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Experimental Study of Hollow-core Slab Containing Waste PET Bottles

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Abstract

This study investigated the utilization of plastic-waste concrete as an effort to reduce urban waste problems. The waste plastic bottles were utilized to form the hollows of the hollow-core slabs (HCSs). The bottles were made of polyethylene terephthalate (PET). As a part of green research to reuse waste material, shredded PET was also added to the concrete mixture to improve the HCS strength. The cast-in-site HCS could be constructed without any difficulties. Three parameters were investigated: the effects of void content, shredded PET content, and steel-fiber (SF) content on the HCS ultimate bending capacity (Mu). Fifteen specimens were tested under static loads until failure, and the results were compared with those of the solid slab. Two different void contents 19% and 24% were studied. The other parameters were the shredded PET content (0.5% and 0.7%) and the SF content (0.19% and 0.32%). The Mu values of the HCS specimens were 12% to 16% less than that of the solid slab. However, the strengths were still within the theoretical capacity of the slab. The addition of the shredded PET could improve the HCS bending capacity by 18% to 38% compared with that of the solid slab. Similar results were also found for the specimens with SFs, whose Mu values were 11% to 46% greater than that of the solid slab.

Abstrak

Kajian Eksperimen Lempengan Inti Berongga yang Berisi Botol-botol PET Limbah. Kajian ini menginvestigasi pemanfaatan beton limbah plastik sebagai suatu upaya untuk mengurangi masalah limbah perkotaan. Botol-botol plastik limbah dimanfaatkan untuk membentuk rongga-rongga dari lempengan inti berongga (*the hollow-core slabs* (HCS)). Botol-botol tersebut dibuat dari polietilena tereftalat (PET). Sebagai suatu bagian dari riset awal (*green research*) untuk menggunakan ulang bahan limbah, PET yang sudah dicacah juga ditambahkan ke campuran beton untuk meningkatkan kekuatan HCS. HCS yang dicor di tempat dapat dikonstruksi tanpa ada kesulitas apapun. Tiga parameter diinvestigasi: efek-efek dari konten kosong, konten PET cacahan, dan konten serat baja (*steel-fiber* (SF)) pada kapasitas pembengkokan akhir HCS (Mu). Lima belas spesimen diuji dengan beban statis sampai kegagalan, dan hasil-hasilnya dibandingkan dengan hasil uji lempengan padat. Dua konten kosong yang berbeda 19% dan 24% dikaji. Parameter-parameter lainnya adalah konten PET cacahan (0,5% dan 0,7%) serta konten SF (0,19% dan 0,32%). Nilai-nilai Mu spesimen-spesimen HCS adalah 12% sampai 16% lebih kecil dibandingkan dengan nilai-nilai MU lempengan padat. Namun demikian, kekuatannya masih berada di dalam kapasitas teoritis lempengan. Penambahan PET cacahan dapat meningkatkan kapasitas pembengkokan HCS sebesar 18% sampai 38% dibandingkan dengan kapasitas pembengkokan lempengan padat. Hasil-hasil serupa juga diperoleh untuk spesimen-spesimen dengan SFs, dengan nilai-nilai Mu sebesar 11% sampai 46% lebih besar dibandingkan dengan nilai-nilai MU lempengan padat.

Keywords: cast-in-site HCS, experimental study, bending capacity, waste PET

1. Introduction

Hollow-core slab (HCS) is a precast prestressed concrete slab with a continuous void in one direction. The removal of concrete volume through the middle section allows low-cost production and easy handling. Therefore, these slabs have been widely applied in concrete and steel structures [1], [2]. Mechanical and electrical wires can be installed in the hollow, and the hollow also minimizes the transmission of sound and vibrations between building floors.

Even though the HCS was developed in the 1950s when prestressing techniques evolved [3], research on the HCS is still ongoing [1]–[7]. One of the issues of the HCS is its shear capacity. The absence of concrete in the middle section does not reduce the slab flexural capacity, yet it decreases the shear capacity. Several researchers have investigated the HCS shear strength [4]–[7]. ACI 318-05 [8] states that the HCS does not need the extra shear reinforcement as long as the ultimate shear strength (*Vu)* exceeds half of concrete shear strength (*0.5φVc)*. However, this condition cannot be applied to a deep one-way slab, as proved by Hawkins and Ghosh [4], who experimentally studied deep one-way prestressed HCS with a thickness of over 300 mm. They found that the ACI equation mispredicted the shear capacity of the slab. Helen and Lundgren [5] found a similar result through a series of studies using the finite element method. The research showed that shear failure is an important aspect to be controlled when designing deep HCS.

