J Therm Anal Calorim (2015) 121:1213–1223
DOI 10.1007/s10973-015-4567-3

Effects of ultrafine fly ash on the properties of high-strength concrete

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Received: 26 December 2014 / Accepted: 12 February 2015 / Published online: 29 March 2015

Abstract Ultrafine fly ash was added in the concrete mixtures in two different replacement ratios: 20 and 35 % in comparison with the control group. The water–to-binder ratio was 0.28. Standard curing and temperature matching curing methods were applied. Results showed that ultrafine fly ash decreased the adiabatic temperature rise of concrete and the bigger the replacement ratio, the more the decrease. It also decreased early compressive strength of concrete under standard curing condition, but it was compensated under temperature matching curing condition. Resistance to permeability of concrete was enhanced by ultrafine fly ash because the pore structure was improved. TG test reveals that the nucleation effect of ultrafine fly ash accelerated cement hydration. Temperature matching curing promoted the pozzolanic reaction of ultrafine fly ash at the early age. Non-evaporable water content was increased by ultrafine fly ash incorporation under standard curing condition, while at later age, under temperature matching curing condition it reduced the non-evaporable water content.

Keywords Ultrafine fly ash · Curing condition · Cement hydration · Compressive strength · Durability

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Introduction

Supplementary cementing materials gradually become an indispensable component for concrete because of their technological, economic, and environmental advantages. Prominent among these is fly ash. Fly ash, whose effects on concrete durability are widely studied by researchers, is applied in high-strength concrete mixture recently. As the cement content is usually large in high-strength concrete, the amount of heat released increases, which often leads to cracking in concrete, especially in massive concrete structures [1]. Mass concrete is defined as any volume of concrete with dimensions large enough to require the measures be taken to cope with generation of heat of hydration from the cement and attendant volume change to minimize cracking (ACI Committee 116 R-85). This is detrimental for durability of high-strength concrete. Fly ash with its low hydraulic activity and heat emission is therefore selected to replace cement. The fly ash replacement level as 15–25 % is recommended for high-strength concrete (ACI Committee 211 2008).

Yen et al. [2] studied the influence of class F fly ash on the abrasion–erosion resistance of high-strength concrete. It was concluded by them that the replacement ratio of class F fly ash for cement should not be beyond 15 % in order to maintain its abrasion–erosion resistance, while Naik et al. [3] found out in their study that the dividing point for class C fly ash is 30 %. From this perspective, the chemical composition of fly ash is important when deciding its incorporation amount. The replacement ratio of low-calcium fly ash incorporated in high-strength concrete with water-to-binder ratio of 0.24 can be up to 45 %, meanwhile reaching the equivalent compressive strength of plain concrete, as was the case in Ref. [4]. But 80 % of the fly ash remained unreacted at the age of 90 days and served as micro-aggregate. Kayali et al. [5] studied the impact of fly ash on the microstructure of lightweight concrete matrix in their research, and the result revealed that fly ash can improve the performance of lightweight concrete when exposed to chloride solution environment due to disconnected pore structure of the dense matrix of concrete. Nath et al. [6] conducted an overall experiment plan regarding the comprehensive effect of fly ash on the durability properties of high-strength concrete. It is indicated that fly ash incorporation improved the durability properties of concrete, including reducing drying shrinkage, sorptivity, and chloride ion permeability. Jaturapitakkul et al. [7] tried to use ground coarse fly ash with median diameter of 3.8 μm to replace condensed silica fume. It is found that 15–35 % replacement was appropriate for producing high-strength concrete and 25 % replacement seemed most beneficial, acquiring high compressive strength among their different ratios in the experiment.

As is mentioned above, fly ash could be ground to replace the expensive condensed silica fume producing high-strength concrete. At the same time, it is suggested that besides the chemical composition, the fineness of fly ash also determines its effects as additional cementing material. Chindaprasirt et al. [8] studied the effect of fly ash fineness on compressive strength and pore size of blended cement paste. The results confirmed the negative effects of original fly ash with median particle size of 19.1 μm and positive effects of classified fly ash with median particle size of 6.4 μm on the mechanical property and microstructure of cement paste. Chindaprasirt et al. [9] conducted experiments on blend cement mortar with five kinds of fineness fly ash. Compared to the original fly ash cement mortar, the compressive strength was enhanced, the drying shrinkage was reduced, and the resistance to sulfate and sulfuric acid attacks was improved when the fine fly ash was added, while the effect of the coarse fly ash was the other way around. Chindaprasirt et al. [10] considered the influence of fly ash fineness on the resistance to chloride penetration of concrete by incorporating three different kinds fineness fly ash. It is found that the decrease in Coulomb charge of concrete at 28 days was promoted when the fly ash fineness increased. Kiattikomol et al. [11] studied five different kinds of ground coarse fly ash with different chemical compositions and fineness. The experiments indicated that it is the fineness not the chemical composition that dominates the effect ground fly ash has, and the coarse fly ash can also be applied after the pozzolanic activity was improved by grinding. Haque and Kayali [12] conducted a research regarding a specific kind of class F fly ash with a fineness of 99 % passing a 45-μm sieve. Three replacement ratios: 0, 10, and 15 % were set. It is found that 10 % was the optimum level of cement replacement as far as the workability was concerned and at this replacement level the concrete showed higher early strength. Additional results such as beneficial effects on water penetrability and drying shrinkage demonstrated that the fine fly ash was a proper mineral admixture producing both high-strength and high-performance concrete. Subramaniam et al. [13] found that ultrafine fly ash significantly reduced the autogenous shrinkage of concrete, thus increasing the potential resistance to restrained cracking. Meanwhile, the decrease in early strength was solved by increasing ultrafine fly ash volume and decreasing the water-to-binder ratio. Besides the macroscopic properties, attention of Chindaprasirt et al. [14] was drawn to the microstructure of blend cement paste. The pore structure was improved, and the calcium hydroxide content was reduced after the fine fly ash was incorporated. Except for the single factor's effect on cement hydration kinetics, the coupled effects of temperature and fineness of Portland cement were also studied in Ref. [15].

