Influence of curing age on the mechanical properties of fly ash concrete exposed to elevated temperature

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Abstract

The mechanical properties of early-age fly ash (FA) concrete was experimentally studied. The splitting tensile strength and compressive strength under different curing ages, temperatures, cooling methods and FA contents were analyzed. The experimental results showed that the splitting tensile strength of concrete increased proportionally with temperature in the early stage and decreased as the temperature further increased. Compared to the concrete with FA content of 10% and 30%, the compressive strength of concrete with FA content of 20% was found to be highest at the age of 90d. The strength of the specimens under water cooling was comparatively lower than that under air cooling. The compressive strength of FA concrete heated to 150 °C was greater than that of the unheated concrete. The compressive strength of FA concrete heated to 550 °C was lower than that of concrete without treatment at high temperature. After high temperature exposure at the age of 90d, the compressive strength of the specimen was higher than that of the specimens at the ages of 7d, 14d and 28d. The microstructures of the specimens aged 90 days were measured by the SEM method before and after being exposed to high temperatures.

Keywords: early age; temperature-related & thermal effects; fly ash; concrete

1. INTRODUCTION

With the increasing application of FA (fly ash) concrete in many concrete structures, FA concrete in construction industries has been reported.^[1-6] In order to make better use of FA concrete, its fire resistance must be studied. The maximum tolerable temperature of FA concrete is 400 °C, after that it has a lower plastic deformation capacity than ordinary concrete.^[7-8] When the temperature exceeds 400 °C, FA concrete show a huge loss in compressive strength. In comparison to natural cooling, the compressive strength of the specimen is reduced when using the water-spraying cooling process.^[9] Therefore, the addition of FA can effectively improve the compressive strength of ordinary concrete, and can slow down the cracking of the concrete in high temperature conditions.^[10] It has been reported that the effect of the cooling method on the properties of concrete is reduced with increasing FA content.^[11] In comparison to air cooling, water cooling leads to a larger reduction in the compressive strength of the specimen after exposure to elevated temperatures. In general, fly ash can effectively enhance the workability, compactness and fire-resistance of concrete.

In recent years, because of the widely accepted applications of concrete, the mechanical properties of early-age concrete after fire damage has attracted increasing attention. The hydration reaction in early-age concrete is generally not fully completed, therefore the internal compositions are in an active state of change.^[12] During this period, the hydration reaction rate and hydration degree inside the concrete is affected by many factors such as temperature, high temperature duration, extinguishing method and later curing time. Therefore, the residual properties of concrete at an early age is very different from that concrete at an adequate age.^[13-14] When the concrete was heated to a high temperature after 3 days and continued to be cured to the 28th day, most of its compressive strength could be recovered. The recovery of compressive strength of concrete cooled by water is more evident.^[13] Increasing the usage of FA can effectively improve the compressive strength of concrete. FA concrete requires a longer curing time than ordinary concrete without FA.^[15] The mechanical properties of early-age FA concrete begin to increase after being cured for 28d^[16-17] analysed the hydration and mechanical properties of high-volume slag and fly ash concrete at different curing temperatures. The results showed that high volume fly ash accelerated the cement hydration at an early age because of

the dilution and filler effects. The hydration process of fly ash concrete was also more sensitive to temperature. The results of^[18] showed that it was important to consider the temperature effect on concrete creep and tensile strength when the temperature variation in concrete was significant at very early ages. However, there is limited research on the mechanical properties of early-age fly ash concrete, especially under the influence of elevated temperatures.

This paper discusses experimental research on the material strength of FA concrete under elevated temperatures. The splitting tensile strength and compressive strength under different curing ages, temperatures, cooling methods and FA contents will be analyzed.

2. RESEARCH SIGNIFICANCE

Fire accidents during the construction period of concrete structures occur occasionally. Once a fire accident occurs during the construction period, the mechanical properties of the concrete that has not yet reached its actual design strength will be significantly changed, which may result in serious security risks for the whole structure. When the concrete is exposed to high temperature before the FA and cement in the concrete has been fully hydrated, the mechanical properties of FA concrete will be different to the unheated FA concrete. Therefore, it is of great practical significance to study the performance of FA concrete that is heated at early ages. It is very important to evaluate the safety of concrete structures affected by high temperature during the construction period.