Using finite element software, Allawi [9] conducted an experimental study on one-way slabs where the holes were occupied by Styropor. The study aimed to determine the effect of the hole length and width. It is found that the greatest percentage of weight decrease was 13.7% where it provided the maximum load strength about 96.8% to 97% of the initial reference slab.

Abed [10] conducted both numerical and experimental studies on the shear strength of concrete slabs with longitudinal hollow cores. Different sizes of hollow cores were examined. The slabs had a length, width, and thickness of 2.05 m, 0.6 m, and 0.25 m, respectively. The study found that the ultimate strength decreased by 5.49% to 20.6% because of the existence of the circular hollow cores with a diameter of 75 to 150 mm. Moreover, the deflection increased by 6.85% to 24.8%.

Wariyatno [11] performed an experimental test on HCS with 12 cm thickness. Two slabs were formed using different materials for the hollow: PVC pipe (type 1) and styrofoam (type 2), where the weight of the structure decreased by 24%–25%. The flexural strength of the type 2 HCS was greater than that of the type 1 HCS, but it was still below that of the solid slab. The crack in the solid slab was a flexural crack, whereas shear cracks occurred in the type 1 and 2 HCSs.

In 2018, Ihsan conducted a state-of-the-art review on HCS research [12]. Based on this paper, it can be concluded that the HCS is an interesting research area. The shear strength, flexural strength, and crack propagation have been actively investigated. The preceding research found that the amount of hollow affects the HCS flexural strength and that the loss of concrete in the middle section leads to shear crack.

To improve the tensile and shear strengths of concrete material, steel fiber (SF) is added to the concrete. Several studies have revealed that the addition of SFs to concrete significantly reduces cracking and improves the concrete flexural strength, energy absorption capacity, ductile behavior, and durability [13]. Previous research has also shown that the addition of SFs substantially increases the concrete shear strength. The SF addition can serve as an effective alternative to the traditional transverse shear reinforcement [14].

Research on green construction, which aims to reduce, reuse, and recycle waste materials, has found that the addition of shredded plastic waste to concrete improves several mechanical properties of concrete [15]–[19]. The shredded plastic waste acts as closely spaced fibers to impede the propagation of microcracks, thus delaying the tensile crack. Jessica [15] found that mixing shredded polypropylene with concrete increases the concrete shear strength and splitting strength. Zainab [17] found that the concrete compressive strength, as well as flexural strength, decreases with the increasing shredded plastic content. The research concluded that waste plastic concretes possess less bonding ability, which affects the concrete compressive strength [17],[18].

The current study proposes a low-cost method of HCS construction that involves the planting of waste bottles made of polyethylene terephthalate (PET) to form the hollow. Waste PET bottles were chosen to resolve some of the solid waste problems created by plastic production. To optimize the waste material utilization, shredded waste PET plastic was also added to HCS concrete as a replacement of fine aggregate to improve the HCS strength.

The research aimed to find a low-cost and simple construction method of the cast-in-site HCS so that the HCS can be widely implemented. The main objective was to study the behavior of the HCS made of concrete strengthened with shredded PET and SF to overcome the lower flexural strength and shear strength of the HCS compared with those of the solid slab.

2. Methods

Specimens. Table 1 lists the specimens used in this study. Three parameters were evaluated: the hole volume and the contents of shredded PET and SF in concrete. A total of 14 HCS specimens were prepared. Each specimen consisted of two samples. The solid slab was used as a reference.

As discussed earlier, the shredded PET and SFs were added to the concrete mixture to improve the concrete strength and hence increase the HCS strength. The PET ratios of 0.5 vol.% and 0.7 vol.% are considered the optimum composition [16]. For comparison, other specimens were strengthened with 15 kg and 25 kg of SF in 1 m^3 concrete volume, which are similar to 0.19% and 0.32% of volume fraction, respectively. A content of less than 1% per concrete volume is considered low. The benchmark is adopted to avoid workability problems, and to minimize the construction cost. SF concrete was used in this research for comparison against shredded PET concrete.

Figure 1 shows the details of the slab specimen and the arrangement of bottles inside the slab. The specimen had a length, width, and thickness of 1750 mm, 600 mm, and 150 mm, respectively. The HCS specimen design was according to ACI 318R-14.

