The Fire Effect on the Performance of Reinforced Concrete Beams with Partial Replacement of Coarse Aggregates by Expanded Clay Aggregates

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ABSTRACT

This paper aims to investigate the flexural behavior of reinforced concrete beams considering fire resistance by adding Lightweight Expanded Clay Aggregates (LECA) to the concrete mix as partial coarse aggregate replacement. LECA is a type of porous clay with a uniform pore structure with fine, closed cells and hard, tightly sintered skin. The experimental work comprised four reinforced self-compacted concrete beams. All the specimens were identical in their geometrical layout of 1600×240×200 mm, reinforcement details, and support condition (simply supported). For all the beams, the main reinforcement was provided by two bars, each having a diameter of 12 mm, while a bar of 6 mm diameter was employed for the top and shear reinforcement. Each beam had a different replacement ratio of LECA for coarse aggregates (0, 10, 20, and 30%). All the specimens were tested under static two concentrated loads after being exposed to the fire of steady-state temperature (500 °C), 1 hr duration, and sudden cooling process. The results showed that adding LECA reduced the number and width of the generated cracks due to fire and reduced the deterioration of the ultimate load capacity and beam rigidity (stiffness).

Keywords-reinforced concrete beams; fire effect; Lightweight Expanded Clay Aggregates (LECA)

I. INTRODUCTION

Concrete is naturally fire-resistant, which gives it an edge over other building materials. However, concrete structures still need to account for fire effects. Concrete and steel reinforcements lose strength and stiffness as they heat up, but they must still support dead and live loads without failing. Moreover, intense fires cause structural elements to expand, creating extra loads and stresses that must be resisted. Sometimes, construction must follow the building code requirements for fire resistance, leading to costly mistakes. Any concrete structure might be subjected to one of the most severe forms of stress during its useful life if exposed to temperatures caused by a fire. When the temperature rises, there is a significant risk that the mechanical properties of the concrete will deteriorate, ultimately resulting in the total collapse and disintegration of the building. Authors in [1, 2] examined the effects of a 24 hr fire on reinforced concrete beams constructed using recycled aggregates. The researchers discovered that concrete beams with a rich mix showed a more significant decrease in flexural strength and a greater rise in load capacity and deflection than those with a normal mix [1, 2]. Lightweight Concrete (LWC) has a higher fire resistance than Normal Strength Concrete (NSC) since its lightweight particles have holes that may be exploited to reduce the pressure caused by fire. This makes LWC more effective in its ability to withstand fire. As a result of the fact that LWC is less susceptible to damage at high temperatures, both during the hot and residual stages, structures made of LWC may fare better in such occasions [3]. The thermal efficiency of Lightweight Aggregate Concrete (LWAC) is better than regular concrete, significantly reducing the energy used by buildings [4, 5]. LWAC has a higher resistance to fire when compared to normal-weight concrete [6] because the holes inside the lightweight aggregates help the vapors escape and lessen the stress created by the evaporated water [7].

LWC can be produced using porous lightweight aggregates, such as Light-Expanded Clay Aggregate (LECA). Expanded clay aggregates are porous ceramic products with a uniform pore structure of fine, closed cells and with a densely sintered, firm external skin. LECA is manufactured in rotary kilns from raw materials containing clay minerals. The raw material is prepared, molded, and then subjected to a firing process at temperatures between 1100 and 1200 °C, resulting in a significant increase in volume due to expansion. The LECA grains' internal cellular structure with thousands of air-filled cavities gives thermal and sound insulation properties [8].

In [9], a comparison was made between the mechanical characteristics of lightweight and regular-weight concretes reinforced with steel fibers. They found that LWC had better fresh properties but performed poorly in a hardened state compared to NWC [9]. Authors in [10] studied the effect of different types of Lightweight Aggregates (LWA) on the strength and appearance of LWAC after being heated up to 800 °C. They made 8 concrete mixtures with three kinds of LWA and two with Normal-Weight Aggregates (NWA). They found that LWAC performed better than NWA concrete up to 500 °C but lost more strength at higher temperatures. Authors in [11-14] found that concrete with LECA has a lower density, better thermal resistance, and slower decline in mechanical properties under high temperatures, making it suitable for fire-resistant structures.

