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Structural Behavior of SCC Hollow Beam Reinforced with GFRP Containing EPS and Plastic Fiber

Mohanad T. Abduljaleel[a]*, Abdulkader Ismail Al-Hadithi[a]

[a] *Civil Engineering Department, College of Engineering, University of Anbar, Ramadi, Iraq*

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ABSTRACT

The purpose of this research is to produce a modified SCC that involves the incorporation of expanded polystyrene (EPS) and waste of plastic type (PET). The goal is to minimize the weight of the material while simultaneously improving its brittleness and reducing the environmental impact. The study focuses on two methods for reducing the weight of structural elements by using EPS beads, which create voids through concrete, and the second method is making a hollow through the element. This study included designing and investigating four concrete beams under concentrated static load. The parameters were hollow position and material types. The results showed that the offsetting hollow from the center of the beam enhanced the ductility index by 10% and increased the load capacity by 10%. Adding EPS beads reduce the concrete density by 11.5% and load capacity by 22%. Toughness was improved by using plastic fiber due to the mechanism of crack bridging. The crack pattern had been changed due to the utilization of waste material, and enhancement was observed through experimental tests by making smooth cracks and changing the probability of sudden failure when using GFRP rebars. It was found that the optimal quantity of EPS was 2 kg to produce SCC in accordance with code requirements. No debonding or slip was observed during monitoring, as evidenced by the absence of spalling or cracking around the reinforcement.

1. Introduction

One effective method to produce lightweight reinforced concrete beams is the incorporation of longitudinal voids, which reduces the amount of concrete in the tension zone at the beam's bottom. Compared to conventional solid beams, hollow concrete beams offer several advantages. The reduction in concrete volume decreases the dead load of the structure, resulting in multiple benefits, including lower overall construction costs, accelerated construction timelines, the feasibility of longer span elements, and maintaining an acceptable strength-to-weight ratio in the beams. Cutting down on concrete in structural components helps with sustainability since it reduces the need for natural resource extraction, which in turn lowers emissions of carbon dioxide (CO2) and the amount of energy that is "embodied" in the material. In addition, mechanical and electrical equipment can be run through longitudinal voids (Al-Maliki et al., 2021). Buildings, bridges, marine structures, and towers often feature

* *Corresponding author.* Tel.: 07817586438
E-mail address: moh22e1001@uoanbar.edu.iq

openings in beams and slabs for a variety of reasons, including decoration, economy, and functionality. These openings can accommodate computer networks, water and sewage pipelines, mechanical and electrical supply lines, and the reduction of element weight to save materials (Alnuaimi et al., 2008). Researchers looked into the flexural behaviours of solid and hollow beams. The characteristics that were tested were the void size reduction percentage, the longitudinal reinforcement ratio, the usage of lateral stirrups, and the incorporation of steel fibres. By reducing the size of the beams by 45 % because of the hole, they discovered that hollow RC beams with a 1% steel fibre content could substitute solid beams. The strength, ductility, and toughness of the beams were not significantly affected(Abbass et al., 2020). Experimental investigations into the behaviour of hollow RC beams with varying opening positions and two concentrated loads have shown that the opening locations significantly impact the final failure loads and stiffnesses. Reduced stiffnesses and greater deflections were characteristics of the tested hollow beams. Additionally, the ductility index values and load capacities of these beams were lowered (S. A. Hassan et al., 2020).

Self-compacting concrete (SCC) provides excellent compaction, simplicity of pumping, and placement due to its very high fluidity especially for concrete components with densely populated reinforcements (Saleh Ahari et al., 2015). SCC, a relatively new innovation in concrete technology, was first discovered in the late 1980s by researchers in Japan. The concrete is considered to be able to self-consolidate and flow freely enough to cover the formwork completely, all while avoiding vibrations caused by machines. In order to provide a high filling capacity of the formwork with various shapes, deep and narrow sections, and crowded structural parts, this concrete type must get fantastic deformability with outstanding stability. An important difference between standard concrete and SCC is the higher volume of supplemental cementitious materials (SCM) such fly ash (FA), blast-furnace slag (BFS), and silica fume (SF) that are used in SCC. Several investigations have thus far examined how SCM affects the fresh and hardened features of SCC. Incorporating SCM into SCC not only enhances the rheological properties and stability of newly mixed concretes, but it also reportedly reduces the cost of SCC and the amount of carbon dioxide gas created by concrete mixes that employ Portland cement (PC). To achieve a balance between development and environmental preservation, however, concrete made with waste or by-products instead of traditional cementitious components is more environmentally friendly. Adding SCM and SCC combinations to concrete improves its mechanical properties, long-term durability, and overall quality (A. Hassan et al., 2012; Şahmaran et al., 2009).

