

Performance of Reinforced Concrete Beam with Polystyrene Blocks at Various Regions

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ABSTRACT

Lightweight materials, such as polystyrene, can be embedded in reinforced concrete (RC) beams to reduce its weight. However, this may, to some extent, affect the performance of the structure. This research investigates the behaviour of the lightweight beams under load and determines the best position of polystyrene blocks in beams. Nine specimens with a size of 175 mm x 300 mm x 1600 mm were tested under four-point load test. The number and position of polystyrene blocks in the beams were varied. The specimens were evaluated for effectiveness in terms of effective strength to weight ratio (s-w ratio). The lightweight beam was effective when the polystyrene blocks were placed at the neutral and tensile region, offering an s-w ratio of greater than 1. The beam lost 3.8% strength with 8.4% reduction of weight.

Keywords: Reinforced concrete; lightweight system; replacement region; beam

Paper type: Research paper

INTRODUCTION

Reinforced concrete (RC) beam is widely used in the construction industry of Malaysia. It withstands the permanent and variable actions on a structure. Since the permanent action constitutes a significant portion of the design load, the cost of a structure could be reduced by using lightweight beams. This can be done by replacing some portions of concrete in the beams with lightweight materials like polystyrene [1], plastic balls [2] and Poly Vinyl Chloride pipe (PVC) [3].

Polystyrene is popularly used in beams as it is light, cheap, and easily handled. It can be positioned in the compression, neutral and tension regions of the beam [4]. However, an efficient lightweight beam design with a decent strength to volume ratio is yet to be found. For some reasons, the beams lose more strength than their weight, in percentage [5]. This leads to a question whether the system has been fully understood and optimized.

Theoretically, the flexural strength of an RC beam is governed by the tensile strength of the reinforcements and the compressive strength of the concrete. For low tensile resistance, the contribution of concrete in resisting bending is marginal. For that, the concrete in the tension region could be removed without significantly affecting the beam performance.

When lightweight materials were placed in the tension region, the reduction of strength was generally less than 7.0% [6]. For the compression and the neutral axis regions [3, 7], the reduction deviated significantly from 2.65% to 15.53%. The position of the lightweight materials seemed to govern the beam performance, hypothetically. However, slight inconsistency is observed from the previous studies [7]. Thus, further study is required to gain a better understanding on lightweight beams.

This paper aims to investigate the performance of lightweight RC beams with polystyrene embedded in various regions of the beam. The beams were tested experimentally, and the responses were analysed in terms of the first crack load (P_i), yield strength (P_y), ultimate load (P_u), stiffness ($E_{0.75P_u}$), effective strength to weight ratio (s-w ratio), deflection (δ), ductility (Δ) and the failure mode.

METHOD

Specimen details:

A solid beam (control specimen) and 8 lightweight beams were tested under the four-point load test (Fig. 1 and Table 1). The beams were 175 mm wide, 300 mm height and 1600 mm long. The effective length of the beam, l_{eff} , between the supports was 1500 mm.

Cylindrical polystyrene blocks (diameter, $d_p = 50$ mm, length, $l_p = 200$ mm, longitudinal spacing = 25 mm) were longitudinally placed in the compression, neutral axis and tension regions of the beam (denoted as C, N and T in Table 1). One to three units of blocks were embedded in the beam, as illustrated in Fig. 2.

All specimens were reinforced with 2T12 and 2T10 high yield steel bars ($f_y = 500 \text{ N/mm}^2$) as the bottom and top reinforcements, respectively. The shear links provided was 11R6 – 150 mild steel bars ($f_y = 250 \text{ N/mm}^2$). The concrete cover was 25 mm.

The specimens were horizontally cast in plywood moulds. Ready-mixed concrete grade 25 was used. The maximum aggregate size was 20 mm and the designed slump was 60 mm to 180 mm. The specimens were cured at the atmosphere temperature of $30 \pm 5^\circ\text{C}$ and tested after 28 days of casting.