Table 1. Specimens

No	Specimens	Hole Content	Concrete Fiber	
			Shredded PET	Steel Fiber
1	Solid Slab	n/a	n/a	n/a
2	HCS-5Void	24%	n/a	n/a
3	HCS-4Void	19%	n/a	n/a
4	HCS-PET0.5	24%	0.50%	n/a
5	HCS-PET0.7	24%	0.70%	n/a
6	HCS-SF15	24%	n/a	0.19%
7	HCS-SF25	24%	n/a	0.32%

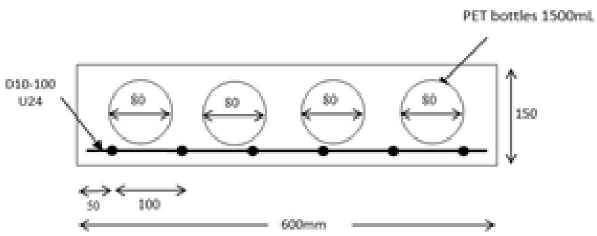

Figure 1. HCS Specimen

(a) (b)

Figure 2. Arrangement of PET Bottles: (a) Four Rows and (b) Five Rows

Figure 2 shows the arrangement of the bottles: four rows and five rows. All specimens (Table 1) consisted of five rows of bottles, accounting for 24% of the total volume, except specimen HCS_4void, which had four rows, accounting for 19 vol.%. The waste PET bottles had a capacity of 1500 ml with 80 mm diameter.

Since the concrete volume used in the research was more than 5 m^3, two batches of ready-mix concrete of K300 (Fc' = 24 Mpa) were purchased. The concrete consisted of small aggregates of 10–20 mm to ensure that the concrete could fill the gap between the bottles. However, the two batches exhibited different compressive strengths: 28 MPa and 33 MPa. The additions of shredded PET and SF to the concrete were conducted separately. The reinforcement bar D10-100, which had a yield stress (Fy) of 240 Mpa, was used as flexural reinforcement for all specimens.

Experimental Setup. The experimental study was conducted in the Materials and Structural Laboratory of Civil Engineering Department, Universitas Indonesia. A four-point loading scheme was used with two hydraulic jacks. The experimental setup is shown in Figure 4. As shown, dial gauges were placed vertically in nine locations. Dials 2, 6, 8, and 9 monitored the movement of the support, whereas dials 3, 4, and 5 measured the deflection at the mid-span. Two dials, 1 and 7, were placed at the slab edge to record the rotation on the support. Dials 3 and 5 were placed next to the mid-span to capture the torque during the test. Observations during the test included recording the load versus deflection, the crack pattern, and the failure mode of HCS.

3. Results

The results of the compressive test of concrete used in this research are presented in Table 2. As can be seen, the shredded PET improved the concrete shear strength by 15.4%. The different contents of shredded PET did not have a significant effect on the concrete strength. The additions of 15% and 25% SF also improved the concrete shear strength by 10% and 16%, respectively. Moreover, the compressive strength of the concrete decreased with the addition of shredded PET. This finding confirms the results found by other researchers [17–18] that the shredded PET decreased the bonding ability of the aggregates, which resulted in the decline of compressive strength.

The test results on load versus deflection based on dials 3, 4, and 5 and moment versus rotation measured from dials 1, 2, 6, and 7 divided by 125 mm, which is the cantilever arm length, are presented. The results were calibrated through the reading on dials 2, 6, 8, and 9. During the test, torsion was not detected, as revealed from the readings of dials 3 and 5.

Flexural crack patterns were detected on the middle one-third length of all specimens according to the four-point loading scheme shown in Figure 3. Examples of the typical crack patterns are presented in Figure 5 and 6. Based on these figures, it can be concluded that all specimens failed due to the yielding of the flexural rebar.

Table 2. Material Compressive Test Results

	Compressive Strength Fc' (Mpa)	
	Batch A	Batch B
Pure Concrete	27.02	33.92
Concrete + PET 0.5%	n/a	33.69
Concrete + PET 0.7%	n/a	32.68
Concrete + SF15	28.19	32.39
Concrete + SF25	28.6	33.6

