Engineered Science
DOI: https://dx.doi.org/10.30919/es934

Behavior of Lightweight Concrete Incorporating Pozzolana Aggregate and Expanded Polystyrene Beads

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Abstract

The inclusion of Expanded Polystyrene (EPS) beads in concrete mixtures presents a practical method for preserving natural aggregate resources and addressing the environmental impact caused by the accumulation of EPS waste. This research aims to explore the compressive strength, response to elevated temperatures, and shear performance of lightweight concrete by substituting pozzolana aggregates (PA) with EPS. Several concrete mixes were prepared by replacing different proportions of coarse and fine aggregates with EPS. The two most promising mixes were selected for further investigation. In the first mix, 12.5% of the coarse aggregate and 25% of the fine aggregate were substituted, while the second mix included 12.5% of the coarse aggregate, 25% of the fine aggregate, and 250 ml of Master Glenium 51a as a superplasticizer. To establish a baseline, a control mix was prepared using pozzolana coarse aggregate without EPS. The density and compressive strength of the concrete mixtures were assessed by testing standard cubes at room temperature, 250 °C, and 500 °C. Additionally, three simply supported beams with a span length of 1.05 m and a square cross-section measuring 150 mm on each side were subjected to a four-point loading scheme to investigate the shear behavior of the concrete produced from the aforementioned mixes. The study findings revealed that the density and compressive strength of the hardened concrete decreased as the percentage of EPS replacement increased. However, the mix incorporating EPS and 250ml of Master Glenium 51a as a superplasticizer achieved a compressive strength of 40.11 MPa at 28 days, indicating the potential of EPS in the lightweight concrete industry. The concrete mixes containing EPS exhibited a lesser reduction in compressive strength at 500 °C compared to the control mix without EPS. Furthermore, the beam made with the mix containing EPS and the superplasticizer demonstrated the highest shear capacity among the other beams. Based on these results, this study suggests that incorporating EPS as a partial substitute for pozzolana aggregate holds promise in the lightweight concrete industry, considering its observed density, compressive strength, resistance to high temperatures, and shear behavior.

Keywords: Expanded polystyrene beads (EPS); Pozzolana; Compressive strength; Master glenium 51; Light-weight aggregate; Shear behavior; Concrete.
Received: 11 July 2023; Revised: 29 July 2023; Accepted: 01 August 2023.
Article type: Research article.

1. Introduction

Concrete, known for its advantageous characteristics such as high ductility,[1] low thermal expansion,[2,3] high stiffness,[4,5] low maintenance requirements,[6] fire resistance,[7,8] and high compressive strength, is extensively utilized in construction globally.[5,9-11] Reinforced concrete structures, in particular, are widely prevalent. By reducing the dead weight of a concrete building, it becomes possible to downsize columns, footings, and other load-bearing components. Structural lightweight concrete mixtures can be formulated to achieve strengths comparable to regular concrete,[12] while maintaining a higher strength-to-weight ratio. This often leads to smaller structural elements, reduced use of reinforcing steel, and decreased volume of concrete, ultimately resulting in lower overall costs, despite the slightly higher expense of lightweight concrete. It is crucial to note that all other requirements for mechanical and long-term performance hold equal importance when employing lightweight structural concrete.

According to the definition provided in EN 206-1, In Ref. [13] lightweight concrete is produced by replacing heavier natural aggregates with lightweight aggregates in order to achieve a density ranging from 800 to 2,000 kg/m^3. The unit

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weight or density of lightweight concrete can be classified and determined within a range of 320 to 1920 kg/m^3. According to the ACI318-19, lightweight concrete is defined as concrete having an equilibrium density from 1440 to 2160 kg/m^3.[14]

Several experimental studies have been conducted to introduce lightweight concrete, employing various types of lightweight aggregates. For instance, in the study by Ref. [12] white limestone, red limestone, clay brick fragments, and pumice aggregate were experimented with, resulting in reduced dry density when pumice was used compared to normal concrete. Another study[15] utilized a novel recycled aggregate and observed that the apparent dry density of the recycled lightweight aggregate concrete specimens decreased with an increase in the replacement ratio of recycled lightweight aggregate. In Ref. [16], ordinary coarse aggregate was replaced with lightweight ceramsite or foam to achieve a C40 lightweight concrete mix ratio that adheres to engineering standards.[17] Employed Pollytag, expanded clay aggregate, and expanded polystyrene beads, while Ref. [18] used perlite, LECA (lightweight expanded clay aggregate), and pumice, resulting in lightweight concrete with a specific gravity 25-30% lighter than conventional concrete.[19] shredded and crumbed waste tires of different sizes (coarse, medium, and fine) and ratios (10, 20, and 30%) were utilized, although these replacements did not meet the criteria for lightweight concrete. Lastly, Ref. [20] employed expanded glass (EG) aggregate, which is produced by crushing waste glass and expanding polystyrene waste.

