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Compressive Behaviour of Reinforced Concrete Columns Using Recycled Building Glass Instead of Sand Aggregate in Concrete

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ABSTRACT

Exploring alternative aggregates or recycled aggregates to substitute traditional concrete aggregates, particularly sand aggregates, which are becoming more limited and must comply with environmental protection standards, is essential. Research has explored various alternative materials to sand in concrete, including concrete from demolished buildings, and broken glass from projects, among others. Investigating the use of recycled broken glass to substitute sand aggregates and implementing this research in compression columns is crucial. This paper examines the compressive behavior of reinforced concrete columns that utilize recycled glass particles as a substitute for sand in concrete. The research findings establish the relationships: load and vertical displacement, load and deformation at the column head, mid-column, and column base; the formation and propagation of cracks in the column, while considering factors such as the percentage of recycled glass, the arrangement of stirrups, and the amount of load-bearing steel influencing the performance of square reinforced concrete columns under compression. The feasibility of using recycled glass as a substitute for sand in column structures subjected to compression has been demonstrated, with the ideal replacement content for sand aggregate in reinforced concrete columns in this study ranging from 0% to 10%. The column's load-bearing ability dropped from 250 kN to 150 kN when 100% recycled glass was used instead of sand. This is a 40% drop, and cracks started to show up sooner. The research will support recycling broken glass instead of using sand in building, improving the environment and reducing natural sand use.

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1. Introduction

The report on the environmental status of Hanoi City for the period of 2015–2020 indicates that the city produced and collected more than 2,000 tonnes of construction solid waste per day [1]. In 2021, the construction floor area resulted in the generation of construction solid waste ranging from 0.22 to 0.41 tons m^{-2}, with an average of 0.31 tons m^{-2}. This translates to an actual amount of construction solid waste equivalent to 4,186 tonnes per day in 2021, and it is projected to increase to 9,431 tonnes per day by 2025 [2]. Tran Thu Hien with the title "Overview: Recycling construction solid waste into aggregates" [3] pointed out that there are about 850 million tons of construction solid waste generated annually in the countries of the European Union. Specifically, the amount of construction solid waste discharged annually in the United States is 534 million tons, France is 349 million tons, the UK is 90 million tons, Japan is 77 million tons, Hong Kong is 15.4 million tons, Australia is 29 million tons, and India is 17 million tons. Yang et al. [4] stated that the rapid development of the Chinese economy has unintentionally created more and more construction solid waste, especially in large cities. China produces approximately 30% of the total construction waste globally. Approximately 300 million tonnes of construction waste are produced annually from new construction and the demolition of old buildings. Consequently, reusing construction waste represents a sustainable development trend—an unavoidable direction that nations are pursuing. It also serves as a means to conserve natural resources and minimise the land area required for landfill management.

Natural sand serves as an important aggregate in the construction industry. The demand for sand continues to rise, keeping pace with the rapid infrastructure development in each country. A report from UNEP [5] indicates that yearly, approximately 47 to 59 billion tonnes of materials are extracted, with sand and gravel representing the largest share (ranging from 68% to 85%), and the rate of extraction is rising at the fastest pace. In recent years, authors have discovered new aggregates or recycled aggregates to substitute traditional concrete aggregate components, particularly sand aggregate—a resource that is becoming increasingly limited [6]. Data indicates that the demand for construction sand in Vietnam is approximately 120–130 million m^3 per year. The demand for sand used for filling during the period from 2016 to 2020 varied between 2.1 and 2.3 billion m^3, whereas the forecasted reserve of construction sand and sand for filling is estimated to be only 2.1 billion m^3.

The supply of natural sand from legal mining areas is projected to satisfy only approximately 40–50% of the demand [7]. In the years ahead, our nation will face a shortage of natural construction sand to meet the demands of various regions. Consequently, identifying the best approach for substituting green materials in the construction industry generates research that holds social importance. Dung et al. [8] assessed the feasibility of substituting natural sand with artificial sand produced from crushed limestone. Aditya and colleagues [9] assessed the feasibility of incorporating waste rock into concrete. The impact of substituting waste rock on strength and durability factors, including permeability, chloride migration, porosity, water absorption, carbonation, acid and sulfate resistance, along with various related studies, etc.

Reinforced concrete columns are commonly utilised structures in construction projects, and their performance capacity is always a key consideration in design and calculations. Long and Cuong [10] conducted experimental research on the long-term deformation of compressed reinforced concrete columns. Quang and colleagues [11] conducted experiments and calculations on compressed reinforced concrete columns featuring true centre reinforcement with carbon mesh reinforced concrete.

Goksu [12] conducted a study on the fragility of reinforced concrete columns that utilise recycled aggregates. Sykhampha and Thang [13] conducted experiments using fly ash as a partial replacement for cement under eccentric compression. They subsequently evaluated the bearing capacity of both conventional reinforced concrete columns and those incorporating fly ash. Results demonstrated the practicality of substituting fly ash for cement as a binder in the concrete mix for columns. Phuong and colleagues [14] conducted a study on the bearing capacity of reinforced concrete columns by employing nonlinear material models from TCVN 5574:2018. They introduced a practical spreadsheet and a method for calculating the bearing capacity of reinforced concrete columns, utilising nonlinear models that simulate the stress-strain relationship of concrete and steel materials through two and three straight lines as outlined in TCVN 5574:2018. Chuong and Quy [15] have introduced a calculation method in accordance with TCVN 5574:2012 for square reinforced concrete columns under eccentric compression. The authors utilised Weber's interpolation method to develop interaction diagrams in accordance with TCVN for calculating reinforcement in columns under eccentric compression.

Li and colleagues [16] examined the axial compressive characteristics of carbon fibre reinforced concrete columns that had undergone secondary corrosion. Liu and colleagues [17] conducted experiments on the eccentric compression behaviour of rectangular concrete columns that were reinforced with steel and BFRP bars. This research focused on examining the eccentric compression characteristics of concrete columns that are reinforced with a combination of steel and basalt fibre reinforced polymer (BFRP) hybrid bars, along with tie bars. Furthermore, Lin et al. [18] investigated the compressive strength of reinforced concrete columns confined by composite materials. This research introduced a model designed to accurately predict the compressive strength of concrete columns confined by composite materials (FRP) and examined the performance differences of FRP-wrapped concrete columns and RC columns under uniaxial compression. Quang and colleagues [19] performed experiments to assess the central compression of reinforced concrete columns that utilised carbon woven mesh. They evaluated the practicality of enhancing the RC column structure through the application of carbon woven mesh reinforced concrete.

Taha and Nounu examined the properties of concrete that incorporates recycled glass as a sand substitute in their study of reinforced concrete columns [20]. Mansour et al. conducted a systematic evaluation of the durability of concrete that incorporates recycled glass [21], offering valuable insights into enhancing concrete quality and minimising environmental impact. Shayan and Xu discussed the value of waste glass in concrete and its utilisation [22], highlighting the significant potential of incorporating waste glass in various forms, such as fine aggregate, coarse aggregate, and GLP. Farshad Rajabipour and colleagues investigated the alkali-silica reaction of recycled glass aggregate in concrete materials [23], showcasing the size effect phenomenon through scanning electron microscopy (SEM) and energy dispersive spectroscopy of mortars with glass particles of varying sizes.