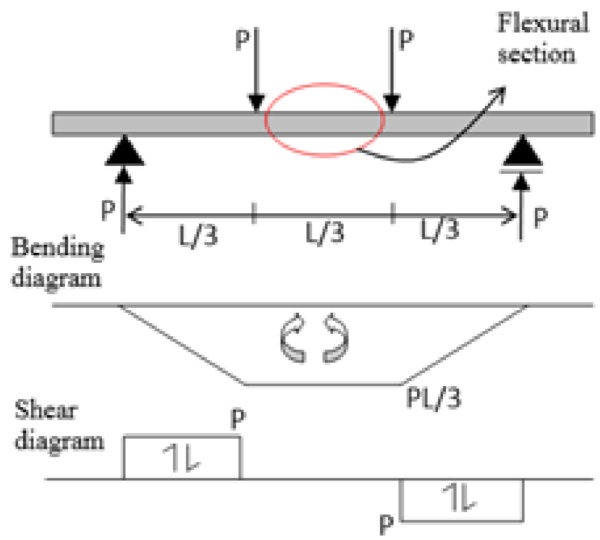

Figure 3. Four-points Loading Scheme

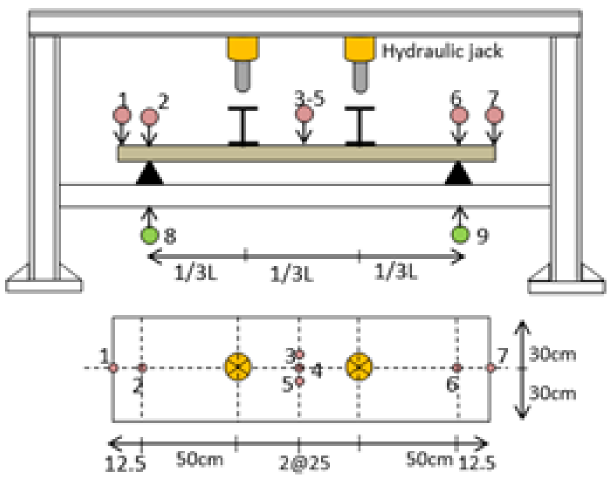

Figure 4. HCS Testing Scheme

The next section discusses the test results. The discussion is divided according to the different parameters. As mention earlier, the difference in the strengths of the two batches of concrete cast in different periods was about 5–6 Mpa. The first batch of cast, which had a concrete strength of 28 Mpa, is designated "A," while the second batch, with a concrete strength of 33 MPa, is designated "B." Symbols 1 and 2 indicate the specimen serial number. The results are presented based on the moment–rotation curve. The moment was determined according to Figure 4, while the rotation was determined based on the vertical displacement recorded by dials 1 and 7 on the left side and dials 2 and 6 on the right side divided by 125 mm.

According to the mechanics design of concrete [20] the one-way HCS can be treated as a reinforced concrete (RC) beam. The nominal bending capacity (Mn) is a function of concrete strength (Fc'), reinforcement bars (As, Fy), and the arm length between the compression and tension areas. The bending capacities of all specimens without considering the strength reduction factor (ϕ) are listed in Table 3.

Figure 5. Crack Pattern of HCS-0.7 PET

Figure 6. Crack Pattern of HCS- SF25

Table 3. Bending Capacities of Specimens

Concrete Content	Specimens	Mn (Nm)	
		Batch A	Batch B
Pure Concrete	Solid Slab, HCS Void	10,840	10,935
Concrete + PET 0.5%	HCS-PET0.5	n/a	10,932
Concrete + PET 0.7%	HCS-PET0.7	n/a	10,921
Concrete + SF15	HCS-SF15	10,860	10,917
Concrete + SF25	HCS-SF25	10,866	10,931

The Effect of Hollow Content on HCS Strength. Figure 7 compares the moment–rotation curves of specimens with different void contents. The void contents of HCS-4void and HCS-5void constituted 12% and 19% of the total HCS area, respectively. The solid slab was used as a reference to determine the effect of the hollow section on bending capacity.

The test results show that reducing the concrete volume reduced the slab flexural stiffness (Figure 7). The HCS exhibited yielding earlier than the solid slab. As presented in Table 2, the HCS bending capacity was about 6%–22% lower than that of the solid slab. This finding is similar to those by Allawi [9] and Abed [10], who found that the void content reduced the HCS flexural strength. Based on the obtained graphs, the HCS specimens seem more ductile than the solid slab. There is no visible difference between the strengths of the specimens with different void contents. The specimens with 12% and 19% of void showed similar bending capacities.