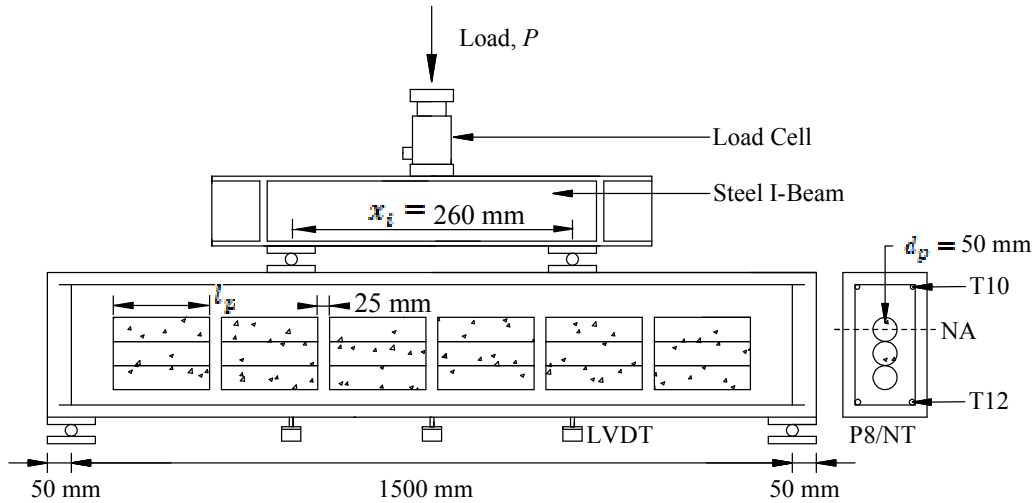


Fig. 1: Test setup

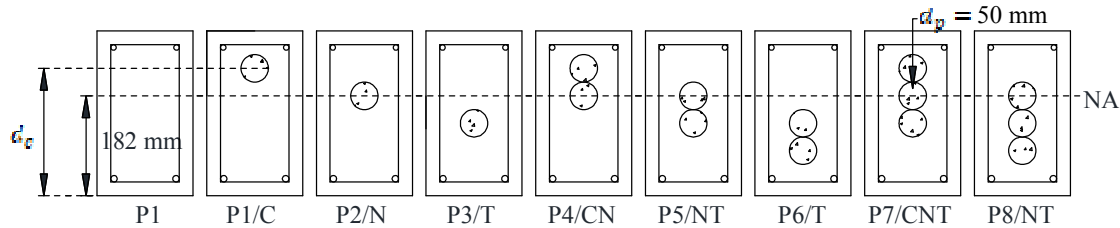


Fig. 2: Position of polystyrene by specimens

TABLE 1. SPECIMENS DETAILS

Specimens	Region ^a	Centroid of Polystyrene from the Soffit, d_p (mm)	Percentage of Replacement, V (%)
P1	-	-	-
P1/C	C	232	2.8
P2/N	N	182	2.8
P3/T	T	132	2.8
P4/CN	C, N	207	5.6
P5/NT	N, T	157	5.6
P6/T	T	107	5.6
P7/CNT	C, N, T	182	8.4
P8/NT	N, T	132	8.4

Note: ^aC = Compression, N = Neutral, T = Tension

Test Setup:

The specimens were tested under the flexural load (Fig. 1). The distance between the applied loads, x_i , was 260 mm, which was equivalent to $1d$. A load cell was placed between the hydraulic cylinder and the distribution beam to measure the applied load. Three Linear Variable Differential Transducers (LVDT) were positioned under the specimen to monitor the deflection; at the mid-span and below the applied loads. All the measuring instruments were connected to a data logger for data acquisition. The specifications of the instrument used are outlined in Table 2.

