Research Article

“Dormancy” and “Awakening” Method Used for Fresh Mortar Waste Recycling and Reuse

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Received 24 August 2020; Revised 11 January 2021; Accepted 28 January 2021; Published 8 February 2021

Academic Editor: Payam Shafigh

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A safe and zero hazardous method is proposed to recycle and reuse fresh mortar waste. In this method, a dormancy agent and an awakening agent were used together in this study to reuse waste cement mortars. Citric acid (CA) was used as the dormancy agent to retard the hydration of cement, and an alkaline accelerator (AA) was used as the awakening agent to accelerate the hydration of cement retarded by CA at an early age. Autogenous shrinkage, dry shrinkage and quality loss, compressive strength, capillary water absorption, and rapid chloride penetration testing were performed for the mortars. A setting time test, X-ray diffraction, and thermogravimetric analysis (TGA) were performed for the pastes (without sand). The results showed that the addition of 0.3% of CA solution increased the setting time significantly. This was because the citrate ions were absorbed onto the surface of the cement particles and a protective film was formed around the cement particles to retard dissolution. However, the retarding effect was eliminated by the AA, which was mainly composed of sodium silicate due to the contribution to initial calcium consumption. With the increasing dosage of the AA, the autogenous shrinkage, dry shrinkage, water absorption, and total charges passed were increased continuously compared to the reference. However, the influence was insignificant at a low dosage of the AA (1% and 1.5%). Obviously, the compressive strengths of the mortars with the AA were increased compared with the reference at the curing times of 3 d and 7 d. On the basis of not reducing the compressive strength of mortar, the reutilization of fresh mortar waste is realized. From this work, it was found that the reuse of waste cement mortars was feasible with the combined utilization of CA and the AA, which could provide some theoretical basis and experimental data for engineering applications.

1. Introduction

In recent decades, infrastructure and real estate have been developed rapidly, and a massive amount of cement-based materials has been rampantly produced. Concrete and mortar are widely used in the world [1]. However, massive wasted amounts of concrete are produced simultaneously. The average annual generation of construction and demolition waste is about 2.36 billion tons [2]. China generated 1.13 billion tons of construction and demolition waste in 2014 [3]. In 2015, there were 3.9 billion tons of construction and demolition waste in China, and the amount of concretes waste was nearly 30% [4]. Most concrete waste has been mainly discarded to landfills in the past few years, which not only consumes valuable public space but also produces harmful substances (breeding of pests) [5]. Various studies

have been conducted concerning the reuse of concrete and mortar wastes. Usage as recycled concrete aggregate (RCA) is a promising solution that can help the sustainability of economics and environmentalism in the respective countries over the long term [6–8]. Additionally, some other studies have focused on recycled hydrated cement paste (HCP) from fine concrete powder waste as a binder for the production of new concretes [9–11]. Utilizing recycling materials of waste concrete in engineering fields will contribute to protecting the environment and making full use of the residual value of waste concrete [12]. RCA and HCP are used mainly for the recycling of hardened waste concrete.

However, in actual building construction, the qualified fresh concrete cannot be used in time in special environments and special circumstances, such as long distances from concrete batching plants to construction sites and the

failure of pumping equipment, resulting in the loss of concrete performance and finally in the discarding of the concrete. The traditional recovery and utilization of fresh concrete waste involve using a sand and gravel separator to separate sand and gravel. However, at the same time, massive waste water and residue will be generated, and a low utilization rate and high cost will be produced. To maximize the recovery utilization rate of fresh concrete waste, chemical additives can be used to adjust the setting time of fresh concrete that cannot be used in time by controlling the hydration process [13]. At present, the setting time of fresh concrete is usually controlled by adding retarders or accelerators separately, but very rarely by adding the combination of both. However, retarders and accelerators are used simultaneously as a functionalization method of “dormancy” and “awakening” to increase significant flexibility during construction. Reiter et al. [14] used mineral addition as an awakening agent to wake up a cement mixture that was delayed heavily. In that research, the addition of a high dosage of superplasticizer in concrete delayed the setting time of the concrete, which was then woken up using bentonite with a high affinity to combine a superplasticizer. Riding et al. [15] used supplementary cementitious material (a nucleating agent) with a superhigh surface area as the accelerator to wake up seriously delayed concrete. Rae and Johnston [16] used a retarder such as sodium gluconate or calcium gluconate as the dormancy agent to produce a storable cement paste which can be activated at a later time (prior to pumping) with sodium silicate as the awakening agent. In addition, nitrilotris(methylene)triphosphonate (NTMP) as a dormancy agent is used to prevent concrete from setting, when the concrete set is desired, an awakening agent (such as calcium nitrate) is added to set the concrete [17]. Pang et al. [18] regulated the hydration kinetics of cement through a combination of strong initial retardation of NTMP and activation of sodium hexametaphosphate.

