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An Experimental Study on One-way Foamed Concrete Slabs Reinforced with Steel Bars

Mohamed Hassaan [1,*], Tarik Youssef [2], Gouda Ghanem [1] , Waleed Tawhed [1]

[1] *Faculty of Engineering, Mataria, Helwan University, Cairo, Egypt.*
[2] *Structural Engineering department, Faculty of Engineering, L'Université Française D'Égypte, Cairo, Egypt.*
[*] *Corresponding Author*

E-mail address: mhahassaan@gmail.com, tarik.youssef@guc.edu.eg, gouda_ghanem@m-eng.helwan.edu.eg, waleed.tawhed@m-eng.helwan.edu.eg

Abstract: An experimental study was conducted to investigate the flexural behavior of foamed concrete (foamcrete) one-way slab specimens reinforced with steel bars. Structural Foamed Concrete (SFC) with an average dry density of 1600 kg/m^3 and compressive strength of 25 MPa was used in this study. FC slabs were cast as orthotropic plates and their load-deflection response was predicted under a three-point bending configuration. A total of six reinforced foamed concrete slab specimens of dimensions 350 x 700 x 100 mm were tested. Two variables were considered: the polypropylene fiber content and the reinforcement ratio. Results demonstrated the reliability of using foamcrete (FC) with a dry density of 1600 kg/m^3 and compressive strength of more than 25 MPa for structural use; as well as the mechanical property enhancement using various percentages of polypropylene fibers (PP) (by weight of cement). The PP ratio of 0.3% stood out as an optimal value that increased the slab-element ultimate load capacity by 9.7% also corresponding to a deflection decrease of 16.46%.

Keywords: Steel reinforced foam concrete; One-way foamed concrete slabs; Three-point bending; Flexural behavior; Polypropylene fibers.

1. Introduction

The flexural response of foamed concrete elements substantially depends on the type of reinforcement material as well as reinforcement ratios, as observed in previous experimental studies. Jones and McCarthy [1] found that the magnitude of mid-span deflections in foamed concrete slabs are approximately twice the design-code predictions; indicating idealized stiffness values. Despite the advantages of lower density and superior thermal insulation, the relatively lower strength and brittleness of lightweight foamed concrete necessitates sufficient steel reinforcement to enhance the overall flexural capacity, shear resistance, and durability [2, 3]. [3] This paper presents an experimental program comprising six one-way foamed concrete slabs reinforced with steel to quantify their first-crack and ultimate flexural strengths. Results provide a comparative evaluation as well as structural adequacy assessment for foamcrete slabs comprising PP fibers and steel reinforcement.

2. LITERATURE REVIEW

2.1 Foamed Concrete with Polypropylene fiber content

Foamcrete is considered a subset of structural lightweight concrete. According to ACI 213 [4], the latter is specified to possess a minimum compressive strength of 18 MPa, while having a hardened dry density between 1400-1800 kg/m^3. The relatively lower tensile, flexural and impact strength of foamcrete arising due to brittle failure can be enhanced through incorporation of micro-fiber reinforcement [5]. Discrete short crimped polypropylene fibers act as rigid inclusions that help arrest the growth of microcracks in the heterogeneous cellular cementitious matrix [6]. After first crack formation, the fibers provide a pseudo strain-hardening response by bridging across cracks and flaws, imparting improved resistance to deformation and fracture. The extent of enhancement depends on the geometry, volume fraction, and interfacial bond strength with the surrounding matrix [7]. Typically, 12 to 20 mm long polypropylene fibers are added between 0.2% to 0.3% by volume of foamed concrete, resulting in flexural strength improvements up to 22% [8]. However, issues related to workability loss, fiber balling, and non-uniform dispersion arise when the proportion of fibers exceeds 0.5% by volume. Careful consideration regarding the mixing process, rheology of fresh concrete composite, and placement techniques is vital alongside mixture proportioning to realize the strength and ductility benefits associated with fine polypropylene fiber reinforcement in foamed Concrete.

2.2 Steel Reinforced Foamed Concrete Slabs

Jones and McCarthy [1] tested steel reinforced foamcrete slabs and observed deflections almost double that of the BS 8110 code predictions [9], indicating differences between the assumed and actual stiffness values, despite obtaining ultimate moment capacities 7 to15% higher than code estimates. Babu et al. [10] also noted a 13 to 51% higher experimental deflection; compared to analytical estimates; using proposed modulus of elasticity expressions made available in codes and guidelines; highlighting the need to assume lower E values for the porous foamed concrete structure. Vargas et al. [11] found satisfactory correlation(s) between experimental and analytical load-deflection curves up to service loads by incorporating a 0.55 reduction factor on the modulus of elasticity and modifying the tensile strength to improve prediction of first crack loads.

