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Heat deformations of fly ash concrete

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Abstract

When dealing with concrete resistance to high temperatures it is important for design purposes to know the elastic parameters, such as the temperature–strain curves and the modulus of elasticity.

Concretes containing a high volume of fly ash differ from conventional mixes in the cementitious phase. This results in a different behaviour under heating compared to plain Portland cement concretes. To find the elastic response of fly ash concrete four series of concrete mixtures were manufactured: one with cement only, another with 30% by mass partial replacement of cement by fly ash, and two with 30% and 40% by mass replacement of cement by ground fly ash. Tests were carried out on cylinders (150 × 300 mm). A high-calcium fly ash was used.

The conditions were selected so that the applied level of stress corresponded to 25% or to 40% of the ultimate compressive strength of concrete, and a transient type of temperature regime was followed. Based on the experiments the critical temperature, the residual deformation and the modulus of elasticity were determined.

The results indicate that concretes containing a high volume of fly ash are more sensitive to high temperatures, since they developed greater deformations. The fineness of the fly ash used also seems to influence the degree of deformation in an adverse way.

Keywords: Fly ash; Concrete; Resistance; High temperature

1. Introduction

Fly ash is universally accepted as the fourth constituent of concrete for the resulting economic and technical advantages. Especially high-calcium fly ashes may, because of their self-cementing capacity, often replace a considerable amount of cement in concrete. Regarding the performance of high-calcium fly ash in concrete, it can be said that it affects workability, setting time and bleeding, as well as strength (especially long-term strength) and durability [1]. The elastic characteristics of concrete are also affected by fly ash content. The response of fly ash concrete to thermal load (this is of interest not only in relation to fire but also in designing prestressed concrete reactor vessels) depends on its temperature–deformation curves and its modulus of elasticity [2]. Therefore, for design purposes it is important to know the strain–temperature relationship, the residual total deformation after cooling to ambient temperature. In addition, critical temperature (Θ_{cr}) at which failure occurs under constant load during heating is one of the parameters necessary for a step-by-step finite element analysis.

2. Experimental part

2.1. Materials

A lignite fly ash (LFA) was used to substitute Portland cement in concrete mixtures. This was a high-calcium self-cementing fly ash from the area of Ptolemaida in Northern Greece. Its chemical composition and some physicochemical characteristics are given in Table 1, together with those of the Portland cement.

The fly ash was used in two fineness levels: Raw (LFA) and Ground (GFA) to about 450–500 m^2/kg Blaine.

Three concrete mixtures were made containing 30% LFA, 30% GLFA and 40% GLFA respectively in replacement of Portland cement. A fourth mixture without fly ash, was used as control concrete.

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Table 1
Chemical composition and other characteristics of PC and LFA

Constituents	Portland cement PC	Lignite fly ash LFA
S_1O_2	23.20	42.80
Al_2O_3	6.87	10.30
Fe_2O_3	3.58	3.45
CaO	61.70	total 36.70 free 9.80
MgO	3.80	3.40
SO_3	2.51	5.50
Alkalis	2.21	1.20
on Loss of ignition	2.10	4.30
Insoluble residue	16.38	21.50
Specific gravity (kg/m^3)	3.10	2.42
Blaine fineness (m^2/kg)	300–350	raw 290–320 ground 450–500

The proportioning of the mixtures were:

Water/(cement+fly ash)	= 0.65 (by mass)
Cementitious material (total)	= 300 kg/m^3
Limestone aggregate/(cement+fly ash)	= 6.2 (by mass)
Max size of coarse aggregate	= 31.5 mm

Fifty cylinder specimens (150 × 300 mm) were cast. Thirty six of them were exposed to heating and 12 of them were used for determining compressive strength. Failure occurred in two cylinders during heating due to explosion.

The specimens were tested at the age of eight months. The mean value of the compressive strength at this age is shown in Table 2.