Expanded polystyrene (EPS) beads have been utilized as a lightweight aggregate by several researchers, including Refs. [13,21-24] to produce concrete with varying percentages of replacement and maximum aggregate size. However, the resulting concrete exhibited significant variation in compressive strength, leading to recommendations against its use in structural elements. In order to tackle this issue, Ref. [25] and Ref. [27] explored different approaches to enhance the strength of lightweight concrete (LWC). Ref. [25] replaced cement with metakaoline and silica fume, resulting in a significant improvement in compressive strength. Similarly, Ref. [26] replaced the aggregate with recycled concrete aggregate and employed silica fume as a cement replacement, which also contributed to increased strength. Ref. [27] utilized eggshell powder and silica fume as cement replacements in LWC concrete with EPS, but noted that the strength decreased with higher percentages of EPS replacement. Finally, Ref. [25] employed lightweight porcelinite coarse aggregate, metakaolin, and silica fume to enhance the strength of LWC. They discovered that an optimal percentage of both metakaolin and silica fume (around 14%) improved the properties of high-strength lightweight aggregate concrete compared to ordinary lightweight aggregate concrete.

Previous studies have not explored the use of polystyrene as a partial replacement for fine aggregate in lightweight concrete. The aim of this study is to achieve lightweight concrete with better normal compressive strength by replacing a specific percentage of sand and coarse aggregate with polystyrene particles. Several mixes were tested, but only three will be presented. The first mix served as the control, with full replacement of coarse mineral aggregate with pozzolana aggregate, normal sand, and no additives. The second mix replaced 12.5% of the coarse pozzolana with EPS and 25% of the sand with EPS, without any additives. The third mix replaced 12.5% of the coarse pozzolana with EPS and 25% of the sand with EPS, and included 250ml Master Glenium as a superplasticizer.

The use of EPS beads as a partial replacement of pozzolana aggregates has never been discussed in the literature. The work presented in the literature explored the partial replacement of natural aggregates with EPS beads, also, the effect of high temperatures on concrete mixes including EPS beads has never been investigated. This study included large scale testing of beams made with concrete including EPS beads and pozzolana aggregates. The literature included studies on the material behavior in terms of cubes and cylinders. There is no literature about the behavior of large beams made with concrete including EPS beads. The objective of this study is to enhance the normal compressive strength of lightweight concrete by substituting a specific percentage of sand and coarse aggregate with polystyrene particles. Various mixes were tested, but only three will be discussed here. The first mix served as the control, wherein the coarse mineral aggregate was fully replaced with pozzolana aggregate, normal sand was used, and no additives were included. In the second mix, 12.5% of the coarse pozzolana was replaced with EPS, and 25% of the sand was replaced with EPS, without the inclusion of any additives. The third mix also replaced 12.5% of the coarse pozzolana with EPS and 25% of the sand with EPS, but additionally incorporated 250 ml of Master Glenium as a superplasticizer.

2. Materials and methods

2.1 Materials

2.1.1 Cement

Ordinary Portland cement (OPC) meeting the requirements of ASTM C150/C150M-19a, Ref. [28] was used in this study. The chemical composition of the cement used is shown in Table 1. The OPC was used without the addition of any additives or additional cementitious materials.

Table 1. Ordinary Portland cement's chemical composition.

Chemical Composition	% By Mass
SiO_2	21.5
Al_2O_3	5.8
Fe_2O_3	3.4
CaO	63.5
MgO	1.1
SO_3	2.8

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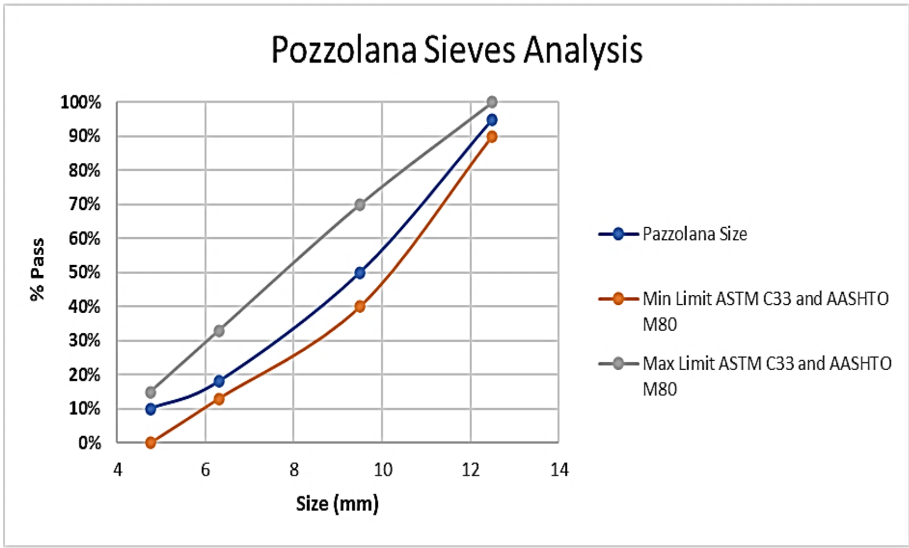

Fig. 1 Sieve analysis of coarse aggregate.

