Behavior of light weight reinforced concrete beam under elevated temperature

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Abstract. This paper presents an experimental investigation on the behavior of six weight reinforced concrete beams under elevated temperature. An expanded clay aggregate (LECA) was used in six reinforced concrete beams with cross sectional dimensions of 150 mm × 240 mm (width × height); and 1250 mm total length. All RC beam specimens were designed according to ACI Committee 318-2014 and exposed to different elevated temperatures. The experimental test results have revealed that the lightweight reinforced concrete beams have more fire endurance than the normal weight reinforced concrete beams under same elevated temperature. Analysis of the test results has also indicated that when the exposed temperature increases, the failure mode of all beam specimens transforms from flexure to combined shear and flexure.

1. Introduction

The elevated temperature induced from fire could cause deterioration of material and mechanical properties of structural members and can lead to progressive collapse and failure of the entire structure. Many practical codes and standards have attempted to address the effect of elevated temperature on the strength of normal concrete in their design procedures. However, the effect of elevated temperature on the behavior and failure modes of reinforced lightweight concrete members has not been investigated yet.

The experimental tests of Fathi and Farhang [1], have shown that the flexural strength of RC beams decreased when the temperature was increased. The results have also indicated that the maximum yield strength of the RC beam decreased when the temperature increase. Also Mwamlamba et al [2] have conducted an experimental study to investigate the effect of elevated temperature on flexural strength of RC lightweight concrete beams. The results have indicated that when the concrete beams were heated at 250°C, the loss in strength was up to 20.1% and 24.88% when RC beams specimens were heated for one hour and two hours respectively.

Kadhum et al. [3] investigated the effect of fire flame on compressive strength, drying shrinkage and load –deflection behavior of rectangular reinforced concrete beams. The results showed that the residual compressive strength ranged between (67-76%) at 400°C, (58-66%) at 600°C and (28-51) % at 800°C. Riad et al. [4] investigated the effect of adding 18mm length discrete glass fibers on the behavior of reinforced concrete beams under different fire and cooling condition, six RC beams were used in the experimental test. The results have shown that the cracks numbers and cracks patterns of the failed beam specimens vary according to
glass fiber content and fire condition and the failure mode varied from shear to pure flexural failure. Kodur et al [5] have experimentally studied the residual capacity of fire damaged reinforced normal concrete columns. The recorded results have indicated that, at inner zones of the concrete core, the temperatures are less. Also, the experiment study conducted by Ahmad, [6] shown that for partially exposed concrete beam, the flexural cracking was observed at 60% of the cracking load of the unexposed normal concrete beam. Real et al. [7] carried out an experimental investigation on the thermal conductivity characteristics of structural lightweight aggregate concrete by using transient test method. The results have showed that under same condition, the thermal conductivity of light weight concrete can be half that of normal weight concrete.

It can be noted that the behavior and failure of reinforced lightweight concrete beams under elevated temperature has not been investigated either experimentally or numerically which is the main objective of the present study.

2. The reinforced concrete beams specimens

2.1 Ingredients and proportioning of concrete mixtures

The expanded clay aggregate (LECA) with a bulk density of 430 kg/m3, maximum size of 9.5 mm, absorption rate of 35.68%, specific gravity of 0.295, and fineness modulus of 3.07 was used as a full replacement of the coarse aggregate (see Fig 1). The sieve analysis test of the expanded clay aggregate shown in Table 1 indicates that the lightweight aggregate used is complying with the requirements of the ASTM C-330 [9]. A water/cement ratio of 0.5 was used for both normal and lightweight concrete mixtures. Based on the selected water/cement ratio, the proportion of the concrete mixtures was designed according to ACI 211.1, [11], and ACI 211.2 [12]. The mix proportions were (1.0:1.25:2.46) and (1:0.93:0.4) (cement: sand: coarse aggregate) by weight, for normal and the light weight concrete respectively. These mixtures proportions were designed to give compressive strength values of 25.5 MPa and 17 MPa for normal and light weight concrete respectively according to the compressive strength tests of the concrete cylinders. Deformed steel bars were used in the present experiment with yield strength of the top bars, bottom and stirrups are 601.7 MPa, 573.2 MPa, and 414 MPa, respectively according to the uniaxial tensile tests.

