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Improvement of Reinforced Concrete Beam with Embedded Polystyrene under Static Load

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ABSTRACT

A reinforced concrete beam is normally used as a skeletal frame to withstand the loads on the building. However, a long-span beam requires a larger beam section due to the concerns of excessive deflection and failure. Under such circumstances, a large portion of beam strength is used to sustain its own weight which is uneconomical. This problem could be overcome by reducing some portions of concrete using lightweight materials like polystyrene. The replacement should technically be applied without affecting the structural performance of the beam. This study aimed to develop an optimum design of a lightweight beam by incorporating polystyrene in the conventional reinforced concrete beam. The specimens were tested with a static load using the four-point load test to investigate the behavior of the beam. The effects of the parameters, such as the spacing of the polystyrene, and the number of reinforcements were observed. The performance of the beams was evaluated in terms of the ultimate load (P_u), strength-to-weight ratio (*s-w* ratio), ductility (Δ), and failure mechanism. The results show that the lightweight beam, with 11.8% concrete replacement, outperformed the conventional beam by 47% to 61%, in terms of the *s-w* ratio.

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1. INTRODUCTION

Nowadays, reinforced concrete has been commonly used in the construction of buildings. It includes structural elements such as beams, columns, slabs, and foundations. All these elements combine to form a frame system which able to sustain and transfer load (Arya, 2015). However, a large amount of design load is contributed by the permanent load. The problems could be overcome using lightweight beams and slabs, thus reducing the construction cost (Lim & Ling, 2019; Ling et al., 2023).

In the 2010s, lightweight slabs like bubble deck slabs have become popular in the Malaysian construction field. The bubble deck slab offers 30% lighter weight with comparable bending strength by removing the concrete which does not perform from the neutral axis of the slab (Garg et al., 2019).

The same principle could apply to reinforced concrete beams. However, although numerous studies have been conducted, an efficient lightweight beam is yet to be found. It seems that the beam loses more strength than the weight reduction. Nevertheless, since the principles between beam and slab are quite identical, it could be possible to develop a lightweight beam by reducing some concrete at the neutral axis and tension region (Lim et al., 2020). Successful weight reduction with comparable strength as the solid beam may reduce the construction cost.

For that, this study investigates the structural response of lightweight beams by incorporating polystyrene in the conventional reinforced concrete beam. The effects of the parameters, such as the spacing of the polystyrene, and the number of reinforcements were observed.

The research gives an understanding of the following aspects:

(a) An alternative building design for the skeletal frame.

(b) The proper procedures to test beams with polystyrene as partial concrete replacement materials.

(c) The knowledge gap of lightweight beam systems under static loads as well as the fundamental principle governing them.

(d) Optimum design of lightweight beam, which is governed by construction materials such as polystyrene, steel reinforcement, and concrete.

2. RESEARCH METHODOLOGY

2.1 Specimens

Ten specimens with dimensions of 175 mm (wide), 300 mm (height), and 1600 mm (long) were prepared. This included a solid beam and nine lightweight beams (see **Table 1**). The ellipse polystyrene is embedded in the lightweight beams with (a) different spacing between polystyrene (0 mm, 25 mm, and 50 mm), and (b) different amount of reinforcement (226.19 mm^2, 339.29 mm^2, and 427.26 mm^2), as shown in **Figure 1** and **Figure 2**.

The steel bars with the yield strength of 500 N/mm^2 were provided as the bottom (2T12) and top (2T10) reinforcement bars. Meanwhile, the shear links used were 11R6-150 with the yield strength of 250 N/mm^2. The concrete cover was 25 mm for all the specimens.

