Behaviour of Fly Ash Concrete at High Temperatures

A. Venkateswara Rao and K. Srinivasa Rao

Abstract The present study deals with the behaviour of fly ash concrete at elevated temperatures. Concrete specimens of cubes of 100 mm, cylinders of 100 mm diameter and 300 mm height and prisms of 100 × 100 × 500 mm are cast by replacing the cement with fly ash in a range of 30–50% by mass of cement. The specimens are cured for 7 and 28 days, then dried and are exposed to elevated temperatures ranging from 100 to 500 °C for a period of 1 and 3 h, to investigate the effect of temperature on compressive strength, split tensile strength and flexural strength. It is observed that the residual compressive strength, split tensile strength and flexural strength of fly ash concrete initially increased with increase in temperature, later decreased with further increase in temperature.

Keywords Fly ash · Compressive strength · Split tensile strength · Flexural strength elevated temperatures

1 Introduction

Concrete is the most extensively used and preferred construction material in development of infrastructure due to its added advantages such as easily mouldable to any shape and sustainability in aggressive environment. In concrete, cement is the binder and also responsible for strength. Manufacturing of cement involves in consuming lot of energy and emitting a lot of CO_2 causing the environmental problem and also the cost of the cement is high. Hence, an alternative material to cement is required to save energy and environment. Previous investigations reveal that concrete has been prepared by introducing some additives called mineral admixtures,

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beside its basic ingredients to investigate their effect on strength, durability and other properties of concrete. Fly ash is one such material which is the waste product in thermal plants and easily available at low cost, if not suitably disposed off creates environmental problems. Past investigations have revealed that fly ash can be used as an important constituent of concrete (Malhotra and Mehta 2005; Hand Book on High volume fly ash concrete technology 2005). It can be used as either an admixture or as partial replacement of cement or replacement of fine aggregate. Concrete may be exposed to high temperatures in nuclear reactors, oil wells, pavements of air craft, fire accidents in buildings, etc. In such situations, concrete should give better performance. In general, when concrete exposed to elevated temperatures, it undergoes many microstructural changes and affects performance of structure. So, the present study involves in replacement of cement with different percentages of fly ash and its behaviour at different elevated temperatures.

2 Previous Studies

Raju and Rao (2001) studied the effect of high temperature on compressive strength of concrete by replacing cement partially with fly ash in range 10–30% at temperatures, of 200–250 °C for 1, 2 and 3 h duration of exposure, and an increase in compressive strength of concrete was reported.

Sarshar and Khoury (1993) tested ordinary Portland cement (OPC)−pulverized fly ash (PFA) paste containing 30% fly ash by weight of cement at various temperatures up to 650 °C. It was reported that the residual compressive strength of fly ash concrete was found to be 88% at 450 °C and 73% at 600 °C.

Khan et al. (2013) prepared specimens of three mixes replacing cement of 43 grade with 40, 50 and 60% fly ash by weight. The specimens after curing for 28 days are exposed to temperature ranging from 100 to 900 °C. From the study, it was reported that, in all mixes, there is an increase in compressive strength up to 300 °C with increase in temperature and with further increase in temperature, the compressive strength is decreased. Also, observed that for same fly ash content (50%), the drop in compressive strength is more in case of specimens with lower water to binder ratio than that with more water to binder ratio.

Srinivasa Rao et al. (2006) have studied M20, M30 grade concrete using OPC of 53 grade, fly ash from Vijayawada Thermal Power Station, Vijayawada and exposing specimens to thermo-cycles at different temperatures and evaluated the compressive strength, split tensile strength and dynamic modulus of elasticity. It was reported that the compressive strength, split tensile strength and dynamic modulus of elasticity were decreased for specimens of OPC, while there is increase in them for specimens with fly ash. It was reported from the results that the concrete with fly ash is more effective in resisting thermo-cycles compared to concrete with OPC.

Diederichs et al. (1989) tested ASTM class F fly ash concrete specimens of 90 MPa exposing them to temperature range of 200–250 °C and observed that there is an increase in strength as the temperature increases.

