



Study on the hydration process and borax retarding mechanism of the magnesium ammonium phosphate cement-based coating system

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Abstract. In this study, the reaction process of the MAPC coating system is investigated. And the delayed curing mechanism of borax in the coating hydration system is proposed. The results suggest that the research process of magnesium oxide-monoammonium phosphate-water diluted ternary suspension system is applicable for the MAPC coating reaction process, which can be divided into three stages: $\text{NH}_4\text{H}_2\text{PO}_4$ dissolution, $\text{MgNH}_4\text{PO}_4 \cdot 6\text{H}_2\text{O}$ primary crystallization and secondary crystallization. Borax can delay the setting and hardening time of MAPC, reduce the pH value and lower the hydration temperature without forming any new hydration product. Borax can improve the fluidity of MAPC coatings, and borax content has an effect on the compressive strength of MAPC hardened paste. The retarding effect is controlled by the formation and rupture of the protective film on the surface of MgO; the other is controlled by lowering the system temperature and adjusting the pH value of the coatings. In the hydration process, borax does not form new hydration products.

Keywords. MAPC; turbid liquid; pH value; hydration; delayed curing.

1. Introduction

Cement is one of the important building materials. According to the difference of main chemical composition, it can be divided into two categories: calcium cement and magnesium cement. Calcium cement mainly includes Portland cement, aluminat cement, sulphoaluminat cement. Magnesium cement mainly includes magnesium phosphate cement, magnesium oxychloride cement and magnesium oxysulfide cement. Calcium cement, especially Portland cement, is widely used in civil engineering, and there are many researches at present. Although magnesium cement has many excellent properties, its many defects such as, early strength and rapid setting, dry shrinkage, and high bond strength with old concrete limit its application in civil engineering [1–5].

The Portland cement concrete structure can no longer satisfy harsh environmental requirements in salt lakes and other areas with heavy soil salinity. Due to the intrinsic characteristics of Portland cement, anti-corrosion measures

should be taken to enhance its durability. There are mainly two methods to prevent and control corrosion. One is to improve concrete compactness, and the other is to coat a protection layer on the concrete surface. Evidence shows [6, 7] that the latter is more economic and practical. The protective coating of concrete structures should be firmly bonded with the structure surface without cracking, with good bending elasticity and good corrosion resistance. Current concrete protection coatings can be classified into two categories. The first is an organic coating, which is with strong hydrophobicity, water-resistance and anti-permeability. Unfortunately, for common organic coatings, there are strict requirements about their working environment. Long-term use of the organic coatings may cause fatal problems such as aging, degradation, and decomposition. The second category is inorganic coating with admixtures, which is characterized by good performance to heat and aging, and high surface hardness, but poor bond performance and low intensity and is likely to peel off at room temperature. In addition to rapid repair of concrete

structure, the inorganic protective coating can also be used for curing optimization, radioactive nuclear waste and spraying anticorrosive coating [8–17].

Magnesium ammonium phosphate cement (MAPC) is an inorganic cementing material with phosphate as the binding phase produced through chemical and physical interaction by using the raw materials of dead-burnt magnesium oxide, monoammonium phosphate and admixtures at a certain ratio [18–22]. Such material is of low temperature curing [23–25], high early strength, high volume stability, and strong binding property. These advantages of MAPC accord with the characteristics of concrete structure protective coating, and can be used on bridges, dam and other structural surface. Therefore, MAPC is expected to be the most ideal inorganic protective coating for Portland cement concrete structure. These features enable MAPC-based materials to be a promising ideal inorganic protection coating for Portland cement concrete structure. However, the rapid setting and workability of MAPC coating is difficult to be controlled and methods to retard setting is not good, which limits its development and wide use. Therefore, how to deal with rapid setting and improving the working performance of the MAPC coating is the main problem faced by the MAPC coating. The research on the hydration process of MAPC coating is the basis of the research on the performance control of MAPC coating.

In this research, the diluted suspension of MAPC-based coating is prepared, while the pH value and hydration temperature during the MAPC coating reaction process are respectively determined with a pH meter and a hydration heat testing machine, so as to investigate the reaction mechanism, which is based on phase analysis. Then the hydration heat release and pH value of this system are determined after adding different borax contents. According to the results of the above tests, a delayed curing mechanism of borax in the coating hydration system is proposed.

