Structural Performance of Lightweight Fiber Reinforced Polystyrene Aggregate Self-Compacted Concrete Beams

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ABSTRACT

This study aims to investigate experimentally the flexural behavior of lightweight Self-Compacted Concrete (SCC) beams made by Expanded Polystyrene (EPS) concrete and reinforced with rebars and steel fibers. To achieve the aims of this study, seven simply supported EPS lightweight fiber-reinforced concrete beams were fabricated and tested up to failure to study the effects of EPS content and the volume fraction of the steel fibers on their flexural behavior. The tested specimens were divided into two groups with one additional reference beam to be cast without using EPS or steel fibers. In the first group, three lightweight specimens were constructed using 25% EPS beads and were reinforced with 0%, 0.75%, and 1.5% steel fiber volume fractions. The second group is similar to the first group but was fabricated using 50% EPS beads. The test results showed that the mechanical properties of the hardened concrete were significantly reduced due to polystyrene EPS beads with some enhancement when steel fibers were added to the concrete mix. The flexure strength of EPS-LWT concrete beams was significantly reduced due to the polystyrene EPS beads. Furthermore, the results revealed remarkable enhancement in the flexure strength of the tested beams due to the steel fiber reinforcement.

Keywords-lightweight concrete; EPS concrete; sustainable concrete; steel fibers; self-compacted concrete; flexural behavior

I. INTRODUCTION

Expanded polystyrene (EPS) wastes are generated from industries and post-consumer products. They are non-biodegradable but are usually disposed by burning or landfilling leading to environmental pollution and recycling solutions are to decrease their negative effects on the environment. This problem can be solved by using wasted EPS as a recycled material to produce sustainable Lightweight Concrete (LWC).

The mechanical properties of LWC are typically predicted using the models of conventional concrete. The estimated values contain significant errors, particularly at lower density levels, due to the differences in the structure and density of LWC, including EPS-LWC [1]. The mechanical properties of concrete, including EPS-LWC, significantly depend on its density. The primary cause of EPS-decreased LWC's mechanical properties, such as its compressive strength, is its lower density [2]. Polystyrene concrete has a significant benefit over alternative materials such as autoclaved normal concrete [3-4]. Authors in [5] provided details on the methods used for mix design and casting concretes containing 40, 50, and 60 vol. % (corresponding to specific densities of 0.8, 1.0, and 1.2, respectively) of polystyrene aggregates. They showed that the compressive strength roughly varies linearly with density. Specific density increased from 0.8 to 1.30, increasing the compressive strength from 3 to 15 MPa. Authors in [6-7] showed the characteristics of treated EPS beads in hardened concrete. The results indicated that the water to cement ratio (w/c) had an impact on strength, stiffness, and chemical resistance of polystyrene aggregate concrete with constant density. The 28-day compressive strength of polystyrene concrete increased from 5.6 MPa to 11.9 MPa when the w/c decreased from 0.60 to 0.35. The compressive strength of LWC was shown to be more sensitive to changes in w/c than the tensile strength [8-10]. According to CEB's assessment criteria, EPS concrete with fly ash had a low absorption rate and "good" concrete quality [11]. These exhibit moisture migration and absorption that is comparable to or even less than normal weight concrete. In [12], the concrete that used EPS and contained fly ash and SF had the lowest absorption. Authors in [13] examined the fresh characteristics of self-compacted LWC using EPS. The results of the compressive strength test showed that using EPS aggregates significantly reduced the compressive strength of self-compacted LWC. Compressive strength, splitting tensile strength, uniaxial compressive strength, and static elastic modulus of EPS concrete with added fibers were significantly improved in [14]. Authors in [15] performed experimental research to investigate the usefulness of EPS in WC sandwich wall panel production. The results proved the effectiveness of the produced EPS lightweight wall panels for load-bearing walls and non-loadbearing walls in single and multi-story buildings. The possibility of using EPS as a partial replacement of coarse aggregates to produce LWC has ignited the research interest during the recent years. However, most of the recent research works focus on the mechanical properties of fresh and hardened EPS concrete. Since the mechanical properties of EPS aggregate concrete are much lower than those of conventional concrete, strengthening with steel fibers when used in flexural members is the main target of the current study. This research presents an attempt to explore the flexural behavior of EPS SCC beams reinforced with rebars and steel fibers under monotonic loading. To achieve this goal, the bending behavior of seven fiber reinforced EPS-LWC concrete beams containing different percentages of EPS and steel fibers were examined. The main variables considered were the EPS replacement of coarse aggregates and the volume fraction of the added steel fibers.