2.1.2. Aggregates

All mixes used pozzolana aggregate (PA) with a maximum aggregate size of 19 mm. All tests including water absorption, specific gravity, and density were carried out in accordance with ASTM C 127,[29] and the results are shown in Table 2. Aggregates were sieved to ensure that they meet the ACI committee E-701 code requirements.[30] The sieve analysis of the pozzolana aggregate is shown in Fig. 1. This study's fine aggregates were silica sand and has a particle size between 0.06 and 2.0 mm.

Table 2. Properties of coarse aggregates.

Property	Value		
	Trial One	Trial Two	Trial Three
Apparent Specific Gravity (ASG)	2.070	2.099	2.090
Water Absorption (%)	1.318%	1.541%	1.452%
Density (Unit weight) (kg/m3)	1336	1354	1324

2.1.3 Expanded polystyrene beads

As shown in Fig. 2, the shape of the expanded polystyrene beds (EPS) used in this study were white medium circles with about 4.5 mm diameter. Table 3 shows the Physical properties of EPS as provided by the manufacturer.

2.1.4 Master Glenium 51

Master glenium was employed in the third mix. This substance is a modified polycarboxylic ether-based concrete superplasticizer with good performance. It is a liquid with a yellowish to straw-colored hue, a relative density of 1.07, and a pH between 7.0 and 8.0.

Fig. 2 Expanded polystyrene beads.

2.2 Details of Mix Proportions

In this study, three concrete mixes were prepared from Pozzolana aggregate with an effective water-to-cement (w/c)

Table 3. Physical and Mechanical properties of EPS.

Physical Properties	
Density	2.00 g/cc
Water Absorption	0.0300 %
Viscosity	1.65 cP
Permeability	2.1

Table 4. Concrete mix proportions.

Mix	Cement	Water	Fine aggregate	Coarse aggregate	Master Glenium 51
	(kg/m³)	(kg/m³)	(kg/m³)	(kg/m³)	(L/m³)
Control	375	180	638	930	-
12.5% Coarse +25% Fine	375	180	479	814	-
12.5% Coarse +25% Fine + 250 ml Master Glenium 51	375	180	479	814	4.25

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ratio of 0.48. All mixes were designed based on the aggregates' properties according to the ACI 318-19.[31] The best three concrete mix proportions were chosen from several mix trials, as shown in Table 4.

Grade 60 rebars have a specified yield strength equal to 420 MPa and a tensile strength of 620 MPa. Grade 40 rebars have a specified yield strength equal to 280 MPa and a tensile strength of 420 MPa.

2.3.2 Geometrical and reinforcement details

For the purpose of examining the shear characteristics of concrete beams formulated using the previously mentioned concrete mixes, three beams were prepared. These beams were supported at both ends and had an overall length of 1200 mm, with a span length of 1050 mm. Their cross-sections were square, each side measuring 150 mm. To ensure eventual shear failure, the beams were adequately reinforced for flexural strength. Fig. 3 provides the dimensions and details of the reinforcement used in the reinforced concrete (RC) beams.

2.3.3 Beams callout

Table 5 presented below illustrates the identification and characteristics of the beams investigated regarding shear behavior. Beam LS corresponds to a beam composed of the control mix without the incorporation of EPS. Beam LS-P represents a beam created using a concrete mix containing EPS, which replaces 12.5% of the coarse aggregate and 25% of the fine aggregate. On the other hand, beam LS-P* denotes a beam formed from a concrete mix that includes EPS substituting 12.5% of the coarse aggregate and 25% of the fine aggregate, alongside the addition of 250 ml of Master Glenium 51.

Table 5. Beams designation.

Beam	Designation	Mix
Control	LS	Control
12.5% Coarse +25% Fine	LS-P	12.5% Coarse +25% Fine
12.5% Coarse +25% Fine + 250ml Master Glenium 51	LS-P*	12.5% Coarse +25% Fine + 250ml Master Glenium 51

2.3.4 Test Setup

The test setup for the beam specimens is depicted in Fig. 4. The beams were placed in a simply supported configuration with roller supports at both ends, and the application of load was facilitated by a transfer beam. Dial gauges were positioned beneath the beam to gauge the displacement.

3. Results and discussion

3.1 Density

ASTM C138/C138M-17a was used to determine the density of specimens and the results are shown in Table 6.