In this study, a new system of “dormancy” and “awakening” was established; that is, the CA and the AA were used as a dormancy agent and an awakening agent, respectively. CA is an organic admixture that belongs to the carboxylic group of acids that can be used to retard the hydration reaction of ordinary Portland cement [19]. Lanzón and García-Ruiz [20] investigated the influence of CA on the hydration of Portland cement; in the results, the hydration reaction of the cement was retarded by slowing down the dissolution of the clinker grains due to adsorption by citric acid, not by complex formation. The same viewpoint has been shown in several studies [21]. An AA is a common chemical admixture that can influence the rate of cement hydration by comprising a range of chemicals, thereby shortening the setting time and increasing the rate of early strength development. AAs are commonly used in sprayed concrete [22]. The new method provided in this study enjoys some advantages compared with previous research methods [17, 18]: (1) CA is a natural constituent and common metabolite of plants [23] and is readily available, such that lemons, oranges, pineapples, and other plants are rich in CA and possess less threat to the safety of the workers. In this study, the main component of the AA was sodium

silicate, which is considered one of the most benign industrial chemicals in use today [24]; (2) CA and AA are nontoxic, noncarcinogenic material and will not cause harm to human health and environment [24]. (3) The hydration of cement is retarded strongly by CA, which is keeping the fresh mortar wastes in a flowing state for a long time. AA was used to wake up the fresh mortar waste which had been retarded by CA when the hydration of cement was needed. This method will not reduce the compressive strength of mortar and can improve the early compressive strength, which means the reutilization of fresh mortar waste is realized.

This study was designed to evaluate the feasibility of a “CA-AA” system. A comprehensive testing method was implemented to examine the effects of the performance of mortars with CA and an AA. Based on this work, it was found that the setting time of the mortars could be controlled by the “CA-AA” system and no negative influence on the compression of the mortars was observed. The combination of the CA and the AA was proven to be feasible. This method could provide a theoretical basis for engineering practice. This study was only a conceptual validation of the method. Some other performance indicators such as cost saving and reduction in CO₂ emissions will continue to be examined in the follow-up work.

2. Materials and Methods

2.1. Materials. The materials used in the experiment included, cement, sand, citric acid (CA), and an alkaline accelerator (AA). Ordinary Portland cement P.O. 42.5 with 28 d compressive strength over 42.5 MPa was used in this study. The chemical composition of the cement is indicated in Table 1. Normal river sand was used for the fine aggregates during the preparation of the cement mortar and the fineness modulus of the sand was 2.6. The water used for the experiment was normal tap water available in the laboratory. The CA (solid particles) was purchased from the Tianjin Province, and the AA was produced in Shan Dong Province.

2.2. Mix Design. The mixing proportion is shown in Table 2. The ratio of water to cement was 0.45 and the sand rate was 50%. The dosage of the CA was 0.3% of the cement weight [21]. The water in the CA solution was deducted from the mixture to keep the w/c ratio constant. In this investigation, six cement pastes and mortars were utilized to determine the mechanical properties and durability, which were named accordingly CON, AA0, AA1, AA1.5, AA2, and AA2.5. CON, representing the reference sample, “AA,” referring to the alkaline accelerator, and “1,” referring to the alkaline accelerator, were added in dosages of 1% by the weight of cement, and so on for the other groups. Table 2 shows the details of the mixtures.