II. EXPERIMENTAL PART

A. Materials

In this research, SCC, designed according to the requirements of EFNARC [16], was adopted as the reference concrete mix. Material constituents used to compose the SCC reference concrete mix included Ordinary Portland Cement (OPC), natural sand, Silica Fume (SF), tap water, and Hyperplast PC202 superplasticizer (SP). Reinforcement steel bars with diameter of 10mm were used as flexure rebars and ϕ8 mm rebars were used as shear reinforcement. EPS was adopted as partial replacement of the coarse aggregates to produce the LWC. Different proportions of hooked steel fibers were used as additional reinforcement. The mechanical properties of the considered steel fibers are illustrated in Table I. Table II presents the proportions of the material constituents used to cast each of the seven beam specimens employed in the experimental program.

TABLE I. PROPERTIES OF HOOKED-STEEL FIBERS

Diameter	Length	Tensile strength	Density
0.9 mm	30 mm	1900 MPa	7800 Kg/m^3

TABLE II. PROPORTIONS OF THE MATERIAL CONSTITUENTS USED IN EACH MIX DESIGN

Mix design	EPS content (%)	SF content (%)	Cement (kg/m^3)	SF (kg/m^3)	Sand (kg/m^3)	Gravel (kg/m^3)	Water (kg/m^3)	EPS (kg)
R	0	0	375	42	746	992	167	0
E25 F0	25	0	375	42	746	744	167	1.284
E25 F75	25	0.75	375	42	746	744	167	1.284
E25 F150	25	1.5	375	42	746	744	167	1.284
E50 F0	50	0	375	42	746	496	167	2.568
E50 F75	50	0.75	375	42	746	496	167	2.568
E50 F150	50	1.5	375	42	746	496	167	2.568

B. Hardened Concrete Properties

Table III presents the mechanical properties of the hardened concrete mix used to fabricate the beam specimens used in this study. It is evident from the results listed that hardened concrete mechanical properties, i.e. compressive strength, elastic modulus, and split tensile strength, were significantly reduced due to the polystyrene EPS content, whereas the steel fibers content enhanced these properties in general. Moreover, the density values for the adopted mix proportion were significantly reduced due to the EPS coarse aggregate replacement indicating LWC especially for 50% EPS content.

TABLE III. MECHANICAL PROPERTIES OF THE CONCRETE OF THE TESTED BEAMS

Beam Symbols	f_{cu} (MPa)	f'_c (MPa)	E_c (MPa)	f_{ct} (MPa)	Density (kg/m^3)
B1-R	43.1	34.5	26819.2	3.81	2243.3
B2–E25 F0	26.1	20.9	16500.5	2.42	1917.9
B3–E25 F75	29.2	23.3	17843.0	3.23	1947.3
B4–E25 F150	25.8	20.6	17923.7	3.54	2035.6
B5–E50 F0	16.2	13	10869.7	1.79	1700.4
B6–E50 F75	20.6	16.5	12947.0	2.21	1764.1
B7–E50 F150	15.5	12.4	11353.0	2.36	1778.7

C. Test Specimens

Seven simply supported EPS fiber-reinforced LWC beams were fabricated and tested up to failure to study the influence of the amount of the replaced coarse aggregates with polystyrene beads and the volume fraction of the steel fibers on their flexural behavior. The tested specimens were divided into two main groups with one additional reference beam that was cast without EPS or steel fibers. The main variable distinguishing these two groups is the percentage of the replaced coarse aggregates with EPS beads.

