Flexural Characteristics of Hollow One Way-Ferrocement Slabs

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ABSTRACT

In this study, five hollow one-way Ferrocement slabs were fabricated, cast, and tested under a four-point loading system. The ferrocement slabs were voided by waste plastic bottles. The main employed parameters were the void presence, void ratio for the waste plastic bottles, and fiber percentage. The waste plastic bottle void method relied on a hollow tube of steel wire mesh that was then filled with waste plastic bottles and installed at the mid-height of slab thickness aiming for the low stress position within slab depth. The ultimate load capacity, flexural stiffness and ductility, crack width, and profile deflection were measured and analyzed. The study demonstrated that the ferrocement voided slab load capacity was affected by the voids compared to the reference specimen, namely the ferrocement solid slab. However, the voided slabs using 1% Polypropylene (PP) Fibers demonstrated a good performance, which was approximately identical to that of the solid slab. From the results, it can be concluded that the addition of PP fibers to empty plastic bottle hollow slabs is an excellent method to increase the latter's total flexural stiffness. Compared to the solid slab, the voids in the slabs not only decreased the dead load, but also ductility and stiffness. Moreover, adding fibers improved these qualities making them similar to those of the original slab. Furthermore, it was observed that when using two lines of hollow plastic tube, the ultimate load capacity dropped by approximately 18.5% compared to that of the solid slab.

Keywords-ferrocement; hollow slabs; plastic waste; crack pattern; ductility

I. INTRODUCTION

Hollow core flexure members, including beams and slabs, play a crucial role in the construction of multi-story buildings because they have several advantages compared to traditional solid specimens. These advantages include faster construction, longer span capabilities, suitable beam and slab strength ratios, accommodations for air conditioning and electrical services, and increased clear story height. Moreover, the use of voids in building structures leads to less self-weight, which diminishes dead loads, and thus decreases overall expenses [1, 2]. Additionally, by reducing resource consumption and carbon dioxide (CO_2) emissions, the removal of concrete from structural components due to voids contributes to sustainability. Employing longitudinal voids in Reinforced Concrete (RC) beams or slabs is a technique to decrease concrete in the tension zone, resulting in a lightweight structure [3, 4]. Ferrocement has been investigated as a structural element for slabs, beams, and even in strengthening issues. The use of fiber to improve ferrocement slab ductility has been investigated, with many types of fibers having been utilized [5-7]. In comparison to traditional RC, ferrocement is a superior building material, demonstrating exceptional performance regarding cracking behavior, resistance to impact, and toughness. This occurs due to the uniform distribution of steel mesh reinforcement inside the mortar and the closeness of steel wires within the mesh. A principal advantage of ferrocement is its adaptability, allowing for constructions with diverse features, properties, and costs suited to the client's requirements and budget [8].

Ferrocement is a form of thin-walled RC, often composed of hydraulic cement mortar reinforced with closely spaced layers of steel wire mesh. The behavior of lightweight ferrocement beams and slabs reinforced with steel meshes has been extensively studied. Authors in [9] investigated ferrocement circular slabs (800 mm diameter, 50 mm thickness) subjected to impact, with different styropor void proportions (24% and 48%) and mesh layers (4 and 6). The study revealed that adding mesh layers enhanced impact energy, resulting in a 41.99% rise for 24% voids as well as a 37.62% rise for 48% voids at the initial cracking stage. The energy for full perforation rose by 21.7% at 24% cavities and by 9.94% at 48% voids. The findings indicated that ferrocement slabs are appropriate for impact-resistant building applications. The addition of fibers improves the behavior of concrete under different conditions of loading as well as the brittle behavior of concrete [10]. Authors in [11] investigated ferrocement slabs voided by PVC pipes, evaluating the influence of various reinforcements: metallic wire mesh, both macro and micro steel fibers, steel bars, and CFRP bars. The results exhibited that macro steel fibers yielded the best flexural strength, steel bars delivered optimal stiffness and little deflection, while the PVC pipes (which created voids) had a negligible impact on strength. All slabs conformed to the lightweight concrete density criterion of less than 2000 kg/m³.

