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Behavior of Multilayer Ferrocement Slab Containing Treated Sponge Layer Core

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Abstract: The current study investigates the structural performance of lightweight concrete panels produced using ferrocement (wire-meshed), hybrid (wire-meshed and steel fiber), and sponge-cementitious immersed layers. These panels presented a novel approach to producing a lightweight concrete panel to be used as an alternative to the traditional Jack-arch masonry slab system. The panels were made in dimensions of 600mm length(l), 200mm width (w), and 54mm thickness (h), using locally available sponge materials and super cementitious mortar incorporated with ferrocement layers. To determine the proper thickness of a sponge layer to be used in panel manufacturing, a material characterization was performed. The obtained results from the material characterization indicated a significant reduction in the density compared with the conventional Jack-arch slab system. The sponge core thickness positively affected the developmental compressive strength. For all sponge thickness modes, the density of developed sponging concrete was within the acceptance criteria of lightweight structural concrete. The average density of developing sponge concrete was 15.6 kN/m^3, and the average absorption ratio was 14.78 %, while the density of cementitious mortar was 21.96 kN/m^3. As for the structural performance of the resulting lightweight concrete panel, the panel with a hybrid layer (incorporating short steel fiber with steel wire mesh) 10mm layer was the best reinforcement method compared with reinforcing with the wire mesh (ferrocement) solely. Furthermore, the findings of this study depicted that the bending moment capacity of the developed lightweight concrete panel was higher than the conventional Jack-arch masonry usually used in traditional residential housing and lower density.

تصرف السقوف الفيروسمنتية متعددة الطبقات الحاوية على طبقة اسفنج معالج

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الخلاصة

قدمت الدراسة الحالية نهجًا جديدًا للتحقيق التجريبي لإنتاج لوح خرساني خفيف الوزن باستخدام مواد إسفنجية وملاط أسمنتي فائق مدمج مع طبقات حديدية. تم إجراء توصيف المواد للإشارة إلى السماكة المناسبة لطبقة الإسفنج المستخدمة في تصنيع الألواح، بناءً على الخواص الميكانيكية والفيزيائية التي تم الحصول عليها. أشارت النتائج التي تم الحصول عليها إلى انخفاض واضح في الكثافة مقارنة مع نظام بلاطة جاك (العكادة) التقليدية. يؤثر سمك اللب الإسفنجي بشكل إيجابي على تطور قوة الانضغاط. بالنسبة لجميع أوضاع سماكة الإسفنج، تكون كثافة الخرسانة الإسفنجية المطورة ضمن الحد الإنشائي الخفيف الوزن، ويبلغ متوسط كثافة الخرسانة الإسفنجية النامية 15.6 كيلو نيوتن / م 3 ومتوسط نسبة الامتصاص 14.78٪، بينما تبلغ كثافة الملاط الأسمنتي 21.96 كيلو نيوتن. / م 3. فيما يتعلق بالأداء الإنشائي للوحة الخرسانية خفيفة الوزن الناتجة، فإن طبقة التسليح الهجين (ألياف فولاذية قصيرة مع شبكة سلكية فولاذية) كانت أفضل طريقة للتسليح مقارنةً بالتسليح بألياف الصلب فقط. علاوة على ذلك، أظهرت نتائج هذه الدراسة أن سعة عزم الانحناء للوحة الخرسانية خفيفة الوزن المطورة كانت أعلى من البناء التقليدي (العكادة) ذات القوس المقوس الذي يستخدم في المساكن السكنية وكذلك الكثافة المنخفضة، على التوالي.

الكلمات الدالة: مونة اسمنتية، سمنت حديدي، سقف خرساني خفيف الوزن، الخرسانة ذاتية الرص، الخرسانة الاسفنجية.

1.INTRODUCTION

Jack-arch masonry slab system represents an encouraging alternative slab system to the steel-reinforced concrete slab system in low-cost residential housing units in developing countries, attributable to the affordability of the available raw materials and the labor cost. The Jack-arch system uses available building units Fig. 1 (b) and (c) [1-3], glued together at the units' adjacent faces using gypsum or cementitious material to form a one-way slab panel with a certain width (w) between two steel beams. These beams consequently transfer the panel load in (l) direction to walls or supporting beams (as a concentrated dead load), as shown in Fig. 1 (a) [1].