2.3. Sample Preparation. Fresh mortars containing sand, cement, and water were prepared, and these mortars were placed indoors. After two hours, fresh reference mortars were mixed for 1 minute and then cast into the molds

TABLE 1: The main chemical composition of the cement.

Compounds	CaO	SiO ₂	Al ₂ O ₃	SO ₃	MgO	Fe ₂ O ₃
Percentage (%)	49.70	29.60	7.77	4.70	3.60	2.40

TABLE 2: Mix proportions of the mortar (g/kg).

Numbering	Cement	Sand	Water	CA + water solution	Accelerator (% by weight of cement)
CON	345	500	155	0	0
AA0	345	500	135	1.035 + 20	0
AA1	345	500	135	1.035 + 20	1%
AA1.5	345	500	135	1.035 + 20	1.5%
AA2	345	500	135	1.035 + 20	2%
AA2.5	345	500	135	1.035 + 20	2.5%

directly. The mortars of the other groups were mixed for 1 minute with a CA solution. The mortars for CON-AA2.5 were subsequently cured in a standard curing room ($23 \pm 1^\circ\text{C}$ and $>95\%$ RH). After 24 hours, the mortars for AA1-AA2.5 were removed from the curing room, mixed with different amounts of alkaline accelerators for 1 minute, and then cast into molds and cured in the standard curing room. The specimens of the mortar were used to determine the compressive strength, autogenous shrinkage, dry shrinkage, quality loss, capillary water absorption, and permeability. The paste samples for determining the setting time, X-ray diffraction, and thermogravimetric analysis (TGA) were prepared with the same procedure as that mentioned earlier without sand.

2.4. Setting Time Test. According to the ASTM C191 [25] specifications, the setting times (initial and final) of the paste were determined by using Vicat apparatus. The initial setting time of CON was measured from the completion of the preparation of the cement paste. After adding the CA solution, the initial setting time of the AA0 start was measured. For AA1-AA2.5, after adding the AA, the initial setting time was measured. The ring and the paste of the cement were put in the Vicat apparatus and the needle was in contact with the surface of the cement paste. The needle was sunk freely into the cement paste vertically, and measurements were taken after waiting for 30 s. This procedure was repeated every 15 min until $4\text{ mm} \pm 1\text{ mm}$ between the needle and the bottom plate was observed. The initial setting time of the cement paste was recorded. The final setting time end point was the first penetration measurement that did not mark the specimen surface with a complete circular impression.

2.5. Autogenous Shrinkage. The autogenous shrinkage test of the mortars was conducted using the corrugated pipe according to ASTM C1698 [26]. The fresh mortars were loaded into a corrugated pipe whose bottom was sealed and vibrated four times. Corrugated pipes were filled with cement mortars then cleaned in the sink, and the pipes were then placed on the waved plates and cured in a curing room (temperature: $23 \pm 1^\circ\text{C}$; relative humidity (RH): not less than 95%). The initial length of the specimen was measured at the final setting time using a dilatometer bench equipped with a

digital gauge at one end, as shown in Figure 1. Three samples of each mortar were measured and the average value was used. The autogenous shrinkage of the specimens at each measuring time was calculated according to equation (1) [27],

$$\mu_a = \frac{(L_T - L_0) \times 10^6}{L_0}, \quad (1)$$

where L_T represents the length of the specimen at the measuring time and L_0 represents the initial length at the final setting time of the specimen.

2.6. Dry Shrinkage and Quality Loss. The total drying shrinkage of the specimens was measured according to ASTM C596 [28]. The mortars were cast into dismountable iron molds with sizes of $25\text{ mm} \times 25\text{ mm} \times 285\text{ mm}$ and the mortars were then cured in a curing room (temperature: $23 \pm 1^\circ\text{C}$, RH: not less than 95%). After 24 h, the mortars were demolded and cured in a saturated Ca (OH)₂ solution for 48 h. The initial lengths and the masses of the specimens were measured at the age of 72 h. Then the specimens were cured in an environment with a relative humidity of $50\% \pm 3\%$. The specimens were measured for a period of 4 weeks. The drying shrinkages and the mass losses of the specimens could be calculated with equations (2) and (3), respectively,

$$\mu_d = \frac{(l_T - l_0) \times 10^6}{l_0}, \quad (2)$$

$$m_d = \frac{100 \times (m_T - m_0)}{m_0}, \quad (3)$$

where l_T represents the length of the specimen at the measuring time, l_0 and m_0 represent the initial length and the initial mass of the sample at the age of 72 h, respectively, and m_T represents the mass at the measuring time of the specimen.