Recycling PET bottles through concrete is no longer a novel concept, and waste materials have the greatest influence on the environment. Several studies have been undertaken by researchers to investigate the impacts of using PET in concrete and the reported results. One viable recycling option is fiber-reinforced concrete, which uses PET bottles as reinforcing fibers. In this particular concrete mix, the fiber volume is estimated to be between 0.35 and 1.5 percent of the total volume (ACI 440.1R-15, 2015; Ochi et al., 2007; Pereira De Oliveira & Castro-Gomes, 2011; Silva et al., 2005). The addition of tape-shaped PET fibers to regular concrete increased its flexural strength by about 3.9%, according to the experimental investigation. Furthermore, by adding the sliced bottles into the concrete, which were 70 mm long and 1 to 2 mm wide, the ductility, energy absorption, and post-cracking behavior were all enhanced (Foti, 2011, 2013). The concrete was mixed with PET fibers in different proportions; the fibers were either straight or curled, and their lengths varied from 3 to 5 cm. Results show that flexural strength is increased and compressive strength is decreased by 8.5% when these fibers are added to concrete. Furthermore, flexural loads are better handled by wavy fibers than smooth ones (Borg et al., 2016). Expanded polystyrene (EPS) concrete is a new lightweight material with acceptable properties. The experiment investigated the compressive strength, tensile strength, and flexural strength of EPS concrete produced with different EPS particle sizes. The testing findings revealed that the mechanical characteristics of EPS concrete correlate with the particle size and granule concentration (Liu & Chen, 2014). Incorporating EPS and waste plastic fibres into concrete resulted in a considerable drop in its density, with the greatest reduction percentage reaching 38.46%. When WPFs were used, the flexural toughness of concrete prisms rose; the biggest increase, 180%, was observed when compared to those made from the reference mix (Al-Hadithi et al., 2023). This study proposes an innovative approach to develop sustainable self-compacting concrete (SCC) by incorporating recycled plastic fibers polyethylene terephthalate

(PET) and polyvinyl chloride (PVC) alongside expanded polystyrene (EPS) beads as lightweight aggregates. An innovative aspect of this material is its capacity to enhance mechanical performance, flowability, and environmental sustainability all at once through the utilization of these recycled elements. In contrast to previous research that has concentrated on specific recycled materials, this study thoroughly assesses the combined impact of plastic fibers and expanded polystyrene (EPS) on a variety of concrete parameters, including rheological behavior, compressive strength, tensile strength, ductility, and fresh and hardened concrete.

2. Methodology

This project encompasses the collection of waste items from the field and the execution of experimental activities. PET bottles gathered from the field and processed into fibre with appropriate shape and functional aspect ratio. Experimental research was conducted at the University of Anbar.

2.1. Materials

Type I ordinary Portland cement conforming to ASTM C150 standards was employed in the production of self-compacting concrete (SCC) (ASTM C150-07, 2007). Silica fume (SF), characterized as a highly reactive pozzolanic material in accordance with ASTM C1240, was incorporated as a fine mineral additive containing approximately 85% silicon dioxide (SiO_2) with a bulk density of 700 kg/m³. The SCC mixtures utilized a high-range water-reducing admixture (superplasticizer) following EFNARC guidelines (2002) to enhance workability. For aggregate selection, crushed coarse aggregate with a maximum particle size of 10 mm was used, meeting the specifications of ASTM C136 and ASTM C33 (ASTM C136-06, 2006; ASTM C33/C33M, 2018), while natural fine aggregate with a fineness modulus of 3.7 was employed. This study also integrated spherical expanded polystyrene (EPS) beads as partial replacements for conventional coarse aggregates, with a bulk density of 10 kg/m³ and an average diameter of 5 mm (see Fig. 1). To improve mechanical performance, waste polyethylene terephthalate (PET) fibers with an aspect ratio of 30 were added to enhance load capacity and ductility. The characteristics of the reinforcing bars and PET fibers are detailed in Tables 1 and 2, respectively. Additionally, limestone powder was introduced to develop an eco-efficient SCC mix while maintaining comparable strength.

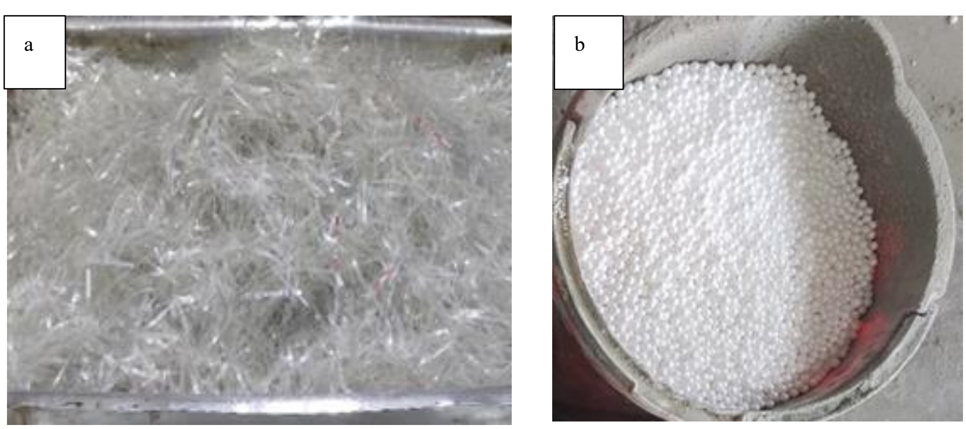


Fig. 1 Waste material: (a); PET fibres (b); Expanded Polystyrene (EPS)

