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Effect of steam curing on class C high-volume fly ash concrete mixtures

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Abstract

The effect of steam curing on concrete incorporating ASTM Class C fly ash (FA), which is widely available in Turkey, was investigated. Cement was replaced with up to 70% fly ash, and concrete mixtures with 360 kg/m^3 cementitious content and a constant water/binder ratio of 0.4 were made. Compressive strength of concrete, volume stability of mortar bar specimens, and setting times of pastes were investigated. Test results indicate that, under standard curing conditions, only 1-day strength of fly ash concrete was low. At later ages, the strength values of even 50% and 60% fly ash concretes were satisfactory. Steam curing accelerated the 1-day strength but the long-term strength was greatly reduced. Setting time of fly ash–cement pastes and volume stability of mortars with 50% or less fly ash content were found to be satisfactory for standard specimens. In addition, for steam curing, this properties were acceptable for all replacement ratios.

Keywords: Compressive strength; Thermal treatment; Fly ash; Volume stability

1. Introduction

Due to increasing energy demand, coal-burning power plants are becoming more widespread in Turkey near low-calorie lignite mines. However, these plants cause significant technical, environmental and economical problems due to the by-products of electric generation.

During coal-fired electric power generation, two main types of coal combustion by-products are obtained, fly ash (FA) and bottom ash. The current annual worldwide production of coal ash is estimated about 700 million tones of which at least 70% is fly ash. In fact, due to its pozzolanic nature, fly ash is a beneficial mineral admixture for concrete. It influences many properties of concrete in both fresh and hardened state. Utilization of waste materials in cement and concrete industry reduces the environmental problems of power plants and decreases electric costs besides reducing the amount of solid waste, greenhouse gas emissions associated with Portland clinker production, and conserves existing natural resources. Although fly ash is a valuable mineral admixture for blended Portland cement and concrete, only about 6% of the total available fly ash is used for this purpose [1]. As for Turkey, there are eleven coal-burning power plants. The annual fly ash production is about 18 million tonnes which is more than the rest of all industrial wastes in the country. However, the utilization ratio of fly ash is only 4%. The main reasons for this situation can be summarized as:

- Lack of sufficient research to demonstrate the suitability of local fly ashes as pozzolanic materials.
- Positive effects of fly ash are not well known in the Turkish construction industry.
- The material is not available in all regions due to high transportation cost.

However, recently, local cement manufacturers are using fly ash in Portland Composite Cement (CEM II) production due to economic reasons. Fly ash content of this cement is about 7% by mass. In addition, some of the ready-mixed concrete plants are producing fly ash concrete by replacing cement with fly ash. However, direct use of fly ash in concrete at very high cement replacement ratios is very limited, and fly ash concrete is not used by cast-in-place concrete industry in Turkey, mainly due to its low early strength values.

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Table 1
Physical, chemical and mechanical properties of cement and fly ash

Chemical composition (%)		
	Cement	Fly ash
SiO_2	19.3	42.1
Al_2O_3	5.6	19.4
Fe_2O_3	3.5	4.6
CaO	63.6	27.0
MgO	0.9	1.8
Na_2O	0.1	
K_2O	0.8	1.1
SO_3	2.9	2.4
Cl^-	0.01	
Loss on ignition	2.8	1.3
Insoluble residue	0.4	
Free CaO (%)	1.2	4.3
Physical properties of cement		
Specific gravity	3.15	
Initial setting time (min)	119	
Final setting time (min)	210	
Volume expansion (mm)	1.00	
Specific surface (Blaine) of cement and fly ash		
Cement (m^2/kg)	352	
Fly ash (m^2/kg)	290	
Compressive strength (MPa) of cement		
2 days	27.2	
7 days	42.4	
28 days	52.7	
Pozzolanic activity index of (%) FA		
7 days	79	
28 days	88	

Nowadays, chemical admixtures are essential components of the concrete mixtures. Newly developed admixtures allow to lower the water/cement ratio to very low levels without loss of workability. By incorporation of superplasticizers (SPs), the early strength development of fly ash concrete can be accelerated to achieve the desired performance. The term “high-volume fly ash concrete” refers to this development. A large number of projects abroad have been implemented with “high-volume fly ash concrete” using ASTM Class F fly ash [1–8]. However, significant amount of fly ashes produced in Turkey are classified as Class C.