3. OVERVIEW OF EXPERIMENT

3.1 Materials and specimens

Cement produced by Huaihai Cement Plant was used in this study, and its grade was PO.42.5. The composition of the cement is shown in Table 1. Fly ash discharged by Pengcheng power Plant in Xuzhou was used. Its fineness (weight of screen residue by 45 μ m square holes) was up to 10% with an ignition loss of 3% and a water content ratio of 92%. The ingredients and parameters for FA are listed in Table 2 and Table 3. River sand was applied as fine aggregates, while gravel was used as coarse aggregates. In order to make the concrete consistent with the concrete used in actual projects, the mix proportion was designed based on the

specification concrete.^[19]

3.2 Grouping of specimens

The amount of FA used in concrete was calculated according to MOC^[20]. The mix proportion of FA concrete is listed in Table 4.

The damage of concrete treated at temperatures above 600 °C is serious and the compressive strength decreases significantly^[7], it is better to be chiseled. There is no significance at this stage for repair. Therefore, in this study the specimens were heated up to only 150 °C, 350 °C and 550 °C. Because the early strength of FA concrete is low, the secondary hydration reaction generally starts after 14 days of concrete casting. The active effect of fly ash is still at the initial stage after curing for 28d.^[21] In addition, according to the determination of design age of fly ash concrete given by Nadem et al.^[9], it is mandatory to consider the type of building and the actual loading time. Further, contribution of FA to the concrete strength in later periods, which should be 28d or 60d for aboveground and ground construction, and 60d or 90d for underground construction. Therefore, in this study the specimens were cured for 7d, 14d, 28d, 60d and 90d, respectively before the high temperature treatments. By combining it with the fire extinguishing methods utilised when a fire occurs in buildings, two cooling methods (natural cooling and water-spraying cooling) are also used.

For FA concrete, cubes of 100mm×100mm×100mm were prepared, and the mold was removed after 24h of pouring. The specimens were put in the curing chamber at a temperature of 20 ± 2 °C and R.H. above 90% for 7d, 14d, 28d, 60d and 90d, respectively. Afterwards, the specimens were taken out to carry out heating tests. The specimens were tested under the conditions within Table 5.

3.3 Experiment equipment

A hydraulic pressure testing machine of WE-1000A type is used for loading with the loading speed controlled at 5kN/s^[22]. The electric furnace whose power is 30kW is used for heating with internal net size of 2000mm × 600mm × 400mm.

The heating rate was fixed at 10 °C /min. In order to make the temperature field uniform

within the specimens, the specimens were maintained at the target temperature for 90 min^[23] and then they were brought out to cool to room temperature. The splitting tensile strength and compressive strength of concrete were measured in accordance with the manual of specification of concrete.^[22]

4. RESULTS AND DISCUSSION

The compressive strength of the FA specimens which were heated at high temperatures at different curing ages are listed in Table 6. Table 6 shows that the concrete with 20% fly ash content displayed better compressive strength at normal temperatures. Therefore, it was selected for the splitting tensile strength experiment. The splitting tensile strengths of FA concrete at different curing ages after being exposed to elevated temperatures are listed above in Table 7.

4.1 Compressive strength of FA concrete

4.1.1 *Effect of high temperature on the compressive strength*

The strength of the naturally cooling concrete containing no FA increases at 150 °C. After being treated at 350 °C at ages of 7d and 14d, the concrete strength increases, while it decreases significantly after being treated at 550 °C. The concrete strength increases after being treated at 150 °C at curing ages of 28d, 60d and 90d, while the compressive strength shows a decrease when the temperature reached 550 °C.

As shown in Fig. 1 (a), the strength of the specimens without FA show an enhancement of 19.81%, when the specimens were heated to 150 °C after being cured for 7d. While the compressive strength of concrete was increased by 30.02% when the specimens were heated to 350 °C. However, a decrease of 15.18 % is reported when the specimens were heated to 550 °C.