2.2. Heating and testing

The system used for the experimental part is shown in diagram and photo (Figs. 1 and 2). The electronically controlled furnace was properly designed to afford adequate internal space for concrete cylinders and to provide heat at a continuously monitored rate. A hydraulic type pressure machine capable of continuously applying a constant compressive load was used. The steel plates of the machine numbered (3) in the diagram (Fig. 1) were connected with two blocks (numbered 1 and 2 in Fig. 1) of heat resisting steel. Through these blocks, the load was transferred inside to the concrete specimen. Asbestos millboard pads were placed at the upper and lower openings of the furnace for insulation purposes. A suitable system of strain dial gauge indicators was adapted to be uninfluenced by temperature rise. In an attempt to simulate the behaviour of concrete in service, a transient-type heating regime was followed. Before testing, specimens were dried at 110 °C to constant weight. Then a percentage of their compressive strength (determined at the time of testing)

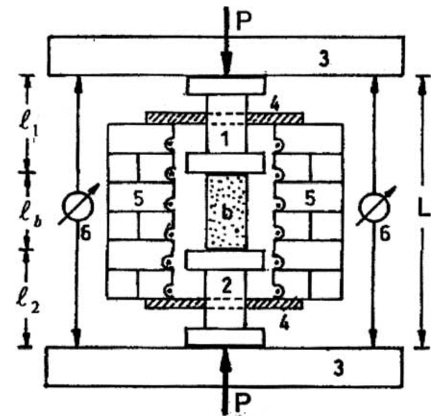

Fig. 1. The heating apparatus. P: load; b: concrete specimen; 1,2: steel materials; 4: asbestos millboard pads; 5: electronically controlled electric furnace; 6: dial gauges.

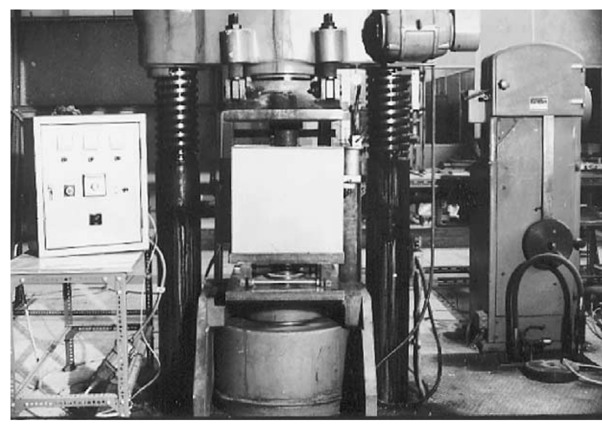
Fig. 2. The heating apparatus at the pressure machine.

Table 2
Compressive strength (f_c) and Modulus of elasticity (E_c) of concrete tested before and after heating

Concrete mixture code	$\Theta° = 0$	$P = 0$	Θ_{max} 310 °C	$P = 0.40$ Pu	$f_{c0} - f_{c\theta}$	$E_{c0} - E_{c\theta}$
	Mpa f_{c0}	Gpa E_{c0}	Mpa $f_{c\theta}$	Gpa $Ec\theta$	$f_{c\theta}$ %	E_{c0}%
PC (D)	27.0	23.5	26.5	17.0	1.8	27.6
LFA 30% (C)	31.0	29.5	27.1	17.0	12.6	42.4
GLFA 30% (A)	43.0	41.0	35.3	15.0	17.9	63.4
GLFA 40% (B)	41.0	39.0	27.3	13.0	33.4	66.7

was imposed as preload. Two types of experiments were carried out. In the first, the dried concrete cylinders were preloaded with 25% or 40% of their compressive strength and heated at a rate of 4.5 °C/min for about 3 h. In this way the critical temperature (Θ_{cr}) at the two levels of preloading (25% and 40%) was recorded. In the second, concrete specimens were preloaded with 40% of their strength and temperature was increased at a rate of 1.4 °C/min up to 310 °C for 2 h. This temperature level was considered (according to the authors' previous experience [3]) to be of particular importance for the deformations of the cementitious phase under question. Afterwards, the heat supply was stopped and deformations with temperature decline were recorded up to ambient temperature. The residual deformations were thus measured. Moreover, for a number of these specimens the residual modulus of elasticity was determined according to ASTM C469-81.

For purposes of comparison the temperature–deformation curves of concrete cylinders without preloading but under the same heating regime were plotted by testing concrete specimens from the four mixtures (PC, LFA 30%, GLFA 30%, GLFA 40%).