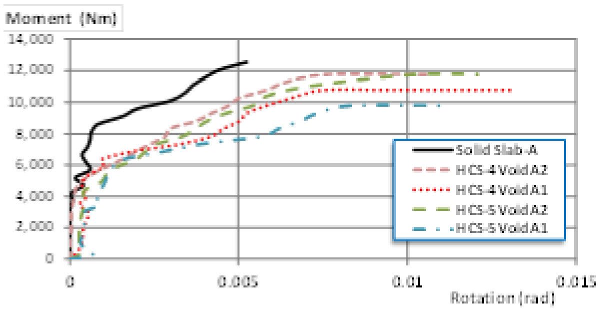

Figure 7. Comparison of Moment–rotation Curves of Specimens with Different Void Contents

Table 4. Ultimate Capacities of HCSs with different Void Contents

Specimens	Mu (Nm)	Compared with Solid	
		Ratio	Percentage
Solid Slab - A	12,544	1.000	
HCS-5VoidA1	9,800	0.781	-22%
HCS-5VoidA2	11,760	0.938	-6%
HCS-4VoidA1	10,780	0.859	-14%
HCS-4VoidA2	11,760	0.938	-6%

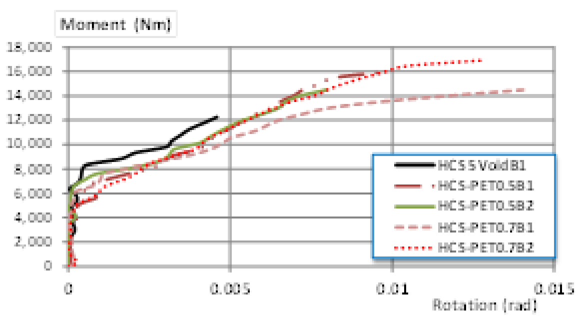

Figure 8. Comparison of Moment–rotation Curves of Specimens Containing Shredded PET

Effect of Shredded PET on HCS Strength. Figure 8 shows the moment–rotation curves of HCS specimens with different concrete strengthening degrees. In the HCS-PET specimen, the concrete was mixed with shredded PET. Two specimens with different shredded PET volume ratios (0.5% and 0.7%) were compared. As shown, changing the PET composition from 0.5% to 0.7% did not significantly affect the moment–rotation curves. The results were compared with those of HCS specimens with 0% shredded PET (HCS 5Void B1). In general, specimen HCS-PET was more ductile, as revealed from its capacity to rotate more than HCS 5Void.

Table 5 presents the bending capacities of the HCS 5Void B1 specimen and the HCS-PET specimens. The bending capacity (Mu) of the HCS with shredded PET was more than 15% higher than that of the HCS without shredded PET. However, the bending capacities of the specimens with different PET composition ratios (0.5% or 0.7%) were not significantly different.

The Effect of SF on HCS Strength. The SF-containing HCSs were prepared in two batches, and hence, the concrete strength difference was 5 MPa. To investigate the effect of SF, the results were compared with those of the SF-free HCSs, i.e., HCS-5VoidA1 and HCS-5Void B1. Figure 9 shows the comparison graphs, and Table 4 presents the ultimate capacity of HCS. Based on the graph, the results were similar to those of the HCS-PET test: the HCS-SF specimens were more ductile than the specimen without SF (HCS-5Void).

Table 5. Ultimate Capacity of HCS with Shredded PET

Specimens	Mu (Nm)	HCS-5Void	
		Ratio	Percentage
HCS-5VoidB1	12,250	1.00	
HCS-PET0.5B1	15,974	1.30	30%
HCS-PET0.5B2	14,504	1.18	18%
HCS-PET0.7B1	14,504	1.18	18%
HCS-PET0.7B2	16,954	1.38	38%

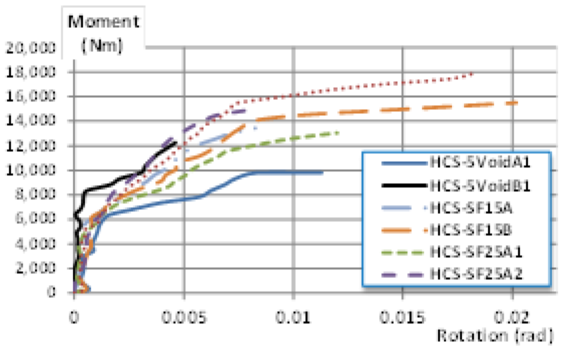

Figure 9. Comparison of Moment–rotation Curves of Specimen with SF

The composition ratios in Table 6 were determined by comparing the Mu of HCS with SF to that of the specimen without SF with the same concrete strength. The addition of SF could improve the HCS ultimate capacity by 11% to 53%. The effect of the SF fluctuated based on the SF content. As presented, HCS-SF25B had 20% higher Mu than HCS-15B. Meanwhile, for the first batch cast specimens, whose concrete strength was 5 MPa less than that of batch two, increasing the SF content did not accordingly improve the ultimate strength. However, the Mu of HCS-SF25A1 was lower than those of HCS-15A and HCS-15B.