Table 6. The density of the mixes.

Mix	Density (kg/m3)	Reduction Percent (%)
Control	2152.70	-
12.5% Coarse +25% Fine	1983.92	7.8%
12.5% Coarse +25% Fine + 250ml Master Glenium 51	1996.08	7.3%

The experimental results indicate that all mixes with 12.5% coarse aggregate replacement and 25% fine aggregate replacement meet the ACI318-19 definition of lightweight concrete, which is defined as having a density of less than 2160 kg/m3. The mix with 12.5% coarse and 25% fine aggregate replacement exhibited a 7.8% reduction in weight compared to the control sample. The curing age did not have a significant effect on the density of the concrete. The control mix showed a density change of 0.58% at 28 days compared to the density at 7 days. Similarly, the mix with 12.5% coarse and 25% fine aggregate replacement showed a density change of -0.02% at 28 days compared to the density at 7 days, while the mix with 12.5% coarse and 25% fine aggregate replacement and 250ml Master Glenium 51 showed a density change of 0.087% at 28 days compared to the density at 7 days. The density of the mixes at different curing ages is illustrated in Fig. 5. It is well known that curing primarily affects the hydration process of cement and does not introduce any additional materials that would change the overall density of the mix. The density of concrete primarily depends on the ratio of its constituent materials.

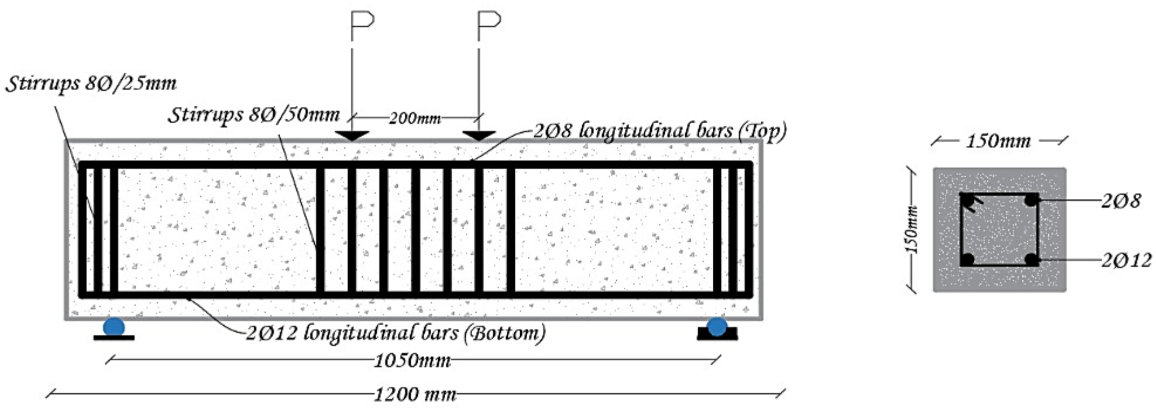

Fig. 3 Beam reinforcement details.

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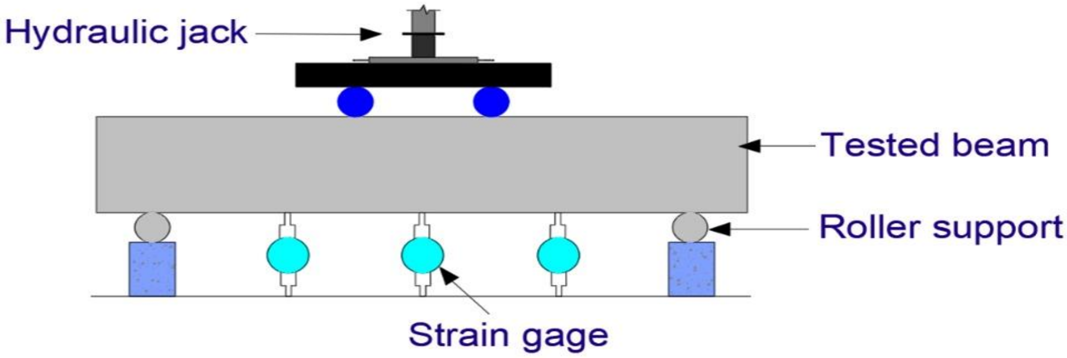

Fig. 4 Beam specimen test setup.

