Hindawi
Journal of Engineering
Volume 2022, Article ID 8672694, 10 pages
https://doi.org/10.1155/2022/8672694

Research Article

Flexural Ductility, Stiffness, and Toughness of New Voided Reinforced Concrete One-Way Slab Using Waste Plastic Bottles

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Received 19 October 2021; Revised 23 May 2022; Accepted 7 July 2022; Published 10 August 2022

Academic Editor: Hao Yi

The enhancement of concrete structures' performance can easily be achieved. However, the main challenge is how to achieve this performance with respect to the economy and sustainability. The aim of this research is to examine the flexural strength, ductility, stiffness, and toughness of RC hollow one-way slabs that are voided by plastic bottles. A new technique of hollowing has been used in this work, where a steel mesh tube was prepared previously and filled manually with blank waste plastic bottles to form a light tube. This technique has some advantages including ease of installation and adequate bonding for the main steel reinforcements. Five RC one-way slabs were cast and tested in the lab to investigate some variables: the presence of hollow, the ratio of reinforcement, and slab thickness. Briefly, a new technique for voids enhances the flexural behavior with less concrete and weight. The ductility is increased by about 100% for the voided specimens for the same section's thickness. Also, the rotation in supports had been reduced by about 30% when the thickness of voided slab was increased by about 15%.

1. Introduction

Yearly, massive quantities of plastic materials from numerous thing products are wasted all over the world. This problem has major environmental effects such as pollution. There have been multiple options for disposing of plastic waste in the previous [1]. Annually, between 4.8 and 12.7 million metric tons of waste is deposited into the ocean. Another way to get rid of waste plastic is by burning it, but this method negatively affects the atmosphere through the generation of CO_2. Furthermore, the remains of the burning process create additional toxic substances [2].

In the field of structural engineering, waste plastic bottles are used widely in concrete structures in different forms to enhance some mechanical properties of hardened concrete and as a sustainable solution to environmental problems. Different previous studies used chopped waste plastic bottles as fine and coarse aggregate in concrete ingredients by partial replacement of natural sand and gravel, respectively. Other investigations used waste plastic bottles in the form of chopped fiber to improve the performance of some types of concrete such as conventional concrete and self-compacting concrete [3–6].

Turning to voided concrete structural elements, there are many research and applications for using such types of structural elements: beams, slabs, and columns. There are many advantages to creating voids inside concrete structural elements. First is to reduce the weight of structural elements and second to provide concrete quantities, especially cement. Reducing the use of cement in concrete structures leads to lower CO_2 emissions. Furthermore, voids can be used as a service path for mechanical and electrical work. Different configurations have been formulated to produce voids inside the concrete structural elements such as bubbles

[5–12] and pipes [13–15]. However, these methods of voids are almost expensive and required complicated formwork to install.

Recently, a little research has been conducted on reinforced concrete elements to study the possibility of using plastic bottles as cavities inside these elements in a specific zone, where the stresses are very low or equal to zero (the center of voided areas locate or nearby at the neutral axis) [16–18]. There are many advantages of installing waste plastic bottles inside the structural elements. First is to reduce the weight of structural elements and second to provide concrete quantities, especially cement. Reducing the use of cement in concrete structures leads to lower carbon dioxide (CO_2) emissions.

Rahadyanto[9] in 2013, investigated the flexural behavior of RC voided beams using waste plastic bottles, which were installed at the midheight of the concrete beam with two grades of cylindrical concrete compressive strength, 25 and 33.2 MPa. The results demonstrated that the voided beam of 33.2 MPa concrete strength has about 98% of the moment capacity of the solid beam having the same concrete strength. In addition, there is no change in moment capacity due to using different concrete quality, 25 MPa or 33.2 MPa of voided reinforced concrete beams. For one-way slab, very little research had been conducted on plastic waste plastic bottles to form voids. Orientilize et al. [11] investigated the effects of using waste plastic bottles as voids to form a hollow core one-way slab on the flexural behavior. Three parametric studies were conducted: the content of voids, chopped PET, and steel fiber content. The studied content of voids was 19% and 24% as compared with zero content (solid slab). The ultimate moment capacity values of all voided slabs were 12 to 16% lower than the solid slab.

Most previous research about the use of waste plastic bottles to form voids in structural elements had no effective method for installing plastic bottles inside the slab correctly. Therefore, the main challenge of this issue is the floating of the plastic bottle during the process of the cast due to Archimedes' law. Some researchers tackle this problem by tying the plastic bottles directly to the longitudinal reinforcement in the tension zone. However, the reinforcing bars, which are connected to the plastic bottles, have no sufficient surrounding concrete layer around the reinforcing bars to provide sufficient bond strength and the voids situated in the critical zone of stress. So, it can affect the bond strength of steel bars, because the PET bottles are positioned at the border of steel bars and inhibited concrete paste flow around reinforcing bars.

