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PUNCHING SHEAR BEHAVIOR OF BUBBLED REINFORCED CONCRETE SLABS

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ABSTRACT: - This work presents the shear capacities and sustainable analysis of reinforced concrete (RC) two way hollow slabs with plastic sphere voids, also known as bubbled RC slab system. A bubbled RC slab has two-dimensional arrangement of voids included to reduce the self-weight. The strength and behavior of bubbled RC slabs with plastic spheres voids is investigated experimentally. Three RC square slabs of 1000mm x 1000mm dimensions have been tested to obtain the punching shear behavior. Variables of the experimental work are: thickness of reinforced concrete slabs, and volume of concrete. It has been found that bubbled RC slab, (with ratio of bubble diameter B to slab thickness H, B/H= 0.80), has about (92.163 %) of the ultimate load capacity of a similar reference solid slab (which has the same slab thickness). Also, bubbled slabs consume about (74 %) of the concrete needed for the similar solid slab. A small increase in the deflection at $0.7P_u$ by about (0.718%), at the same time, the cracking load is found to be decreased by about (6.286%) relative to solid slab system. For approximately the same volume of concrete, the bubbled slabs result an increase in the ultimate load capacity of bubbled slab by about (6.4%) and a reduction in the deflection at $0.7P_u$ by about (1.10%). At the same time, the cracking load is found to be increased by about (10%).

Analysis of the amount of input raw materials, energy consumption, and CO_2 emissions for the bubbled RC slabs, showed that there is a reduction in the amount of the input raw materials used such as sand, gravel and cement up to 28% and this leads to a reduction in the cost of these materials. Sustainable analysis gives a fact that the energy consumption and CO_2 emission can be reduced by about (12 to 21%), so it can be said that, the use of bubbled RC slabs is very useful in terms of sustainable building and has important contribution to construct the environmentally friendly buildings.

KEYWORDS: Bubbled RC slab, environmentally friendly buildings, Sustainable buildings, Two-way slab, and plastic sphere.

1- INTRODUCTION

In buildings, the slab is very important structural member to make a space. It is one of the largest members consuming concrete. In a general way, the slab is designed to resist vertical loads only. However, as people are getting more interest in residential environment recently, noise and vibration of slab are getting more important. In addition, when the span of the slab increases, the deflection increases also. Therefore, the slab thickness is on the increase. The increase of slab thickness makes the slab heavier, and it leads to increase column and foundation size. Thus, it makes buildings consume more materials such as concrete and steel (1). To avoid these disadvantages which were caused by increasing of self-weight of slabs, the bubbled RC slab system, also known as voided slab system, was suggested. This system consists of hollow plastic spheres cast into the concrete to create a grid of void forms inside the slab (2), and have a major contribution to the objective of sustainable building (3), by:

- Saving on the use of primary raw materials, the flexibility offered in the lay-out of the building and the making of passages and recesses and, finally: in the event of demolition a substantially smaller amount of concrete granulate and recyclable plastic spheres which do not adhere to the concrete.
- Smaller amounts of concrete have to be transported by road and smaller amounts of cement, sand and gravel have to be transported by road and by water.
- Saving on energy and emissions concerning the production and transport of building materials.

This slab system could optimize the size of bearing walls and columns by reducing the weight of slabs (4). Most slabs are two-way members in buildings. Thus, it is important whether the bubbled RC slab with plastic sphere voids acts like general reinforced concrete two-way slab or not. To verify the shear behavior of this two-way bubbled RC slab such as ultimate load capacity, service deflection, concrete compressive strain, and crack pattern; the shear capacities were performed by using a special loading frame which consists of hydraulic jack system.

2- EXPERIMENTAL PROGRAM

2.1 MATERIALS

For the slab specimens, the design concrete compressive strength of 45MPa was used. The concrete mixture proportions are presented in Table 1. For each series of casting, the specified compressive strength is measured by testing three concrete cylinders. Different diameters of reinforcing bars 4 and 5mm were used in the specimens. For each bar size, three samples were tested under uniaxial tension. The yield stress and the ultimate strength of different bars are given in Table 2.

The plastic spheres used in this study were manufactured in Iraq from recycled plastic with diameter of (64 mm) see Figure 1. The purpose of using recycled material is to curb consumption of finite natural resources such as oil and minimize the burden on the environment through the cyclical use of resources, therefore the recycling martial reduces inputs of new resources and limits the burden on the environment and reduces the risks to human health.