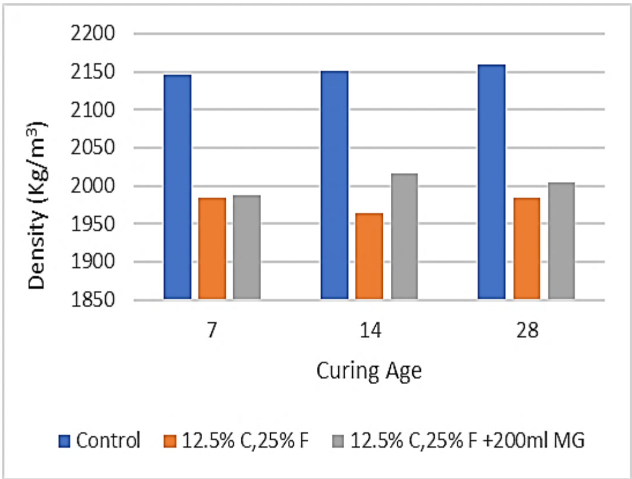

Fig. 5 The density of the mixes.

3.2 Compressive strength

Standard cubes were tested for compressive strength at 7, 14 and 28 days after casting. The compressive strength results for the mixes are shown in Table 7.

Based on the results of trials one and two, it was observed that the mix with a 12.5% replacement of coarse aggregates and a 25% replacement of fine aggregates with polystyrene exhibited sufficient strength while maintaining a relatively low density, indicating its potential for achieving good strength characteristics. In the case of the mix with a 12.5% replacement of coarse aggregates and a 25% replacement of fine aggregates without the use of superplasticizer, the compressive strength decreased from 48.59 MPa to 27.15 MPa compared to the control mix. Although a noticeable reduction in compressive strength of about 23.5% was observed without any additives, the achieved strength was still comparable. For the mix incorporating superplasticizer, the replacement of both coarse and fine aggregates with EPS resulted in a decrease in compressive strength from 48.59 MPa to 40.11 MPa at 28 days, representing a reduction of approximately 17.4% compared to the control mix. Notably, the mix containing 250 ml of Master Glenium 51 superplasticizer demonstrated the highest compressive strength among all mixes incorporating polystyrene beads, with its strength even comparable to the control mix containing 100% Pozzolana aggregate. This suggests a promising approach for achieving relatively high strength with lightweight characteristics. Fig. 6. depicts the compressive strength at 7, 14, and 28 days, showing a parallel increase in strength with the curing age from 7 to 28 days.

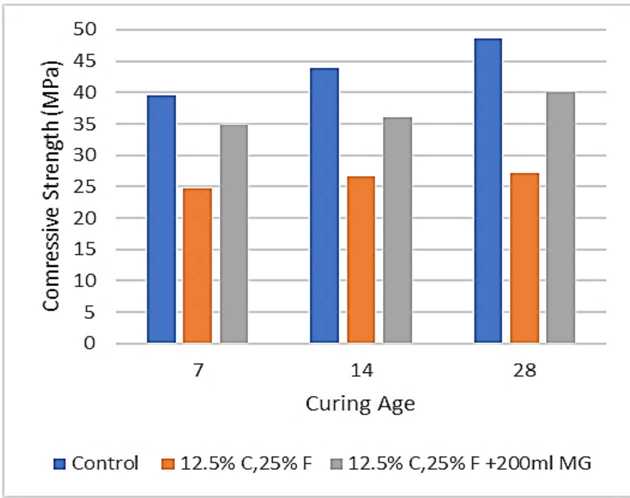

Fig. 6 Compressive strength of the mix.

Table 7. Compressive strength results.

Mix	Density (kg/m³)	f_{cu} (MPa) 7-Days	14-Days	28-Days	Reduction Percent @ 28 days (%)
Control	2152.70	39.47	43.81	48.59	-
12.5% Coarse +25% Fine	1983.92	24.72	26.64	27.15	23.5
12.5% Coarse +25% Fine + 250ml Master Glenium 51	1996.08	34.90	36.11	40.11	17.4

* f_{cu} refers to the compressive strength of cubes

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3.3 Failure Modes of Targeted Concrete

During compressive stress testing, the control mix exhibited brittle behavior, with the concrete cubes being completely crushed without any noticeable bridging effect from the aggregate particles. In contrast, the concrete containing EPS demonstrated a more ductile response, as the cubes were able to withstand a higher compression load before reaching complete failure. The cracks observed in the EPS-containing concrete appeared to be tighter, with less propagation at the point of failure. This can be attributed to the bridging effect of the polystyrene particles, which partially replaced the fine and coarse aggregate. Fig. 7 illustrates the different failure modes observed in the control mix and the concrete mixes incorporating EPS.