TABLE 2. INSTRUMENT SPECIFICATIONS

Instrument	Model	Description	Unit	Accuracy
Hydraulic Jack	RR-10018	Push +933 kN, Pull -435 kN	–	–
Hydraulic Pump	CEHCAP0001	Control the hydraulic Jack	–	–
Load Cell	CLJ-300KNB	Capacity 300 kN	kN	0.01
LVDT	CDP-100	Capacity 100 mm	mm	0.01
Data Logger	TDS-530	30 Channels static data acquisition	–	–

Test Procedure:

Prior to the test, all the readings of the instruments were initialised to zero. The beam was preloaded to not greater than 10% of the predicted beam capacity for 5 minutes to consolidate the test setup. The applied load was then released for 5 minutes to observe the reading recovered to zero to check the validity of the measuring instruments. The process was repeated twice.

Next, the readings were re-initialised to zero and the test was started. An incremental load was applied at an interval of 5 kN or 0.1 mm mid-span displacement, whichever achieved first. The load was maintained for at least 1 minute before the readings were recorded. The test stopped when the beam failed. The developments of cracks with respect to load were monitored and observed throughout the test.

DISCUSSION*Material Properties:*

Tables 3 and 4 outlines the specifications of the materials used for the fabrication of beam. The properties were consistent, and the materials achieved the desired strengths.

TABLE 3. TEST RESULTS OF CONCRETE

Specimens	Concrete Cube (N/mm ²) ^a		Average Compressive Strength (N/mm ²)	Density (km/m ³) ^a		Average Density (km/m ³)
	S1	S2		S1	S2	
P1	25.0	25.5	25.3	2304.0	2325.3	2314.7
P1/C	25.5	25.2	25.4	2349.6	2353.8	2351.7
P2/N	25.5	25.2	25.4	2349.6	2353.8	2351.7
P3/T	26.1	26.8	26.5	2388.7	2372.7	2380.7
P4/CN	27.8	26.1	27.0	2372.7	2388.7	2380.7
P5/NT	27.0	25.7	26.4	2354.4	2333.6	2344.0
P6/T	25.8	25.2	25.5	2386.7	2384.6	2385.7
P7/CNT	25.8	25.2	25.5	2386.7	2384.6	2385.7
P8/NT	25.0	25.5	25.3	2304.0	2325.3	2314.7

Note: ^a S1 = Sample 1, S2 = Sample 2

TABLE 4. TEST RESULTS OF REINFORCEMENT

Type of Steel Bar	Diameter (mm ²)	Yield Stress (N/mm ²) ^a			Average Yield Stress (N/mm ²)
		T1	T2	T3	
High yield steel bar	10	590	640	635	621.7
	12	531	670	660	620.3
Mild steel bar	6	290	279	285	284.7

Note: ^a T1 = Sample 1, T2 = Sample 2, T3 = Sample 3

Test Results of Specimen:

The load-deflection response ($P-\delta$ curve) of the specimens are given in Fig. 3 and 4. In general, the beam underwent (a) pre-cracking elastic stage, (b) post-cracking elastic stage, (c) yield point, (d) post-yielding stage, and (e) the ultimate stage. These responses were corresponded with the development of cracks on the beam. The typical crack pattern of the beam at the ultimate state is shown in Fig. 5.

Initially, prior to development of crack, the beam possessed a high degree of the stiffness. The first crack occurred at the mid-span around 30.45 kN to 36.65 kN. The crack initiated from the beam's soffit and gradually propagated upward as the load increased.

Subsequently, the concrete in the tensile region forfeited from contributing the flexural strength. The tensile stress in the concrete transferred to the reinforcement bars in the beam. Under tension, the reinforcements elongated. The cracks developed when the deformability limit of the surrounding concrete was exceeded. As the load increased, the beam deflection enlarged, the cracks widened and propagated further, and the cracking regions expanded sideways toward the supports. Then, the ultimate load was identified when the applied load peaked.