In 2020, a new technique for installing waste plastic bottles inside the one-way slab has been used to address all the aforementioned difficulties [12]. The new technique was to make a steel wire mesh tube, which was filled manually with waste plastic bottles to form a hollow tube. The advantages of manufactured hollow tubes are to install the plastic bottles at any height through the section of the slab by tying them with steel bar spacers (chair bars). Therefore, the process will be quicker and easier than previous methods of fixation due to the previous fabrication of hollow tubes. Furthermore, steel wire mesh can contribute to steel reinforcing bars to sustain the tensile force, especially from the bottom side of a hollow tube. It is found that using a new technique to form new voided slabs systems has no effect on ultimate load capacity compared with solid slabs. In addition, the new system of voided slabs demonstrated pretty much the same behavior as solid slabs in terms of load-displacement curves [12]. Shishegaran et al. introduced the fixed RC frames using the transferred stress system (TSS) and conventional steel bars in 2020 [13]. Their outcomes are compared in order to specify and assess the performance of ordinary and TSS fixed frames. A novel test configuration for the fixed frame is created and carried out. Because of the different stress distributions in TSS beams, the crack expansions for the TSS fixed frame differ from the crack expansions for the conventional fixed frame. A nonlinear FE model was also given to mimic TSS and regular fixed frames. To assess the validity of the FE nonlinear models, the FE results are compared to the experimental data. Whereas, Shishegaran in 2019 [14] developed a substantial and new approach for increasing the flexural capacity of simply supported reinforced concrete beams. The suggested approach employs a novel reinforcing bar system comprised of bent-up bars wrapped in rubber tubes. This method avoids the contact of bent-up bars with concrete. They are situated in the zone, where compressive and tensile forces interact. The compressive force is applied to the endpoint of the bent-up bars placed under the neutral axis from the top point of the bent-up bars. In 2021, Shishegaran et al. [15] used a finite element (FE) model to simulate the performance of RCCs in post-earthquake fires (PEF). The residual load-carrying capacity of an RCC under PEF is then predicted using surrogate models such as multiple linear regression (MLR), multiple natural logarithm (Ln) equation regression (MLnER), gene expression programming (GEP), and an ensemble model. Bigdeli et al. in 2021 [16] evaluated the influence of several parameters on the percentage of damaged surfaces (PDS) of the reinforced concrete tunnel RCT, the maximum deflection at the top of the RCT, and the effective tensile plastic strain of each sample including the compressive and tensile strengths of concrete, the dimensions of the longitudinal reinforcement bar, the transverse bar diameter, and the internal water pressure. Shishegaran et al. in 2020 [17] sought to lessen the environmental impact of steel wire rope and steel powder wastes by employing them in the manufacturing of conductive concrete. The primary application of this electrically conductive concrete is route deicing. Steel powder waste is generated during the cutting and bending of steel profiles, plates, and reinforcing bars. Because such waste material has excellent conductive qualities, putting it in concrete can assist reduce waste, while boosting the conductive properties of concrete? To evaluate the conductive characteristics of concrete, mixed proportions of conventional concrete with steel wire rope wastes and steel powder wastes are used. Karami et al. in 2021 [18] proposed a nonlinear analysis and prediction model for assessing and forecasting the performance of a composite castellated steel beam (CCSB) under fire and static stress. This research is divided into two parts: the parametric study and the prediction models. In parametric research, the independent variables are the beam size, concrete thickness, temperature, and beam length. Among the independent factors evaluated in this study, increasing concrete thickness has a minimal beneficial influence on load-bearing capacity.

One of the major issues confronting the production of the concrete element is the high production cost caused by greater use of cement and chemical additives, as well as environmental issues caused by large emissions of greenhouse gases, particularly carbon dioxide (CO_2), caused by cement manufacturing [19]. Because of the fast evolution of lifestyles, waste glass is created on an annual basis [20–22]. Unfortunately, most waste glass is not reused and is instead disposed of as residue in landfills [16]. The amount created from recycled glass containers in the United States was 11.4 million tons in municipal solid trash in 2017, (MSW). While recycled and combusted glass were relatively modest (3 million tons and 1.5 million tons, respectively), landfill sites collected over 7 million tons of waste glass [23]. However, recently many researchers are involved with PET plastics as sustainable material because it is contributed in shrink cement production and in reducing waste and carbon dioxide emissions [24, 25].

In this study, a new technique of hollowing has been used in this work, where a steel mesh tube was prepared previously and filled manually with blank waste plastic bottles to form a light tube. This technique has some advantages: it is easy to install and it provides a sufficient bond for the main steel reinforcements. The aim of this study is to investigate further mechanical properties of the new voided slab system, i.e., flexural stiffness, toughness, and ductility, as well as to investigate the flexural behavior of such voided one-way slabs by illustrating the deflection profile and rotation under bending test.

2. Experimental Program

2.1. Material Properties. The ingredients of a normal concrete mixture are cement, sand, gravel, and water. The cement that was used in the concrete mixture is Portland type I. The physical and chemical properties were previously tested in the civil engineering lab [12]. The results of these tests coincided with Iraqi limitations I.Q.S. 5/1984 [26]. Local sand was used as fine aggregate with a fineness modulus of 2.65. Natural crushed gravel as coarse aggregate was also used with a 12 mm maximum size. The physical properties and sieve analysis for fine and coarse aggregate were also tested previously by the same authors [12]. For the preparation of the hollow tube, steel mesh wires were used to produce mesh tubes and tested by Tan and Du [20]. The waste plastic bottles were collected from the waste disposal regions and used to fill mesh tubes. Several trial mixtures were carried out according to ACI 211.1 specifications to obtain the compressive strength of normal concrete (about 35 MPa) at 28 days. The mix proportions are given in Table 1.

Table 1: Ingredients of the concrete mixture.