2.2 TEST SPECIMENS AND INSTRUMENTATIONS

Test specimens were designed of three RC slabs, one was a conventional solid RC slab and the others were bubbled RC slabs. The test parameters included the effect of plastic sphere voids with bubble diameter (B) to slab thickness (H), (B/H) was (0.80), and the approximately the same volume of concrete. Details and dimensions of the test specimens are illustrated in Table 3 and Figure 2. All slab specimens are reinforced with two steel layers, the bottom steel layer area equal to $485mm^2/m$ and the top steel layer area equal to $310mm^2/m$. The three RC slab specimens are divided into two groups; Table 4 shows the details of each group. The slab was simply supported at all edges by four steel rods. Specimens were tested under a one-point load system using a hydraulic jack and a loading plate to satisfy the actual loading condition, see Figure 3.

The deflection of the specimens was measured at mid-span using dial gauge attached to the soffit of the tested slabs see Figure 4. All specimens were instrumented with one concrete strain gauge bonded on the surface along the diagonal. The concrete strain gauges used in the experimental program were type PFL-30-11-3L from TML, with the following characteristics: wire-type, with a resistance of $120.4 \pm 0.5\ \Omega$, a gauge factor of $2.13 \pm 1\%$, a gauge length of 30 mm and a gauge width of 2.3 mm with a maximum strain of 2%; see Figure (5 b). The strain gauges were bonded, using CN-E cyanoacrylate adhesive, to the previously treated surface of the slab with PS-XC09F two component adhesive; see Figure (5 c and d). Figure (5 a) shows the arrangement of the concrete strain gauge along the diagonal.

The load was increased gradually at increments of (5 kN) to record the deflection up to failure.

3- EXPERIMENTAL RESULTS

3.1 GROUP A

This group consists of two slabs – the first is solid RC slab (reference) and the other is bubbled RC slab with bubble diameter to slab thickness (B/H) ratio which was considered equal to 0.80, as shown in Table 5.

3.1.1 ULTIMATE LOAD CAPACITY OF SLABS IN GROUP A

The primary aim of this study is to determine the ultimate load capacity of bubbled RC slab specimen with plastic spheres voids and to compare it with the ultimate load capacity of the reference solid RC slab specimen. The observed ultimate load of the tested slabs in this group (A) is shown in Table 6. Test results show that the ultimate load capacity for bubbled slab BS1-bu64 with B/H=0.80, decreased in comparison with the references solid slab specimen SS1 by about 7.837%. These slabs consumed only about 74% of the concrete volume required for solid slab.

3.1.2 LOAD-DEFLECTION RELATIONSHIP OF SLABS IN GROUP A

Figure 6 shows the load versus central deflection relationship of the slabs in this group. It should be noted that the effect of the self-weight of the test slabs is not included in the calculation of the test loads as it has negligible effect on the results. At same load, the deflection of bubbled slabs at 70% of reference ultimate load (Δ @ $0.7P_u$) is greater than the deflection of solid slab because the plastic spheres voids decreased the flexural rigidity of bubbled RC slabs. As a result the deflection is increased. The percentage of the increased deflection in specimen BS1-bu64 reached to (0.718%) over the deflection of the reference solid slab specimen (SS1).

3.1.3 CONCRETE COMPRESSIVE STRAIN OF SLABS IN GROUP A

As shown in Figure 7, test results show that, the bubbled slab specimen shows a slight increase in the concrete compressive strain over that of the reference solid slab specimen. This is due to reduced concrete volumes in compression zone by voids created because of the existence of the plastic spheres.

3.1.4 CRACK PATTERNS OF SLABS IN GROUP A

The test results of first cracking loads of slabs in group (A) are presented in Table 6. It is noted that the bubbled slab specimen BS1-bu64 shows a slight decrease in the first cracking load in comparison with reference solid slab specimen SS1 by about 6.286%. This is due to the reduction of the concrete volumes in tension zone due to the plastic spheres voids. All specimens showed punching failure mode. Some small longitudinal cracks appeared in BS1-bu64 specimen. This may be due to relatively thin bottom cover between soffit of the slab the bottom of the void. Figures 8 and 9 illustrate load-first crack width and crack patterns for slabs in group (A), respectively.