The yield strength, P_y and secant stiffness, $E_{0.75P_u}$ of the specimen were determined using the method proposed by Noushini et al. [8] and Park [9]. From the $P-\delta$ curve (Fig. 3), two horizontal lines were constructed at the ultimate point, P_u , and $0.75P_u$. The value of $0.75P_u$ was used to determine secant stiffness, $E_{0.75P_u}$ which was represented by the gradient of the straight line connecting the origin to the point $0.75P_u$. The straight line was subsequently extended to intercept with line P_u . The yield point was below the interception on the $P-\delta$ curve (Fig. 3).

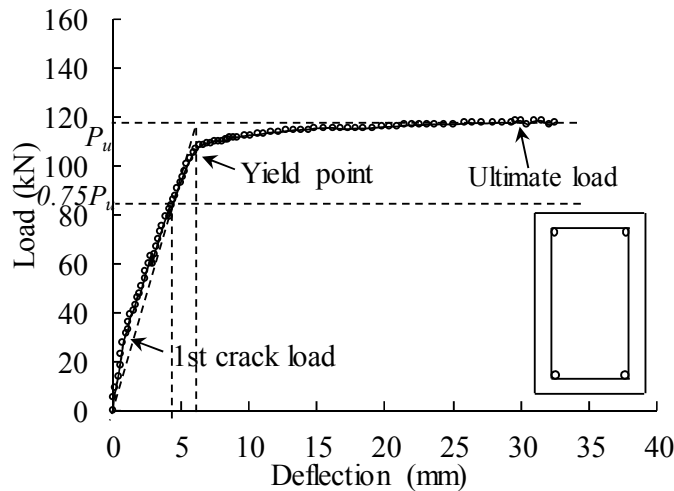


Fig. 3: Typical load-deflection response of solid beam (P1)

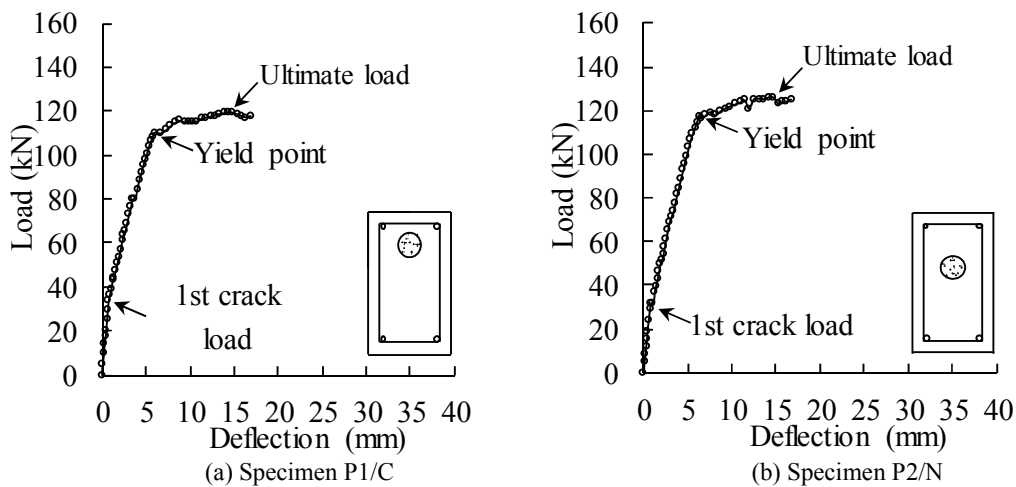
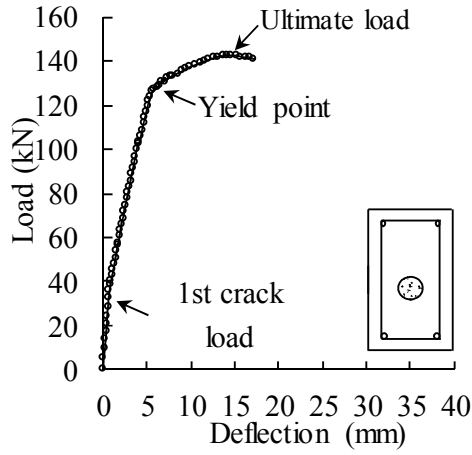
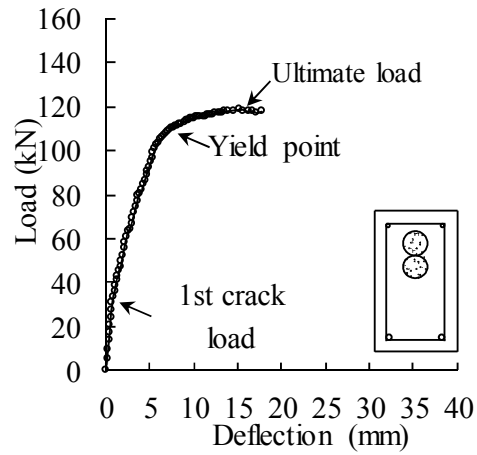