3. MATERIALS

3.1 Structural Foam Concrete

Structural Foamed Concrete (SFC) with an average dry density of 1600 kg/m^3 and compressive strength of 25 MPa was cast - in this study - using one type of cement (Portland CEM 1 52,5 N) [12] from a local producer; complying with the EN 197-1 [13] standards; for proportioning the main constituting elements in all samples. Calcium carbonate ($CaCO_3$) - less than 150µ diameter - was used as filler type 1. Sand - less than 800µ diameter, passing by sieve no. 25, with bulk density 1.55 t/m^3 according to EN 1097-3 – was used as filler type 2. MICROCORE® C4T [14] was used as an additive material and MICROCORE® T500 [15] was used as a foaming agent material. Polypropylene fiber (Belmix 12) [16] of 12 mm length was used. Table 1 shows the mix proportions of the used mix design.

Table 1. Shows the mix proportions of the used mix design.

Cement	Water	$CaCO_3$	Sand	MICROCORE® C4T	P. fiber 12mm	MICROCORE® T500
kg	kg	Kg	kg	kg	Kg	Kg
650	262.5	300	300	7	2	19.6

3.2 Steel Reinforcement

High grade steel reinforcement, complying with ES262-2:2021 [17] of 8 mm diameter bars, was used for the one-way structural foamcrete solid slabs. Mechanical properties are presented in Table 2, below:

Table 2. Mechanical properties of steel.

RTF Type	Steel
Grade	B500DWR
Yield Stress	550 MPa
Tensile Stress	580 MPa
Max Strain	0.10212

4. EXPERIMENTAL PROGRAM

4.1 Specimens

Four one-way foamcrete slabs (350 x 700 x 100 mm) with the same steel reinforcement ratio but varying polypropylene fiber content by weight of cement (0%, 0.1%, 0.3%, 0.5%) were tested for flexural capacity to determine the most effective fiber content. Another two slabs of the same dimensions but with different reinforcement ratio, along with the same 0.3% polypropylene fiber content, were tested for flexural capacity. The details of the six one-way foamcrete slab specimens are provided in Table 3.

4.2 Test Setup

Three-point bending load test was conducted to determine the flexural behavior of the slabs. The flexural behavior studied was in term of its ultimate load, crack pattern, and load-deflection profile. The load deflection profile and crack pattern of a structure was obtained by conducting a three- point bending test according to BS EN 12390:5 [18] as shown in Figure 1.

All the specimens were cast with 25 mm concrete cover. The slab specimens were cured for 28 days before commenced the flexural test. The details of each slab cross section were shown in Figure 2.

Table 3. One-way foam concrete slabs.

Specimen	Group 1			Group 2		
	S1	S2	S3	S4	S5	S6
RFT %	0.43	0.43	0.43	0.43	0.57	0.29
Cement (kg per m^3)	650	650	650	650	650	650
PP % (by weight of cement)	zero	0.1	0.3	0.5	0.3	0.3
PP (kg per m^3)	zero	0.65	1.95	3.25	1.95	1.95