2. Materials and experiments

2.1 Materials

The MAPC is prepared by mixing magnesia oxide powder, $\text{NH}_4\text{H}_2\text{PO}_4$, and a compound retarder set to a certain proportion in the laboratory. The preparation of MAPC is introduced in detail in Section 2.3. The dead burned magnesia (MgO) powder, with a specific surface of $280 \text{ m}^2/\text{kg}$, calcined at $>1700 \text{ }^\circ\text{C}$ and with an averaged particle size of about $20 \text{ }\mu\text{m}$ is obtained from the Huashan Plant, Shenyang. The particle size parameters and specific surface area of MgO were measured by laser particle sizer and specific surface area tester. The specific gravity of the powder is approximately 3.67. The composition of MgO is determined by X-ray florescence (XRF). The chemical

Table 1. Main components of MgO powder.

Component	MgO	CaO	SiO ₂	Fe ₂ O ₃	Al ₂ O ₃	Loss
Mass fraction/%	91.85	3.14	3.68	0.87	0.16	0.30

compositions of the commercial dead burned MgO are presented in table 1.

Industrial-grade $\text{NH}_4\text{H}_2\text{PO}_4$ is used as soluble phosphate. The maximum particle size of the $\text{NH}_4\text{H}_2\text{PO}_4$ is $700 \text{ }\mu\text{m}$, the purity of which is higher than 98%. The retarder $\text{NaB}_4\text{O}_7 \cdot 10\text{H}_2\text{O}$, termed as B, is prepared in the laboratory. The maximum particle size of $\text{NaB}_4\text{O}_7 \cdot 10\text{H}_2\text{O}$ is $800 \text{ }\mu\text{m}$ and its purity is higher than 98%. Deionized water is used as the mixing water.

2.2 Disposition of diluted suspension of MAPC coatings

The MAPC coatings are made by mixing the raw materials with a magnesia-to-phosphate molar ratio (M/P) of 2, 4, 6, 8, 10 and a phosphate paste-to-magnesia molar ratio (m_B/m_{MgO}) of 0.05. The water-to-cement mass ratio (W/C) of the cement, which contains magnesia and $\text{NH}_4\text{H}_2\text{PO}_4$, is 0.12. Mixture proportions used in the dilute MAPC systems are shown in table 2.

The powdered materials, consisting of MgO, $\text{NH}_4\text{H}_2\text{PO}_4$, and $\text{NaB}_4\text{O}_7 \cdot 10\text{H}_2\text{O}$, are dry-mixed in a mixer pan for 3 minutes. Finally, after adding 1000 mL deionized water, the diluted suspension of MAPC is obtained.

2.3 Experimental methods

2.3a Hydration temperature At 20°C environment temperature, 12 g water is added into 100 g MAPC dry powder, and then the lowest temperature is measured. A minute later, MAPC paste is sufficiently mixed. During this period, the initial temperature of the MAPC paste is measured with a thermometer; the K-type thermocouple is inserted into the paste center; the temperature changes of the hydration system are recorded by the SMT-32 automatic temperature

Table 2. Mixture proportions used in the dilute MAPC systems.

System	Magnesia (g)	NDP (g)	M/P	Water (mL)
1	4.102	5.897	2	100
2	5.818	4.182	4	100
3	6.761	3.239	6	100
4	7.356	2.644	8	100
5	7.767	2.233	10	100

recording machine (Beijing SaiWeiGuanGao Science and Technology Co., Ltd).

2.3b pH value The hydration reaction rate of MAPC paste is high, with great temperature variation amplitude during the hydration process. As a result, the conventional methods to determine the pH value of turbid liquid are inappropriate for the MPC paste before final set. The turbid liquid is continuously stirred to prevent the paste from precipitating, and the pH value is measured with the pH electrode at the specified time. The MAPC turbid liquid is further stirred for subsequent test.

2.3c X-ray diffraction (XRD) With the proceeding of the MAPC reaction, the MAPC turbid liquid is rapidly filtered when the specified time is reached. Meanwhile, the residue on the filter is washed with absolute ethanol to terminate the hydration reaction. Then, the residue is dried in the ventilating environment 24 hours. And the small pieces of MAPC were crushed and ground. Then they were sealed with sealed bag and marked the number. After drying, X-ray analysis is performed on the residue to investigate the hydration reaction process of the MAPC coating. Bruker D8 X-ray diffractometer in Germany was used. (The working voltage is 40 Kv; the working current is 30 mA; the step width is 0.02 °; the scanning speed is 1s / step; and the scanning range is 0-90 °.)

In this study, the crystalline phase composition of the test specimen is determined with the D/max—RB X-ray diffraction (XRD) machine (RIGAKU, Japan; working conditions: CuK α , tube voltage 40 kV and tube current 100 mA).