For the naturally cooled FA concrete as shown in Fig. 1 (c), (e) and (g), the compressive strengths of concrete heated to 150 °C at curing ages of 7d and 14d are greater than those of the unheated specimens. While, the strength of FA concrete decreases if the specimens were treated at 350 °C and 550 °C. After exposure to 150 °C and 350 °C at curing ages of 28d, 60d and 90d, the compressive strength of FA concrete increase significantly. After exposure to 550 °C, the compressive strength is significantly lower than that of the concrete without treatment to high temperature.

For the concrete exposed to 150°C at early ages, the internal cement hydration reaction is not finished. High temperature treatment promotes the continuing hydration of unhydrated cement particles leading to an increase in the hydration process and products.^[15] At the same time, the dehydration reaction of C-S-H gel occurs due to the evaporation of free water, which causes hardening of the cement slurry, and an increase in both the chemical binding forces and the compressive strength.^[24]

After exposure to 350 °C, the free water in concrete begins to evaporate, and part of the crystal water begins to decompose due to high temperatures. The evaporation of pore water and chemical-bound water results in increasing porosity in the cement slurry. Due to the relatively low hydration degree of FA in concrete at curing ages less than 28d, the damage in concrete caused by the high temperature is more significant than the improvement in strength caused by the accelerated hydration of cement due to high temperature. Therefore, the strengths of specimens heated at ages of 7d and 14d were lower than that of the unheated concrete. On the other hand, after being exposed to 350 °C at curing ages of 28d, 60d and 90d, the cement will have completed most of the hydration reaction and the internal structure will be intact^[28], which may cause an enhancement in compressive strength.

After exposure to 550 °C, the concrete completely loses its free water, pore water and crystal water. At 550 °C, and the gap increases as the $\text{Ca}(\text{OH})_2$ starts to decompose. The differences of thermal expansion performance cause the development of cracks between the aggregate and cement stone. The increase in the number and width of the cracks cause macroscopic damages and a rapid decrease in concrete strength.^[26]

4.1.2 Effect of cooling method on the compressive strength

From Fig. 2, it can be determined that the compressive strength of the water-spraying cooled specimen is smaller than that of the naturally cooled specimens when the FA concrete was heated to high temperature at different curing ages. It also shows that the decreasing rate increases with the increasing temperature.

In Fig. 2 (c), taking the concrete with FA content of 20% as an example, the influence of the cooling method on the residual compressive strength was significant. For FA20 concrete subjected to 150, 350 and 550 °C at a curing age of 7d, the compressive strength of water-

spraying cooled specimens was reduced by 6.96%, 12.7% and 17.07% compared to that of naturally cooled concrete. While the compressive strength of FA0 concrete cooled by water-spraying was reduced by 4.86%, 9.75% and 15.48%, respectively as compared to the naturally cooled specimens when subjected to 150, 350 and 550 °C temperatures. At the curing age of 90d, after the FA20 concrete specimens were heated at 150, 350 and 550 °C, the compressive strength of the water-spraying cooled specimens was reduced by 7.49%, 10.4% and 14.9%, respectively as compared to the naturally cooled specimens.

The sudden drop of temperature caused by spraying water, uneven thermal expansion and contraction cause the formation of multiple cracks in the concrete, which results in a decrease in the compressive strength. After being treated at 150 and 350 °C, the expansion deformations of aggregate and gel were small. Due to stress, the differences in the compressive strength of naturally cooled and water-spraying cooled concrete were small. However, after treatment at 550 °C, the differences in expansion of aggregate and gel were greater. The difference in the volume change is found to be incongruous in between the aggregate and slurry, which leads to the formation of more cracks. The formation of micro-cracks damages the cementation between the aggregate and slurry, which results in a reduction of the compressive strength.^[11]

4.1.3 Effect of FA on the compressive strength

Fig. 3 shows that the variation in the compressive strength of concrete with different fly ash content were similar to each other at the same curing time.

