Strength of Modified Foam Concrete-Filled Hollow Section Using Fly Ash as Sand Replacement

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Abstract: Hollow sections for columns, beams and trusses have been used in the steel construction industry for a decade. Concrete-filled hollow section (CFHS) has been widely used due to its aesthetic efficiency and to improve the load-carrying capacity. However, the use of normal concrete as infilled in steel hollow section has increased the dead load of structures. A modified foam concrete filled hollow section using fly ash as sand replacement (FCFHS-FA) is proposed to reduce the structure’s dead weight. This study aims to determine the strength performance of FCFHS-FA structure by using two types of steel hollow section thickness and compare the strength between FCFHS and FCFHS-FA. Steel, preformed foam, and fly ash were used to increase the strength. Nine specimens were prepared and a compression test was conducted. The strength index was calculated to compare the strength of FCFHS with FCFHS-FA. Result shows that FCFHS-FA has a similar strength index compared with FCFHS.

1. Introduction
Steel Hollow sections (SHS) have been widely used in steel construction for a decade because the steel has strong durability and strength. The elongation of steel prevents structures to sudden failure. The rectangular hollow lattice structure shows the best mechanical compression resistance, and the highest bending properties are obtained by the truss-shaped prism structure [1]. Hollow steel sections have high strength, ductility and lightweight properties. However, they are prone to buckling. The ductility of a column decreases with the increase in depth-to-width ratio, concrete compressive strength and axial load level. Steel hollow sections are available in cold and hot rolled steel sections. Steel hollow sections have higher thermal conductivity than concrete structures [2]. Therefore, steel section filled with concrete is one of the solutions to reduce its buckling.

Concrete-filled hollow section (CFHS) is extensively used in the steel construction industry. CFHS is a steel hollow section with concrete infill. Concrete filler in steel hollow sections can provide flexural support, and steel hollow sections can influence concrete confinement to improve steel hollow performance. The performance of CFHS with various filling materials varies depending on the materials and cement used in the concrete infilled [2]. This approach decreases the deformation and buckling problem of the steel construction and increases the strength of CFHS. CFHS components are commonly used in various structural applications, including high-rise buildings, multitype bridges, towers and bracing systems [3]. The ability of CFHS to delay buckling of hollow sections [2, 4] increases the ductility and energy dissipation of the member. Steel hollow sections with concrete infill have a high
local buckling and bending capacity and can be used to delay local buckling by placing the steel at the section’s outer perimeter, where the moment inertia and radius of gyration are the greatest. However, studies show that the use of normal concrete raises a structure’s dead weight [5], resulting in the expense of construction and lightweight concrete (LWC) [6].

According to Nurizaty et al. [2], CFHS outperforms reinforced concrete and steel section elements in terms of seismic performance. The flexural loading increases cyclically under constant axial load. Concentrally loaded circular CFHS columns may have better postyield behavior and stiffness than rectangular CFHS due to their larger diameter-to-thickness ratio. High-strength steel has a tendency to have a higher yield-to-ultimate stress ratio than mild steel but a lower strain ductility. The lighter and more slender the CFHS columns, the better they can replace traditional steel or reinforced columns in terms of resistance [4].

The application of CFHS has been improvised from time to time from NCFHS to lightweight LCFHSs. Thus, lightweight aggregate concrete may replace standard aggregate concrete in composite construction due to the former’s low specific gravity and thermal conductivity levels, which can create lighter structures. LWC is approximately 20% to 30% lighter compared with normal weight concrete due to the composite action of LCFHS. The steel hollow section confines the LWC core and increases the strength, ductility and stiffness. The infill concrete protects the steel hollow sections and postpones or prevents local folding [3].

LCFHS is commonly used in buildings due to its density between 400 and 1,600 kg/m³ that contributes to a decreased dead weight of a structure [5]. Khairuddin [6] used foamed concrete with a density of 40 kg/m³ to 1,600 kg/m³ and a strength of 10 MPa to 35 MPa. This lightweight foam concrete is made to strengthen the concrete by combining conventional cement, fine aggregate, foaming agent and compressed air [7-8]. The purpose of the foam is to provide a mechanism for producing a high ratio of air cells that produce a porous solid when mixed with cement [9]. However, the use of foamed concrete alone does not result in significant strength improvements [10].

1.1. Fly ash (FA)
Satpathy et al. [11] stated that the strength of structural LWC with FA cenospheres (FACs) and sintered FA aggregate (SFA) is less than the normal concrete but has a high density compared with the normal concrete. The concrete has an optimum strength with desired density, containing 50% of FAC and 75% of SFA.

