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# An explanation for the negative effect of elevated temperature at early ages on the late-age strength of concrete

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**Abstract** Elevated curing temperature at early ages usually has a negative effect on the late-age strength of concrete. This article aims to study the mechanism of this phenomenon. The results show that elevated curing temperature at early ages has a negative effect on the late-age strength of hardened cement paste, but it has a greater negative effect on the late-age strength of cement mortar. After elevated temperature curing at early ages, the late hydration of cement is hindered, but the late reaction of fly ash is not influenced. Owing to the continuous reaction of fly ash, the late-age pore structure of cement–fly ash paste under elevated curing temperature is finer than that under standard curing temperature, and the late-age strength of cement–fly ash paste under elevated curing temperature is higher. However, the late-age strength of cement–fly ash mortar under elevated curing temperature is lower. Apparently, there are differences between the effects of elevated curing temperature on hardened paste and mortar. It is the deterioration of transition zone between hardened paste and aggregate that makes the negative effect of elevated curing temperature on the mortar (or concrete) be greater than the hardened paste. As the water-to-binder ratio decreases, the negative effect of elevated curing temperature on the transition zone tends to be less.

## Introduction

Cement concrete is one of the most widely used construction materials in the modern society. The hydration of cement releases heat. For high strength concrete whose binder content is high, the temperature rise is usually high at early ages. In the large structural concrete elements (e.g., foundation plates) where heat dissipation is low, the inner temperature rise of concrete is also high at early ages. Stream curing method is used during the production of precast concrete elements. In these cases, the actual temperature of concrete at early ages is higher than the standard curing temperature in the laboratory.

Elevated temperature accelerates the early hydration of cement, and thus accelerates the rate of strength gain of concrete [1, 2]. However, elevated curing temperature at early ages may result in a low the rate of increase in late-age strength of concrete [1–6]. The reasons for this phenomenon are complicated. Some researchers [1, 7, 8] found that the late-age hydration degree of cement becomes low with the elevation of early curing temperature. Kjellsen [9] and Cao [10] found that increasing early curing temperature may increase the porosity of late-age cement paste. Kondo [6] found that high curing temperature makes the internal hydration products of cement clinker very dense, which decreases its further reaction rate.

Nowadays, mineral admixtures (e.g., fly ash, ground granulated blast-furnace slag, and silica fume) are widely used in concrete to replace part of cement [11–14]. Elevated temperature also has a great impact on the hydration of mineral admixtures [15–18]. The reaction kinetics of complex binder may be more complicated than those of pure cement under the condition of elevated curing temperature.

At present, the reasons for the negative effect of elevated curing temperature at early ages on the late-age

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**Table 1** Chemical composition of materials w/%

| Composition | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | CaO | MgO | $SO_3$ | $Na_2O_{eq}$ | Loss on ignition |
|---|---|---|---|---|---|---|---|---|
| Cement I | 21.86 | 4.25 | 2.66 | 63.59 | 2.19 | 2.42 | 0.55 | 1.75 |
| Cement II | 21.41 | 4.46 | 2.43 | 62.95 | 2.00 | 2.72 | 0.89 | 2.92 |
| Fly ash I | 48.67 | 30.95 | 5.62 | 2.44 | 1.15 | 0.63 | 0.78 | 7.65 |
| Fly ash II | 57.60 | 21.90 | 7.70 | 3.87 | 1.68 | 0.41 | 4.05 | 0.43 |

*Note*: $Na_2O_{eq} = Na_2O + 0.658K_2O$

strength of concrete are not completely understood. The current investigation presents some results of cement and cement–fly ash pastes under different curing temperature conditions, which include: non-evaporable water content, $Ca(OH)_2$ content, Mercury Intrusion Porosimeter results, and the results of hydration degree of fly ash. It also presents the compressive strength results of cement and cement–fly ash pastes, as well as cement and cement–fly ash mortars. The purpose of this study is to further explore the mechanism of elevated curing temperature at early age affecting the late-age strength of concrete negatively.

## Experimental

### Raw materials

Two cements and two fly ashes were used. The chemical compositions of these materials can be seen in Table 1.

### Curing conditions

Curing condition A (standard curing condition): Samples were cured at temperature of 20 ± 1 °C till testing age.

Curing condition B (elevated temperature curing condition at early ages): Samples were first cured at temperature of 65 ± 1 °C for 14 days and then at temperature of 20 ± 1 °C for the remaining ages.

### Hardened paste experiments

Cement I and Fly ash I were used in the hardened paste experiments. The mix proportions of the pastes are listed in Table 2. The pastes for the tests of non-evaporable water content, Mercury Intrusion Porosimeter, TG/DTG, and hydration degree of fly ash were cast into plastic centrifuge tubes and sealed tightly immediately after being stirred uniformly. At the testing ages, the hydration was stopped by soaking the samples in acetone. The pastes for strength test were cast into steel molds of 40 × 40 × 160 mm. After 24 h, the specimens were demolded. At the testing ages, compressive strength was tested according to Chinese National Standards GB/T 17671-1999.

Non-evaporable water content was obtained as the difference in mass between the sample heated at 105 and 1000 °C normalized by the mass after heating 105 °C, and correcting for the loss on ignition of unhydrated samples [19, 20].

Pore characteristics were measured using an AutoPore IV9510 Mercury Intrusion Porosimeter with an operating pressure up to 60000 psi, which could intrude mercury into pores as small as 3.2 nm in diameter.