Fig. 1 Conventional Jack Arch-System; (a) Load Distribution Mechanism[1], (b) Jack-Arch Slab System Using Clayey Brick Units [2], (c) Jack-Arch Slab System Using Thermo-Stone Blocks[3].

However, the quality of these (Jack-arch system) in-situ systems of slabs depends on several factors; (1) skillful workers, (2) the materials' quality and the variability (weather sensitivity) and materials preparation used in producing these systems due to the uncontrolled environmental conditions in the construction site, and (3) the speed in completing these systems (time-consuming) [1, 2]. Nonetheless, the growing population continued the rising demand for Jack-arch masonry slabs in affordable housing construction. Therefore, many researchers have devoted considerable efforts to searching for an alternative system of slabs and materials to overcome the above factors of the in-situ system of slabs and to compete with the low-cost and better-quality control of the common (conventional) slab systems [4-6]. Moreover, researchers studied producing alternative slab systems that are not only economically affordable compared with the conventional Jack-arch slab system but lighter in the dead load (self-weight) weight. Hence, a reduction occurs in the dead load transmitted from the slab to the load-carrying walls. Consequently, this reduction minimizes the likelihood of damage to the walls carrying the slab system. This reduction is favorable because it is believed that approximately 50-56% of the total weight of a building comes from the slab system[7]. Furthermore, many studies were conducted to extend the service life of the affordable Jack-arch slab system by creating better retrofitting or repairing techniques [1, 2].

Alfeehan and Alkerwei (2014) experimentally explored the structural performance of an alternative precast slab system using a steel frame filled with thermos-stone blocks (a.k.a. autoclaved aerated concrete AAC). Two different configurations were used with respect to the glued sides of the blocks, i.e., horizontal and vertical gluing, respectively. The maximum carrying loads achieved was 18.5 tones/m² in the horizontal configuration and 185 tones/m² in the vertical configuration [3]. Yardim et al. (2013) conducted an experiment using AAC blocks as a filler material for a semi-precast panel and compared the resulting capacity of this panel with a conventional solid precast concrete panel. Their findings showed a reduction in the dead load without deteriorating the load capacity, compared with the conventional solid panel [8]. Saheed et al. (2021) used lightweight expanded polystyrene (LEPSF) to produce lightweight expanded concrete with 35 MPa compressive strength and a density of 1980 kg/m³ to be used as precast c-shaped panels [9]. The findings of this study showed that the produced lightweight panels were 20% less than the weight of the conventional concrete slab and had better ductility (not abrupt failure) [9]. Ferrocement material has been widely used in construction for more than 100 years [7, 10-16]. Due to the recent evolution in material technology, composite structures and materials have become widespread, and construction materials are no longer limited to using nature's conventional materials. Ferrocement is a composite material consisting of a cementitious material and wire mesh that behave together as one structural material [7]. Structural components, such as wall panels and precast roofing elements, are made using ferrocement material [7]. Chassib et al. investigated the punching shear behavior of a lightweight bubbled ferrocement element to reduce the weight and cost during the construction process [17]. Memon et al. (2008) [18] fabricated a sandwich block using lightweight AAC encased in a ferrocement box. Different types of wire mesh for the ferrocement layer were investigated. The resulting sandwich block weight met the lightweight structural component specifications [18]. The effect of incorporating 25 mm-long steel fibers and the partial replacement of cement with silica fume was investigated as regards the flexural strength of simply supported ferrocement panels [19]. The study showed an enhancement in flexural strength compared with a control panel [19, 20]. Naser et al. (2021) [21] studied the effect of using PVC pipes as a core material in a ferrocement thin hollow slab on flexural behavior. The findings of this study showed that the macro steel wire mesh slab had the highest flexural strength and the lowest weight achieved, compared with the slab reinforced with conventional steel reinforcement [20-22]. In conclusion, ferrocement layers embedded with lightweight material contributed to producing an efficient slab system. This efficiency was obtained from the good mechanical properties of the ferrocement thin layer and the lightweight core material that provided an adequate thickness between the top layer and bottom layer to withstand the applied flexural stresses attained from the self-weight of the slab. Consequently, the geometric configuration (thickness of the core material of ferrocement panels (element) is considered an essential requirement in the manufacturing of lightweight precast ferrocement panels [7, 10-12, 23-29]. Additionally, the performance of the ferrocement layer has developed obviously due to the advancement in the concrete materials and additives and the types of wire mesh and fibers, respectively [30-40]. All the previous studies reviewed in the present study showed that the resulting panels made from Jacketing ferrocement layers filled with different types of lightweight cores were nonhomogeneous due to the difference between the Jacketing and the core material, respectively. Furthermore, the flexible sponge layers' usage as a filler material (core material) in producing lightweight ferrocement slab panels (units) has yet to be studied. This study presented a novel approach in utilizing the flexible sponge layer as an absorbent medium and immersing it with high flowability, high strength cementitious mortar to produce a lightweight porous core material analogous to foam core material [9, 39, 41-44]. Thus, the resulting lightweight core material was combined with ferrocement layers to behave as a lightweight precast slab unit and compare its mechanical properties with the conventional Jack-arch masonry unit.