Potha Raju et al. (2004) carried out experiments on M28, M33 and M35 grades of concrete, investigated the effect of temperature on the flexural strength of fly ash concrete by partial replacing cement with fly ash (10, 20 and 30%) and heated to 100, 200 and 250 °C for 1, 2 and 3 h duration It was reported that fly ash concrete showed consistently the same pattern of behaviour as that of concrete without fly ash under elevated temperatures during flexure. The fly ash concrete with fly ash content up to 20% showed better performance compared with the specimens without fly ash by retaining a greater amount of its strength.

3 Experimental Program

3.1 Mix Proportions

In the present experimental investigation on concrete, cement is replaced with varying fly ash content of 30, 40 and 50% by weight of cement besides one mix without fly ash, total four mixes are selected. The mix proportion for the present study is 1:1.39:3.43 (cement:fly ash:fine aggregate:coarse aggregate) arrived after several trial mixes from guide lines of IS:10262-2009 and IS:456-2000. The ordinary Portland cement of 53 grade (IS:12269), fine aggregates conforming to zone-II (IS:383-1970), coarse aggregate as per IS 383 code provisions and class F fly ash are used for present study.

3.2 Method of Exposure and Testing

The cubes of 100 mm size are cast for studying the response of different concrete mixes at elevated temperatures. The specimens are demoulded after 24 h from time of casting and placed in potable water for curing. After specified period (7 and 28 days) of curing, the cubes are removed from water and allowed to dry in air before exposing to elevated temperatures. Three control specimen cubes of 100 mm size are tested at ages of 7 and 28 days for each percentage and age, and the average value of compressive strength is considered. Weights of specimens are measured with digital balance before and after heating are recorded.

An electric furnace with a maximum operating temperature of 1050 °C is used to heat the specimens. Inside temperature of the furnace is at room temperature at the time of placing the specimens in furnace. The temperature of furnace as set with help of digital temperature control panel board (PID controller) of the furnace. After reaching the desired temperature, it is kept constant throughout the duration of exposure (1 h or 3 h).

As the specified duration of exposure is completed, the furnace is switched off and the specimens are allowed to cool to room temperature in air (air cooling) and tested for compression (IS:516-1959), in 3000 kN compression testing machine and

Fig. 1 Cast of prisms on table vibrator

Fig. 2 Specimens arranged for heating in furnace

for split tension (Short et al. 2001) and flexure in 10 MT universal testing machine. Photographs of the cast specimens are shown in Fig. 1 and arrangement of specimens for heating in furnace is shown in Fig. 2.

4 Results and Discussions

4.1 Residual Compressive Strength

Residual compressive strength is the ratio of compressive strength of heated specimen of any percentage of fly ash or age to that of 28 day strength of controlled concrete (reference concrete) at room temperature multiplied by 100. The percentage residual compressive strength at age of 7 days and 28 days are shown in Table 1. Figures 3, 4, 5, 6, 7, 8, 9 and 10 show the graphical representation.

At the age of 7 days, the maximum residual compressive strength of 94.5% is exhibited by SC without fly ash at 200 °C and 1 h exposure duration while minimum 54.6% is exhibited by SC with 50% fly ash at 500 °C and 3 h duration of exposure. At age of 28 days, the maximum residual compressive strength of 105.3% is exhibited by SC with 30% fly ash at 300 °C and 1 h exposure duration while minimum 66.5% is exhibited by SC with 50% fly ash at 500 °C and 3 h duration of exposure.

Khan et al. (2013) have also reported similar trend. Diedrichs et al. (1989) tested fly ash concrete in a temperature range of 200–250 °C and reported that there was an increase in strength of concrete with an increase in temperature as observed in this study.

4.2 Residual Split Tensile Strength

Residual split tensile strength is the ratio of split tensile strength of heated specimen of any percentage of fly ash or age to that of 28 day strength of controlled concrete (reference concrete) at room temperature multiplied by 100 (Table 2).