3. Results and discussion

3.1 pH value of the borax-free MAPC coating system

The pH-temperature-time curve for turbid liquid of the MAPC coating is presented in figure 1. figure 1 shows the

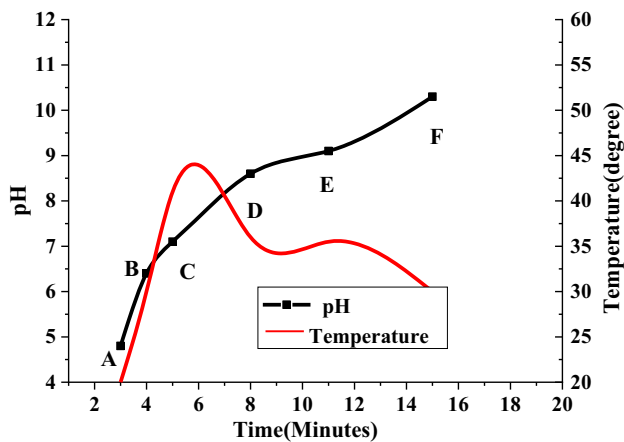


Figure 1. Typical pH-temperature development and the characteristic points of the dilute MAPC system.

temperature change of MAPC coating reaction solution prepared by mixing MgO and NH $_4$ H $_2$ PO $_4$ in a certain proportion at 20 °C \pm 2 °C ambient temperature (the initial temperature is the lowest temperature of the reaction solution). After MgO and NH $_4$ H $_2$ PO $_4$ are mixed, the temperature of the mixed solution drops slightly, but soon returns to the ambient temperature. With the hydration reaction, the temperature rises from 20 °C to the highest temperature 52 °C within 6 minutes. Then the temperature of the mixed solution decreased gradually and reached 35 °C after about 3 min. As the hydration reaction continues, the temperature of the mixed solution will gradually drop, and the temperature of the final reaction solution will remain basically unchanged at 30 °C.

figure 1 shows the change of pH value of the reaction solution of MAPC coating prepared by MgO and NH $_4$ H $_2$ PO $_4$ at room temperature (20 °C). At the beginning of the hydration reaction, because NH $_4$ H $_2$ PO $_4$ is a strong acid and weak base salt, it is easily soluble in water, so the solution is acidic and the pH value is about 5. When the reaction lasted for 9 min, the hydration reaction speed decreased, the hydration product MgNH $_4$ PO $_4$ ·6H $_2$ O (MNP) increased, the increase of pH value decreased, and finally stabilized at about 10, and the mixed solution was alkaline.

Monoammonium phosphate rapidly dissolves in water, and the pH-time curve rapidly decreases within the acidic range, and then elevates to the first local peak due to the neutralization of magnesium oxide. Afterwards, the pH value slowly reduces at the beginning and then increases either slowly or rapidly. The temperature-time curve increases at first and tends to stay at the pH of about 8.5. According to the temperature curve, it is the severe exothermic reaction between magnesium oxide and monoammonium phosphate.

For a better understanding, the solid phase and solution composition at the characteristic points in figure 1 are analyzed. The characteristic points in figure 1 are named as follows for easy description: the first local peak is denoted as point “A”; “C” represents the turning point from slow increase to rapid increase; “E” is the turning point from rapid increase to slow increase; “B” and “D” are the transient points between “A” and “E”, as well as “C” and “E”; the final stable point is denoted as “F”.

3.2 Effects of M/A and liquid-to-solid L/S on the pH value of coating system

The curve regarding the effects of various M/P ratios on the pH value of the MAPC hydration system is displayed in figure 2. The pH value of the solution maintains at 5 to 6 in the presence of low M/P (\leq 4), and the pH value slowly increases, which could not elevate to the basic range within 30 minutes. As M/P is over 4, the pH value rapidly increases with the increase in M/P, and the reaction time is shortened. Due to the increase in M/P (or the decrease in

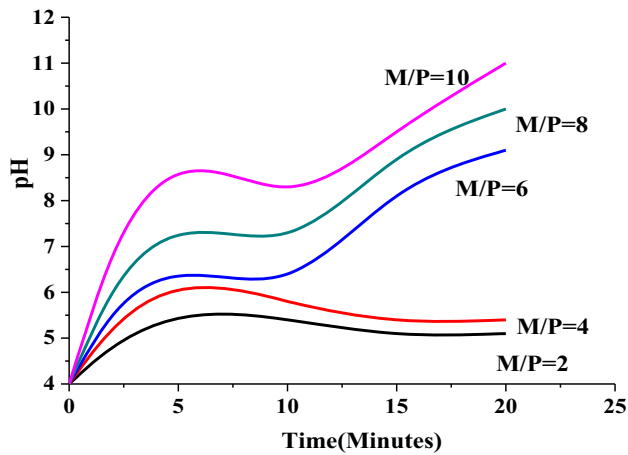


Figure 2. Effect of M/P on the pH development of MgO- $\text{NH}_4\text{H}_2\text{PO}_4 \cdot 6\text{H}_2\text{O}$ system.

monoammonium phosphate dose), the pH value at each characteristic point increases as well. The dissolved magnesium oxide increases the effects on the pH value of the MAPC hydration system, which also contributes to the production of the reaction product. Based on such changes, the optimal M/P value is 4.