3.2 GROUP B

This group consists of two slabs (one slab is solid (reference slab) and the other slab is bubbled (B=64mm)). These slabs are identical in tension steel reinforcement area (A_S=485mm^2/m) and approximately have the same volume of concrete, but are different in slab thickness, as shown in Table 7.

3.2.1 ULTIMATE LOAD CAPACITY OF SLABS IN GROUP B

The ultimate load of the tested slabs in this group (B) is shown in Table 8. Test results show that the bubbled slab BS2-bu64 consumes 95% of the concrete volume used in solid slab and give an increase in the ultimate load over that of the reference solid slab specimen SS1 by about 6.4%. This is due to the increased slab thickness of 25%, resulting in an increase of the moment of inertia and the flexural stiffness of the bubbled slab.

3.2.2 LOAD-DEFLECTION RELATIONSHIP OF SLABS IN GROUP B

Figure 10 represents the load-central deflection curve of tested slabs in this group (B). It is noted that, in specimen BS2-bu64 the deflection at $0.7P_u$ decreased, the percentage of the drop in deflection reaches 1.10% in comparison with the reference solid slab specimen SS1.

3.2.3 CONCRETE COMPRESSIVE STRAIN OF SLABS IN GROUP B

As shown in Figure 11 the bubbled slab gives an increase in the concrete compressive strain over that of the reference solid slab specimen. This is due to the slight reduction of the concrete volumes in the compression zone due to the existence of plastic spheres voids.

3.2.4 CRACK PATTERNS OF SLABS IN GROUP B

The test results of the first cracking loads of slabs in group (B) are presented in Table 8. It is noted that the bubbled slab BS2-bu64 shows an increase in the first cracking load over that of the reference solid slab specimen SS1 by about 10%. This is due to an increase in slab thickness, resulting in an increase of the moment of inertia and flexural stiffness of bubbled slab specimen. Figures 12 and 13 illustrate load-first crack width development and crack patterns for slabs in group (B), respectively.

4- SUSTAINABLE ANALYSIS OF BUBBLED RC SLABS

The “sustainable” is defined as the capability of being maintained at a steady level with minimum long-term effect and less causing ecological effect [5]. Construction field relates to a large amount of material use, energy generation, heat producing and pollution as well as waste. To minimize the harm to the environment, one of the significant methods is by adopting the “sustainable element” into construction activities [6]. The energy consumption during the production of bubbled RC slabs is comparable by nature to the energy consumption of similar solid RC slab system. The greatest part of the energy consumption concerns the production of the raw materials cement, sand, gravel and reinforcing steel. These productions take place in existing cement factories and concrete products factories which play a pioneer's role in the reduction of the energy consumption [7]. From the viewpoint of energy saving, however, the most important aspect is the substantial savings if the bubbled RC slab system is used instead of comparable solid RC slab system. These result in a quantitative sense in an almost proportional saving on energy consumption, i.e. proportional to the saving in materials quantities.

The following raw materials are required for realizing a bubbled RC slab: Sand, Gravel, Cement, Water, Reinforcing Steel and Plastic. In order to allow a comparison; the required quantities, embodied energy, and CO_2 emissions are given in the following Tables (Tables 9 and 10). The percentages mentioned indicate which level of saving is achieved with the bubbled RC slab system. In order to calculate the embodied energy and CO_2 emission, the researcher has been used the ALCORN method (used in New Zealand) [8], where the weights of the input raw materials that are used in production of the slab specimens (cement, sand, gravel, etc.), are multiplied by different factors for each material, for example: Cement:

Weight of cement in specimen (SS1) = 38 kg

Factor of cement for embodied energy = 6.16 (MJ/kg)

Factor of cement for CO_2 emission = 0.994 (kg/kg)

So: Embodied energy of cement in (SS1) = 38 kg × 6.16 MJ/kg = 234.08 kg.

CO_2 emission of cement in (SD2) = 38 kg × 0.994 kg/kg = 37.772 kg.

The listed sustainable advantages of the bubbled RC slab system imply that the sustainable aspect is integrated into the entire process. This can be summarized as follows:

1. Up to 28% less raw materials required.
2. Up to 12% to 21% saving on energy required for extracting and manufacturing of these raw materials.