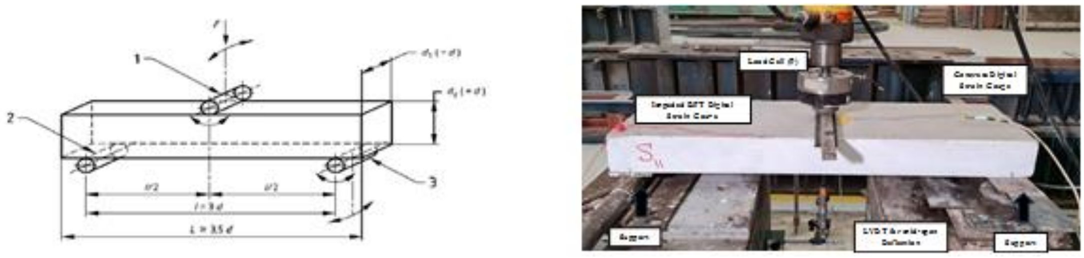


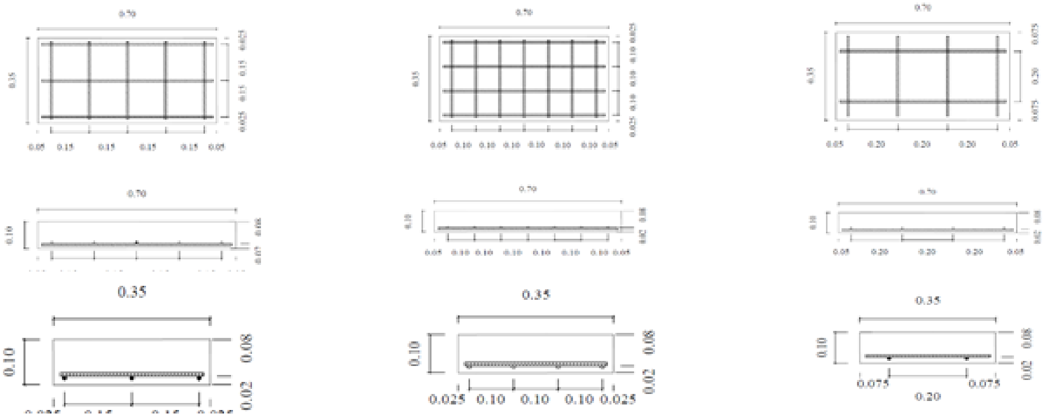
Figure 1. Test setup of slab specimens (S1 to S6).

5. EXPERIMENTAL RESULTS FOR ONE-WAY FOAM CONCRETE SLABS

The experimental results for ultimate first crack (**P*Cr***), ultimate failure load (**P*ultexp***) and its corresponding deflection (**Def*exp***) as well as the allowable deflection limit according to ECP [19] were recorded for all six-foam concrete one-way slabs tested for flexure bending as illustrated in Table 4. Flexural failure mode for slab specimens is shown in Figure 3.

5.1 First Crack and Ultimate Failure Load

Figure 4 represents the comparison between first crack Load (**P*cr***) and the ultimate failure load (**P*ult exp***) for all slabs tested. It is clear from this figure that **P** ***cr*** for all slab specimens represents an average of about 48% of the **P** ***ult exp*** varying from a minimum of 38% to a maximum of 60%. It is clear that, slab S5 recorded the maximum ultimate load capacity of 43.17 kN and first cracking load of 16.31 kN due to the maximum steel reinforcement percentage of 0.57 of concrete cross-section, while slab S6 recorded the minimum ultimate load capacity of 21.6 kN and first cracking load of 9.65 kN due to the minimum steel reinforcement percentage of 0.29 of concrete cross-section.



(a) RFT arrangement and dimensions of slab (S1, S2, S3, S4). (b) RFT arrangement and dimensions of slab (S5). (a) RFT arrangement and dimensions of slab (S6).

Figure 2. RFT arrangement and dimensions of slab (S1 to S6).

Figure 3. Flexural failure mode for slab specimens (S1 to S6).

Tabel 4: Experimental Results for One-way foam concrete slabs

Slab Specimen	S1	S2	S3	S4	S5	S6
P_{Cr} (kN)	16.81	14.24	15.9	15.17	16.31	9.65
$P_{ult\ exp}$ (kN)	28.15	30.28	30.88	31.93	43.17	21.60
$P_{Cr\ /\ ult\ exp}$ (unitless)	0.6	0.47	0.51	0.48	0.38	0.45
Deflection $_{exp}$ (mm)	4.07	3.93	3.40	4.16	2.37	3.36
Allowable Def $_{ECP}$ (mm)	2.4	2.4	2.4	2.4	2.4	2.4
Deflection $_{exp/ECP}$ (unitless)	1.70	1.64	1.42	1.73	0.99	1.40
Failure Mode	Flexural	Flexural	Flexural	Flexural	Combined (flexure +Shear)	Flexural

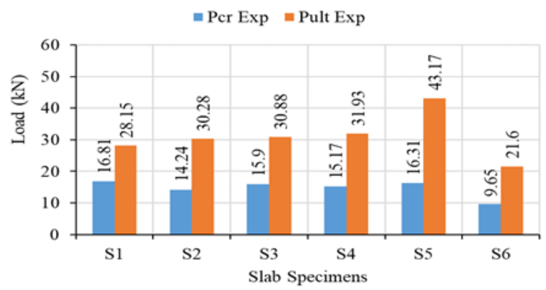


Figure 4. First crack load verses ultimate failure load for slab specimens.

5.2 Load Versus Deflection Relationship

As shown in Figure 5, the load-deflection curves for slabs (S1, S2, S3, S4), with the same reinforcement steel ratio of 0.43 but different polypropylene fiber ratio, nearly behaved the same, i.e. having similar values for ultimate failure load and their corresponding deflection despite that S3 curve for 0.3% PP is the highest which reflects the slab flexure capacity on increasing the polypropylene fibers content.

Slab specimen S5 (max steel reinforcement) showed lowest deflection of 2.37 mm but highest ultimate load of 43.17 kN, enhancing flexural capacity by 40% over S3 (same fiber content, different reinforcement ratio), indicating reinforcement ratio effect. Slab specimen S6 (min steel reinforcement) had shortest load-deflection curve, minimum ultimate load 21.6 kN, proving reinforcement ratio's impact.