**Table 2** Mix proportions of pastes

| Samples | Binder proportion (%) | | Water-to-binder ratio | Curing condition |
|---|---|---|---|---|
| | Cement | Fly ash | | |
| 0%FA-0.42 W/B-20 °C | 100 | 0 | 0.42 | A |
| 22.5%FA-0.42 W/B-20 °C | 77.5 | 22.5 | 0.42 | A |
| 45%FA-0.42 W/B-20 °C | 55 | 45 | 0.42 | A |
| 0%FA-0.42 W/B-65 °C | 100 | 0 | 0.42 | B |
| 22.5%FA-0.42 W/B-65 °C | 77.5 | 22.5 | 0.42 | B |
| 45%FA-0.42 W/B-65 °C | 55 | 45 | 0.42 | B |
| 0%FA-0.34 W/B-20 °C | 100 | 0 | 0.34 | A |
| 22.5%FA-0.34 W/B-20 °C | 77.5 | 22.5 | 0.34 | A |
| 45%FA-0.34 W/B-20 °C | 55 | 45 | 0.34 | A |
| 0%FA-0.34 W/B-65 °C | 100 | 0 | 0.34 | B |
| 22.5%FA-0.34 W/B-65 °C | 77.5 | 22.5 | 0.34 | B |
| 45%FA-0.34 W/B-65 °C | 55 | 45 | 0.34 | B |

TG/DTG curves were obtained using a TA-Q5000 instrument with a heating rate of 10 °C/min in nitrogen atmosphere.

The reaction degree of fly ash was determined by a selective dissolution procedure using concentrated hydrochloric acid and water [21, 22]. The HCl solution was prepared by mixing concentrated hydrochloric acid with de-ionized water at the ratio of 1:2 (volume ratio). The insoluble residues of the as-received cement and fly ash, and the cement–fly ash paste in the HCl solution were filtered and then burned in an electric furnace at 950 °C for 1 h. The insoluble residues were weighed after cooling to room temperature. The fraction of reacted fly ash is determined by Eq. 1:

$$x = 1 - \frac{M_P - p_C M_C}{p_F M_F} \tag{1}$$

where $x$ is the fraction of reacted fly ash, $M_P$ is the residue per gram of cement–fly ash paste, $M_C$ and $M_F$ are the residue per gram of plain cement paste and residue per gram of fly ash, $p_C$ and $p_F$ are the weight percent of cement and fly ash of the complex binder, respectively.

### Mortar experiments

Mortar bars of 40 × 40 × 160 mm were prepared. The binder-to-sand ratio of mortar was 1:3. ISO standard sand was used. Cement I and fly ash I were used in mortars I. Cement II and fly ash II were used in mortars II. The mix proportions of mortars I and mortars II are listed in Tables 3 and 4, respectively. After 24 h, the specimens were demolded. At the testing ages, compressive strength was tested according to Chinese National Standards GB/T 17671-1999.

## Results and discussion

### Hydration degree of fly ash

Figure 1 shows the hydration degrees of fly ash in cement–fly ash pastes. This figure shows that the hydration degree of fly ash at early ages is very low under standard curing condition (20 °C). Even at the age of 14 days, the hydration degrees of pastes 22.5%FA-0.42 W/B-20 °C and 45%FA-0.42 W/B-20 °C are only 5.11 and 1.24%, respectively. A similar result has been reported by others [19, 23–25]. However, at the age of 3 days, the pastes 22.5%FA-0.42 W/B-65 °C and 45%FA-0.42 W/B-65 °C have a degree of fly ash reaction of 10.24 and 8.62%, respectively, which are much higher than the degrees of fly ash in pastes 22.5%FA-0.42 W/B-20 °C and 45%FA-0.42 W/B-20 °C even at the age of 14 days. At the end of elevated temperature curing period (14 days), the hydration degrees of fly ash in pastes 22.5%FA-0.42 W/B-65 °C and 45%FA-0.42 W/B-65 °C reach 24.44 and 14.68%, respectively. This implies that the early reaction activity of fly ash is significantly accelerated by elevated curing temperature. For cement–fly ash paste under elevated temperature, fly ash makes a considerable chemical contribution to the hardening process of paste at early ages. It should be noted that at the age of 720 days, the

**Table 3** Mix proportions of mortars I

| Samples | Binder proportion (%) | | Water-to-binder ratio | Curing condition |
|---|---|---|---|---|
| | Cement | Fly ash | | |
| MC-0.50 | 100 | 0 | 0.50 | A |
| MF1-0.50 | 77.5 | 22.5 | 0.50 | A |
| MF2-0.50 | 55 | 45 | 0.50 | A |
| MCH-0.50 | 100 | 0 | 0.50 | B |
| MFH1-0.50 | 77.5 | 22.5 | 0.50 | B |
| MFH2-0.50 | 55 | 45 | 0.50 | B |
| MC-0.42 | 100 | 0 | 0.42 | A |
| MF1-0.42 | 77.5 | 22.5 | 0.42 | A |
| MF2-0.42 | 55 | 45 | 0.42 | A |
| MCH-0.42 | 100 | 0 | 0.42 | B |
| MFH1-0.42 | 77.5 | 22.5 | 0.42 | B |
| MFH2-0.42 | 55 | 45 | 0.42 | B |
| MC-0.34 | 100 | 0 | 0.34 | A |
| MF1-0.34 | 77.5 | 22.5 | 0.34 | A |
| MF2-0.34 | 55 | 45 | 0.34 | A |
| MCH-0.34 | 100 | 0 | 0.34 | B |
| MFH1-0.34 | 77.5 | 22.5 | 0.34 | B |
| MFH2-0.34 | 55 | 45 | 0.34 | B |