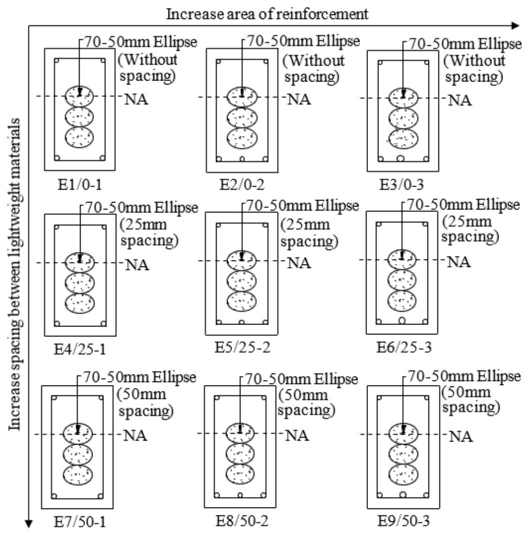

Figure 1. Cross Section of the Lightweight Beams

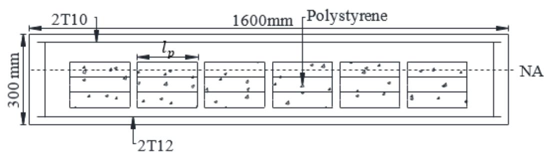

Figure 2. Detailing of Specimen E1/0-2

Table 1. Test Results of Specimens

Specimens	Percentage of Replacement (%)	Length of Polystyrene (mm)	Spacing between Polystyrene (mm)	Area of Steel Reinforcement (mm^2)	
				Tension	Compression
P1	0	0	0	226.19	157.08
E1/0-1	13.0	1325	0	226.19	157.08
E2/0-2				339.29	
E3/0-3				427.26	
E4/25-1	11.8	200	25	226.19	
E5/25-2				339.29	
E6/25-3				427.26	
E7/50-1	10.6	180	50	226.19	
E8/50-2				339.29	
E9/50-3				427.26	

2.2 Experimental Setup

Figure 3 shows the experimental setup. The beam specimens were tested under the four-point load test. Each specimen with an effective length of 1500 mm was supported by a steel rocker at both ends. Two-point loads were applied to the specimen. The distance between the applied loads was equal to the effective depth of the beam (260 mm). The load was applied to the specimen using a hydraulic cylinder of 300 kN capacity, a distribution "I" beam, and the rocker system. The distribution beam transformed the load induced by the hydraulic cylinder into two-point loads acting onto the specimen via the rocker system.

The load cell was positioned between the "I" beam and the hydraulic cylinder to determine the applied load. Meanwhile, three Linear Variable Differential Transducers (LVDT) were installed below the specimen to monitor the vertical deflection. These measuring devices were linked to a data logger and subsequently to a computer for data acquisition. The cracks were traced throughout the sides of the specimen. The load was applied until the specimen failed.

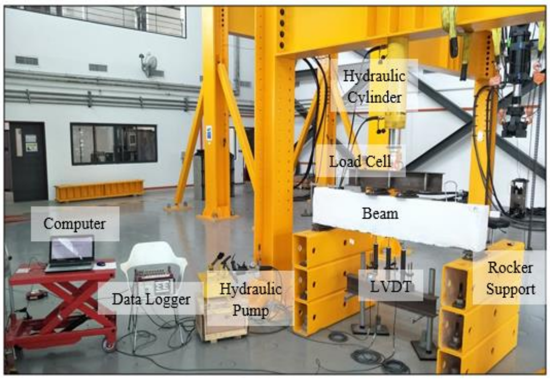

Figure 3. Setup of Laboratory Test

2.3 Test Procedure

Initially, the specimen was preloaded to 10% of the predicted ultimate load for 5 minutes. The applied load was then released for another 5 minutes to observe the reading recovered to zero to ensure the measuring instruments worked properly. This process was repeated two times (ASTM E564-06, 2006).

Next, the instruments were adjusted to zero before the testing. The static load was applied at the range of about 5% of the predicted ultimate load and maintained for 1 minute before recording the readings (ASTM E564-06, 2006). The test proceeded until the breaking point or till the material failure was achieved. The cracks were monitored during the test.

3. RESULTS AND DISCUSSIONS

The performance of the lightweight beams was presented in the load-deflection curve. The structural performance was discussed in the aspects of the ultimate load (P_u), ductility (**Δ**), strength-to-weight ratio (*s*-*w* ratio), and failure mechanism.