Taha et al. explored the use of recycled waste glass as a substitute for sand/cement in concrete in their experimental studies [24]. This research examined the practicality of incorporating recycled glass into concrete in the form of recycled glass sand and pozzolanic glass powder. Hongjian presented a study on concrete incorporating recycled glass as fine aggregate [25]. This study utilised recycled glass as a substitute for sand in concrete, with replacement rates of 0%, 25%, 50%, and 100%. The properties of the concrete specimens were evaluated in both fresh and hardened states across three types of concrete, exhibiting compressive strengths of 30, 45, and 60 Pa. Kou and Poon [26] conducted an experimental study on the substitution of glass chips for river sand at ratios of 10%, 20%, and 30%, along with 10mm granite at 5%, 10%, and 15% in a self-compacting concrete mixture. Or some other research on recycled aggregates [27–30].

In this study, the authors have conducted the following research contents:

- Experimental study of the compressive behaviour of square reinforced concrete columns using recycled glass to replace sand (alkali-silica reaction risks in concrete were not considered in this study): constructing a diagram of the relationship between load and deformation, load and vertical displacement, and a diagram of formation and propagation of cracks in columns through load levels.
- Examining the impact of factors including recycled glass content as a substitute for sand in concrete, variations in stirrups within reinforced concrete columns, and the influence of load-bearing steel content on the performance of square reinforced concrete columns.

The research will include designing reinforced concrete columns, producing glass particles with the modulus of natural sand, pouring concrete columns, testing, and reporting on the results.

Glass is increasingly recognized as a sustainable substitute for traditional sand in concrete structures. This shift is driven by the growing demand for environmentally friendly building materials and the need to recycle waste products.

The selection of sand modules for concrete mixing follows the TCVN 7570-2-2006 standard, which provides guidelines for aggregates in concrete and mortar applications [31].

2. Materials and Methods

2.1. Experimental Model of the Samples

Research indicates that the proportion of recycled glass substituting sand in concrete can vary from 10% to 100% [32, 33], based on 0.12 × 0.12 × 1 column size and permitted steel content in concrete. The authors will conduct compression tests on seven column samples using the parameters outlined below: (1) Four column samples with varying recycled glass content substituting sand at 0%, 100%, 50%, and 10%, respectively, ∅8 rebars and stirrup spacing of ∅6a200; (2) One column sample with recycled glass content substituting sand at 10%, ∅10 rebars, and stirrup spacing of ∅6a200; (3) One column sample with recycled glass content substituting sand at 10%, ∅8 rebars, and stirrup spacing of ∅6a100; (4) One column sample with recycled glass content substituting sand at 10%, ∅8 rebars, and stirrup spacing of ∅6a200 in the middle of the column, with ∅6a100 at the support. Consequently, the author performed experiments on seven column samples with defined parameters, as detailed in **Table 1** and **Table 2** below:

Table 1. Experimental column sample.

Column Title	Sizes (m)	Percentage of Glass Replacing Sand (%)	Rebar	Stirrups		
				Column Head	Middle of the Column	Column Base
C1	0.12 × 0.12 × 1	0	4∅8		∅6a200	
C2	0.12 × 0.12 × 1	100	4∅8		∅6a200	
C3	0.12 × 0.12 × 1	50	4∅8		∅6a200	
C4	0.12 × 0.12 × 1	10	4∅8		∅6a200	
C5	0.12 × 0.12 × 1	10	4∅10		∅6a200	
C6	0.12 × 0.12 × 1	10	4∅8		∅6a100	
C7	0.12 × 0.12 × 1	10	4∅8	∅6a100	∅6a200	∅6a100

Table 2. Sample parameters.

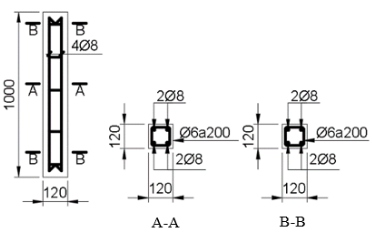
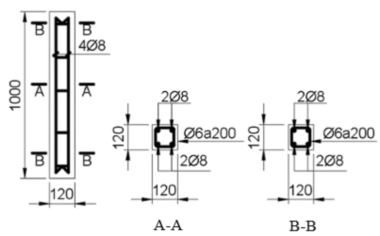
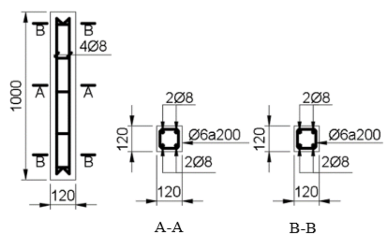
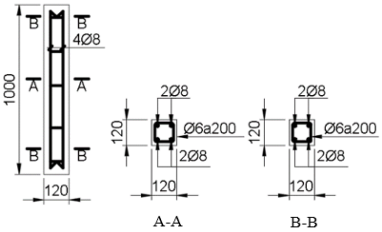
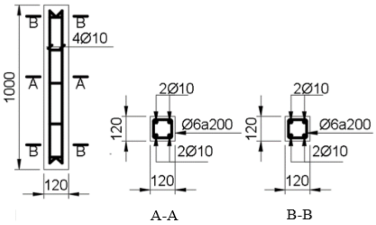
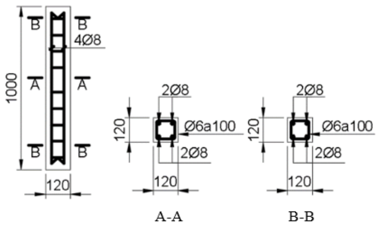
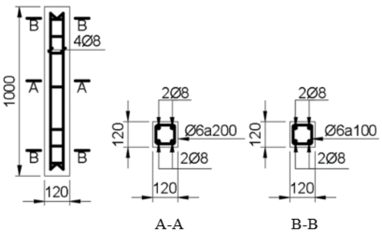
No.	Column Title	Sample Parameters
1	C1 (percentage of glass replacing sand, 0%)	
2	C2 (percentage of glass replacing sand, 100%)	
3	C3 (percentage of glass replacing sand, 50%)	

Table 2. *Cont.*

No.	Column Title	Sample Parameters
4	C4 (percentage of glass replacing sand, 10%)	
5	C5 (percentage of glass replacing sand, 10%)	
6	C6 (percentage of glass replacing sand, 10%)	
7	C7 (percentage of glass replacing sand, 10%)	

2.2. Manufacturing Glass Aggregate Instead of Sand

Processing steps for recycled glass aggregate:

- Collection and Sorting: recycled glass is sourced primarily from demolition projects, post-consumer glass waste, and industrial glass scraps. Careful sorting is conducted to eliminate contaminants such as plastics, metals, and ceramics.
- Crushing: The collected glass is crushed into smaller particles using manual or mechanical methods. The goal is to achieve uniformity in size to facilitate subsequent processing (**Figure 1**).
- Sieving: The crushed glass is passed through various types of sieves to ensure the grain size meets specific requirements for sand replacement in concrete. This step is crucial for achieving the desired workability and strength of the final concrete mix (**Figure 2a**). The particle sizes for sieving, according to TCVN 7572-6:2006[], are 5, 2.5, 1.25, 0.63, 0.315, and 0.14 mm.
- Washing: To remove dirt, debris, and any remaining contaminants, the sieved glass aggregate is thoroughly washed with water (**Figure 2b**). This washing process is essential to ensure the purity and performance of the glass aggregate in concrete.
- Drying: After washing, the glass aggregate is dried to eliminate moisture, which can affect the mixing process and the overall performance of the concrete.