**Table 4** Mix proportions of mortars II

| Samples | Binder proportion (%) | | Water-to-binder ratio | Curing condition |
|---|---|---|---|---|
| | Cement | Fly ash | | |
| NC-0.50 | 100 | 0 | 0.50 | A |
| NF1-0.50 | 75 | 25 | 0.50 | A |
| NF2-0.50 | 50 | 50 | 0.50 | A |
| NCH-0.50 | 100 | 0 | 0.50 | B |
| NFH1-0.50 | 75 | 25 | 0.50 | B |
| NFH2-0.50 | 50 | 50 | 0.50 | B |
| NC-0.43 | 100 | 0 | 0.43 | A |
| NF1-0.43 | 75 | 25 | 0.43 | A |
| NF2-0.43 | 50 | 50 | 0.43 | A |
| NCH-0.43 | 100 | 0 | 0.43 | B |
| NFH1-0.43 | 75 | 25 | 0.43 | B |
| NFH2-0.43 | 50 | 50 | 0.43 | B |
| NC-0.36 | 100 | 0 | 0.36 | A |
| NF1-0.36 | 75 | 25 | 0.36 | A |
| NF2-0.36 | 50 | 50 | 0.36 | A |
| NCH-0.36 | 100 | 0 | 0.36 | B |
| NFH1-0.36 | 75 | 25 | 0.36 | B |
| NFH2-0.36 | 50 | 50 | 0.36 | B |

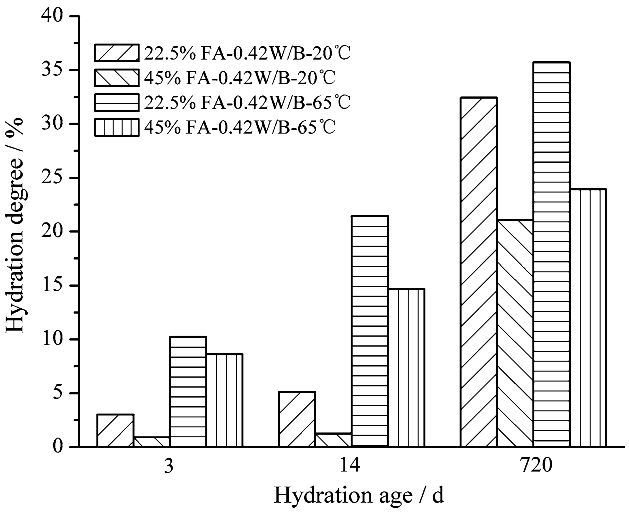

**Fig. 1** Hydration degrees of fly ash in different pastes

hydration degrees of fly ash in pastes 22.5%FA-0.42 W/B-65 °C and 45%FA-0.42 W/B-65 °C are still higher than those in pastes 22.5%FA-0.42 W/B-20 °C and 45%FA-0.42 W/B-20 °C, respectively. This is an indication that the late hydration of fly ash is not hindered by elevated temperature curing.

### Non-evaporable water content

For binders with the same hydration products, the non-evaporable water contents can be used to compare their relative hydration degrees. Figure 2 shows the non-evaporable water contents of different pastes. At the age of 3 days, the non-evaporable water content of paste 0%FA-0.42 W/B-65 °C is apparently higher than that of paste 0%FA-0.42 W/B-20 °C, indicating that elevated curing temperature promotes the hydration of cement. However, at the ages of 90 and 720 days, the hydration degree of cement in paste 0%FA-0.42 W/B-65 °C is lower than that in paste 0%FA-0.42 W/B-20 °C, indicating that early elevated temperature curing hinders the late hydration of cement. This result is consistent with the results of other researchers [1, 7]. This may be due to the formation of dense hydrated phases around the unreacted cement particles, preventing further hydration [6].

Similar to cement paste, cement–fly ash paste cured at elevated temperature has larger non-evaporable water content at early ages and smaller non-evaporable water content at late ages than the paste cured at standard condition. At the age of 3 days, the non-evaporable water content of pastes 0%FA-0.42 W/B-65 °C, 22.5%FA-0.42 W/B-65 °C, and 45%FA-0.42 W/B-65 °C are 24.82, 26.93, and 30.01% higher than those of pastes 0%FA-0.42 W/B-20 °C, 22.5%FA-0.42 W/B-20 °C, and 45%FA-0.42 W/B-20 °C, respectively. It is clear that the promoting effect of elevated temperature on the early hydration of cement–fly ash paste is more significant than that of cement paste. This is because elevated temperature promotes the early hydration of cement as well as fly ash. It agrees with the fly ash's hydration degree results as shown in Fig. 1. At late ages, though the hydration degrees of fly ash in pastes 22.5%FA-0.42 W/B-65 °C and 45%FA-0.42 W/B-65 °C