For the concrete subjected to high temperature at curing ages of 7d, 14d and 28d, the high content of FA reduces the residual strength. The main reason for this is that the proportion of cement clinker minerals decreases after the addition of FA in the early stages of hydration, which results in the decrease of hydration products in the concrete. The addition of FA also causes a decrease in the Ca^{2+} concentration in the solution and the total hydration rate in the cement-FA system. Since the hydration degree is very low, the particle connection between the generated hydration products is not close enough, which causes an increase in the total porosity and a decrease in the compactness of the hydrate. Therefore, the concrete with high content of FA have a lower compressive strength.

For the concrete specimens subjected to high temperatures at 60d and 90d, the compressive

1 strength of concrete containing fly ash contents of 10% and 20% was found to be much greater
2 than that of concrete containing no FA. The strength of the concrete specimens with FA content
3 of 20% was found to be the highest. Because the effective water to cement ratio of cement
4 clinker in the specimen with FA was relatively large, the hydration of the cement clinker is fast
5 and the secondary hydration reaction of FA occurs. FA particles with smaller particle size than
6 cement particles fill the pore spaces and reduce the porosity of the FA concrete, so the internal
7 microstructure was found to be much denser than the standard concrete, which cause an increase
8 in the compressive strength [2].

9 Nevertheless, the compressive strength of concrete with FA content of 30% was found to
10 be lower than that of the concrete with FA contents of 10% and 20%. The main reason is that
11 when the FA content is too much, the calcium hydroxide content, which plays the excitation
12 role in the concrete, becomes too small. This causes a large decrease in the FA hydration
13 conditions, which is not conducive to the development of later compressive strength.

15 *4.1.4 Effect of curing age before high temperature on the compressive strength*

16 From Fig. 4, it can be determined that the compressive strength of FA concrete increases
17 with an increase in curing age before heating. The increase in compressive strength of
18 specimens containing FA is more significant than that of the specimens without FA.

19 Under high temperature at curing ages of 7d and 14d, FA has almost not contribution to
20 the hydration reaction. As part of the cement is replaced by FA, the proportion of minerals in
21 the cement clinker decreases, which cause a reduction of hydration products. The hydration
22 product particles are not tightly connected and the microstructure is loose. Therefore, the
23 compressive strength reduced following the high temperature treatment.

24 For the concrete subjected to high temperature at 28d, the hydration reaction of fly ash is
25 still occurring, and so the filling effect of FA particles and aggregate helps in establishing a
26 cross connection among the hydration products. At this stage, there is a decrease in porosity
27 and an increase in the structural density at 7d and 14d, which causes a significant enhancement
28 in the compressive strength.

29 Exposure to high temperature at the age of 60d causes the porosity of hydrates in the
30 concrete to be further reduced and therefore the structure becomes dense, so the compressive

1 strength of FA concrete is increasing. But the activity of FA at this time has not yet fully
2 developed, and there exist gaps between the FA particles and cement gel; FA is required for
3 further hydration of the gel.

4 With the increase in curing age, the increase in the compressive strength of FA concrete
5 after high temperature treatment at 90d is clear, and the secondary hydration effect of FA
6 happens to produce more C-S-H gel. At the same time, the FA particles with smaller particle
7 size than the cement particles fill up the pores of the concrete and reduce the porosity of the FA
8 concrete. This cause densification and compactness of the internal microstructure of the
9 concrete and helps in increasing the compressive strength of concrete.

11 **4.2 Splitting tensile strength of FA concrete**

12 *4.2.1 Effect of high temperature on the splitting tensile strength*

13 Fig. 5 shows the splitting tensile strength residue rate of FA concrete with different curing
14 ages and different fly ash content after being exposed to temperatures of 150 °C, 350 °C and
15 550 °C. From Fig. 5, it can be seen that the changing rule of FA concrete under air cooling and
16 water cooling after exposure to elevated temperatures was similar, but the regularity differed
17 between concrete of different curing ages. From the comparison between FB0 and FB20, it can
18 also be seen that the changing rule of the splitting tensile strength of FA concrete after exposure
19 to elevated temperatures was different in normal concrete.