LECA is a useful material for enhancing the fire performance of concrete, reducing its weight, and improving its workability and insulation. The structural behavior of fire-exposed concrete structures containing LECA as a partial coarse aggregate replacement has not been significantly covered by the research. The present study aims to fill this knowledge gap. This is an experimental study that investigates the structural behavior of reinforced concrete beams containing LECA as a partial coarse aggregate replacement after exposure to fire flame.

II. EXPERIMENTAL PROGRAM

A. Materials

The concrete mix utilized for casting all samples and their control specimens consisted of ordinary Portland cement (CEM I 42.5R) manufactured in Iraq by the Mass brand. The cement's compliance is tested in accordance with the limits of Iraqi Specification No. 5/2019 [15]. The study employed natural sand with a maximum particle size of 4.75 mm. The grading complied with the Iraqi specification (IQS, No.45:1984) and its modifications [16]. The coarse aggregates utilized in the study were siliceous crushed gravel with a maximum size of 10 mm. The conformity of grading of coarse aggregates complies with [16]. The LECA used in the created concrete mix had diameter ranging between 4 and 10 mm (Figure 1). LECA properties and grading are shown in Tables I-II.

TABLE I. LECA PROPERTIES

Properties	Value
Density (kg/m^3)	320
Specific gravity	0.55
Water absorption %	21.6
Fineness modulus	3

TABLE II. LECA GRADING.

Sieve Size (mm)	% Passing by weight
37.5	100
20	100
14	100
10	95.36
5	2.18
2.36	0.6

Fig. 1. LECA.

A very fine pozzolanic material (micro silica) as an addition (pozzolanic material) and Viscocrete-5930 (a product of Sika) were utilized in the chosen concrete mix to generate Self-Compacted Concrete (SCC) for all the specimens.

B. Tested Specimens

The research comprised testing four simply supported reinforced SCC beams. Each beam had a different volumetric replacement ratio (0, 10, 20, and 30%) of the coarse aggregates by LECA. All had an identical geometric layout; the beams' dimensions were 1600×200×240 mm, and the clear span was 1400 mm, as shown in Figure 2. The details of the mixes are given in TABLE III, where:

TABLE III. DETAILS OF CONCRETE MIXTURES.

Mix	Mix Proportion (kg/m^3)					SP	SF*
	Water	Cement	Sand	Gravel	LECA	(lit/m^3)	%
F-0**	185	441	750	950	0	4	2
F-10**	185	441	750	855	18.8	4	2
F-20**	185	441	750	760	37.6	4	2
F-30**	185	441	750	665	56.4	4	2

* Replacement by weight of cement. F: Fire exposure, ** LECA volumetric percentage (%)

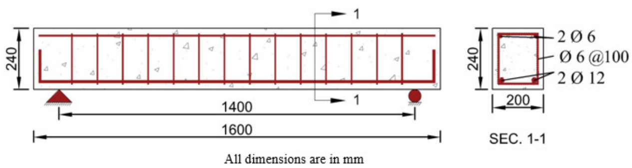

Fig. 2. Dimensions of the tested specimens and reinforcement details.

C. Burning and Cooling

The specimens were exposed to burning inside a gas furnace, using direct fire, while maintaining consistent conditions (namely, a steady-state temperature of 500±10 °C and an exposure duration of 1 hr), as seen in Figure 3. A temperature measurement device, namely a digital thermometer reader equipped with a K-type sensor wire, was used to monitor and record the temporal variations in temperature inside both the specimen and the furnace environment. The temperature-time relation criteria were established by adopting the ASTM E-119 [17]. A uniformly constant equivalent dead load effect provided 40% of the service load was applied during the burning process. After burning, the specimens were sprayed with water (sudden cooling).