2.7. Compressive Strength. The compressive strengths of the mortars were determined according to ASTM C109 [29]. Fresh cement mortars were cast into the cubic molds with sizes of $50\text{ mm} \times 50\text{ mm} \times 50\text{ mm}$ and the mortars were

FIGURE 1: Schematic diagram of autogenous shrinking instrument [24].

then cured in a curing room (temperature: $23 \pm 1^\circ\text{C}$; RH: not less than 95%). After 24 h, the mortar specimens were demolded and then cured in a saturated $\text{Ca}(\text{OH})_2$ solution. The compressive strengths of the mortars were determined after 3 d, 7 d, and 28 d. The average value of three specimens was used as the compressive strength.

2.8. Capillary Water Absorption. The capillary water absorption of the specimens was tested according to ASTM C642-13 [30]. The size of each cylindroid specimen was 100 mm in diameter with a thickness of 50 mm. The specimens were cured in a standard curing room ($23 \pm 1^\circ\text{C}$ and $>95\%$ RH). After curing for 28 d, all of the other surfaces of the specimens were covered with epoxy except the bottom surface, and the specimens were dried in the oven at 110°C for not less than 24 h. A capillary water absorption test was conducted in a room in which the temperature was controlled at $23 \pm 2^\circ\text{C}$. At scheduled time intervals, the quality of the specimens was weighed in time to determine the mass of water absorbed.

2.9. Rapid Chloride Penetration Test. Rapid chloride penetration tests of the cylindroid specimens (diameter = 100 ± 1 mm and thickness = 50 ± 2 mm) were performed at the age of 28 d according to ASTM C1202 [31]. A potential difference of 60 V DC was at both ends of the cylindroid specimens. One end was immersed in a solution of NaOH and the other end was immersed in a solution of NaCl. This test method was used to monitor the amount of electrical current that passed through cylindroid specimens during a 6 h period. The specimens were recorded once every 5 min to ensure that the target was reached. The total amount of electrical current passed was related to the resistance of the specimen to chloride ion penetration. The total charge passed during the rapid chloride penetration test of each specimen was calculated according to equation (4),

$$Q = 900 (I_0 + 2I_{30} + 2I_{60} + \dots + I_t + \dots + 2I_{300} + 2I_{330} + I_{360}), \quad (4)$$

where Q in coulombs represent the total charge passed, I_0 in amperes represents the current immediately after the voltage was applied, and I_t in amperes represents the current at t min after the voltage was applied [32].

2.10. Sample Characterization. TGA was conducted in this work to further determine the quantitative composition of

the hydration products, using a TGA/DSC 1/1600 high-temperature thermogravimetric analyzer. Powder samples were loaded in ceramic crucibles and heated from ambient temperature to 800°C at a heating rate of $20^\circ\text{C}/\text{min}$. The furnace was purged with 20 ml/min N_2 gas. The hydration products in the paste were verified with an X-ray diffractometer that was operated using Cu (K α), a current of 200 mA, and 40 kV. Paste samples for the XRD and TGA analyses were collected at the ages of 3 d and 7 d. The samples were immersed in isopropanol, dried, and then ground into powders whose diameter was less than $75 \mu\text{m}$. MIP (Mercury intrusion porosimetry) test was also measured to observe the microstructure of mortars.

3. Results and Discussion

3.1. Setting Time. The initial and final setting times of the cement pastes of each group are shown in Figure 2. It can be observed from the data shown in Figure 2 that the initial as well as final setting times of the paste of the AA0 group increased significantly because the CA solution was added [20, 33, 34]. Thereafter, the recorded setting time decreased gradually with the further increase in the dosage of the AA. Compared with CON, the addition of 0.3% of the CA solution resulted in the initial setting times and final setting times of the samples being increased by approximately six times. The addition of the AA resulted in a decrease in the initial setting time and final setting time to values close to those of CON or even lower than those of CON. This was because the CA solution that was added to the cement pastes retarded the hydration strongly. In contrast, the AA promoted cement hydration. The detailed analysis is described in Section 3.7.