4.3 Residual Flexural Strength

Residual flexural strength is the ratio of flexural strength of heated specimen of any percentage of fly ash or age to that of 28 day strength of controlled concrete (reference concrete) at room temperature multiplied by 100. It is observed that at age of 7 days, maximum residual flexural strength of 88.9% is exhibited by SC without fly ash at 200 °C and 1 h exposure duration while minimum 44.4% is exhibited by SC with 50% fly ash at 500 °C and 3 h duration of exposure. While at age of 28 days, the maximum residual flexural strength of 104% is exhibited by SC with 30% fly ash at 300 °C and 1 h exposure duration while minimum 57.6% is exhibited by SC with 50% fly ash at 500 °C and 3 h duration of exposure (Table 3; Figs. 11, 12, 13 and 14).

4.4 Loss of Weight

The results of the percentage loss in weight of specimens exposed to 100, 200, 300, 400 and 500 °C at an age of 7, 28, 56 and 91 reveal that the percentage loss of weight of concrete specimens increased with increase in the temperature. For a given temperature, the percentage loss of weight increased with increase in fly ash content as well as increase in duration of exposure.

Table 1 Percentage residual compressive strength at various temperatures

S. No.	Age in days	Temperature (°C)	Percentage replacement of fly ash							
			0		30		40		50	
		Duration of exposure	1 h	3 h	1 h	3 h	1 h	3 h	1 h	3 h
1	7	27	90.2		87.9		85.4		77.2	
2	7	100	94	92.5	89.1	89	84.6	84.1	73.5	71.8
3	7	200	94.5	92.8	89.9	89.3	83.7	80.8	72.5	69.3
4	7	300	93	91.6	90.6	89.5	82.7	78.1	71.8	67.5
5	7	400	82.9	81.1	80	77.1	75.3	66.6	66.4	63.7
6	7	500	79.5	74.3	78.2	63.6	65.7	57.1	55	54.6
7	28	27	100		102.2		89.6		79.3	
8	28	100	102	101	103	102.4	87.8	86.8	75.6	75.2
9	28	200	102.6	101.6	104.8	103	85.5	84.8	74.4	73.9
10	28	300	101.2	100.3	105.3	104.1	83.1	80.3	72.6	71.7
11	28	400	101.2	93.6	102.8	98.8	80.9	78.2	69.3	68.9
12	28	500	90.5	73.7	96.9	81.2	78.4	75.2	67.2	66.5

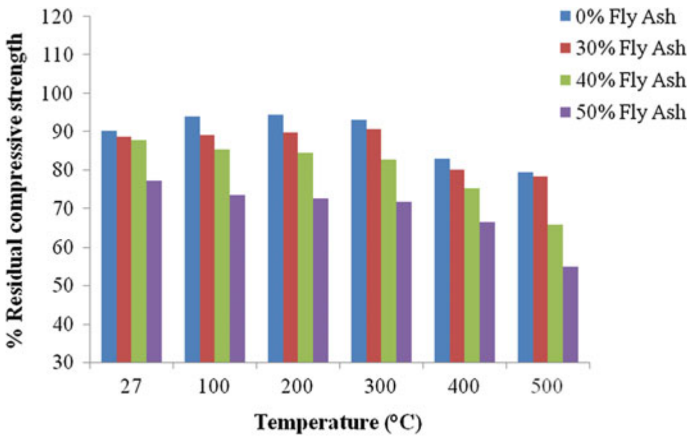

Fig. 3 Variation of percentage residual compressive strength with temperature for M30 grade concrete for 7 days at 1 h exposure duration