3.4 Heat Effect on Compressive Strength

This section deals with the temperature effect on the compressive strength of the three mixes. Standard cubes (15 cm × 15 cm × 15 cm) were exposed to two elevated temperature levels: 250 °C and 500 °C for 120 minutes. The standard temperature-time curve ISO 834 was followed in this study. After heating the specimen were left to cool in the

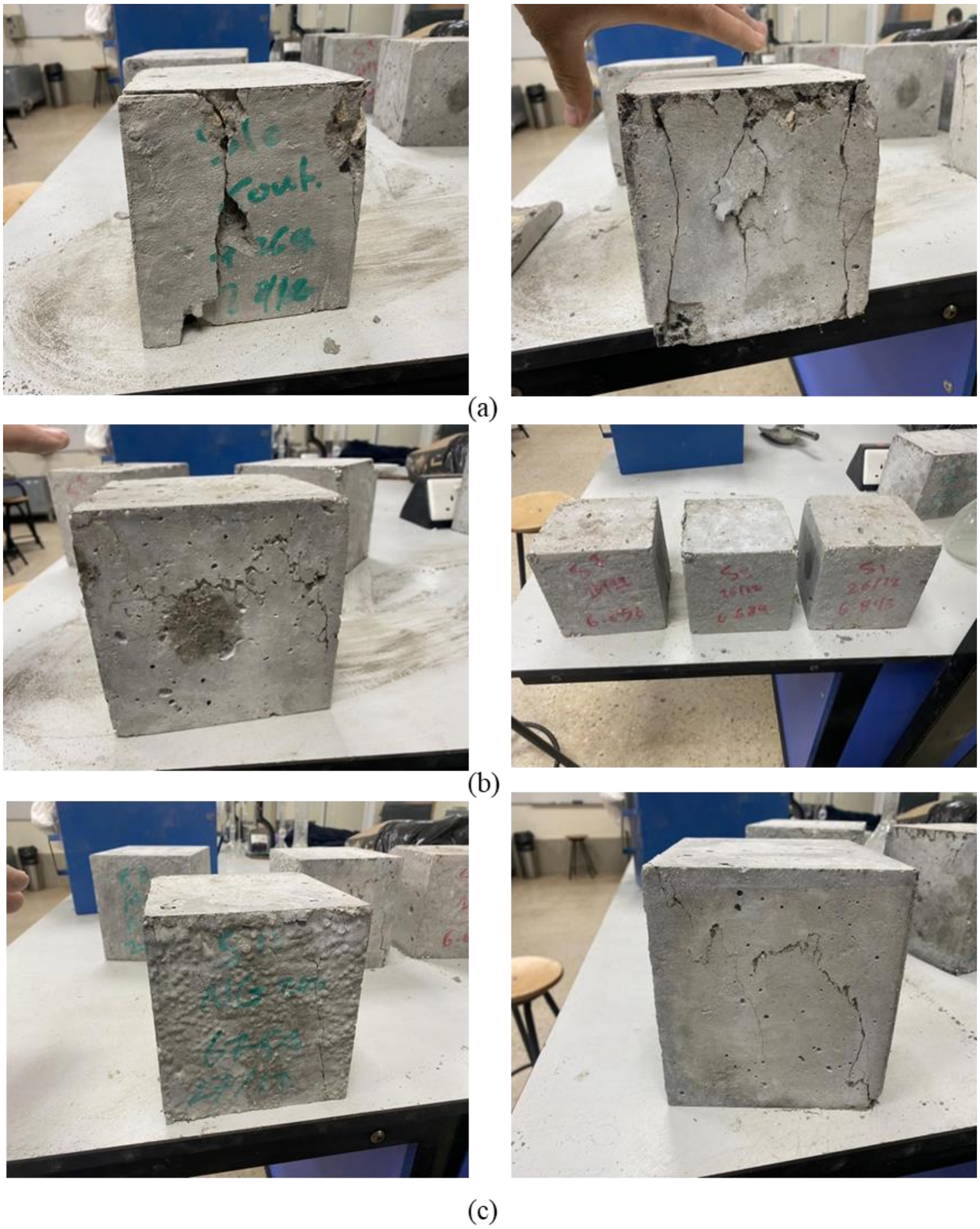

Fig. 7 Failure mode of a) Control samples b) 12.5% Coarse +25% Fine samples c) 12.5% Coarse +25% Fine + 250ml Master Glenium 51 samples.

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furnace and removed. Table 8 shows the compressive strength of the cubes at the ambient temperature, 250 °C and 500 °C.

Table 8. Compressive strength of heated samples.

Mix/ Temperature	25 °C	250 °C	500 °C
Control	48.59 MPa	54.22 MPa	27.65 MPa
12.5% Coarse +25% Fine mix	27.15 MPa	26.63 MPa	24.97 MPa
12.5% Coarse +25% Fine + 250ml Master Glenium 51	40.11 MPa	41.72 MPa	33.66 MPa

Figure 8 shows the percentage of gain and reduction of compressive strength of the three mixes after heating. It is believed that the slight increase in the compressive strength at temperature level 250 °C is due to the fact that this level of temperature helps in the continuation of the concrete hydration process. Fig. 8, also shows that the reduction in compressive strength was very high for the control mix without EPS, from 25 to 500 °C, which was about 43.1%. For mixes with EPS and with EPS and Master Glenium 51, the reduction was 8.0 and 16.03%, respectively. It is believed that inclusion of EPS will act as confining element inside the concrete and thus reducing the formation of the micro cracks. This conclusion needs future research to deeply investigate the microstructure of the concrete including EPS at high temperature levels.

