The Effect of the Shear Connectors Layout on the Sustainable Lightweight Concrete Sandwich

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Abstract. Sandwich Slab is a modern shape of structural construction. It contains a low density layer known as the core layer confined by two strong layers. In the present study, the two layers of light weight concrete [LWC] were tied together by a cage of steel reinforcement named as shear connectors, sandwiched between them a layer of polystyrene. The experimental investigation was conducted on six slabs. Two parameters were investigated (the steel area of the shear connectors which is depended on the number of W-Shaped shear connectors and the layout of W-shaped shear connectors). The main reason for using crushed bricks as a lightweight aggregate was to the benefit from the recycling broken bricks as a sustainability material. The slabs were tested as simply supported under two line loads. Continuous truss-shaped shear connector showed better behaviour than discrete W-shapes shear connectors. Experimental test results indicated that the presence of discrete shear connectors at the ends of the specimens in distance of one-fourth of span had significant better performance than at the center of the specimen.

Keyword: The Sandwich slab, Sustainable lightweight concrete, Crushed bricks, Shear connectors.

1. Introduction

Concrete sandwich slabs are a layered system composed of two thin, and high strength layers held together by shear connectors [1-4]. Those layers usually separated by a lightweight insulating layer, such as extruded polystyrene (XPS) or expanded polystyrene (EPS) [5]. For more than 50 years concrete sandwich slabs were used for many different structures as exterior and interior walls [6]. The presence of the low-density core layer provides high thermal resistance and structural performance [6]. The manufacturers are looking for new, applicable product lines and because of energy performance and general aesthetics of the panels so the urgent need to develop concrete sandwich panels [3]. Concrete sandwich slab may be regarded as fully composite, a semi-composite or non-composite panel. Full composite panel is accomplished by providing full shear transfer between the two layers on another meaning Full composite panel are designed and manufactured so that the two concrete layers act together as a single unit to resist applied loads till failure [2]. When sandwich slab was used as a structural member, the slab must be designed as a full composite slab in order to take full advantage of the strength of the two layers and to prevent individual layer buckling [7]. The main aim of this work is producing structural lightweight concrete sandwich slabs with high strength over weight ratio. The over-exploitation of natural materials raises controversy about protection natural resources so that the researchers studied this problem and tried to develop a solution to balance the lack of natural future resources [8]. The reuse of broken bricks to produce new and good concrete is a possible solution.
Previous studies showed that the crushed bricks are possible option to use as a structural material in terms of mechanical properties and structural behavior [9]. One of the important properties of the crushed bricks is the low density. It’s density is about 40% less than the normal coarse aggregate [9]. Panels with crushed bricks as coarse lightweight aggregate exhibit better structural performance than panels with normal aggregate [10]. Lower density means more advantages to reduce the labor, reduce the construction’s time, and contribute to green building ideology. From the previous researches, it is clear that studies on sandwich slabs are still limited and there is a weakness. Most of concrete wythes in the sandwich panels were made of conventional concrete. So these sandwich panels are strong but they have lower strength over weight ratio. Therefore, further investigation on using both lightweight concrete in the wythes and polystyrene core layer was required.

2. Experimental Work
The experimental program involves testing one solid slab, one sandwich specimen with normal concrete, and four sandwich slabs with lightweight concrete in the wythe layers. Three of the lightweight sandwich specimens were built with different shear connectors layout, but with same shear reinforcement ratio. All specimens have been tested under two-line load. In current experiment, three parameters were investigated. The first parameter was the steel area of the shear connectors; the second one was the effect of different shear connectors layouts which arrangement gives better composite ratio. The first slab specimen denoted by (RN). RN is a solid slab with normal weight concrete reinforced with longitudinal steel bars (Ø6 @ 6mm) and it considered as a control slab for this experiment. The second slab specimen (SN-C45) was sandwich slab with normal weight concrete in the skin layers. SN-C45 was reinforced with continuous steel truss as shear connectors. The inclined angle for each bent in this specimen was 45°. The third slab specimen (SB-45) was sandwich slab with crushed bricks as coarse lightweight aggregate in skin layers. SB-45 was reinforced with continuous truss as a shear connector. The inclined angle for each bent in this specimen was 45°. The fourth specimen (SB-L1), the fifth specimen (SB-L2), and the sixth specimen (SB-L3) were sandwich slabs with crushed bricks as coarse aggregate in skin layers, and they were with different layouts of discrete W-shape shear connectors as illustrated in the Figure 1.