Previous researches have taken into account the fineness, chemical composition, and replacement ratio of fly ash but one factor. In massive concrete structures where high-strength concrete is casted like giant columns and slabs, the fresh concrete mixture lies in a gradually elevated temperature surroundings, which may possess potential influence on the concrete properties. Hence, two different curing conditions, standard curing condition and temperature matching curing condition, were set in this experiment.

Experimental

Raw materials

The cement was Portland cement with the strength grade of 42.5 complying with the Chinese National Standard GB 175-1999. The ultrafine fly ash was ground to pass the 800-mesh sieve (15 μm). The coarse aggregates were crushed limestone aggregates of 5–25 mm in size. The fine aggregates were natural river sands with fineness of 2.8. Polycarboxylate superplasticizer (PS) was used to adjust the fluidity of concrete. The chemical compositions of cement and fly ash were determined by X-ray fluorescence spectrometer in a XRF-1800 machine. The chemical composition of the cement used consists of CaO 63.83 %, SiO_2 21.56 %, Al_2O_3 4.44 %, Fe_2O_3 2.78 %, MnO 2.57 %, SO_3 3.14 %, MgO 2.32 %, and P_2O_5 2.68 %. The chemical composition of the ultrafine fly ash used consists of CaO 3.45 %, SiO_2 53.60 %, Al_2O_3 28.12 %, Fe_2O_3 11.45 %, SO_3 0.43 %, and MgO 0.87 %.

Mix proportions

Table 1 shows the mix proportions of concrete. Concretes of groups C, F20, and F35 were cured under standard curing

Table 1 Mix proportions of concrete/kg m^{-3}

Samples	Cement	Fly ash	Fine aggregates	Coarse aggregates	Water
C	550	0	751	995	154
F20	440	110	751	995	154
F35	357.5	192.5	751	995	154
BC	550	0	751	995	154
BF20	440	110	751	995	154
BF35	357.5	192.5	751	995	154

condition, and those of groups BC, BF20, and BF35 were cured under temperature matching curing condition. In concretes F20 and BF20, 20 % of cement was replaced by ultrafine fly ash. In concretes F35 and BF35, 35 % of cement was replaced by ultrafine fly ash. The water-to-binder ratios of all the concretes are 0.28. The slumps of concretes were kept at about 17 cm by adding superplasticizer.

Test methods

Adiabatic temperature rise in each group was measured by Boyuan BY-ATC/A device. A total of 60 liters of concrete mixture was cast into the barrel for test each time till the age of 7 days.

Specimens of 100 × 100 × 100 mm were prepared for the compressive strength test. The standard curing condition groups were cured in a room with 20 ± 1 °C and 95 ± 5 % relative humidity until 28 days, while the temperature matching curing condition group was first cured in the steam curing box for 7 days, during which the temperature was set according to the adiabatic temperature rise data. Then, the specimens were transferred to the standard curing condition. At the ages of 7 and 28 days, the compressive strength of the concrete was measured.

The permeability of concrete to chloride ion at the age of 28 days was measured according to ASTM C1202 "Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration."

Thermogravimetric analysis (TG) tests of the hydrated cement pastes, whose mix proportions were each correspondingly consistent with the above concrete mix proportions, were conducted by Instrument 2050 TGA V5.3C at the ages of 3, 14, and 28 days. The solid fractions of cement pastes were crushed and ground in acetone, dried at 40 °C, and then used for TG. TG was carried out in N_2 atmosphere on about 10 mg of powdered cement pastes at 10 °C min^{-1} up to 900 °C.

Mercury intrusion porosimetry (MIP) tests of the hydrated cement pastes were conducted in the AutoPore IV 9500 V1.0 machine. The crushed cement pastes were washed in acetone then dried at 105 °C before sent to test at the age of 28 days.

Non-evaporable water tests were carried out at the ages of 7 and 28 days. At the defined times, the specimens were heated at 1000 °C for 6 h, after drying at 105 °C for 24 h. The amount of non-evaporable water was considered as the mass reduction on heating from 105 to 1000 °C.

Results and discussion

Adiabatic temperature rise

The adiabatic temperature rise test lasts 7 days when the temperature curve became stable as is depicted in Fig. 1. The maximum temperature rise was approximately 55.6 °C for the control group C: plain cement concrete. Incorporation of ultrafine fly ash decreased the adiabatic temperature rise and the larger the replacement ratio, the more it declined. As for samples F20 and F35, it declined for 8.63 and 14.93 %, respectively. The decline in unit replacement percentage was 0.432 and 0.427, respectively. Low activity of ultrafine fly ash in early age and dilution of the cement should account for the decrease. This is consistent with Ref. [16], where the decline in unit replacement percentage was 0.473 and 0.649, respectively, for 50 and 70 % fly ash incorporation. The relatively higher unit decline may be probably due to lower activity of ordinary fly ash compared to ultrafine fly ash.

