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SHEAR RESPONSE OF REINFORCED CONCRETE DEEP BEAMS UTILIZING WASTE FIBER-REINFORCED EXPANDED POLYSTYRENE CONCRETE UNDER STATIC LOADING

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Abstract

Deep beams are favorable in resisting high load creating shear due to their reduced span to depth ratio; nonetheless, they are known to produce diagonal shear brittle failure under service load including its own weight. A lightweight structure is required to reduce the overall load. In this study, seven lightweight deep beams were constructed using expanded polystyrene (EPS) as a partial replacement of coarse aggregate in concrete at 20% and 30%. The density of the EPS beams is 10.5% lower than that of the control beams. To increase shear behavior and comprehend deep beam failure under monotonic loading, 0.4% waste tire steel fiber by volume of concrete was incorporated in the concrete mix. Although the compressive and tensile strengths of control beams were higher than those of the EPS beam, reducing the weight of the beam by 20% EPS with tire fiber can improve both deep beam capacity and ductility. The capacity and ductility were 1% and 57% higher, respectively, than the control beam. Beams with tire fiber were also found to have a rough large crack width due to strain hardening characteristic, which allows them to withstand more load. This phenomenon is critical for structures in service.

1.0 INTRODUCTION

Concrete, as it is commonly known, is the primary material used in structural building and accounts for a significant portion of a structure's overall weight. Over the years, there has been a growing demand for lighter structural components, and numerous ways have been developed to suit this demand, with the advent of lightweight concrete (LWC) being one of the key approaches. The production of lighter concrete structures while retaining adequate/efficient structural qualities has been a highly desired feat in the construction sector. LWC is a cement-based composite material made of lightweight particles. LWC has densities ranging from 300 to 2000 kg/m^3, while normal weight concrete (NWC) ranges from 2200 to 2600 kg/m^3 [1–3].

Environmental contamination produced by inappropriate garbage disposal has long been a topic of concern worldwide, as it significantly contributes to climate change. When materials such as expanded polystyrene (EPS), used as a cushion during the packing of electronics or other sensitive products, and damaged tires are not recycled, they pose a significant environmental concern [4]. EPS is a non-

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biodegradable material composed of 98% air and 2% polystyrene. It has an extremely low impermeability, great electrical/thermal insulation, and high acoustic resistance. Additionally, the building sector has sought to assure sustainability by finding more ecologically friendly materials and repurposing waste. Work on waste recycling has recently increased [5–9]. Waste tire steel fibers, in particular, have been shown in several studies over the years to greatly improve the mechanical and impact strength qualities of concrete [10–13]. Fiber-reinforced concrete (FRC) provides higher crack resistance and post-crack performance and is extensively utilized in airport roadway pavements, bridge decks, and offshore platforms [14,15]. Internal cracks generated due to shrinkage and creep during fatigue loading can damage the mechanical and durability performance of FRC, limiting its service life [14,16–18]. At the onset, EPS was used as lighter replacements for aggregates but was subsequently adopted as a material for making nonstructural elements such as blocks and wall panels.

Rosca [19] described EPS as a type of foam consisting of little granules made of thermoplastic polymer matrix and separated air voids. In a study of the properties of expanded polystyrene concrete by Babu et al. [20], EPS was described as a stable low-density foam of non-absorbent, hydrophobic, and closed-cell nature. EPS beads were used as lightweight aggregates, both in concrete and mortar. According to Kaya and Kar [21] replacing cement with EPS powder up to 80% mixed with resin reduces the strength, durability, and physical qualities of concrete structures. It has also been reported that the amount of EPS incorporated in concrete can influence the hardening properties of lightweight concrete [22]. According to Mohammed and Aayeel [23], sixteen beams using recycled expanded polystyrene (EPS) concrete were produced, and percentage replacement of aggregate with the EPS was conducted using 15, 20, 25,35,45, and 60%. It was discovered that replacement up to 35% could withstand the applied load effectively better than 45 and 60%. Shaaban *et al*. [24] studied the size effect and location of the opening of deep beams with LWC using polystyrene balls to replace 30% coarse aggregate and compared it with NWC under shear behavior. The size of the opening has a significant effect on the shear capacity and behavior of LWC underloading. In research by Augustino *et* al. [25] the behavior of waste tire steel fiber deep beams with web openings of different sizes and orientations was studied, the results showed that the fiber can increase the stiffness of the beam however, interruption of the strut width can affect the shear resistance of the beam. The behavior of self-compacting concrete on reinforced concrete deep beam enhancement has also been studied [26,27].