3.2. Autogenous Shrinkage. The autogenous shrinkages of the six mortar mixtures were recorded from the final setting for 4 weeks. Figure 3 illustrates the measured length changes of the mortar specimens. The shrinkage values of the CON-AA2.5 sample were $282.14 \mu\epsilon$, $443.23 \mu\epsilon$, $279.76 \mu\epsilon$, $306.35 \mu\epsilon$, $473.49 \mu\epsilon$, and $672.62 \mu\epsilon$ at day 28. The autogenous shrinkage of the mortars increased continuously with the increasing dosage of the AA. In the mortars, the alkaline accelerator contributed to reactions between the cement and water to cause water consumption. The water in the remaining small capillaries formed menisci and exerted hydrostatic tension forces. These capillary forces reduced the distance between the solid particles, leading to autogenous shrinkage [35]. The concentration of SiO_3^{2-} was improved dramatically due to addition of the AA. Then the SiO_3^{2-} reacted with calcium hydroxide (CH) to generate abundant hydrated calcium silicate (C-S-H) to lead to the pore structure at early stages of hydration being refined significantly, leading to faster self-desiccation in all mortars. Consequently, higher autogenous shrinkage was produced by lower RH [36]. Nevertheless, very little difference of the autogenous shrinkage could be observed between the CON and AA1.5 samples, indicating that smaller autogenous shrinkage was produced when dosages

FIGURE 2: Results of setting time determination.

FIGURE 4: Dry shrinkage curve of each group.

FIGURE 3: Autogenous shrinkage curve of the test piece.

of 1.5% of the AA were added in mortars compared with other groups with the AA.

3.3. Dry Shrinkage Quality Loss. Figure 4 presents the total shrinkages of all of the mixtures during the 28 day recording period. The drying shrinkages of all of the specimens increased significantly with time because the internal relative humidity of the specimens decreased with the concrete age since casting [37]. The final measured dry shrinkages of CON, AA0, AA1, AA1.5, AA2, and AA2.5 were as high as 1398.81 $\mu\epsilon$, 1356.43 $\mu\epsilon$, 1436.43 $\mu\epsilon$, 1462.14 $\mu\epsilon$, 1502.38 $\mu\epsilon$,

and 1547.57 $\mu\epsilon$, respectively. Compared with the other group, AA0 exhibited the lowest dry shrinkage during the entire recording period. This was because the decreased consumption of water due to cement hydration was hampered by the adsorption of citrate ions onto the available surfaces of the Portland cement grains.

The results are shown in Figure 4. This figure indicates that the dry shrinkage of the samples increased with the increasing dosage of the AA. Thus, the AA seemed to play a relevant role in increasing the dry shrinkage of the mortars. Two reasons were responsible for this reduction of the total shrinkage. First, the autogenous shrinkage was increased by the addition of the AA, leading to more total drying shrinkage. Second, this was because the increased consumption of water that resulted from the speed of the cement hydration was accelerated by the addition of the AA, as indicated by Figure 5. It can be seen from the figure that more water for the samples with AA was consumed and that the amount of the evaporated water increased with the increasing added dosage of the AA. Additionally, this was probably caused by the evaporation of water by increasing the internal temperature, because of the high heat of hydration of the cement with the AA [38]. Nevertheless, the dry shrinkages of the AA1 and AA1.5 specimens were only slightly higher than those of the CON specimens.

3.4. Compressive Strength. Figure 6 presents the compressive strengths of each group at the ages of 3 d, 7 d, and 28 d. It can be seen from the figure that the compressive strength of the AA0 at 3 d was 0 MPa. The decrease of the compressive strength was produced because the hydration of the cement was delayed by adding CA at an early age. Cement mortars that had been “dormant” due to CA were added.

In the “dormant” cement mortars, the addition of the AA with the dosages of 1%, 1.5%, 2%, and 2.5% provided

FIGURE 5: Quality loss curves of dry shrink test pieces.

