The early-age performance of MPC is jointly controlled by MgO reactivity, M/P ratio, water-to-binder ratio, retarder dosage, and curing conditions. These factors are strongly coupled: highly reactive MgO promotes early strength but may cause flash setting, while inappropriate M/P or water content can reduce hydration efficiency and increase porosity. Therefore, MPC mix design should balance reaction rate, workability, and early strength rather than optimize a single parameter.

(3) MPC is particularly suitable for localized repairs requiring short closure periods, including pavements, bridge decks, airport runways, and railway facilities. Its main advantages are rapid setting, high early-age strength, low shrinkage, and good bonding. However, short working time, heat release, early-age water sensitivity, and relatively high cost remain major limitations. Future research should focus on multi-objective mixture optimization, durability under realistic service conditions, lower-cost raw materials, and standardized reopening criteria.

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