Flexural Behavior of Reinforced Concrete Beams using Recycled Glass as a Sand Substitute

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ABSTRACT

Construction waste, representing a major part of the total solid waste generated in urban areas, contains glass and recycling this glass can partially replace sand as aggregate in concrete. This study experimentally investigates the flexural behavior of 7 Reinforced Concrete (RC) beams, utilizing Recycled Glass (RG) as fine aggregate to substitute 0%, 10%, 50%, and 100% of the sand component's weight in the concrete mix. The study identified the load at which the beams cracking initiated, the progression of the cracks, and the subsequent damage. It established relationships between load and Vertical Displacement (VD), as well as load and deformation in the Tension Zone (TZ) and Compression Zone (CZ) at the mid-span of the RC beam using a 4-point bending test. The research findings indicate that a 10% RG content can effectively substitute sand in concrete beams, with stirrups measuring 125 mm at the ends of the beam and 100 mm at the midpoint of the beam span.

Keywords-construction waste; solid waste; fine aggregate; concrete; recycled glass; stirrup

I. INTRODUCTION

As presented in the Plan for the Development of the Construction Materials Industry in Vietnam for 2021-2030 and the orientation towards 2050, the projected demand for construction sand in Vietnam is expected to reach approximately 200-220 million m^3/year by 2030 [1]. Approximately 35% of the total solid waste is construction waste [2]. In Vietnam, construction waste constitutes approximately 25% of urban solid waste in Hanoi and Ho Chi Minh City and 12%-15% in other provinces and cities [3]. Glass is present within that construction waste, and recycling glass serves as a method to reduce and address landfill issues. The glass will undergo sorting, crushing, and recycling, and will be presented as either sand or fine particles. Authors in [4] used recycled fine aggregate, coarse aggregate, and steel fibers to create recycled aggregate concrete. The findings indicated that the load-bearing capacity of beams incorporating 100% recycled aggregate and 1% steel fiber improved by 13% and 8%, respectively. Authors in [5] investigated the impact of fine and coarse recycled concrete aggregates on the mechanical performance of precast reinforced beams through simulation, theoretical analysis, and experimental methods on beams. This study demonstrates the effectiveness of combining coarse and fine recycled aggregates to partially substitute aggregates in self-compacting concrete, focusing on the mechanical performance of precast beams. Some studies focus on the flexural properties of recycled RC beams [6-8], which have been damaged in bending and shear [9, 10]. There are many experimental investigations into the behavior of RC beams containing recycled materials [11] and research on the long-term flexural properties of beams with recycled coarse aggregates [12]. Additionally, studies examine the deflection and long-term flexural behavior of RC beams with recycled aggregates [13-15].

Several RC beam types have been tested to evaluate their deflection, cracking, and damage. The results have shown that beams made with coarse recycled concrete aggregates performed similarly to those made with normal aggregates in both service and damage conditions. Authors in [16, 17] examined the flexural behavior of multilayer recycled concrete beams reinforced with carbon fiber-reinforced polymers. Their goal was to understand how damage affects the overall performance of RC structures during use and after failure. Authors in [18] focused on high-strength recycled concrete beams. These beams were initially cracked and had different water-cement ratios and varying amounts of recycled coarse aggregate. In recent years, numerous studies have explored the application of recycled crushed glass in concrete. Crushed glass is an effective alternative to sand due to its favorable chemical composition and physical properties. Furthermore, the smooth surface and relatively low water absorption of glass sand can enhance the properties of fresh concrete [19-23]. Numerous studies and experiments have been conducted on the flexural behavior of RC beams utilizing recycled materials [24]. The authors have selected this experimental approach to analyze and evaluate the viability of the use of RG as a substitute for sand in concrete. Authors in [25] examined the flexural deformation of RC beams, establishing the moment-curvature relationship in the presence of cracks. Authors in [26] found that using fine glass particles instead of sand in concrete causes a non-expanding pozzolanic reaction. This reaction forms calcium silicate hydrate with a low calcium-silicate ratio. However, the results varied depending on the color of the glass particles and the amount of glass in the mixture [27].