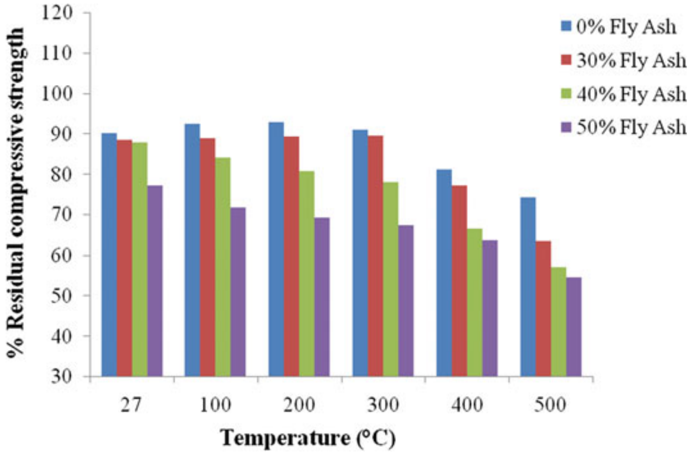

Fig. 4 Variation of percentage residual compressive strength with temperature for M30 grade concrete for 7 days at 3 h exposure duration

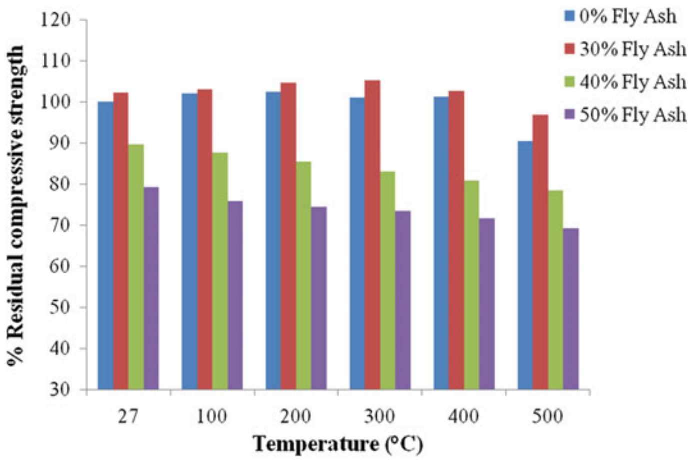

Fig. 5 Variation of percentage residual compressive strength with temperature for M30 grade concrete for 28 days at 1 h exposure duration

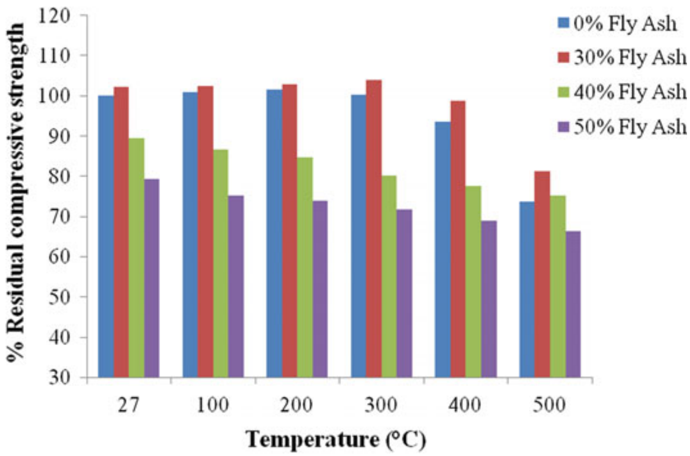

Fig. 6 Variation of percentage residual compressive strength with temperature for M30 grade concrete for 28 days at 3 h exposure duration

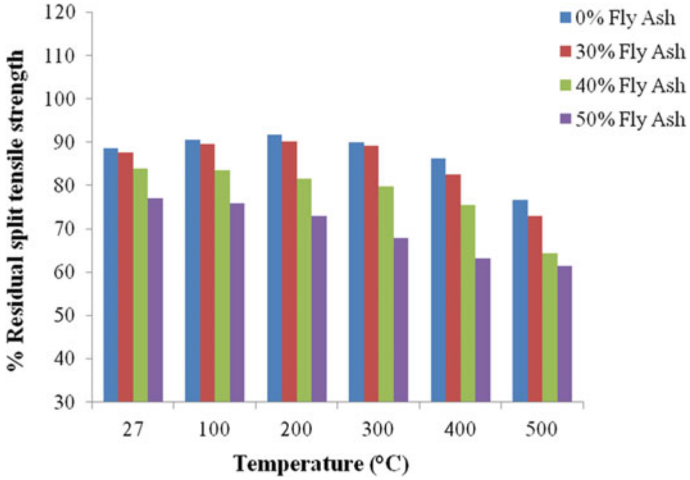

Fig. 7 Variation of percentage residual split tensile strength with temperature for M30 grade concrete for 7 days at 1 h exposure duration

