Impact behaviour of crushed-brick lightweight RC sandwich slabs

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Abstract: In recent construction practice, sandwich panels have been increasingly adopted due to the fact that they are lightweight, energy efficient, aesthetically attractive, and easy to handle and erect. This study examines the impact behaviour of lightweight reinforced concrete (RC) sandwich slabs produced from local lightweight coarse aggregate. The experimental program included testing two slabs produced with normal coarse aggregate (solid slab + sandwich slab) and six concrete sandwich slabs (CSSs) produced using crushed clay bricks as lightweight coarse aggregate with various shear connector configurations and types and steel fibre volume fractions (VF%). The impact load was applied at the midpoint of each slab using an 8 kg drop-weight from a height of 2 m. The test results showed CSS behaviour variation with different VF% and the optimum layout and location of shear connectors.

Keywords: concrete sandwich slabs, lightweight concrete, crushed bricks, shear connectors, impact load.

1. Introduction

Concrete sandwich slab (CSS) construction is an advanced modern construction method involving the use of two reinforced concrete (RC) layers separated by an insulating material such as polystyrene. Many different shear connectors have been used to hold such concrete layers together, though steel truss-shaped shear connectors are generally the most powerful shear connectors. The essential functions of such shear connectors are to transmit shear to ensure that the faces of slabs do not slip over each other when the panel is bent, and to link the concrete layers to enable them to operate as a single unit. Each part of a composite is relatively weak and flexible, though together they offer opportunities to create extremely stiff, sturdy, and lightweight structures. The main advantages of such systems include high bearing capacity, useful insulation, simpler handling due to lightness of weight, and reduced material and labour costs. Other important advantages of these CSSs include low self-weight and high thermo-acoustic adequacy, facilitating applications in residential, commercial, and industrial buildings in North America and Europe [1-4]. The structural behaviours of CSS differ according to the
stiffness and strength of the shear connectors, while the configuration and spacing of the shear connectors differs according to the loads applied, the extent of the composite action, the length of the shear connectors, and their materials [5]. Currently, there are no specific rules, guidelines or design codes to determine the number or arrangement of connectors required [6]. While the bounding layer between the insulation core and concrete layers has been found to provide shear transfer, this reduces in capacity over time and does not retain the strength of the shear connectors over the panel's lifespan [7-9].

Previous research has shown the possibility of using crushed bricks as a structural material based on the resulting mechanical properties and structural behaviours [10]. Low density is one of the main properties of crushed bricks, which offer about 40% lower density than normal coarse aggregate [9]. Panels using crushed brick as coarse lightweight aggregates exhibit better structural performance than normal aggregate panels [11], and lower density also offers advantages in terms of reducing labour cost, reducing construction time, and supporting the philosophy of creating green buildings [12, 13].

2. Experimental Work

The experimental programme in this work included the testing of one solid slab, one normal concrete sandwich specimen, and six lightweight concrete slabs with two layers. All specimens were designed with one-way action and with the same dimensions of 1,100 mm total length × 400 mm width × 90 mm thickness. The CSSs consisted of 30 mm RC with a 30 mm thick layer of polystyrene at its core. The two concrete layers were reinforced with steel wire mesh with spacing c / c of 150 mm and a wire diameter of 6 mm. The reinforcement cover was 12 mm deep. The steel truss cage connectors were linked to the two concrete layers with a spacing of 150 mm, and the diameter of the shear connectors’ deformed steel bar was 4 mm. These steel bars were bent to form continuous w-shaped zigzags (see Plate 1), with the angle of each bend being 45°. Table 1 shows the description of the slabs and Plate 2 shows details of the reinforcement of the slabs.

| Symbol | Description |
|--------|-------------|
| SS | Solid slab |
| SN | Normal sandwich slab with continuous truss shear connectors and 0% steel fibre. |
| SBC-0% | Brick sandwich slab with continuous truss shear connectors and 0% steel fibre. |

Plate 1. Bent shear connector bars in 45°

Table 1. Experimental programme
SBD-0%  Brick sandwich slab with discontinuous truss shear connectors and 0% steel fibre.

SBC-0.5%  Brick sandwich slab with continuous truss shear connectors and 0.5% steel fibre.

SBD-0.5%  Brick sandwich slab with discontinuous truss shear connectors and 0.5% steel fibre.

SBC-1%  Brick sandwich slab with continuous truss shear connectors and 1% steel fibre.

SBD-1%  Brick sandwich slab with discontinuous truss shear connectors and 1% steel fibre.

Plate 2. Details of reinforcement of testing slabs.

2.1 Concrete Mix

The structural lightweight aggregate concrete was a concrete with an oven dry density less than 2000 kg/m³ and a cylinder compressive strength greater than 17 MPa at 28 days. The mixes were designed according to the ACI 211.2-98 [14] Committee guidelines.