20 For specimens aged less than 28 days, in which the hydration reaction is not finished, the
21 temperature promoted further hydration. Therefore, the splitting tensile strength of each sample
22 increased with higher temperatures. Moreover, the strength residue rate of normal concrete after
23 exposure to elevated temperatures was larger than that of fly ash concrete.

24 The hydration reaction of the samples aged more than 28 days was nearly finished. When
25 exposed to a temperature of 150°C, the precipitation of free water inside the concrete and the
26 intermediary water of C-S-H damaged the internal structure of the concrete, leading to a
27 reduction of the splitting tensile strength. For the concrete samples exposed to a temperature of
28 350°C, the damage to the microstructure of the concrete was stable, and the splitting tensile
29 strength reduced slowly. After the sample was exposed to a temperature of 550°C, the chemical
30 components decomposed. The C-S-H gel and a large quantity of CaO broke down, leading to a

sharp decline in concrete strength.^[27] Compared with normal concrete, the fly ash of the FA concrete continued to react after the hydration of the cement was finished. At curing ages of more than 28 days, due to the better fire-resistance properties of fly ash, the splitting tensile strength of the FA concrete at elevated temperatures was higher than that of normal concrete. This conclusion agrees with that reported by Mendes et al.^[28]

4.2.2 Influence of cooling method on the splitting tensile strength of FA concrete

Comparisons of the splitting tensile strength residual rate of FA concrete exposed to high temperatures and cooled by either air or water are shown in Fig. 6.

From Fig. 6, it can be seen that the splitting tensile strength of concrete exposed to high temperatures followed by water cooling was lower than that followed by air cooling. This difference was greater with increasing temperatures. Fig. 6(b) shows that, for the FA concrete aged 7 days with 20% fly ash content, the remaining splitting tensile strength of the specimen under water cooling was 7.32%, 12.8% and 12.9% less than that under air cooling after being exposed to temperatures of 150°C, 350°C and 550°C respectively. It can be concluded that the strength difference between the concrete under the two cooling methods increased with higher temperatures.

When exposed to a temperature of 150°C, the splitting tensile strength of FA concrete under air cooling increased within a small range. This was because the dehydrated fly ash and cement particles reacted to form calcium silicate hydrates. For the specimens under water cooling, some of the samples were partly strengthened and partly reduced before heating. Water cooling supplemented the water that had evaporated and promoted further hydration inside the concrete. However, water cooling also led to a severe temperature change on the surface of the specimen, which caused cracking inside the concrete.

With increasing temperatures, the influence of the cooling method on the splitting tensile strength tended to be stronger. The strength difference between the concrete under the two cooling methods increased with temperature. As water cooling led to a large temperature gradient on the surface of the specimen, cracking was accelerated. The temperature difference on the surface increased and the cracking was more severe when the specimen was exposed to a higher temperature. Therefore, the remaining strength of the FA concrete was much lower.

Elevated temperatures made the components of the concrete expand or shrink, which led to uncoordinated deformation. Moreover, the $\text{Ca}(\text{OH})_2$ dehydrated into CaO when the temperature of the concrete exceeded 400°C . This made the concrete shrink and crack. If the water cooling method was applied, the CaO quickly absorbed water and rehydrated into $\text{Ca}(\text{OH})_2$. The re-expansion of the cement made the ionic compounds decompose into smaller particles which led to sharp decreases in the splitting tensile strength.

4.2.3 Influence of curing age on the splitting tensile strength of FA concrete

The tensile strength of FA concrete after exposure either to elevated temperatures or to normal temperature (20°C) was compared and analyzed. In this paper, this is designated the splitting tensile strength residue rate.

From Fig. 7 it can be seen that the longer the curing age, the higher the splitting tensile strength of the FA concrete. The magnitude of the strength increase for fly ash concrete was much greater than that of normal concrete without fly ash.

For FA concrete aged 7 and 14 days and exposed to elevated temperatures, the fly ash did not participate in the hydration reaction. As the content of cement was reduced by the addition of extra fly ash, the hydration product was also reduced.