Two values were adopted for the ratio of the EPS beads used to generate LWC, i.e. 25% and 50% of the volume of the coarse aggregates. Each group consisted of three specimens. Three values of the ratio of steel fibers volume fraction were used in each group, namely 0%, 0.75%, and 1.5%. The tested specimens had cross-section dimensions of 125×250 mm, total length equal to 2000 mm, and span length equal to 1800 mm. The dimensions and reinforcement details of the experimental beam models are shown in Figure 1. After one day from the casting, all specimens were cured by covering with burlap pieces. The burlap was soaked with water continuously for seven days to accommodate the required curing treatment. Figure 2 shows concrete casting and curing treatment.

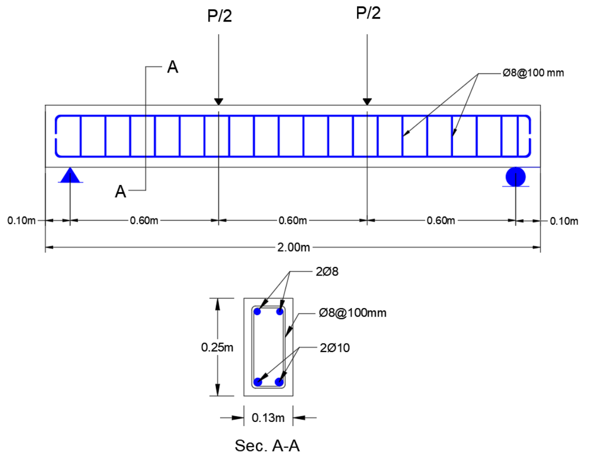

Fig. 1. Dimensions and reinforcement details of the test specimens.

Fig. 2. Casting and curing of the test specimens.

D. Testing Procedure

The beam specimens were supported on two steel supports that allowed both horizontal and angular movement at one end of the specimens and only angular movement at the other end and, hence, simulated roller and pin supports, respectively. Hydraulic jack load was applied to the beam specimens through load cells to the rigid transverse steel beams to transmit the acting load to two points on the specimen top face in order to simulate the four-point loading testing setup, as shown in Figure 3. Steel rods of Ø30 mm in diameter were used to convey the testing load on the RC beam through steel plates at each point to avoid stress concentration at the contact area. The two-point loading was applied at the one-third point of the beam span to create pure flexure region at the middle-third of the specimen. Strain gauges and LVDTs were attached to their specific locations and connected to a data acquisition system to record setup readings. After that, the static loading was applied manually. The readings of the load cell, strain gauges, and LVDTs were recorded by the data acquisition logger and were automatically saved to a PC. The deflections at the mid-span were recorded at each loading increment.

III. EXPERIMENTAL RESULTS

A. Mode of Failure

A comparison of the test results for cracking load, yielding load, and ultimate failure load is presented in Figure 4, whereas Figure 5 shows the cracking pattern of the tested specimens at failure. All were obviously initiated at the tension face as the load was raised within the constant moment area and propagated throughout the length and depth of the beams (Figure 6). These are referred to as "flexural cracks". Figure 5 shows that the first crack appears faster as the EPS percentage rises and that the first crack is delayed in the presence of steel fibers. Yield load and ultimate load increased with the steel fiber content, but decreased when the EPS content increased.