Table 1- GFRP and steel rebars

Diameter	Type	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Elasticity Modulus (GPa)
6	Steel	383	524	200
10	GFRP	-	650	45

Table 2- Plastic fiber (PET) properties

Length (mm)	Width (mm)	Thickness (mm)	Aspect ratio	Specific gravity
33	3	0.3	30	1.4

2.2. Specimens detail

For studying the flexural behaviour of hollow beams, three concrete beams with dimensions of 150×200×1500 mm have been designed according to ACI-4401R15 (ACI 440.1R-15, 2015). The specimens were reinforced with two 10 mm diameter of GFRP bars at the tension zone and one 6 mm diameter bar at the compression zone. The beam was provided with a concrete cover of 20 mm and designed to resist shear failure when the longitudinal tensile reinforcement cracked, resulting in a flexural failure mode in the center of the beam. The beam was reinforced with 6 mm diameter stirrups spaced 65 mm apart to prevent shear failure. Fig. 2 shows the specimen in cross-sectional view. Adhesive was used to attach the 120 Ohm strain gauge to the mid-span of the tension bar and on the external surface of the concrete face. The surface should be smoothed with fine sandpaper to remove any debris before installing the strain gauge. The reinforcement ratio was 0.62% for all beams.

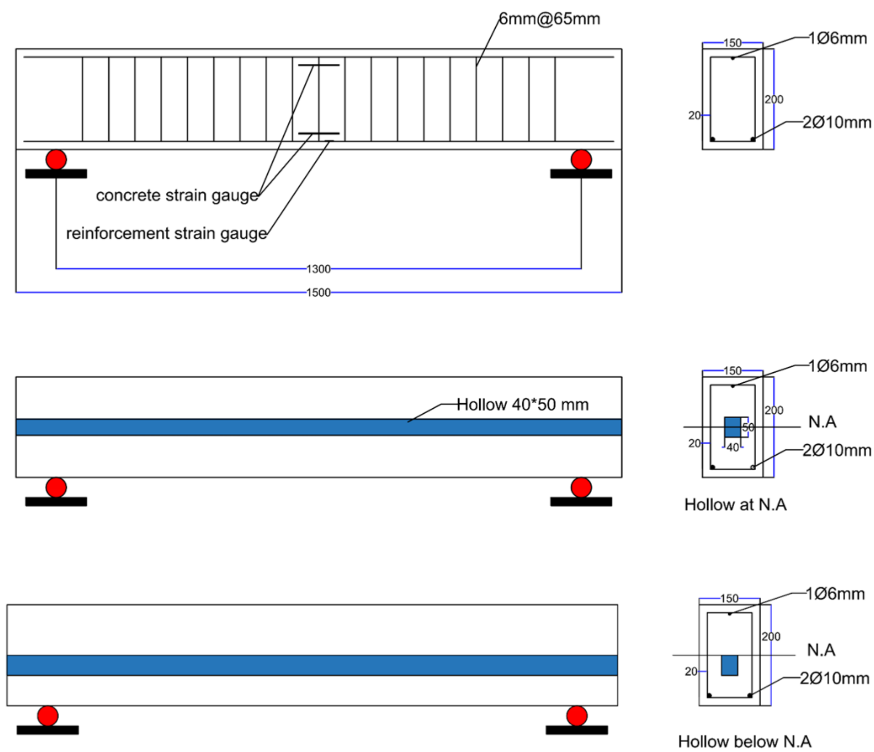


Fig.2 Explains the reinforcement and hollow position

2.3. Trial mix and concrete casting

SCC has a unique feature unlike normal concrete; SCC is tremendously affected by the substances and additives. The physical properties and quality of aggregate can reduce the fresh properties of SCC. The fresh properties tested were the passing ability and filling ability, in addition the aggregate distribution and segregation (Castano & Abdel-Mohti, 2024).The concrete was mixed in a planetary mixer; substances were gradually added into the mixer after the matrix became homogenous. EPS and fiber were introduced, and mixing continued until a uniform and flowable concrete paste was obtained. The SCC fresh properties were tested and reported. Table 3 demonstrates the mix proportion and properties, while Fig. 3 describes the part of the experimental work.