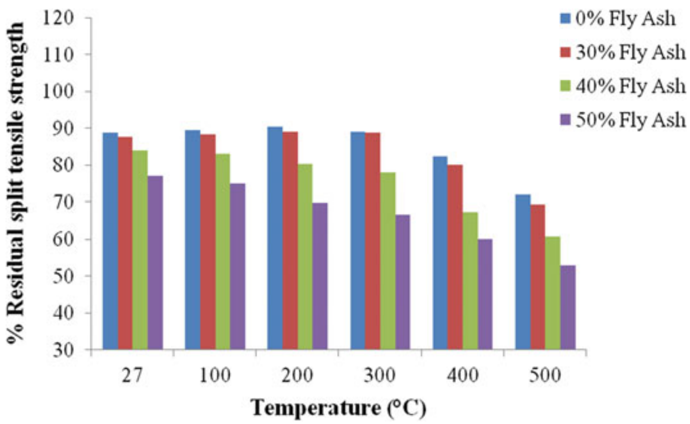

Fig. 8 Variation of percentage residual split tensile strength with temperature for M30 grade concrete for 7 days at 3 h exposure duration

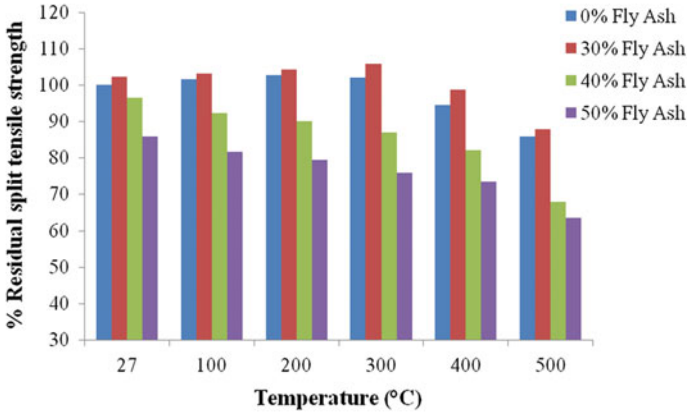

Fig. 9 Variation of percentage residual split tensile strength with temperature for M30 grade concrete for 28 days at 1 h exposure duration

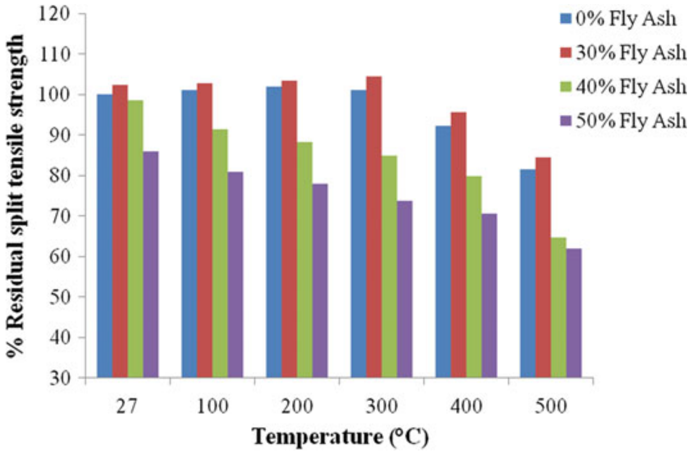

Fig. 10 Variation of percentage residual split tensile strength with temperature for M30 grade concrete for 28 days at 3 h exposure duration