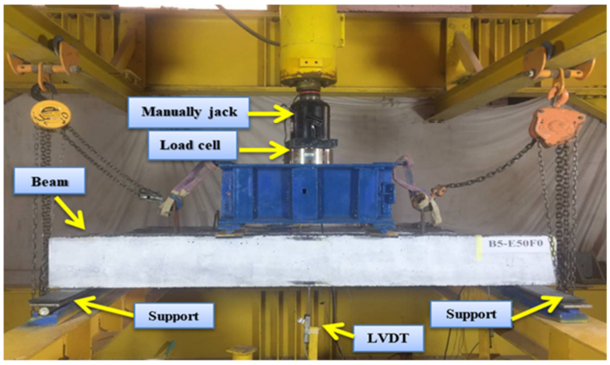

Fig. 3. Testing setup.

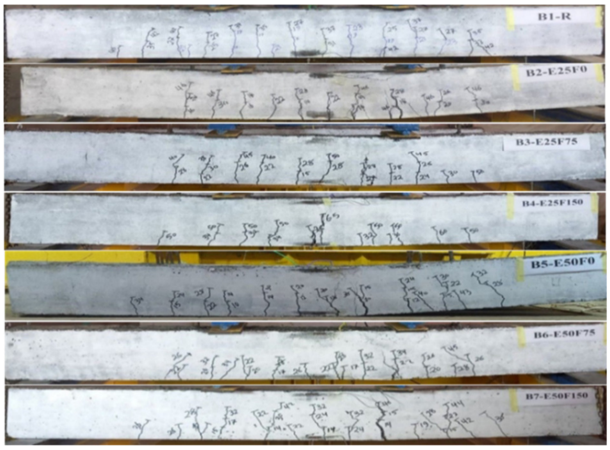

Fig. 4. Modes of failure of the tested specimens.

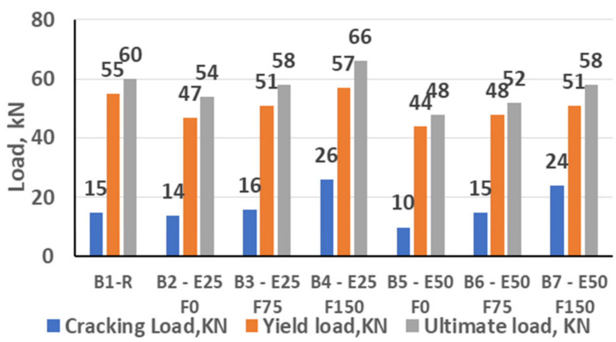

Fig. 5. Variation of cracking, yield, and ultimate load of the tested beams.

B. Load-Displacement Behavior

The test results for the load-deflection behavior are shown in Figure 6. The comparison of these results can be seen in Table IV. Figure 6 shows that the second group with EPS content of 50% has much divergent behavior from the reference beam than the first group with EPS content of 25%.

This observation is confirmed by the test results shown in the third group in which the EPS content effect is presented for zero fiber content. Furthermore, the test results shown in group 4 and 5 indicated that steel fiber content significantly enhances flexure strength behavior. Generally, the results in Figure 6 indicate a proportional relation for load-displacement behavior up to about 15 kN, followed by a descending behavior indicating post-cracking. After that a flatten behavior is noticed up to final failure.