Table 3- Trail mix properties of SCC

No.	Cement Kg/m^3	Fine agg. Kg/m^3	Course agg. Kg/m^3	Water Kg/m^3	SF Kg/m^3	Fiber Kg/m^3	SP Kg/m^3	EPS Kg/m^3	Limestone Powder Kg/m^3	SCC fresh* requirement
1	420	860	850	170	90	-	10	-	-	NOT Passed
2	410	860	-	172	110	7	12	2.9	-	NOT Passed
3	410	860	-	187	110	7	12	2.9	-	NOT Passed
4	450	900	-	174	130	7	12	2	-	NOT Passed
5	450	900	-	200	130	7	12	2	-	NOT Passed
6	550	900	-	234	130	7	15	2	-	NOT Passed
7	500	900	-	217	130	7	15	2	-	NOT Passed
8	500	450	450	213	120	7	15	2	-	NOT Passed
9	500	900	800	201	75	-	15	-	-	NOT Passed
10	525	900	250	198	75	5	12	1.5	-	NOT Passed
11	490	880	200	195	100	5	12	1.5	-	NOT Passed
12	490	1100	400	189	100	-	12	2	-	Passed
13	490	1100	400	189	100	5	13.7	2	-	Passed
16	295	980	700	180	-	-	6	-	160	NOT Passed
17	330	980	700	225	-	-	10	-	231	Passed

The majority of the mix did not meet the required standards due to issues with passing ability and segregation. The concrete exhibited segregation and settlement in front of the reinforcement bars, which can be attributed to the type of fibers used and the lack of material homogeneity.

Fig. 3. Experimental work: (a); reinforcement and wooden frame (b); Concrete casting

3. Results and discussion

The primary objective of the research is to examine several parameters: load, strain, ductility, cracking, deflection, and carrying capacity, as well as the fresh properties of SCC, which incorporate waste materials.

3.1. Material properties

Depending on the experimental test and the results presented in Table 3, the 13:17 mix proportion was within the limitation of the SCC requirement (EFNARC, 2005). Table 4 explains the details of the fresh properties of the designed materials.

Table 4- Properties of fresh and hardened chosen materials

No.	Material* ID	Compressive Strength (MPa)	Tensile strength (Mpa)	Density Kg/m^3	Slump (mm)	T_{50} (S)	J-Ring (mm)	V-funnel (S)
13	EF	22	3.25	1933	700	2	10	11
17	SR	22.4	2.5	2227	770	1.5	9	9

Material ID* (EF); E indicates EPS, F indicates fibre and SR means concrete reference without waste fibre and EPS

According to the fresh properties test, adding (SF) has enhanced the cohesion of the matrix and prevents EPS beads from floating, and prevents aggregate segregation (EFNARC, 2005). The experimental test of fresh characteristics is shown in Fig. 4, and due to the density difference, EPS beads have a lower density and tend to float to the surface when mixed. Therefore, the cohesiveness of the materials at the fresh test was enhanced by the use of (SF) and an enormous quantity of cement. It has been found that the EPS beads should not exceed more than 2 kg/m3 of the total concrete volume for developing SCC with EPS beads. Additionally, it was found that 0.35% of PET fibres produced SCC properly. The compressive strength of cylinders measuring 150 mm in diameter and 300 mm in height was tested over a range of time periods followed ASTM C39 (ASTM C39/C39M, n.d.), and displayed in Fig. 5. Despite the perfect distribution of EPS beads, no significant strength increase was observed over a 90-day period because of the weak voids created by the EPS beads, because the cracks start from the weak point surrounding the EPS beads. Unlike coarse aggregate, EPS beads lack the feature of load carrying but significantly reduced the concrete density by 13.5% lower than SCR specimen, because the density of EPS beads. According to a line of earlier research, increasing EPS resulted in lower concrete capacity (Medher et al., 2021).

Fig. 4. The fresh test of SCC: (a) slump flow test; (b) V-funnel test; (c) J-ring test

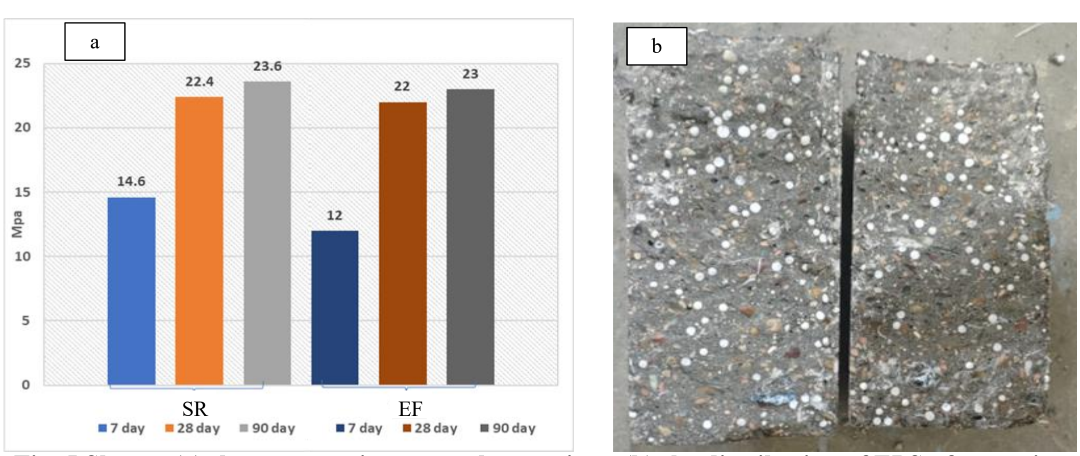


Fig. 5 Shows: (a) the compressive strength over time; (b) the distribution of EPS after testing