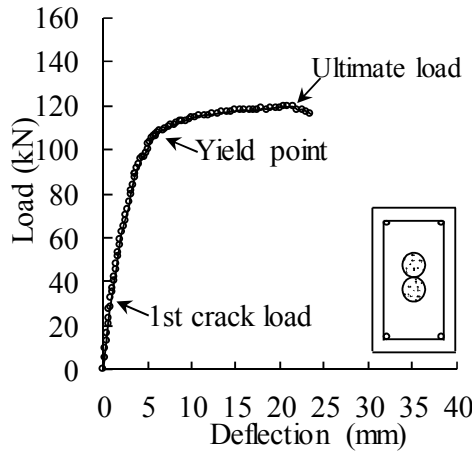
Fig. 4: Load-deflection response of lightweight beam



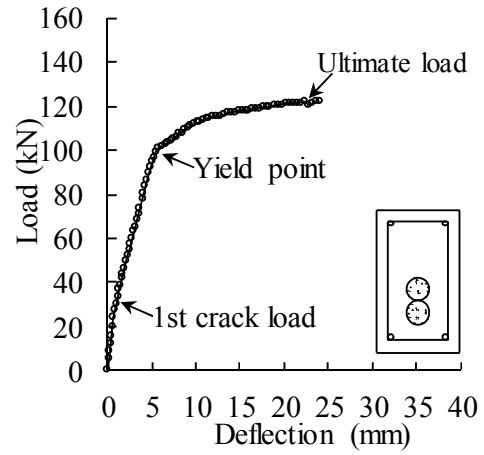
(c) Specimen P3/T



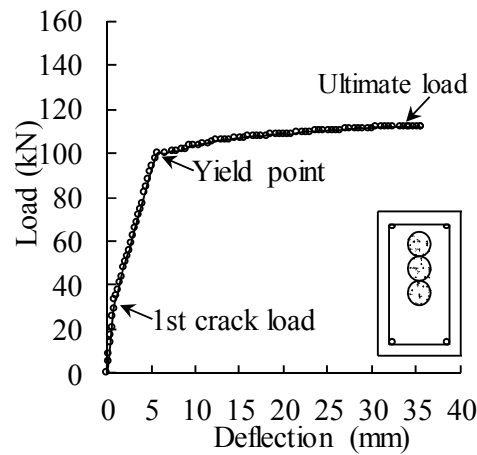
(d) Specimen P4/C



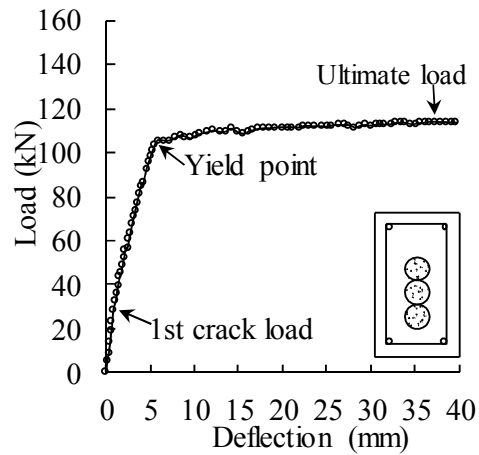
(e) Specimen P5/N



(f) Specimen P6/T



(g) Specimen P7/C



(h) Specimen P8/N

Fig. 4: Load-deflection response of lightweight beam (cont)

Note: The deflection of the curves represent the mid-span deflection of beam.