5- CONCLUSIONS

From the tests results obtained in this study the following conclusions can be drawn:

1. The stiffness of bubbled RC slab is different from solid RC slab; especially, BS1-bu64 specimen that showed some one-way flexural cracks and lower stiffness in the early loading stages. In view of the results so far achieved, two-way bubbled RC slabs act basically like general solid RC slabs and their punching shear capacities were good enough to use.
2. The deflections at $0.7P_u$ of bubbled RC slab specimens were a little higher than those of an equivalent solid RC slab which has the same slab thickness.
3. The comparison between the bubbled RC slab and the reference solid RC slab showed the following results:

3.1 A bubbled slab with B/H=0.80 has 92.163% of the ultimate load capacity of a similar reference solid slab which has the same slab thickness but only consumed 74% of the concrete volume, and an very small increase in the deflection at $0.7P_u$ by about 0.718%. At the same time, the cracking load is found to be decreased by about 6.286%.

3.2 A bubbled slab consumed 95% of the concrete volume that is used in solid slab, (which is different in the slab thickness), results in an increase in the ultimate load capacity of bubbled slab by about 6.4% and a reduction in the deflection at $0.7P_u$ by about 1.1%. Additionally, the cracking load is found to be increased by about 10%.

4. A bubbled slab has a saving on the concrete consumption, and therefore on the primary raw materials: sand, gravel and the cement an up to 28%, with the additional sustainable advantage that smaller amounts of concrete have to be transported.
5. A bubbled slab has an up to (12% - 21 %) saving on energy and CO_2 emissions based on the production and transport of primary building materials.

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Table (1): Concrete mixture design.

Designation	Cement kg/m^3	Aggregate kg/m^3		Water kg/m^3	w/c for Slump 120±10 mm
		Sand	Gravel		
C45	470	750	900	235	0.50

Table (2): Mechanical properties of reinforcing bars.

Nominal Diameter, mm	Measured Diameter, mm	Cross-sectional Area, mm^2	f_y, MPa	f_u, MPa
4	4	12.566	557	835
5	4.994	19.588	663	817

Table (3): Properties of slab specimens.

No.	Specimen Designation	Slab Thickness **H**, mm	Bubble Diameter **B**, mm	No. of Bubbles	Distance between Bubbles, c/c, mm	**B/H**	Notes
1	SS1	80	---	---	---	---	Solid (Reference)
2	BS1- bu 64	80	64	144	72	0.80	
3	BS2-bu 64	100	64	144	72	0.64	

Table (4): Details of slab groups.

Group	Description	Specimens
A	$\mathbf{A_s}$= 485 mm^2/m, Slab Thickness (**H=80mm**) (Effect of Plastic Spheres Voids)	1- SS1 , (**B**=0mm , **B/H**=0.00) 2- BS1-bu64, (**B**=64mm, **B/H**=0.80)
B	$\mathbf{A_s}$= 485mm^2/m, Approximately the Same Volume of Concrete	1- SS1, (Wt.=200 kg.) 2- BS2-bu64, (Wt.=190 kg.)

Table (5): Details of slabs in group A

Slab Thickness H, mm	Slab Designation	Bubble Diameter B, mm	B/H	Weight, kg	Decrease in Weight, %
80	SS1	---	---	200	---
	BS1-bu64	64	0.80	149	26

Table (6): Test results of slabs in group A

Slab Designation	$\mathbf{P_{cr}}$, kN	Decrease in Cracking Load, %	$\mathbf{P_u}$, kN	Decrease in Ultimate Load, %	$\mathbf{P_{cr}/P_u}$	Deflection Δ@0.7$\mathbf{P_u}$ mm	Increase in Δ@0.7$\mathbf{P_u}$, %	Ultimate Deflection Δ_u, mm	Increase in Δ_u, %
SS1	35	---	159.5	---	0.219	8.35	---	13.41	---
BS1-bu64	32.8	6.286	147	7.837	0.223	8.41	0.718	14.0	4.4

Table (7): Details of slabs in group B

Slab Designation	Slab Thickness **H**, mm	Increase in Slab Thickness, %	Bubble Diameter **B**, mm	**B/H**	Weight , kg	Decrease in Weight, %
SS1	80	---	---	---	200	---
BS2-bu64	100	25	64	0.64	190	5