3.3 Effects of borax on the pH value changes of the MAPC coating system

figures 3 and 4 present the effects of borax on the pH value and temperature curves of the MAPC coating system at M/P=4. These pH curves have a similar shape regardless of the borax addition amounts, and the pH variation displays a similar rule. With the increasing addition of borax content, the time lasted at the second stage is markedly extended. As for borax-free MAPC, that period of time is about 240 s; it is 400 s at the borax addition mass amount of 5%, and 900 s

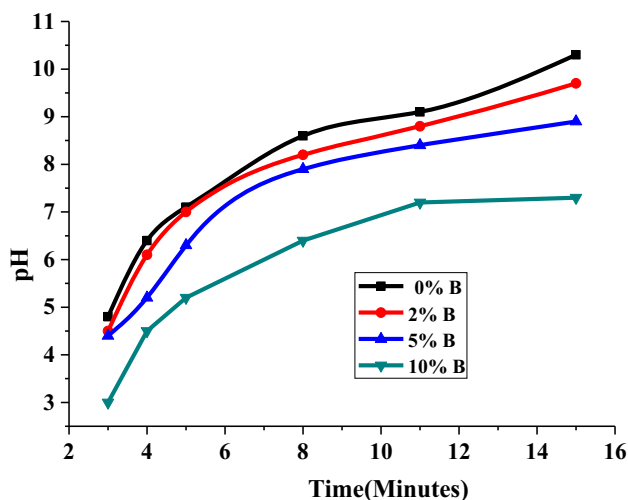


Figure 3. Effect of borax on the pH curve of MAPC (M/P=4).

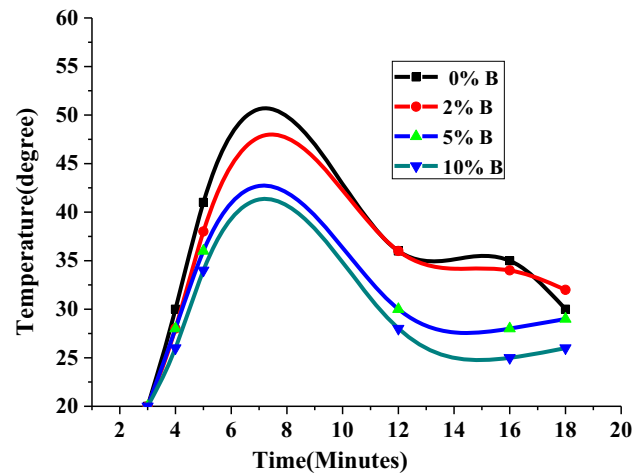


Figure 4. Effect of boric acid on the temperature curve of MAPC (M/P=4).

at the borax mass addition amount of 10%. Another significant change of the pH curve is that, with the increase in borax addition amount, the pH value of the MAPC coating system is decreased from 10.7 to 8.7 and 8.3.

The temperature curve in figure 4 indicates that, 5% borax and 10% borax have little influence on the temperature of the MAPC coating system, and the temperature variation trends are alike. The three temperature variation curves peak at 6–8 minutes. The highest temperature for test specimens with various borax amounts is 52°C. The temperature is 43°C for specimen with 5% of borax and 40°C for those with 10% of borax. With the increase in borax content, the lowest temperature of MAPC paste and the heating rate decreases gradually, yet more time is required to reach the highest temperature, and the extension effect is not obvious.

Borax on MAPC coating can have a regulating effect on pH value, the reason: borax is a strong base and weak acid salt, easy ionization in water to generate tetraborate ions and sodium ions, so that the aqueous solution is alkaline. $\text{NH}_4\text{H}_2\text{PO}_4$ is an acidic salt of multiple weak acids, which is easy to ionize hydrogen ions in water, making the aqueous solution acidic. When borax is mixed with $\text{NH}_4\text{H}_2\text{PO}_4$ in water, the tetraborate ions generated by the ionization of borax are easy to combine with the hydrogen ions ionized by $\text{NH}_4\text{H}_2\text{PO}_4$ to form weak electrolyte tetraboric acid, which reduces the hydrogen ions in the solution, accelerates the ionization of $\text{NH}_4\text{H}_2\text{PO}_4$ in the aqueous solution and strengthens the dissolution. At the same time, the dissolution of borax in the acidic reaction solution is also strengthened. Due to the mutual promotion and dissolution of $\text{NH}_4\text{H}_2\text{PO}_4$ and borax. As the hydrogen ions in the solution decrease, the pH value of the solution increases. The effect of pH adjustment was obvious only in a certain range of borax content, and weakened with the further increase of borax content.