The present research adopts EPS as a partial substitute for coarse aggregate in reinforced concrete deep beams to comprehend the behavior of lightweight RC deep beams under the applied load. According to Quadri [28] deep beams are structural members with an entire span to effective height ratio (l/d) of 4 or fewer, or a shear span to effective depth ratio of 2 or less [29]. A deep inclined crack that emerges to form within the shear distance independently of flexural damage is what defines deep beam response. The cracks start adjacent to the support and progress to the face of the beam, where they mix with the damage at the compression zone brought on by the applied stress forming softening damage. As the evaluation of tire fiber in the literature improves the mechanical behavior of beams, the authors believe adding EPS to concrete can reduce shear performance and change the failure mechanism of the beam. Consequently, adding tire steel fiber to lightweight concrete can help concrete's shear behavior under loading. Nine deep beams in all were cast, seven of which were considered for the insertion of EPS and three of which received tire fiber reinforcement. Figure 1 depicts a typical EPS and tire fiber.


Crumbed EPS 20 mm Tyre fiber 50 mm long

Figure 1: EPS and tire steel fiber

2.0 METHODOLOGY

2.1 Specimen Detailing and Casting

A total of nine deep beams having length, width, and depth of 750 × 150 × 225 mm, respectively, the beams were subjected to the applied load at shear span to an effective height ratio of 1.4 were tested for this investigation, two of the beams (DB1 and DB2) were selected as control beams, one of which contains shear reinforcement (DB2) as presented in Table 1. DB3, DB4, DB5, and DB6 contain 20% EPS replacing the natural coarse aggregate by volume. DB7, DB8, and D9 contain 30% EPS replacing natural coarse aggregate by volume, while DB5, DB6, and DB9 contain 0.4% waste tire steel fiber (50 mm in length) by volume of concrete together with the percentage

EPS. DB2, DB4, DB6, and DB8, beams have shear reinforcement. The longitudinally reinforced beams (beams without shear reinforcement) have 10 mm diameter (Ø) longitudinal reinforcing bars (two bars were used for both tension and compression zone as shown in Figure 2), the remaining four beams have shear reinforcement of Ø8 mm at a spacing of 100 mm c/c. the yield and ultimate strengths of the reinforcement of Ø8 mm are 386 and 521 N/mm^2 while those of Ø10 mm are 416 and 540 N/mm^2, respectively. The description of the beams is presented in Figure 2. The concrete strengths (compressive and split tensile) were checked at 28 days using a cube mould of dimensions 150 × 150 × 150 mm and cylindrical sizes of 200 mm height and 100 mm diameter cast with the beams with a water-to-binder ratio of 0.5 and 1:2:4 mix ratio. The 28 days strength values and the density of the beams are listed in Table 1 for each description of the casting beam.

Table 1: Description of the deep beams for this investigation

Beam ID	% of EPS replacing aggregate	% of Tire fiber in concrete	Shear links	Number of shear reinforcement	Tensile strength N/mm^2	Compressive strength N/mm^2	Density Kg/m^3
DB 1	0	0	None	0	2.36	24.5	3440
DB 2	0	0	present	8	2.36	24.5	3630
DB 3	20	0	None	0	2.15	12.44	3035
DB 4	20	0	present	8	2.15	12.44	3260
DB 5	20	0.4	None	0	1.81	13.7	3120
BD 6	20	0.4	present	8	1.81	13.7	3283
BD 7	30	0	None	0	1.17	10.1	3010
DB 8	30	0	present	8	1.17	10.1	3250
DB 9	30	0.4	None	0	1.77	11.5	3080