3.1 Material Properties

From **Table 2**, the concrete strength of the specimens attained the nominal strength of 25 N/mm^2. Meanwhile, as shown in **Table 3**, the high-yield steel and mild steel attained the nominal tensile strength of 500 N/mm^2 and 250 N/mm^2, respectively.

3.2 Load-Displacement Relationship

The typical load-displacement response of the beam is shown in **Figure 4**. At the pre-cracking stage, the beam initiated with a high degree of stiffness. It deflected slightly and proportionally to the load. Then, the first crack (a flexural crack) occurred around 30.45 kN to 38.37 kN at the mid-span. It started from the beam's soffit and propagated upward as the load increased.

Next, during the multiple cracking stages, the concrete in the tensile region forfeited from contributing flexural strength to the beam. For that, the tensile stress in the concrete was fully transferred to the reinforcement. Under tension, the reinforcement elongated. As the deformation exceeded the deformability limit, cracks occurred.

Then, the post-yielding stage was indicated by the intensification of existing cracks under incremental load. The load was mainly carried by the reinforcing system of the beam. The beam deflection increased more rapidly, and the cracks propagated and extended sideways from the mid-span toward the supports at both ends.

Figures 5 to **13** show the load-displacement response of the specimen E1/0-1 until specimen E9/50-3.

Table 2. Test Results of Concrete

Specimen	Density (kg/m^3)*[1]		Average Density (km/m^3)	Concrete Cube (N/mm^2) at 28 days*[1]		Average Compressive Strength N/mm^2)*[2]
	S1	S2		S1	S2	
P1	2304.0	2325.3	2314.7	25.0	25.5	25.3
E1/0-1	2368.6	2408.6	2388.6	27.0	25.2	26.1
E2/0-2	2354.4	2333.6	2344.0	27.0	25.7	26.4
E3/0-3	2388.7	2372.7	2380.7	26.1	26.8	26.5
E4/25-1	2323.3	2384.0	2353.7	25.2	25.7	25.5
E5/25-2	2368.6	2379.0	2373.8	27.0	25.8	26.4
E6/25-3	2388.7	2372.7	2380.7	26.1	26.8	26.5
E7/50-1	2339.6	2303.4	2321.5	25.3	24.7	25.0
E8/50-2	2339.6	2303.4	2321.5	25.3	24.7	25.0
E9/50-3	2368.6	2379.0	2373.8	27.0	25.8	26.4

Notes: *[1]S1 = Specimen 1, S2 = Specimen 2

*[2]The mean values of two concrete cubes were taken as stated in BS EN 12390-3:2002.

Table 3. Test Results of Reinforcement

Type of Steel Bar	Diameter (mm^2)	Yield Stress (N/mm^2)*[1]			Average Yield Stress (N/mm^2)
		T1	T2	T3	
High-yield steel bar	10	580	587	602	589.7
	12	629	526	650	601.7
	16	595	605	590	596.7
Mild steel bar	6	283	295	270	282.7

Notes: *[1]T1 = Specimen 1, T2 = Specimen 2, T3 = Specimen 3

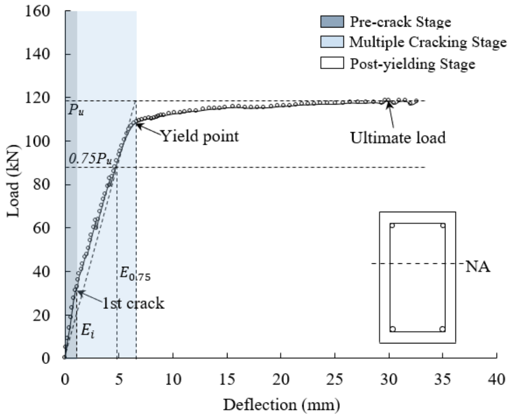

Figure 4. Load-Deflection Response of Solid Beam (P1)