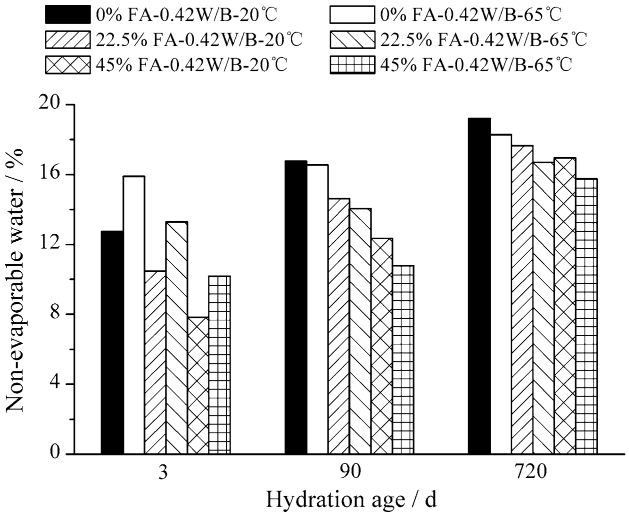

**Fig. 2** Non-evaporable water contents of pastes

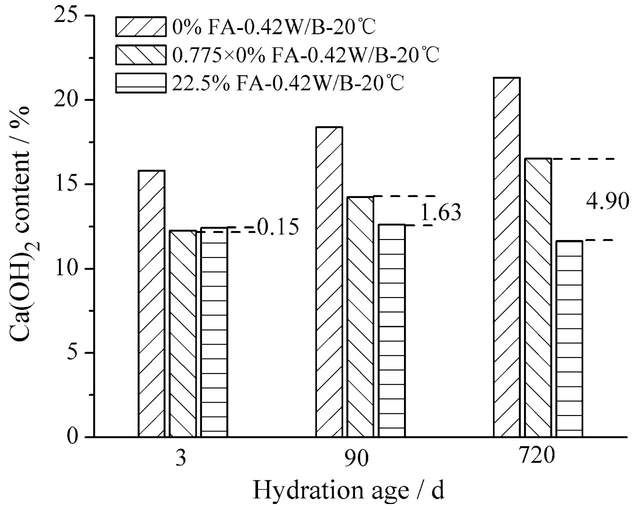

**Fig. 3** $Ca(OH)_2$ contents of paste 0%FA-0.42 W/B-20°C and paste 22.5%FA-0.42 W/B-20°C

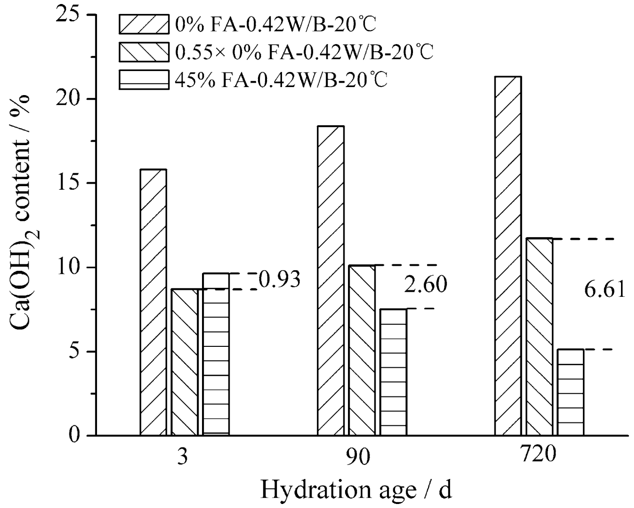

**Fig. 4** $Ca(OH)_2$ contents of paste 0%FA-0.42 W/B-20°C and paste 45%FA-0.42 W/B-20°C

are higher, the cement whose late hydration is hindered by elevated temperature curing is the main fraction in cement–fly ash paste, so the non-evaporable water content of pastes 22.5%FA-0.42 W/B-65 °C and 45%FA-0.42 W/B-65 °C are smaller than those of pastes 22.5%FA-0.42 W/B-20 °C and 45%FA-0.42 W/B-20 °C at late ages.

### $Ca(OH)_2$ content

The samples of this study were sealed tightly in plastic centrifuge tubes during the curing period. Moreover, the TG/DTG experiment was conducted in nitrogen atmosphere. Therefore, there was no carbonation in the samples. The DTG plots of cement paste and cement–fly ash paste show an distinct region for the decomposition of $Ca(OH)_2$ (about 400–500 °C) [26–28].

Figure 3 shows the $Ca(OH)_2$ contents of pastes 0%FA-0.42 W/B-20 °C and 22.5%FA-0.42 W/B-20 °C. The hydration degree of fly ash in 22.5%FA-0.42 W/B-20 °C is 3.02% at the age of 3 days (Fig. 1), which means that some $Ca(OH)_2$ produced by cement is consumed by fly ash. However, at the age of 3 days, the $Ca(OH)_2$ content of paste 22.5%FA-0.42 W/B-20 °C is a little higher than 77.5% of that of paste 0%FA-0.42 W/B-20 °C. This is an indication that the hydration degree of cement in paste 22.5%FA-0.42 W/B-20 °C is higher than that in paste 0%FA-0.42 W/B-20 °C. There are three possible reasons causing this phenomenon. First, the actual water-to-cement ratio in paste 22.5%FA-0.42 W/B-20 °C is higher than that in paste 0%FA-0.42 W/B-20 °C. Second, hydrated product may be accelerated to precipitate on the surface of fly ash [15]. Third, there is more space available for hydration product to form in paste 22.5%FA-0.42 W/B-20 °C than in paste 0%FA-0.42 W/B-20 °C [2]. Figure 4 shows the $Ca(OH)_2$ contents of pastes 0%FA-0.42 W/B-20 °C and 45%FA-0.42 W/B-20 °C. At the age of 3 days, the $Ca(OH)_2$ content of paste 45%FA-0.42 W/B-20 °C is higher than 55% of that of paste 0%FA-0.42 W/B-20 °C. This further proves that fly ash promotes the early hydration of cement in the hydration process of cement–fly ash complex binder. Moreover, it seems that the promoting effect is more significant with higher fly ash content.

Figure 5 shows the $Ca(OH)_2$ contents of pastes 0%FA-0.42 W/B-65 °C and 22.5%FA-0.42 W/B-65 °C. Figure 6 shows the $Ca(OH)_2$ contents of pastes 0%FA-0.42 W/B-65 °C and 45%FA-0.42 W/B-65 °C. At the age of 3 days, the $Ca(OH)_2$ contents of paste 22.5%FA-0.42 W/B-65 °C and 45%FA-0.42 W/B-65 °C are lower than 77.5 and 55% of that of paste CH-0.42, respectively. This result further