Table 5 - The experimental data of four concrete Beams

Beam's name*	Material ID	First crack Load (KN) P_{cr}	Ultimate load(KN) P_u	First crack Deflection Δ_{cr} (mm)	Ultimate deflection (mm) Δ_u	Failure mode	E elastic	Total Energy kN.mm	Ductility Index
BR	SR	5.5	83.25	0.4	31	C	825	1602	1.47
BS	EF	6	63.9	0.25	29	C	883	1231	2.3
BH1	EF	5	58	0.22	24	C	326	868	1.83
BH2	EF	8	63.9	0.7	32	C	464	1405	2.01

*The first B for all means concrete beam, R for references beam without fiber and EPS, S means solid section without hollow, while H1 hollow at center and H2 hollow below center

3.2.Load-deflection

The specimen's characteristics were evaluated under identical conditions by subjecting the concrete beams to a three-point load. Fig. 6 shows the position of the two LVDTs: one at L/4 and one in the specimen's center. Fig. 7 and Table 5 display the characteristic curves of load deflection and the experimental results. Prior to the initial crack, all specimens had displayed the same load-deflection behaviour. The BR specimen showed a consistent stiffness after 20% of the ultimate load, unlike the other beams, which explained the nonlinearity due to the materials and section (hollow). The maximum load capacity was recorded by BR beams, while the lowest load capacity was by BH1 beams, and that may be attributed to the position of the hollow at the center of the beam, which directly affects the compression zone size. Using EPS beads contributes to increasing the deflection and reducing the beam stiffness. Comparing between BR and BS, the capacity was reduced by 20% due to the. Moving the hollow under the neutral axis increased the load capacity by 10% due to the central hollow simultaneously weakening the compression and tension zones by reducing the moment of inertia (I), unlike the hollow below the neutral axis, which increased the modulus section of the beam.

Fig. 6 Demonstrates the specimen under test

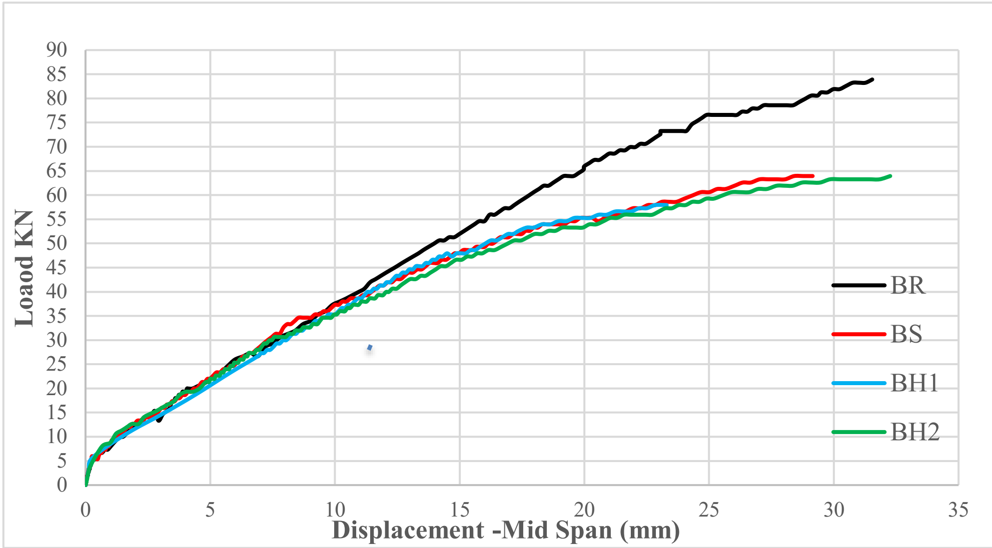
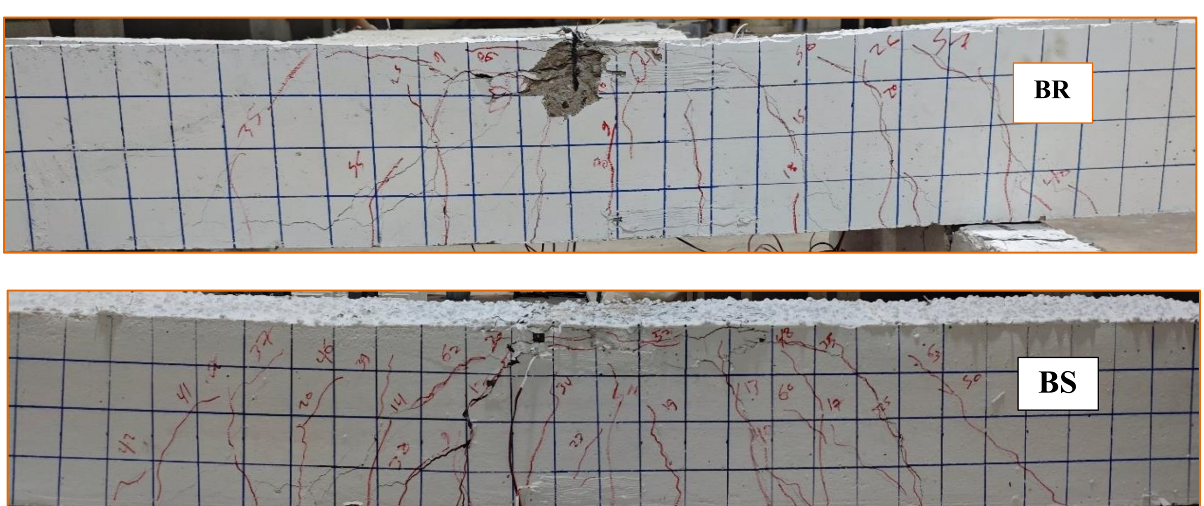
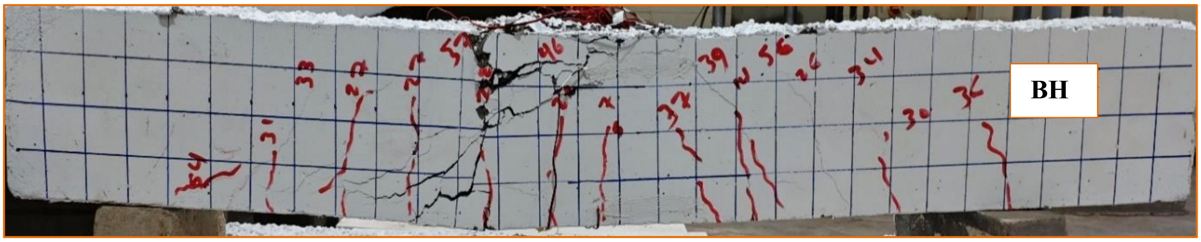


