Punching shear behaviour of solid and bubble reinforced light Weight aggregate concrete two-way slabs

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Abstract. Punching shear is the most important problem in flat slabs, which usually required reducing the self-weight of the slab. A lightweight concrete as well as the bubble deck technology were used to allow for lighter self-weight of the structure. This study aims to investigate the use of lightweight aggregate concrete (LWAC) with the bubble deck technology in flat slab. The behavior of two-way LWAC voided slab (with and without shear reinforcement) under punching shear effect with respect to solid normal weight and solid LWAC specimen were studied. The behavior of six specimens having the same dimensions, slab thickness and flexural steel reinforcement were studded. The main changed variables were concrete type, percent of void and punching shear reinforcement existence. The results show that the load carrying capacity for light weight aggregate concrete voided slab without shear reinforcement decreased by (60%, 53%) with respect to solid normal weight and solid LWAC slabs without shear reinforcement respectively. In addition, the load carrying capacity for LWAC voided slab with shear reinforcement decrease by (67%, 47%) with respect to solid normal weight, solid LWAC slabs with shear reinforcement respectively. Also, for lightweight aggregate concrete, solid and voided slab, shear reinforcement existence did not significantly increase the slab capacity for punching shear. But cause a reduction in maximum deflection with respect to slabs without shear reinforcement.

1. Introduction
In a reinforced concrete structure, the span between columns is the main design limitation of the slab. To design a large slab span between columns, peripheral beams and/or very thick slabs are required. Which leads to increase the weight of the structure because of large amounts of used concrete (1). Another option for reducing weight is the bubble deck technology which uses spheres made of recycled industrial plastic to create air voids while providing strength through arch action. It attempts to utilize the positive aspects of concrete slab construction while minimizing the negative attributes of solid slabs by lightening the self-weight of the structure (2). Many experimental investigations were conducted on voided slab. But, there is no research study on the behavior of lightweight concrete voided slab.
The use of lightweight concrete (LWC) and voids can reduce the self-weight of structures. So, the cross sectional area of structural member will be reduce too.
2. Experimental work
A real flat slab system with dimensions of (7.5*7.5) m supported on columns only, represent the prototype in this research. Its zero-point moment lies approximately at (0.22 L) from the column axis. The punching shear specimen represent the column strip with scale of 1/3 which exposed to punching shear due to column of square cross section, that have the scaled dimension equal to (10*10) cm. The experimental work consists of six two way flat slabs specimens. Simply supported along all edges with dimension equal to (1100*1100*100) mm and designed to fail in punching shear.

A series of tests is carried out, including raw materials, fresh and hardened concrete, as well as tests conducted on specimens under punching shear loads.

2.1. Materials

2.1.1 Lightweight aggregate
Light Expanded Clay Aggregate (LECA) is a porous ceramic product with a uniform pore structure and density ranges from 600 kg/m3 to 1900 kg/m3 see plate (1). It is manufactured in Rotary kilns from raw materials containing clay minerals, between 1100 °C and 1200 °C, resulting in a significant increase in volume due to expansion (3). Structural LECA of gradations 0-8 mm was used to produce the concrete for light weight aggregate specimen. Its bulk dried density equal to 740 kg/m3.

![Plate 1](image)

Plate 1. (a) Ordinary leca. (b) Structural leca.

The LECA pebbles internal cellular structure with thousands of air-filled cavities gives thermal and sound insulation properties. Leca aggregate is chemically neutral, with pH of (7-7.2). It does not affect or be affected by other materials, and even preserves materials intact from chemical hazards (4).

2.1.2. Reinforcement
In order to achieve punching failure and to prevent bending failure in the slab specimens. A constant reinforcement ratio, (which was more than what normally used in practice) was selected. Steel bar of 10 mm in diameter, spaced at 65 mm in two directions was used. For punching shear reinforcement, a three vertical bars 6mm in diameter, mechanically anchored at each ends at an angle of 90 degrees. Each three bars were welded on via hooks to steel rail have the dimension (20*1.25) cm as shown in plate (2). Reinforcement arranged at three control perimeter lies at 0.5d, d and 2d from column face as shown in fig (1).

![Plate 2](image)

Plate 2. Shear reinforcement

![Figure 1](image)

Figure 1. Shear reinforcement Arrangement
2.1.3. Plastic Spheres

Oval with dimensions of (80*80*40) mm made from plastic were manufactured and used. The void should be covered by concrete from all direction with at least one ninth of the ball diameter\(^*(5)\). Which means that the maximum bubble diameter that could use in a voided slab equal to (0.82 * overall depth of the slab). Figure (2a,b) shows specimens details.