No.	Material	Content (kg/m^3)
1	Water	200
2	Cement	450
3	Sand	690
4	Crushed gravel	975

2.2. Specimens Preparations. Five specimens of solid and voided one-way slabs were cast and tested in the civil engineering lab. One main mixture was prepared to cast all the tested slabs. From the cast mixture, six cylinders with a size of (150×300 mm) and six prisms with a size of ($100 \times 100 \times 500$) mm were taken, cured, and tested for 28 days. The average compressive strength and tensile strength were 33 MPa and 4.3 MPa, respectively. The process of curing was by packaging all specimens with brown gunny accompanied by spraying water continuously for up to 28 days according to (ASTM C309) [27]. The operations of casting and curing are shown in Figure 1.

3. Detailing of Reinforcements

All tested specimens were reinforced by one layer and two directions of steel bars. The voided slabs were hollowed by an innovative method using steel wire mesh tubes filled with waste plastic bottles. The constant dimensions of all tested slabs are as follows: slab width = 440 mm and the overall length of the specimen = 1100 mm (1000 mm between the centers of two simple slab supports). The reinforcement of the tension zone was plain bars in each direction. The steel wire mesh tubes were prepared and filled previously with waste plastic bottles as shown in Figure 2. The length of this tube is 900 mm and the diameter is 75 mm. The steel wire mesh tubes are installed inside the RC slabs at a specific position using steel bar spacers (chair bars), which are tied with steel reinforcement of the slabs (Figure 3).

The symbol of each slab was selected according to the studied parameters: S-T#-XY: (S) letter refers to slab specimen. (T#) represents slab thickness, e.g. T100 refers to a 100 mm slab thickness. XO: represents whether the slab is solid or voided, i.e., SO refers to a solid slab and VO for a voided slab. The studied parameters in this study were the presence of voids and slab thickness (i.e., the area of concrete in the solid section as compared to the voided section). Table 2 and Figure 3 illustrate the studied parameters and details of the tested slabs, respectively. As shown in Table 2, the voided slab (ST130VO) has approximately the same cross-sectional concrete area as the solid slab (ST100SO) (approximately the same amount of concrete), but the same depth as the solid slab (ST130SO) (less concrete due to the voided tube). The main objective of the voided (ST130VO) configuration is to get higher strength and stiffness compared with ST100SO with the same amount of concrete but higher depth and to get a lighter slab compared to the solid slab (ST130SO) by reducing the concrete amount using hollow tubes.

4. Test Setups

Five specimens of solid and voided one-way slabs were tested in the lab of civil engineering using a hydraulic Jack machine

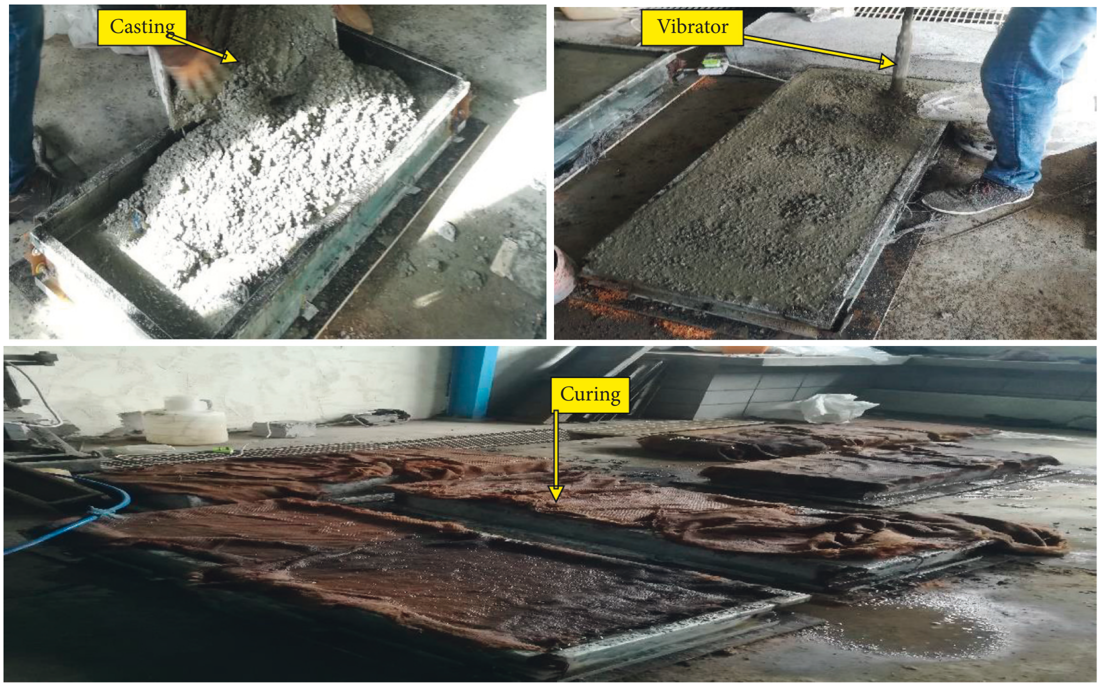

Figure 1: Casting and curing of five specimens.

Figure 2: The manufactured steel wire mesh tubes filled with waste plastic bottles.

with a 500 kN capacity as shown in Figure 4. The load deflections along the length of the slab were recorded from zero until failure loading and for each five kN step. Five dial gauges were used for deflection measurement to find both load verse midspan deflection curves and deflected shapes along the specimens. In addition, the strain gauges were also used to find strains in steel and concrete for tension and compression zones. Figure 4 shows the test setup.