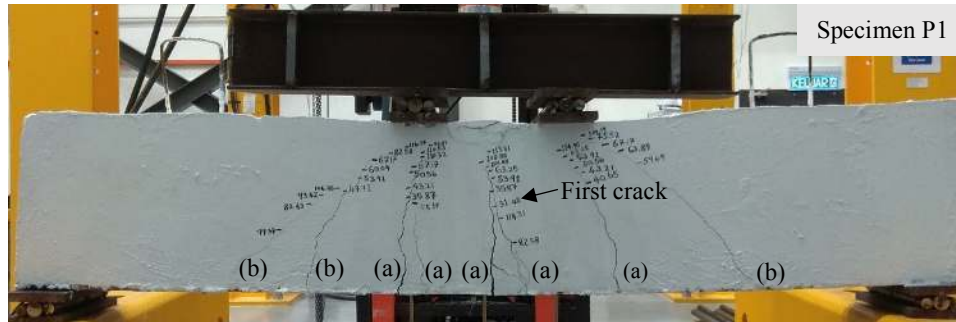


Fig. 5: Failure mode of solid beam

Note: (a) Flexural failure, (b) Diagonal tension

Failure Mode:

The failure mode of the beams was identified from the crack patterns through visual observation and based on the characteristics outlined in Table 5.

Visually, most of the cracks were found to be flexural, followed by diagonal tension, and shear compression (Table 6). In general, there was about (a) 4 to 5 flexural cracks, (b) 2 to 3 diagonal tension cracks, and (c) 0 to 1 shear compression crack. In term of crack width, the flexural crack was always more critical than any other cracks. This indicates that the specimens failed under flexural mode.

TABLE 5. CRITERIA OF FAILURE MODE

Type of crack	Flexural	Diagonal tension	Shear compression
Cracking region	At bottom near the mid-span, propagating upwards ^a	At 1.5d to 2.0d distance from the support ^a	At the support, crush toward compression zone ^a
Cracking angle ^d	60° to 90°	30° to 60° ^b	About 45° ^c
Crack width ^e	$W_f > W_s$	$W_f \approx W_s$	$W_f < W_s$

Note: reference: ^a Nor and Roslli [10], ^b Kum [11], ^c Moayyad and Naiem [12]

^d Cracking angle from soffit

^e W_f = crack width of flexural crack, W_s = crack width of shear crack

TABLE 6. FAILURE MODE OF SPECIMENS

Specimens	Number of crack			Crack width			Failure
	Flexural failure	Diagonal tension	Shear compression	$W_f > W_s$	$W_f \approx W_s$	$W_f < W_s$	
P1	5	3	-	√	X	X	Flexural
P1/C	4	3	-	√	X	X	Flexural
P2/N	4	3	1	√	X	X	Flexural
P3/T	4	3	-	√	X	X	Flexural
P4/CN	5	2	-	√	X	X	Flexural
P5/NT	4	3	-	√	X	X	Flexural
P6/T	5	2	-	√	X	X	Flexural
P7/CNT	5	2	-	√	X	X	Flexural
P8/NT	4	3	-	√	X	X	Flexural

Table 7 outlines the experiment results of the lightweight beam. In general, the lightweight beams gave a comparable ultimate load capacity as a solid beam. The ultimate load of the beams fell within a range of -5% to +20% of the solid beam (P1).