4. Hydration product analysis

4.1 Hydration product of the borax-free MAPC coating system

The XRD results at 5 min, 11 min, 15 min of the coating process at M/P=4 are presented in figure 5. By comparing the XRD patterns of MAPC hardening bodies with different reaction times, no significant difference was found in the peak position, indicating that the hydration products of MAPC slurry in different time periods were basically the same. There are 6 characteristic peaks of magnesium ammonium phosphate crystal in the map, indicating that the main hydration product of MAPC slurry hydration is MNP crystal. The strong diffraction peak of MgO indicates that there is still a lot of excess MgO in the hardened body, and the characteristic peak of $\text{NH}_4\text{H}_2\text{PO}_4$ indicates that there is a crystallization of $\text{NH}_4\text{H}_2\text{PO}_4$ in the hardened body. The height of MgO characteristic peak and MNP characteristic peak of the MAPC hardening body with different reaction time was obviously different. After 5 min reaction, MNP hardening body had been found in MAPC coating system. The MNP characteristic peak height of MAPC hardening body after 15 min reaction is significantly higher than that of MAPC hardening body after 5 min reaction, indicating that the crystallization degree of MNP crystal of hydration product generated by the former is better. The MgO characteristic peak of MAPC hardening body after 15 min reaction was higher than that of MAPC hardening body after 5 min reaction, indicating that more MgO did not participate in hydration reaction.

As could be seen from Figure 5, the θ values of the two main characteristic peaks of XRD curve range from 40° to 45° . The peaks within the range of 5° - 45° are presented in figure 5. The results suggest that $\text{MgNH}_4\text{PO}_4 \cdot 6\text{H}_2\text{O}$ is the major only crystallization product at each characteristic point of the system. With continuousness of the experiment,

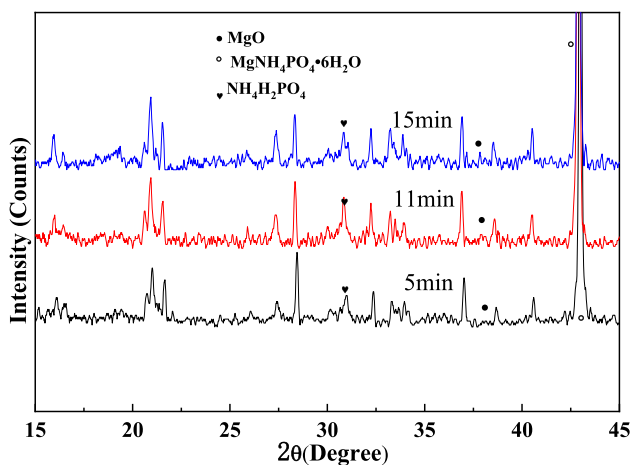


Figure 5. Phases transition at different translation times for MAPC with M/P of 4.

the characteristic peak intensity of $\text{MgNH}_4\text{PO}_4 \cdot 6\text{H}_2\text{O}$ enhances, while that of the unreacted MgO at 37° weakens. Such results suggest that the amount and crystallization degree of the produced $\text{MgNH}_4\text{PO}_4 \cdot 6\text{H}_2\text{O}$ increase with increasing additions of the MgO.

4.2 Effect of borax on the hydration production of MAPC coating system

To verify whether the delayed curing effect is related to the formation of some borax-containing compounds, XRD analysis on the powder sediments at C and F is carried out to identify the reaction product in this study. The XRD results are presented in figure 6. The results suggested that no obvious difference is observed during the entire process after adding borax and that no new crystallization product is found. Meanwhile, besides the unreacted MgO, the major hydration product is $\text{MgNH}_4\text{PO}_4 \cdot 6\text{H}_2\text{O}$ [26, 27]. No borax-containing compound crystal is generated during the reaction process. It is different from the borax delayed curing mechanisms reported by other scholars. As different phosphates may be adopted to prepare MAPC, the experiments may present different reaction mechanisms or processes. In addition, the pH-temperature variation and composition analysis suggest that borax would not change the product during the reaction.