Based on previous research, no study to the best of the authors' knowledge has used waste plastic bottle tubes to create voids in ferrocement slabs, as in the case of RC slabs. This void method has several advantages, including its effectiveness in waste plastic disposal. The steel wire mesh around the plastic bottles may contribute to the tensile strength of concrete. Additionally, this method facilitates the installation of plastic bottles inside the slab as a bundle. The main aim of this study is to examine the flexural behavior of one-way ferrocement slabs voided with waste plastic bottles.

II. EXPERIMENTAL PROGRAM (MATERIALS, MIX PROPORTIONS, SLAB FABRICATION AND TESTS)

The materials used in the current study involve Ordinary Portland cement (Type I), with 3.15 specific gravity, conforming to Iraqi Specification (I.S.) No. 5/2019 [12]. In addition, 5 mm (maximum size) of sand was utilized as fine aggregate, with 2.45 fineness modulus and 2.6 specific gravity. The physical properties of sand met the Iraqi standard I.S. No. 45 [13]. To make the mix more flowable, Sika ViscoCrete-5930 (types G and F) served as a high-performance superplasticizer, meeting the criteria of ASTM C 494. PP fibers were also added to the voided specimens to substitute the potential loss of tensile strength due to the void presence. Fiber length was 12 mm, and their diameter 18 μm. The waste plastic bottles were collected from a container to form the voids. The steel wire mesh layer was obtained from the local market. The yield and ultimate strength of the steel wire mesh, which was used to reinforce the ferrocement slab, were 240 and 350 MPa, respectively, according to the tests conducted in the lab. The mix proportion was 1:3 cement: sand, 0.38 W/C ratio, 1.5% superplasticizer from cement, and 1% fiber, all mixed by volume. Three cubes of 70 × 70 × 70 mm size were utilized to test compressive strength. The average compressive strength value at 28 days was 38.5 MPa.

Five test specimens were prepared, fabricated, cast, and tested, with dimensions of 1000 mm length, 400 mm width, and 70 mm thickness. The effective span was 900 mm. All ferrocement slabs were reinforced with 2 layers of steel wire mesh with a constant diameter of 2 mm, in two directions with different spacing, as shown in Figure 1. The woven steel wire mesh, constituting another wire type, was fabricated as a hollow tube and then filled with plastic bottles to form a waste plastic bottle tube. The tubes were subsequently placed in one and two lines to form different void ratios for the HB1-FPP0 and HB2-FPP0 specimens, and were compared with the reference solid slab S-FPP0. To enhance the flexural behavior of the two voided slabs, HB1-FPP1 and HB2-FPP0, 1% of PP fibers was added for them to be formed. Table I provides the specimen description, and Figure 2 presents the fabrication of the ferrocement slabs.

TABLE I. DESCRIPTION OF SPECIMENS

No.	Slabs	Type of slab (solid/ voided)	No. of line of void	PP fibers (%) by volume
1	S-FPP0	Solid	None	None
2	HB1-FPP0	Voided	1	None
3	HB2-FPP0	Voided	2	None
4	HB1-FPP1	Voided	1	1%
5	HB2-FPP1	Voided	2	1%