The first crack load of the lightweight beam generally increased as the polystyrene was placed further away from the soffit, as observed from specimens P4/CN, P5/NT and P6/T. The first crack load increased 17.3% as the polystyrene moved from the tension region (P6/T) to the compression region (P4/CN). For a larger concrete volume near the soffit to share the tensile stress with the tension reinforcement bars, the development of the first crack delayed (Fig. 6).

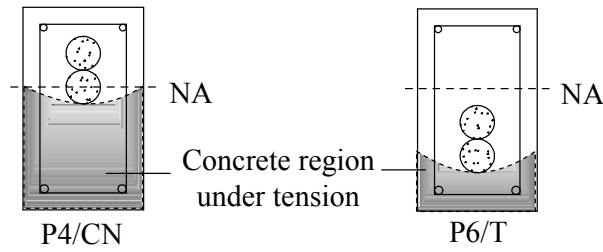


Fig. 6: Concrete region undertaking tensile stress prior to cracking

The yield strength and the ultimate load increased as the centroid of polystyrene from soffit (\bar{d}_2) decreased. It was observed through a comparison between specimens P1/C, P2/N and P3/T. When the centroid of polystyrene from soffit decreased from 232 mm to 132 mm, the ultimate load increased by 16.3% (Table 6). Such beneficial effects amplified as the polystyrene was positioned in the lower region of the beam. The concrete at the tension region contributed negligible flexural strength of the beam [13], particularly after the beam cracked. Thus, it could be removed without significantly affect the beam strength.

On the other hand, the ultimate deflection and ductility increased as the percentage of polystyrene increased. Regardless of the replacement region, when the polystyrene in the beam increased by from 2.8% to 8.4%, (a) the average deflection of the lightweight beams increased from 14.44 mm to 34.62 mm, and (b) the average ductility ratio increased from 2.38 to 5.93. As the percentage of polystyrene increased, the cross-sectional area of the lightweight beam decreased, the second moment of inertia of the beam section decreased, and thus, larger deflection was developed (Fig. 7).

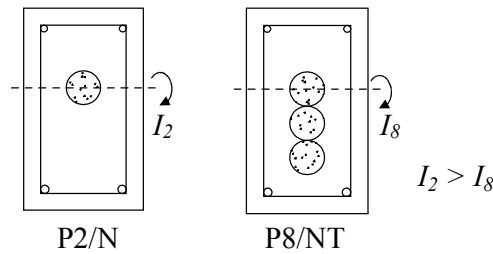


Fig. 7: Second moment of inertia of beam cross-section

TABLE 7. EXPERIMENTAL RESULTS OF THE SPECIMENS

Specimens	Elastic State		Yield State		Ultimate State		Ductility, $\Delta = \frac{\delta_u}{\delta_y}$
	First Crack Load, P_i (kN)	Stiffness, $\frac{E_p \cdot F_{su}}{L}$ (kN/mm)	Yield Strength, P_y (kN)	Yield Deflection δ_y (mm)	Ultimate Load, P_u (kN)	Ultimate Deflection, δ_u (mm)	
P1	31.02	18.84	108.75	6.69	118.45	30.02	4.49
P1/C	36.65	20.87	110.32	6.02	119.37	14.35	2.38
P2/N	31.38	20.42	116.52	6.61	126.01	14.27	2.16
P3/T	35.73	24.43	126.22	5.64	142.69	14.71	2.61
P4/CN	35.80	19.09	104.75	6.22	118.52	11.80	2.46
P5/NT	32.52	24.00	107.26	6.05	119.48	20.99	3.47
P6/T	30.45	18.85	103.18	6.85	121.94	22.04	3.28
P7/CNT	33.30	18.82	100.26	5.81	111.96	32.50	5.59
P8/NT	32.73	21.34	105.56	5.86	113.95	36.73	6.27

Effective Strength to Weight Ratio:

The lightweight beams were evaluated for effectiveness based on the effective strength-to-weight ratio ($s - w$ ratio) using Equation 1. W and S in Equations 2 and 3 represent the reduction of the weight and the strength of the lightweight beam, respectively, with respect to the solid beam (Specimen P1). An effective lightweight beam would have a higher reduction of the weight than the strength. For that, the $s-w$ ratio is preferably greater than 1 [4].