For FA concrete aged 28 days and exposed to elevated temperatures, the porosity in the concrete was reduced because of the hydration reaction of the fly ash. The splitting tensile strength was much greater than that of the FA concrete aged 7 and 14 days.

For FA concrete aged 56 days and exposed to elevated temperatures, the porosity between the hydration production was reduced and the microstructure became denser, leading to an increase in the splitting tensile strength of the FA concrete. However, the fly ash had not fully reacted. It needed further hydration.

The specimen aged 90 days and exposed to elevated temperatures exhibited the highest splitting tensile strength. The secondary hydration of the fly ash produced a large amount of C-H-S gel. Moreover, as the fly ash particles were smaller than that of the cement particles, they could effectively fill the pores, making the microstructure of the concrete much denser.

4.3 Analysis of microstructures of FA concrete

1 The microstructures of the specimens aged 90 days were measured by the SEM method
2 before and after being exposed to high temperatures, as shown in Fig. 8 below.

3 From Fig. 8 and Fig. 9, it can be seen that the microstructure of the FA concrete was not
4 dense. There was obvious cracking, which greatly reduced the contact area of the hydration
5 products. This contributed to the conclusion that the splitting tensile strength of concrete under
6 water cooling was comparatively lower than that under air cooling.

7 After the samples were exposed to temperatures of 150°C or 350°C, the C-H of the FA
8 concrete decreased, and the secondary reaction of fly ash was more significant meaning that
9 150°C and 350°C promoted the hydration of fly ash and cement. Therefore, the splitting tensile
10 strength of FA concrete aged 90 days slightly increased after being exposed to temperatures of
11 150°C and 350°C. The comparison of Fig. 9(a) and (b) with Fig. 9(c) and (d) shows that the
12 hydration reaction degree of FA concrete exposed to 150°C was lower than that exposed to
13 300°C. Fig. 9(e) and (f) show that the microstructure of the FA concrete exposed to 550°C was
14 porous. Fly ash particles which had not fully hydrated were found. It can be concluded that after
15 being exposed to temperatures of 550°C, the orderly cycle hydration of fly ash and cement
16 inside the FA concrete broke, which led to a sharp decrease in the splitting tensile strength of
17 the FA concrete.

19 5. CONCLUSIONS

20 According to the experimental results in this paper, the effects of high temperature, cooling
21 method, FA content and curing age on the compressive strength and splitting tensile strength of
22 concrete with fly ash were analyzed. The following conclusions were drawn:

- 23 (1) The compressive strength and splitting tensile strength of concrete with different fly ash
24 content after elevated temperatures tended to have a similar regularity, but the values were
25 greatly different. The specimens cured for more than 28 days, with 20% fly ash, behaved
26 best after being exposed to elevated temperatures. The strength of concrete with a curing age
27 of less than 28 days reached its peak value at 150°C, while that of FA concrete cured for
28 more than 28 days reached its peak value at 350°C. The strength of FA concrete aged 28
29 days experienced the maximum change when temperature was increased. The FA concrete

- 1 with a curing age of 90 days was the most fire-resistant;
- 2 (2) For all curing ages, compressive strength and splitting tensile strength after exposure to
- 3 elevated temperatures for FA concrete cooled by the water cooling method was lower than
- 4 that of FA concrete cooled by the air cooling method. Moreover, the strength difference in
- 5 FA concrete cooled by different methods was greater when exposed to higher temperatures;
- 6 (3) When the curing age was less than or equal to 28d, the concrete with FA content of 10% had
- 7 the highest strength after being heated to high temperature. When the specimens were cured
- 8 for more than 28 days, the compressive strength of the concrete with FA content of 20% was
- 9 the highest after being treated at high temperature;
- 10 (4) The residual compressive strength of FA concrete after high temperature treatment increased
- 11 proportionally with curing age. The increase in the compressive strength of FA concrete after
- 12 high temperature at 28d was more pronounced than that of the concrete without FA; and
- 13 (5) Because of the superior fire-resistance properties of fly ash, the splitting tensile strength of
- 14 FA concrete exposed to elevated temperatures was higher than that of normal concrete.