Fig. 7 Load vs displacement curves

3.3. *Cracks pattern*

For solid section beams (without hollow), the first crack initiates in the beam BR at a lower load compared to the BS beam by 10 %, which is mainly attributed to the plastic fiber. The effect of the hollow position on first crack was notable; the BH2 explained 35% more load capacity before first crack initiation compared to the specimen BH1. Fig. 8 shows the experimental test of four specimens, using EPS and plastic fiber type (PET), which reduced the crack distribution and delayed the first crack. A different crack pattern has been observed as shown in beam BS, which was probably due to stiffness reduction and ductility enhancement. Using PET fiber in beams creates a three-dimensional reinforcing network by filling up tiny gaps and spreading stress across cracks, which effectively delays the expansion of fractures. The location of the hollow at the beam center contributed to reducing the compression zone size and created more cracks around the concentrated load, unlike the hollow below the center of beam BH2, which showed smoother and finer cracks. All concrete beams demonstrated a notable compression failure, which was aligned with the ACI code, which recommends the compression failure for GFRP rebars to prevent a sudden failure (ACI 440.1R-15, 2015). Using waste materials as EPS beads with GFRP rebars reduced the beam stiffness and increased the ductility, allowing more cracks to be generated before sudden failure.





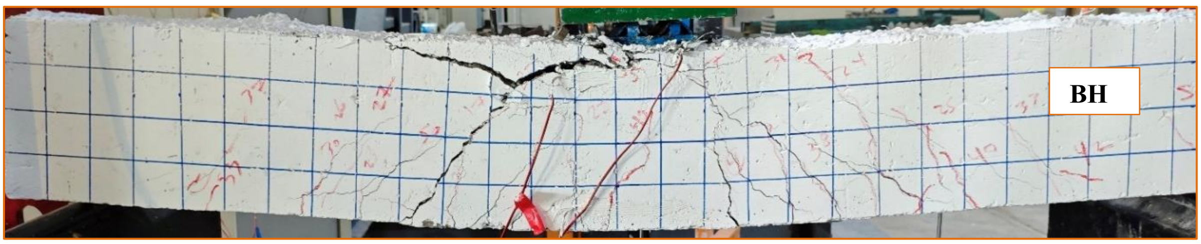


Fig. 8 Cracks pattern and failure mode

3.4. *Load-strain behavior*

The load-strain behavior of all specimens is demonstrated in Fig. 9. The response of load-strain was similar before the first crack, acting linearly elastic. After the first crack, the strain increased rapidly and showed a notable decrease in stiffness. For a similar reinforcement ratio of GFRP, specimens showed excessive strain before the concrete collapsed. Using EPS beads decreased the strain by 20% due to the ductility enhancement and reduction in concrete stiffness. The notable degradation in strain could be attributed to the new transition zone between EPS beads and cement paste, resulting in a weak area around reinforcement bars. The location of the hollow reduced the strain due to the decrease in compression area, unlike the tension zone, the concrete could be neglected after cracking. In contrast, concrete in the compression zone has the responsibility of load carrying. Similar to the load-deflection curves behavior, no yield point has been observed for the GFRP rebars specimens.