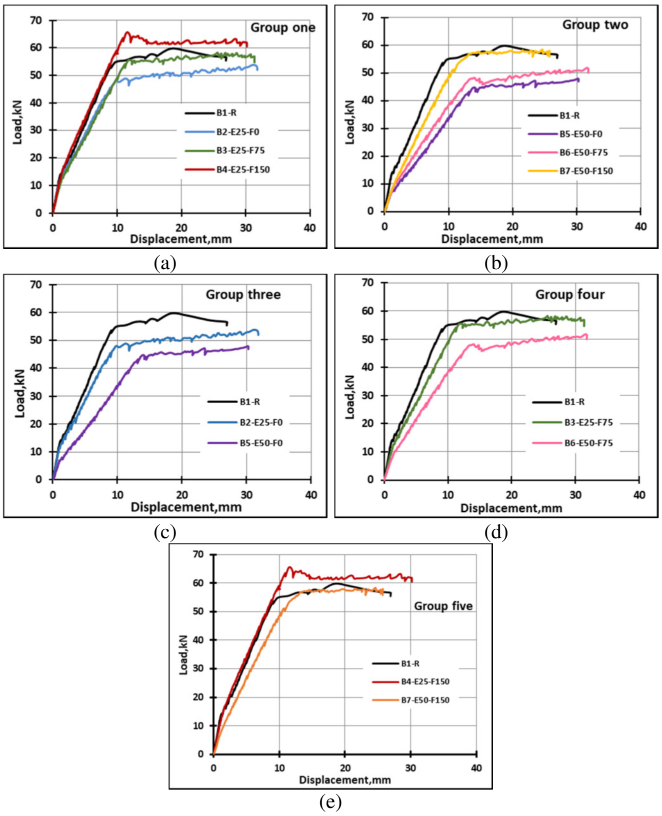

Fig. 6. Load-displacement behavior.

The results listed in Table IV, for the third group with 0% steel fiber content, indicate that increasing the EPS content from 0% to 25% and 50% reduces maximum load values or beam flexure strength by about 10% and 20%, respectively. On the other hand, the results listed for the first and the second group showed the constructive effect of added steel fibers on the flexure strength of the tested beams. The maximum or failure load decrease results due to 25% EPS content ranged from -10% for 0% steel fibers to about -3.33% and +10% for 0.75% and 1.5% steel fiber volume fraction of concrete, respectively, showing superior effect for 1.5% of steel fiber content on the flexure strength. However, for the second group, the results for the failure load decrease due to 50% EPS content ranged from -20% for 0% steel fibers content to -13.33%, and -3.33% for 0.75%, and 1.5% steel fibers content, respectively.

For groups 4 and 5 with steel fiber proportion of 0.75% and 1.5%, a maximum decrease in the flexure strength of about 13% is observed due to increasing EPS content up to 50%. From the above, it is evident that all beam models have a lower maximum load than the reference beam when EPS and steel fibers are utilized, with the exception of B4-E25F150. This shows that the use of EPS in LWC accompanied with the addition of a specific amount of steel fibers improves flexure strength. As for the deflection values for the tested beam specimens, the results listed in Table IV indicate that, generally, as the EPS and steel fiber content increase, the deflection values increase, indicating a more ductile behavior. Finally, the results presented in Table III reveal that using 50% EPS content in the mix resulted in a non-structural concrete for which $f_c' < 17$ MPa [17]. However, the concrete beams cast with 50% EPS content and reinforced with steel fibers showed remarkable flexure strength almost similar to that of beams cast using conventional concrete.

TABLE IV. FLEXURE BEHAVIOR OF THE TESTED BEAMS

Specimen	Max. load (kN)	% variation	Δ at max. load (mm)	% variation
Group 1				
B1-R	60	---	18	---
B2-E25F0	54	-10	31	72.22
B3-E25F75	58	-3.33	26	44.44
B4-E25F150	66	10	12	-33.33
Group 2				
B1-R	60	---	18	---
B5-E50F0	48	-20	34	88.89
B6-E50F75	52	-13.33	30	66.67
B7-E50F150	58	-3.33	25	38.89
Group 3				
B1-R	60		18	---
B2-E25F0	54	-10	31	72.22
B5-E50F0	48	-20	34	88.89
Group 4				
B1-R	60	---	18	---
B3-E25F75	58	-3.33	26	44.44
B6-E50F75	52	-13.33	30	66.67
Group 5				
B1-R	60	---	18	---
B4-E25F150	66	10	12	-33.33
B7-E50F150	58	-3.33	25	38.89