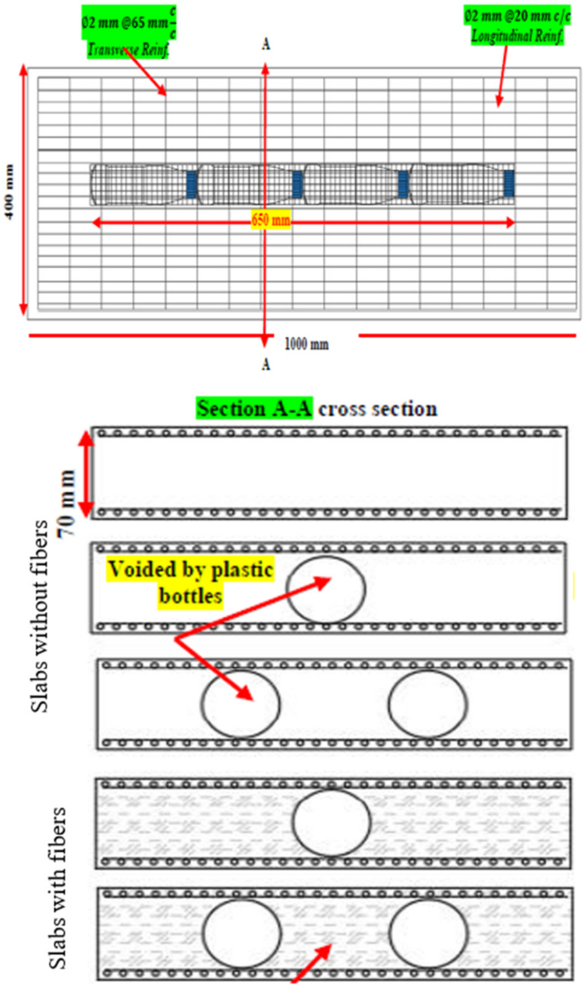

Fig. 1. Layout of specimens.

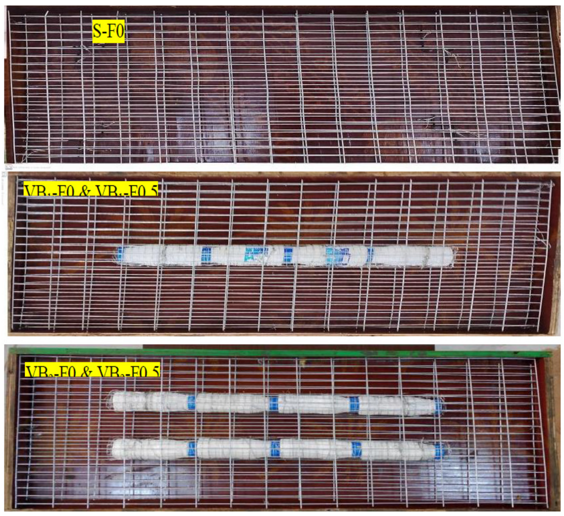

Fig. 2. Fabrication of ferrocement slabs.

The universal machine with 500 kN capacity was used to test the ferrocement slab specimens under a four-point loading system. The schematic plan and the actual test of the specimens are displayed in Figure 3. The load was applied gradually from zero till failure. Three LVDTs were deployed to measure both mid-span deflection and profile deflection along the slabs. Crack strips were also utilized to monitor crack width. Based on recorded load-displacement relationships, test specimen ductility and stiffness were calculated and analyzed.

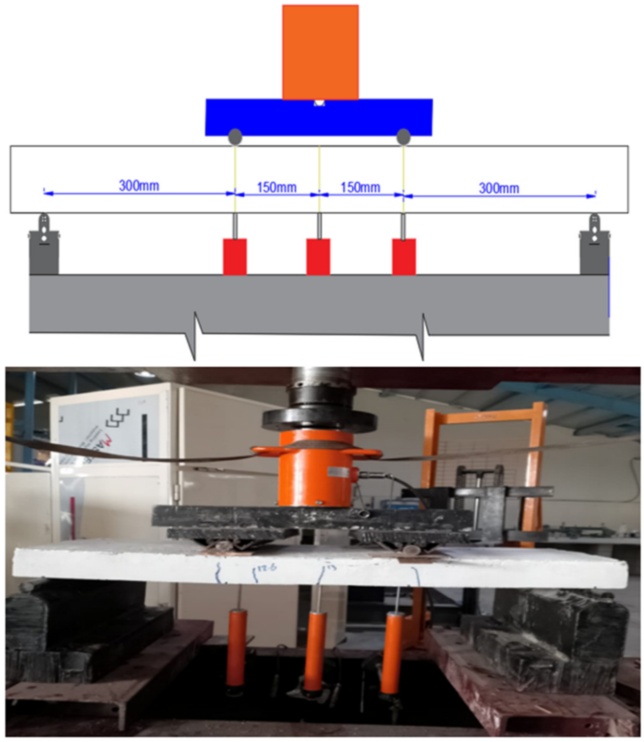

Fig. 3. Test setup.