1.1.Objectives of the study

The study investigated the development of an affordable precast lightweight concrete panel made from sponge-high strength immersed with cementitious mortar (CM) combined with ferrocement layers to be used as a precast slab system. Also, its mechanical properties and structural performance were investigated. The structural performance of the resulting product was then compared with the conventional Jack-arch slab system.

2.EXPERIMENTAL PROGRAM

2.1.Materials

2.1.1.Sponge layer

The sponge is a porous plastic, rubber, or other material similar in absorbency to the skeleton of a marine sponge. Sponges are used in many applications, and the most important practical applications of sponges are the furniture industry, insulation, packaging, buoyancy, and cleaning. The basic materials are polium polyol and toluene diisocyanate Fig. 2.

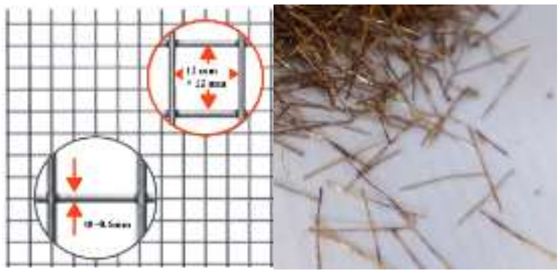
Fig. 2 Samples of Sponge with Various Porosity.

2.1.2.Steel welded wire mesh

The ferrocement in this study was made from hybrid reinforcement, i.e., a welded square steel wire mesh and a 10mm short steel fiber (SF). The opening (hole) dimension of the welded wire mesh was (12 ×12) mm, and the wire diameter Φ was 0.6 mm, while the SF fibers length was 10 mm, and its diameter was 0.5 mm Fig.3.

2.1.3.Cementitious material

High-strength mortar matrices containing various combinations of silica fume and fly ash, besides a good percentage of superplasticizer ensures a good balance between flowability and strength [30]. Cementitious grout of chemical base of cement, selected fillers and aggregates, special additives, and denoted as SikaGrout-212 IQ were used [45]. The Fresh mortar plastic density was (22.0-24.0 kg/m^3), while its maximum aggregate size was modified to be compatible with sponge porosity (D max.= 0.6 mm (600 micrometers)). The proper mixing (water/binder) ratio that guaranteed the required highest flowability was 33% under ASTM C 1437 [46]. Fig.4 shows the cementitious base material.



(a) Welded Wire Mesh (b) Steel Fibres (SF)

Fig. 3 Used Steel Reinforcement Fashions.

Fig. 4 Cementitious Base Material.

2.2.Experimental work

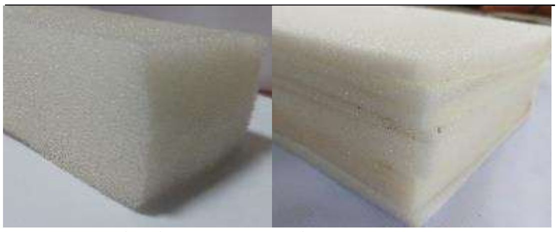
The experimental work of this study was divided into two parts:

2.2.1.The development of a lightweight sponging concrete core layer

The experimental program consisted of casting and testing various sets of cubes and prisms of various sponge field thicknesses to inspect the mechanical and physical properties of the developed lightweight sponge concrete. Besides, the effectiveness of sponge layer thickness upon the mortar flow through the sponge domain and the corresponding developed strength was investigated. A brief description of the adopted sample is listed in Table 1, while Fig.5 shows the sponge field discretionary modes that dominated the applied thickness.