Generally, the long term ultimate mechanical properties of fly ash concretes are higher than those of plain Portland cement concretes. However, the setting and hardening rates of fly ash concrete at early ages are slower, especially under cold weather conditions. Extended hydration period makes the material more sensitive to curing conditions. These problems may be solved by using various methods such as steam curing. However, there are few studies on the effect of steam curing on high-volume Class C fly ash concrete.

In this study, mechanical properties of fly ash concretes, incorporating 0% to 70% Class C fly ash, as a cement replacement material has been investigated under different curing conditions up to 90 days. The curing conditions were standard curing in water, curing in laboratory atmosphere and steam curing. Furthermore, soundness of high-volume fly ash concretes was determined with the expansion of mortar bar specimens.

The results of this study may be useful to investigate the utilization of high-volume of fly ash in prefabricated concrete, mass concrete, foundation concrete and hot weather concreting in Turkey.

2. Experimental

The physical, chemical and strength characteristics of Portland Cement (CEM I 42.5 N) used in this study are presented in Table 1. A natural river sand and crushed limestone were used as fine and coarse aggregates. The properties of aggregates are in conformity with the Turkish Standard for Concrete Aggregates (TS 706 EN 12620). A superplasticizer (SP) of sulfonated naphthalene formaldehyde type was used meeting standard specifications ASTM C 494 Type F and TS EN 934-2. The chemical composition and other properties of the fly ash (FA) are also presented in Table 1. The pozzolanic activity index of FA is 88%, which is relatively low, but this value provides the ASTM C 618 limit (75%).

Table 2
Concrete mixture proportions

Component	FA0	FA10	FA20	FA30	FA40	FA50	FA60	FA70
Fly ash (%)	0	10	20	30	40	50	60	70
Cement (kg/m^3)	360	324	288	252	216	180	144	108
Fly ash (kg/m^3)	0	36	72	108	144	180	216	252
Water (kg/m^3)	143	143	143	143	143	143	143	143
Water/cement	0.40	0.44	0.5	0.57	0.66	0.79	0.99	1.32
Water/binder	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Sand (kg/m^3)	460	459	457	455	452	449	447	444
0–5 mm limestone (kg/m^3)	463	461	460	457	454	452	449	446
5–15 mm limestone (kg/m^3)	671	669	667	663	660	656	652	648
15–25 mm limestone (kg/m^3)	286	285	285	283	281	280	278	276
Superplasticizer (L/m^3)	8.50	8.64	8.93	9.47	9.47	9.47	10.80	12.17
Unit weight in fresh state (kg/m^3)	2470	2460	2455	2440	2424	2403	2383	2370

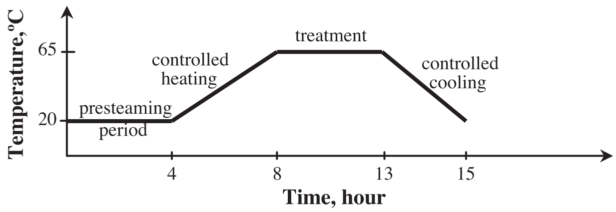

Fig. 1. Heat treatment.

Cylindrical specimens, 100/200 mm, were used to determine the compressive strength of concrete. The concrete mixtures were prepared in a horizontal-axis mixer for about 2 min, and then vibrated on a vibration table. In order to keep a constant slump value at about 80±20 mm, the dosage of the superplasticizer was varied. Mixture proportions are shown in Table 2. Note that the total cementitious materials content and the water/binder ratio were kept constant at 360 kg/m^3 and 0.40, respectively.

Both the steam-curing temperature and its duration have an important effect on the progress of hydration reaction and its products [9]. The heat-treatment cycle is shown in Fig. 1. After steam curing, the specimens were demoulded. One group was tested immediately to measure the compressive strength. In this study, a relatively short steam-curing period is chosen considering the precast industry applications. On the other hand, due to the increasing curing sensitivity of high-volume FA concrete, another group of specimens was placed into a standard curing tank of saturated lime water at 20±2 °C, after the steam curing. These specimens were used to determine the compressive strength at various ages. Furthermore, to establish the effect of water curing after the steam curing, a third group of specimens was kept in air after steam curing. The compressive strength of each mix was determined as an average of three specimens.