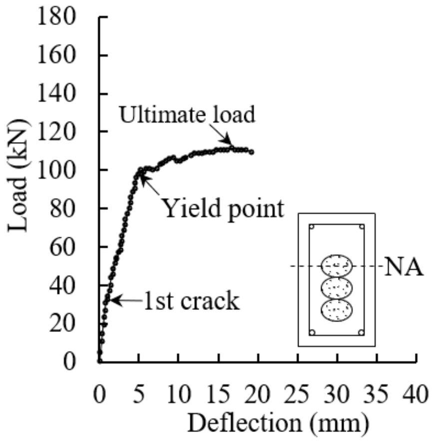

Figure 5. Load-Deflection Response of Light-weight Beams Specimen E1/0-1

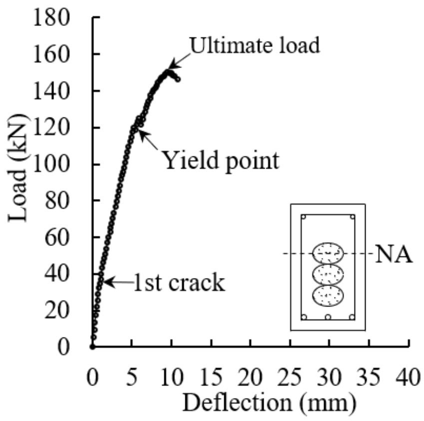

Figure 6. Load-Deflection Response of Light-weight Beams Specimen E2/0-2

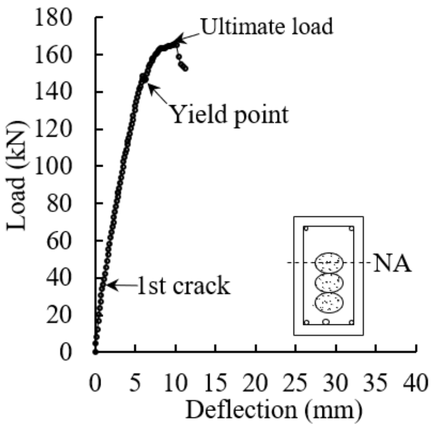

Figure 7. Load-Deflection Response of Light-weight Beams Specimen E3/0-3

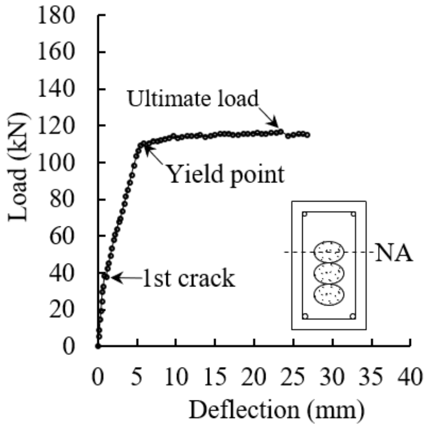

Figure 8. Load-Deflection Response of Light-weight Beams Specimen E4/25-1

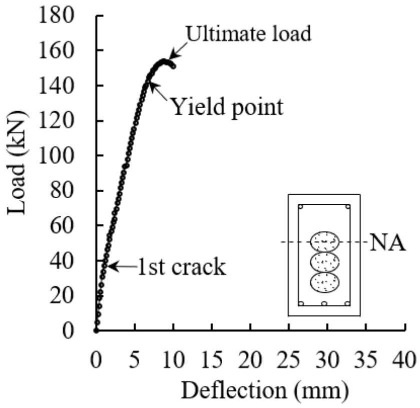

Figure 9. Specimen Load-Deflection Response of Lightweight Beams E5/25-2

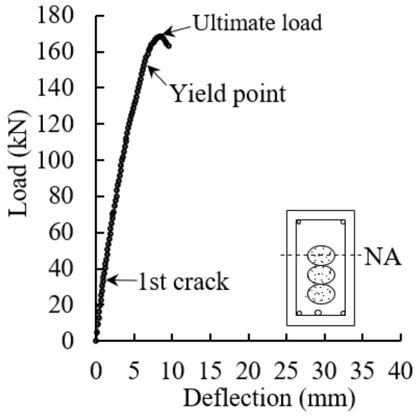

Figure 10. Load-Deflection Response of Light-weight Beams Specimen E6/25-3

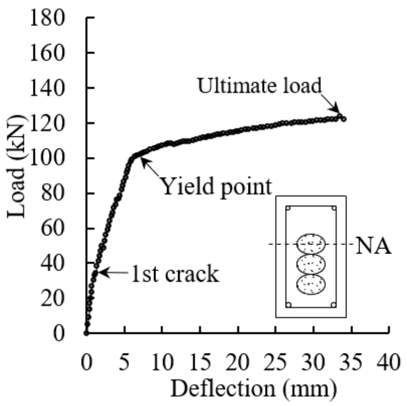

Figure 11. Load-Deflection Response of Light-weight Beams Specimen E7/50-1

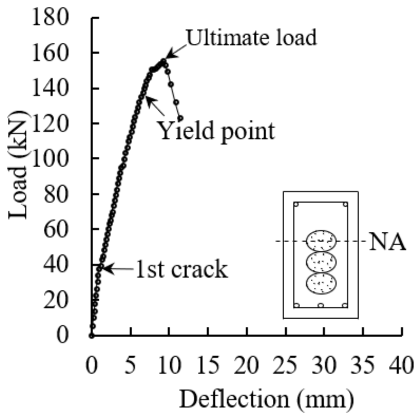

Figure 12. Load-Deflection Response of Light-weight Beams Specimen E8/50-2

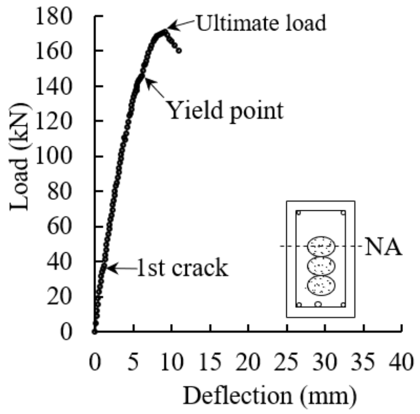

Figure 13. Load-Deflection Response of Light-weight Beams Specimen E9/50-3

3.3 Crack Pattern

The failure mode of the specimens was investigated through the crack patterns as outlined in **Table 4**. **Figures 14** to **23** shows the crack pattern of the specimens. For lightweight beams with a longitudinal reinforcement ratio greater than 0.49% ($A_s >$ 226.19 mm^2), the diagonal crack developed after the formation of the flexural crack. Additional reinforcement areas strengthened the flexural resistance of the beam. The stress was distributed from the mid-span sideways to the supports. This led to high-stress concentration near the supports and eventually triggered the diagonal crack in the beam.