3.5 Shear Behavior of Beams

The crack patterns observed at failure for beams LS, LS-P, and LS-P* are shown in Fig. 8. through 10. Initially, a flexural crack was identified in the mid-third region of each beam, extending from the bottom fibers to a position above the midpoint of the beam. This initial flexural crack was detected at load levels of 18 kN, 19 kN, and 12 kN for beams LS, LS-P, and LS-P* respectively. As the load was further increased, flexural-shear cracks began to appear outside the middle-third region. The width of these cracks progressively increased with the applied load. Eventually, all beams experienced failure due to diagonal shear, as illustrated in Figs. 9-11. Beam specimen LS demonstrated an ultimate load capacity of 45 kN, while specimen LS-P failed at a load level of 36 kN, and specimen LS-P* failed at a load level of 45.5 kN.

The correlation between the compressive strength of the concrete mixes and the shear strength of the beam specimens is evident. Among the tested specimens, LS-P* exhibited the highest shear capacity, while LS-P displayed the lowest shear capacity. This observed trend aligns with the previously discussed compressive strength findings in the preceding section. Consequently, these results strongly endorse the prospective application of EPS in concrete mixes for structural members. Notably, the beams composed of a combination of 12.5% coarse aggregates, 25% fine aggregates, and 250 ml of Master Glenium 51 exhibited the lowest density as well as the highest compressive strength and shear capacity.

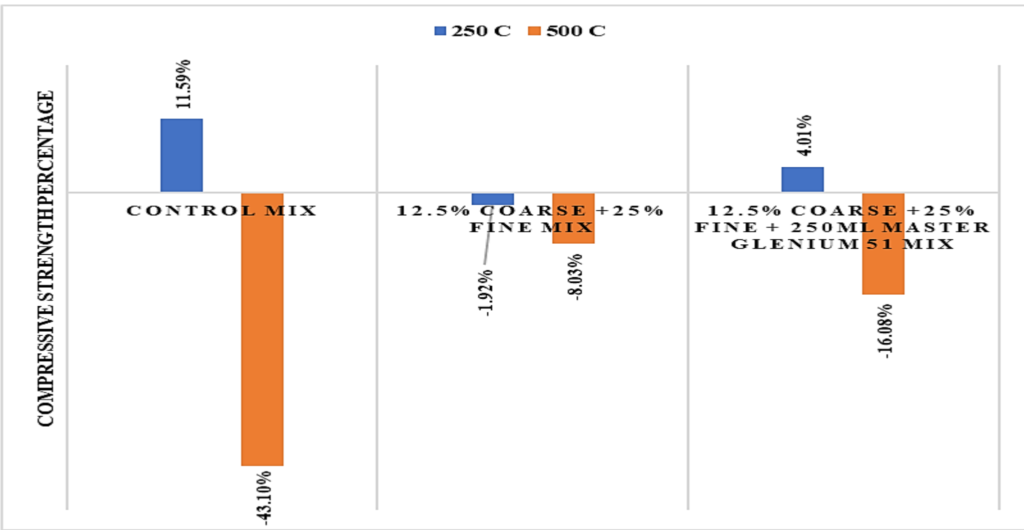

Fig. 8 Compressive strength percentage after heating.

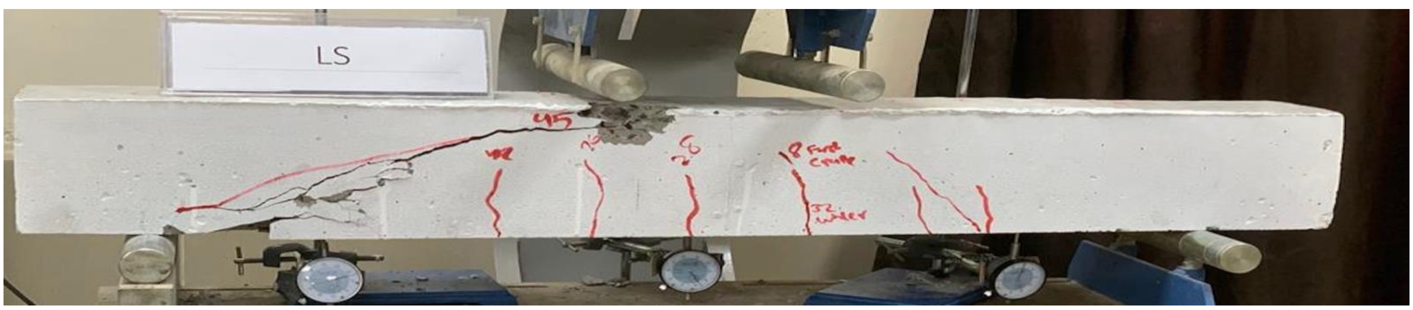

Fig. 9 Crack pattern at failure of beam LS.