Comparing the XRD patterns of the MAPC hardening body at the two characteristic points C and F, no significant difference was found in the peak position, indicating that the hydration products of MAPC slurry in different time periods were basically the same. The effect of borax on the hydration products of MAPC hardening body is only shown in the effect on the structure and morphology of the hydration products. At the beginning of the hydration reaction, there are many cracks in MNP due to the faster hydration reaction. This is because the faster the rate of formation of hydration products, the more defects in the

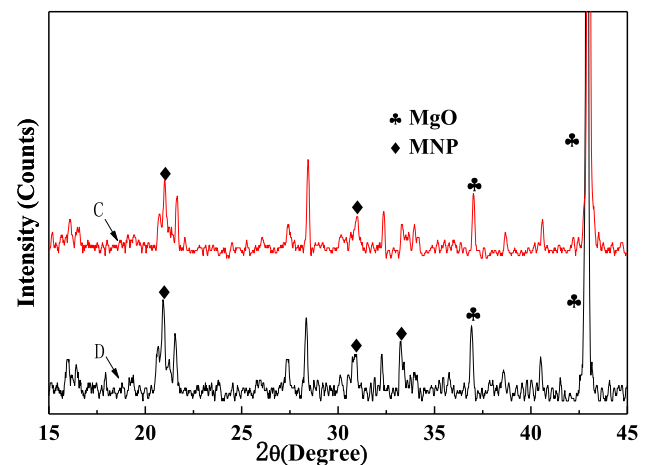


Figure 6. XRD at the location of C, F for MAPC with 5% borax.

crystal, the more contact points between them [28–30]. As the reaction goes on, the hydration reaction slows down, the hydration product generation rate slows down, the crystal defect decreases, the phenomenon of recrystallization decreases, the structure of the hardened cement slurry is more perfect and the strength is higher. However, at the end of hydration, effective components involved in the hydration reaction are reduced, hydration products are reduced, and there are other crystal particles in the MAPC hardening body that do not participate in the reaction. Their surface is smooth, their strength is very low, and their adhesion with cementing material is very small, which forms the weak link in the MAPC hardening body.

The composite retarder makes the early hydration reaction speed of the MAPC hydration system slow down, the early hydration products are less, the hydration products are gradually crystallized and precipitated, the crystal nucleus is less and large, the crystal crystallization degree is high, there are few defects, and the crystal stability is good. With the gradual progress of hydration, the crystals of hydration products can grow well and have few defects. As the early hydration reaction slows down, the total hydration heat release is reduced and mildly released. The hydration reaction continues slowly, and the generated hydration product crystals gradually fill the structural pores, making the hardened body structure more and more compact.

The colloidal microcrystals generated are not stable and can gradually recrystallize and grow up. The unhydrated MgO particles are tightly wrapped in the cement slurry and gradually hardened to form cement stone with certain mechanical strength. Later, with the increase of age, the hydration is further improved and the hydration structure is more denser.

The result of the experiment indicates that borax can reduce the pH value and temperature of the MAPC solution and thus delay the reaction, which is mainly ascribed to the suppression of hydrolysis of MgO particles in water or the buffering effect of magnesium hydration product. Additionally, the dissolution of magnesium oxide in acid is an exothermic reaction; the heat can accelerate the reaction of MAPC; and borax can delay the reaction by partly absorbing the heat.

5. Mechanism analysis

5.1 Borax-free MAPC coating system

The MAPC formation process can be divided into 3 stages based on the changes in pH value and sediment crystalline phase composition, as presented in figure 7.

Stage I (before point C) - $\text{NH}_4\text{H}_2\text{PO}_4$ dissolution. $\text{NH}_4\text{H}_2\text{PO}_4$ immediately dissolves when magnesium oxide and $\text{NH}_4\text{H}_2\text{PO}_4$ powder mix with water. The acid solution forms and then the magnesium oxide slightly dissolves. As $\text{NH}_4\text{H}_2\text{PO}_4$ is water-soluble and a relatively great amount

of water is used, the time required at this stage is extremely short, generally shorter than 5 minutes [31].

Stage II (from point C to point E)- $\text{MgNH}_4\text{PO}_4 \cdot 6\text{H}_2\text{O}$ crystallization. With the continuous dissolution of magnesium oxide, acid is slowly neutralized, and the solution pH value slowly goes up. Meanwhile the H_2PO_4^- anion easily reacts with Mg^{2+} from the dissolution of magnesium oxide to produce the phosphate. $\text{MgNH}_4\text{PO}_4 \cdot 6\text{H}_2\text{O}$ will crystallize when its concentration reaches the solubility product.

Stage III (after point E)- continuous crystallization of $\text{MgNH}_4\text{PO}_4 \cdot 6\text{H}_2\text{O}$. Apart from that, the pH value of the solution slightly drops due to the consumption of hydroxyl ions at the late stage when crystallization dominates.