![Specimens details](image)

**Figure 2.** Specimens details (a) specimens without shear reinforcement (b) specimen with shear reinforcement

2.2. Mix proportions

Two types of concrete were used in preparing the specimens:

1. Normal weight concrete was used for casting two solid control specimen. Ordinary Portland cement, Natural sand and normal weight gravel was used as shown in table (1).
2. Lightweight aggregate concrete was used to cast all other specimens. Ordinary Portland cement, Natural sand and LECA was used (6). As shown in table (1).

Also, to improve the physical and mechanical performance of concrete. High performance concrete hyper plasticizer (HP 580) Epsilone HP 580 was used (7). The Basic mechanical properties for concrete, reinforcement and aggregate were obtained laboratory. To obtained the mechanical properties of the hardened concrete. A (150×150×150 mm) cubic samples and standard concrete cylinders with dimension (150×300 mm) where tested to obtain the compressive strength and Split tensile strength according to ASTM C496 (8). Also, a Prism concrete specimen with dimension (10×10×40) cm where tested to determine the flexural strength capacity, and the same cylindrical samples that used to determine the split tensile strength was tested to find modulus of elasticity first. Specimens details and mechanical properties are shown in table (2).
Table 1. Mix proportion for normal and light weight concrete

| Mix No. | concrete type | Compressive Strength (fc), MPa | Cement Content, Kg/m³ | Sand Content, Kg/m³ | LECA Content, Kg/m³ | Gravel Content, Kg/m³ | Water L/m³ | HP-80 L/m³ |
|---------|---------------|-------------------------------|-----------------------|---------------------|---------------------|----------------------|-------------|------------|
| 1       | normal weight | 40                            | 325                   | 550                 | _                   | 1300                 | 146         | 0.9        |
| 2       | light weight  | 40                            | 550                   | 550                 | 500                 | _                    | 133         | 0.57       |

Table 2. Specimens’ details and mechanical properties

| No. | Labeling | slab thickness (mm) | shear reinforcement | bubble dimension | voided % | comp. strength | Fr (Mpa) | Ft (Mpa) | Fr (Mpa) | Ec (Mpa) | reduction in weight due to lightweight % | reduction in weight due to punching shear % | total reduction % |
|-----|----------|---------------------|--------------------|------------------|----------|----------------|----------|----------|----------|----------|----------------------------------------|------------------------------------------|--------------------|
| 1   | SNW 1    | 100                | without            | 0                 | 0        | 48.7           | 6.4      | 3.877    | 28318.3  | 0.00 %   | 0.00 %                                 | 0.00 %                                    | 0.00 %             |
| 2   | SNW 2    | 100                | with               | 0                 | 0        | 49.0           | 6.8      | 4.013    | 28322.5  | 0.00 %   | 0.00 %                                 | 0.00 %                                    | 0.00 %             |
| 3   | SLW 1    | 100                | without            | 0                 | 0        | 42.1           | 3.5      | 2.222    | 11292.2  | 0.00 %   | 33.14 %                                | 33.14 %                                   | 66.28 %            |
| 4   | SLW 2    | 100                | with               | 0                 | 0        | 40.7           | 3.2      | 2.207    | 11845.8  | 0.00 %   | 32.25 %                                | 32.25 %                                   | 64.50 %            |
| 5   | BLW 1    | 100                | without            | 80*80* 40         | 0.8      | 20.9           | 39.8     | 3.1      | 2.033    | 11671.0  | 20.95 %                                 | 36.34 %                                   | 57.29 %            |
| 6   | BLW 2    | 100                | with               | 80*80* 40         | 0.8      | 20.1           | 39.6     | 3        | 2.01     | 10769.0  | 20.06 %                                 | 36.37 %                                   | 56.42 %            |

2.3. Tests

2.3.1. Test setup and measurements

The tests were done by using a universal testing machine of high load (1000 kN). A steel frame (used to support the slab specimen, act as simply support on all sides.) with dimension of (1000*1000*90) mm welded to a stiff steel beam that fixed to the fitted center of main hydraulic jack and piston of testing machine. The stiff steel beam, the steel frame and the specimen move upward as one unit with the movement of the piston.