5. Result and Discussion

Figure 5 shows the relationships between the midspan deflection and the applied load of tested specimens. Figure 6 shows the effect of the voided elements on the behavior of reinforced concrete one-way slabs. The main findings from these figures were if the slabs having internal longitudinal voids in the reinforced concrete slab's body effects initial stiffness, but the ultimate capacity had been slightly reduced. Also, the voided slab (using steel mesh with tact's bottles) presents enhancement in the behavior and it has the highest capacity when compared with the same slabs that have the solid section (i.e., the concrete area of the solid section is the same as the concrete area of voided section). Where, it is concluded that the enhancement of voided section strength had occurred, due to an increase in the height of the section, which is a means of an increase in the moment of inertia of the section. Also, in the same manner, it is resulted to reduce the deflection of RC one-way slabs, as shown in Figure 7.

For all specimens, the first cracking was seen at the midspan, where the highest moment developed with loads ranging from 12 to 30 kN. Because of the direct reduction in moment of inertia caused by the removal of a significant concrete volume by voids, the voided specimens ruptured at lower forces than the reference slab. The reduction in cracking load became increasingly apparent as the depth of the voided specimens increased, as given in Table 3. When the applied loads were increased for specimens that failed in flexure, additional vertical splits and cracks developed and propagated over the flexural span. The fractures then multiplied, expanded, and spread higher as the load increased. Flexure-shear fractures also developed in the ST140VO specimen's shear span at the loading sites. Nonetheless, these defects cracks did not spread and expand sufficiently to cause collapse. Flexural failure was distinguished in these slabs by the appearance of flexural cracks close to the upper portion at the midthird of the specimen depth, as well as the crushing of concrete on the top surface of samples at the midspan and along the width of the specimen.

6. Ductility

A reinforced concrete beam's ductility can be defined as its ability to withstand inelastic deformation without a reduction in load-carrying capacity before failure [13–15].

It is important that ductility is taken into account prior to the failure of any structure. As compared to

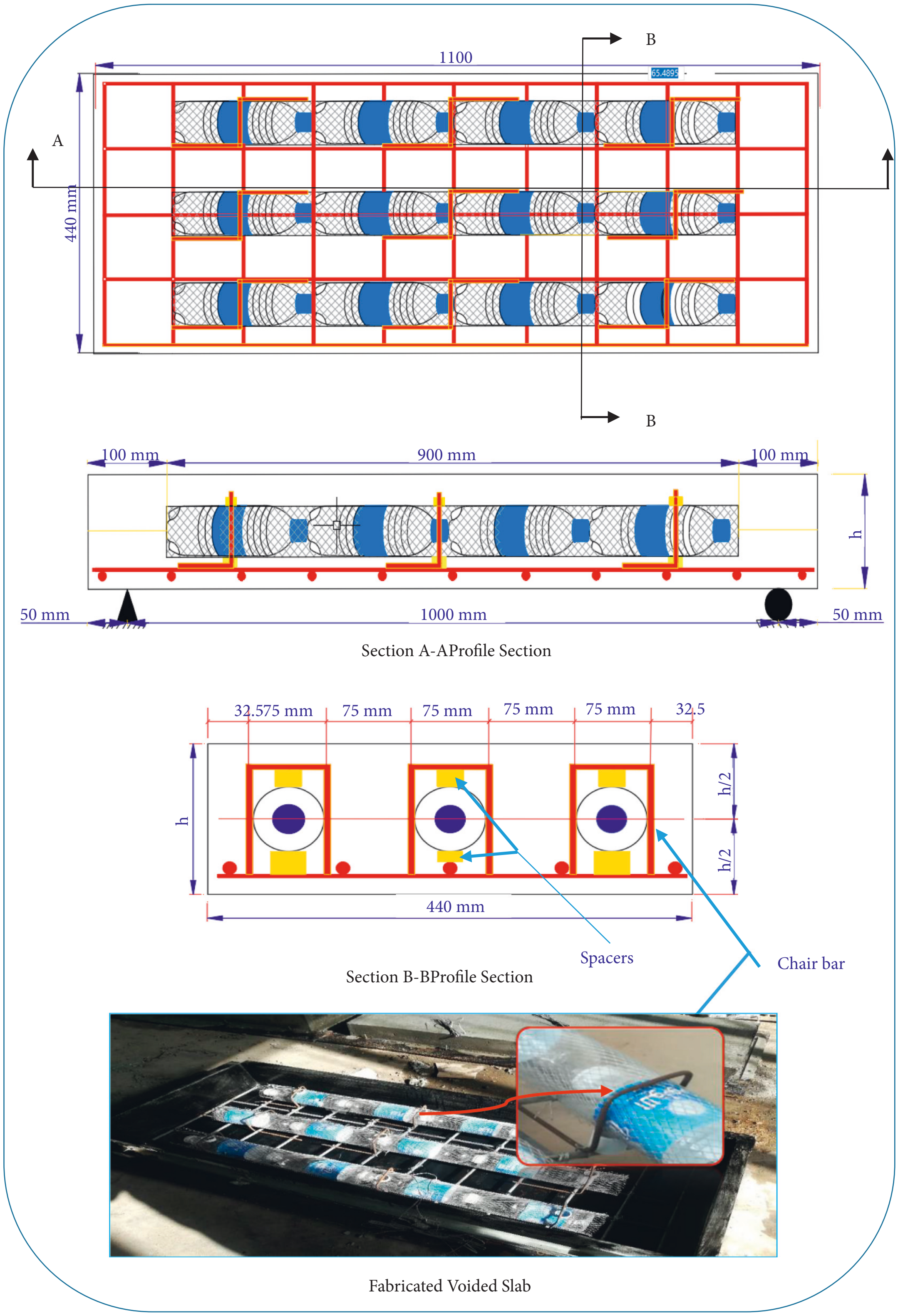

Figure 3: The details of voided slabs.

brittle structures, RC structures with ductile properties provide ample warning before failure [28–31]. The deflection ductility index of the specimen is derived using the load deflection diagram by using the following equations, displacement method in equation (1), and energy method in equation (2):

Table 2: Details of specimens.