The diagonal crack developed about 45° upward from the soffit and extended toward the loading zone are shown in **Figures 14** to **23**. It indicated the likelihood of the lightweight beam failing in shear, and the flexural capacity as offered by the longitudinal reinforcement might not be fully attained (Marta, 2018). The details of the failure mode can be seen in **Table 5**.

For that, caution should be given to the shear capacity of the beam, particularly when a higher percentage of reinforcement is provided in the lightweight beam. For the intended ductility, flexural failure of the beam is always preferred.

Table 4: Type of Failure Mode

Failure Mode	Criteria
Flexural	• The cracks take place at the bottom near the mid-span and propagate upwards (Nor and Roslli, 2014). • The crack width of the most critical flexural crack, W_f > shear crack, W_s.
Diagonal tension	• The diagonal tension failure arises when the crack propagates about 1.5d to 2.0d from the support (Nor and Roslli, 2014). • Crack developed near the support at an angle of 30° to 60° from the soffit (Kum, 2011). • The crack width of the most critical flexural crack is about similar to the shear crack ($W_f \approx W_s$).
Shear compression	• The crack propagates from the support crush toward the loading zone (Nor and Roslli, 2014). • Cracks arise near the support at approximately 45° and extend toward the compression zone (Moayyad and Naiem, 2013). • The crack width of the most critical flexural crack, W_f < shear crack, W_s.