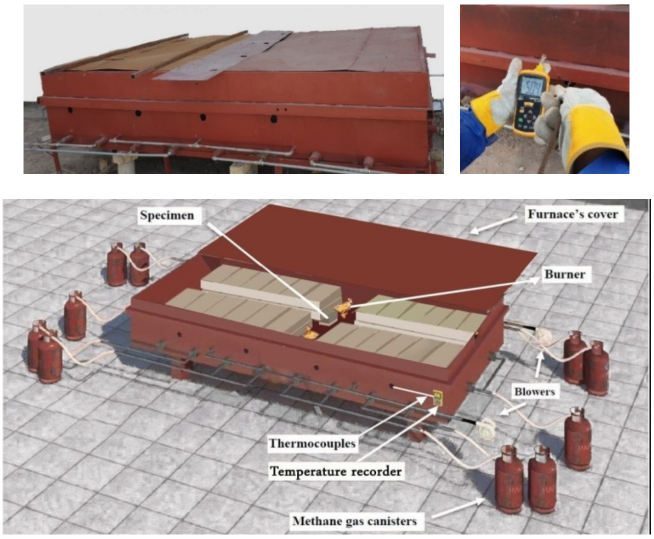

Fig. 3. Specimen burning procedure.

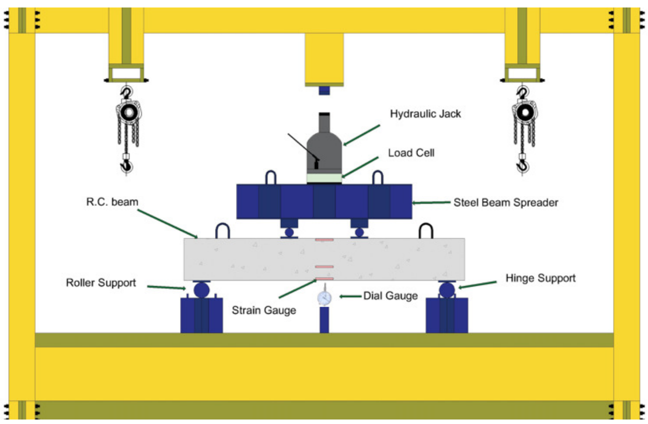

Fig. 4. Details of the test setup.

D. Procedures for Testing

The strain gauges were positioned in their appropriate locations on both the top and bottom fibers of the specimen midline on the front face of the specimen. The beams were set on 2 cylindrical supports (simple supports) with a span length of 1400 mm. The load was applied by a hydraulic jack with a capacity of 100 tons that was transferred to a steel I-section girder, which divided the weight into two equal forces and left a distance of 400 mm between them. During each loading step, the amount of the load, the vertical deflection at the beam center, and the strain on the concrete surface were all measured and recorded. The load was gradually increased until failure (at a rate of 250 kg / step), and the progression of the crack was noted after each load increase. The details of the test setup are shown in Figure 4.

III. TEST RESULTS AND DISCUSSION

To better understand the structural behavior of the beam, five categories were used in the finding's discussion, which are:

1. Effect of LECA on concrete properties.
2. Burning cracks.
3. Crack pattern, ultimate load, and mode of failure.
4. Load-deflection behavior.
5. Load-strain relation.

A. Effect of LECA on Concrete Properties

Mixtures containing LECA had lower mechanical properties at ambient temperature (30 °C) because LECA is generally weaker than the traditional aggregates. This can lead to a reduction in the overall strength of the concrete. However, after burning at a steady state temperature (500 °C) and the sudden cooling process, the mixtures containing LECA maintain their stiffness better due to reduced heat degradation (Table IV). LECA introduces thousands of tiny spaces in the clay, which form a honeycomb structure, giving LECA its low density and decreasing the weight of concrete. LECA is porous and has low thermal conductivity. These properties demonstrate that LECA can insulate concrete from heat transfer, avoid spalling and cracking caused by thermal stress, and keep mechanical strength and thermal insulation capabilities better than conventional aggregates after fire exposure [18, 19].