Vertical deflection due to specimen loading was measured at three points by using digital dial gauges with Accuracy equal to (0.001 or 0.01) mm. These points were allocated at: center of the tested slab (C) on the tension face while the other two points allocated at distance (0.375L,0.25L from the support center) on the compression face. The readings from these gauges can be recorded for each (0.1 kN). A set of reading ranged from (50-150) were selected depending on the magnitude of ultimate load and severity of changes in load–deflection curve patterns.

To measure the strain in steel reinforcement during the test, two steel strain gages were used on bending reinforcement for (SNW1, SNW2, SLW1, SLW2) specimen. To register the values of stress in reinforcement at failure. To indicate whether the slab failure is due to punching shear or bending.

Before testing, specimens were prepared by painting them to show a clearer picture of crack plate (3a). The position of load, support, dial gauges and concrete strain gages were marked also. After the concrete strain gages fitting, the specimen placed at the exact location on the support. Then the dial gauges centered in their position. As shown in plate (3b)
Specimens were tested under a static load to study their punching shear behavior as shown in figure (3). The load was applied in load control mode at a load rate of 5 kN/min, and the strain gauges' data were collected by a data acquisition system. Plate (4) represent the specimen after failure.

Plate 3. (a) Model preparing before test. (b) Loading setup (model after testing before releasing).

Figure 3. Punching shear setup.

Plate 4. Punching shear specimen after test.

2.3.2. Test results
ACI 318-14 Code and the Euro code 2 were adopted in analyzing and discussing the results of this study. All the factors influencing the section resistance to the punching shear force according to ACI 318-14 Code or Euro code were fixed. The parameters are (concrete compressive strength, the flexural reinforcement ratio ρ, the thickness of the slab, and the ratio of the dimension of supporting column to the effective depth of slab). To give a clear extent to the effect of changing concrete type on the behavior of the section, to be study and know.

In ACI318-14 code, the critical section is parallel to the column face at a distance equal to half the effective depth of the slab (9). While the Euro code take the critical section at 1.5d to 2.0d from the face of the column (10). A critical distance between 0.5d- 2d were studded in this research. As shown in figure (4).
3.1. Ultimate Load Capacity and maximum Deflection

Table (3) shows all specimens details, ultimate punching shear load and deflection. The results show that:

Table 3. Specimen's details, ultimate load and deflection.

| No. | Labeling | Slab Thickness H (mm) | shear reinforcements | bubble diameter | voided % | d/t | As (mm²) at 1/2 d u=700mm | As (mm²) at d u=1000mm | As (mm²) at 2d u=1000mm | Compression strength | Pu ultimate load (kN) | Max. deflection (mm) |
|-----|----------|-----------------------|----------------------|----------------|---------|----|----------------------------|------------------------|----------------------|---------------------|--------------------|---------------------|
| 1   | SNW 1    | 100                   | without              | 0              | 0       | 0  | 0                          | 0                      | 0                    | 48.7                | 195.4              | 10.66               |
| 2   | SNW 2    | 100                   | with                 | 0              | 0       | 0  | 452.57                     | 452.57                 | 452.57               | 49.0                | 255.5              | 12.9                |
| 3   | SLW 1    | 100                   | without              | 0              | 0       | 0  | 0                          | 0                      | 0                    | 42.1                | 168                | 11.81               |
| 4   | SLW 2    | 100                   | with                 | 0              | 0       | 0  | 452.57                     | 452.57                 | 452.57               | 40.7                | 159.8              | 10.2                |
| 5   | BLW 1    | 100                   | without              | 80*80*40       | 20.9    | 0.8 | 0                          | 0                      | 0                    | 39.8                | 79.1               | 12                  |
| 6   | BLW 2    | 100                   | with                 | 80*80*40       | 20.1    | 0.8 | 452.57                     | 452.57                 | 452.57               | 39.6                | 84.8               | 8                   |

- The existence of shear reinforcement causing an increase in slab loading capacity for specimen with same concrete type. The increase in the failure load for solid normal weight, bubble light weight concrete equal to (23.5% and 6.7%) respectively. But the solid light weight specimen shows an (4.9%) increase in loading carrying capacity for slab without shear reinforcement. This may be attributed to the slight difference in compressive strength of normal and light weight concrete.
- The failure load of specimens was ranged from (255.5 to 79.1) kN as shown in table (3). So, the reduction percent in load caring capacity between specimens with different concrete type was as shown in table (4).