Table 1 Description of The Sponge Layer.

No.	Batch Mode	Description	thickness (mm)
1	Mode 0	Plain cementitious mortar	50
2	Mode I	Sponge blocks (two 50mm thickness separated) immersed with	100
3	Mode II	Sponge block immersed with cementitious mortar	50
4	Mode III	Immersed (separated 10mm thickness) sponge layers with cementitious material	10



a. Block b. Discrete Layers

Fig. 5 Sponge Material.

2.2.2.Panel preparation

Wired sponging concrete panels (ferrocement layers with immersed sponge layers with cementitious mortar) were prepared and investigated to show the feasibility of the developed concrete in specific structural applications. This study implemented two types of concrete reinforcement: the ferrocement (wire mesh) and steel fiber (SF) concrete styles. The experimental program consisted of manufacturing five panels; three panels (elements) were made from ferrocement with different numbers of wire mesh layers, one hybrid specimen that had a wire mesh layer and short steel fiber layer, and a control specimen (panel) made from unreinforced layers and only one layer of sponging concrete. The brief description of the specimens is summarized in Table 2, while Fig. 6 illustrates the specimens' geometrical configuration details. Figs. (6 -10) exhibit the materials' preparation, mixing procedure, manufacturing procedure, and test setting of the current experimental program.

Table 2 Specimens (Panels) Description

No.	Group label	Description of the sponging-concrete layers of the panels	Rein. volume Fraction (V_f)%	Dimension, $l{\times}w{\times}h$ (mm)	Clear span length, l (mm)
1	S_0	Unreinforced panel (control)	0	600x200x54	500
2	S_{W1}	1 wire mesh ferrocement layer	0.042	600x200x54	500
3	S_{W2}	2 wire mesh ferrocement layers	2×0.042	600x200x54	500
4	S_{W3}	3 wire mesh ferrocement layers	3×0.042	600x200x54	500
5	S_{S1}	1 wire mesh ferrocement layer with SF	0.042+0.042	600x200x54	500

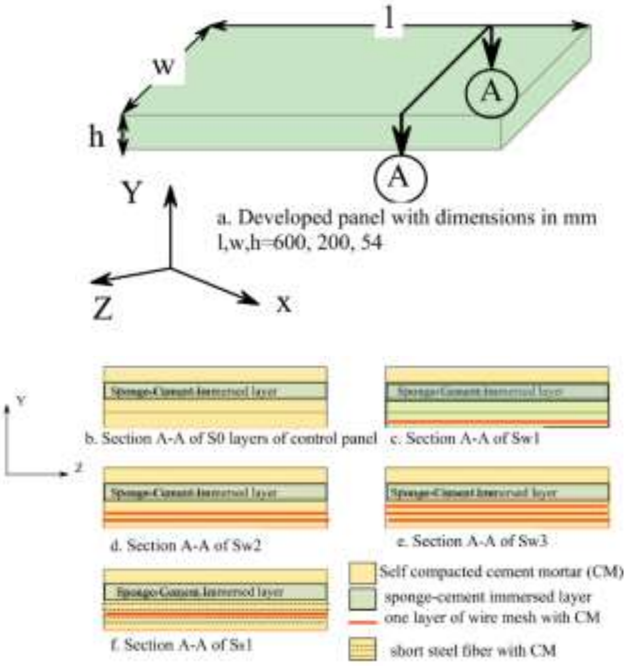


Fig. 6 Details of Each Layer of The Developed Panels.

Fig. 7 Mixing and Immersing Process.

Fig. 8 Used Materials.

Fig. 9 Manufacturing Process of Specimens (Panels).

Fig. 10 Test Setup.