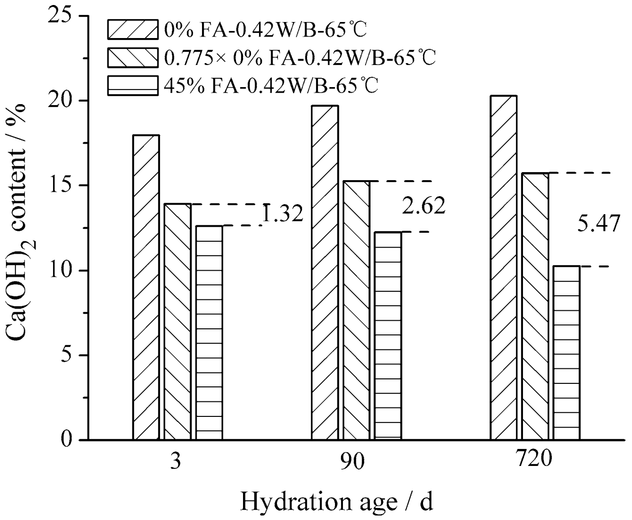

**Fig. 5** Ca(OH)$_2$ contents of paste 0%FA-0.42 W/B-65°C and paste 22.5%FA-0.42 W/B-65°C

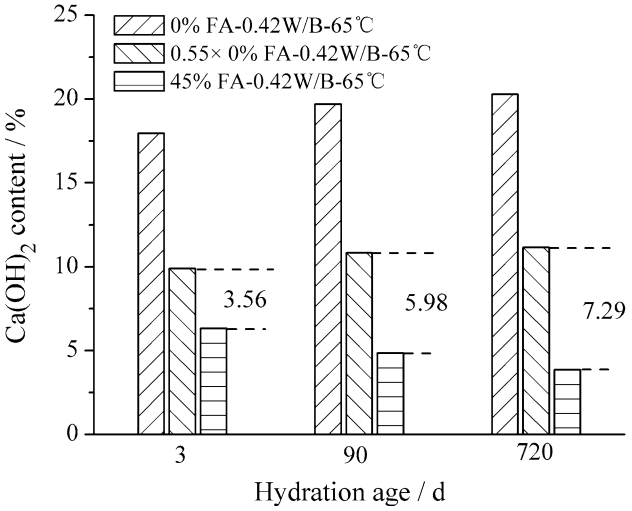

**Fig. 6** Ca(OH)$_2$ contents of paste 0%FA-0.42 W/B-65°C and paste 45%FA-0.42 W/B-65°C

confirms that the early hydration of fly ash is significantly accelerated by high temperature. The consumption content of Ca(OH)$_2$ can be used to measure the hydration of fly ash. It can be seen by comparing Fig. 3 and Fig. 5 that the hydration degree of fly ash in paste 22.5%FA-0.42 W/B-65 °C is higher than that in paste 22.5%FA-0.42 W/B-20 °C at the same hydration ages. It also can be seen by comparing Fig. 4 and Fig. 6 that the hydration degree of fly ash in paste 45%FA-0.42 W/B-65 °C is higher than that in paste 45%FA-0.42 W/B-20 °C at the same hydration ages. This result further confirms that the hydration degree of fly ash under elevated curing temperature is higher even at late age. The Ca(OH)$_2$ content of paste 0%FA-0.42 W/B-65 °C is 1.26 and 0.95 times of that of paste 0%FA-0.42 W/B-20 °C at the age of 3 and 720 days, respectively. This result further proves that elevated temperature curing at early ages promotes early hydration of cement but hinders its later hydration.

## Pore distribution

The pore size distributions of pastes at the age of 3 days are shown in Fig. 7. As expected, under standard curing condition, the pore structure of paste becomes coarser at early ages by replacing part of cement by fly ash. This is because the early hydration activity of fly ash is much lower than that of cement. It is clear that the pore structure of paste at early ages becomes finer by raising the curing temperature. Furthermore, under elevated temperature curing condition, the pore structure of cement–fly ash paste is finer than that of cement paste at the age of 3 days. As mentioned above, fly ash improves the hydration condition of cement due to three reasons during the hydration process of cement–fly ash. It is believed that the hydration degree of cement in cement–fly ash paste is also higher than that in cement paste under high temperature curing conditions. In the meanwhile, the hydration activity of fly ash is accelerated by high temperature, and the pozzolanic reaction results in the increase of C–S–H gel which fills the pores of paste. Therefore, the pore structure of cement–fly ash paste is improved more significantly than that of cement paste by raising the curing temperature at early ages.

Figure 8 shows the pore size distributions of pastes at the age of 720 days. The pore structures of pastes 22.5%FA-0.42 W/B-20 °C and 45%FA-0.42 W/B-20 °C are improved significantly from the age of 3 days to 720 days. At the age of 720 days, the pore structures of pastes 22.5%FA-0.42 W/B-20 °C and 45%FA-0.42 W/B-20 °C are even finer than that of paste 0%FA-0.42