Table 4. Reduction percent in load caring capacity

| No. | The comparison between | Specimen with shear reinforcement | Specimen without shear reinforcement |
|-----|------------------------|-----------------------------------|-------------------------------------|
| 1   | normal and light weight concrete | 68.3%                            | 14%                                 |
| 2   | normal and bubble light weight | 35.3%                            | 59.5%                               |
| 3   | solid and voided light weight | 51.7 %                           | 52.9%                               |
For light weight concrete solid and voided slab, specimen without shear reinforcement show maximum deflection larger than slabs with shear reinforcement. Even though, the punching shear reinforcement existence did not significantly increase the slab capacity for punching shear because of light weight concrete properties control the failure criteria. That's mean, shear reinforcement existence increases the deformation capacity for the specimen. But the effect of reduced mechanical properties of lightweight concrete (relative to normal weight concrete with the same compressive strength) govern the failure criteria. While in the normal weight concrete, things seem to be reversed. Punching shear reinforcement existence gave maximum deflection larger by (17.4%), which can be explained by the significantly increase in slab capacity by (23.5%).

The failure load was ranged from (234 to 79.1) KN as shown in table (2). Which gives 68.3% reduction percent between normal and lightweight concrete. 35.3% between normal and bubble lightweight. And 51.7 % between solid and voided lightweight for specimen with shear reinforcement. While the reduction percent for slabs without shear reinforcement was (14%, 59.5% and 52.9%) respectively.

For normal weight concrete, punching shear reinforcement existence gave maximum deflection larger by (17.4%). Which can be explained by the significantly increase in slab capacity with (23.5%) increase on the failure load.

For lightweight concrete solid and voided slab, specimen without shear reinforcement show maximum deflection larger than slabs with shear reinforcement. Even though, the punching shear reinforcement existence did not significantly increase the slab capacity for punching shear.

3.2. Load deflection curves
The central deflection values are plotted against loading for the six models together to explain the differences in behavior more clearly as shown in figure (5).

Figure 5. Load-central deflection curve for case one specimen.

1. In general, the load–deflection curve for all specimens shows identical behaviors which seems to be straight with linear relationship until reaching the peak load. Which could be attributed to symmetry for all specimens in geometry of supports and arrangement and applied load. Although, there is a clear difference between the magnitude of maximum load and deflection that occurred before failure because it depends on slab stiffness.

2. All specimens with shear reinforcement before reaching failure load show less deflection at the same load level compare to the specimen have the same geometrical and mechanical properties but without shear reinforcement.

The load deflection curve for all six specimens individual are shown in Figure (6). Three curves represented the three points where deflection was measured (0.5L, 0.375L and 0.25L) are shown.

1. The deflation for all solid specimens (normal and lightweight), at point 0.375L shows an asymptotic performance and values close to central deflection. While at 0. 25L the deflection shows less magnitude
than central deflection but with the same behavior. But for lightweight voided specimen the deflection at the three-point show an identical behavior with very close value.

That is means, for lightweight voided specimen. The area around column, which extended a distance equal 2. d from column face in all directions, was moving as a single block and expressing a deflection at the same level approximately. So the punching shear stresses were concentrated at the first row of voids. That located after the solid area around column, and represent the first weakness area.

Figure 6. Load deflection curve for individual specimen continue.
3.3. Toughness and deformation factor
The material toughness is the maximum amount of energy it can absorb before fracturing [11]. The term "toughness" represented by the area of the post cracking region under the load deflection curve. [12] Also, the percent of deflection that accord after first crack was calculated to measure specimen's ability to show significant deformation before rupture. Table (5) show toughness value and deformation factor for first case specimen.

$$\text{Deformation factor} = \frac{\Delta u - \Delta cr}{\Delta u} \times 100$$  \hspace{1cm} (1)

The material toughness is the maximum amount of energy it can absorb before fracturing (11). The term "toughness" represented by the area of the post cracking region under the load deflection curve (12) Also, the percent of deflection that accord after first crack was calculated to measure specimen's ability to show significant plastic deformation before rupture. Table (5) show toughness value and plastic deformation percent for first case specimen.

| Labeling | concrete density (kg/m³) | toughness (kN*mm) | Cracking load (kN) | deflection at first crack load (mm) | ultimate load (kN) | deflection at ultimate load (mm) | deformation factor $\frac{\Delta u - \Delta cr}{\Delta u}$ |
|----------|--------------------------|-------------------|-------------------|-----------------------------------|-------------------|-------------------------------|---------------------------------------------------|
| SNW 1    | 2281.5                   | 27192.98          | 57                | 1.5                               | 195.4             | 6.6                           | 77                                                |
| SNW 2    | 2314.7                   | 42215.14          | 55                | 1.5                               | 255.5             | 8.4                           | 83                                                |
| SLW 1    | 1727.5                   | 30371.99          | 35                | 1.75                              | 168               | 7.9                           | 78                                                |
| SLW 2    | 1739.1                   | 18019.61          | 55                | 2.35                              | 159.8             | 6.8                           | 66                                                |
| BLW 1    | 1686.9                   | 3633.301          | 57                | 2.5                               | 79.1              | 5.9                           | 58                                                |
| BLW 2    | 1686.6                   | 1702.24           | 54                | 1.8                               | 84.8              | 3.4                           | 48                                                |