No.	Specimen	Solid/voided slab	Slab thickness (h) (mm)	Cross-sectional area (mm^2)	Reinforcement ratio (ρ)
1	ST100SO	Solid	100	44000	0.007
2	ST130SO	Solid	130	57200	0.005
3	ST130VO	Voided	130	43953	0.005
4	ST140VO	Voided	140	48353	0.0045
5	ST150VO	Voided	150	52753	0.004

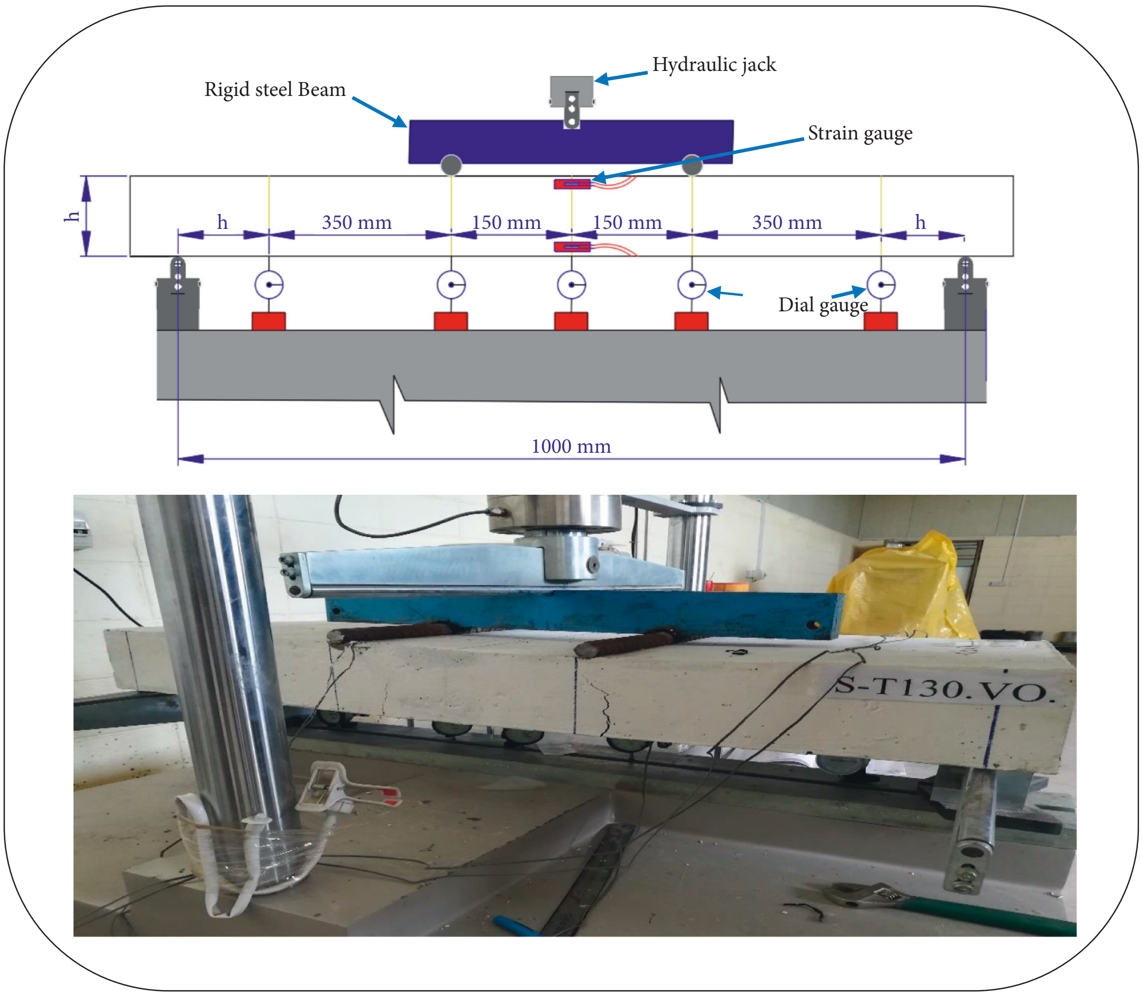

Figure 4: Test setup.

$$\mu = \frac{\Delta_u}{\Delta_y}, \quad (1)$$

$$\mu_o = \frac{\Delta_u}{\Delta_y} \cdot \left\{ \frac{S\Delta_y \left[P_y \left(\Delta_u - \Delta_c \right) + P_u \left(\Delta_u - \Delta_y \right) + P_c \Delta_y \right]}{P_u^2 \Delta_u} \right\}, \quad (2)$$

where P_u and P_y are the deflection ductility indices at ultimate and yield loads, respectively, and Δ_u and Δ_y are the deflection ductility indices at ultimate and yield loads, respectively. The ductility index at ultimate and failure loads shows an improvement with increasing void ratio tested specimens.