Table 2 Percentage residual split tensile strength at various temperatures

S. No.	Age in days	Temperature (°C)	Percentage replacement of fly ash							
			0		30		40		50	
		Duration of exposure	1 h	3 h	1 h	3 h	1 h	3 h	1 h	3 h
1	7	27	88.7		87.7		84		77.1	
2	7	100	90.1	89.4	89.5	88.3	83.4	83	75.8	74.9
3	7	200	91.3	90.5	90.1	89	81.6	80.2	**73**	69.8
4	7	300	90	89	89.2	89.5	79.8	78	67.9	66.6
5	7	400	86.3	82.2	82.6	80	75.5	67.3	63.1	60
6	7	500	76.7	72	73	79.3	64.3	60.7	61.3	53
7	28	27	100		102.4		96.5		85.9	
8	28	100	101.5	101.5	103.2	103.7	92.4	92	81.6	81
9	28	200	102.7	102.5	104.2	104.5	90	89.2	79.5	78
10	28	300	102	101.9	105.9	105	86.9	85.9	75.9	74.6
11	28	400	94.6	93.9	98.7	96.6	82.2	80.8	73.4	70.7
12	28	500	85.7	84.9	87.9	85.6	67.9	64.7	63.7	61.9

Table 3 Percentage residual flexural strength at various temperatures

S. No.	Age in days	Temperature °C	Percentage replacement of fly ash							
			0		30		40		50	
		Duration of exposure	1 h	3 h	1 h	3 h	1 h	3 h	1 h	3 h
1	7	27	87.6		82.5		78.7		74.6	
2	7	100	88.3	87,9	83.7	83	76.5	76.2	70.7	70.1
3	7	200	88.9	88.4	84.8	84.2	75.6	74.8	68.9	68
4	7	300	87.9	87.4	85.6	85	71.6	70.1	65.8	66.9
5	7	400	75.7	72.4	72.9	70.1	69.5	68.5	60.6	58.7
6	7	500	65.6	61.6	61.7	55	55	48.2	47.9	44.4
7	28	27	100		101		94.3		92.4	
8	28	100	101.2	100.6	102	101.5	92.6	91.6	90.7	88.2
9	28	200	101.9	101	102.8	102	85.7	83.4	80.6	78.9
10	28	300	101	100.4	104	103	80.5	77.9	70,7	75.6
11	28	400	96.7	94.2	98.5	96.6	75.5	72.9	65.6	63.2
12	28	500	90.2	89	92.8	89.8	67.6	62.9	62.7	57.6

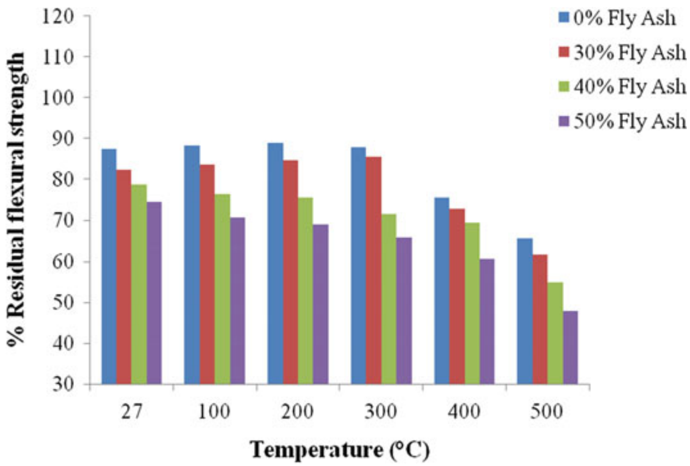

Fig. 11 Variation of percentage residual flexural strength with temperature for M30 grade concrete for 7 days at 1 h exposure duration

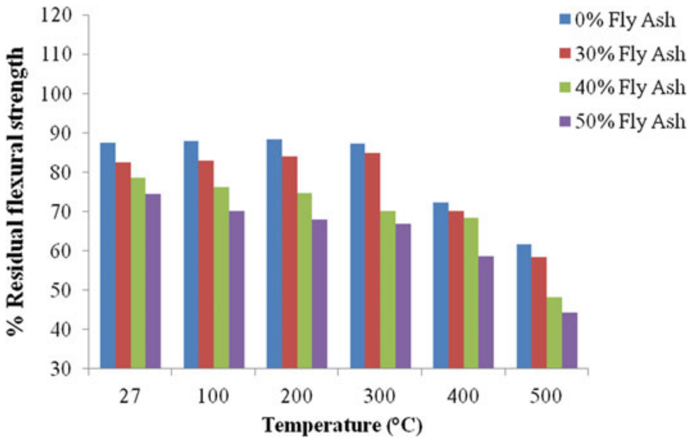

Fig. 12 Variation of percentage residual flexural strength with temperature for M30 grade concrete for 7 days at 3 h exposure duration