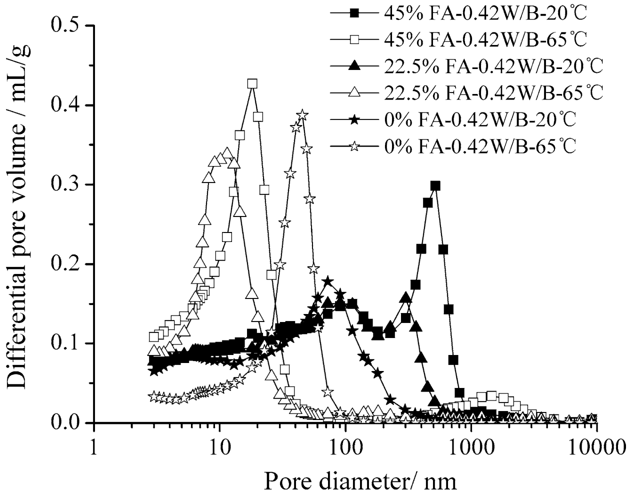

**Fig. 7** Pore size distributions of pastes at the age of 3 days

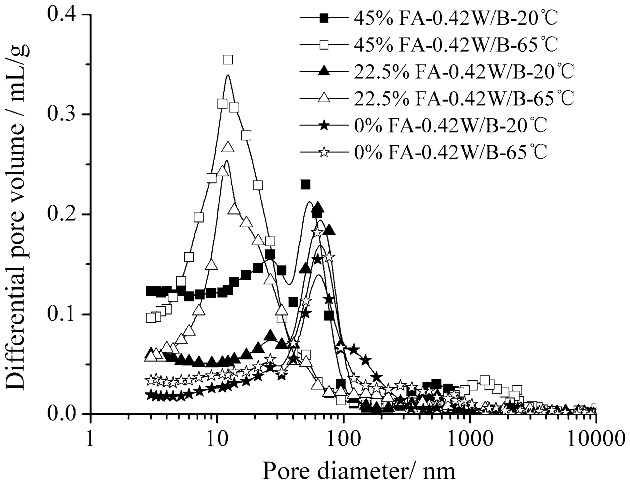

**Fig. 8** Pore size distributions of pastes at the age of 720 days

W/B-20 °C. Similar results have been reported by several researchers [29–33]. This is mainly due to the pozzolanic reaction of fly ash which results in the increase of solid phase volume. Moreover, the unreacted particles of fly ash act as microaggregates which can fill massive large pores in hardened paste [29, 30].

The pore size distribution of paste 0%FA-0.42 W/B-65 °C is similar to that of paste 0%FA-0.42 W/B-20 °C at the age of 720 days. But paste 0%FA-0.42 W/B-65 °C has more pores with diameter larger than 200 nm than paste 0%FA-0.42 W/B-20 °C. This is due to at least two possible reasons. First, as mentioned above, elevated temperature at early ages hinders the late hydration of cement. Another is that elevated temperature curing results in non-uniform distribution of hydration products, which leads to the formation of large pores in the hardened paste [17, 34]. It should be note that the pore structures of pastes 22.5%FA-0.42 W/B-65 °C and 45%FA-0.42 W/B-65 °C are much finer than those of other pastes at the age of 720 days. The hydration degrees of fly ash in pastes 22.5%FA-0.42 W/B-65 °C and 45%FA-0.42 W/B-65 °C are higher than those in pastes 22.5%FA-0.42 W/B-20 °C and 45%FA-0.42 W/B-20 °C at the age of 720 days, respectively (Fig. 1). It is believed that the late pozzolanic reaction of fly ash is not hindered by high curing temperature at early ages, which makes further contributions to the improvement of pore structure of pastes 22.5%FA-0.42 W/B-65 °C and 45%FA-0.42 W/B-65 °C.

## Compressive strengths of pastes

Table 5 shows the compressive strength results of different hardened pastes at the age of 28, 90, 360, and 720 days. The compressive strength of each sample is the mean value of six test results. The maximum standard deviation is 0.57 MPa. As shown in Table 5, the compressive strengths of 0%FA-0.42 W/B-65 °C and 0%FA-0.34 W/B-65 °C are higher than those of 0%FA-0.42 W/B-20 °C and 0%FA-0.34 W/B-20 °C, respectively, at the age of 28 days. At the age of 90 days, the compressive strengths of 0%FA-0.42 W/B-65 °C and 0%FA-0.34 W/B-65 °C are close to those of 0%FA-0.42 W/B-20 °C and 0%FA-0.34 W/B-20 °C, respectively. At the age of 360 and 720 days, the compressive strengths of 0%FA-0.42 W/B-65 °C and 0%FA-0.34 W/B-65 °C are lower than those of 0%FA-0.42 W/B-20 °C and 0%FA-0.34 W/B-20 °C, respectively. Results imply that the hardened cement paste has a low rate of increase in late-age compressive strength under elevated curing temperature at early ages. Different from hardened cement paste, the hardened cement–fly ash paste under elevated curing temperature at early ages has a higher compressive strength in all ages. It agrees with the Mercury Intrusion Porosimeter results as shown in Fig. 8.

**Table 5** Compressive strengths of pastes (MPa)

| Samples | Ages (days) | | | |
|---|---|---|---|---|
| | 28 | 90 | 360 | 720 |
| 0%FA-0.42 W/B-20 °C | 66.2 | 74.6 | 85.4 | 88.1 |
| 22.5%FA-0.42 W/B-20 °C | 48.6 | 68.9 | 75.5 | 83.2 |
| 45%FA-0.42 W/B-20 °C | 42.7 | 56.6 | 74.2 | 85.0 |
| 0%FA-0.42 W/B-65 °C | 72.4 | 76.5 | 83.1 | 84.4 |
| 22.5%FA-0.42 W/B-65 °C | 62.4 | 72.1 | –[a] | 87.6 |
| 45%FA-0.42 W/B-65 °C | 58.8 | 68.3 | 81.1 | 88.3 |
| 0%FA-0.34 W/B-20 °C | 78.2 | 86.4 | 89.1 | 92.6 |
| 22.5%FA-0.34 W/B-20 °C | 72.4 | 85.3 | –[a] | 91.5 |
| 45%FA-0.34 W/B-20 °C | 67.2 | 75.4 | 81.1 | 88.4 |
| 0%FA-0.34 W/B-65 °C | 85.7 | 86.2 | 85.4 | 89.6 |
| 22.5%FA-0.34 W/B-65 °C | 81.2 | 88.5 | 92.2 | 96.1 |
| 45%FA-0.34 W/B-65 °C | 75.1 | 83.7 | 87.6 | 91.4 |

[a] The result is invalid

## Compressive strengths of mortars

Table 6 shows the compressive strengths of mortars I at the age of 3, 7, 28, 90, 360, and 720 days. Table 7 shows the compressive strengths of mortars II at the age of 3, 7, 28, 90, and 180 days. The compressive strength of each sample is the mean value of six test results. The maximum standard deviation is 0.73 MPa. As expected, each sample under elevated curing temperature has a higher early-age compressive strength. However, at late ages (e.g., 90, 180, 360, and 720 days), most samples under elevated curing temperature have a lower compressive strength.