Figure 6 compares ultimate failure loads and corresponding deflections for all slab specimens. Slabs S1-S6 behaved similarly, with S5 (highest steel ratio) achieving minimum deflection of 2.37 mm and greater ultimate load, reflecting higher steel ratio's ability to enhance capacity for same reinforcement type.

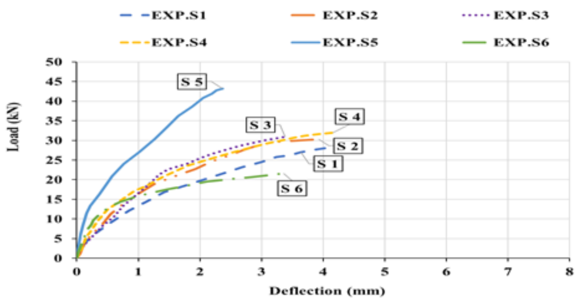


Figure 5. Load deflection curve for all slabs.

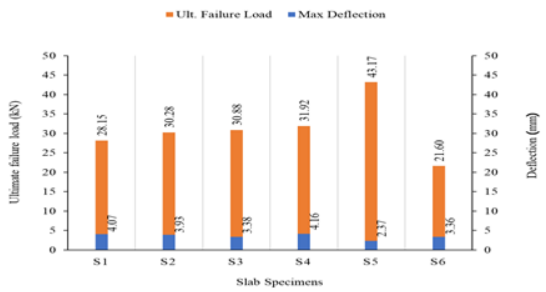


Figure 6. Ultimate failure load verses max deflection.

The allowable deflection according to ECP was calculated for all slab specimens as illustrated previously in Table 4. According to ECP S5 only did not exceed the allowable deflection limit. S1, S2, S3, S4 and S6 showed a little bit higher deflection value than allowable.

5.3 Effect of Polypropylene Fiber content on One-way Slabs

Investigating different polypropylene fiber contents (0%, 0.1%, 0.3%, 0.5%) for slabs S1-S4 with same 0.43% steel ratio showed small differences in ultimate load capacity. However, S3 (0.3% fibers) exhibited lowest deflection of 3.38 mm, indicating best capacity performance. This confirms polypropylene fibers play an important role in improving the structural performance of foamed concrete slabs. Compared to control S1, ultimate loads increased by 7.57% (S2), 9.7% (S3), 13.43% (S4) with fiber addition. Deflections decreased by 3.44% (S2) and 16.46% (S3) but remained unaffected for S4 (0.5% fibers) as shown in Figure 6.

It was noticed that, increasing the polypropylene fiber content in foam concrete can have a positive impact on the flexural capacity of one-way slabs. The fibers act as reinforcement within the concrete matrix, helping to distribute the applied load and resist cracking under bending moments. As the polypropylene fiber content increases, the flexural capacity of foam concrete slabs tends to improve. The fibers act as bridging elements across cracks, effectively resisting crack propagation and increasing the overall strength and stiffness of the slab. This reinforcement mechanism helps to enhance the load-carrying capacity of the slab under bending loads as shown in Figure 7.

Figure 7. Fibers effect as bridging elements resisting crack propagation.

5.4 Effect of Steel RFT on One-way Slabs

Investigating the effect of steel bar reinforcement ratio (0.29%, 0.43%, 0.57%) with constant 0.3% fiber content, Figure 6 shows ultimate failure loads of 21.6 kN (S6), 30.88 kN (S3), 43.17 kN (S5) corresponding to reinforcement ratios of 0.29%, 0.43%, 0.57% respectively. Slab S5 with highest 0.57% steel ratio exhibited lowest deflection of 2.37 mm, indicating best capacity performance. Increasing steel reinforcement area enhances and increases the ultimate load capacity of foamed concrete one-way slabs. Specifically, increasing steel ratio by 48% and 96.55% led to ultimate load capacity increases of 42.96% and 99.86% respectively for the tested slabs.

6. CONCLUSIONS

Experimental and analytical studies investigated flexural behavior of steel reinforced foamed concrete one-way slabs. Slabs cast as orthotropic plates; load-deflection predicted under three-point bending. Six slab specimens were tested: four of which were cast with the same RFT ratio and another two were cast with maximum and minimum RFT ratio respectively. Observations and conclusions based on experimental and analytical results are as follow:

1. The strength and stiffness of the slabs increase with increasing of the slab reinforcement, increasing steel ratio by 48% and 96.55% led to ultimate load capacity increases of 42.96% and 99.86% respectively for the tested slabs.
2. increasing the polypropylene fiber content in foam concrete can have a positive impact on the flexural capacity of one-way slabs, and 0.3% remains the best percentage for polypropylene fiber content.
3. Foam concrete is suitable for use as structural material.

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