17 ACKNOWLEDGEMENTS

18 The authors wish to thank the financial support by the National Natural Science Foundation
19 of China (Grant No. 51208504).

21 Due to privacy and ethical concerns, neither the data nor the source of the data can be made
22 available.

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LIST OF FIGURES

- FIG. 1** Variation of compressive strength of FA concrete along with temperature (a) FA0-Cooled in the air; (b) FA0-Cooled by water; (c) FA10-Cooled in the air; (d) FA10-Cooled by water; (e) FA20-Cooled in the air; (f) FA20-Cooled by water; (g) FA30-Cooled in the air; (h) FA30-Cooled by water
- FIG. 2** Effect of cooling method on the compressive strength of FA concrete: (a) FA0; (b) FA10; (c) FA20; (d) FA30
- FIG. 3** Effect of the content of fly ash on compressive strength: (a) 7d-Cooled in the air; (b) 7d-Cooled by water; (c) 14d-Cooled in the air; (d) 14d-Cooled by water; (e) 28d-Cooled in the air; (f) 28d-Cooled by water; (g) 56d-Cooled in the air; (h) 56d-Cooled by water; (i) 90d-Cooled in the air; (j) 90d-Cooled by water
- FIG. 4** Effect of the curing age on compressive strength of FA concrete: (a) FA0-Cooling in air; (b) FA0-Cooling in water; (c) FA10-Cooling in air; (d) FA10-Cooling in water; (e) FA20-Cooling in air; (f) FA20-Cooling in water; (g) FA30-Cooling in air; (h) FA30-Cooling in water
- FIG. 5** Relation of splitting tensile strength to temperature: (a) FB0 Air Cooling; (b) FB0 Water Cooling; (c) FB20 Air Cooling; (d) FB20 Water Cooling
- FIG. 6** Relation of splitting tensile strength to cooling methods; (a) FB0; (b) FB20
- FIG. 7** Splitting tensile strength of concrete with and without FA at different curing ages: (a) Air Cooling; (b) Water Cooling
- FIG. 8** Microstructure of 90 day specimen before being exposed to high temperature: (a) FA0; (b) FA20
- FIG. 9** The microstructure of 90 day specimen after being exposed to high temperatures: (a) FA20–150°C air cooling; (b) FA20–350°C air cooling; (c) FA20–150°C water cooling; (d) FA20–350°C water cooling; (e) FA20–550°C air cooling; (f) FA20–550°C water cooling;

TABLE 1 Composition of cement

Component	Na ₂ O	MgO	Al ₂ O ₃	SiO ₂	K ₂ O	CaO	Fe ₂ O ₃	MnO	TiO ₂	P ₂ O ₅	SO ₃
Content (%)	0.17	2.5	7.0	22.5	0.78	59	3.3	0.33	0.31	0.1	1.8

TABLE 2 Composition of cement and fly ash

Component	Na ₂ O	MgO	Al ₂ O ₃	SiO ₂	K ₂ O	CaO	Fe ₂ O ₃	MnO	TiO ₂	P ₂ O ₅	SO ₃
Content (%)	0.15	0.75	32.8	54.5	1.4	2.7	4.1	0.02	1.3	0.15	0.4

TABLE 3 Material parameters of fly ash

Type	Fineness (45µm square hole sieve remain) /%	Loss of ignition /%	Ratio of water demand /%	Content of sulphurtrioxide /%
Class I	10	3	92	1.6

TABLE 4 Mix proportion of concrete

Group	Mix proportion (kg/m ³)						Water cement ratio
	cement	Fly ash	water	Fine aggregate	Coarse aggregate	admixture	
FA0	300	0	180	792	1095	3	0.6
FA10	270	36	180	785	1095	3.06	0.59
FA20	240	72	180	779	1095	3.12	0.58
FA30	210	108	180	772	1095	3.18	0.57