Table 8 shows the ratio of late-age compressive strength under curing condition B to that under curing condition A. When the water-to-binder ratio is high (e.g., 0.50), as the

**Table 6** Compressive strengths of mortars I (MPa)

| Samples | Ages (days) | | | | | |
|---|---|---|---|---|---|---|
| | 3 | 7 | 28 | 90 | 360 | 720 |
| MC-0.50 | 28.1 | 39.2 | 52.6 | 66.8 | 77.6 | 79.4 |
| MF1-0.50 | 22.4 | 29.3 | 43.7 | 58.7 | 73 | 78.4 |
| MF2-0.50 | 13 | 19 | 31 | 42.4 | 64.2 | 72.4 |
| MCH-0.50 | 41.7 | 53.3 | 55.7 | 60.1 | 73.8 | 73.2 |
| MFH1-0.50 | 32.6 | 46.2 | 47.1 | 52.4 | 62.9 | 68.8 |
| MFH2-0.50 | 25.5 | 37.1 | 37.5 | 38.1 | 45.2 | 53.1 |
| MC-0.42 | 38.9 | 49.2 | 61.1 | 70.4 | 80.2 | 82.6 |
| MF1-0.42 | 29.9 | 37.7 | 43.8 | 66.9 | 73.9 | 80.1 |
| MF2-0.42 | 16.9 | 24.2 | 38.6 | 51.4 | 70 | 81.2 |
| MCH-0.42 | –[a] | 58.4 | 62.3 | 64.6 | 71.2 | 70.6 |
| MFH1-0.42 | –[a] | 54.5 | 59.2 | 61.3 | 70.1 | 72.4 |
| MFH2-0.42 | –[a] | 42.3 | 45.2 | 47.9 | 61.2 | 69.3 |
| MC-0.34 | 51.1 | 61.7 | 75.3 | 84.1 | 87.2 | 88.4 |
| MF1-0.34 | 42.4 | 53.8 | 67 | 82.2 | 83.8 | 88.3 |
| MF2-0.34 | 27.9 | 34.5 | 54.8 | 64.3 | 73.6 | 81.2 |
| MCH-0.34 | –[a] | 73.8 | 78.4 | 81.2 | 83.4 | 83.2 |
| MFH1-0.34 | –[a] | 62.3 | 73.7 | 77.4 | 81.6 | 84.6 |
| MFH2-0.34 | –[a] | 55.6 | 58.6 | 60.7 | 71.2 | 80.1 |

[a] No result

**Table 7** Compressive strengths of mortars II (MPa)

| Samples | Ages (days) | | | | |
|---|---|---|---|---|---|
| | 3 | 7 | 28 | 90 | 180 |
| NC-0.50 | 17.7 | 31.9 | 47.2 | 58.3 | 63.1 |
| NF1-0.50 | 18.1 | 26.5 | 43.3 | 58.7 | 66.6 |
| NF2-0.50 | 12.0 | 16.3 | 32.9 | 40.5 | 56.4 |
| NCH-0.50 | 29.9 | 37.7 | 44.0 | 50.1 | 54.5 |
| NFH1-0.50 | 31.7 | 38.0 | 42.3 | 43.5 | 46.6 |
| NFH2-0.50 | 26.2 | 25.7 | 29.0 | 31.2 | 32.2 |
| NC-0.43 | 39.7 | 53.7 | 56.7 | 62.5 | 62.2 |
| NF1-0.43 | 21.9 | 31.3 | 41.6 | 50.6 | 53.2 |
| NF2-0.43 | 13.1 | 17.7 | 34.9 | 48.0 | 64.7 |
| NCH-0.43 | 36.0 | 42.9 | 47.9 | 54.6 | 58.4 |
| NFH1-0.43 | 38.7 | 45.0 | 47.4 | 47.3 | 50.8 |
| NFH2-0.43 | 30.3 | 32.9 | 36.0 | 34.3 | –[a] |
| NC-0.36 | 49.3 | 58.6 | 70.1 | 71.5 | 71.5 |
| NF1-0.36 | 34.1 | 47.7 | 54.6 | 66.4 | 65.6 |
| NF2-0.36 | 21.2 | 29.8 | 49.1 | 57.6 | 73.8 |
| NCH-0.36 | 53.0 | 60.4 | 66.4 | 66.2 | 72.9 |
| NFH1-0.36 | 59.1 | 64.5 | 67.6 | 72.0 | 74.9 |
| NFH2-0.36 | 58.0 | 63.6 | 65.3 | 64.8 | 67.8 |

[a] The result is invalid

amount of fly ash increases, elevated curing temperature at early ages tends to have greater negative influence on the compressive strength gain in late age. As the water-to-binder ratio decreases, elevated curing temperature at early ages tends to have less negative influence on the compressive strength gain in late age.

## Discussion

The reasons for low rate of increase in late-age strength of concrete under elevated curing temperature at early ages are various. This article further confirms some viewpoints of other researchers. First, the non-evaporable water content and $Ca(OH)_2$ content of paste 0%FA-0.42 W/B-65 °C are smaller than those of paste 0%FA-0.42 W/B-20 °C at late ages, confirming that elevated curing temperature at early ages would decrease the rate of increase in late-age hydration degree of cement [1, 7, 8]. It is believed that the dense gel layer around cement particles formed under elevated curing temperature which decreases the further reaction rate of cement, is a key reason for the low late-age hydration degree of cement [6]. Second, the paste 0%FA-0.42 W/B-65 °C has more pores with diameter larger than 200 nm than paste 0%FA-0.42 W/B-20 °C at late ages, confirming that increasing early curing temperature would increase the porosity of late-age cement paste [9, 10].