In order to reveal the reaction mechanism of the MAPC diluent system, the pH-temperature changes and turbid liquid at the filter characteristic points are monitored and the residue phase is identified. Meanwhile, the element ion concentration is also determined. The MAPC three-step reaction is constructed based on the experimental complementary results.

5.2 Delayed curing mechanism of borax

The delayed curing mechanism of borax can be obtained based on the its effects on pH value, hydration temperature and the absence of newly produced hydration product. This experiment is conducted in the liquid phase.

1. In the case of low borax addition amount (2%), borax mainly dissolves in the MAPC hydration system. A small amount of borax sufficiently dissolves in the liquid phase of the MAPC hydration system. The boric acid anions are rapidly adsorbed around MgO particles. After the MAPC raw material is added with water, $\text{NH}_4\text{H}_2\text{PO}_4$ dissolves rapidly in water to form an acid saturated solution of $\text{NH}_4\text{H}_2\text{PO}_4$. Mg^{2+} divalent positive ion, coordination number 4, belongs to weak complex. In

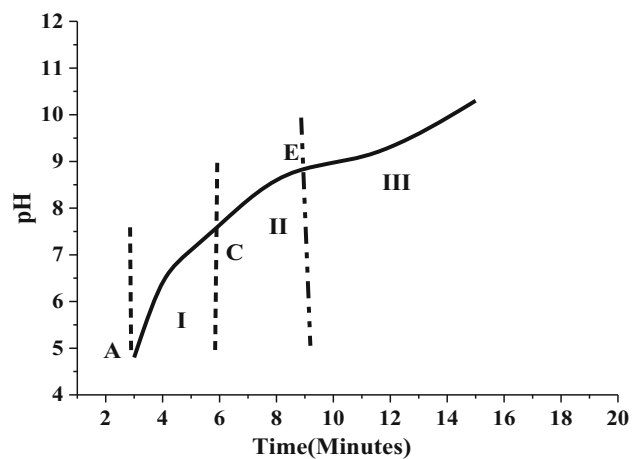
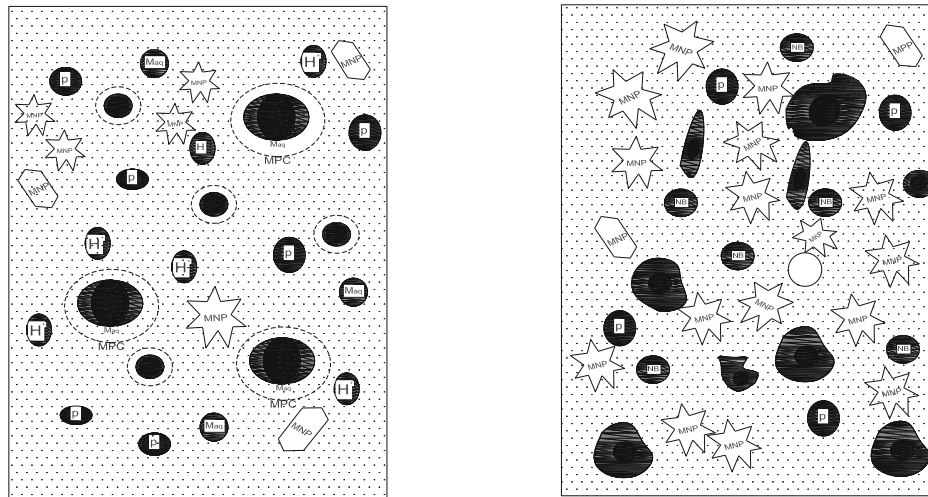
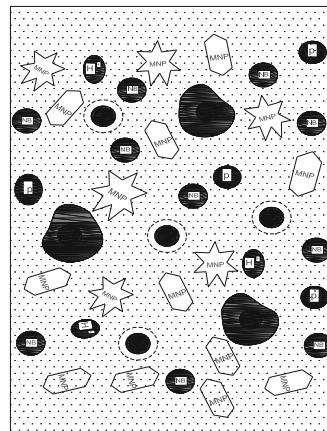


Figure 7. Classification of the reaction stages of the MAPC system.



(a) Borax and MgO dissolve and struvite form

(b) Borax reduces pH and hinders hydration reaction



(c) Borax absorbs heat, a large amount of monoammonium phosphate distribution

Figure 8. Mechanism model of MAPC Retarded by NB.