The materials used in the mixture were
• Cement: Resistant Portland cement for which laboratory testing of physical and chemical properties was carried out to ensure adherence to Iraqi specification No. 5, 1984.
• Fine Aggregate: Natural sand was used with a maximum grain size of 4.75 mm. The grading test results conformed to Iraqi specification No. 45.
• Normal weight coarse aggregate: The normal weight coarse aggregate used throughout this work had a maximum size of 10 mm.
• Lightweight coarse aggregate: Crushed clay brick, obtained from the demolition of buildings, was used as a lightweight coarse aggregate to produce the lightweight concrete. The brick samples were crushed into smaller pieces using a hand-held hammer, creating a final product of approximately 10 mm maximum aggregate size. Plate 3 shows the crushed clay bricks and hammer. Sieve analysis of the crushed clay bricks was carried out according to ASTM C330-05[15], as shown in Figure 1.

Plate 3. Crushing clay bricks with a hammer

Figure 1. Grading of crushed clay brick

• Steel Fibres: Straight steel wire fibres of 13 mm length with a tensile strength of 2,850 N/mm², made by Ganzhou Daye Metallic Fibres Co. Ltd., China, were used in this research, as shown in Plate 4.
• Chemical Admixture: For the required analysis, a high-performance concrete superplasticizer (High Range Water Reduction Agent, HRWRA) was used, known as SikaViscocrete-5930. This was imported from the Sika Company in Egypt. Sika ViscoCrete -5930 is a third-generation concrete and mortar superplasticizer, being an aqueous solution of modified polycarboxylates that meets the specifications of ASTM-C-494-99 for type G and F super plasticizers.

**Table 2. Mixes used in the study**

| Mix                  | N  | B1   | B2   | B3   |
|----------------------|----|------|------|------|
| Cement kg/m³         | 365| 365  | 365  | 365  |
| Fine aggregate kg/m³ | 769| 769  | 769  | 769  |
| Coarse aggregate kg/m³ | 408| 408  | 408  | 408  |
| W/C                  | 0.4| 0.4  | 0.4  | 0.4  |
| Steel fibre%(SF)     | 0  | 0    | 0.5  | 1    |
| Superplasticizer%    | 0.25| 0.38| 0.38| 0.48 |
| Slump, mm            | 50 | 50   | 30   | 30   |
| Cube compressive strength, MPa | 40.5| 27  | 34   | 37   |
| Density kg/m³        | 2081| 1763| 1801 | 1868 |

N: normal weight Concrete, B: Crushed clay brick aggregate concrete, W/C: Water cement ratio.

2.2 Impact testing

Two load cells of type SS 300, with capacities of 5 tons each, were used. One load cell was located in the concrete deck's mid span to measure the direct impact load, while to test the reaction load, the second load cell was placed in one of the supports. A laser displacement sensor type LK-081- KEYENCE was used to acquire the displacement-time history responses
for slabs subjected to impact loads, as shown in Plates 5 and 6. All other sensors and load cells were linked to Lab VIEW 2018 software, with data automatically loaded in to Excel. The impact load was determined by dropping an impactor with a constant mass of 8kg from a height of 2 m. The impactor consisted of two-parts: the top, a stainless-steel ball with a diameter of 100 mm, and a cylinder with a height of 200 mm and a diameter of 100 mm.

Plate 5. Schematic of impact test apparatus

Plate 6. Impact test
3. Experimental results

The results recorded for the slabs, including the impact force and corresponding reaction force, midpoint displacement, and crack propagation, are shown in Table 3.

Table 3. Centre impact load, reaction load, maximum deflection and residual deflection for all tested slabs.

| Specimen symbol | Center-load (kg) | Reaction-load (kg) | Max. deflection (mm) | Residual(permanent) deflection (mm) | Time (ms) | Total weight of the slab (kg) |
|-----------------|------------------|--------------------|----------------------|-------------------------------------|-----------|-----------------------------|
| SS              | 1035             | 279                | 1                    | 0.33                                | 13        | 85                          |
| SN              | 686              | 148                | 0.96                 | 0.49                                | 5         | 59                          |
| SB-C0%          | 671              | 148                | 1.08                 | 0.63                                | 4         | 50.7                        |
| SB-D0%          | 639              | 146                | 1.09                 | 0.46                                | 4         | 50.5                        |
| SB-C0.5%        | 770              | 154                | 0.75                 | 0.22                                | 9         | 51.7                        |
| SB-D0.5%        | 751              | 150                | 0.77                 | 0.43                                | 7         | 51.5                        |
| SB-C1%          | 884              | 238                | 0.65                 | 0.6                                 | 13        | 53.5                        |
| SB-D1%          | 837              | 225                | 0.65                 | 0.41                                | 8         | 53.3                        |