Table (8): Test results of slabs in group B

Slab Designation	P_{cr}, kN	Increase in Crack Load, %	P_u, kN	Increase in Ultimate Load, %	P_{cr}/P_u	Deflection $\Delta@0.7P_u$ mm	Decrease in $\Delta@0.7P_u$, %	Ultimate Deflection Δ_u, mm	Decrease in Δ_u, %
SS1	35	---	159.5	---	0.219	8.35	---	13.41	---
BS2-bu64	38.5	10.0	169.7	6.4	0.227	8.26	1.10	13.0	3.06

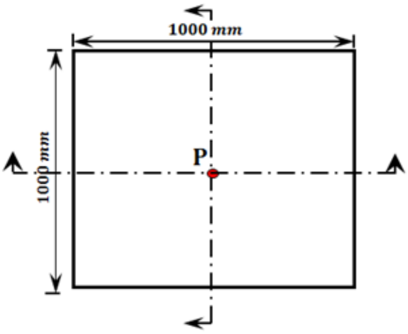
Table (9): Comparison between required quantities of raw materials and saving achieved by using the bubbled RC slab system and a solid RC slab.

Material	Solid RC Slab (Thickness 80mm) SS1	Bubbled RC Slab (Thickness 80mm) (BS1-bu64)
Sand	60 kg/m^2 (100%)	43 kg/m^2 (72%)
Gravel	72 kg/m^2 (100%)	52 kg/m^2 (72%)
Cement	38 kg/m^2 (100%)	27.5 kg/m^2 (72%)
Water	19 kg/m^2 (100%)	13.5 kg/m^2 (72%)
Reinforcement Steel	11 kg/m^2 (100%)	11 kg/m^2 (100%)
Recycled Plastic	(0%)	2 kg/m^2

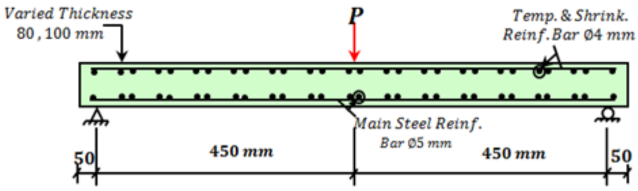
Table (10): Comparison of embodied energy and CO_2 emissions achieved by using the bubbled RC slab system versus a solid RC slab

Material	Solid RC Slab (Thickness 80mm) SS1		Bubbled RC Slab (Thickness 80mm) (BS1-bu64)	
	Embodied Energy, MJ	CO_2 Emissions, kg	Embodied Energy, MJ	CO_2 Emissions, kg
Sand	6.0	0.42	4.3	0.301
Gravel	2.88	0.144	2.08	0.104
Cement	234.08	37.772	169.4	27.335
Reinforcement Steel	344.41	13.66	344.41	13.66
Total	587.37 (100%)	51.996 (100%)	520.19 (88.5%)	41.4 (79.6%)

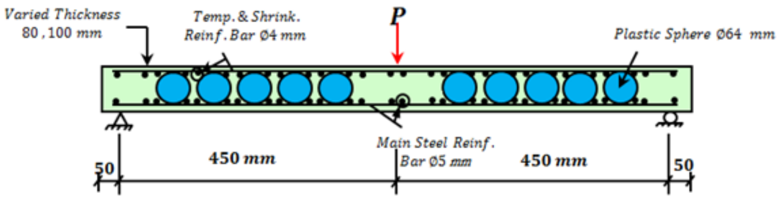
Figure (1): Plastic spheres made from recycled material



(a) Top View of Tested Slab



(b) Cross-Section in Solid Slab



(c) Cross-Section in Bubbled Slab

Figure (2) Details and dimensions of tested slab specimens

Figure (3) Test setup of solid and bubbled RC slab **Figure 4.** Position of Dial Gauge

a) Strain gauges arrangement   b) PFL-30-11-3L strain gauge   c) PS-XC09F adhesive   d) CN-E adhesive