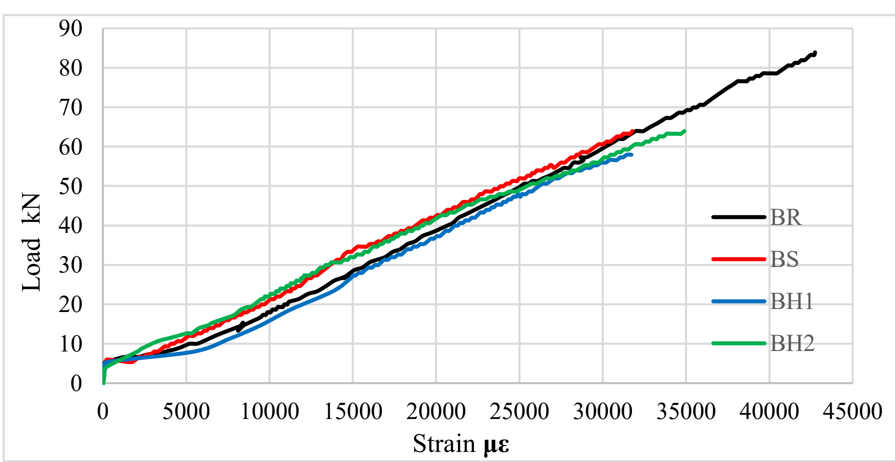


Fig. 9 Shows the load-strain for GFRP rebars

3.5. Ductility index

Ductility, which includes yielding and plastic behavior, represents the amount of plastic strain a member is resistant before failure. Deformability, on the other hand, describes the maximum amount of deformation an element can experience before failure, regardless of whether it has yielding or plastic behavior (Oudah & El-Hacha, 2012). For adequate ductility, an elastic member should possess a higher reserve of strength than a ductile member (ACI Committee-4401R15, 2015). In case of a steel reinforced beam, the ratio of the yield deflection to the final deflection is known as the ductility index or ($\mu_\Delta = \Delta_u/\Delta_y$). Because the stress–strain properties of GFRP rebars lack the yield section of steel bars, the normal equation for calculating the ductility index of steel reinforced concrete is not suitable for GFRP-reinforced concrete specimens. Therefore, Naaman and Jeong(Naaman A, 1995), suggested using the energy balance approach to determine the ductility index of FRP-reinforced concrete (FRP-RC) beams (see Eq. (1,2)). Fig. 10-11 provides a schematic representation of the ductility index computation of FRP-RC beams based on the energy calculation technique, using the load–deflection of the GFRP reinforced beam as an example. The result of the ductility index is explained in Table 5. Using EPS beads improved elastic energy storage more quickly than total energy, while PET fiber increased the specimens' ductility, which was also found by other research(Ali H. Allawi, 2021). In summary, because the EPS beads minimized the rigidity, the BS beam showed 36 % higher ductility than the BR beam. PET fiber, which increased the overall energy, is responsible for the improvement in BS beam ductility performance over BR beam because PET fibers will bridge fractures, disperse stresses in the matrix, and limit the spread of cracks because of their high tensile strength, excellent flexibility, and elongation capacity. This behavior increases the ductility of the beams by increasing the deflection and number of fractures until the specimen fails, ultimately(Medher et al., 2021). The GFRP beams' average ductility index value was 1.94, falling within the range of the indications that were noted(Li et al., 2024; Yoon et al., 2011). Because the load–deflection curve of the GFRP specimens is bilinear, thus $P_1 = P_{cr}$ and P_2 can be calculated from the slope inclination which equal the point of intersection as shown in Fig.10.