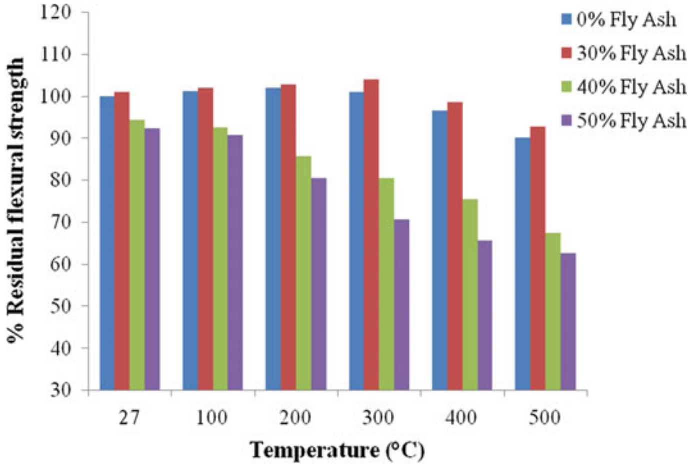

Fig. 13 Variation of percentage residual flexural strength with temperature for M30 grade concrete for 28 days at 1 h exposure duration

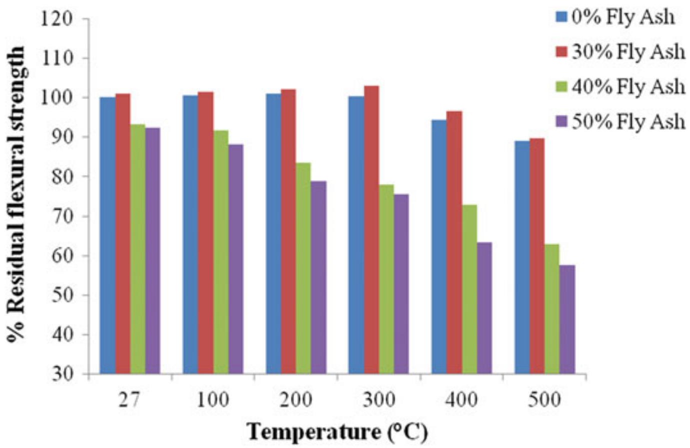

Fig. 14 Variation of percentage residual flexural strength with temperature for M30 grade concrete for 28 days at 3 h exposure duration

5 Conclusions

The following conclusions are drawn from the present experimental investigation on the behaviour of fly ash concrete at different temperatures.

1. The residual compressive strength, residual split tensile strength and flexural strength of fly ash concrete increased initially with increase in temperature up to 300 °C.
2. At a particular temperature, the percentage residual compressive strength increased for concrete with 30% fly ash, while the values decreased for 40 and 50% fly ash compared to that for concrete without fly ash.
3. At the age of 7 days, the values of residual compressive strength, split tensile strength and flexural strength for mixes containing fly ash are less than respective values for concrete without fly ash at all temperatures for both 1–3 h durations of exposure.
4. The percentage loss of weight of concrete specimens increased with increase in the temperature as well as duration of exposure.
5. For a given temperature, the percentage loss of weight increased with increase in fly ash content.
6. The deterioration of concrete increased with increase in temperature. No crack formation is observed up to the temperature of 500 °C.
7. At early ages, compressive strength of fly ash concrete is less than that of concrete without fly ash, and at later ages, compressive strength of fly ash concrete is better.
8. Finally, from the present investigation, it is concluded that replacement of cement up to 30% of fly ash in concrete is preferable for design of structures exposed to temperatures up to 300 °C.

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