Figure (5) Strain gauge type, arrangement, and adhesive materials

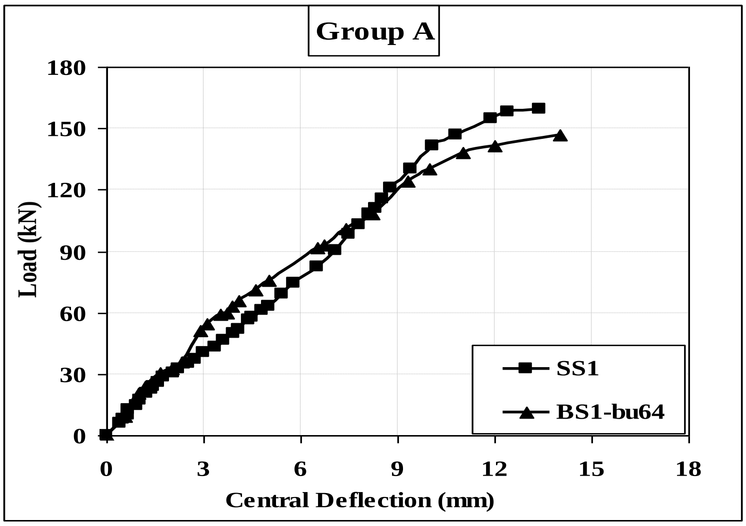


Figure (6): Load-central deflection curve of slabs in group A

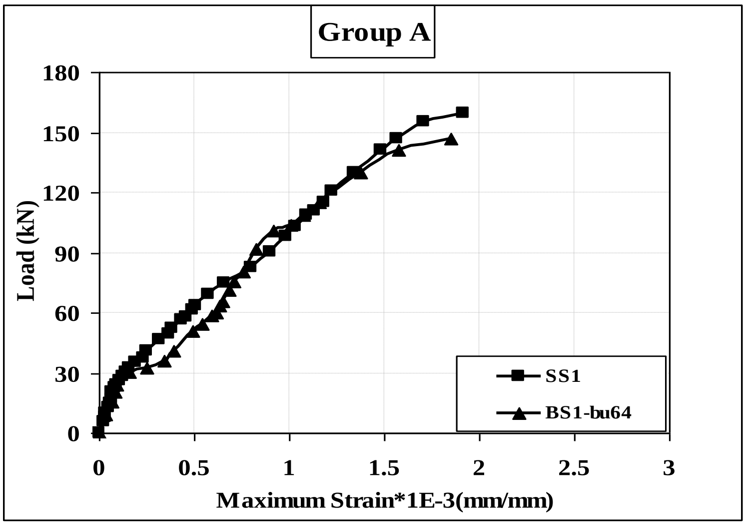


Figure (7): Load-maximum concrete compressive strain curve of slabs in group A

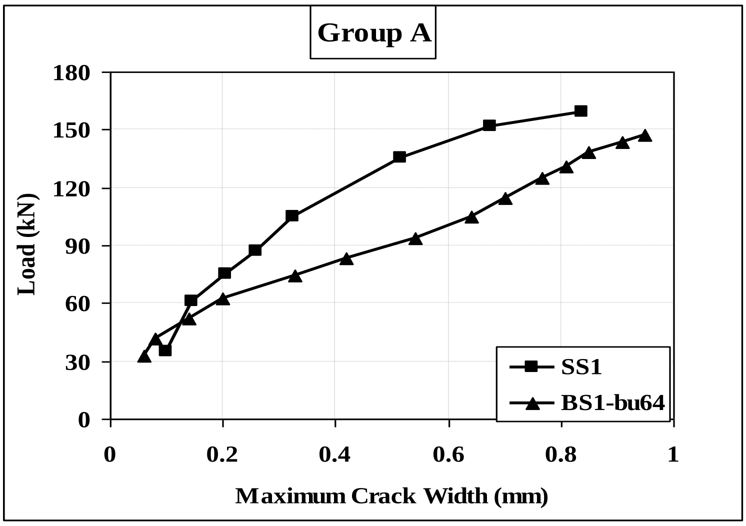


Figure (8): First crack width development of slabs in group A

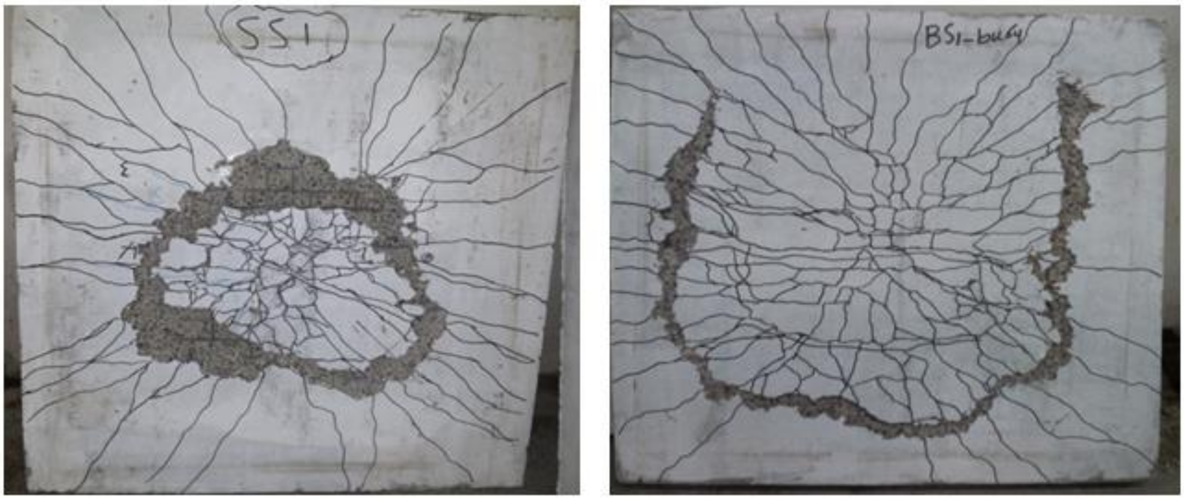


Figure (9): Crack patterns of slabs in group A (bottom face)