$\text{NH}_4\text{H}_2\text{PO}_4$ acid solution, only unstable complex can be formed. However, in $\text{NH}_4\text{H}_2\text{PO}_4$ acid solution, carboxyl group and free Mg^{2+} can form complex [50–52]. Only part of monoammonium phosphate dissolves due to limited water to ionize H^+ and phosphate anions. Part of monoammonium phosphate is distributed into the MAPC system in solid form. MgO particles dissolve in the acidic liquid phase of MAPC hydration system to produce the hydrated magnesium ions that surround MgO particles. Among the hydrated magnesium ions produced, only a few disperse into the liquid phase and then rapidly react with the boric acid anions, successfully producing $\text{MgNH}_4\text{PO}_4 \cdot 6\text{H}_2\text{O}$ [31]. Some boric acid anions and hydrated magnesium ions around the MgO particles cover the MgO surface to form the ion layer, which occupies the position of boric acid anions, thus indirectly hindering the contact between boric acid anions and the hydrated magnesium ions, and slows

down the hydration reaction. When the phosphate anions at the liquid phase gradually penetrate the ion layer and then react with the hydrated magnesium ions around the MgO particles to produce phosphate hydration product (MNP), a fraction of the ion layer is broken. As a result, the hydrated magnesium ions and $\text{MgNH}_4\text{PO}_4 \cdot 6\text{H}_2\text{O}$ diffuse into the MPC liquid phase. Then the hydrated magnesium ions react with phosphate anions to generate a large amount of $\text{MgNH}_4\text{PO}_4 \cdot 6\text{H}_2\text{O}$ which disperse into the MPC liquid phase (figure 8a).

- When the borax addition increases to 5%, its major role in the MAPC coating system is to reduce the pH value. Borax increases the solubility of the acidic MAPC hydration system. While more boric acid anions are rapidly absorbed around the MgO particles, the remained boric acid anions disperse into the liquid phase of the MAPC coating system and release H^+ . In this way, the pH value of the MAPC hydration system liquid phase

reduces, which further reduces the solubility of MNP at the liquid phase and lower phosphate anion content. MgO particles dissolve in the liquid phase of the acidic MAPC hydration system to produce hydrated magnesium ions around the MgO particle surface, while the hydrated magnesium ions disperse into the liquid phase rapidly and react with the boric acid anions to produce $\text{MgNH}_4\text{PO}_4 \cdot 6\text{H}_2\text{O}$. Some hydrated magnesium ions and more boric acid anions cover the MgO surface to form a thick ion layer. This layer occupies an extended position of phosphate ions in the liquid phase, and thus hinders the contact between phosphate anions and hydrated magnesium ions (figure 8b). However, the ion layer is rapidly penetrated due to a large amount of phosphate anions in the liquid phase, which then reacts with hydrated magnesium ions and produces the phosphate hydration product. Meanwhile, there are many hydrated magnesium ions and $\text{MgNH}_4\text{PO}_4 \cdot 6\text{H}_2\text{O}$ dispersed into the MAPC liquid phase, and the hydrated magnesium ions in the liquid phase react with phosphate anions to produce excessive MNP.

- When the borax increases to 5%, it cools down and dissolves in the MAPC hydration system. A few boric acid anions are rapidly absorbed around the MgO particles, while those remained disperse into the liquid phase. During the dissolution process of borax in the acidic liquid phase, a great amount of hydration heat is absorbed, which reduces the temperature of the MPC hydration system, thus weakening the solubility of monoammonium phosphate in the liquid phase. Therefore, the phosphate anion in the liquid phase becomes less concentrated and most of the remaining monoammonium phosphate is distributed into the MNP hydration system in a homomorphic manner (figure 8c). The MgO particles dissolve into the liquid phase of the acidic MAPC hydration system, producing hydrated magnesium ions around the MgO particle surface. Part of these hydrated magnesium ions disperses in the liquid phase, rapidly reacting with phosphate anions to produce MNP. The dissolution of MgO in acid is an exothermic reaction, and the heat released can accelerate reaction, while borax can absorb some heat to slow down the reaction.

6. Conclusions

- The reaction process can be divided into three stages: $\text{NH}_4\text{H}_2\text{PO}_4$ dissolution, $\text{MgNH}_4\text{PO}_4 \cdot 6\text{H}_2\text{O}$ primary crystallization and secondary crystallization.
- Borax has the effect of endothermic cooling and pH adjustment on MAPC coatings. Borax in solution promote the dissolution of each other to produce an endothermic cooling effect, reducing the hydration reaction rate and activation energy. At the same time,

the pH value of MAPC slurry was decreased, and the dissolution of magnesium oxide particles was inhibited.

- Borax can delay the setting time of MAPC coatings. The retarding effect is controlled by the formation and rupture of the protective film on the surface of MgO; the other is controlled by lowering the system temperature and adjusting the pH value of the coatings. In the hydration process, borax does not form new hydration products.

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