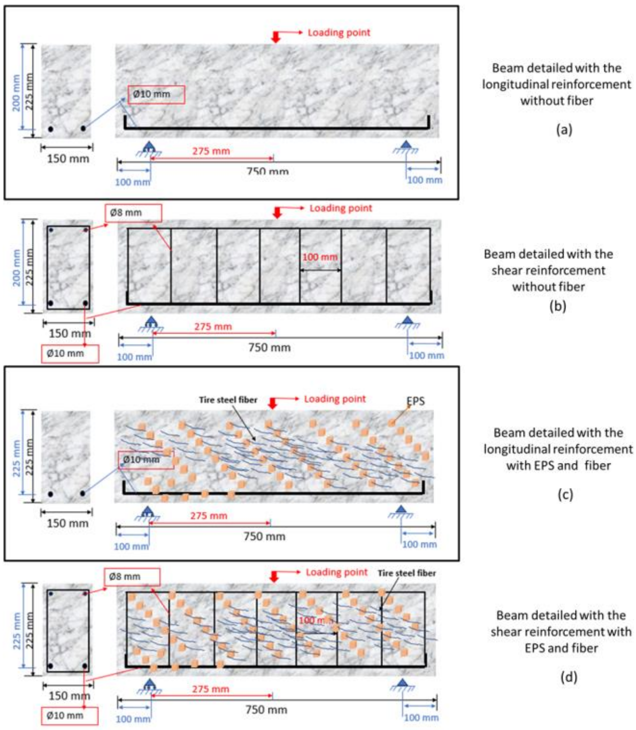

Figure 2: Description and detailing of deep beams

2.2 Specimen Loading

The specimens were tested under the three-point bending with a gradually static load increment at 20 kN/min using a Universal Testing Machine (UTM) of 300 kN capacity [28]. The load was transferred from the machine head to the beam. The propagation of cracks was observed by physical examination, while the crack width was measured after the final damage. Beam displacement was taken using the linear variable displacement transducers (LVDTs) positioned on the midpoint (underside of the loading point) as displayed in Figure 3.

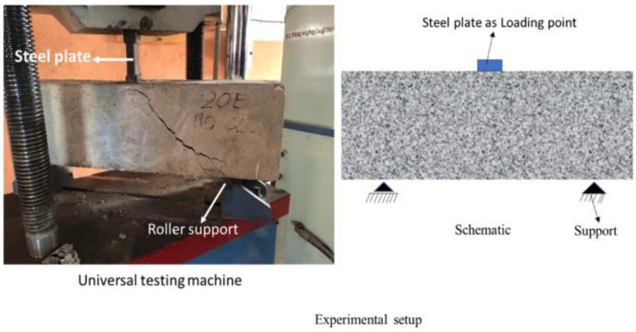

Figure 3: Experimental loading setup for deep beam specimen

3.0 RESULTS AND DISCUSSION

3.1 Damage Pattern of Deep Beams

Figure 4 shows the failure response of the control beam without shear links, DB1 (left), and with shear links, DB2 (right). Generally, deep beams fail in shear, indicating an interaction between the support and the loading point. The failure observed in the present investigation propagates from the support section to the underside of the loading point. It is indispensable to note that, the exact failure mode depends on several parameters, such as vertical and horizontal shear reinforcement ratio, shear span-to-depth ratio, concrete strength, and tensile reinforcement ratio. The cracking load, P_{cr} of DB1 and DB2 are 52.72 kN and 67.47 kN respectively. The load versus displacement relationship of these beams shown in Figure 5 reveals an elastic relationship between DB1 and DB2 at about 8 kN before deviation from linearity. The initial crack in DB1 emerged at the flexural zone close to the support, and an increase in load resulted in diagonal tension failure, having a failure load of 70 kN with a displacement of 4.5 mm. DB2 failed in shear with a failure load of 92 kN and displacement of 14 mm. The presence of shear reinforcement contributed to a 31% increase in overall capacity and a 211% increase in beam ductility.


(a): DB1 (Control, No SL) (b): DB2 (Control, SL present)

Figure 4: DB1 and DB2 at failure under static loading

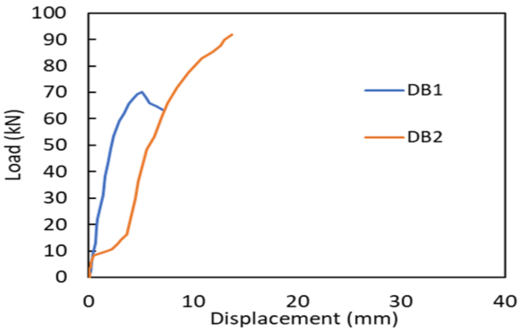

Figure 5: Load-displacement curve of DB1 and DB2 under static loading

The damage response of deep beams having 20% EPS without shear links, (DB3), and with shear links (DB4) is presented in Figure 6. The observed cracks are similar in width compared with the control specimens. The damage mode of DB3 is shear brittle damage as seen in Figure 6. The quick damage indicated that the crack propagated through the EPS being the weaker aggregate substitute in the RC matrix, resulting in softening action. DB4 shows an irregular shear crack propagation from the support to the compression zone, resulting in compression damage. There was enough ductility and capacity when DB4 with the shear link is compared with DB3 without the shear link as shown in Figure 7. The ultimate capacity of DB4 is 83 kN which is 19% higher than that of DB3 (70 kN), while the displacement of DB4 is 122% longer than DB3.