3.RESULTS AND DISCUSSIONS

3.1.Mechanical properties of the lightweight sponging concrete core: material characterization

The obtained results and related analysis of the adopted sponge-cementitious merging modes are reported in Table 3. The adopted experimental test procedures were conducted under standard practice [47-49]. The sponge field thickness significantly affected the developmental 28-day compressive strength. As the thickness decreased from 100 mm to 10 mm, the compressive strength increased from 13.3 MPa to 33.2 MPa, which corresponded to Mode III of layered sponge elements of 10 mm, while the compressive strength of the plain cementitious mortar was 35.14 MPa. For all modes, the density slightly varied within the acceptable limit of the structural lightweight concrete limit (12-18 kN/m3). The average density of developed sponge concrete was 15.6 kN/m3, the average absorption ratio was 14.78 %, and the density of cementitious mortar was 21.96 kN/m3. As a result, the developed concrete could be classified as lightweight concrete as the achieved density was 15.6 kN/m3, within the ACI limit range according to the Guide for Structural Lightweight-Aggregate Concrete, American Concrete Institute Reported by ACI Committee 213 [31]. For illustration purposes, the comparative analyses were introduced as a compressive strength to density ratio. The developed sponging concrete core layer of various modes had a value of more than 1. The variations of compressive strength, strength rating, and the related rates of strength rating are shown in Fig. 11. Fig. 12 depicts the predicted failure trends of various adopted modes.

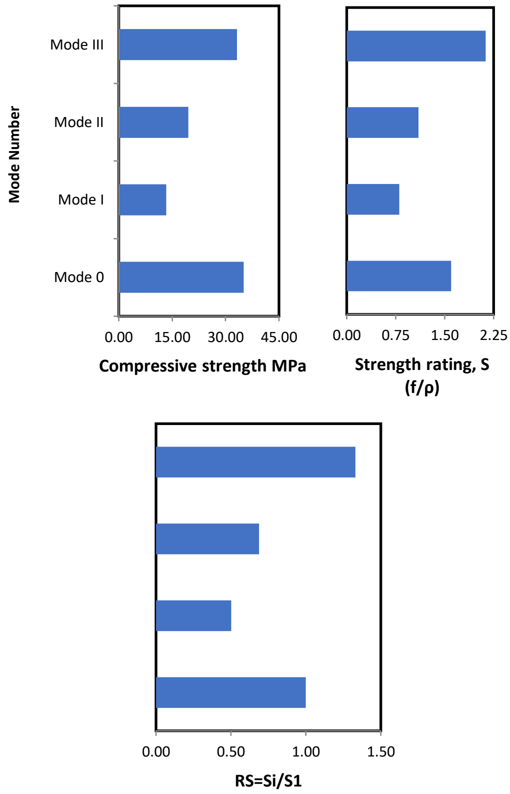


Fig. 11 Variations of Density, Strength Rating, and The Related Rates of Strength Rating.

Table 3 Mechanical Properties; Comparative Analysis

No.	Batch Mode	Description	Thickness (mm)	Compressive strength' (MPa)	Fracture strength, f_r (MPa)	Density, ρ (kN/m3)	Strength rating, S (f/ρ)	R_S=Si/S1
1	Mode 0	Cementitious mortar	50	35.14	7.04	21.96	1.60	1.00
2	Mode I	Immersed sponge blocks (two separated blocks) with cementitious mortar	100	13.30	_	15.6	0.85	0.53
3	Mode II	Immersed sponge block with cementitious mortar	50	19.57	5.50	15.6	1.25	0.78
4	Mode III	Immersed sponge layers (separately)	10	33.20	6.00	15.6	1.94	1.21

(a) Mode I

(b) Mode II

(c) Mode III

Fig. 12 Failure Modes of Various Adopted Modes.