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

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

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

W_S = weight of solid beam

W_L = weight of lightweight beam

S_S = ultimate strength of solid beam

S_L = ultimate strength of lightweight beam

From Table 8, the effectiveness *s-w* ratio of lightweight beams met the requirement of greater than 1. The lightweight beams may not necessarily be stronger than the solid beam, particularly for specimens P7/CNT and P8/NT. For a high volume of concrete replacement, the reduction of weight always exceeded the reduction in strength, the lightweight beams were more effective than the solid beam in terms of the strength per unit weight of concrete.

For the industry application, the percentage of concrete being replaced should be significant so that the initiative of reducing the beam's weight is meaningful. For that, specimens P7/CNT and P8/NT with 8.4% concrete replacement were considered acceptable.

TABLE 8. EFFECTIVE STRENGTH TO WEIGHT RATIO OF PRELIMINARY BEAM

Specimens	Reduction of Strength, S (%) ^a	Reduction of Weight, W (%)	Effective Strength to Weight Ratio, (s-w ratio)	Remarks (A/NA) ^b
Equation	(2.2)	(2.1)	(2.3)	-
P1	-	-	1.00	A
P1/C	-0.8	2.8	1.04	A
P2/N	-6.4	2.8	1.09	A
P3/T	-20.5	2.8	1.24	A
P4/CN	-0.1	5.6	1.06	A
P5/NT	-0.9	5.6	1.07	A
P6/T	-2.9	5.6	1.09	A
P7/CNT	5.5	8.4	1.03	A
P8/NT	3.8	8.4	1.05	A

Note: ^a Negative sign indicates increase of strength

^b A = Adequate (s-w ratio \geq 1.0), NA = Non-adequate (s-w ratio $<$ 1.0)

CONCLUSIONS

This study aimed to investigate the behaviour of the lightweight beams and determines the best position of polystyrene blocks in beams. The specimen was evaluated in terms of (a) the load-deflection responses, (b) the failure modes, (c) the mechanical properties, and (d) the s-w ratio.

From the results, it is found that:

- The occurrence of the first crack delayed as the centroid of the polystyrene blocks from the soffit increased, thus higher first crack load can be achieved.
- The yield strength and ultimate load of lightweight beams increased as the centroid of the polystyrene blocks from the soffit decreased.
- The ultimate deflection and ductility of lightweight beams increased as the percentage of concrete replacement increased.
- The effective strength-to-weight ratios for all the beams were greater than 1.0, which was considered effective. Less concrete was required to achieve comparable strength as a solid beam.

For that, it is possible to reduce the weight of the lightweight beam up to 8.4% without compromising the effectiveness of the beam. This can be achieved by embed polystyrene block in the neutral and tension region of RC beam.

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SYMBOLS

d	Effective depth of beam, mm
d_c	Centroid of polystyrene from soffit, mm
d_p	Diameter of polystyrene, mm
$E_{0.75u}$	Secant Stiffness before the yield state of beam, kN/mm
f_y	Specified yield strength of reinforcement bars, N/mm ²
l_{eff}	Effective length of beam, mm
l_p	Length of polystyrene, mm
P	Load capacity of beam, kN
P_i	First crack load of beam, kN
P_u	Ultimate load of beam, kN
P_y	Yield strength of beam, kN
$s-w$ ratio	Effective 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, %
W_f	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, %
x_i	Distance between two loading points, mm
δ	Deflection of beam, mm
δ_u	Ultimate deflection of beam, mm
δ_y	Yield deflection of beam, mm
Δ	Ductility of beam

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