$$\mu = \frac{1}{2}\left(\frac{E_{total}}{E_{elastic}} + 1\right) \quad (1)$$

$$s = \frac{P_1 S_1 + (P_2 - P_1) S_2}{P_2} \quad (2)$$

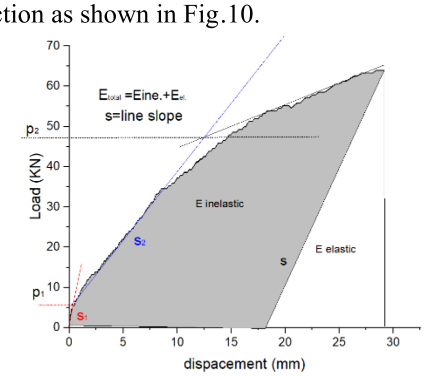


Fig. 10 Example ductility index

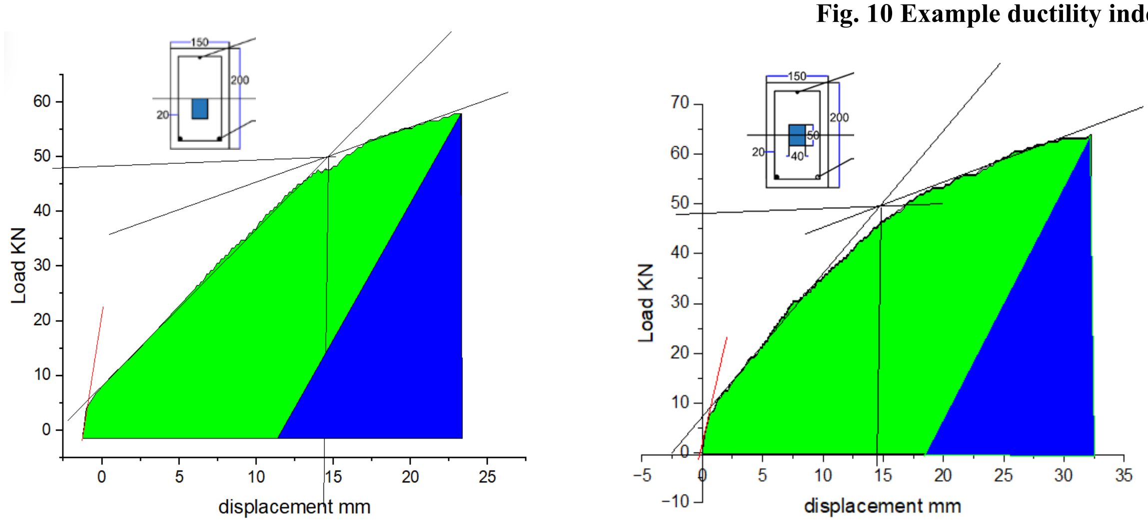


Fig. 11 Demonstrates the effect of hollow location on the ductility index

3.6. *Toughness*

The area under the load and deflection curve from the zero-load stage to the ultimate load are associated with toughness, which can be described as the structure's ability to absorb energy and resist plastic deformation (Hamad & Sldozian, 2019).The toughness values for the beams were calculated according to ASTM C1609 specifications (ASTM C1609/C1609M-12, 2009). The area under the load and deflection curve was determined using (Origin Pro programs). The results are demonstrated in Fig. 12. The position of the hollow has notably affected, the reduction in toughness was 38% compared with the hollow at the neutral axis. The addition of PET fibers improved the toughness of the hollow beam BH2 and probably reduced the cracks around the hollow edges. These results are consistent with the study of (Ismail Al-Hadithi & Ahmed Abbas, 2018) as the increase in plastic fibers led to an increase in energy absorption.

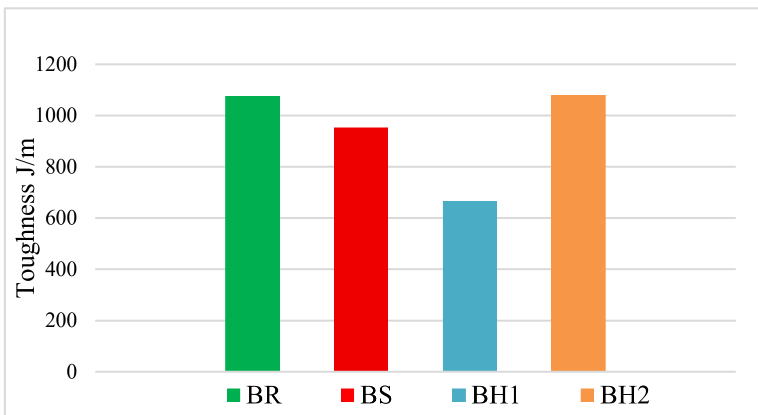


Fig. 12 Toughness result for beams

4. Conclusion

This work focused on clarifying the mechanical properties of self-compacting concrete (SCC) including waste materials, specifically polyethene terephthalate (PET) and expanded polystyrene (EPS), both of which have considerable environmental effects and require an extended duration for degradation. Four reinforced concrete beams with GFRP rebars have been tested using the three-point load method. The concrete density ranged from 2227 to 1927 kg/m³, the compressive strength varied between 21.5 and 22.5 MPa, and the reinforcing ratio was 0.62%. The flexural load capacity, deflection, toughness, failure mechanism, and ductility of GFRP hollow beams were examined, and the principal conclusions are stated as follows:

1. The failure mode of Beams was concrete compression, because it exceeded the strain limitation of concrete.
2. Although EPS lowered compressive strength, thereby decreasing peak loads (BS: 63.9 kN; BR: 83.25 kN); beams containing plastic fibers and EPS beads showed increased ductility compared to the reference beam.
3. In a symmetrical design, central hollows (BH1) reduced the ultimate load (58 kN) and rigidity of the beams. Avoiding strength loss (64 kN) was achieved by including hollows below the neutral axis (BH2).
4. Fibers enhanced post-crack performance by bridging microcracks, delaying failure, and increasing energy absorption.
5. While hollows decreased their weight, they lowered their structural strength. Strength retention was maximized by strategic placement (BH2), while both the tension and compression zones were weakened by central hollows (BH1).
6. BS and BH2 proved to be practical lightweight options for ductile-requiring applications. Fibers could be

essential in dynamic loading environments due to BR's brittleness.

Declaration

The authors state that any known conflicting financial interests or personal relationships may have influenced none of the studies described in this paper.

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