The damage response of the deep beams having 20% EPS as shown in Figure 8 was assessed by incorporating 0.4% waste tire fiber by volume of concrete. The damage response of deep beams with 20% EPS and waste tire fiber without shear links (DB5) has a very rough shear crack and showed enough ductility as shown in Figure 9. This response is similar to the damage response from Amin et al. [30] and Zeybek et al. [31]. After the aggregate interlock action loss, the fiber held the damaged planes in place which could increase the capacity of the beam with a large crack width. Contrarily, the failure of the beam with shear links having 20% EPS and waste tire fiber (DB6) shows an initial flexural crack at an applied load of 23 kN, another crack which propagated from the support section to the loading point culminates the beam damage while the flexural crack fully matured leading to diagonal tension damage with rough cracks. The shear link resisted the cracks producing a smaller crack width than DB5. A 13% difference in failure capacity was recorded between DB5 (82 kN), and DB6 (93 kN). The beam ductility is higher in DB6 than in DB5 by 78%.

It can be seen that waste tire fiber ensured more ductility and increased the beam shear capacity when the failure responses of DB3 and DB5 without shear links were compared. The crack damage of DB3 is smaller and smoother than in DB5, the fiber holds the large crack together giving rise to larger displacement in DB5. This phenomenon is also observed between DB4 and DB6, several cracks were observed in DB6 with higher displacement. There is a significant difference in the observed shear capacity between DB4 and DB5, showing the contribution of the waste tire fiber without using the shear link.


(a): DB3 (20% EPS, 0% TF, No SL) (b): DB4 (20% EPS, 0% TF, SL present)

Figure 6: DB3 and DB4 at failure under static loading

Figure 10 is the damage response of the beam having 30% EPS replacing natural coarse aggregate in concrete. Shear links and waste tire steel fiber were not provided in DB7. DB8 has shear links but no waste tire fiber, while DB9 contains 0.4 % waste tire steel fiber without shear links. Comparing DB7 and DB9 without the shear links, the crack width in DB9 is rough with larger ductility than in DB7 due to the waste tire fiber contributing to resisting the cracks. The failure of DB7 is a shear brittle failure, the crack passed through the EPS aggregate at the weakest beam section. The crack width as well as the shear capacity in DB7 is thinner and smaller than in DB3, which could be due to an additional EPS percentage in DB7. The damage mode in DB8 is tension failure propagating from the flexural zone to the compression zone. Shear failure was detected in DB9.

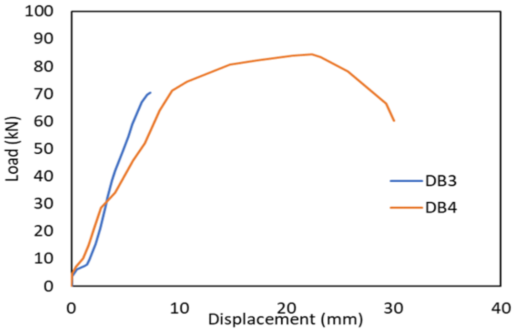

Figure 7: Load-displacement curve of DB3 and DB4 under static loading

(a): DB5 (20% EPS, 0.4% TF, No SL) (b): DB6 (20% EPS, 0.4% TF, SL present)

Figure 8: DB5 and DB6 at failure under static loading

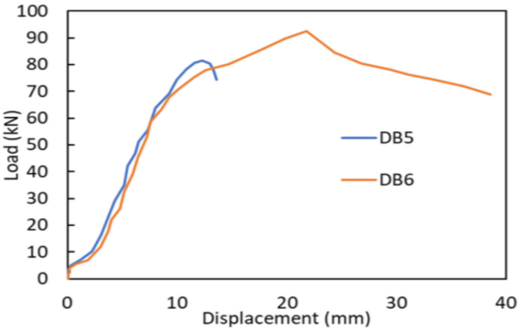

Figure 9: Load-displacement curve of DB3 and DB4 under static loading

The load capacity and ductility of DB9 are 27% and 98% higher than DB7 as indicated in Figure 11. DB8 has the highest shear capacity among these beams, 18% and 49% higher than DB9 and DB7 respectively. The ductility is higher than DB7 by 37% and lower than DB8 by 31%.