3. Tests results and discussion

Figs. 3–7 gives the curves of temperature–deformation for concrete mixtures with and without fly ash. The behaviour of all concretes under transient-type heating at a low rate (1.4 °C/min) seems to follow the same pattern. Concretes without preloading ($P = 0$) initially shrink, up to about 400 °C, and then an expansion is

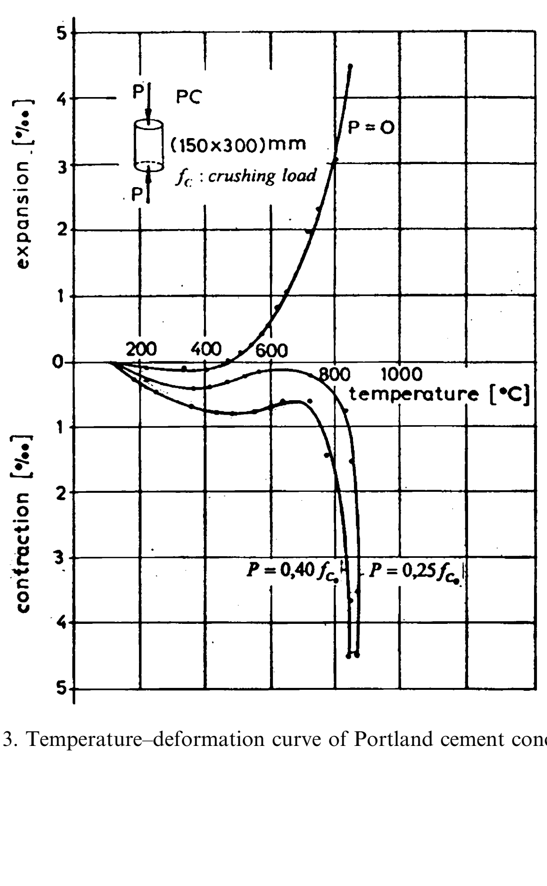

Fig. 3. Temperature–deformation curve of Portland cement concrete.

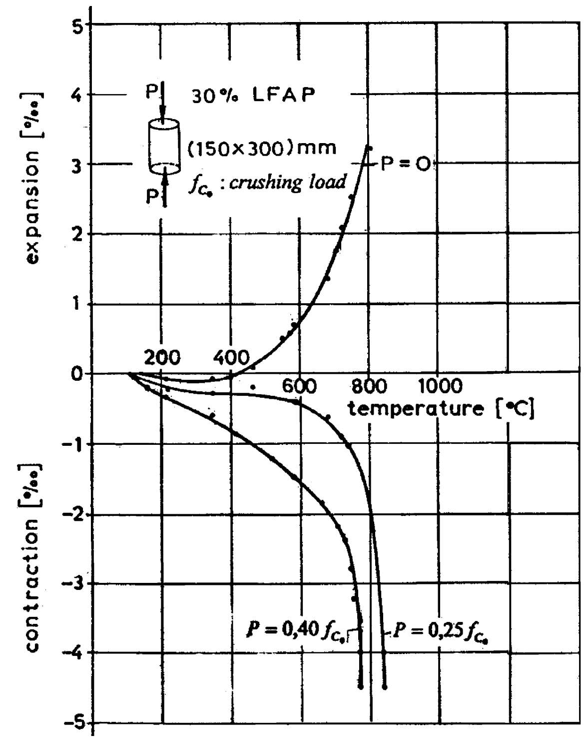

Fig. 4. Temperature–deformation curve of fly ash concrete.