Several studies have explored the application of RG in concrete. Nonetheless, experimental studies are very limited in assessing the appropriateness of RG sand as a partial substitute for sand in concrete. The characteristics and applications of RG are influenced by the origin and variety of the RG [28-30], as well as the impact of incorporating glass on the durability of concrete combined with pozzolan. Many studies report enhanced characteristics of concrete based on the fineness and the level of replacement [31]. Several studies examine the impact of varying recycled glass content, along with changes in rebars and stirrups, on load displacement and deformation in bending beams. In this study, seven RC beams were tested, with sand replaced by recycled glass by 0%, 10%, 50%, and 100%. To analyze crack formation and growth, graphs were created to show the relationships between load and VD, as well as load and deformation in the CZ and TZ at the beam's midpoint.

II. METHODOLOGY

A. Beam Design

Seven RC beam specimens with dimensions of 150 mm × 200 mm × 1200 mm were tested and categorized into three groups: Group 1 consists of beams D1, D2, D3, D4, with variations in the percentage of RG replacing sand aggregate at 0%, 10%, 50%, and 100%. Group 2 includes beams D4, D5, D6, focusing on modifications to the distance of stirrup steel within the beam. Group 3 features beams D4 and D7, which involve changes to the embodied steel in the beams. Details of the beams are presented in Table I.

TABLE I. DETAILS OF THE TESTED RC BEAMS

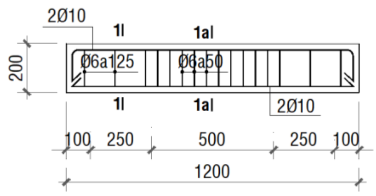
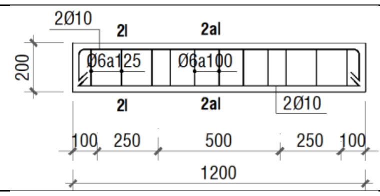
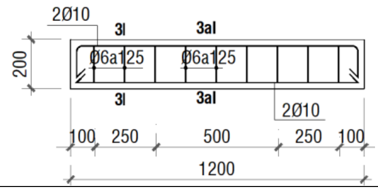
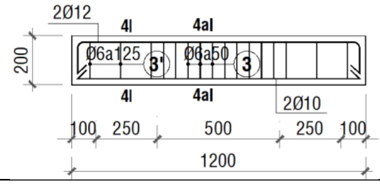
	RG (%)	Rebars (mm)	Stirrups (mm)	
			End of beam	Middle of beam
D1	0	4Ø10	Ø6a125	Ø6a50
D2	100	4Ø10	Ø6a125	Ø6a50
D3	50	4Ø10	Ø6a125	Ø6a50
D4	10	4Ø10	Ø6a125	Ø6a50
D5	10	4Ø10	Ø6a125	Ø6a100
D6	10	4Ø10	Ø6a125	Ø6a125
D7	10	2Ø12 + 2Ø10	Ø6a125	Ø6a50

The concrete mix, utilizing Grade B15 [32], features a slump of 10±2 cm, as detailed in Table II.

TABLE II. MIXTURE COMPOSITION OF CONCRETE [kg/m^3]

Cement (kg)	Sand (kg)	Stone (kg)	Water (liters)
360	611	1.222	203

TABLE III. BEAM DETAILS

No.	Beam	Details (mm)
1	D1, D2, D3, D4	
2	D5	
3	D6	
4	D7	

B. Producing RG Materials to Serve as a Substitute for Fine Aggregate

Glass is processed into particles that match the size of sand particles and follow TCVN 7570:2006 [33]. Once collected, the glass will go through crushing and be processed through sieves as illustrated in Figure 1.

Fig. 1. Produced RG in particle sizes similar to sand particles.

III. RESULTS AND DISCUSSION

A. Crack Formation and Propagation

Each beam is equipped with two PDTs to measure compressive strain, two PDTs to measure tensile strain, and one vertical displacement meter. Figure 2 illustrates the crack formation and propagation from the initial loading stage until the beams reach failure.