Compressive strength

Figure 2 displays the compressive strength development of all groups of concrete. At the age of 7 days, the compressive strength of C reached 72.5 MPa. It decreased when the ultrafine fly ash incorporation increased under standard curing condition, which was caused by the low pozzolanic activity of ultrafine fly ash. The reductions for samples F20 and F35 were 6.06 and 16.83 %, respectively. Both reduction scopes were smaller than the corresponding replacement ratios. These values are obviously smaller than those of results presented in Ref. [6], where the compressive strength reductions in high-strength concrete with water-to-binder ratio of 0.29 were 35.29 and 41.17 % for

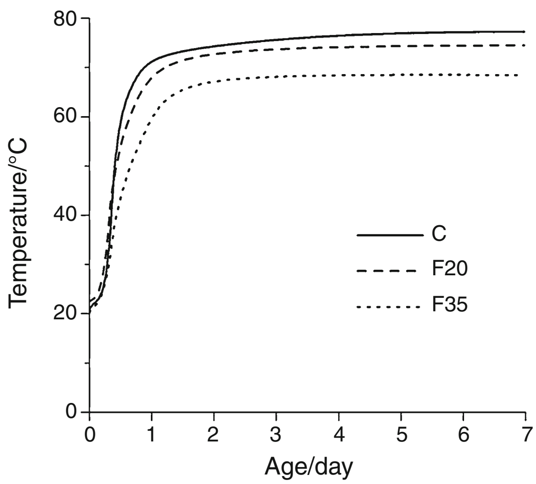

Fig. 1 Temperature rise of concrete

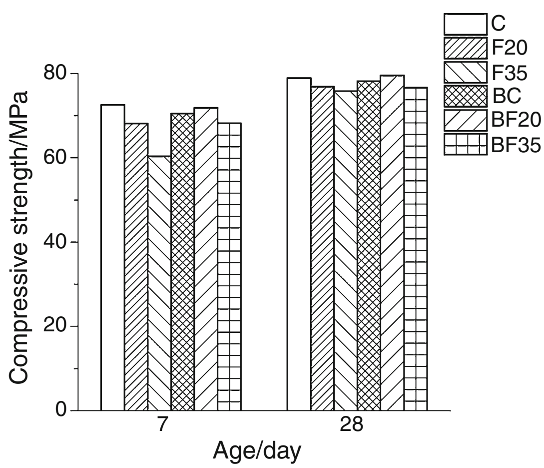

Fig. 2 Compressive strength of concrete

fly ash replacement ratio of 30 and 40 %, respectively. This was possibly due to the excellent filling effect and pozzolanic effect of ultrafine fly ash and the consequently compacted concrete microstructure. But under temperature matching curing condition, the differences among the groups were reduced and the compressive strength of sample BF20 even surpassed that of sample BC. This may be attributed to the enhanced pozzolanic activity of ultrafine fly ash under elevated temperature environment. But this trend was contrary concerning on the control group, which was probably caused by the fast precipitation and heterogeneous distribution of the accelerated hydration products at early age under temperature matching curing condition [17].

Till the age of 28 days, the compressive strength of ultrafine fly ash concretes became close to control groups under both standard curing condition and temperature matching curing condition. Still, the compressive strength of sample BF20 even surpassed that of the control group. The increase in amplitude of compressive strength of sample F35 was the largest (15.5 MPa), indicating the pozzolanic reaction of ultrafine fly ash.

Permeability to chloride ion results

Permeability to chloride ion of concrete is closely related to the porosity and connectivity of pores of concrete [18]. It influences the durability of concrete significantly. Permeability to chloride ion of concretes at the age of 28 days was tested (Fig. 3). Apparently, incorporation of ultrafine fly ash decreased the permeability of concrete under both standard curing condition and temperature matching curing condition. In the latter situation, the decreasing extent was larger. This was caused by the denser microstructure of ultrafine fly ash concrete, possibly due to the filling effect and pozzolanic effect, which was more obvious under temperature matching curing condition. But the resistance to chloride ion of sample BC was worse than sample C due to the loose microstructure of BC. This is because for pure cement concrete, elevated temperature tends to hinder the late hydration of cement and make the hydration products distribute non-uniformly [19, 20]. The permeability result of the pure cement concrete is in line with the conclusion drawn from the above compressive strength analysis.

MIP results

Porosity and pore size distribution were tested using MIP test. Porosity and the pore structure are critical to the durability of concrete because they are the passage through which water and chemical ions transfer into the inner part of concrete from the exterior. The cumulative pore volume curves under standard curing condition and temperature matching curing condition are shown in Figs. 4 and 5, respectively. For the standard curing groups, total porosities

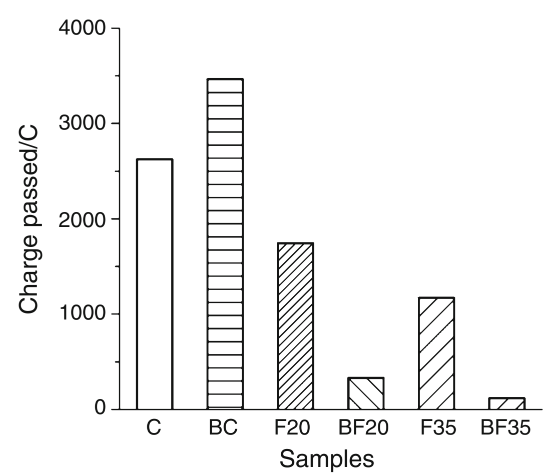

Fig. 3 Permeability to chloride ion of concrete

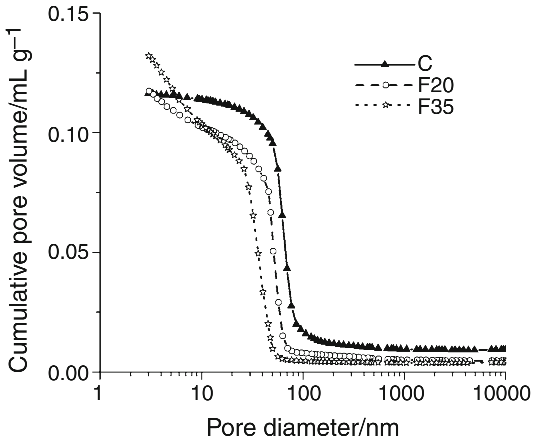

Fig. 4 Cumulative pore volume of pastes under standard curing condition

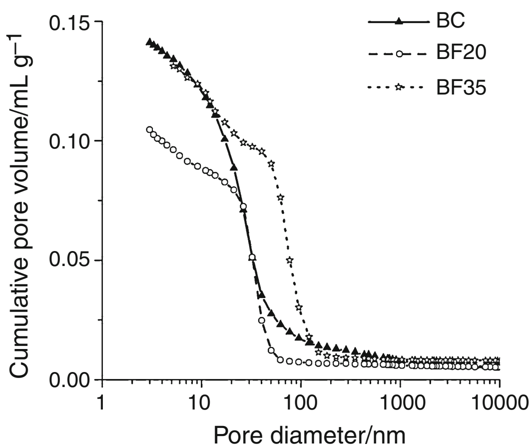

Fig. 5 Cumulative pore volume of pastes under temperature matching curing condition

of samples C, F20, and F35 were 21.5, 21.7, and 23.2 %, respectively. For the temperature matching curing condition groups, the values were 24.7, 19.0, and 22.8 %, respectively.