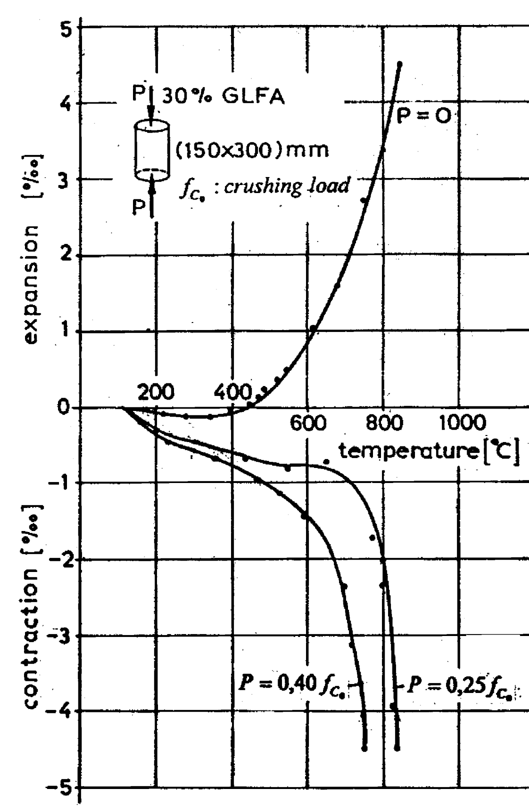

Fig. 5. Temperature–deformation curve of fly ash concrete.

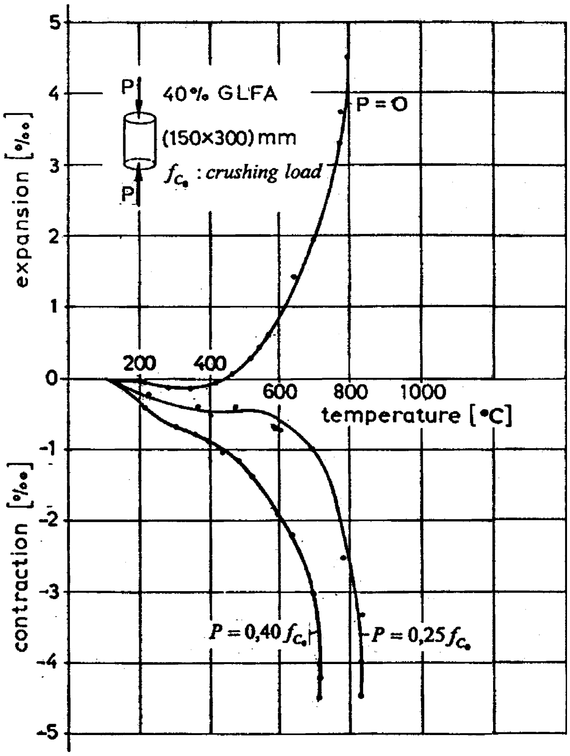

Fig. 6. Temperature–deformation curve of fly ash concrete.

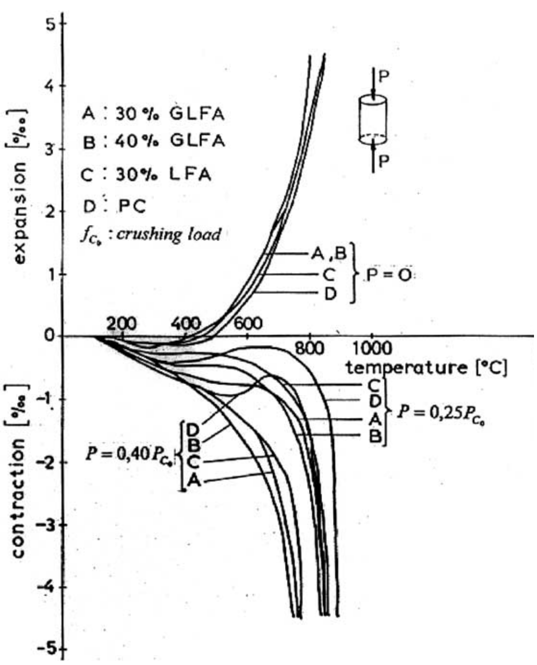

Fig. 7. Temperature–deformation of all concrete mixtures tested under two levels of preloading.

observed which increases rapidly up to failure. This is not in conformity with what other researchers have found [4,5], namely that the only change in dimensions

Table 3
Critical temperature (Θ_{cr}) of concretes tested under heating and preloading. $P = 0.25$–0.40 Pu

Concrete mixture code	$P = 0$	$P = 0.25$ Pu Θ_{cr} (°C)	$P = 0.40 f_{c0}$
PC (D)	870	870	845
LFA 30% (C)	866	830	767
GLFA 30% (A)	862	834	750
GLFA 40% (B)	830	825	715

occurred at zero preloading in expansion. The critical temperatures at which failure occurred are recorded in Table 3, and they ranged from 870 to 830 °C. The higher value corresponds to PC concrete and the lower to 40% GLFA concrete. Comparing fly ash concretes with PC concrete, it can be said that they deteriorated earlier at lower Θ_{cr} and that this is more obvious in the case of 40% GLFA, the compressive strength of which is higher than that of the control PC concrete.