The material properties of glass aggregates are discussed in **Table 3** below.

Figure 1. Glass is crushed into modules of sand aggregate.

(**a**)

(**b**)

Figure 2. Recycled glass has been created: (**a**) Glass is filtered using various kinds of sieves; and (**b**) sieved glass aggregate.

Table 3. Glass aggregate properties.

Property	Description
Chemical composition	SiO_2: 70–75%, Na_2O: 12–15% CaO: 8–10%, Al_2O_3: 1–2% Fe_2O_3: <1%, Others: MgO & K_2O
Specific gravity	2.4 to 2.6
Color	White or light grey
Pozzolanic activity	High silica content
Mechanical properties	Enhanced mechanical properties
Durability aspects	Resistance to porosity and chemical attack
Environmental impact	Waste glass disposal is reduced thus reducing environmental impact.

2.3. Formwork Processing, Steel Reinforcement, Concrete Pouring for Columns

The process for constructing concrete columns followed key steps: formwork preparation, steel reinforcement placement, and concrete pouring.

First, formwork was set up to shape the columns, and steel reinforcement bars were placed inside to provide tensile strength (**Figure 3**). Next, aggregates were weighed before mixing to ensure the correct concrete composition (**Figure 4**). The materials included cement, recycled glass aggregate and stone aggregate. No adjustments are made to the water-cement ratio when substituting recycled glass for sand in the concreting process.

Finally, the concrete mix was poured into the formwork, surrounding the steel reinforcement (**Figure 5**). Vibrators were used to remove air pockets, and the formwork remained in place while the concrete cured, ensuring a strong and stable column.

2.4. Testing of Reinforced Concrete Columns

The experimental setup for testing reinforced concrete columns is shown in **Figure 6**, which consists of two views of the column: (**a**) Front of the column and (**b**) Back of the column.

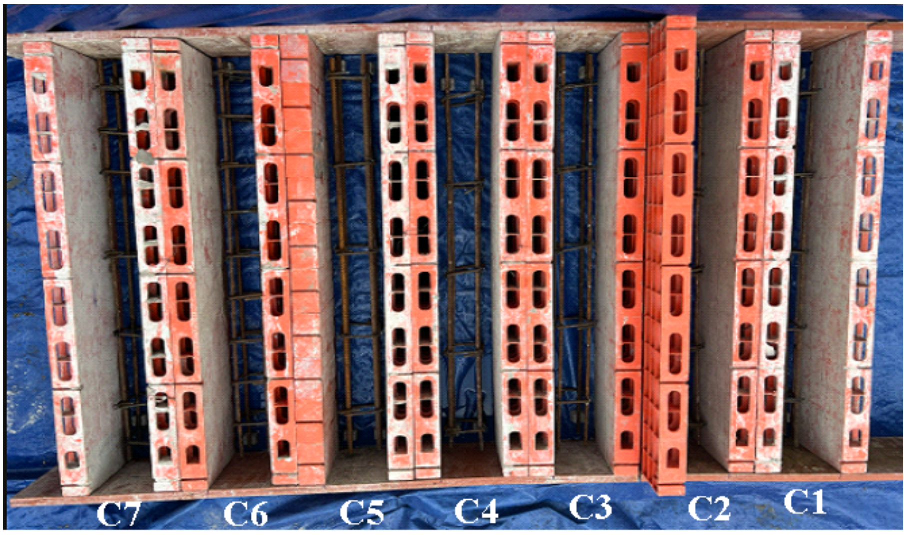


Figure 3. The formwork and reinforcement for the columns have been created.

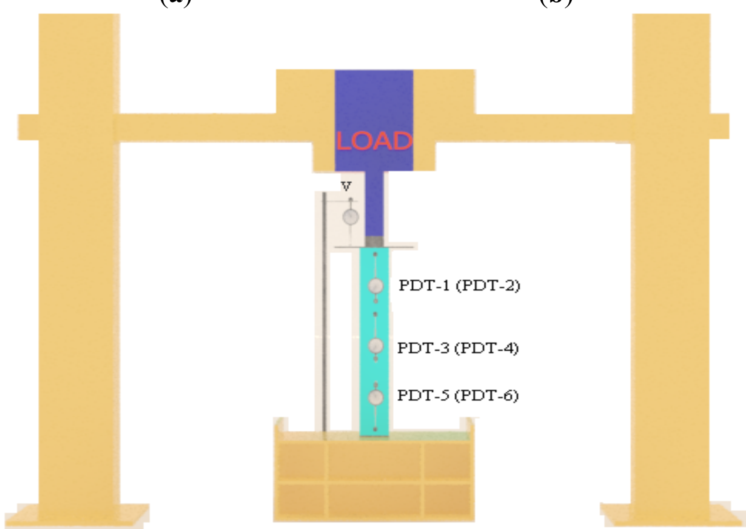
(**a**) (**b**) (**c**)

Figure 4. Aggregates are weighed before mixing: (**a**) cement (**b**) recycled glass (**c**) stone aggregate.

Figure 5. Columns of concrete have been poured.

(**a**)

(**b**)



(**c**)

Figure 6. The experimental equipment layout: (**a**) front of column, (**b**) back of the column, and (**c**) installation of measuring devices.

The reinforced concrete column is vertically positioned, with various measuring devices attached to record the column's response to applied forces. The column is mounted on a testing platform, where the base is secured to a round support plate designed to simulate load conditions with strain gauges mounted on the column. A hydraulic jack is placed at the top, exerting compressive force on the column.

3. Results and Discussion

Figure 7 illustrates the final condition of these columns, capturing any visible damage, bending, crushing, or failure modes that have occurred as a result of the testing process.

3.1. Effect of Recycled Glass Substituting Sand Aggregate in Concrete

Group 1 includes columns C1, C2, C3, and C4, which investigate the impact of varying percentages of recycled glass substituting sand. Column C1 has 0% recycled glass, while C2 is entirely composed of recycled glass at 100%. Column C3 has 50% recycled glass, and Column C4 has 10% recycled glass. This group aims to assess how these variations affect the load-bearing capacity and cracking behavior of the columns.

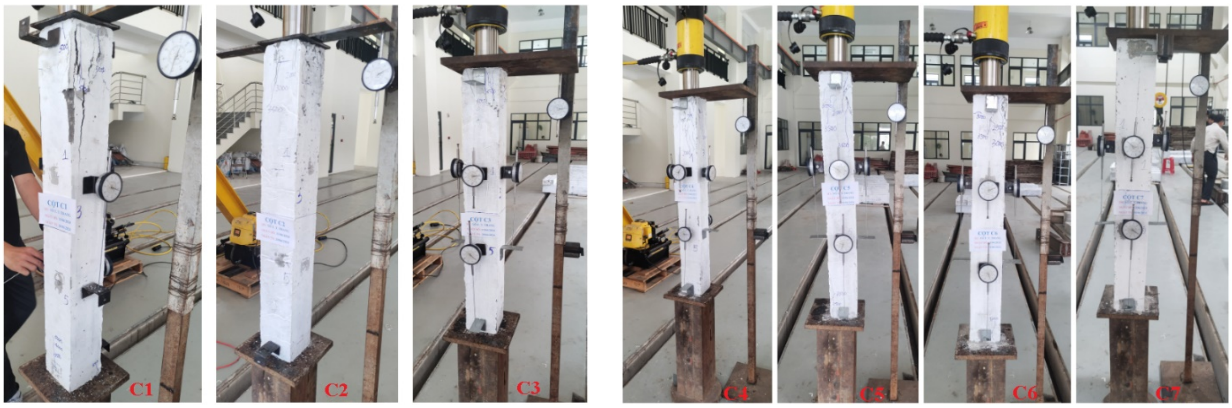


Figure 7. After tests, the shape of the column samples.