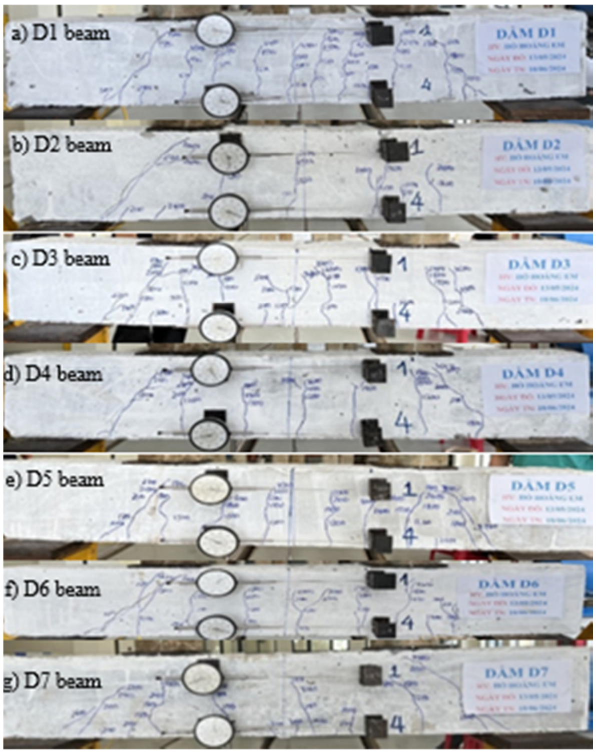


Fig. 2. Crack forming and propagation in the beams

The crack shape observed in the experimental beams aligned with [8]. Glass content substituting sand increased from 0% to 10% (from 225 kN to 195 kN). When the glass content increased to 50%, the beam's load-bearing capacity continued to decrease, ultimately reaching 165 kN. As the glass content reached 100%, the beam's load-bearing capacity dropped to 135 kN, reflecting a 40% decrease in comparison to the beam containing 0% RG. The cracks in the beams were observed sooner at the 45 kN load level for those incorporating 50% and 100% RG as a substitute for sand. In contrast, normal concrete beams and those with 10% RG showed cracks at the 60 kN load level, indicating that a 10% RG content as a sand replacement in concrete is optimal. The cracks in the beams were measured to have widths ranging from approximately 1 mm to 2 mm.

B. Impact of Varying Percentages of RG as a Sand Substitute

1) Load-Strain (L-S) in CZ

RG as a substitute for concrete sand resulted in a comparable development of CZ deformation in the beams, although the progression differed from that of normal concrete beams. When the load was below 90 kN, the deformation of all beams was the same; however, beyond this load, normal concrete beams exhibited slower deformation compared to the beams made with RG as the load increased until the beams were damaged. As the RG content increased to 10%, the deformation in the CZ of D4 showed a significant rise at the load level of 195 kN, measuring 263.83% in comparison to beam D1. As the percentage of RG rises to 50%, at a load level of 165 kN, the deformation in the CZ of D3 reaches approximately 312% compared to beam D1. At a load level of 135 kN, when the RG content reaches 100%, the CZ deformation of beam D2 is 356% that of beam D1. Therefore, using a beam with more than 50% recycled glass significantly reduces its bearing capacity—by more than 3.5 times—making it unsuitable for design purposes.

TABLE IV. INITIAL CRACKING LOAD AND FAILURE LOAD VALUES

	Initial cracking load (kN) (1)	Failure load (kN) (2)	Ratio of (1), (2) (%)	Initial cracking load/D1 (%)	Failure load/D1 (%)
D1	105	225	46.6	100	100
D2	105	135	77.7	100	60.0
D3	105	165	63.6	100	73.3
D4	105	195	53.8	100	86.6
D5	105	210	50,0	100	93.3
D6	105	210	50.0	100	93.3
D7	105	225	46.6	100	100

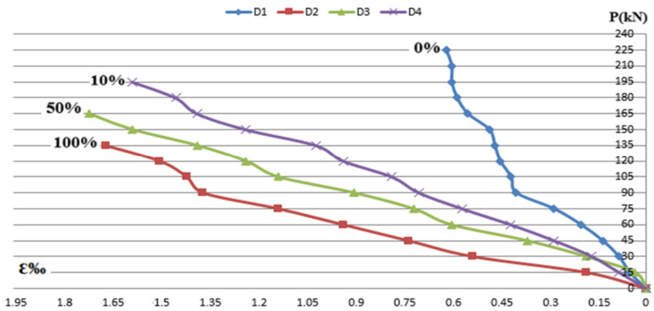


Fig. 3. The L-S relationship of the CZ of the beams.