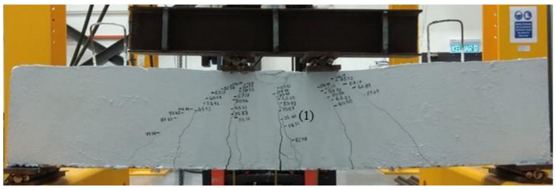

Figure 14. Failure Mode of Specimen P1

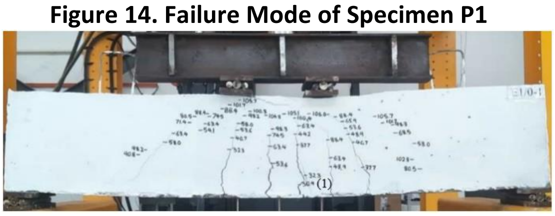

Figure 15. Failure Mode of Specimen E1/0-1

Figure 16. Failure Mode of Specimen E2/0-2

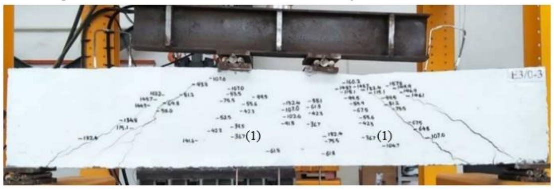

Figure 17. Failure Mode of Specimen E3/0-3

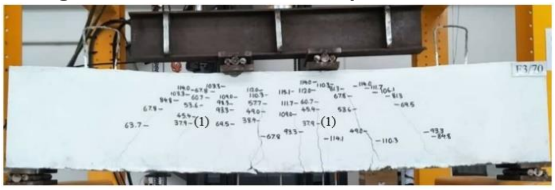

Figure 18. Failure Mode of Specimen E4/25-1

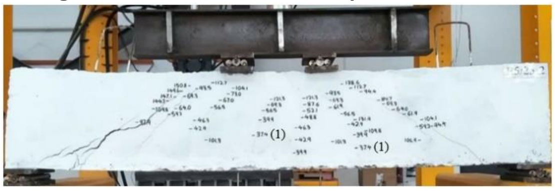

Figure 19. Failure Mode of Specimen E5/25-2

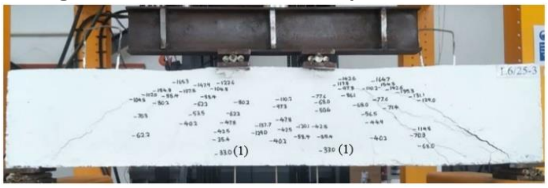

Figure 20. Failure Mode of Specimen E6/25-3

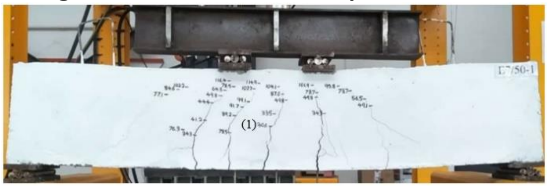

Figure 21. Failure Mode of Specimen E7/50-1

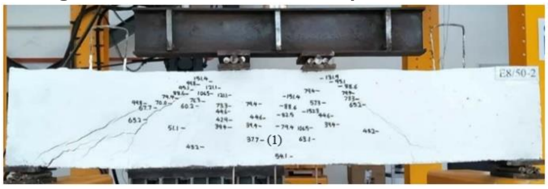

Figure 22. Failure Mode of Specimen E8/50-2

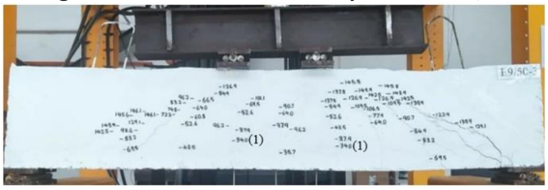

Figure 23. Failure Mode of Specimen E9/50-3

Note: (1) First crack

Table 5. Failure Mode of Specimens

Specimen	Criteria			Failure
	$W_f > W_s$	$W_f = W_s$	$W_s > W_f$	Mode
P1	√	X	X	Flexural
E1/0-1	√	X	X	Flexural
E2/0-2	X	X	√	Shear compression
E3/0-3	X	X	√	Shear compression
E4/25-1	√	X	X	Flexural
E5/25-2	X	X	√	Shear compression
E6/25-3	X	X	√	Shear compression
E7/50-1	√	X	X	Flexural
E8/50-2	X	X	√	Shear compression
E9/50-3	X	X	√	Shear compression