1. The effect of recycled glass substituting sand on column bearing capacity under centric compression (**Figure 8**).
   The results depicted in **Figure 8** highlight the impact of substituting sand with recycled glass on the load-bearing capacity of concrete columns.
   - C1 and C4 (0% to 10% recycled glass): When recycled glass content increased from 0% to 10%, the columns' bearing capacity remained unchanged at 250 kN, and initial cracks appeared at 175 kN in both samples. This suggests that replacing sand with 10% glass has no noticeable effect on the structural performance, as the columns maintained similar strength and resistance to cracking.
   - C1 and C3 (0% to 50% recycled glass): As recycled glass substitution increased from 0% to 50%, the bearing capacity dropped from 250 kN to 200 kN, indicating that column C3's capacity was 80% of column C1's. The first crack in C3 occurred earlier, at 125 kN, compared to C1. This decrease in performance can be attributed to the higher glass content, which likely weakened the bond between the concrete aggregates, given the differing shapes and surface textures of glass and sand.
   - C1 and C2 (0% to 100% recycled glass): With 100% of the sand replaced by glass, the bearing capacity fell significantly from 250 kN to 150 kN, making C2's capacity only 60% of C1's. Column C2 also exhibited earlier cracking, with the first crack appearing at 75 kN. The full substitution of sand with glass greatly reduced the cohesion between aggregates, leading to a notable decline in both the structural strength and cracking resistance.
2. Effect of recycled glass content replacing sand on compressive strain at column head through load levels (**Figure 9**).
   The results presented in **Figure 9** indicate the following:

- C1 and C4 (0% to 10% recycled glass): As the percentage of recycled glass substituting sand increased from 0% to 10%, the compressive strain at the column head of C4 showed greater fluctuations between load levels of 0–100 kN and 175–250 kN compared to C1. However, the difference was not significant, suggesting that using recycled glass as a sand substitute at levels below 10% has minimal impact on the compressive strain at the column head.
- C1 and C3 (0% to 50% recycled glass): When the percentage of recycled glass increased from 0% to 50%, the compressive strain at the column head of C3 exhibited more variability than C1. It demonstrated a relatively stable increase in strain at load levels of 0–100 kN, but an unstable increase between 125–200 kN. At a load level of 200 kN, the compressive strain at the head of column C3 was approximately 4.1 times greater than that of C1.
- C1 and C2 (0% to 100% recycled glass): With 100% of the sand replaced by recycled glass, the compressive strain at the column head of C2 displayed even greater variability compared to C1. At load levels ranging from 0–125 kN, the strain in C2 increased steadily, followed by a sudden rise at 150 kN. At this load level, the compressive strain at the head of column C2 was approximately 14 times greater than that of C1.

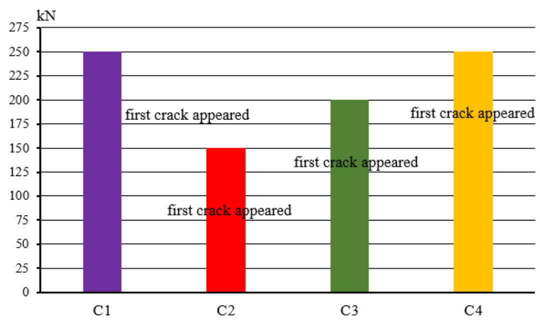


Figure 8. The load-bearing capacity.

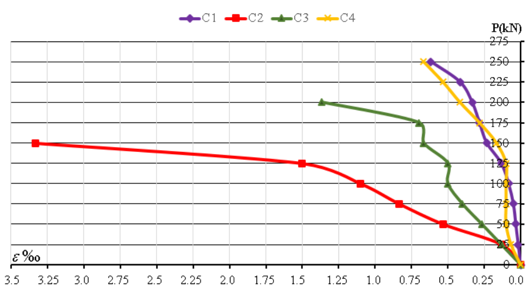


Figure 9. Load-compression strain (column head).

3. Effect of recycled glass content replacing sand on compressive strain at the middle of the column through load levels (**Figure 10**)

   The results presented in **Figure 10** indicate the following:

- C1 and C4 (0% to 10% recycled glass): As the percentage of recycled glass substituting sand increased from 0% to 10%, the compressive strain at the midpoint of column C4 exhibited greater fluctuations compared to column C1 at various load levels. At a load level of 250 kN, the compressive strain at the midpoint of column C4 was approximately 1.65 times greater than that of column C1.
- C1 and C3 (0% to 50% recycled glass): With the percentage of recycled glass rising from 0% to 50%, the compressive strain at the midpoint of column C3 also displayed more significant fluctuations compared to column C1. At a load level of 200 kN, the compressive strain at the midpoint of column C3 was about 2.4 times greater than that of column C1.
- C1 and C2 (0% to 100% recycled glass): When the sand was fully replaced by recycled glass, the compressive strain at the midpoint of column C2 showed significantly greater variability than that of column C1. At a load level of 150 kN, the compressive strain at the midpoint of column C2 was approximately 10.7 times greater than that of column C1.

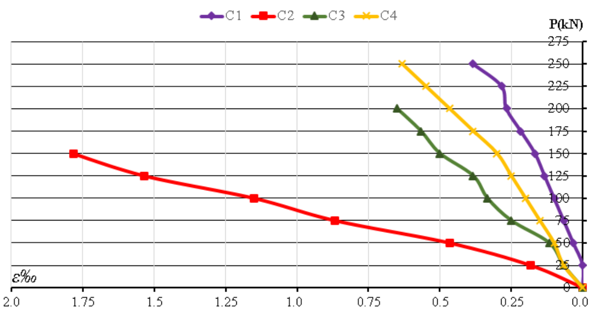


Figure 10. Load-compression strain (mid-column).

4. Effect of recycled glass content replacing sand on compressive deformation at column base through load levels (**Figure 11**).

   The results presented in **Figure 11** indicate the following:

- C1 and C4 (0% to 10% recycled glass): As the percentage of recycled glass substituting sand increased from 0% to 10%, the compressive strain at the base of columns C4 and C1 showed comparable values at load levels between 0 and 100 kN. However, at load levels from 100 to 250 kN, the compressive strain at the base of column C4 exceeded that of column C1. Specifically, at a load level of 250 kN, the compressive strain at the base of column C4 was approximately 2.5 times greater than that of column C1.

- C1 and C3 (0% to 50% recycled glass): With the percentage of recycled glass increasing from 0% to 50%, the compressive strain at the base of column C3 exhibited greater fluctuations compared to column C1. Notably, at a load level of 200 kN, the compressive strain at the base of column C3 was approximately 2.1 times greater than that of column C1.
- C1 and C2 (0% to 100% recycled glass): When the sand was fully replaced by recycled glass, the compressive strain at the base of column C2 showed significantly greater variability than that of column C1. At a load level of 150 kN, the compressive strain at the base of column C2 was approximately 4.8 times greater than that of column C1 across various load levels.