In both methods in the determination of the ductility indices, it was found that the ductility is reduced, when the voids are used. But it has occurred because the voided specimens have a capacity more than the solid tested slab. Also, the initial stiffness was higher than the reference specimen.

7. Toughness

Toughness is the amount of energy absorbed during fracture and may be measured by calculating the area under the load-displacement curve; it is the effort per volume spent in a material's deformation. This characteristic calculates the quantity of energy that can be stored that a material can take

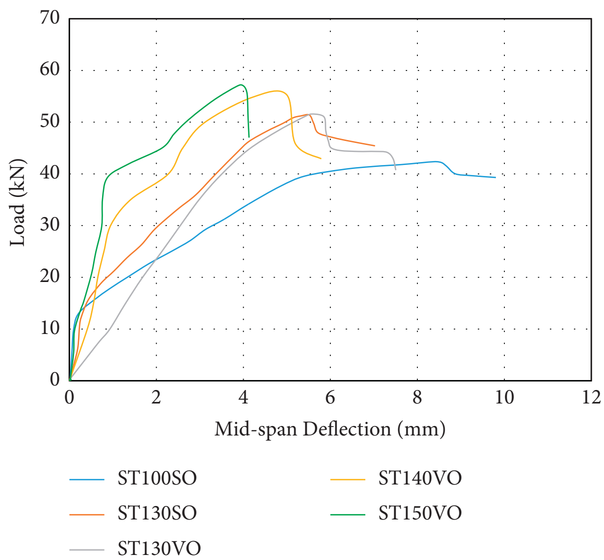

FIGURE 5: Load verse midspan deflection relations of all specimens.

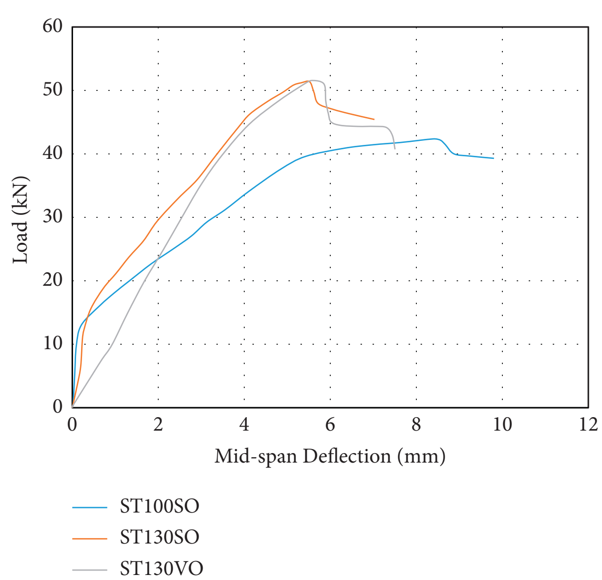

FIGURE 6: Comparison of voided and solid RC slabs.

without breaking and is essential in fracture resistance and crack propagation, whereas a strong material has a high ultimate load. The region beneath the load-displacement curve of a tough material is big [32]. Engineers are interested in ductility and fracture for two main reasons. The first is that a sufficient level of ductility is essential for failure prediction before it occurred. The second point to make is that a certain level of toughness is necessary to avoid failure in performance. To absorb energy, some plastic deformation is required. The vertical displacement toughness findings are given in Table 4.

The test results indicated that voided specimens had higher toughness than reinforced concrete solid with the voided ratio and depth of their original load capacity.

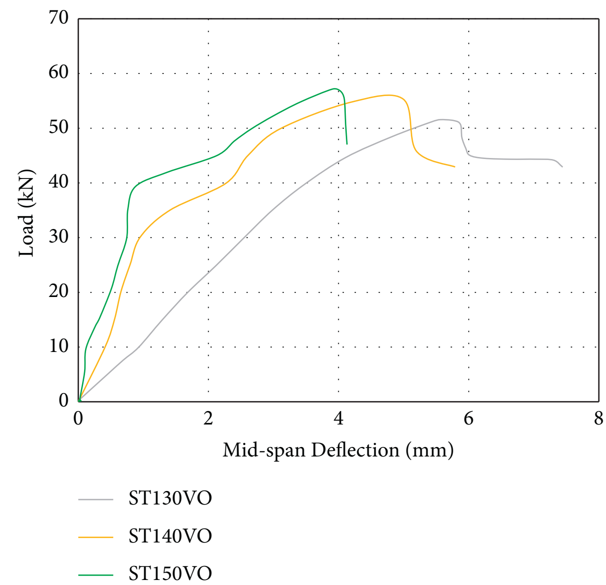

FIGURE 7: Comparison of voided RC slabs having a variable thickness.

TABLE 3: Test results of the slabs (solid and voided).

	ST100SO	ST130SO	ST130VO	ST140VO	ST150VO
P_{cr}	12.65	14.2	13	30	33
Δ_{cr}	0.2	0.35	1.1	0.9	1.1
P_y	37.8	46.5	33	39	40
Δ_y	4.85	4.2	2.25	2.2	1.5
P_u	42.36	51.38	51.56	55.3	57.15
Δ_u	8.39	5.52	7.44	5.75	4.10

Furthermore, the solid and voided sections failed with the same value of the midspan deflection (51.38 and 51.56 mm), respectively.