3.2.Structural performance of the hybrid ferrocement layers combined with the sponging core layer

Wired sponge lightweight concrete elements of hybrid reinforcement (ferrocement and steel fiber) were developed and inspected under the bending condition effect. A standard flexural strength test (using a simple beam with a third-point loading test) was adopted [50]. The test results are summarized and illustrated in Table 4, Figs. (13, 14). The ferrocement reinforcing fashion was assigned the best reinforcement fashion compared with steel fiber reinforcing. This observation could be related to the use of welded wire mesh continuity. The predicted ultimate strengths varied positively from 2.108 kN to 4.413 kN as the fraction volume of provided steel wire changed from 0.00042 (one wire mesh layer) to 0.00126 (three wire mesh layers). The corresponding upgrading strength rates with respect to the unreinforced specimen (S_o) of ultimate strength of 1.667 kN varied from 1.265 to 2.647, respectively. The strength upgrading was accompanied by significant ductility improvement where the plastic deformation became more sustainable than the control specimen. The measured midspan deflection varied from 2.335 mm to 6.035 mm as the fraction volume of provided steel wire changed from 0.00042 (one wire mesh layer) to 0.00126 (three wire mesh layers). The corresponding deflection rates with respect to that of the unreinforced specimen (S_o) of maximum deflection 0.831 mm varied from 2.81 mm to 7.262 mm, respectively. Fig. 15 exhibits the P-Δ response of wired sponging concrete verse control specimen (So) and the P-Δ response of wired sponging concrete verse fiber sponging concrete. They were predominantly trilinear. The two main turning points, which define the ends of the first two linear portions, were due to the cement matrix cracking and the yield of the wire mesh. The strength of fiber specimen (SS1) slightly improved, 1.765 kN with a modest improving rate (1.059) with respect to control specimen strength (So), while the ductility rate relatively improved to 1.982. The failed specimens are shown in Fig. 16, while Fig. 17 shows cross-section surface texture within the failure fraction that dominated the failure mechanism. The wired reinforcing technique provided a sufficient constraint and eliminated the brittleness problem, which is a characteristic construction problem. After the initiation of flexural cracks, the stiffness reduced, and the linear load-deflection behavior vanished as the internal steel wire mesh began to yield.

Table 4 Results Analysis

No.	Panel label	Ultimate strength, P_u (kN)	R_{pu} =(P_{ui}/P_{u1})	Max. Deflection, Δ (mm)	R_Δ = (Δ_i/Δ_1)
1	S_o	1.667	1.000	0.831	1.000
2	S_{W1}	2.108	1.265	2.335	2.810
3	S_{W2}	3.300	1.979	5.567	6.699
4	S_{W3}	4.413	2.647	6.035	7.262
5	S_{S1}	1.765	1.059	1.982	2.385

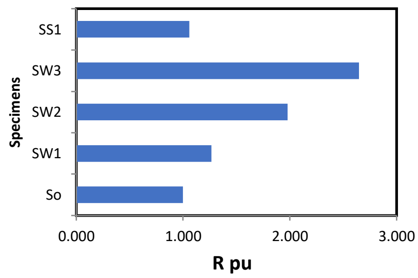


Fig. 13 Strength Variation Rates.

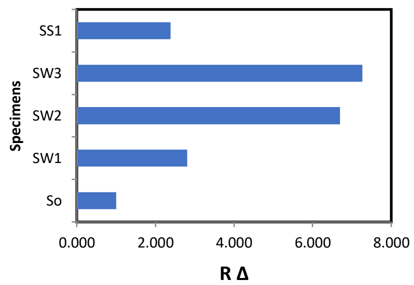


Fig. 14 Deformation Variation Rates.

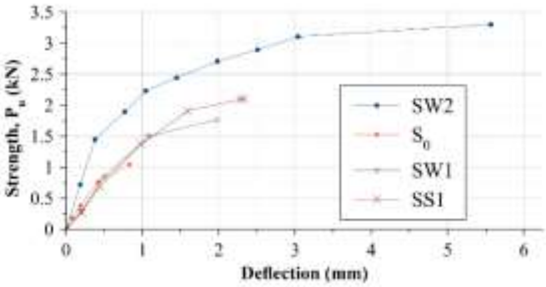


Fig. 15 P-Δ Response of Wired Sponging Concrete Verse Sponging Concrete.