Note: The crack width of the beam was visually observed in **Figures 14-23.**

3.4 Strength-to-Weight Ratio

The specimens were evaluated using the strength-to-weight ratio ($s - w$ ratio) as shown in Equation 1.

$$s - w\ ratio = \frac{100 - S}{100 - W} \quad (1)$$

Where:

$$W = \frac{W_S - W_L}{W_S} \times 100\% \quad (2)$$

$$S = \frac{S_S - S_L}{S_S} \times 100\% \quad (3)$$

W_S and W_L represent the weight of the solid and lightweight beam, respectively. Meanwhile, S_S and S_L are the strength of the solid and lightweight beam, respectively.

W and *S* in Equation 1 signify the weight and strength reduction concerning the solid beam, respectively. The strength-to-weight ratio, *s-w* ratio, is preferably more than 1. Otherwise, the beam is considered ineffective (Lim et al., 2021).

From **Table 6**, all the specimens achieved the *s-w* ratio of more than 1.

Table 6. Results of Specimens

Specimen	Ultimate Load, P_u (kN)	Ultimate Deflection, δ_u (mm)	Ductility, Δ	Reduction of Weight, *W* (%)	Reduction of Strength, *S* (%)*[1]	Strength to Weight Ratio, *s-w* ratio
Equation	-	-	-	2	3	1
P1	118.45	30.02	4.49	-	-	1.00
E1/0-1	111.10	16.56	3.12	13.0	6.21	1.08
E2/0-2	150.11	9.49	1.54	13.0	-26.73	1.46
E3/0-3	165.65	9.95	1.61	13.0	-39.85	1.61
E4/25-1	116.81	23.45	3.98	11.8	1.38	1.12
E5/25-2	153.82	8.67	1.30	11.8	-29.86	1.47
E6/25-3	168.36	8.44	1.34	11.8	-42.14	1.61
E7/50-1	123.87	33.47	4.60	10.6	-4.58	1.17
E8/50-2	155.03	9.31	1.37	10.6	-30.8	1.46
E9/50-3	171.03	9.14	1.50	10.6	-44.39	1.62

Note: *[1]Negative sign indicates the increment of strength

3.5 Effects of Spacing between Polystyrene

In general, the lightweight beam performed better when there was spacing between the polystyrene. **Table 6** shows that when the spacing increased from 0 mm to 50 mm, the ultimate load and *s-w* ratio increased by 11.49% and 8.33% respectively. It created a series of concrete ribs in the beam, for a better distribution of stresses in the concrete (Izzat et al., 2014).

For a better degree of compaction, the minimum spacing between polystyrene would be at least equivalent to the concrete cover, or 5 mm larger than the size of the largest aggregate, whichever is larger, so that the aggregate can easily pass through it.

3.6 Effects of Amount of Reinforcement

The moment resistance of the beam is strongly influenced by the area of reinforcement. Comparing specimens E1/0-1 and E3/0-3, the ultimate load increased by 49.1%. This is in line with the findings from Mohammad, Rajai, and Ayman (2017). A larger reinforcement area led to a larger tensile resistance of the bar, and for the lever arm, the beam withstands a higher moment load. The maximum and minimum allowable area of reinforcement should comply with Eurocode 2.

3.7 Performance Evaluation of the Lightweight Beams

The evaluation criteria for the lightweight beams are outlined in **Table 7**. The specimens were evaluated based on the following criteria:

(a) For a lighter beam, the amount of concrete being replaced by lightweight materials should be significant, probably at least 10%, for a remarkable saving in terms of construction cost. As the majority of the specimens had at least 10% concrete replacement, the criteria were taken as the mean value of all specimens, which was 11.8%.

(b) The lightweight beam must be more efficient than a solid beam. For that, the s-w ratio should be at least 1.0. Again, as all of the specimens fulfilled the criteria, the mean value of 1.40 was used.