2) L-S relationship in TZ

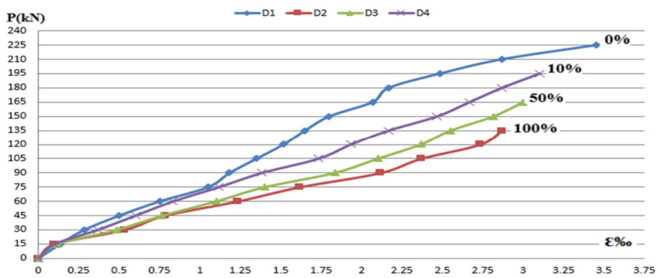


Fig. 4. The L-S relationship of the TZ of the beams.

For the same compression strain, the tensile strain of the beams is twice as large. When the load is under 75 kN, the tensile strain of the beams remains consistent. Following this load level, the strain development in the beams made with RG rises steadily, whereas the normal concrete beam exhibits a slower strain progression. As the proportion of glass substitute sand in the concrete rises to 10%, at a load level of 195 kN, the tensile strain of beam D4 reaches approximately 125% of that of beam D1. Replacing 10% of the sand mass in the beam with RG maintains the load-bearing capacity compared to standard concrete beams. At a load level of 165 kN, when increased to 50%, the tensile strain of beam D3 reaches 145% of that of beam D1. When the RG content replacing sand in concrete reaches 100%, there is a notable increase in the tensile strain of the beam. At a load level of 135 kN, the tensile strain of beam D2 is 173% compared to beam D1. Consequently, restrict the application of beams that incorporate 50% RG mass as a substitute for sand to maintain the bearing capacity of the beams.

3) *L-D Relationship at theMid-Span of the Beam*

As the amount of RG content used to replace sand aggregate in concrete increases, there is a corresponding increase in the displacement at the mid-span of the beam. However, the higher content also leads to earlier failure. As the RG content substituting sand in concrete rises to 10%, the VD of the beam under a load of 195 kN indicates that the VD of D4 is approximately 121.6% of that of beam D1. In the same way for beam D3, as the RG content rises to 50%, the VD of the beam at the load level of 165 kN for D3 is approximately 161.4% of that of beam D1. Regarding D4, with the RG content at a load level of 135 kN, the VD of beam D2 is approximately 237% that of beam D1. The VD at mid-span of the beam increased from 5.9 mm to 6.7 mm, then to 7 mm, and finally reached 8.3 mm, corresponding to 0%, 10%, 50%, and 100% RG content replacing sand in the concrete.

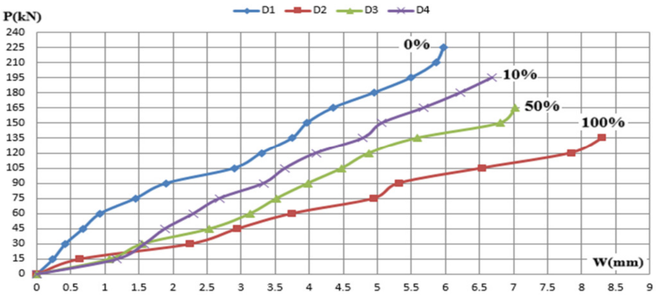


Fig. 5. The L-D relationship of the beam.

C. *Influence of Stirrup Spacing*

1) *L-S Relationship in CZ*

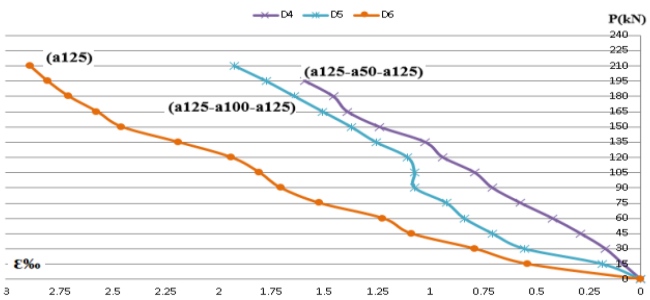


Fig. 6. The L-S relationship of the CZ of the beams.