More importantly, this article reflects two novel results:

(1) The influence of high curing temperature on the cement–fly ash paste is different from the cement paste. At early ages, fly ash improves the hydration condition of cement, resulting in an increase of the hydration degree of cement. In the meanwhile, the early hydration activity of fly ash is accelerated by elevated curing temperature, consuming more $Ca(OH)_2$ and promoting the hydration of cement. The hydration degree of cement in cement–fly ash paste is higher than that in pure cement paste under elevated curing temperature, so a denser C–S–H layer formed around cement particles in cement–fly ash paste at early ages. The late reaction of fly ash is not influenced by elevated temperature curing at early ages, but the late hydration of cement is hindered greatly, so the non-evaporable water content of cement–fly ash paste under elevated temperature curing condition is less than that of cement–fly ash paste under standard curing condition at late ages. But because the late reaction of fly ash makes further chemical contribution to the hardened paste structure, so at late ages, the pore structure of cement–fly ash paste under elevated temperature curing condition is finer than that of cement–fly ash paste under standard curing condition, and it is also finer than that of cement paste whether under standard or elevated temperature curing condition. In the meanwhile, the

**Table 8** Compressive strength ratio of samples under different curing temperatures

| Samples | Ages (days) | | | Samples | Ages (days) | |
|---|---|---|---|---|---|---|
| | 90 | 360 | 720 | | 90 | 180 |
| MCH-0.50/MC-0.50 | 0.8997 | 0.9510 | 0.9219 | NCH-0.50/NC-0.50 | 0.8593 | 0.8637 |
| MFH1-0.50/MF1-0.50 | 0.8927 | 0.8616 | 0.8776 | NFH1-0.50/NF1-0.50 | 0.7411 | 0.6997 |
| MFH2-0.50/MF2-0.50 | 0.8986 | 0.7040 | 0.7334 | NFH2-0.50/NF2-0.50 | 0.7704 | 0.5709 |
| MCH-0.42/MC-0.42 | 0.9176 | 0.8878 | 0.8547 | NCH-0.43/NC-0.43 | 0.8736 | 0.9389 |
| MFH1-0.42/MF1-0.42 | 0.9163 | 0.9486 | 0.9039 | NFH1-0.43/NF1-0.43 | 0.9348 | 0.9549 |
| MFH2-0.42/MF2-0.42 | 0.9319 | 0.8743 | 0.8534 | NFH2-0.43/NF2-0.43 | 0.7146 | –[a] |
| MCH-0.34/MC-0.34 | 0.9655 | 0.9564 | 0.9412 | NCH-0.36/NC-0.36 | 0.9259 | 1.0196 |
| MFH1-0.34/MF1-0.34 | 0.9416 | 0.9737 | 0.9581 | NFH1-0.36/NF1-0.36 | 1.0843 | 1.1418 |
| MFH2-0.34/MF2-0.34 | 0.9440 | 0.9674 | 0.9864 | NFH2-0.36/NF2-0.36 | 1.1250 | 0.9187 |

[a] The result is invalid

compressive strength of cement–fly ash paste under elevated curing temperature is higher.

(2) The influence of elevated curing temperature on the compressive strength of paste is different from the mortar. The cement–fly ash paste under elevated curing temperature at early ages has a high rate of increase in late-age compressive strength. On the contrary, the cement–fly ash mortar under elevated curing temperature at early ages has a low rate of increase in late-age compressive strength. The cement–fly ash mortar can be divided into three parts: the hardened cement–fly ash paste, the sands, and the transition zone between hardened paste and sands. Elevated curing temperature has no negative effect on the late-age strength of hardened cement–fly ash paste, and it has little effect on the sands. Therefore, it is clear that elevated curing temperature has a negative effect on the transition zone. The compressive strengths of hardened cement paste and cement mortar also prove it: At the age of 720 days, the compressive strengths of paste 0%FA-0.42 W/B-65 °C and 0%FA-0.34 W/B-65 °C account for 95.8 and 96.7% of those of paste 0%FA-0.42 W/B-20 °C and 0%FA-0.34 W/B-20 °C, respectively; but the compressive strengths of mortar MCH-0.42 and MCH-0.34 account for 85.5 and 94.1% of those of mortar MC-0.42 and MC-0.34, respectively. It can be seen that the elevated curing temperature has a greater negative effect on the compressive strength of mortar than hardened paste when the water-to-cement ratio is the same. So the influence of elevated curing temperature on the transition zone cannot be neglected.

What's more, as the water-to-binder ratio decreases, the negative effect of elevated curing temperature on the transition zone tends to be less, especially for the cement–fly ash mortar. Table 8 shows that when the water-to-binder ratio decreases to 0.36 (or 0.34), the compressive strength of mortar under curing condition B is very close to or even higher than that under curing condition A. This may be because the aggregates are wrapped more closely by the hardened paste when the water-to-binder ratio is low, and the area of transition zone is small. So the negative effect of elevated curing temperature on the transition zone is less.

## Conclusions

(1) After elevated temperature curing at early ages, the late hydration of cement is hindered, but the late reaction of fly ash is not influenced. The late reaction of fly ash makes further chemical contribution to the structure system. The pore structure of cement–fly ash paste under elevated curing temperature is finer at late ages. The compressive strength rate of increase in cement–fly ash paste under elevated curing temperature is higher at late ages. But the compressive strength rate of increase in cement–fly ash mortar under elevated curing temperature is lower at late ages.

(2) The negative effect of elevated curing temperature on the transition zone between hardened paste and aggregates cannot be neglected, and it is a reason for low rate of increase in late-age strength of concrete under elevated curing temperature at early ages. As the water-to-binder ratio decreases, the negative effect of elevated curing temperature on the transition zone tends to be less, especially for the cement–fly ash mortar.

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