FIGURE 6: Compressive strength of test blocks at different ages.

increases of 0.5%, 20.5%, 14.9%, and 12.4% in the compressive strengths of the cement mortars at the age of 3 d, respectively. At the age of 7 d, the strengths of AA1, AA1.5, and AA2 still exceeded that of the CON, providing increases of 2.8%, 6.2%, and 2.2%, respectively. However, the compressive strength of the AA2.5 group was lower than that of the CON. The compressive strength of AA1.5 still surpassed that of the CON at 28 d, while for the other group, the compressive strength is lower than that of the CON. Therefore, the compressive strengths of the cement mortars with AA were increased at an early age. The addition of these AAs contributed to initial Ca^{2+} consumption because the concentrations of Ca^{2+} were lowered in the fluid, which

favorable the dissolution of cement compounds to stabilize the calcium concentration in the chemical equilibrium. Additionally, the AA was mainly composed of sodium silicate, and the concentration of SiO_3^{2-} was improved dramatically. The H_2SiO_3 produced by the SiO_3^{2-} hydrolysis could react with the CH, which was one of the hydration products, and the H_2SiO_3 could generate hydrated calcium silicate (C-S-H) [39], which has a denser structure to enhance strength. Nevertheless, when the dosages of the AA were increased, a compressive strength reduction was observed. There were many bubbles in the mortars with the AA due to the short setting time, resulting in the bubbles not being able to be removed from the mortars in time. Additionally, autogenous shrinkage and dry shrinkage might have resulted in microcracks and macrocracks that impaired strength [35]. Figure 7 shows the pore size distribution and cumulated pore volume of mortar samples. It can be seen from Figure 7(a) that the pore size was mainly distributed between 10 nm and 100 nm and the addition of AA increased the pore volume at 100 nm. The cumulated pore volume for AA1.5 was smaller than mortar without AA as shown in Figure 7(b). This is the reason why the AA1.5 has higher compressive strength than the mortar without AA.

3.5. Capillary Water Absorption. Figure 8 shows the evolution law of the water absorption amount per unit area of the specimen for each group. It can be seen from Figure 6 that the amount of absorbed water for each group increased with the square root of time. AA0 exhibited the lowest amount of absorbed water during the entire recording period, which was apparently related to the impact of the CA. The addition of CA strongly retarded the hydration of the Portland cement used to retard the development of the pore structure to the compact pore structure of cement mortar. It could also be observed that the higher the dosage of the AA was, the higher the amount of absorbed water was. The final measured water absorption amounts of CON, AA1, AA1.5, AA2, and AA2.5 were 4.19, 4.25, 4.46, 4.54, and 4.7, respectively. First, the porosity increased due to the decrease in the setting time, which caused the amount of absorbed water to be high, the MIP result could support this. In Figure 7(b), the pore volume of specimens between 100 nm–10000 nm was increased causing the increase of water absorption. Second, the increase of the autogenous shrinkage and dry shrinkage might have resulted in the number of microcracks and macrocracks being higher as well as the voidage of the specimen increasing.

3.6. Rapid Chloride Penetration Test. The results of the rapid chloride penetration test for each group at 28 d of curing are summarized in Table 3. The measured total charge passed for each group specimen is presented in Figure 9. The test results demonstrated that the total charge passed for the AA0 actually decreased. It was obvious that the CA improved upon the pore structure of the mortar. Nevertheless, for the case of the specimen with the AA, the results showed that the coulomb charges that passed through the mortars increased with the dosage of the AA increasing. The AA decreased the

FIGURE 7: MIP results of the specimen with and without AA/CA. (a) Pore size distribution. (b) Cumulative pore volume.

FIGURE 8: Capillary water absorption curve of the specimen.

TABLE 3: Rapid chloride penetration test results for each group.

Specimen	Charge passed (coulombs)	Chloride permeability
CON	2064	Moderate
AA0	1022	Low
AA1	2548	Moderate
AA1.5	3431	Moderate
AA2	6170	High
AA2.5	6008	High

FIGURE 9: Total charge passed for each group specimen.

chloride penetration resistance and it had a higher total charge passed than the CON group. According to ASTM C1202, the groups of CON, AA1, and AA1.5 were classified as moderate (2000–4000 C) and the group of AA0 was classified as low (1000–2000 C). The high dosage of the AA decreased the observable chloride penetration resistance.