When the concretes are heated under the stress of an imposed load which corresponds to ($P = 0.25 f_{c0}$, $0.40 f_{c0}$), a continuous shrinkage is recorded which depends on the level of preloading. As is clear from the table (Fig. 7, Table 3) the higher the imposed preload before heating, the lower the Θ_{cr} of concrete.

For the PC concrete, the Θ_{cr} appeared in the region of 870–840 °C under 0.40 f_{c0} and 0.25 f_{c0} preload respectively. For the fly ash concretes, the values of Θ_{cr} are displaced to lower temperatures. The lowest are noted for 40% GLFA concrete, where the strain curves become nearly vertical (Fig. 7), at 700 and 820 °C under 0.25 f_{c0} and 0.40 f_{c0} preload respectively.

Based on Figs. 3–7 it could be said that fly ash concretes are more sensitive to temperature and that failure occurs earlier. This sensitivity is more intensive if the fineness of fly ash is higher. This could be explained by the higher creep deformation of high volume fly ash concrete.

Regarding the strain components of the total deformation of concrete as it is given by Anderberg, Thelanderson and Scheider, [4,5] $E_{total} = E_{th} + E_s + E_{cr} + E_{tr}$ where

- E_{th} is the thermal expansion without extreme load (including drying shrinkage)
- E_s is elastic and plastic deformation caused by externally applied loads
- E_{cr} is creep which is temperature/time/stress dependent
- E_{tr} is transient strain caused by heating under load due to chemical transformation in the cementitious phase

It could be said that the contribution of some of these to total deformation is decreased in the case of the examined concretes. The time-dependent E_{cr} is of very low value for the short heating period (2 h) of the experiment. Separate measurements of the E_{ς} made on the tested specimens indicated that it is in the elastic area. The most significant component seems to be the E_{tr} or a sum of $E_{tr} + E_{cr}$. This leads to the suggestion that deformations of the cementitious phase prevail at temperatures under 400 °C.

The high-calcium fly ash paste under examination was studied by the authors by using DTA-TG analysis. It showed [3] a wide endothermal band at 120 °C greater than that of cement paste. No exothermal peak owing to decomposition of calcium hydroxide was observed at 400 °C, since calcium was bound by active silica oxide of this LFA. It seems, therefore, that in fly ash–cement pastes only loss of water from the hydrates occurs up to 300 °C.

According to Piasta [7,8], the dehydration of the hydrates of the cementitious phase causes shrinkage, while the unhydrated cement grains and the portlandite crystals, $Ca(OH)_2$, expand at temperatures up to 400 °C.

However, in the case of fly ash–cement pastes the amount of $Ca(OH)_2$ has been considerably reduced. Therefore, the expansion is not expected to be great.

Besides, Mehta [9] states that at temperature approximately 300 °C the interlayer and chemically combined water from C–S–H compounds and from sulfoaluminate hydrates can be lost.

With all this in mind, a second series of experiments was decided on for better understanding. The transient type of heating and the value of preloading (40% of compressive strength) were kept constant as in the first experiments, but a slower rate of heating (1.4 °C/min) and an upper temperature limit of 310 °C were selected. The results are plotted in Figs. 8–11. It proved that under these heating conditions higher deformations are obtained, especially for 30% GLFA and 40% GLFA concretes in comparison with PC concrete. For the GLFA concretes an extra steep decline of the total deformation appeared at temperatures from 260 to 310 °C. This also results in higher residual deformations after cooling. It could be said that the difference is due to the dehydration of hydrated products (C–S–H phases

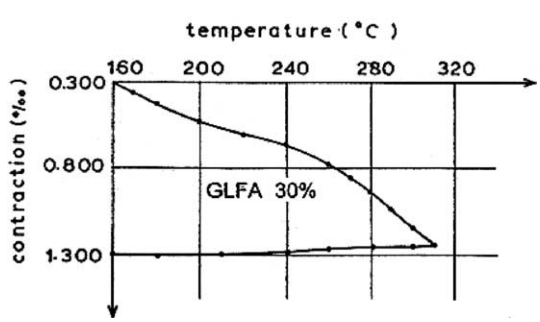

Fig. 8. Residual deformation of PC concrete (D) under transient type heating.