III. RESULTS AND DISSCUSION

A. Load-Deflection Behavior

As can be seen in Figures 4 and 5, the ultimate load capacity dropped by about 11.4% due to the one-line void formation inside the slabs to obtain HB1-FPP0. The ultimate load capacity for HB1-FPP1 was the same as that of the reference solid slab S-FPP0, as shown in Table II. This can be attributed to the addition of 1% PP fibers to substitute the decrease in load capacity, caused by voids. By using two lines of plastic tube with voids (specimen HB2-FPP0), the ultimate load capacity dropped by approximately 18.5% compared to that of the solid slab S-FPP0. Adding 1% PP fibers to the ferrocement slabs with two hollow tubes to get HB2-FPP1, the ultimate load capacity enhanced up to 20.8% compared to HB2-FPP0, as portrayed in Table II. This may indicate that the 1% PP fiber addition is sufficient to tackle the reduced loads due to the void ratio of both HB1-FPP0 and HB2-FPP0.

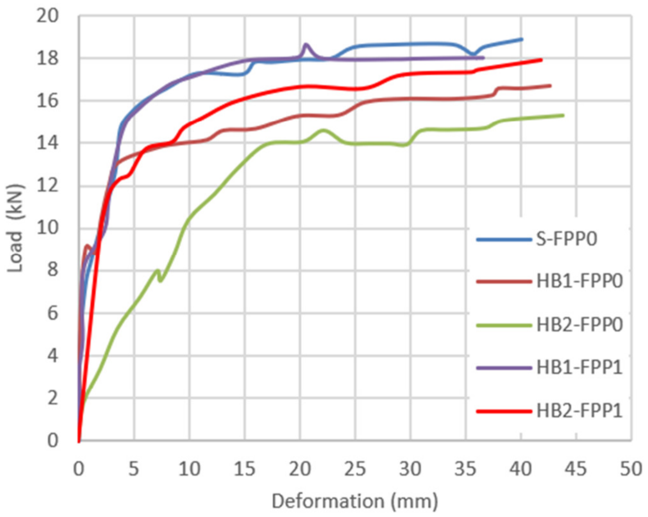

Fig. 4. Load–deflection for all tested slabs.

TABLE II. LOAD AND RELATED DEFLECTION

No.	Slab	P_{cr}	$\triangle_{cr}$	P_u	$\triangle_u$
1	S-FPP0	7.5	1.28	18.8	40
2	HB1-FPP0	7	1.53	16.65	42.66
3	HB2-FPP0	6.5	2.67	15.32	43.8
4	HB1-FPP1	7.5	1.08	18.65	36.58
5	HB2-FPP1	6.85	1.5	18.50	40.2

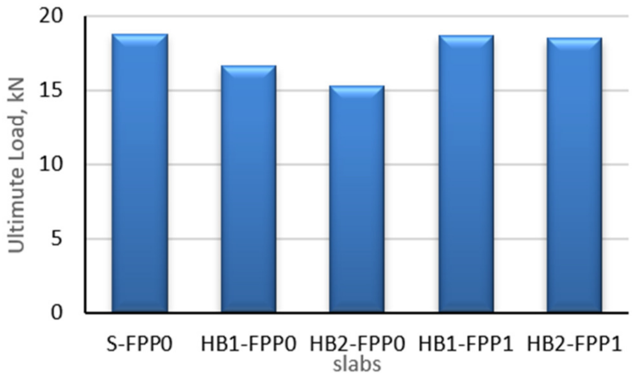

Fig. 5. The effect of voids and PP fibers on ultimate load capacity of all tested slabs.

B. Influnce of Voids and Fibers on Tested Slab Ductility

A reinforced ferrocement concrete slab's ductility is its capacity to withstand inelastic deformation without lowering its load-carrying capacity before failure [14]. Ductility needs to be taken into account before any structure fails. Compared to brittle structures, reinforcing constructions with ductile properties provides greater warning before failure [15, 16]. The slab's deflection ductility index is determined by applying the displacement method in (1) and the energy method in (2), as well as the load detection diagram:

$$\text{Ductility}= (\Delta_\mathbf{u}/\Delta_\mathbf{y}) \quad (1)$$

where $\frac{\Delta_u}{\Delta_y}$ is the ultimate deflection to yield deflection ratio.