8. Average Flexural Stiffness (AFS)

The flexural stiffness is the product of the modulus of elasticity (E) and moment of inertia (I) of the beam about the neutral axis. When increasing the value of flexural stiffness the strength of the beam to resist bending also increases. The flexural stiffness of components can be increased by raising the moment of inertia of cross section or by choosing the material with a higher modulus of elasticity. Stiffness is the line's slope that connects the origin of the load-lateral displacement curves and a point corresponding to a deflection of L/250 (L is the beam's span length) [33]. On the other hand, the stiffness of each phase was calculated as the ratio of the maximum load and its corresponding displacement k_i [34]. Due to the section in this study is not prismatic therefore it can be assumed the calculation of stiffness for the critical section (i.e., the void has the parametric maximum void at midspan). It is called average flexural stiffness (AFS) = P_u/Δ_u. The average flexural stiffness of tested specimen findings is given in Table 4.

Table 4: Ductility and toughness indices.

	ST100SO	ST130SO	ST130VO	ST140VO	ST150VO
Ductility (Δ_u/Δ_y) conventional method	1.73	1.31	3.31	2.61	2.73
S	5.41	8.39	17.39	6.92	17.50
Ductility by energy method (μ_o)	1.57	1.17	3.31	1.02	1.70
Response of load-deflection curve	Trilinear	Trilinear	Bilinear	Trilinear	Bilinear
Average flexural stiffness (AFS) kN/mm P_u/Δ_u	5.05	9.31	6.93	9.62	13.94
Toughness (kN·mm)	323.511	258.8	255.75	235.83	174.93

Table 5: The support rotation magnitude for the tested specimens.

Specimen symbols	Central deflection at ultimate load (mm)	Support rotation corresponding to shear span (°)	Central deflection at end of the test (mm)	Support rotation corresponding to midspan (°)
ST100SO	3.8	0.0190	8.39	0.0419
ST130SO	2.2	0.0110	5.52	0.0276
ST130VO	2.25	0.0112	5.56	0.0278
ST140VO	4.50	0.0225	5.0	0.0250
ST150VO	2.28	0.0114	3.91	0.0195

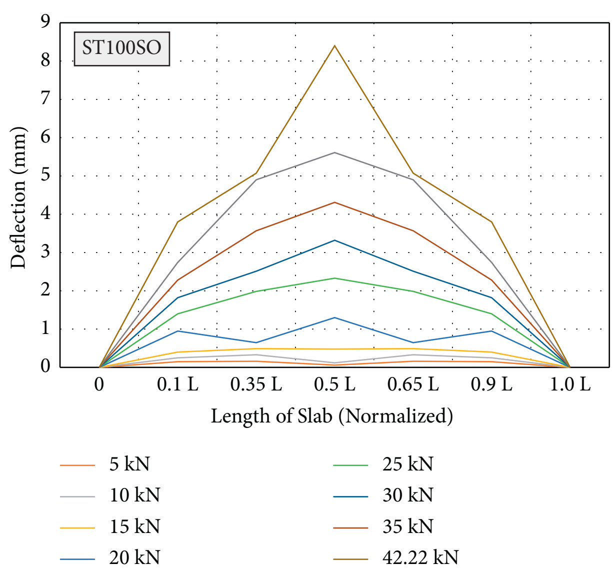

Figure 8: Deflection profile of slab ST100SO.

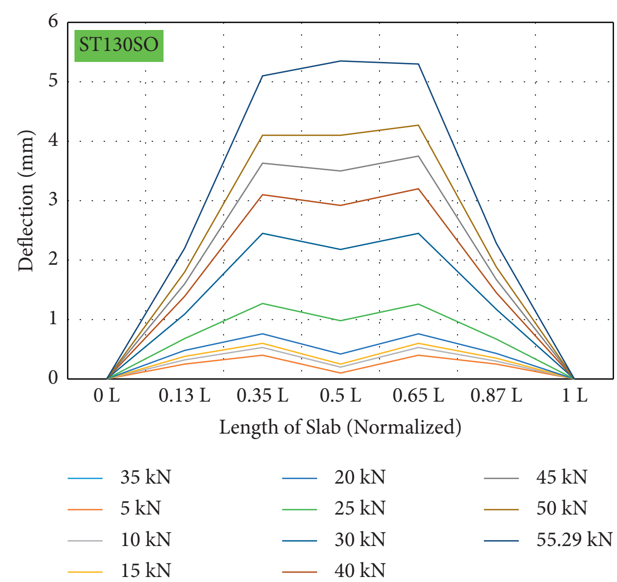

Figure 9: Deflection profile of slab ST130SO.

9. Support Rotation and Deflection Profiles

This section included the calculation of support rotation for the RC solid and voided one-way slabs under static load. The support rotation is measured from equation (3) [35]:

$$\theta = \tan^{-1}\left(\frac{\delta}{L_1}\right), \quad (3)$$

where θ is the support rotation (degree); δ is the deflection at midspan (mm); L_1 is the distance between support and concentrated load (mm).