Discussion of Test Results. As shown in Figure 2, the PET bottles were placed on top of the flexural reinforcement. The difficulties were found during the casting process, where the bottles will float, due to Archimedes' law. To overcome this problem, the bottles were tied to the flexural rebar and formwork during casting. In general, the construction of HCS with PET bottles did not present any significant difficulties. Hence, the low-cost cast-in-site HCS proposed in this research can be applied to low-rise buildings.

Table 6. Ultimate Capacity of HCS with SF

Specimens	Mu (Nm)	Compared with HCS-5Void	
		Ratio	Percentage
HCS-5VoidA2	11,760	1.00	
HCS-5VoidB1	12,250	1.00	
HCS-SF15A	13,524	1.15	15%
HCS-SF15B	15,484	1.32	32%
HCS-SF25A1	13,034	1.11	11%
HCS-SF25A2	14,994	1.28	28%
HCS-SF25B	17,934	1.53	53%

Table 7. Comparison of Mu with Predicted Values

Specimens	Bending Capacity (Nm)		Ratio (b)/(a)
	Predicted (a)	Experimental Results (b)	
Solid Slab-A	10.840	12.544	1.16
HCS-4VoidA1	10,840	10,780	*0.99*
HCS-4VoidA2	10.840	11.760	1.08
HCS-5VoidA1	10,840	9,800	*0.90*
HCS-5VoidA2	10.840	11.760	1.08
HCS-5VoidB1	10.840	12.250	1.13
HCS-PET0.5B1	10,932	15,974	1.46
HCS-PET0.5B2	10.932	14.504	1.33
HCS-PET0.7B1	10.921	14.504	1.33
HCS-PET0.7B2	10,921	16,954	1.55
HCS SF15A	10.860	13.524	1.25
HCS SF15B	10.917	15.484	1.42
HCS SF25A1	10,866	13,034	1.20
HCS SF25A2	10.866	14.994	1.38
HCS SF25B	10.931	17.934	1.64

In general, the M-φ graphs of all HCS specimens had similar patterns and could be idealized as a trilinear curve. Before cracking, the specimen is still in a linear elastic stage where concrete and steel rebar work as a unity. The behavior of this stage is described by the first trilinear line. The first concrete crack propagates on the bottom part of the slab because the stress exceeds the concrete tensile stress. At this stage, some parts of the concrete under tensile lose their strength. Hence, steel rebar and some parts of the concrete take over the loads until the steel reaches its yield stress, which can be idealized as the second trilinear line. The last trilinear line is a post-yielding phase of steel rebar, where the structure can no longer withstand the load but can still to deform.

The bending capacity of the HCS specimens with shredded PET or SF was higher than that of the standard HCS. It can be explained that the shredded PET and SF decelerate the crack opening of the concrete. After the first crack, the crack rate is restrained by shredded PET or SF. Therefore, the specimens are stronger and more ductile than specimens without those ingredients.

The bending capacities (Mu) of all specimens are presented in Table 8. As listed, the capacities obtained in the experiment are higher than those obtained based on the RC design equations [20]. If the strength reduction factor is considered, then the calculated Mu values are 10% to 15% lower than the experimental result. It can be concluded that waste plastic bottles can be utilized to form hollows on HCS, whereby the bending capacity of HCS still meets the design criteria of RC structures.

4. Conclusion

A series of experimental tests was performed to study the flexural strength of the one-way HCSs. PET bottles were utilized to form hollows. Three parameters were investigated: the void content, shredded PET content, and SF content. The difficulties were found during the casting process since the PET bottles tend to move upward due to Archimedes' law. However, this could be easily overcome by tying the bottles to the rebar and slab formwork.

Theoretically, the void content does not affect the ultimate moment (Mu) of specimens; however, the results indicated that the strengths of the HCS specimens were about 12% to 16% less than that of the solid slab. However, the bending capacity of HCS specimens still met the design criteria of RC slab. In general, the HCSs tended to behave more ductile than the solid slab.

The ultimate strengths (Mu) of the HCS based on concrete with shredded PET of 0.5 vol.% and 0.7 vol.%

were 1.18–1.38 times that of the HCS without shredded PET. The Mu of the HCS with steel-fiber concrete was improved by 11% to 46% compared with that of the SF-free HCS.

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