2.1 Specimens Details
All specimens were designed to act in one-way action and had the same total dimensions which they were (1100mm total length × 400 mm width × 90mm thickness). The sandwich slabs consist of two 30 mm thick skin layers of lightweight concrete, and 30 mm thickness cork layer between them. Figure 1 shows details of the reinforcement for each slab.
2.2 Materials
Sulfate resistance cement (Type V) was used in the mix to prepare all specimens. The laboratory tests of the physical and chemical properties were performed according to the specification No.5 1984 of Iraqi Specification. Crushed coarse aggregate within the maximum size of 9.5 mm was used in the mix of the normal weight concrete, and crushed bricks with maximum size of 9.5 mm and bulk density of 805 kg/m³ was used in the mix as a lightweight coarse aggregate. The grading of the crushed bricks and normal coarse aggregate was same and conforming the ASTM C330-05. The mixing proportions of the conventional normal concrete and lightweight concrete were (1:2.1:1.2) with w/c = 0.4 and 0.5% superplasticizer from the weight of the cement. Hyperplast PC 200 was used as high Performance Super-Plasticizer Concrete Admixture (known commercially as Flocrete PC200). All sandwich specimens were reinforced with a mesh of 6 mm diameter bars of spacing 150 mm deformed steel reinforcement. The steel mesh had yielding strength of 533 MPa. The meshes centered at both of the concrete layers of the slabs as shown in Figure 2. The outer concrete layers tied together with steel truss shear connector of 4mm diameter deform bars. After one day of casting, the forms were removed and the slabs were submerged in water at room temperature for 28 days of curing.
2.3 Tests Procedure and Equipment

The test setup was simply supported under two lines load applied equally at (1/3 of the span). Effective span was (990mm). The Test was conducted by using universal machine with load cell capacity equal to (1000kN) as illustrated in Figure 3. For top and bottom concrete layers, Strains were measured at mid span by using demec points. At one end of all specimens, the end slip was measured at the center of width for the upper concrete layer by using LVDT with 100mm range, and the end slip for the lower concrete layer was measured at the center of width by using LVDT with 10mm range. At mid-span LVDT with 100-mm range was used to measure the deflection. Figure 3 displays the supports and the location of the applied load arrangement. Note (1,2&3 represent the LVDTs). When the load was zero, first readings of LVDT were recorded, then the load gradually increased in stages while deflection and end slip measurements simultaneously recorded up to failure.

3. Results and discussion

The experimental results were analyzed in the context of Load-Deflection curves, Load- Strain relationship and cracks pattern at the failure. The results indicate that hardened density for lightweight aggregate concrete when using crushed bricks are below 1945 kg/m³ with cylinder compressive strength 25.2 MPa. And tensile strength 2.83 MPa.

3.1 The Load Deflection Relationship

To understand the effect of the layout of the shear connectors on the flexural strength of the sandwich slabs, load- deflection curves for the solid and sandwich slabs at mid span were showed in the Figure4. All tests of the slabs were conducted under load increment 3 kN. Table (1) displays total weight, failure loads and deflection of tested slabs, and a comparison with a reference slab as appropriate.
Table 1. Failure Loads and Deflection of Tested Slab.

| Specimen symbol | Total Weight of specimen (Kg) | First Cracks Load (kN) | Failure load (kN) | Mid-span Deflection (mm) | Reference slab | The Difference in the ultimate load compared with the reference slab % | The Difference in the deflection compared with the reference slab % |
|-----------------|-------------------------------|------------------------|-------------------|--------------------------|----------------|------------------------------------------------|------------------------------------------------|
| RN              | 94.5                          | 11.86                  | 33                | 11.00                    | _              | _                                              | _                                              |
| SN-C45          | 65                            | 10                     | 30                | 13.50                    | RN             | -9.09                                          | 22.72                                          |
| SB-C45          | 57.4                          | 12                     | 27.84             | 22                       | SN-C45         | -7.20                                          | 62.96                                          |
| SB-L1           | 56.4                          | 6                      | 21.65             | 15.42                    | SB-C45         | -22.23                                         | -29.91                                         |
| SB-L2           | 56.3                          | 3                      | 17.60             | 18.00                    | SB-C45         | -36.78                                         | -18.18                                         |
| SB-L3           | 55.8                          | 6.6                    | 19.89             | 16.23                    | SB-C45         | -28.55                                         | -26.23                                         |

From the table 1 can be noticed that:

• For the same type of coarse aggregate (normal weight aggregate) used in the concrete mix, the flexural load capacity for the SN-C45 slab was decreased by about 9.09% from the flexural load capacity for the solid slab. From another point of view using a sandwich slab will increase the deflection value by about 22.72% and ductility index will increase by 2.27 % as compared with the RN slab. Also, the total weight will decrease by about 31.21%.