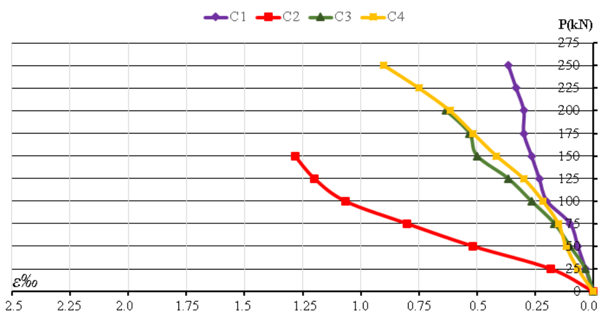


Figure 11. Load-compression strain (column base).

5. The influence of recycled glass content replacing sand on vertical displacement of columns through load levels (**Figure 12**).

   The results presented in **Figure 12** indicate the following:

- C1 and C4 (0% to 10% recycled glass): As the percentage of recycled glass substituting sand increased from 0% to 10%, the vertical displacement of column C4 was comparable to that of column C1 within the load range of 0–125 kN. However, at load levels between 125 and 250 kN, the vertical displacement of column C4 increased significantly, greatly exceeding that of column C1. At a load level of 250 kN, the vertical displacement of column C4 was approximately 2.8 times greater than that of column C1.
- C1 and C3 (0% to 50% recycled glass): As the percentage of recycled glass increased from 0% to 50%, the vertical displacement of column C3 exhibited greater fluctuations compared to column C1. At a load level of 200 kN, the vertical displacement of column C3 was approximately 2.4 times greater than that of column C1.
- C1 and C2 (0% to 100% recycled glass): When the sand was completely replaced by recycled glass, column C2 demonstrated greater variability in vertical displacement compared to column C1. At a load level of 150 kN, the vertical displacement of column C2 was approximately 3.2 times greater than that of column C1.

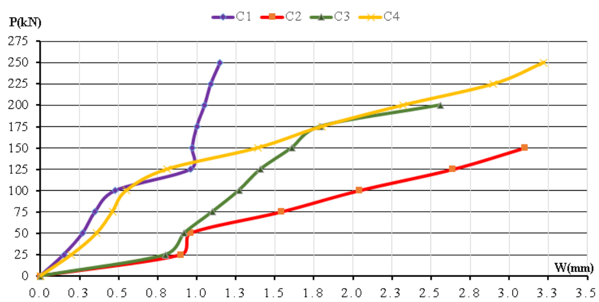


Figure 12. Load-vertical displacement.

The results obtained from the diagrams in **Figures 8–12** provide an overview about the deformation of the column as the percentage of recycled glass substituting sand varies from 0% to 10%, 50%, and 100% as outlined below: The compressive strength of recycled glass is not as effective as that of sand; therefore, as the percentage of glass replacing sand increases, both the working capacity of the column before cracks develop and its load-bearing capacity will decrease. As the percentage of recycled glass used as a substitute of sand in the reinforced concrete column rises, there is a corresponding increase in both the compressive deformation and vertical displacement of the column. The content of recycled glass influences the bearing capacity of the reinforced concrete column when subjected to normal compression. The recycled glass particles weren't treated with surface treatment or partial substitution with pozzolanic materials.

3.2. Investigation of How Reinforcement Content Affects Column Behaviour under Centric Compression

Group 2 focuses on columns C4 and C5, comparing their performance with different reinforcement contents while maintaining a constant recycled glass percentage of 10%. Column C4 is reinforced with 4∅8, whereas column C5 has increased reinforcement with 4∅10. This comparison aims to determine how enhanced reinforcement affects the overall structural integrity and cracking loads of the columns.

1. The influence of the content of steel reinforcement on the load-bearing capacity of columns under centric compression (**Figure 13**).
   The results presented in **Figure 13** indicate the following:
   - C4 and C5: With both columns containing the same recycled glass content substituting sand (10%), the load-bearing capacity remained unchanged despite an increase in reinforcement content (from 4∅8 to 4∅10). However, the load level at which the first crack occurred in column C5 was higher than in column C4. Specifically, column C4 exhibited cracks at 175 kN, while column C5 showed cracks at 200 kN. This demonstrates that enhancing the reinforcement content contributes to improving the column's performance prior to the onset of cracking.

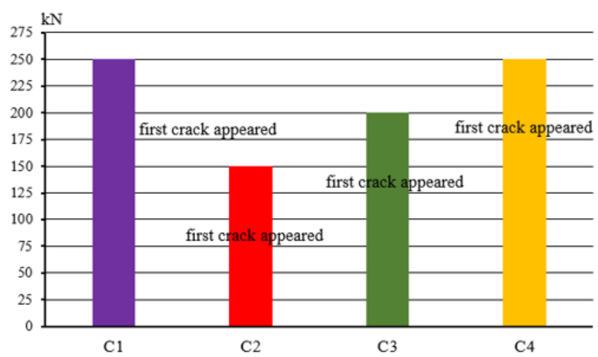


Figure 13. The load-bearing capacity.

2. The influence of steel reinforcement content on compressive deformation at column head (**Figure 14**).
   The results presented in **Figure 14** indicate the following:
   - C4 and C5: In the reinforced concrete column samples where 10% of the sand was replaced by recycled glass, the steel content varied from 4∅8 to 4∅10. The compressive strain at the column head for both C4 and C5 showed minimal variation at load levels between 0 and 175 kN. However, starting at a load level of 200 kN, the compressive strain at the column head of C5 exhibited greater variability compared to C4. At a load level of 250 kN, the compressive strain at the head of column C5 was approximately 0.4 times that of column C4.

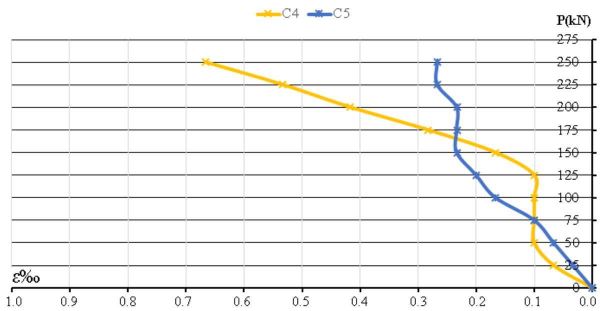


Figure 14. Load-compression strain (column head).

3. The influence of steel reinforcement content on compressive deformation at the middle of the column (**Figure 15**).
   The results presented in **Figure 15** indicate the following:
   - C4 and C5: The compressive strain at the midpoint of column C5 varied similarly to that of column C4, with negligible differences in values. At a load level of 250 kN, the compressive strain at the midpoint of column C5 was approximately 0.8 times that of column C4.

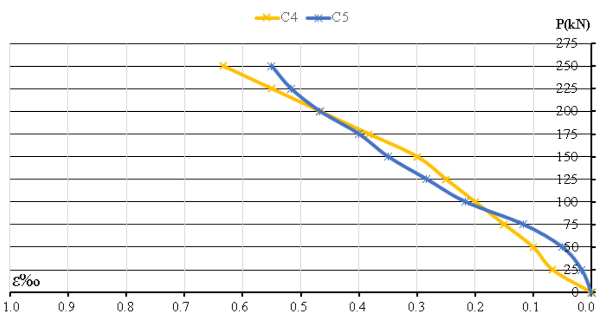


Figure 15. Load-compression strain (mid-column).