When the stirrups at both ends of the beam remain constant at 125 mm, and only the distance between the stirrups in the middle changes from 50 mm to 100 mm, the CZ deformation of beam D5 exceeds that of beam D4 across the load levels. At a load level of 195 kN, the CZ deformation of beam D5 is 111% of that of beam D4. When the stirrups at both ends of the beam are maintained at 125mm and only the distance between the stirrups in the middle changes from 50 mm to 125 mm, the CZ deformation of beam D6 exceeds that of beam D4. At a load level of 195 kN, the CZ deformation of D6 is 176% of that of D4. Beam D4 includes a thicker stirrup spacing (a50) compared to beam D5 (a100) yet beam D5 exhibits later failure. This indicates that beam D4 has utilized excessive reinforcement, surpassing the concrete's capacity, resulting in damage from plastic deformation. Consequently, it is essential to account for this surplus reinforcement in the design calculations.

2) *L-S Relationship in TZ*

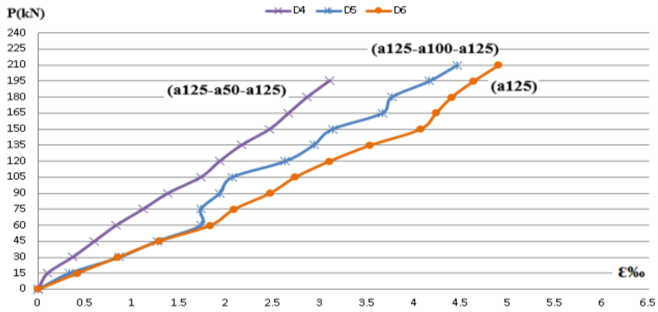


Fig. 7. The L-S relationship of the TZ of the beams.

When the stirrups at both ends of the beam remain constant at 125 mm, and only the distance between the stirrups in the middle of the span changes from 50 mm to 100 mm, the tensile strain of the D5 beam exhibits greater fluctuations compared to the D4 beam across the load levels. At a load level of 195 kN, the tensile strain of the D5 beam attains 134% of that of the D4 beam. When the stirrups at both ends of the beam remain constant at 125 mm, and the distance between the stirrups in the middle of the span changes from 50 mm to 125 mm, the tensile strain of the D6 beam exceeds that of the D4 beam. At a load level of 195 kN, the tensile strain of the D6 beam is 150% of that of the D4 beam. Increasing the distance between the stirrups in the middle of the span from a50 to a100 results in a larger tensile strain compared to the increase from a100 to a150, and the D5-D6 beams fail at the same load level of 210 kN.

3) *L-D Relationship at the Mid-Span of the Beam*

D4 and D5: When the stirrups at both ends of the beam remain constant at 125 mm, and the distance between the stirrups in the middle of the span changes from 50 mm to 100 mm, the VD of beam D5 exceeds that of beam D4, with the difference being minimal.

D4 and D6: When the stirrups at both ends of the beam remain constant at 125 mm, and the distance between the stirrups in the middle of the span changed from 50 mm to 125 mm, the VD of beam D6 is significantly greater than that of beam D4. At a load level of 195 kN, the VD of D6 is 119% compared to D4. During compressive deformation, D4 and D5 are in proximity to one another, whereas in the case of tensile deformation, D5 and D6 are situated closely together. In terms of VD, D6 exhibits the greatest displacement. Consequently, beam D5, featuring a stirrup spacing of a100 at the midpoint of the beam span, is optimal and suitable for use in the design.

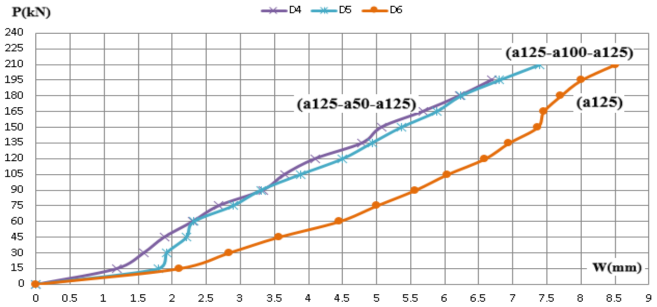


Fig. 8. The L-D relationship of the beam.