Figure 4. Load Deflection curves for the RN & SN-C45 slabs.
- Flexural strength was decreased about 7.20% when using crushed bricks as a coarse aggregate in the outer concrete layers of the SB-C45 slab instead of normal coarse aggregate SN-C45 slab. This decrease accompanies by an increase in deflection value and ductility index by 69.23 %, and 39.64%; respectively. Also, the total weight will decrease by about 39.25% when compared with RN slab.

![Load Deflection curves for the SN-C45 & SB-C45 slabs.](image)

- When discrete shear connector with a steel area (2/3) of the continuous truss steel area was used: -
  I. Flexural strength was decreased about 22.23% when using SB-L1 slab, compared with ultimate strength when SB-C45 slab. So that, max deflection value and ductility index were decreased by about 29.91 %, 1.97 %: respectively.
  II. When using SB-L2 slab, flexural strength was decreased about 36.78% compared with ultimate strength when SB-C45 slab, and max deflection will decrease by 18.18 %. While ductility index will increase by 14.57%.
  III. Ultimate strength and max deflection value will decrease by about 28.55%, 26.22%; respectively, when using SB-L3 slab as compared with SB-C45 slab with an increase in ductility index by 3.31%.

Also, when using sandwich slabs with discrete shear connectors, the total weight of reached more than 40% when compared of RN slab.
3.2 Load-Strain Relationship

The composite behaviour of the concrete sandwich slabs was predicted by using load strain profiles. When each layer acts independently accompanied with a relative slip occurring at the interface, this means the panel behaved as non-composite. While when the two concrete layers are connected with full or efficient shear transformation, the panel behaved as full-composite [11]. From Figures 7-11, it is clear that SN-C45 slab exhibits full composite action till the load was 78.26% of the ultimate load, while SB-C45 & SB-L2, SB-L3 slabs show full action till the load reach 72.46%, 73.5%, 71.79% of the ultimate load. SB-L1 slab exhibits minimum composite action when the load was 40% of the ultimate load.

![Figure 6. Load Deflection curves for the SB-C45, SB-L2, SB-L2, SB-L3 slabs.](image-url)

![Figure 7. Strain Distribution along Depth of SN-C45 slab with a Different load stages.](image-url)
Figure 8. Strain Distribution along Depth of SB-C45 slab with a Different load stages.

Figure 9. Strain Distribution along Depth of SB-L1 slab with a Different load stages.

Figure 10. Strain Distribution along Depth of SB-L2 slab with a Different load stages.
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3.3 Crack Pattern

Figure (1) shows cracks patterns that appeared in the lower face of tested slabs. All slabs exhibited flexural cracks which developed along the width of the panel. Small cracks were noticed in the top concrete layer. This behavior is agreed with previous researchers [2, 8]. All sandwich slabs show ductile behaviour, exhibiting large deformation before the failure, more than the solid conventional panel. All sandwich slabs failed due to the tension failure at the bottom layer except the solid conventional panel which failed in the tension zone accompanied by concrete crushing.

![Crack Pattern](image)

Figure 12. Cracks Distribution of the Different Tested slabs.

4. Conclusions

Structural lightweight aggregate concrete, with a cylinder compressive strength about 25.2 MPa and air dry density of 1954 kg/m could be produced from waste crushed bricks as a coarse lightweight aggregate, natural sand, and high-performance superplasticizer (PC-200).

I. Solid slab with normal aggregate showed an increase in flexural ultimate strength capacity as compared with the sandwich slab with normal aggregate while SN-C45 slab had less hardened density than solid slab. Also, sandwich slab will increase the deflection value, and ductility index.

II. The sandwich slab that contains crushed bricks as a coarse aggregate with 45 inclined angle continuous shear connectors bent had less total weight compared with normal
aggregate SN-C45 sandwich slab, this reduction was accompanied by reduce in load capacity while the ductility and toughness will increase.

III. SB-C45 slab was represented the best layout of shear connectors than the other tested sandwich slabs.

IV. The presence of shear connectors at the ends of the panel section had significant effect on the flexural strength and the composite ratio of the tested slabs, when using discrete truss shear connectors. (SB-L1), (SB-L2), (SB-L3) slabs exhibited decreasing in load capacity as compared with SB-C45 slab. This reduction accompanies by a reduction in total weight. The area of steel shear connectors (which is considered an expensive material) has reduced.

V. It was clear that SN-C45 slab show better composite action and less slip value when compared with SB-C45 due to the density of concrete which increases when the compressive strength increase.

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