Under the standard curing condition, porosity of sample F20 was close to that of C, but it is higher for sample F35, while under the temperature matching curing condition, total porosity of BC was the biggest. This was possibly caused by the accelerated cement hydration and uneven distribution of the hydration products. Total porosity of samples BF20 and BF35 was a little lower than that of samples F20 and F35, respectively. This may be attributed to the accelerated pozzolanic reaction, proved in the below TG conclusion part, of the ultrafine fly ash, whose hydration products involved in interweaving the dense microstructure. In Fig. 4, it can be seen that incorporation of ultrafine fly ash shifts the curve to left a little. Nonetheless, the situation was slightly different in Fig. 5, where the curve of sample BF35 was a bit shifted toward right.

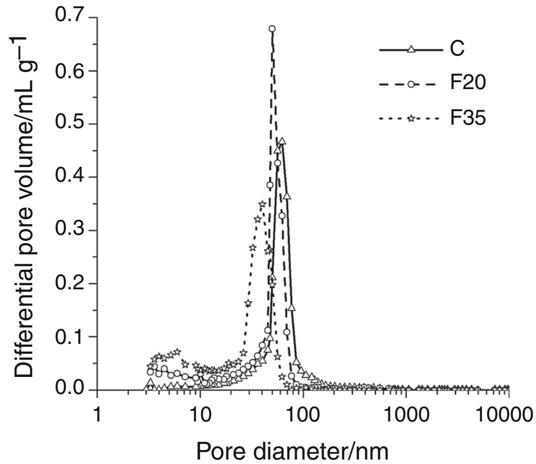

Fig. 6 Differential pore volume of pastes under standard curing condition

Differential pore volume curves of cement pastes under standard curing condition and temperature matching curing condition are displayed in Figs. 6 and 7, respectively. From Fig. 6, it can be concluded that the pore size corresponding to the dominant peak shifts left and the most probable pore size decreased after incorporation of ultrafine fly ash. The more the replacement, the more obvious the effect ultrafine fly ash brought about. However, it is not the same in Fig. 7. Under temperature matching curing condition, the curve of BF35 lies at the right side of samples BC and BF20. The value of most probable pore size of sample BC was the smallest. It means that under temperature matching condition even though the total porosity of pure cement paste was increased a little, the pore size distribution was also improved by its accelerated hydration. This could be evidenced by the following comparison between the pore content figures.

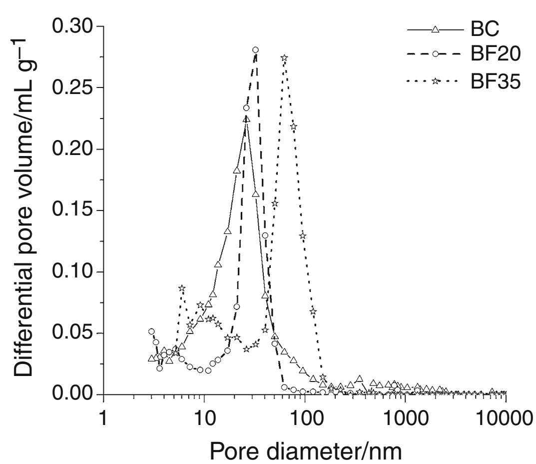

Fig. 7 Differential pore volume of pastes under temperature matching curing condition

In order to directly visually grip the improvement ultrafine fly ash had on the cement pastes' microstructure, the pores were divided into four ranges according to the theory of Metha [21] regarding the porosity assortment. The details of the pore content of pastes cured by standard condition and temperature matching condition are shown in Figs. 8 and 9, respectively. From Fig. 8, it can be seen that the pore structure was obviously refined by incorporation of ultrafine fly ash under standard curing condition. Although the total porosity increased a little, the volume of pores with diameter under 50 nm increased a lot. Then, the compacted microstructure contributed to the resistance to permeability to chloride ion of concrete, as is displayed above in Fig. 3.

In comparison with Fig. 8, it can be clearly seen that the microstructure of each paste got refined under temperature matching curing condition in Fig. 9. The pores whose size was less than 50 nm occupied most of the porosity.

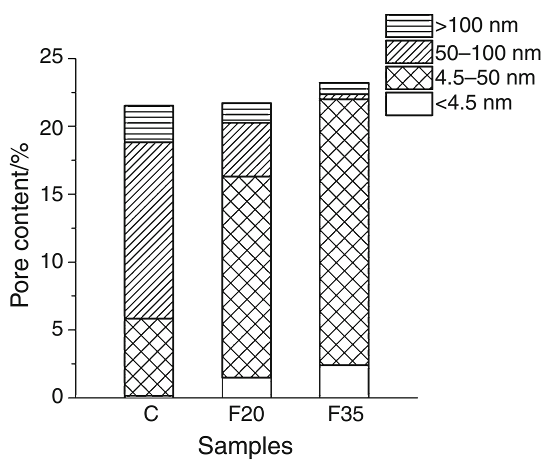

Fig. 8 Pore size distribution of pastes under standard curing condition

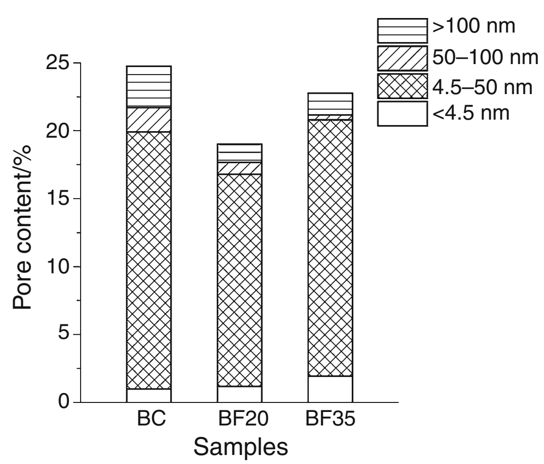

Fig. 9 Pore size distribution of pastes under temperature matching curing condition