![Figure 1. Expanded clay aggregate (LECA)](image)
2.2 Geometrical properties and reinforcing details

Six reinforced concrete beams with cross sectional dimensions of 150mm×240mm (width×height) and total length of 1250 mm were tested in the present study. Three beams were made from lightweight concrete (LWRC) and three made from normal weight concrete (NWRC), as shown in Table 2. Lightweight concrete with a compressive strength of 17MPa was used in first group and in the second group normal weight concrete was used with a compressive strength of 31.45 MPa. This was as per the compressive strength tests. All RC beams were designed to fail under same value of the lateral concentrated load at beams mid-span at ambient temperature which is equal to 150kN. Therefore, as can be seen from Table 2, there is a difference in the number of the top reinforcement between the normal and lightweight RC beam. This difference is due to the difference in compressive strength of the two types of concrete as mentioned above. The beams were exposed to different elevated temperatures and remained in furnace for about half an hour, then, they were naturally cooled down to ambient temperature (i.e. 20 ºC). The geometrical and reinforcing details of normal and lightweight concrete beams are shown in Table 1 and Figure 2.

| Sieve size (mm) | 12.5 | 9.5 | 4.75 | 2.36 | 1.18 |
|-----------------|-------|-----|------|------|------|
| Cumulative passing % | 100   | 87  | 6    | 1.0  | 0.4  |
| ASTM Specifications | 100   | 80-100 | 5-40 | 0-20 | 0-10 |

**Table 1.** Sieve analysis of light weight expanded clay

![Diagram](image)

(a) LWRC

(b) NWRC

**Figure 2.** Dimensions and reinforcement details of LWRC and NWRC beams
3. Thermal tests

In the thermal tests phase (the heating–cooling phase), six RC beams were exposed to different elevated temperature, namely: 390 °C, and 460 °C using almost similar heating rate as shown in Figure 3. For each beam, the temperature was maintained constant for about half an hour in the furnace when it reaches the intended value. An electric furnace was designed, manufactured and calibrated for this study and used to heat up the RC beam specimens. The average heating rate of the furnace was controlled to be 10°C/min. When the target elevated temperature is reached, the RC beams were cooled down naturally to the ambient temperature. Type - K thermocouples were attached to the RC beams to monitor and record the raise in temperature with respect to the time at the surfaces of beams and reinforcement steel bars.

### Table 2: Material and reinforcing details of RC beam specimens used in this study

| Group | Symbol | concrete type | Reinforcement details | Target temperature |
|-------|--------|---------------|-----------------------|---------------------|
| LWRC  | L 20°C | Light weight  | 3Ø12mm bottom bars and 2Ø10 mm top bars | 20°C |
|       | L 390°C| Light weight  | 3Ø12mm bottom bars and 2Ø10 mm top bars | 390°C |
|       | L 460°C| Light weight  | 3Ø12mm bottom bars and 2Ø10 mm top bars | 460°C |
| NWRC  | N 20°C | Normal weight | 3Ø12mm bottom bars and 2Ø8 mm top bars | 20°C |
|       | N 390°C| Normal weight | 3Ø12mm bottom bars and 2Ø8 mm top bars | 390°C |
|       | N 460°C| Normal weight | 3Ø12mm bottom bars and 2Ø8 mm top bars | 460°C |

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![Figure 3. Longitudinal section in electric furnace](image-url)
3.2 Mechanical tests
In the mechanical tests, the heated RC beam specimens together with the control specimens were subjected to an incrementally increased lateral concentrated static load at the beams mid span up to failure using the Universal Test Machine available at the College Engineering/University of Al-Qadisiyah/ Iraq (see Figure 4). The Universal Test Machine is capable of applying load up to 2000kN with a minimum incremental load of 5 kN. The load cells were inserted between the hydraulic jack and the bearing I section steel beam to measure the load at each load increment as shown in Figure 4-a. In addition, a linear variable displacement transformer (LVDT) was placed underneath the middle of the beam specimens to measure and monitor the lateral displacement corresponding to each load increment as shown in Figure 4-b. The recorded values of the load and displacement at each load increment were used to capture the load-lateral displacement relationships of the RC beams under different elevated temperatures. The ends support conditions of the RC beam specimens were arranged in the tests to simulate the simply supported condition by allowing the ends to move in axial directions and to rotate in the axis perpendicular to the beam plane.