3.7. XRD and TGA Patterns. The phase assemblage of the six mixtures was characterized by XRD, and the results were presented. Figure 10 shows only the representative results of the specimens at the ages of 3 d and 7 d. $\text{Ca}(\text{OH})_2$, CaCO_3 , SiO_2 , C_2S , and C_3S were the major crystal compositions in these mortars. Figure 10(a) compares the diffraction patterns obtained at 3 d. Higher intense peaks of the C_2S and C_3S phases were observed in the AA0 specimen compared with the other specimens and the peak intensity of the $\text{Ca}(\text{OH})_2$ was lower than those of the other groups. It could be seen that the hydration of the cement was strongly retarded by the CA. In comparison to the AA0, the addition of the AA reduced the peak intensity of the C_3S and C_2S and increased the peak intensity of the $\text{Ca}(\text{OH})_2$. When the curing age was extended to 7 days, as shown in Figure 10(b), the contents of the C_3S and C_2S were reduced in the AA0, and the peak intensity of the $\text{Ca}(\text{OH})_2$ was slightly higher than those of the other groups. The low content of $\text{Ca}(\text{OH})_2$ in the AA0 at the age of 3 d was the result of the low hydration degree of the cement because the CA was added. Then the hydration degree of the AA0 was increased with the increasing curing time, and the contents of $\text{Ca}(\text{OH})_2$ were increased. Nevertheless, the peak intensities of the $\text{Ca}(\text{OH})_2$ of the groups with different dosages of AA were slightly lower than those of the CON group at the ages of 3 d and 7 d and of the AA0 group at the age of 7 d. This was because a mass of $\text{Ca}(\text{OH})_2$ was consumed due to the SiO_3^{2-} reaction with the $\text{Ca}(\text{OH})_2$ to generate hydrated calcium silicate (C-S-H) [39].

Figure 11 presents the TGA-DTG thermograms of six pastes at ages of 3 d and 7 d. There were four major endothermic peaks in the DTG curves, indicating the

decomposition of the hydration products of ettringite (AFt), monosulfate (AFm), portlandite (CH), and calcium carbonate (CaCO_3). Existing studies have shown that the hydration products of cement have typical decomposition temperature regions, 80°C – 130°C , 180°C – 200°C , 400°C – 500°C , and 600°C – 800°C , representing AFt, AFm, CH, and CaCO_3 , respectively [40–42]. At 105°C , the C-S-H started to lose the chemically bound water. Nevertheless, the decomposition temperature of the C-S-H partially overlapped with that of the AFt. Hence, the decomposition temperature region of the weight loss of the AFt was considered at 80°C – 105°C [43]. As shown in Figure 11(a), the endothermic peaks of the DTG curves weakened due to the retarding effect of the CA. However, the retarding effect seemed to vanish with the addition of the AA. Some of the CH was carbonated to form CaCO_3 because the samples were cured in open air. Hence, the total weight loss of the CH included the water loss (400°C – 500°C) of the CH and the mass loss of the CO_2 (600°C – 800°C), as calculated according to equation (5),

$$m_{\text{total CH}} = \frac{74}{18} \Delta m_{\text{CH}} + \frac{74}{44} \Delta m_{\text{CaCO}_3}, \quad (5)$$

where $m_{\text{total CH}}$ represents the total weight loss of the CH and Δm_{CH} and Δm_{CaCO_3} represent the mass loss of the CH and the CaCO_3 , respectively.

The quantitative analysis of the contents of the hydration products is presented in Table 4. The total weight loss of the CH is shown in the last column. This column shows that the total weight loss of the CH of the AA0 group was less than that of the other group at the age of 3 d, indicating that the hydration of the cement was retarded by the CA. The AFt and AFm contents of the AA0 group were the least when compared with other groups, which also supported the strong retarded effect of the CA. However, the total weight loss of the CH and AFt increased with the increasing dosage of the AA at the age of 3 d, indicating that the AA promoted cement hydration. This was in agreement with the results of the XRD and setting time testing shown in Figure 10(a) and

FIGURE 10: The XRD patterns of paste cured for 3 d and 7 d: (a) 3 d pastes; (b) 7 d pastes.