3. Results and discussion

The results of compressive strength of test specimens under various curing conditions, long-term expansion of mortar bars with different amount of FA, and the effect of FA addition on setting times are discussed in the following sections.

3.1. The effect of fly ash content on fresh concrete properties

Generally, FA particles are spherical in shape, and this has a very positive effect on the water requirement and workability of concrete mixtures [1]. However, in this study, replacement of cement with FA especially in percentages over 20% caused an increase in superplasticizer demand. This behavior may be attributed to the increase of paste volume in FA concretes because the specific gravity of FA is lower than cement. Besides, when FA is incorporated in the mix, more admixtures may be required due to the increasing carbon content [9,10].

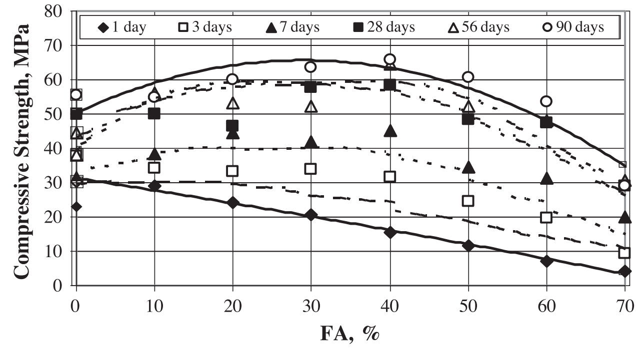

Fig. 2. The influence of fly ash content on compressive strength under standard curing conditions.

3.2. Influence of fly ash content on compressive strength under standard curing conditions

The compressive strength gain with time under standard curing conditions is presented in Fig. 2. The results show that the 1-day compressive strength decreased sharply with increasing fly ash content. However, at later ages (beyond 3 days), this difference diminished. It can be seen from the figure that, the strength of 30% fly ash mixture was approximately equal to control mix strength at 3 days. At 7 days, 40% fly ash mixture exceeded the control mix strength, while the 50% and 60% fly ash mixtures reached the control mix strength at 28 days and 56 days, respectively. Note that strength was approximately 10 MPa at 1-day and 20 MPa at 3 days with 50% and 60% fly ash content, which is quite satisfactory for most cast-in-place structural elements.

3.3. Influence of steam curing on compressive strength

Fig. 3 shows the influence of fly ash content on compressive strength of steam-cured concretes at different ages. With increasing amount of fly ash content, compressive strength at early ages also decreased under steam-curing conditions.

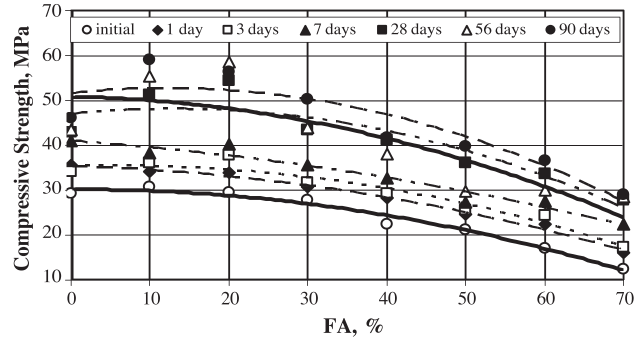

Fig. 3. The influence of fly ash content on compressive strength of steam-cured concrete at different ages.

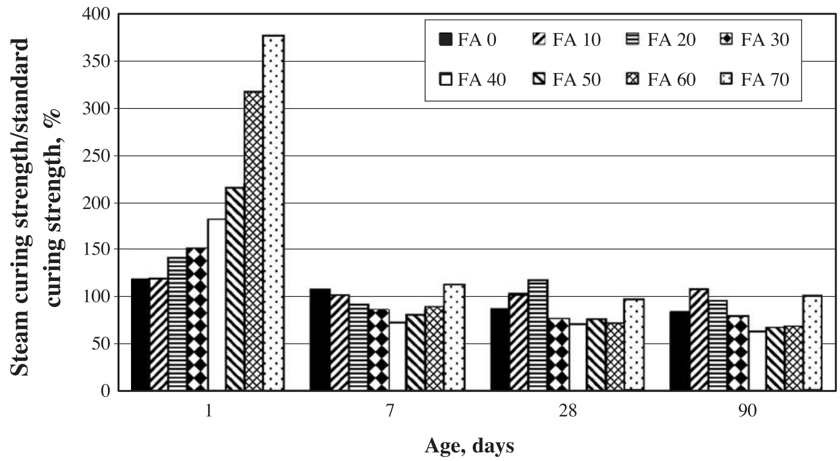

Fig. 4. The effectiveness of steam curing.