According to the results presented in Figure 6, ductility decreased when voids were created in the solid slab and the ductility of the one-line hollow slabs was higher than that of the two-line hollow slabs. However, the addition of PP fibers increased slab ductility, in that it was close to that of the solid slab. Thus, by incorporating voids using plastic waste bottles and fibers, one can get the same strength and ductility with those of the solid slab, but with a lower dead load, leading to reduced cost. There are two primary reasons why engineers are interested in ductility and fracture. Initially, before failure prediction, a high ductility degree is required. Secondly, in order to prevent performance failure, a certain amount of toughness is needed, while there must be some plastic deformation in order to absorb energy.

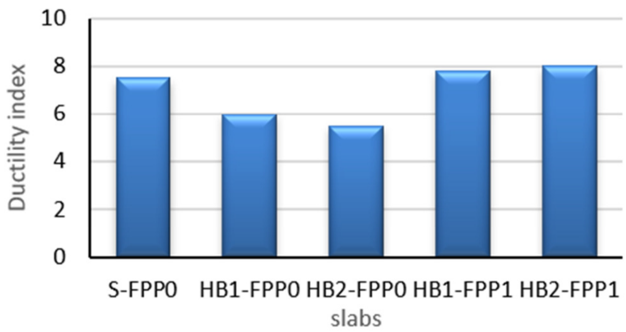

Fig. 6. Ductility indexes for all tested slabs.

C. Influnce of Voids and Fibers on Tested Slab Stiffness

Bending stiffness (or flexural stiffness) is the result of multiplying the slab's moment of inertia (I) by its modulus of elasticity (E) with respect to the neutral axis. As the flexural stiffness rating grows, so does the slab's ability to tolerate bending. Component flexural stiffness can be increased by either choosing a material with a higher E or by increasing the cross section's I. The stiffness of each phase was calculated as the ratio of the maximum load to the corresponding displacement [17].

It is reasonable to infer that the stiffness calculation for the study's pivotal section, meaning the parametric maximum void at mid-span, is accurate. This is known as Average Flexural Stiffness (AFS):

$$\text{AFS}= (\text{ultimate load}/\text{ultimate deflection}) \quad (2)$$

As illustrated in Figure 7, the stiffness of the one-line hollow slabs is higher than that of the two-line hollow slabs, while the stiffness decreases when voids are created in the solid slab. PP fiber addition, however, made the slabs more rigid to a level that was comparable to that of the solid slab. In this way, one can achieve the same strength and stiffness with those of the solid slab while reducing dead load, which is cost-effective.

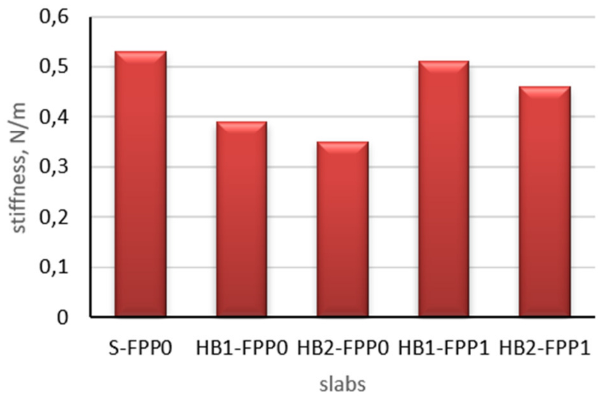

Fig. 7. Average stifness for all tested slabs.

D. *Influnce of Voids and Fibers on Failure and Crack Pattern of Tested Slabs*

Figure 8 depicts the cracking patterns detected during the testing of each flexural specimen. No top fiber crushing was seen in the mid-span area of any of the tested slabs. Every crack began on the specimens' bottom face and eventually spread to the slabs' two sides. All specimens exhibited ductile flexural failure, with the primary cracks frequently beginning in the middle zone encompassing the lines of load application. It is clear that the number of hollow lines and fiber content influence the number of cracks. As evidenced by the cracking patterns of HB1FPP1 and HB2FPP1, fiber integration led to a large number of distributed cracks.