TABLE IV. PROPERTIES OF CONCRETE MIXTURES BEFORE AND AFTER FIRE EXPOSURE

Mix	f_{cu} (MPa)		Residual f_{cu} (%)	f_t (MPa)		Residual f_t (%)	Ec (MPa)		Residual Ec (%)
	Temp. (°C)			Temp. (°C)			Temp. (°C)		
	30	500		30	500		30	500	
F-0	60.1	41.2	68.6	4.46	1.39	31.2	31606	9208	29.1
F-10	57	43.5	76.3	4.16	1.72	41.3	27896	10109	36.2
F-20	53	41.8	78.9	3.88	1.89	48.7	25687	9657	37.6
F-30	48.9	39	79.8	3.56	1.9	53.4	23453	9151	39.0

B. Burning Cracks

After the burning and cooling process, cracks appeared on the surfaces of the beams, and flexural cracks appeared on the sides, as a result of the fire and the imposed load. On the concrete surface, there was noticeable discoloration. The concrete has a bluish color on the sides' surface, as shown in Figures 5-8. The reference specimen (F-0) had a greater number and width of cracks than the other specimens. It is worth noting that the cover of the reference specimen had little spalling, as shown in Figure 5. The number of cracks was substantially reduced, and no spalling in the specimens containing LECA was detected, see Figures 6-8. LECA reduced the number and width of the generated cracks. LECA has lower thermal conductivity and higher fire resistance than normal aggregates, so it can withstand higher temperatures and prevent cracking or spalling of the concrete surface due to fire exposure. As a consequence of the porous nature of LECA, evaporating water has a place to hide, which reduces the amount of cracks and the damage that occurs inside the concrete. The percentages of the specimens' damage, including the generated cracks and spalling were 1.48, 1.07, 0.93, and 0.84% for the specimens F-0, F-10, F-20, and F-30, respectively. Crack length and spalling area as a percentage of the specimen surface area were considered in order to evaluate the specimen's damage.

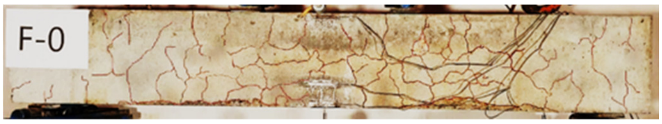

Fig. 5. Cracks due to burning and cooling of specimen F-0.

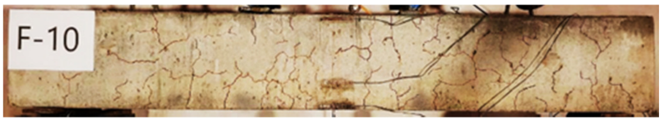

Fig. 6. Cracks due to burning and cooling of specimen F-10.

Fig. 7. Cracks due to burning and cooling of specimen F-20.

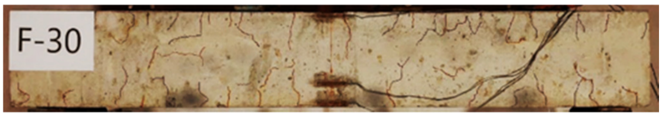

Fig. 8. Cracks due to burning and cooling of specimen F-30.

C. *Crack Pattern, Ultimate Load, and Mode of Failure*

Flexural collapse occurred in all the burnt beams. New cracks developed on both sides of the beams. The burned specimens' crack patterns are shown in Figures 9-12. The results showed that despite the reduction in the mechanical properties in the unburned control specimens after adding LECA, the beams that contained LECA remained more conservative in their ultimate load capacity after burning, which means that adding LECA reduced the deterioration of the ultimate load capacity for the burned specimens under the same conditions. The variations of the ultimate load for the specimens that contain LECA (F-10, F-20, and F-30) were +4.69, +2.35, and -1.41% respectively when compared to the control specimen, because LECA has lower thermal conductivity and higher fire resistance than the normal aggregates. Thus, LECA reduced the effect of fire on the models containing it by reducing the vapor pressure generated as a result of burning. Table V shows the result of the ultimate load and maximum deflection.