The density of beams with EPS is typically 10.5% lower than the density of control beams, on average (see Table 1). Comparing beams with shear links, DB2 possessed a 10.8% higher failure capacity than DB4 and DB8, with DB6 having the maximum failure capacity (1% higher than DB2). Additionally, it can be shown that 0.4% tire fiber improved the ductility of DB6, which was about 57% higher than the control beam, and had strain-hardening behavior at the post-peak region. Thus, incorporating waste tire fiber in lightweight beams can improve the ultimate and the serviceability states of deep concrete beams.

(a): DB7 (30% EPS, 0.% TF, No SL) (b): DB8 (30% EPS, 0% TF, SL present)

(c): DB9 (30% EPS, 0.4% TF, No SL)

Figure 10: DB7, DB8 and DB9 at failure under static loading

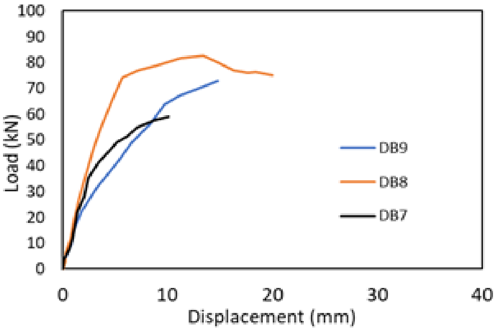

Figure 11: Load-displacement curve of DB7, DB8 and DB9 under static loading

Figure 12 compares the failure capacities of the experimental beams. DB1, DB3, and DB7 are detailed beams with no shear links. The capacity of DB1 and DB3 is comparable; however, an increase in EPS of more than 20% can significantly lower shear capacity, as in the case of DB7. A similar situation is seen in DB8 when compared to beams DB2 and DB6 with shear link and EPS. There is also evidence of a capacity drop between DB5 and DB9, featuring

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similar concrete material constituents. Comparing DB4 and DB8 indicated no significant difference in shear capacity. Incorporating less than 20% EPS can provide appropriate capacity while also ensuring a lightweight structure capable of serving its intended purpose.

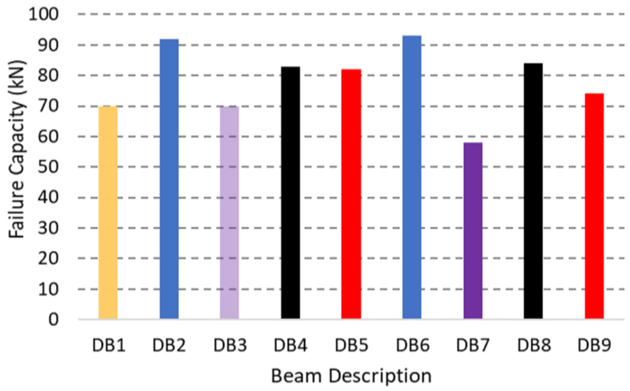

Figure 12: Comparison of the failure capacity of the test beams

4.0 CONCLUSION

Assessment of the response of RC deep beams incorporating waste tire steel fibers and expanded polystyrene in place of coarse aggregate has been carried out experimentally in this research. The following conclusions were therefore drawn: Beyond a 20% replacement of EPS with natural coarse aggregate, the compressive strength and shear performance of the tested beam remain unchanged. Deep beams made of EPS aggregate suffered shear brittle damage. Adding waste tire steel fiber to the EPS deep beam caused rough crack propagation due to the hardening characteristic of steel, which held the crack planes in place. This enhanced the failure load and ductility of the beams. The shear-reinforced beam with EPS substituting 20% of the natural coarse aggregate and waste tire fibers accounting for 0.4% by volume of the beam performed the best under monotonic load while maintaining adequate ductility and capacity of 57% and 1%, respectively higher than the beam without EPS and fiber.

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