Figure 4. Test setup of RC beam specimens (a) RC beam under concentrated load (b) Position of LVDT
4. Tests results

4.1 Temperature–time histories

The temperature time history inside the furnace, at concrete surface and at the steel bars surfaces were measured for all heated specimens using type - K thermocouples attached at the three aforementioned locations in the previous section. Figure 5 shows the temperature-time histories for all heated RC beam specimens and for different values of the elevated temperature. It can be seen from these figures that, each RC beam exposed to almost similar heating rate characterized by a rapid increase in the temperatures up to 200 ºC during the first ten minutes of the heating. Afterward, the heating rate considerably decreased to 10°C/min up to temperature of 350°C and beyond this temperature, the heating rate further decreased to reach 1°C/min and, maintained constant up to end of the test. A natural cooling rate was adopted for all beam specimens. Figure 5 shows that for all heated RC beams, the recorded temperature at the steel bars are considerably lower than that of the concrete surface. It can also be noted that the difference in measured temperature between the concrete and the steel bars increases in the case of the lightweight concrete compared to normal weight concrete. This can be attributed to the low thermal conductivity and high thermal insulation of the lightweight concrete as concluded from the previous research studies [7]

![Temperature-time histories](image)

**Figure 5.** Temperature–time histories at furnace, RC beam specimens and the steel bars used in the present study
4.2 Load–displacement behavior

The structural behavior of the RC beams exposed to different elevated temperatures and subjected to one lateral concentrated load are firstly presented in Figures 6 and 7 in terms of load–mid-span displacement relationships. It can be seen from these figures that as the lateral load increases, each beam exhibits three distinct phases of responses namely: linear elastic response, inelastic response, and crushing or failure response. Figure 6 clearly show that the ultimate load capacity of LWRC beams has decreased by 2.5%, and 11.95% compared to the control beam when exposure to different temperature of, 390 ºC and 460 ºC, respectively. It can also be noted from Figure 6 that the ultimate load capacity of the NWRC beams at ambient temperature was higher than that for LWRC beams by about 18.24 %. However, Figure 7 shows that the ultimate load capacity NWRC beams has considerably increased by 6.45% compared to the load capacity of LWRC beam when exposure to elevated temperature of 390 ºC and further decreased by 10.7% compared to the load capacity of LWRC beam when exposure to temperature of 460 ºC. Nevertheless, the ultimate load capacity NWRC beams has considerably decreased by 12.3% and 33.5% compared to the control beam when exposure to different temperature of 390 ºC, and 460 ºC, respectively. Table 3 shows the exposed temperature, failure load and failure modes for all RC beam specimens considered in this study. The second column of Table 2 lists the symbols of the RC beams used in the tests. The first letter refers to the type of concrete used (L letter for lightweight and N letter for normal weight concrete) while the followed number refers to the degree of the elevated temperature used in the test.

**Table 3. Summary of the tests results**

| Group | Type of beam* | Failure load (kN) | Failure mode            |
|-------|---------------|-------------------|-------------------------|
| LWRC  | L20           | 159               | flexure                 |
|       | L390          | 155               | Combined shear and flexure |
|       | L460          | 140               | Combined shear and flexure |
| NWRC  | N20           | 188               | flexure                 |
|       | N390          | 165               | Pure shear              |
|       | N460          | 125               | Pure shear              |
Figure 6. Load-displacement behavior of LWRC and NWRC beams under different elevated temperatures

Figure 7. Comparison of the load-displacement relationship of LWRC, and NWRC beams under different elevated temperatures

5. Conclusions

The following conclusions can be drawn from the present study:

1. The residual lateral load capacity of reinforced lightweight reinforced concrete beams under elevated temperature is about 12% greater than that in normal weight reinforced concrete beams exposed to the elevated temperatures of 460 ºC and 3.6% less than that in normal weight reinforced concrete beams exposed to the elevated temperatures of 390 ºC.

2. When the applied elevated temperature is increased, the failure load is considerably decreased. The effect of elevated temperature on the reduction in the failure load is lower in lightweight reinforced concrete beams as compared to normal weight reinforced concrete beams.

3. Increasing the temperature has an effect on changing the failure mode for all tested RC beam specimens from flexure failure mode to pure shear and combined shear and flexure failure mode.
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