Four variables were assessed based on the results of the tests:

1. **Replacement of traditional solid slabs with CSS.**

The main benefits of using the sandwich principle include minimisation of the overall weight by about 30.6% and a load reduction of about 33.72% as compared with the solid slab. Figures 2 and 3 show the load-time and deflection-time histories for SS and SN.
Figure 2. Load-time history for SS and sandwich slab SN

Figure 3. Deflection-time-history for SS and sandwich slab SN

Figures 2 and 3 show that the SS response took longer than that of the SN, and that permanent deformation of about 0.49 mm occurred in the SN. This suggests that, unlike the SN, the SS behaves as a single unit under the influence of the impact load, allowing the SS to hit the impactor and increase the load again at 9 ms.

2. Efficiency of using lightweight coarse aggregate concrete in structural members.

The use of clay bricks as a lightweight coarse aggregate promotes behaviours similar to those seen in normal coarse aggregate under impact loads of the same parameters, with a decrease in load of about 2.2% and an increase in the deflection of about 12.5%. Overall, the total weight of the specimen is reduced by about 14.1%. Figures 4 and 5 show the load-time and deflection-time histories for SN and SBC-0%.
3. Optimum layout of shear connectors

From Table 3, it is apparent that the use of continuous truss shear connectors, as compared with discontinuous truss shear connectors, enhances the load by about 4.75%, 2.5%, and 5.3% (see Figure 6), and decreases the deflection by about 0.9%, 2.67% and 0% for SBC-0%, SBC-0.5%, and SBC-1% as compared with SBD-0%, SBD-0.5% and SBD-1% respectively. Figures 7 and 8 show the load-time history and deflection-time history for SBC-0% and SBD-0%.
Figure 6. Effect of layout of shear connectors

Figure 7. Load-time history for SBC-0% and SBD-0%

Figure 8. Deflection-time history for SBC-0% and SBD-0%
4. The effect of using different percentages of steel fibres in CSS.

The addition of 0.5% steel fibre increases the load by about 14.75 % and 17.53 % for continuous and discontinuous shear connectors, respectively, while the use of 1.0% steel fibre increases the load by about 31.74 % and 30.98% for continuous and discontinuous shear connectors, respectively, as compared with 0% steel fibre. Further increasing the percentage of fibre causes a significant decrease in deflection as a result of improvements in the tensile properties of the concrete. Figures 9, 10, and 11 show the load-time and deflection-time histories for all tested sandwich specimens.

![Figure 9](image1.png)

**Figure 9.** Load-time history for SBC-0%, SBC-0.5% and SBC-1%

![Figure 10](image2.png)

**Figure 10.** Load-time history for SBD-0%, SBD-0.5% and SBD-1%
Figure 11. Deflection-time history for SBC1%, SBC-0.5%, SBD-1% and SBD-0.5%.

Generally, the behaviours of SBC-1% are very similar to those of the SS, as shown in Figure 12.

Figure 12. Load-time history for SS and SBC-1%

3.1 Cracking patterns

All cracks in the tested slabs exhibited behaviour consistent with the different parameters studied, as Plate 7 shows. SS had only one crack at the bottom, with no cracks appearing at the top, but that was a very large crack width as compared to those in the CSSs. In general, the use of continuous truss shear connectors leads to a better distribution of load, thus increasing the number of cracks, while the addition of steel fibre in different percentages significantly affects both the number of cracks and their widths. With an increase in the steel fibre percentage, the number of cracks and their widths in CSSs decrease significantly, due to the addition of steel fibre making the concrete more homogeneous and isotropic, converting it from a brittle material to a more ductile material. The randomly oriented fibres also arrest the micro cracking mechanism when concrete cracks, limiting the propagation of cracks, and thus improving strength and ductility.
Plate 7. Crack distributions in the top and bottom of several tested slabs.

4. Conclusion

1. The behaviours under impact load of concrete sandwich slabs produced using crushed clay bricks as lightweight coarse aggregate were similar to those of concrete sandwich slabs produced using normal coarse aggregate.
2. The use of discontinuous truss shear connectors decreased the load slightly, by about 2.5 to 5.3%, in exchange for a reduction in steel reinforcement by about 4.92%.
3. The addition of steel fibres has a positive effect on CSS behaviour, as the sandwich behaviour becomes more similar to the solid behaviour with increases in the percentage of addition.
4. The deflection and the number of cracks in CSSs decrease significantly with increases in the steel fibre percentage.
5. Excellent CSS behaviour was recorded for the SBC-1%, which behaved in a very similar manner to SS, reducing the response load by about 14.6%.
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