Differences among the pure cement paste and the blended cement pastes were lessened. Considering the results presented in Fig. 3, concrete resistance to permeability to chloride ion was enhanced in blended cement concrete cured by temperature matching curing method, except the pure cement concrete, whose resistance declined. This indicates that the microstructure of concrete depends not only on the cementing materials hydration and the distribution of its hydration products, but also on its filling effect into the pores between the cementing materials and the aggregates. This could account for the combined results of the permeability to chloride ion test on the pure cement concretes and MIP test on the pure cement pastes.

TG results

The main hydrated products of cement are ettringite, calcium hydroxide, and calcium silicate hydrate. TG measures the mass loss due to the decompositions of the hydration products. Some mass loss within a temperature range of 600–780 °C associated with the decomposition of calcium carbonate. The first quantity of calcium hydroxide was estimated through this chemical reaction: carbonation of calcium hydroxide. The second important quantity was the mass loss corresponding to the decomposition of calcium hydroxide, which occurs approximately between 430 and 520 °C. Total amount of calcium hydroxide was then acquired through the summing up to investigate the effect of ultrafine fly ash on cement hydration process.

Figures 10 and 11 show the results of pastes under standard curing condition at the age of 14 and 28 days, respectively. Figures 12–14 show the results of pastes under temperature matching curing condition at the age of 3, 14, and 28 days, respectively. Figures 15–17 show the results of pure cement pastes under different temperature matching curing condition at the age of 3, 14, and 28 days,