1- For normal weight concrete solid slab, shear reinforcement existence leads to make the slab more tough and ductile by percent equal to (155%, 107%), respectively.
2- For light weight concrete, shear force existence reduces the toughness of slab by (40.7%, 53.2%) for solid and voided slab, respectively.
3- Lightweight concrete solid slab without shear reinforcement (SLW1) absorbed energy larger than solid normal weight (SNW1) by (11.7%). But (SNW2) slab showed higher energy absorption reached to (234%) than (SLW2) because of shear reinforcement effect.
4- Brittle materials have small toughness, because large elastic and plastic deformations lead to absorb large amounts of energy [13]. This means that shear reinforcement existence makes normal weight concrete more ductile while the void and shear reinforcement existence with light weight concrete creating a more brittle specimen.

3.4 Crack pattern
As the specimens start to be loaded, the punching shear force is transferred from column through surrounding slab concrete. Immediately after the stresses with in the concrete reach the ultimate tensile stress, first crack forming. When the loading continuo to increase, the other cracks forming at the slab central region. Cracks start to extended away from the area where higher values of tensile stresses towards the edges of the slab where lower stresses existence until rupture accord.
In general, the behavior of normal weight concrete specimen was different from lightweight concrete. Because of the high percent of small void existence in lightweight aggregate structure (leca). Which leads to different failure crack mode.
In lightweight concrete, there is a flexural crack noticed on the compression side in addition to column penetration crack. Also, in tension sides there is a clear cracks map with no damaged zone. While in normal weight concrete, there is no flexural cracks on the compression side. The only crack is the crack formed due to column penetration. But in tension face there is a clear damaged zone. Plate (5) show crack patron for all specimen.

**Plate 5.** Crack patron for all specimen in case one.

### 3.5. Failure Zone and Failure Angles

The failure modes for slabs with punching shear reinforcement have several different cases. The position of the effective control perimeter changes depending on concrete mechanical properties, bending reinforcement ratio, shear reinforcement type and ratio (13).

The mode of punching failure was typically pyramid in shape. Which produce an angle ($\theta$) with the tension face of the slab as shown in Fig. (7) (14). Where the distance between columns face to failure perimeter denoted by (Y). And the specimen plan direction named (N, S, E, W) which represent (north, south, east, west) directions.

The angle magnitude ranges between 20° and 45°. Which depends on the type and ratio of flexure and shear reinforcement on the slab (14).

![Figure 7. Punching shear failure angle.](image)

Figure (8) shows the failure zone and the effective control perimeter position for all slab specimen in this case. Also table (6) show the magnitude of failure angle and the extend of punching zone in all direction.
Figure 8. Failure zone and angle.
4. Conclusion

- The load carrying capacity for lightweight voided slab without shear reinforcement decreased by (60%, 53%) with respect to solid normal weight, solid lightweight slabs without shear reinforcement respectively.

- The load carrying capacity for lightweight voided slab with shear reinforcement decrease by (67%, 47%) with respect to solid normal weight, solid lightweight slabs with shear reinforcement respectively.

- For voids ratio equal to (20%), the shear reinforcement existence leads to reduce the deflection magnitudes at ultimate load by (25%, 32.3%) for slabs with hook, shear reinforcement with respect to solid normal weight and solid light weight control specimen without shear reinforcement respectively.

- For normal weight concrete, shear reinforcement existence leads to make the slab more tough and ductile by percent equal to (155%, 107%) respectively. But for lightweight concrete, shear reinforcement existence reduces the toughness of slab by (40.7%, 53.2%) for solid and voided slab respectively.

- In lightweight concrete, there is a flexural crack are noticed on the compression side in addition to column penetration crack. Also, in tension sides there is a clear cracks map with no damaged zone. While in normal weight concrete, there is no flexure cracks on the compression side. The only crack is the crack formed due to column penetration. But in tension face there is a clear damaged zone.

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