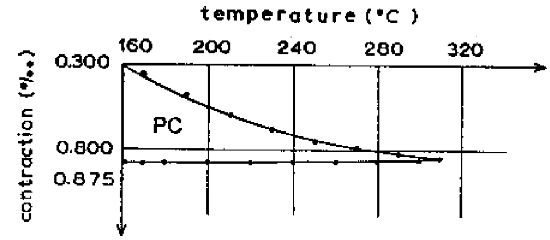

Fig. 9. Residual deformation of LFA concrete (C) under transient type heating.

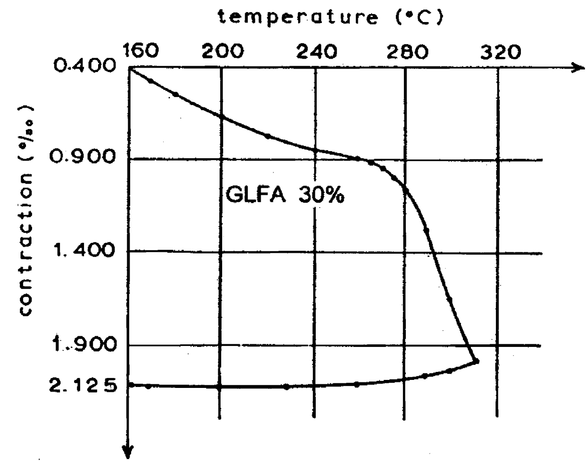

Fig. 10. Residual deformation of GLFA concrete (A) under transient type heating.

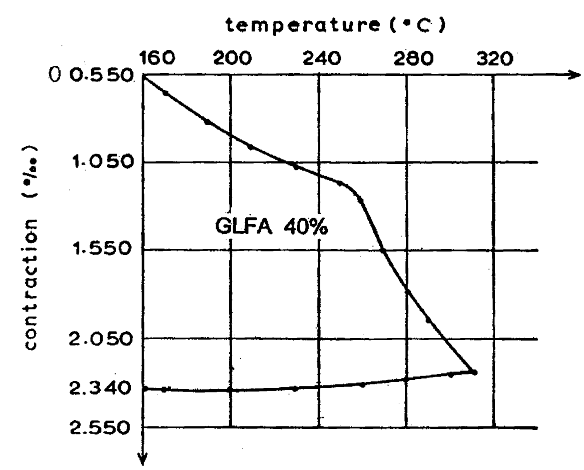

Fig. 11. Residual deformation of GLFA concrete (B) under transient type heating.

and sulfoaluminates) which are in excess in fly ash–cement paste in comparison with plain cement pastes.

Regarding the values of the static modulus of elasticity (E_c) of concrete specimens subjected to the test cycles specified above and tested after cooling, they all show a significant decrease, which is higher for the concretes containing fly ash, especially in ground form. This is a logical consequence to what is indicated in the temperature–strain diagrams.

4. Conclusions

Based on the experimental results it can be said that:

Up to 400 °C all tested concretes (stressed and unstressed) heated under a transient temperature regime shrink. The deformation of stressed specimens depends on the value of preloading. Higher loading induces higher deformation.

The critical temperatures range from 700 to 800 °C. The lower ones appear in concretes with GLFA.

The rate of heating plays an important role when deformations of concretes are considered. Slower rate results in higher deformations.

The residual deformation is greater in the concretes with GLFA. A greater decrease in the static modulus of elasticity is also observed for these GLFA concretes.

It is suggested that the cementitious phase of concretes containing fly ash is more sensitive to heating. This could be attributed to higher loss of water entrapped by the hydrates of fly ash–cement paste and to their higher creep-like deformations.

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