Fig. 9. Crack pattern for specimen F-0.

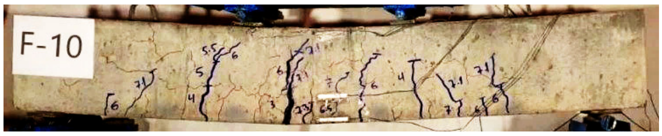

Fig. 10. Crack pattern for specimen F-10.

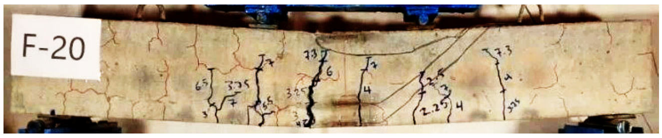

Fig. 11. Crack pattern for specimen F-20.

Fig. 12. Crack pattern for specimen F-30.

TABLE V. LOAD CAPACITY AND ULTIMATE DEFLECTION FOR BURNED SPECIMENS

Specimen	Ultimate Deflection (mm)	Ultimate load (kN)	% Variation of ultimate load (with respect to F-0)
F-0	31.93	80.33	---
F-10	30.50	84.10	+4.69
F-20	31.45	82.22	+2.35
F-30	32.94	79.20	-1.41

D. *Load-Deflection Behavior*

For each load increment of the static test, the vertical deflection of the burned specimens was measured at mid-span. The load-deflection behavior of specimens was investigated at service and ultimate load. The service load in the current study was assumed to be 65% of the ultimate load. Figure 13 shows the effect of the LECA volume ratio on the load-deflection behavior at mid-span. The results showed that adding LECA reduced the deflection at the service load stage and yielding load stage and reduced the deterioration in the beam's rigidity (stiffness), as shown in Table VI. The reduction in beam stiffness is attributed particularly to the decrease in the mechanical properties of concrete as a result of heating. The addition of the LECA reduced the degradation in the stiffness after the fire effect, which belongs to the lower thermal conductivity and the higher porosity of LECA. This means that concrete containing LECA can resist high temperatures better than normal aggregate concrete and it can maintain its structural integrity longer under fire exposure. Also, this can reduce internal stresses and prevent spalling during fire exposure. Spalling reduces the strength and stiffness of concrete and exposes the reinforcement bars to further damage [20, 21]. In stiffness calculations, the stage of linear load-deflection behavior was considered.

TABLE VI. MIDSPAN DEFLECTIONS OF SPECIMENS IN SERVICE AND ULTIMATE LOADS.

Specimen	Deflection at service load (mm)	Deflection at yielding load (mm)	Stiffness, K=P/Δ (kN/mm)
F-0	4.9	7.31	12.9
F-10	4.2	6.42	16.1
F-20	4.6	7.15	14.1
F-30	5.0	7.59	11.8

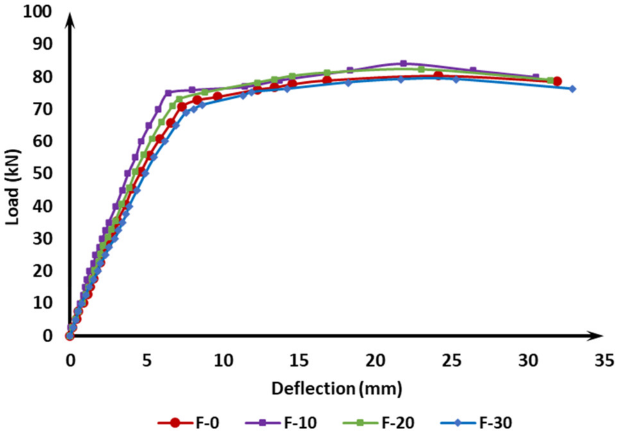

Fig. 13. Effect of LECA ratio on load-deflection behavior at mid-span.