4. The influence of steel reinforcement content on compressive deformation at column base (**Figure 16**).
   The results presented in **Figure 16** indicate the following:
   - C4 and C5: The deformation at the base of column C5 was similar to that of column C4 at load levels from 0 to 125 kN. However, starting from 150 kN, the compressive strain at the base of column C5 exhibited less

variation compared to column C4. At a load level of 250 kN, the compressive strain at the base of column C5 was approximately 0.6 times that of column C4.

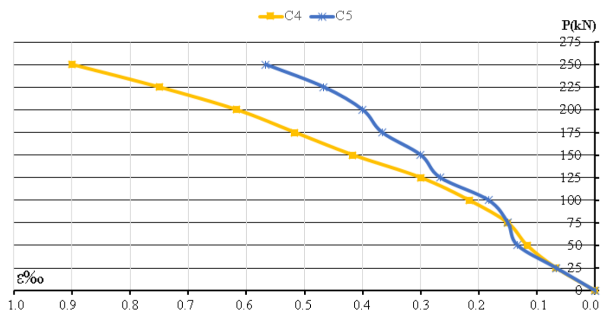


Figure 16. Load-compression strain (column base).

5. The influence of steel reinforcement content on vertical displacement of columns under centric compression (**Figure 17**).

   The results presented in **Figure 17** indicate the following:

   - The vertical displacement of column C5 was less than that of column C4. At a load level of 250 kN, the vertical displacement of C5 was approximately 0.8 times that of C4.

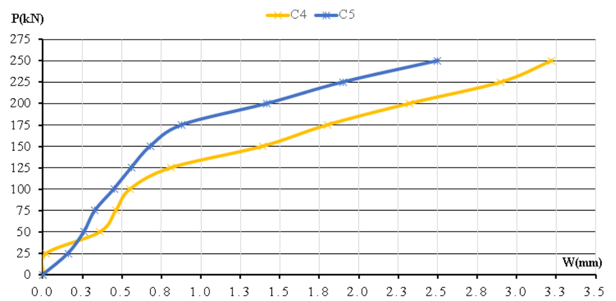


Figure 17. Load-vertical displacement.

The results from **Figures 13–17** indicate that when the columns include the same percentage of recycled glass substituting sand, but there is a variation in the steel reinforcement content, the compressive strain value in the columns decreases. This leads to an increase in the working capacity of the column, demonstrating that the load level at which the first crack occurs in column C5 is greater than that in column C4. This aligns with the theory that an increase in axial reinforcement leads to a corresponding increase in the compressive strength of the column, as the higher steel reinforcement content improves the column's bearing capacity.

3.3. Investigation of the Influence of Stirrup Spacing on Column Behavior under Centric Compression

Group 3 comprises columns C4, C6, and C7, which examine the influence of stirrup spacing on the performance of the columns. In this group, C4 has a stirrup spacing of 200 mm, while C6 has a reduced spacing of 100 mm, and C7 maintains 100 mm at the column head and 200 mm in the midsection. The analysis in this group is designed to evaluate how variations in stirrup spacing can impact the load-bearing capacity and cracking behavior of the columns.

1. The influence of stirrup spacing on the load-bearing capacity of columns under centric compression (**Figure 18**).

   The results presented in **Figure 18** indicate the following:

   - C4 and C6: When the stirrup spacing was reduced from 200 mm to 100 mm, the load-bearing capacity of the column remained unchanged at 250 kN. However, column C6 exhibited a higher load level for the first crack compared to column C4, with C6 showing its first crack at 200 kN, while C4 showed its first crack at 175 kN.
   - C4 and C7: With the stirrup spacing set at 200 mm at the column head and 100 mm in the middle of the column, the load-bearing capacity again remained unchanged at 250 kN. Column C7 demonstrated a higher load level for the first crack compared to column C4, with the first crack in column C7 occurring at 200 kN, while column C4 experienced its first crack at 175 kN.

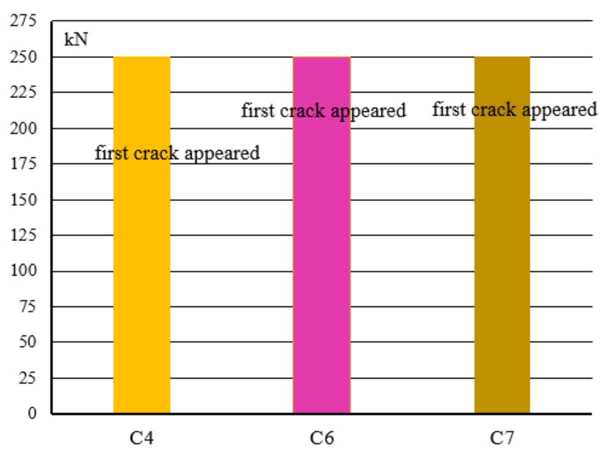


Figure 18. The load-bearing capacity.

2. The influence of stirrup spacing on compressive deformation at column head (**Figure 19**).
   The results presented in **Figure 19** indicate the following:

   - C4 and C6: The compressive strain at the column head of C6 was comparable to that of column C4 at load levels ranging from 0 to 150 kN. However, starting at a load level of 175 kN, the compressive strain at the column head of C6 was lower than that of column C4. At a load level of 250 kN, the compressive strain at the column head of C6 was approximately 0.4 times that of column C4.
   - C4 and C7: The compressive strain at the column head of C7 matched that of column C4 at load levels from 0 to 175 kN. However, beginning at a load level of 200 kN, the compressive strain at the column head of C7 was less than that of column C4. At a load level of 250 kN, the compressive strain at the column head of C7 was approximately 0.7 times that of column C4. This indicates that a reduction in stirrup spacing results in a decrease in the strain observed at the column head of the test sample.

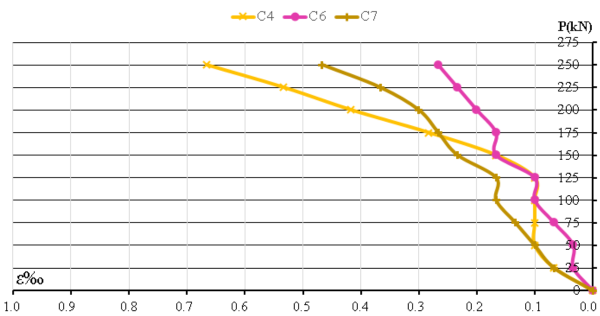


Figure 19. Load-compression strain (column head).

3. The influence of stirrup spacing on compressive deformation at the middle of the column (**Figure 20**).
   The results presented in **Figure 20** indicate the following:

   - C4 and C6: The compressive strain at the midpoint of column C6 was consistently lower than that of column C4 at various load levels. At a load level of 250 kN, the compressive strain at the midpoint of column C6 was approximately 0.4 times that of C4.
   - C4 and C7: The compressive strain at the midpoint of column C7 was comparable to that of column C4 at load levels ranging from 0 to 150 kN. However, starting from a load level of 175 kN, the compressive strain in column C7 exhibited less variation compared to that of C4. At a load level of 250 kN, the compressive strain at the midpoint of column C7 approached approximately 0.9 times that of C4.

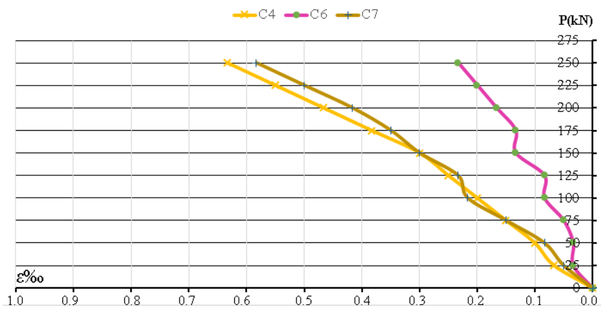


Figure 20. Load-compression strain (mid-column).