FIGURE 11: TGA-DTG thermograms of 3 d and 7 d pastes. (a) 3 d pastes; (b) 7 d pastes.

TABLE 4: Contents of hydration products of 3 d and 7 d pastes.

Age (d)	Specimen	Mass loss (%) related to the decomposition of				Total CH (%)
		AFt (80–105°C)	AFm (180–200°C)	CH (400–500°C)	CaCO ₃ (600–800°C)	
3	CON	2.09	0.37	2.89	4.07	18.73
	AA0	1.94	0.17	1.25	4.22	12.23
	AA1	2.36	0.35	2.62	5.14	19.41
	AA1.5	2.18	0.35	2.61	5.31	19.65
	AA2	2.95	0.42	2.64	6.00	20.90
	AA2.5	2.86	0.35	2.61	6.16	21.07

TABLE 4: Continued.

Age (d)	Specimen	Mass loss (%) related to the decomposition of				Total CH (%)
		AFt (80–105°C)	AFm (180–200°C)	CH (400–500°C)	CaCO ₃ (600–800°C)	
7	CON	2.44	0.45	2.75	6.453	22.14
	AA0	2.63	0.37	2.33	6.55	20.57
	AA1	2.74	0.44	2.77	4.03	18.16
	AA1.5	2.85	0.48	2.79	4.23	18.56
	AA2	2.89	0.49	2.76	4.20	18.38
	AA2.5	2.98	0.53	2.86	4.50	19.32

Figure 2. At 7 d, the CH contents of the cement paste with AA were lower than those of the AA0 and CON group, indicating that the mass of CH was consumed due to the reaction with the SiO_3^{2-} of the AA, which was in agreement with the XRD results shown in Figure 10(b).

According to the XRD and TGA analysis, the following conclusions could be drawn: The CA could significantly delay the hydration of the cement and the addition of the AA could accelerate the hydration of the cement, especially in the early curing age. The combination of CA and AA achieved the effect of dormancy and awakening.

4. Conclusions

This study describes the investigation of the effect of CA and AA on the properties of pastes and mortars. Conclusions were drawn based on the experimental results:

- (1) The hydration of cement was retarded significantly due to the addition of CA. The content of C_2S and C_3S was more than that of CON and the content of $\text{Ca}(\text{OH})_2$ was fewer than that of CON which can be observed from the XRD and TGA test results. The macroperformance of deserve is that the setting time of the cement pastes was increased significantly after the addition of the CA (increased by approximately six times).
- (2) AA woke up the reactivity of mortars causing the consumption of C_2S and C_3S and the production of $\text{Ca}(\text{OH})_2$ observed from XRD and TGA test results. The setting hardening of the cement pastes was restored after the addition of the AA.
- (3) The compressive strength of the cement mortars with CA was decreased because the number of pores whose diameter was 100 nm was increased which can be found from the MIP test result. On the contrary, AA reduced the total pores content which caused the increase of compressive strength of mortars.
- (4) Both CA and AA have an adverse effect on autogenous shrinkage and drying shrinkage except CA can lightly mitigate the drying shrinkage. CA has a positive effect on the durability properties of mortars. The water absorption amount and total charge passed for the mortars were decreased after the addition of CA. Nevertheless, AA reduced the durability of mortars.

This study demonstrates that using CA and AA as a dormancy agent and an awakening agent was feasible via comprehensive testing. This usage could achieve the recycling and utilization of fresh cement mortar waste and effectively reduce the waste of resources and environmental pollution. However, this study was only a conceptual validation of the method, and some other performance indicators such as cost saving and reduction in CO_2 emissions will continue to be examined in the follow-up work.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors state that they have no known conflicts of interest or personal relationships that may affect the work reported in this paper.

Acknowledgments

This work was funded by the Natural Science Foundation of Universities in Anhui Province (KJ2019A0129), Natural Science Foundation of Anhui Province (2008085QE244), and Key Research and Development Project of Anhui Province (201904a07020081).

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