TABLE 5 Test conditions for the concrete specimens

Group of concrete	Curing age before heating (d)	Heating temperature	Cooling method
FA0、FA10、FA20、 FA30	7、14、28、56、90	Room temperature	-
		150°C、350°C、 550°C	Cooling in the air, Cooling by water

TABLE 6 Compressive strength of concrete after being heated at early age(MPa)

Curing age before heating		7d		14d		28d		56d		90d	
FA	Temperature	Air	Water	Air	Water	Air	Water	Air	Water	Air	Water
0%	20 °C	17.52		26.73		32.9		34.96		37.34	
	150 °C	20.99	19.97	29.79	28.26	35.24	31.2	37.58	33.77	39.61	36.15
	350 °C	22.78	20.56	31.01	27.96	32.36	26.3	34.57	27.68	35.96	29.98
	550 °C	14.86	12.65	22.27	17.75	24.02	17.84	27.06	19.91	27.94	20.79
10%	20 °C	20.49		26.43		30.59		36.54		42.85	
	150 °C	21.82	20.55	28.27	26.51	33.87	30.85	36.77	33.52	43.02	39.18
	350 °C	20.07	17.86	25.9	23.02	35.13	31.51	40.72	36.76	45.26	40.28
	550 °C	16.15	13.54	20.6	17.34	25.57	21.97	30.52	26.48	36.64	31.14
20%	20 °C	14.84		22.07		27.96		39.71		45.48	
	150 °C	16.24	15.11	23.61	21.94	32.35	29.27	39.88	36.97	46.01	42.56
	350 °C	14.56	12.71	20.95	18.44	33.24	30.011	44.33	39.8	49.92	44.71
	550 °C	11.13	9.23	16.82	13.93	24.88	21.31	35.17	29.83	38.98	33.16
30%	20 °C	10.45		18.31		25.88		32.6		39.95	
	150 °C	11.98	11.03	20.52	18.89	28.87	26.35	33.78	31.01	40.25	37.04
	350 °C	10.27	8.91	17.5	15.23	30.36	27.02	35.15	31.62	42.14	38.01
	550 °C	7.69	6.32	13.38	10.97	22.78	19.36	27.94	23.31	32.76	27.18

1 **TABLE 7** Splitting strength of FA concrete after being heated at early age (MPa)

Age			7d		14d		28d		56d		90d	
Fly ash content	Temperature (°C)	Cooling method										
		Air	Water	Air	Water	Air	Water	Air	Water	Air	Water	
0%	20	1.93		2.95		3.63		3.91		4.26		
	150	2.32	2.2	3.29	3.12	3.8	3.38	4.17	3.75	4.5	4.03	
	350	2.51	2.27	3.42	3.09	3.51	2.81	3.75	3.04	4.09	3.27	
	550	1.61	1.4	2.46	1.96	2.79	1.99	2.48	1.71	2.93	2.01	
20%	20	1.64		2.44		2.71		4.02		4.92		
	150	1.79	1.67	2.61	2.42	3.09	2.86	4.31	4.06	4.97	4.61	
	350	1.61	1.4	2.31	2.04	3.25	2.89	4.45	3.91	5.05	4.58	
	550	1.23	1.02	1.86	1.54	2.13	1.77	2.97	2.52	3.94	3.34

(a)

(b)

(c)

(d)

(e)

(f)

(g)

(h)

(a)

(b)

(c)

(d)

(a)

(b)

(c)

(d)

(e)

(f)

(g)

(h)

(i)

(j)

(a)

(b)

(c)

(d)

(e)

(f)

(g)

(h)

Fig. 5 Relation of splitting tensile strength to temperature

(a)

(b)

Fig. 6 Relation of splitting tensile strength to cooling methods

(a)

(b)

Fig.7 Splitting tensile strength of concrete with and without FA at different curing ages

(a)

(b)

Fig. 8 Microstructure of 90 day specimen before being exposed to high temperature

(a)

(b)

(c)

(d)

(e)

(f)

Fig. 9 The microstructure of 90 day specimen after being exposed to high temperatures