4. The influence of stirrup spacing on compressive deformation at column base (**Figure 21**).
   The results presented in **Figure 21** indicate the following:

   - C4 and C6: The compressive strain at the base of column C6 was comparable to that of column C4 at load levels ranging from 0 to 125 kN. However, starting at a load level of 150 kN, the compressive strain at the base of column C6 exhibited less variation compared to that of C4. At a load level of 250 kN, the compressive strain at the base of column C6 was approximately 0.5 times that of C4.
   - C4 and C7: The compressive strain at the base of column C7 matched that of column C4 at load levels from 0 to 125 kN. From a load level of 150 kN onward, the compressive strain at the base of column C7 showed fewer fluctuations compared to column C4. At a load level of 250 kN, the compressive strain at the base of column C7 was approximately 0.7 times that of C4.

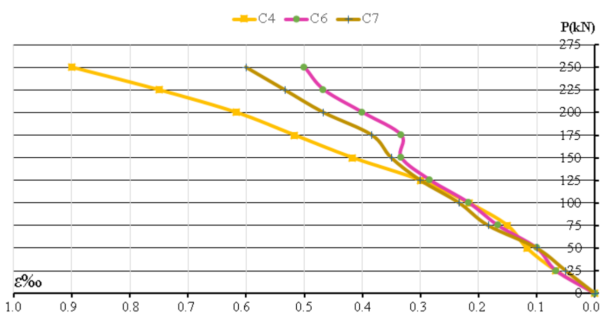


Figure 21. Load-compression strain (column base).

5. The influence of stirrup spacing on vertical displacement

of columns under centric compression (**Figure 22**).

The results presented in **Figure 22** indicate the following:

- C4 and C6: The vertical displacement of column C6 was less than that of column C4. At a load level of 250 kN, the vertical displacement of C6 was approximately 0.2 times that of C4.
- C4 and C7: The vertical displacement of column C7 was also less than that of column C4. At a load level of 250 kN, the vertical displacement of C7 was approximately 0.3 times that of C4.

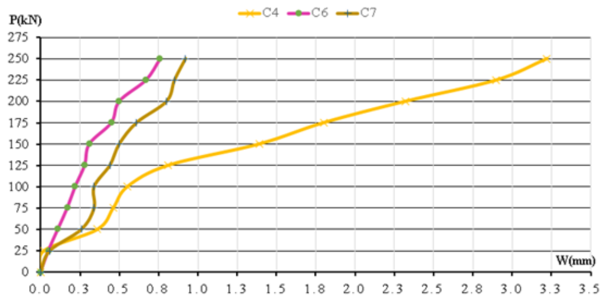


Figure 22. Load-vertical displacement.

The results from **Figures 18–22** indicate that when the reinforced concrete column includes the same percentage of recycled glass substituting sand, variations in stirrup spacing, as seen in group 3, lead to a reduction in deformation at the column sections across different load levels. The thicker the stirrup spacing, the greater the working capacity of the column will be, while the deformation and vertical displacement of the column will decrease.

3.4. Optimization Problem

1. Compressive deformation at the column head (**Figure 23**).

   In terms of bearing capacity and compressive deformation at the column head, column C6 is the most favorable option among the tested columns. This is attributed to the fact that the deformation at the column head of C6 is the lowest compared to the others. Additionally, the bearing capacity of column C6 is consistent with that of a standard reinforced concrete column. Notably, the load level at which cracks first appear in column C6 is higher than that of the standard column, with initial cracks occurring at a load level of 200 kN for C6, compared to 175 kN for the standard reinforced concrete column.

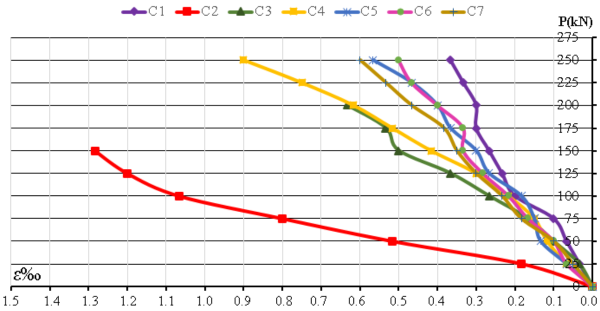


Figure 23. Load-compression strain (column head).

2. Compressive deformation at middle column (**Figure 24**).

   The results presented in **Figure 24** indicate that, regarding bearing capacity and compressive deformation at the middle of the column, C6 stands out as the most favorable option among the columns. The deformation at the middle of column C6 is the lowest among all columns, and concurrently, the bearing capacity of column C6 matches that of a normal reinforced concrete column.

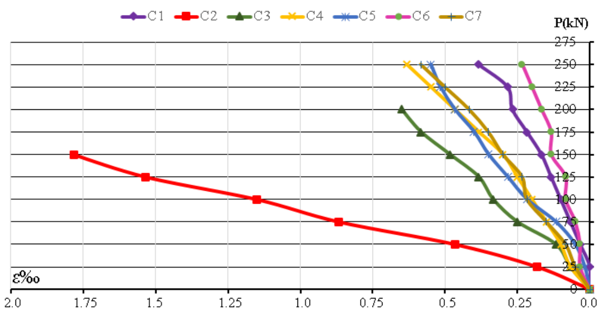


Figure 24. Load-compression strain (mid-column).

3. Compressive deformation at column base (**Figure 25**).

   The results presented in **Figure 25** indicate that: C6 is the optimal choice among the columns regarding bearing capacity and compressive deformation at the column base. The deformation at the base of column C4 is the smallest among the columns, excluding the normal reinforced concrete column.

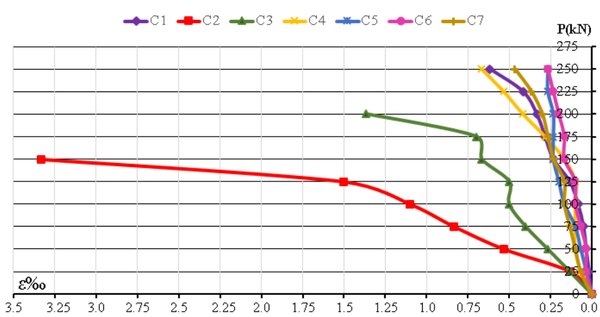


Figure 25. Load-compression strain (column base).

4. Vertical displacement of columns (**Figure 26**).

   The results presented in **Figure 26** indicate that C6 is the most optimal choice among the columns regarding bearing capacity and vertical displacement. The vertical displacement of column C6 is the smallest among the columns. Additionally, the bearing capacity of column C6 matches that of a normal reinforced concrete column. Notably, the load level at which the first crack appears in column C6 is greater than that of a normal reinforced concrete column, with C1 experiencing its first crack at P = 175 kN, while C6 shows its first crack at P = 200 kN.