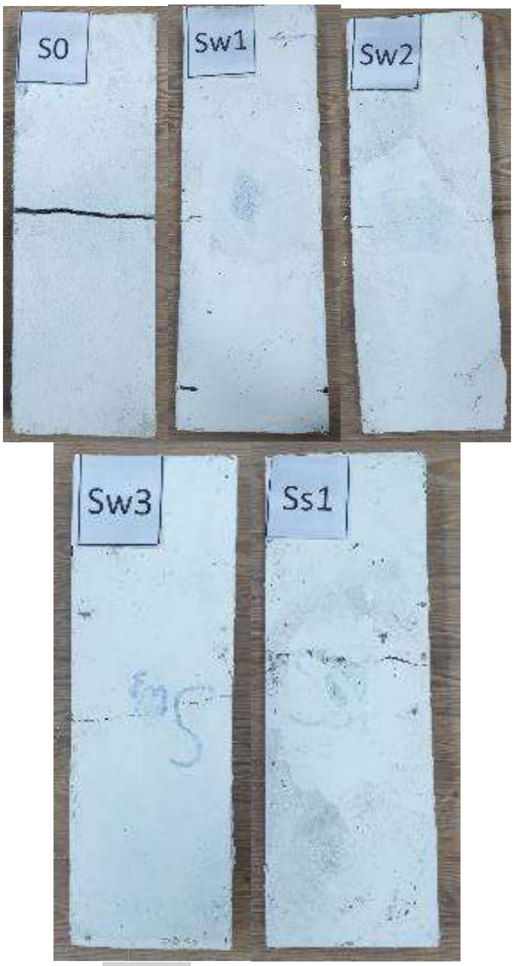


Fig. 16 Failed Specimens.

Fig. 17 Failure Surface Texture.

3.3.Comparison of the proposed structural performance of the panels with the conventional jack-arch slab panels from previous studies

Comparative analysis of the developed wired sponging concrete with the traditional Jack arch brickwork was achieved to inspect the structural reliability of developing sponging concrete as an alternative ceiling trend. Recently, the behavior of customary Jack-arch slabs in the south of Iraq was investigated by Resan and Dawod [2], and the program included spectrum variables. The current study's results were compared with those of a brickwork specimen with a length of 700 mm and a width of 320 mm. The brickwork is traditionally constructed from traditional materials (clay bricks and gypsum) [2]. Fig. 18 illustrates the Jack arch slab configuration, while Fig. 19 shows the developed and tested specimen. The comparative analysis is tabulated in Table 5. The comparison was achieved in terms of flexural moment capacity, as shown in Fig. 18. The moment capacity of the wired sponging concrete element (S_{W0}, S_{W1}, S_{W2}, and S_{W3}) with respect to the moment capacity of the Jack arch ceiling brickwork J7, which varied from 0.61 to 1.61 as the fraction volume varied from 0 (without wire mesh) to 0.00126 (three wire mesh layers), as shown in Fig. 17. Generally, the comparative analysis in the scope of material weight showed another positive side of utilizing the new lightweight concrete, which was of (86 kg) per (m^2) compared to (146.9 kg) per (m^2) of the tradition Jack arch brickwork. Besides, the adopted element of a thickness of (40 mm) was assigned as the proper thickness to get a thin element with good structural characteristics. The adopted thickness was compatible with the ACI ferrocement thickness limit according to State-of-the-Art Report on Ferrocement, American Concrete Institute Reported by ACI Committee 549 [24].

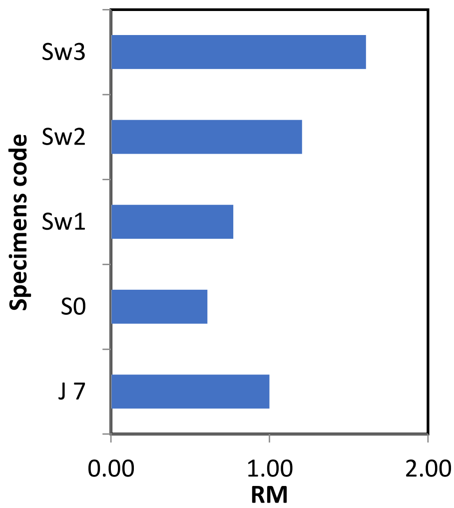


Fig. 18 Moment Capacity Variation Rates.