E. Load-Strain Relation

The load–strain behavior of the concrete front face was recorded for burned specimens in specific positions. The strain of concrete was measured by 30 mm strain gages that were installed on the concrete front face of the tension and compression zone, as shown in Figure 14.

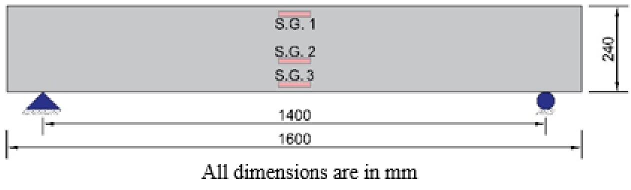

Fig. 14. Locations of the concrete strain gauges.

Figure 15 shows the effect of the LECA ratio on the load–strain behavior of the concrete in the compression zone. The concrete compression strain at the ultimate load was 2362, 2329, 2236, and 2089 micro-strain for the burned specimens F-0, F-10, F-20, and F-30, respectively. Adding LECA to the concrete mix reduced the strain after the fire effect by slowing down the heat transfer inside the concrete due to its low thermal conductivity and high porosity. The strain gauge readings placed in the tensile zone (S.G.2 and S.G.3) were neglected due to the cracks generated during the test, which affected the accuracy of the readings.

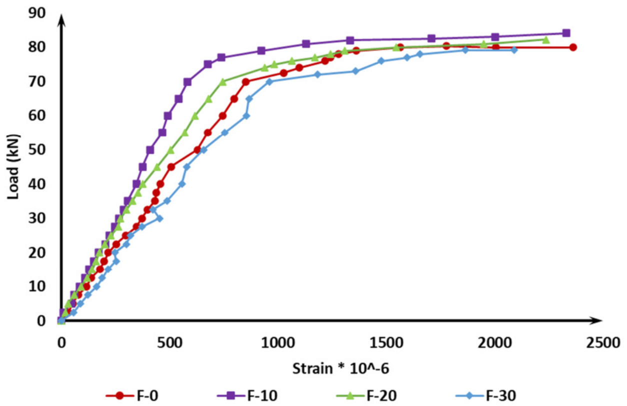

Fig. 15. Load–strain relation (S.G. 1) for concrete.

IV. CONCLUSIONS

The structural behavior of fire-exposed concrete structures containing LECA as a partial coarse aggregate replacement is not significantly covered by the scientific research. The present study aims to strengthen this weak point. The present study is an experimental study that investigates the structural behavior of reinforced concrete beams containing Lightweight Expanded Clay Aggregate (LECA) as a partial coarse aggregate replacement after exposure to fire flame. Based on the outcomes of the experimental research, the following conclusions were drawn:

1. Utilizing LECA as a partial volumetric substitute for the coarse aggregates in concrete results in a reduction of all the mechanical properties of concrete. The extent of this reduction is directly proportional to the LECA content.
2. Increasing LECA content results in improved strength retention in the mechanical characteristics of concrete, which are inversely related to the burning steady-state temperature.
3. Adding LECA substantially reduced the number and width of cracks in the concrete due to fire. Also, there was no spalling in the specimens containing LECA, while a little spalling occurred at the cover of the reference specimen.
4. Adding LECA reduced the deterioration of the ultimate load capacity for specimens burned under the same conditions. After burning, beams that contained LECA remained more conservative in their ultimate load capacity.
5. Increasing the LECA content reduced strain in the concrete. The recorded strain at the ultimate load was 2362, 2329, 2236, and 2089 micro-strain for the burned specimens at 500 °C of LECA ratios of 0, 10, 20, and 30%, respectively.

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