D. Impact on the Main Steel Diameter in Beams

1) L-S Relationship in CZ

When the RG content replacing sand is 10%, the stirrup spacing at the mid-span of the beam is 50 mm, and the main load-bearing steel changes from 4Ø10 to 2Ø10 tensile and 2Ø12 compressive, the CZ strain of beam D4 exceeds that of beam D7 (from 0.66% to 1.6%) at the load of the damaged beams. The load-bearing capacity of the beam rises from 195 kN to 225 kN, while the compression strain shows a notable decrease as the diameter of the compression steel expands from 2Ø10 to 2Ø12.

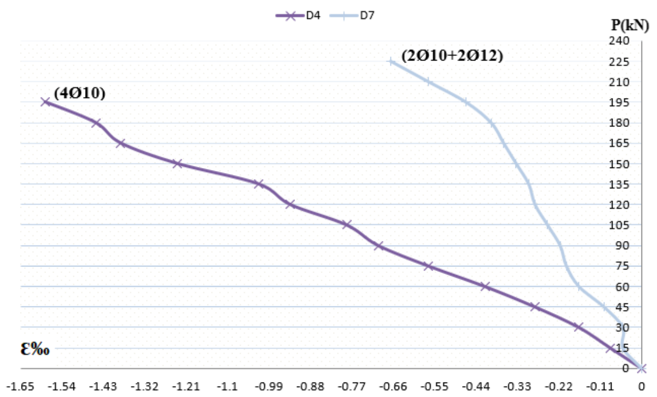


Fig. 9. The L-S relationship of the CZ of the beams.

2) L-S Relationship in TZ

Increasing the diameter of the compression steel affects the deformation of the TZ in the beams, but the difference is minimal and insignificant. The findings suggest that to effectively reduce deformation in a specific area, it is best to increase the diameter of the tensile steel in that region.

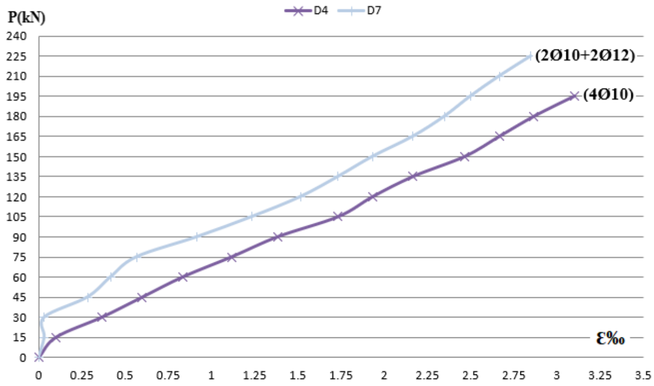


Fig. 10. The L-S relationship of the TZ of the beams.

3) L-D Relationship at the Mid-Span of the Beam

Increasing the steel diameter in the CZ not only leads to a noticeable reduction in CZ deformation but also results in an increase in the destructive load from 195 kN to 225 kN. Additionally, the displacement at the mid-span of the beam decreased from 6.7 mm to 4.5 mm.

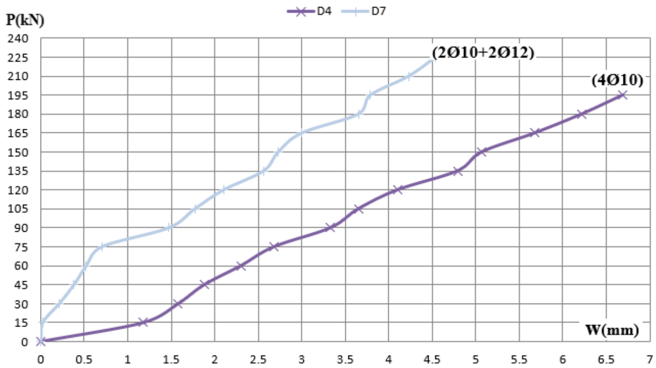


Fig. 11. The L-D relationship of the beams.