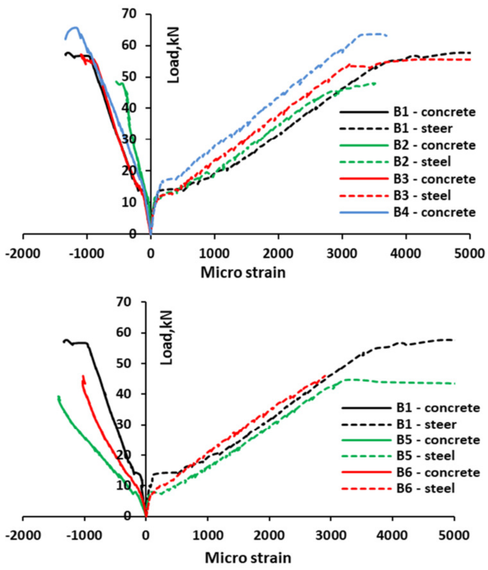

Fig. 7. Load-strain behavior of the tested beams.

C. Load-Strain Behavior

Figure 7 shows the load-strain curves for the concrete and reinforcement in the tested beam specimens. The indicated strain values were measured using strain gauges at the concrete top face and bottom flexure rebars located at the mid span of each beam. It should be noticed that strains were proportional to the applied load up to about 10-15 kN load. After that, the strains increased rapidly with the increasing applied load. This range of loading corresponds to the load of the first crack. The results presented in Figure 7 reveal that reinforcement rebar strains have exceeded the yield strain at failure indicating tension-controlled failure as required by ACI 318-19 [17]. The results for steel rebar strains reveal that reinforcement was less stressed when EPS and steel fibers were used for LWC and the reinforcement stress is increasingly reducing as the steel fiber content increases. On the other hand, concrete compressive stress increase as the EPS content increases.

D. Ductility

The ability of a material to withstand deformation over the elastic limit until complete failure is referred to as ductility. The maximum deflection (Δ_{max}) that the material can withstand before failing should be taken into account when assessing ductility. The ductility of two different materials might vary even when they have comparable maximum deflections at failure due to different load-deflection characteristics. So, it is preferable to define the ductility using a dimensionless ductility index, μ, as follows:

$$\mu = \frac{\Delta_{max}}{\Delta_y} \quad (1)$$

TABLE V. DUCTILITY INDEX VALUES

Specimen	Δ_{max} (mm)	Δ_y (mm)	μ	% variation
Group 1				
B1-R	18	10	1.80	----
B2 – E25 F0	31	11	2.82	56.57
B3 – E25 F75	26	10	2.60	44.44
B4 – E25 F150	12	9	1.33	-25.93
Group 2				
B1-R	18	10	1.80	----
B5 – E50 F0	34	14	2.43	34.92
B6 – E50 F75	30	13	2.31	28.21
B7 – E50 F150	25	11	2.27	26.26

Table V illustrates that when EPS is utilized with steel fibers, the ductility increases, whereas increasing EPS content mostly causes reduction in the ductility. From the first group, it is clear that using 25% EPS leads to increased ductility by 56.57% when using 0% steel fibers and 44.44% when using 0.75% steel fibers. In the second group, using 50% EPS increases ductility by 34.92%, 28.21%, and 26.26% when using 0%, 0.75%, and 1.5% steel fibers, respectively. One conclusion, based on the above presented results, is that the addition of a small percentage of EPS and a certain amount of steel fibers enhances the material's ductility to a large extent.

E. Stiffness

Stiffness is the resistance of an elastic body to deflection or deformation by an applied force [18]. Flexural stiffness is a bending characteristic of the member that can be defined as the resistance of the structure to deflection under bending loading. The flexure stiffness is normally characterized by the slope of the line drawn from the origin of the load-deflection curve and intersecting the curve at the point of interest. The results of the variation of the flexural stiffness due to EPS and steel fiber content are listed in Table VI. They show that beam's stiffness is generally reduced when EPS is utilized, whereas steel fibers enhance stiffness and EPS content has a major impact on it. For specimens with 0% steel fibers, the results showed that a decrease of 51.7% and 12.4% in the stiffness value was achieved when utilizing 50% EPS and 25% EPS content, respectively. Moreover, a maximum enhancement of about 50% in the stiffness values is observed when adding 1.5% volume fraction of steel fibers.