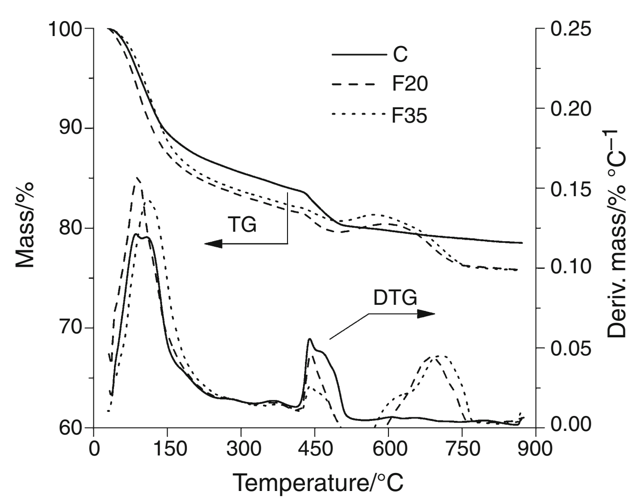

Fig. 10 TG of pastes under standard curing condition at 14 days

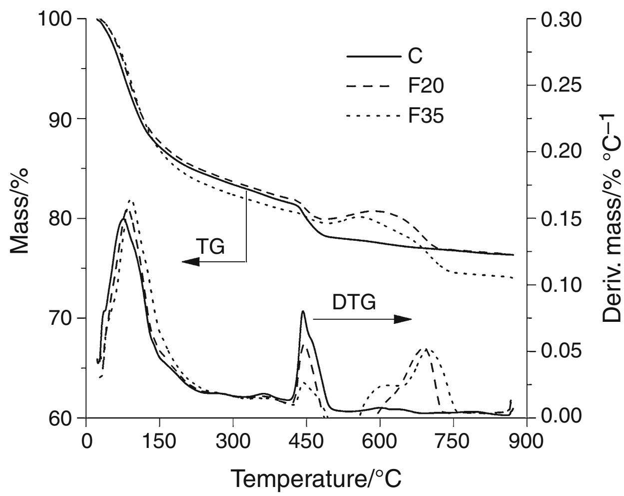

Fig. 11 TG of pastes under standard curing condition at 28 days

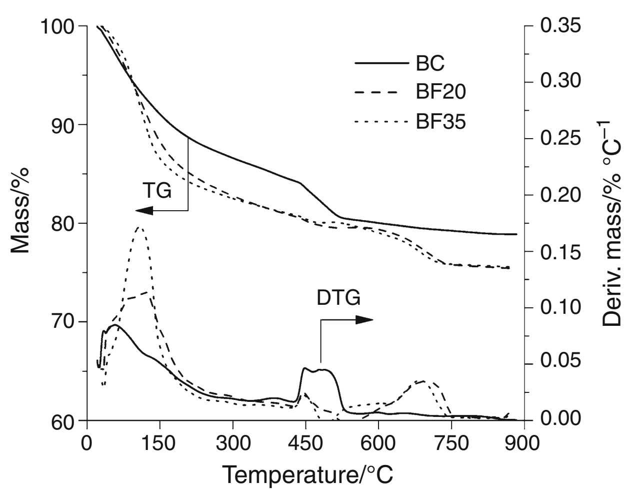

Fig. 12 TG of pastes under temperature matching curing condition at 3 days

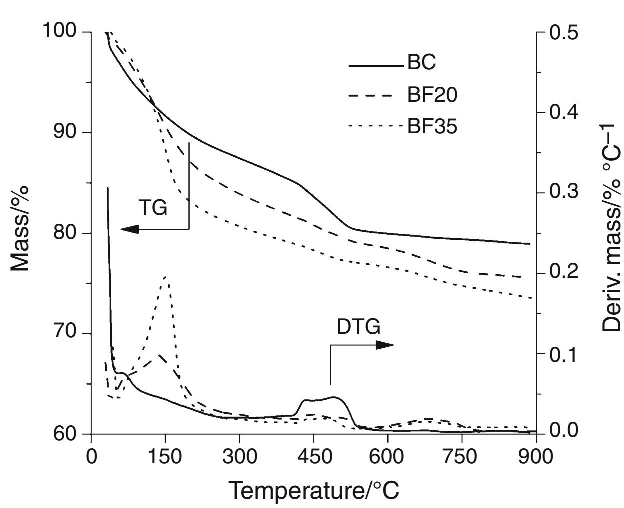

Fig. 13 TG of pastes under temperature matching curing condition at 14 days

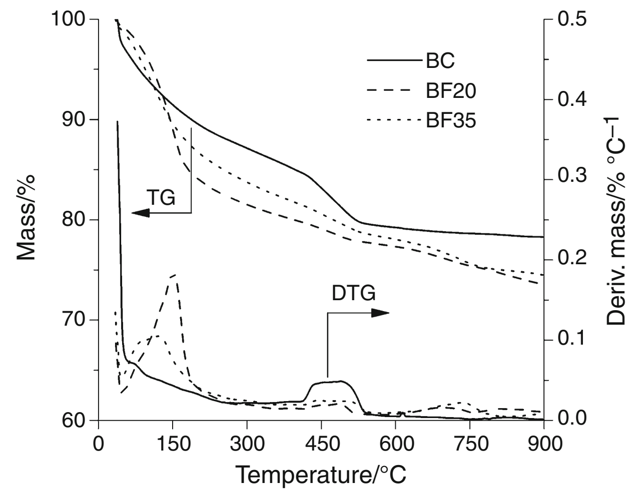

Fig. 14 TG of pastes under temperature matching curing condition at 28 days

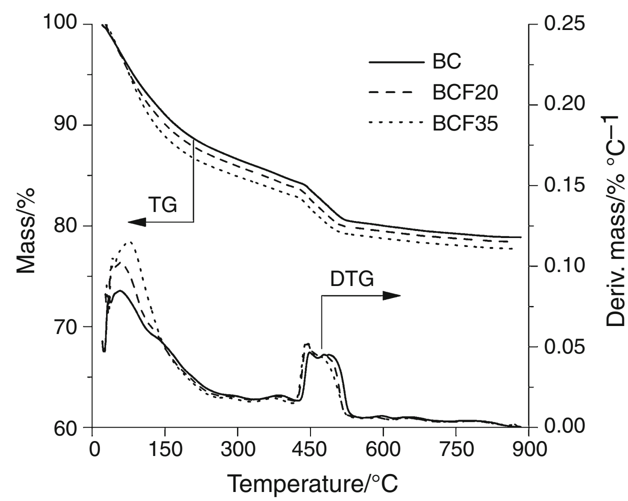

Fig. 15 TG of pure cement pastes under different temperature matching curing conditions at 3 days

respectively. Samples BCF20 and BCF35 mean the pure cement pastes cured under temperature matching condition according to the temperature data from adiabatic results from concrete groups of F20 and F35. This procedure was set to compare the pure cement paste with samples BF20 and BF35 to study the pozzolanic effect of ultrafine fly ash under the same curing condition.

According to the method mentioned above, the amount of calcium hydroxide was estimated and the results are shown in Figs. 18–21. In all figures, the columns p20 and p35 denote the calcium hydroxide content per cement mass of blended cement pastes with 20 and 35 % ultrafine fly ash, respectively. Figure 18 shows the calcium hydroxide content of cement pastes at the ages of 14 and 28 days cured under standard curing condition. It can be seen that the calcium hydroxide content declined as incorporation of

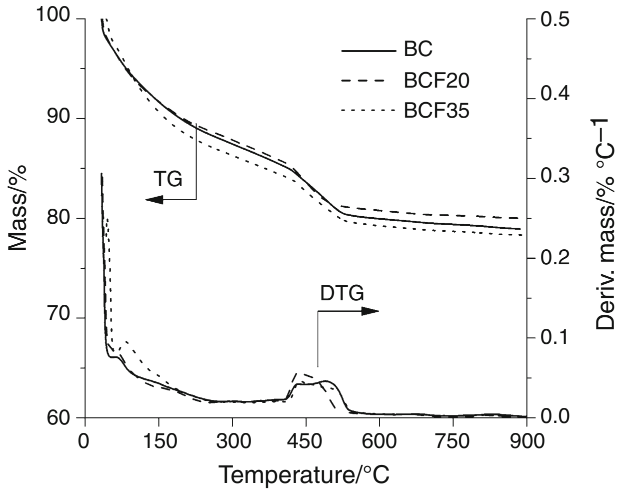

Fig. 16 TG of pure cement pastes under different temperature matching curing conditions at 14 days

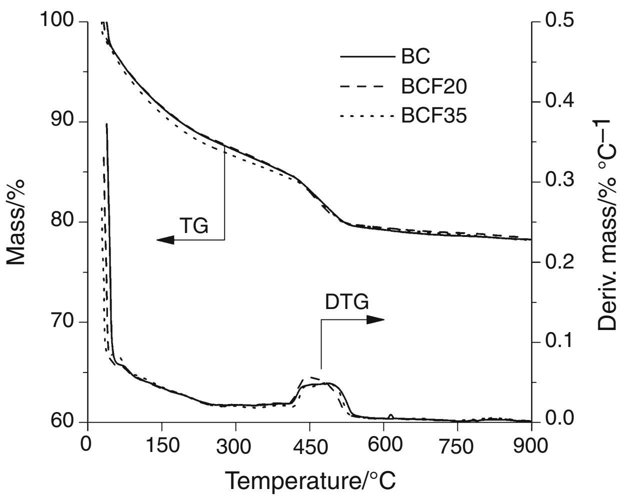

Fig. 17 TG of pure cement pastes under different temperature matching curing conditions at 28 days