(c) The lightweight beam should not fail in a brittle manner. It should give ample warning signs before its failure, so that remedy can be taken immediately. For that, the ductility (Δ) of the lightweight beam should be at least equivalent to the solid beam, which is 4.49 as presented by the control specimen (P1).

(d) Concrete ribs in the lightweight beam are recommendable for a better performance of the beam. For that, the spacing between polystyrene should be at least equivalent to the concrete cover, 25 mm.

Based on **Table 7**, none of the lightweight beams achieved all the evaluation criteria. For that, the selection of the lightweight beam was based on the greatest number of achieved criteria.

Table 7. Selection Criteria of the Specimens

Specimen	Concrete Replacement, V (%)		*s-w* ratio		Ductility, Δ		Spacing between Polystyrene (mm)		Number of "√"*1	Remark
	Value	Req. (≥ 11.8)	Value	Req. (≥ 1.40)	Value	Req. (≥ 4.49)	Value	Req. (≥ 25)		
E1/0-1	13.0	√	1.08	X	3.12	X	0	X	1	NA
E2/0-2	13.0	√	1.46	√	1.54	X	0	X	2	NA
E3/0-3	13.0	√	1.61	√	1.61	X	0	X	2	NA
E4/25-1	11.8	√	1.12	X	3.98	X	25	√	2	NA
E5/25-2	11.8	√	1.47	√	1.30	X	25	√	3	A*2
E6/25-3	11.8	√	1.61	√	1.34	X	25	√	3	A*2
E7/50-1	10.6	X	1.17	X	4.60	√	50	√	2	NA
E8/50-2	10.6	X	1.46	√	1.37	X	50	√	2	NA
E9/50-3	10.6	X	1.62	√	1.50	X	50	√	2	NA
Mean	**11.8**		**1.40**							

Notes: *1The "√" signified the specimen achieved the design criteria.
*2The configuration of the lightweight beam was applicable with a high degree of efficiency and provided adequate strengthening in shear resistance.

Specimen E5/25-2 and E6/25-3 achieved 3 out of 4 evaluation criteria. However, the specimens could not offer a ductility response at least equivalent to the solid beam, which was mainly due to the shear failure. Should they be specimen put into applicable, additional shear reinforcement may be required.

From the results, the performance of the lightweight beam can be improved by:

(a) Increasing the spacing between the polystyrene, to ensure a satisfactory degree of concrete compaction and bonding strength of the reinforcement bars.

(b) Increasing the reinforcement area to increase the moment capacity and the efficiency of the lightweight beam.

4. CONCLUSIONS

This paper aimed to determine the optimum design of the lightweight beam. The specimens were investigated in the aspect of ultimate load, strength-to-weight ratio, ductility, and failure mechanism. From the results, the following conclusions were drawn:

(a) The ultimate load and *s-w* ratio increased as the spacing between polystyrene and the area of reinforcement increased.

(b) About 66.7% of the lightweight beams achieved the required effectiveness of *s-w* ratio ≥ 1.40.

(c) The ductility of the lightweight beams was lower than the solid beam.

(d) Specimens E5/25-2 and E6/25-3 (optimum design) were recommended for application, provided sufficient shear reinforcement is provided. The specimen had 11.8% concrete replacement with effectiveness ranging from 1.47 to 1.61.

The results showed that the reduction in strength can be minimized by using the ellipse polystyrene with larger spacing between the lightweight materials and increased the amount of reinforcement. This can increase further the efficiency of the beam.

DISCLAIMER

The authors declare no conflict of interest.

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SYMBOLS

d	Effective depth of beam (mm)
f_y	Specified yield strength of reinforcement bars (N/mm2)
P_u	Ultimate load of beam (kN)
s-w ratio	Strength to weight ratio
S	Reduction of strength (%)
S_L	Strength of the lightweight beam (kN)
S_S	Strength of the solid beam (kN)
W	Reduction of weight (%)
Wf	Width of the flexural crack (mm)
W_L	Weight of lightweight beam (kg)
W_S	Weight of solid beam (kg)
W_s	Width of the shear crack (mm)
V	Percentage of Concrete Replaced
δ_u	Ultimate deflection of beam (mm)
Δ	Ductility of beam

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