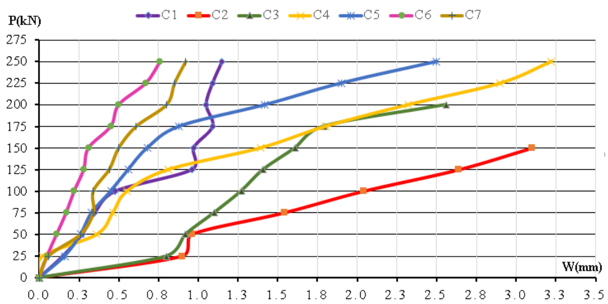


Figure 26. Load – vertical displacement.

The results of displacement and deformation in the columns indicate that the compressive strain of the column containing 50% recycled glass as a substitute for sand aggregate in concrete shows a sudden change in value. Consequently, recycled glass can only be used in concrete with a content less than this value.

3.5. FTIR Analysis

FTIR analysis was conducted to identify the chemical bonds and functional groups present in the samples. FTIR spectra were recorded in the wavenumber range of 4500–400 cm^{-1} to capture the relevant functional groups.

C1 (0% Recycled Glass): The FTIR analysis depicted in **Figure 27** revealed peaks related to common concrete components, such as C–H stretching vibrations in aliphatic compounds, which appeared around 2900–3000 cm^{-1}. Additionally, peaks around 2348 cm^{-1} and 852 cm^{-1} indicated the presence of Si–O bonds typical of silica and quartz. There was an absence of any peaks associated with recycled glass components.

C2 (100% Recycled Glass): The mix fully replaced sand with recycled glass. The FTIR results depicted in **Figure 28** showed prominent peaks in the 700–1000 cm^{-1} region and 2000–3000 cm^{-1} corresponding to bending vibrations of Si–O–Si bonds, which are common in glass structures. Additionally, there was a reduced intensity of peaks associated with concrete components, such as C–H stretching, indicating lower cement content due to the absence of natural sand.

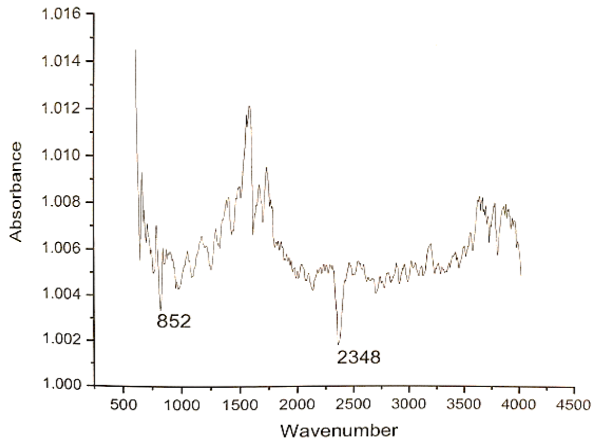


Figure 27. FTIR graph of sample C1.

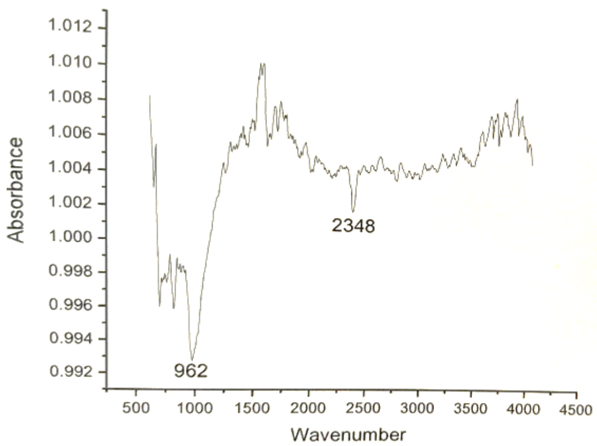


Figure 28. FTIR graph of sample C2.

C3 (50% Recycled Glass): The mix contained half recycled glass and half natural sand. The FTIR results revealed peaks indicating both Si–O bonds from the sand and glass components, demonstrating a blend of traditional concrete characteristics and glass properties. Moderate peaks in the 1000–1200 cm^{-1} range showed Si–O stretching, although they were less pronounced than those in the 100% glass mix. Additionally, there was a presence of peaks associated with cement hydration products, though the intensity varied depending on the degree of hydration related to the glass content.

C4 (10% Recycled Glass): The mix contained a small percentage of recycled glass, representing a minor substitution of sand. The FTIR results showed minimal peaks in the 1000–1200 cm^{-1} range, indicating the presence of Si–O bonds from the recycled glass, albeit with a strong background of traditional concrete peaks. Dominant peaks around 2900–3000 cm^{-1} were observed for C–H stretching vibrations from the cement matrix. Additionally, there was evidence of some interaction between the glass and the cement matrix, possibly indicated by shifts or changes in the peak shapes or positions due to the introduction of recycled materials.

4. Conclusions

The following are some of the conclusions that are derived from the results of the study:

- Load and Deformation Relationships: Experiments conducted on square reinforced concrete columns under centric compression established clear diagrams illustrating the relationships between load and deformation, load and vertical displacement, and the formation and propagation of cracks at various load levels. This foundational data offers a basis for understanding column behavior under compression.
- Impact of Recycled Glass on Bearing Capacity: The study demonstrated that increasing the percentage of recycled glass substituting sand negatively impacts the column's bearing capacity. Specifically, as the recycled glass content rises from 0% to 100%, the bearing capacity of the columns decreased by approximately 40% (from 250 kN to 150 kN). This indicates a direct correlation between higher recycled glass content and diminished performance before crack formation, with associated increases in compressive deformation and vertical displacement.
- Influence of Steel Content: Increasing the steel reinforcement in columns while maintaining a fixed percentage of recycled glass led to significant variations in compressive strain. For instance, with a 10% recycled glass substitution, the compressive strain in the column with higher reinforcement (4∅10) was approximately 0.4 times lower than in the column with less reinforcement (4∅8) at a load of 250 kN. This highlights the importance of steel content in enhancing the structural performance of columns incorporating recycled glass.
- Effect of Stirrup Spacing: Changes in stirrup spacing resulted in corresponding variations in compressive strain at the columns. Reducing the spacing from 200 mm to 100 mm improved the performance, with columns exhibiting compressive strain values that were approximately 50% lower at peak loads compared to those with wider stirrup spacing. This finding emphasizes the critical role of stirrup configuration in the working capacity of recycled glass reinforced concrete columns.
- Optimal Proportion of Recycled Glass: The study concluded that incorporating recycled glass as a sand substitute in column structures subjected to centric compression is beneficial. The ideal proportion for substituting glass for sand aggregate in reinforced concrete columns, based on experimental results, ranges from 0% to 10%. Beyond this threshold, the performance diminishes significantly, reinforcing the idea that a balanced approach to recycled materials can enhance sustainability without compromising structural integrity. This study determined that a 10% ratio of recycled glass substituting sand in concrete was optimal for compression columns.
- The FTIR analysis of the various mixes demonstrated that the incorporation of recycled glass significantly influenced the presence and intensity of specific peaks associated with chemical bonds and functional groups, revealing distinct characteristics in the spectral profiles: as the percentage of recycled glass increased, the peaks related to traditional concrete components, such as C–H stretching vibrations, diminished, while those corresponding to Si–O bonds became more pronounced, suggesting varying degrees of interaction between the recycled materials and the cement matrix across the different samples.

Author Contributions

Conceptualization, data curation, literature review, first draft, editing, and proofreading, T.-Q.-K.L.; Experiment and software, T.-T.-T.V.; and FTIR Analysis, K.S.

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Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

The data used to support the findings of this study are included within the article.

Conflicts of Interest

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

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