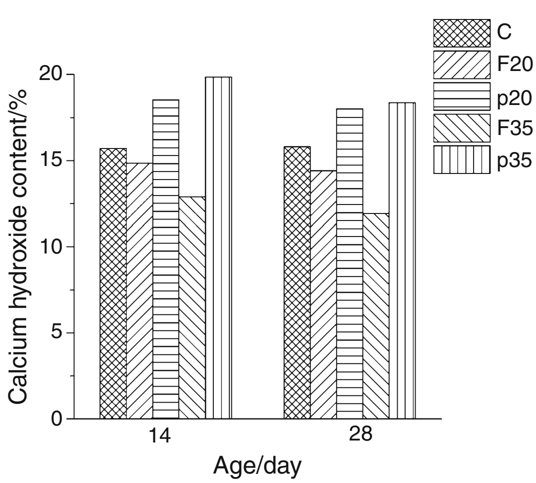

Fig. 18 Calcium hydroxide content of pastes under standard curing condition

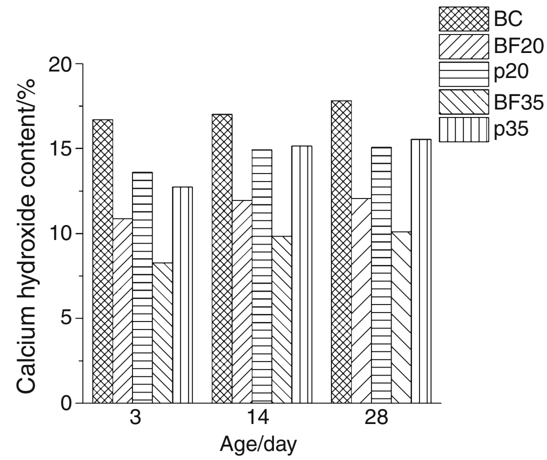

Fig. 19 Calcium hydroxide content of pastes under temperature matching curing condition

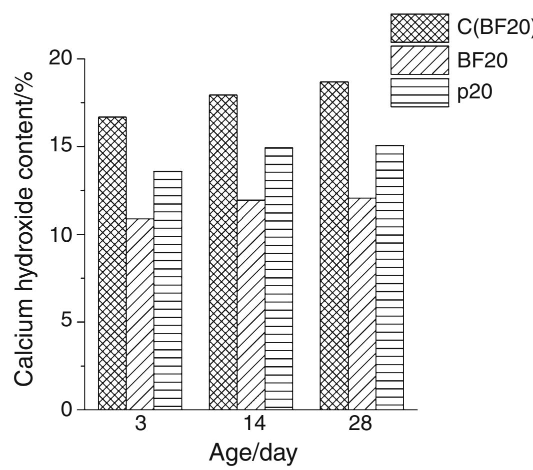

Fig. 20 Calcium hydroxide content of pastes F20 under temperature matching curing condition

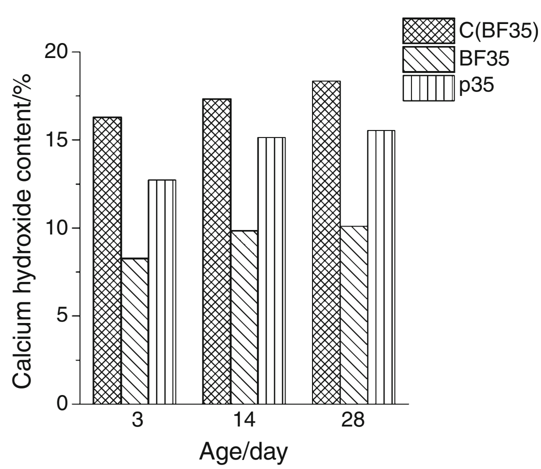

Fig. 21 Calcium hydroxide content of pastes F35 under temperature matching curing condition

ultrafine fly ash increased both at the ages of 14 and 28 days. As the cement amount declined, the content of calcium hydroxide as its hydration product declined because calcium hydroxide is a main hydration product of cement. Different from cement, the pozzolanic reaction of ultrafine fly ash does not produce but consumes, calcium hydroxide. In the meanwhile, the real water-to-cement ratio is higher for the paste containing fly ash. So the combined result of pozzolanic effect and nucleation effect was expressed as the empty columns p20 and p35 in Figs. 18–21.

In Fig. 18, as the ultrafine fly ash incorporation increased, the calcium hydroxide content per cement mass increased both at the 14 and 28 days, which indicates under standard curing condition, the nucleation effect rather than the pozzolanic activity of the ultrafine fly ash is the dominant effect of ultrafine fly ash. Figure 19 depicts the calcium hydroxide content of cement pastes under temperature matching curing condition at the age of 3, 14, and 28 days. Similar to Fig. 18, the calcium hydroxide content decreased as the ultrafine fly ash incorporation increased while the absolute calcium hydroxide contents of the control group (BC) at the ages of 14 and 28 days were higher than those (sample C) under standard curing condition. This was because the elevated curing temperature promoted the cement hydration at early age. On the other hand, the decreasing extents of samples BF20 and BF35 were larger than samples F20 and F35, respectively. Besides, the calcium hydroxide contents per cement masses of samples BF20 and BF35 were lower than those of both the control group (sample BC) under temperature matching curing condition and the corresponding groups (samples F20 and F35) under standard curing condition. This phenomenon reveals that under temperature matching curing condition, the pozzolanic reaction of ultrafine fly ash was promoted and the calcium hydroxide was consumed. These micro-level results suggested that the pozzolanic hydration product C–S–H gel generated compactness, which was beneficial to mechanical and durable properties of concrete, as were demonstrated in the above macrolevel results: strength and permeability parts. The conclusion was also proved in Ref. [22].