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Fig. 10 Crack pattern at failure of beam LS-P.

Fig. 11 Crack Pattern at Failure of Beam LS-P*

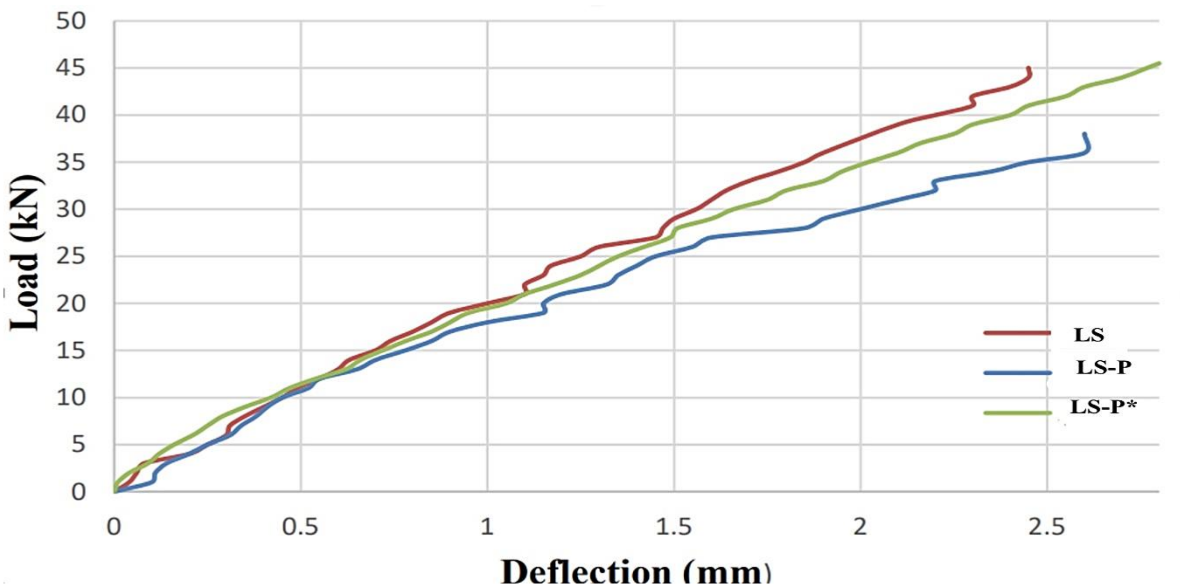

Fig. 12 Load-Displacement curves.

The load-displacement curves shown in Fig. 12. demonstrate that beam LS-P* achieved greater load and displacement capacity compared to the remaining specimens. Conversely, beam LS-P exhibited the lowest capacity and displacement, as evident from the figure. This behavior is mainly attributed to the difference in the compressive strength of the beams.

4. Conclusions

This study investigates the effect of replacing fine and coarse aggregates with EPS beads and full replacement of coarse aggregates with pozzolana in the production of lightweight concrete with and without additives. From the scope of this study, the following inferences can be drawn:

• The proportion of EPS beads in the concrete mix affects the density and compressive strength properties of hardened concrete.

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• Coarse aggregates replacement plays a larger role in reducing the density of concrete made with EPS beads than fine aggregates replacement• A significant decrease in density was observed when coarse and fine aggregates were replaced with EPS in the same mix

• In order to produce lightweight aggregates from EPS beads with an acceptable reduction in strength, both coarse and fine aggregates maybe replaced.

• The addition of master glenium 51 superplasticizers at the same replacement ratio of fine and coarse aggregate with EPS enhanced the compressive strength.

• The addition of EPS to concrete helps in resisting high temperature effects, then it may be considered a useful concrete in the areas that would be exposed to fire.

Shear investigation results strongly endorse the prospective application of EPS in concrete mixes for structural members. The beam composed of a combination of 12.5% coarse aggregates, 25% fine aggregates, and 250 ml of Master Glenium 51 exhibited the lowest density as well as the highest compressive strength and shear capacity.

This study covered the potential of using EPS in lightweight concrete as a partial replacement of pozzolana aggregates. Further studies are required to develop a constitutive model for such concrete at different percentages of EPS. Also, further investigation is required to study the flexural behavior of large-scale beams with different ratios of longitudinal reinforcement.

Acknowledgements

This work was carried out during the sabbatical leave granted to the author Mu'tasime Abdel-Jaber from University of Jordan during the academic year 2022-2023.

Conflict of Interest

There is no conflict of interest.

Supporting Information

Not applicable.

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