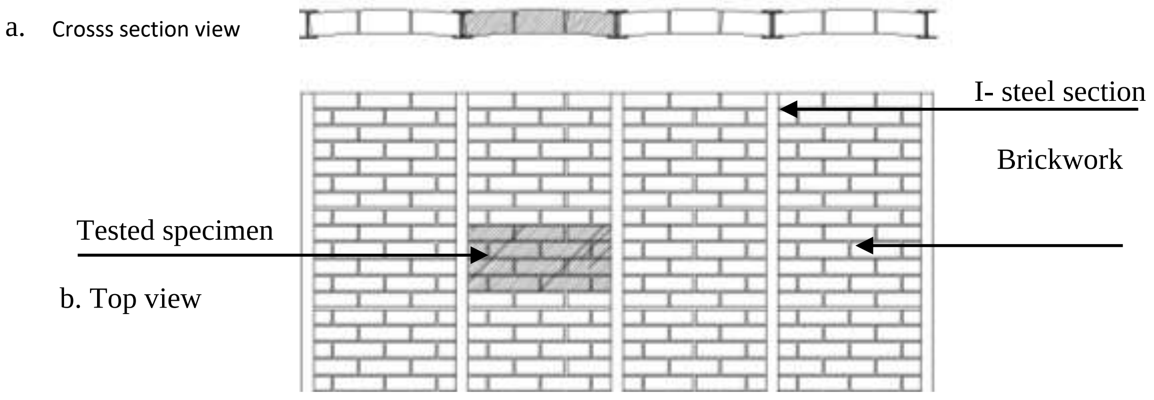


Fig. 19 Jack Arch Slab Configuration [27].

Table 5 Comparative Analysis

No.	Slab mode	Code	Description: Dimension l×w×h(mm)	l/h	Weight, kg/m²	Ultimate strength	Moment capacity, kN.m/m	$R_M = M_i/M_1$
1	J-arch brickwork panel[2]	J 7	700×320×80	8.75	146.89	3.36	1.71	1.00
	Wired sponging concrete panel	S_o	500×200×54	9.26	86	1.67	1.04	0.61
2		Sw_1	500×200×54	9.26	86	2.11	1.32	0.77
3		Sw_2	500×200×54	9.26	86	3.30	2.06	1.20
4		Sw_3	500×200×54	9.26	86	4.41	2.75	1.61

4.CONCLUSIONS

The present study introduced a new type of lightweight concrete trend using the traditional sponge material as a continuous field immersed by the super cementitious slurry. The obtained results confirmed the main target of the study. The developed concrete had lightweight concrete features like density, absorption ratio, and strength rating. Generally, the following structural and mechanical aspects were indicated for all sponge thickness modes, the density of developed sponging concrete was within the structural lightweight concrete limit, and the sponge field thickness affected the obtained compressive strength, as the thickness decreased from 100 mm to 10 mm. Regarding the structural aspects of the developed wired sponging concrete, the ferrocement reinforcing of layered sponges of 10 mm, was the best fashion compared with steel fiber reinforcing of the same fraction volume. This observation could be related to the continuity of using welded wire mesh. Besides, the sponge layers aligned the wire mesh spacing. The predicted ultimate strengths of the ferrocement panels positively varied from 2.108 kN to 4.413 kN as the provided steel wire mesh changed from one layer (approximate reinforcement volume fraction V_f of 0.042%) to three wire mesh layers (V_f= 0.126%). The corresponding upgrading strength rates with respect to the unreinforced specimen of the ultimate strength of 1.667 kN varied from 1.265 to 2.647. The comparative analysis between the rational Jack-arch slab trend and the developed element trend indicated that the flexural moment capacity of the developed ferrocement sponging concrete elements (panels) of a proper fraction volume sw2 and sw3 were higher than that of the traditional Jack-arch brickwork J7. Moreover, this strength improvement was accompanied by a significant reduction in overall weight. The upgraded predicted strength was accompanied by significant ductility improvement.

NOMENCLATURE:

l: Specimen length, mm
w: Specimen width, mm
h: Specimen height, mm
M: Moment capacity, kN.m
P_u: Ultimate load, kN
R_i: The relative rate of initial parameter of reference specimens
$f'c$: Compressive strength, MPa
f_r: Modulus of rubture, MPa
ρ: Density, kN/m³
Δ: Midspan deflection, mm

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