Figures 20 and 21 show the calcium hydroxide contents of the control group and the blended groups under the same temperature matching curing condition to compare with that under standard curing condition. This experiment condition was set to study the pozzolanic activity of ultrafine fly ash when the curing temperature differences, as were shown in Figs. 15–17, were eliminated. Both figures show that the calcium hydroxide content increased along with the age and decreased as the ultrafine fly ash incorporation increased. These are consistent with those under standard curing condition, but the calcium hydroxide contents per cement mass were lower. This depletion of calcium hydroxide again proved the enhanced pozzolanic activity and the advanced start time point of pozzolanic reaction of ultrafine fly ash, even at the very early age: 3 days, under temperature matching curing condition. This effect of temperature was similar to that observed in previously reported studies [23–25].

Non-evaporable water content results

The non-evaporable water content test is commonly used to determine the hydration degree of pure cement pastes. It is influenced by such factors as the water-to-binder ratio, the supplementary cementing material kind, and incorporation ratio. It is described in Ref. [26] that C–S–H hydrates with different water contents were formed. And due to the difference of polymerization of C–S–H gel and CH depletion in the pozzolanic reaction, the C–S–H from neat cement possibly contains more water than that formed from pozzolanic reaction [27]. It is also found in Ref. [28] that slag displays a hydraulic nature, retaining significant water amount in its hydrates, while pozzolanic materials shows small amounts of water content despite their CH consumptions in pozzolanic reaction. So it is not possible to compare the non-evaporable water of neat cement paste with the blended ones directly. But a modified approach to compare the two situations more accurately was verified by excluding the CH water loss. It is concluded from their research that the pozzolanic reaction products incorporate water due to additional C–S–H formation by CH consumption. This conclusion could be used in the following explanation regarding the non-evaporable water content changes.

The non-evaporable water content results were displayed in Fig. 22. Firstly, the effect of curing temperature was apparent in all groups at the age of both 7 and 28 days. It is especially distinct in neat cement pastes (samples C and BC). The elevated curing temperature accelerated the cement hydration and the more hydrates contained more water.

At the age of 7 days, the non-evaporable water contents of blended cement pastes were a bit higher than of the neat ones. The incorporation of ultrafine fly ash diluted the cement particles, and the effective water amount for cement hydration increased so the more sufficient hydration produced more hydration products. Besides, the nucleation effect of ultrafine fly ash accelerated the cement hydration. But the difference due to the incorporation was weakened under temperature matching curing condition. This was possibly caused by the CH consumption in pozzolanic reaction of ultrafine fly ash, as was demonstrated in the above TG part, which reduced the water in the hydration products.

At the age of 28 days, the difference between the neat cement paste (sample C) and the blended ones (samples

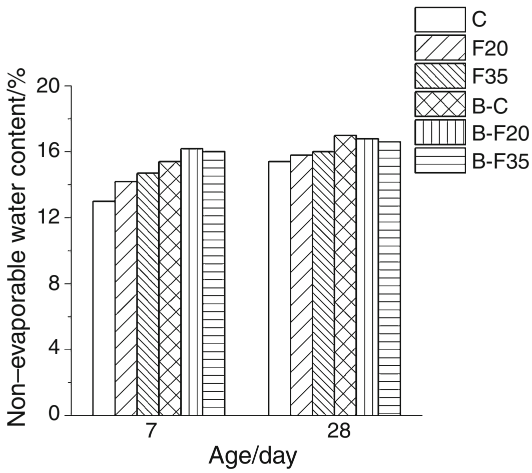

Fig. 22 Non-evaporable water content of pastes

F20 and F35) under standard curing condition became less because the cement hydration continued and the more the cement content, the hydration products and their containing water amount increased faster. This phenomenon was more obvious under the temperature matching curing condition. The non-evaporable water content of sample BC even surpassed the blended ones (samples BF20 and BF35).The amount of water in blended ones under temperature matching curing condition seemed to change a little from 7 to 28 days. Even the cement hydration continued to accumulate the water in hydration products; the simultaneous pozzolanic reaction consumed CH and countervailed the former accumulation of water content. The combined effects resulted in the relatively lower water content. Under standard curing condition, the increase in ultrafine fly ash incorporation led to the increase in non-evaporable water content, while it reversed under temperature matching curing condition. This was possibly due to the different dominating effect of the ultrafine fly ash under different curing condition. When cured under standard condition, the nucleation effect accelerated the cement hydration, while the pozzolanic effect occupied the main position.

Conclusions

1. Incorporation of ultrafine fly ash decreases the adiabatic temperature rise of concrete. The more replacement ratio, the more it decreases. Compressive strength of concrete decreases with the increase in ultrafine fly ash incorporation at the early age under standard curing condition, but the temperature matching curing condition makes up for the reduction. At the age of 28 days, the compressive strengths of all groups are close to each other.
2. Ultrafine fly ash improves the resistance to the permeability to chloride ion because its good filling effect leads to the refined pore structure of concrete. And the improvement is emphasized under temperature matching curing condition due to the pozzolanic reaction of the ultrafine fly ash. This is beneficial to both mechanical and durable properties of concrete.
3. At the early age, the nucleation effect of ultrafine fly ash accelerates the cement hydration, but it shows little pozzolanic activity under standard curing condition. While its pozzolanic activity is enhanced under temperature matching curing condition and even at the age of 3 days, the ultrafine fly ash involves in the hydration process.
4. Ultrafine fly ash increases the total non-evaporable water content of the cement paste under the standard curing condition. But the temperature matching curing condition weakens the increase, and at the age of 28 days, incorporation of ultrafine fly ash even reduce the non-evaporable water content due to its accelerated pozzolanic reaction with calcium hydroxide.

Acknowledgements Authors acknowledge the support from Shandong Provincial Natural Science Foundation, China (ZR2012EEQ014), and Youth Science and Technology Innovation Project of Shandong Agricultural University.

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