E. Optimizing the Effects of Parameter Changes

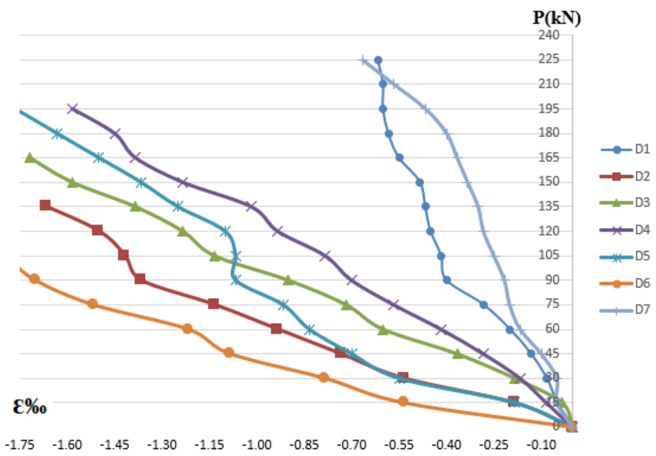


Fig. 12. The L-S relationship of the CZ of the beams.

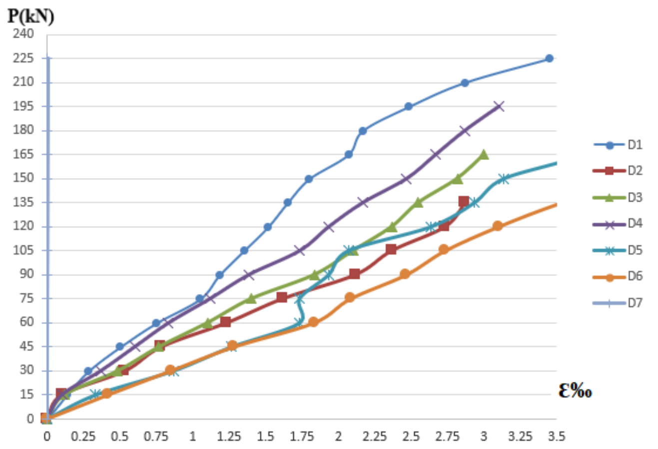


Fig. 13. The L-S relationship of the TZ of the beams.

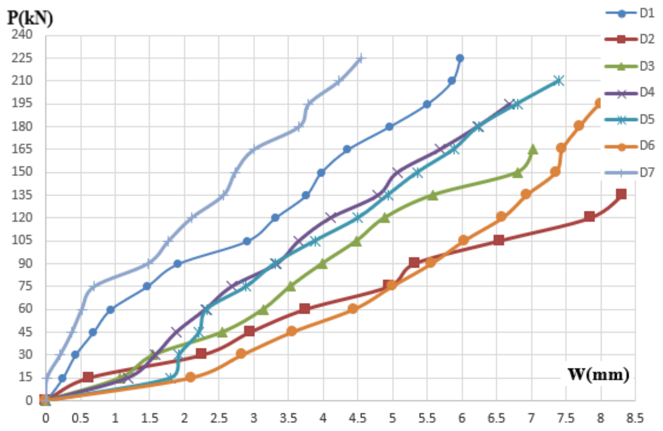


Fig. 14. The L-D relationship of the beams.

Data analysis indicates that the beam utilizing 10% RG mass as a substitute for sand in concrete, along with a stirrup spacing of 100 mm in the middle of the beam span, is the most effective configuration. Consequently, beam D5 is the proposed option in beam design.

IV. CONCLUSION

Research findings indicate that RG can be utilized in construction projects to substitute a portion of the sand content in concrete, thereby addressing the diminishing availability of natural sand resources. The study's findings regarding compressive (tensile) deformation and VD at the mid-span of the beams indicated that replacing sand in concrete with 10% RG is feasible. The investigated glass contents included 0%, 10%, 50%, and 100%, demonstrating that these values are optimal for design purposes. It is essential to accurately calculate the stirrup distance between the beam spans, ensuring it is not placed too thick (this study is a50), as this not only incurs additional costs but also reduces the load-bearing capacity. Table IV indicates that the initial cracking load of all beams is consistent; however, the percentage change in the failure load for each beam compared to the reference beam (normal concrete, D1) is uniform at D7, followed by D5-D6, and subsequently declines at D4-D3-D2.

CONFICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this paper.

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