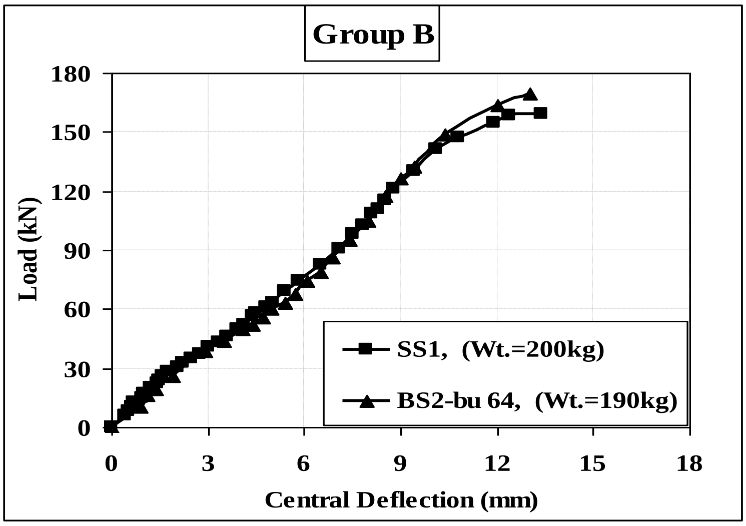


Figure (10) Load-central deflection curve of slabs in group B

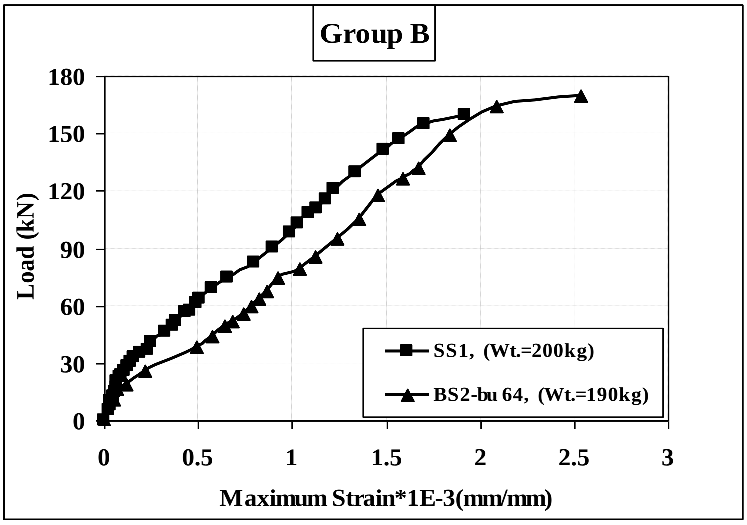


Figure (11) Load-maximum concrete compressive strain curve of slabs in group B

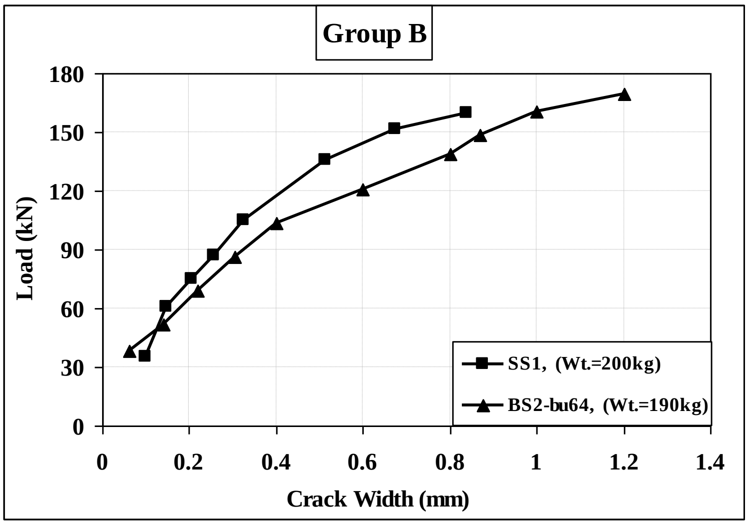


Figure (12) First crack width development of slabs in group B

Figure (13) Crack patterns of slabs in group B (bottom face)

سلوك القص الثاقب للسقوف الخرسانية المسلحة الحاوية على فجوات كروية

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الخلاصة

يهتم هذا العمل بدراسة تحمل القص الثاقب وتحليل الاستدامة للسقوف الخرسانية المسلحة الحاوية على كرات بلاستيكية مجوفة والمعروفة بنظام السقوف المجوفة. استخدام التجاويف في كلا الاتجاهين في السقوف يلعب دور كبير في تقليل الوزن الذاتي. ان مقاومة وسلوك السقوف الخرسانية المسلحة الحاوية على فجوات كروية تحريت عمليا, شمل العمل اختبار ثلاث سقوف خرسانية مسلحة مربعة وبأبعاد 1000ملم×1000ملم فحصت للحصول على تصرف القص الثاقب. ان المتغيرات التي أخذت بنظر الاعتبار هي: سمك السقف الخرساني المسلح وكمية الخرسانة المستخدمة. وجد ان السقوف الخرسانية المجوفة, والحاوية على الكرات البلاستيكية والتي فيها نسبة قطر الكرة الى سمك البلاطة بمقدار (0,80) تمتلك تحمل بحدود (92,163%) من قيمة الحمل الاقصى للسقوف المرجعية الصلدة (التي لها نفس السمك). لهذه السقوف المجوفة كانت كمية الخرسانة المستخدمة لاتتجاوز (74%) من كمية الخرسانة التي استخدمت للسقوف المرجعية الصلدة. في الوقت نفسه وعند حمل مقداره 70% من الحمل الاقصى تبين بأن قيمة الهطول للسقوف المجوفة تزداد بحدود (0,718%) مقارنة مع السقوف الصلدة. وان حمل التشقق للسقوف المجوفة اقل من حمل التشقق للسقوف الصلدة بمقدار (6,286%). عند استخدام نفس كمية الخرسانة تقريبا المستخدمة في السقوف الصلدة واستخدامها في السقوف المجوفة, لوحظ بأن السقوف المجوفة تولد زيادة في الحمل الأقصى بمقدار (6,4%) وتقليل في الهطول (في مرحلة 70%) بمقدار (1,10%) وفي نفس الوقت لوحظ زيادة الحمل المسبب للتشقق بمقدار (10%).

اظهرت نتائج التحليل للسقوف الخرسانية المسلحة الحاوية على فجوات كروية من حيث كمية المواد الاولية الداخلة, الطاقة المستهلكة, وانبعاث CO_2 ان هنالك تقليل في كمية المواد الاولية المستخدمة كالرمل , الحصى والسمنت بحدود 28% وهذا يؤدي الى التقليل في عملية نقل هذه المواد. وبين التحليل المستدام ان الطاقة المستهلكة وانبعاث CO_2 يقل بحدود (12 الى21%). لذلك يمكن القول ان استخدام السقوف المجوفة مفيد جدا في موضوع البنايات المستدامة ويساهم في انشاء بنايات صديقة للبيئة.