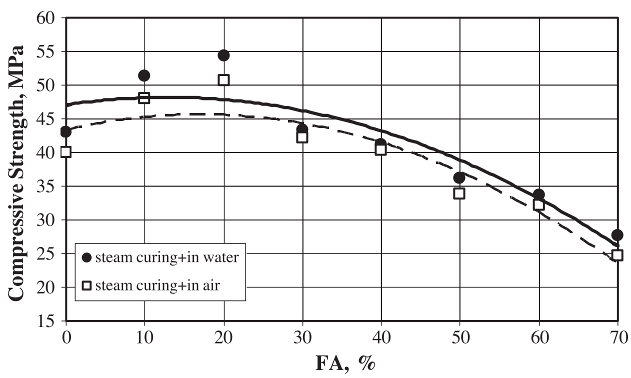

Fig. 5. The effect of curing conditions on compressive strength of steam-cured concrete.

However, application of steam curing increased the 1-day compressive strength of 50% FA concrete to 20 MPa, which is adequate for formwork removal, and therefore, beneficial for fabrication of precast products.

Test results also indicate that application of steam curing did not improve the later-age compressive strength of high-volume fly ash concrete as much as standard curing. Note that the steam-cured high-volume fly ash concrete mixture containing 50% fly ash showed only 40 MPa strength at 90 days compared to 60 MPa for the standard-cured mixture at the same age. The effectiveness of steam-curing vs. standard curing for different ages for all concrete mixtures as shown in Fig. 4, clearly proves that, with high-volume fly ash systems containing 40% or more fly ash, steam-curing may be of interest only when 1-day strength is the sole consideration.

3.4. Influence of different curing conditions on compressive strength of steam-cured concrete

In order to determine the effect of curing conditions after application of steam curing, a group of test specimens were kept in water while others were left in air. The effect of two different curing conditions on compressive strength of steam-cured concrete specimens at 28 days is presented in Fig. 5. It seems that curing in water marginally increases the compressive strength of concrete.

3.5. Influence of fly ash content on volume stability

Due to the presence of a significant amount of free CaO, it is possible that the use of Class C fly ash may influence

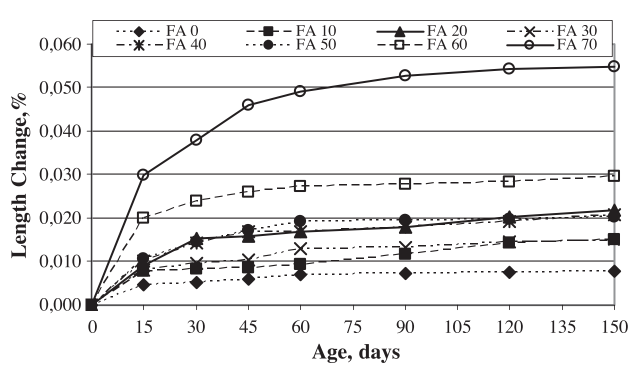

Fig. 6. Length change of mortar specimens stored in water at room temperature.

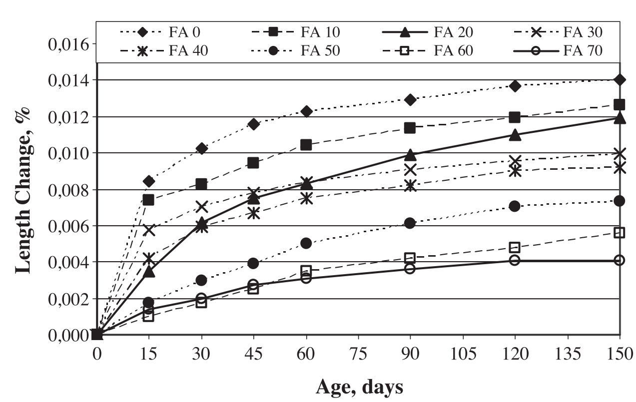

Fig. 7. Length changes of steam-cured mortar specimens.