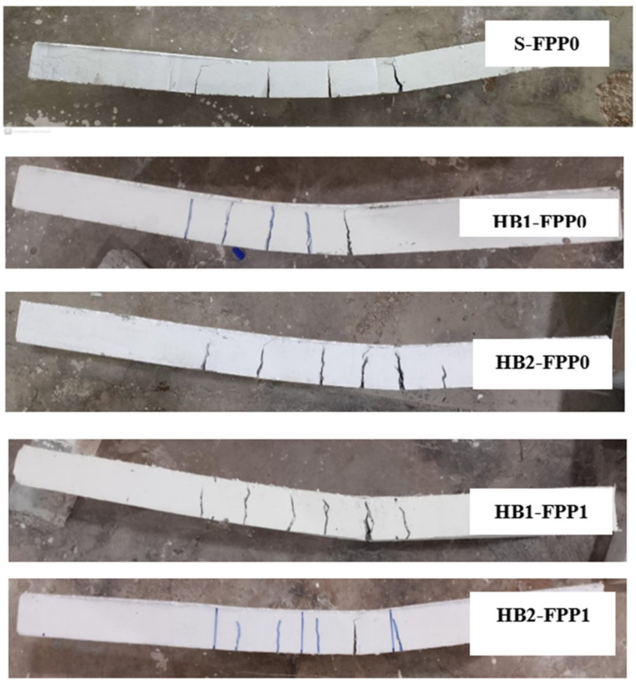

Fig. 8. Crack pattren for all tested slabs.

It was additionally observed that the flexural cracks were more equally distributed in the PP fiber-reinforced slabs under examination than in the non-fiber-reinforced slabs, while overall flexural stress was the cause of both hollow and solid slab failure. A tough material's load-displacement curve has a large region beneath it [18]. Therefore, plastic deformation needs to take place in order to absorb energy. Then, by improving the concrete's short- and long-term behavior, fiber addition will enhance hollow slab weakness [19], and the void formation in any structural unit will reduce the dead load [20].

IV. CONCLUSIONS

In order to facilitate the safe and responsible application of the proposed technology in civil infrastructure and construction, this study examines the flexural behavior of voids in one-way ferrocement slabs. A composite tube was created that can be inserted within the slab's section by using waste plastic bottles with steel mesh. The results meet this study's objectives and bridge the identified knowledge gap:/ Based on the obtained results, the following conclusions were drawn:

The ultimate load capacity dropped by about 11.4% due to the formation of one-line voids inside the slabs, to obtain slab HB1-FPP0. The ultimate load capacity for HB1-FPP1 was close to that of the solid slab S-FPP0. This may be attributed to the addition of 1% PP fibers to substitute the decrease in load capacity, caused by voids.

The use of two lines of hollow plastic tube (specimen HB2-FPP0), reduced the ultimate load capacity by approximately 18.5% compared to the solid slab S-FPP0.

The addition of 1% PP fibers to the ferrocement slab with two hollow tubes to get HB2-FPP1 increased the ultimate load capacity up to 20.8% compared to HB2-FPP0.

The stiffness of the one-line hollow slabs was higher than that of the two-line hollow slabs, and was decreased when voids were created in the solid slab.

Flexural cracks were more equally distributed in the PP fiber-reinforced slabs under examination than in the non-fiber-reinforced slabs, while overall flexural stress was the cause of both hollow and solid slab failure.

The ductility decreased when voids were created in the solid slab and the ductility of the one-line hollow slabs was higher than of two-line hollow slabs. However, adding PP fibers increased slab ductility, which was close to that of the solid slab.

Finally, the addition of PP fibers to empty plastic bottle hollow slabs is an optimal method to increase their total flexural stiffness. Compared to the solid slab, the hollow slabs not only decreased dead load, but also ductility and stiffness; therefore, adding fibers improved these qualities making them similar to those of the original slab.

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