TABLE VI. STIFFNESS VALUES

Specimen	P_u	45% (P_u)	Δ @ 45% (P_u)	Stiffness (kN/mm)	% variation
Group 1					
B1-R	60	27	4.05	6.67	----
B2-E25F0	54	24	4.16	5.84	-12.38
B3-E25F75	58	26	4.00	6.53	-2.13
B4-E25F150	66	30	3.82	7.77	16.62
Group 2					
B1-R	60	27	4.05	6.67	----
B5-E50F0	48	22	6.71	3.22	-51.71
B6-E50F75	52	23	5.5	4.25	-36.18
B7-E50F150	58	26	5.23	4.99	-25.14

TABLE VII. FLEXURE TOUGHNESS

Specimen	Toughness (kN.mm)	% variation
Group 1		
B1-R	1293	----
B2-E25F0	1100	-14.927
B3-E25F75	1190	-7.966
B4-E25F150	1350	4.408
Group 2		
B1-R	1293	----
B5-E50F0	1085	-16.087
B6-E50F75	1112	-13.998
B7-E50F150	1149	-11.137

F. Toughness

Toughness is an indication of the energy absorbed by the test specimen determined due to loading in terms of the area under the load deflection curve. Toughness indices identify the material behavior up to the selected deflection level determined by dividing the area under the load-deflection curve up to a specified deflection level [19]. Flexural toughness is defined as the total energy absorbed by the specimen before it fails due to flexure [20]. Table VII shows the total flexure toughness values for the tested beams. The results show that the toughness values reduce when EPS is utilized, whereas steel fibers enhance stiffness and EPS content has a major impact on toughness. For specimens with 0% steel fibers, a decrease of 16.1% in the toughness value was achieved due to utilizing 50% EPS content as compared with 14.9% reduction for 25% EPS content. Moreover, an increase of about 4.4% in the toughness values is observed when adding 1.5% volume fraction of steel fibers for group one specimens with 25% EPS content as compared to the reference beam.

IV. CONCLUSIONS

Expanded polystyrene is a generated industrial product and waste disposed by burning or landfilling which needs a recycling solution to decrease its negative effects on the environment. In this study, an attempt was carried out to manage this problem by investigating the possibility of using waste EPS in producing structural lightweight concrete. After studying the results obtained for the concrete mix properties and the structural behavior of the tested beams, the following conclusions were drawn:

- The mechanical properties of the hardened concrete were significantly reduced due to the addition of EPS beads in the concrete mix. However, steel fiber content improves the mechanical properties of the mix.
- The flexure strength of EPS-LWT concrete beams is significantly reduced with the addition of EPS beads. A maximum reduction of about 20% in the ultimate load capacity due to 50% EPS content was observed.
- Remarkable enhancement was noticed in the flexure strength of EPS-LWT concrete beams when adding steel fibers. A maximum reduction of about 3.3% in the ultimate load capacity due to 50% EPS content was accomplished with 1.5% steel fiber volumetric ratio.
- When using EPS, the first cracking appears quickly and visibly in the beams, whereas its appearance is delayed to a large extent when using steel fibers, indicating higher cracking load.
- The results revealed that flexure rebars were less stressed and concrete compressive stress increased due to the addition of EPS and steel fibers for LWC mix.
- The ductility of the tested beams improved significantly for EPS-LWT concrete beams compared to the normal weight concrete beam.
- Beam's stiffness and toughness values reduced when EPS was utilized in the concrete mix.
- Steel fibers enhance the stiffness and toughness values while EPS has a major impact on stiffness and toughness.

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