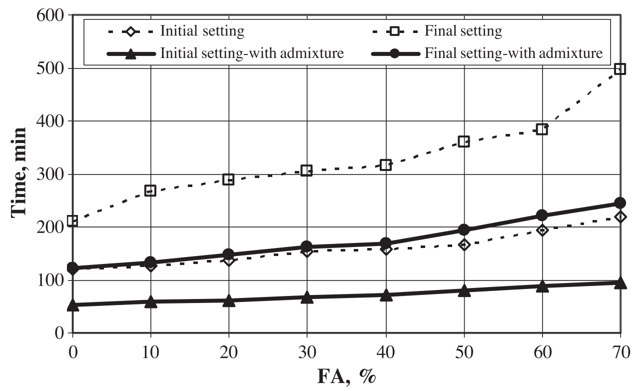

Fig. 8. The initial and final setting time of cement pastes containing fly ash.

the volume stability of concrete adversely, especially with high replacement levels. To determine this effect, mortar bar specimens (25×25×285 mm) were prepared and immersed in water up to 150 days. The expansion data are presented in Fig. 6. To simulate concrete behavior, some modifications were made in the mix design of mortar specimens, such as the aggregate/binder ratio was decreased and the coarse aggregate was replaced with the same type of fine aggregate. Thus, similar compressive strength levels were obtained with mortar specimens.

As shown in Fig. 6, with increasing fly ash content, the expansion of mortar bars in water increased especially in the case of mortars containing 60% and 70% cement replacement with fly ash. Interestingly, with steam curing, increasing ratios of fly ash replacement decreased the length change of the specimens (Fig. 7). This phenomenon may be due to the fact that free CaO hydrates rapidly at high temperature. There would be no expansion if the CaO hydrated before sufficient strength development. Although there is no universally accepted limit for this value, ASTM C 157 states that 14-days expansion value of hydraulic cement mortars must not exceed 0.02%. If this criterion is accepted for maximum expansion limit, not all steam-cured specimens even kept in water for 150 days exceeded this limit. Furthermore, the expansion values of nonsteam-cured mixes, specimens incorporating 50% or less fly ash were lower than 0.02% in the same curing conditions.

3.6. Influence of fly ash content on setting time

The setting times of cement pastes were determined by using the Vicat needle. As seen in Fig. 8, the setting times of the pastes are somewhat prolonged with increasing fly ash content. The setting times of cement pastes that contain superplasticizers are also given in Fig. 8. At 50% and 60% cement replacement with fly ash, the initial set is retarded by approximately 1 h, and the final set by 2.5 to 3 h. The accelerating effect of the superplasticizer on setting time is clear from Fig. 8. Generally, type F (ASTM C 494) admixtures have a retarding effect. However, pastes with low water/binder ratios show an accelerating behavior comparing with the pastes without superplasticizer.

4. Conclusions

For standard-cured superplasticized concrete specimens with 0.40 water/binder, the compressive strength at 1-day decreased sharply with increasing content of Class C fly ash used in this study. However, at ages 3 days and more, there was a considerable increase in the strength even with high-volume fly ash concrete mixtures. For instance, at 50% of cement replacement with fly ash, the 3-day strength was 20 MPa, and, at 90-day, the strength was 60 MPa.

Steam curing improved the 1-day strength values of high-volume fly ash concrete mixtures (at 40%, 50% and 60% FA replacement) from about 10 to 20 MPa, which is adequate for the precast concrete products industry. However, the 90-day strength was only 40 MPa. The ultimate compressive strength of steam-cured high-volume fly ash concrete is therefore much lower than that of standard-cured concrete.

The setting times of high-volume fly ash cement pastes were somewhat prolonged; however, the set retardation was reduced by the use of superplasticizers. This behavior is probably due to the reduction in water/binder ratio with SP pastes.

Due to the presence of a significant amount of free CaO in the high-calcium fly ash, there was some concern about the volume stability of blended cement made with this ash. Mortar prism expansion data showed that for nonsteam-cured specimens containing 50% or less fly ash, the expansions were not high enough to be deleterious. However, in general, the steam curing appears to significantly decrease the expansion of fly ash mortars (all FA percentages) due to the reaction of free lime with water.

It can be concluded that, high-volume Class C fly ash concrete mixtures are suitable for use by the Turkish construction industry for both cast-in-place and precast concrete products. Steam curing will be required to develop adequate compressive strength for form removal at age 1-day.

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