The support rotation of the tested slabs is given in Table 5. From the results, it is noticed that the voided slabs with voided have maximum support rotation corresponding to central deflection at ultimate load as compared to control specimens, except for solid specimens that have maximum support rotation rather than reinforced concrete (RC) other solid slabs, this is referred to the effectiveness of inclined

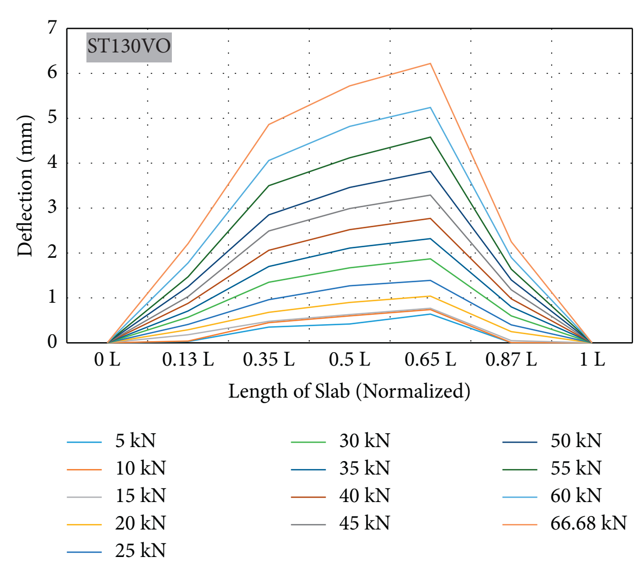

Figure 10: Deflection profile of slab ST130VO.

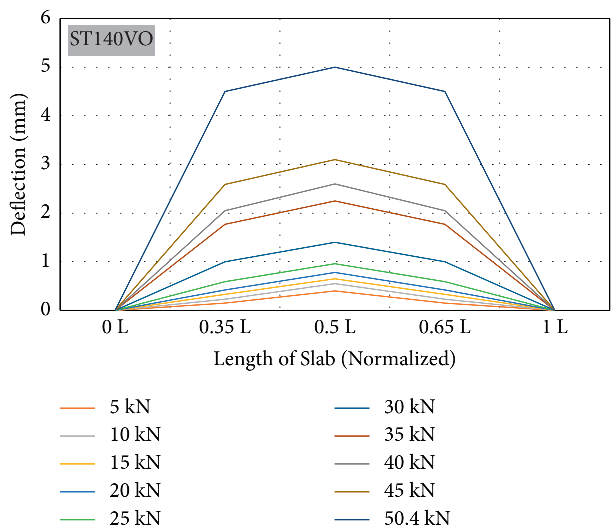

FIGURE 11: Deflection profile of slab ST140VO.

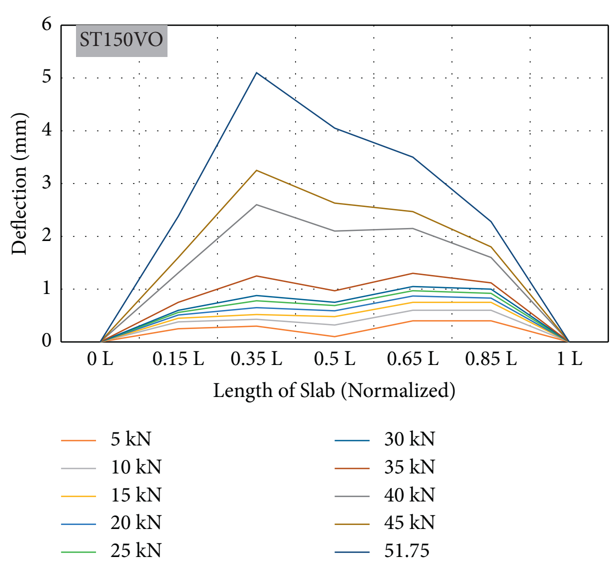

FIGURE 12: Deflection profile of slab ST150VO.

angle rather than the other voided slabs to give a greater rotation angle at failure load. In addition, the specimen (ST140VO) has shear span rotations that were more than the control due to the cracks were appeared at support side hardly. Figures 8–12 illustrate the beam profile of the tested specimens. It was seen that the midspan deflection has maximum deflection values. Also, the shear span deflection had been under the load points due to cracks within this region for specimens ST130VO and ST150VO.

10. Conclusions

This study deals with the flexure behavior of a new voided technique in the one-way slab, it used waste PET bottles inside steel mesh to produce a combined tube that can be inserted within the slab's section. Many outcomes can be got from this study that explains how their results address the aims of the study and fill the gap of knowledge highlighted:

(1) Inclusion of a new method of voided slabs showed a slight reduction in the ultimate midspan deflection for the same slab's thickness, it was reached up to 5.52 mm and 5.56 mm, for solid and voided 130 mm thick slabs, respectively.

(2) The first crack capacity had been enhanced in the voided specimen, that is occurred due to an increase in the thickness and increase in the tension area arm of the voided sections. However, the voided slab increased the ultimate capacity to 100% if the thickness of voided slab had been increased 15% only.

(3) The ductility indexes, there are calculated using both methods (ultimate deflection or energy methods) can be descripted in the same manner as the result but they do not have the same results.

(4) The cracks firstly appeared in the bottom face. Also, flexural failure was distinguished in these slabs by the appearance of flexural cracks close to the upper portion at the midthird of the specimen depth, as well as the crushing of concrete on the top surface of samples at the midspan and along the width of the specimen.

(5) The toughness of voided tested specimen had been reduced because of the reduction in ultimate deflection. However, it almost seems that the toughness have been slightly affected when compared with the same thickness of the test specimen.

(6) The rotation of supports had been reduced by about 30% when the thickness of voided slab was increased by about 15%. That it occurred due to the increase in thickness of the slab lead to reduce in deflection reading of the tested point.

Data Availability

The data used to support this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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