FA is an agricultural by-product used for renewable construction materials. It has an application density of 1,800 kg/m³ without synthetic polyolefin fibres (macro or micro) for a power of 40 MPa [12]. According to Ahmaruzzaman [13], FA is typically grey in colour, abrasive in nature, often alkaline and refractory. Pozzolans, silica or silica and aluminium materials that form cement products at ambient temperatures along with water and calcium hydroxide are admixtures. In nature, FA usually is grey, abrasive, sometimes alkaline and refractory.

FA is the primary raw material needed for the production of SFA aggregates. One of the main issues associated with FA is the divergence in its fineness. With the increase in fineness of the FA, the average size of the manufactured aggregate increases, and the coarser FA particles require more moisture content to produce a fraction of the aggregate size. FA has various advantages, such as reduced the dead load, higher strength-to-weight ratio, low-cost construction, improved durability, higher tensile strain power, minim thermal expansion, greater insulation properties and improved fire resistance [14].

According to Golewski [15], Concrete with the addition of FA of up to 23% is distinguished above this limit in terms of normal fracture strength and low fracture toughness. The optimum FA content for foamed concrete is 20% to 25% to improve the higher short-term compressive strength. The compressive strength of structural lightweight foam concrete is 11.25 MPa, and the corresponding dry density value at 28 days is 1170 kg/m³ [8]. According to Reddy and Dongkarar [16], the optimum FA used as a sand replacement is 70% and achieves the maximum value of compressive strength of 9.6 MPa. Therefore, a study on the foam concrete filled hollow section using FA as sand (FCFHS-FA) should be conducted.
1.2. Strength Index

Strength index (SI) is the ratio of ultimate load of the concrete-filled section column to the strengths of the composite column. Jamaluddin [17] suggest, SI values higher than 1.0 suggest have a positive interaction between the steel tube and concrete core and good concrete confinement. SI is described as Equation (1).

\[ SI = \frac{N_e}{N_u} \]  

where \( N_e \) is the ultimate load of the experiment and \( N_u \) is the compression resistance of composite column as defined in EN 1994-1-1[18] as

\[ N_u = A_s f_{sk} / \gamma_{ms} + A_c f_{ck} / \gamma_{mc}, \]  

where \( N_u \) is the ultimate short-term axial load for short column; \( f_{sk} \) and \( f_{ck} \) are the characteristic strengths of steel and concrete, respectively; \( \gamma_{ms} \) and \( \gamma_{mc} \) are the material partial safety factors for steel and concrete, respectively. BS EN 1994-1-1:2004 [18] recommends that the values of characteristic strength of steel and concrete as \( f_{sk} = f_y \) and \( f_{ck} = 0.83 \times f_{cu} \), respectively. The values of \( f_y \) and \( f_{cu} \) refer to the yield strength of steel and cube compressive strength of concrete, respectively

2. Material and experimental work

2.1. Material preparation

The preparation of FCFHS-FA requires the following raw materials: FA, preformed foam, ordinary Portland cement (OPC), sand, water, foaming agent and additive of superplastisier. The size of mould used for the modified foam concrete is 100 mm (length) × 100 mm (width) × 100 mm (height). The mixed design proportion can be referred in table 1. In this study, FA was used as a sand replacement for the modified foam concrete. The FA used is 60% [19] and 40% of sand.

The sand used for this concrete mix design is fine sand with a diameter less than or equal to 2.36 mm. The fine sand used for modified foam concrete (FC-FA) is dried under the sun to decrease its moisture content. The superplasticiser used is an additive material to increase the strength of concrete, and approximately 0.01 kg is used in the concrete mixture design. The volume method is used to find the weight of materials in kilogram (kg). The mix design for the foamed concrete is shown in table 1.

| Mixture                        | Foamed concrete | Modified foam concrete |
|-------------------------------|----------------|-----------------------|
| Cement–sand ratio (C/S)       | 0.5            | 0.5                   |
| Foamed–cement ratio (F/C)     | 0.7            | 0.7                   |
| Water–content ratio (W/C)     | 0.55           | 0.55                  |
| FA (%)                        | -              | 60                    |
| Foamed agent                  | 1:20           | 1:20                  |

2.2. Specimen size of hollow section

The dimension of the hollow section used for this experiment is 100 mm (width) × 100 mm (height) × 350 mm (length) with a thickness of 2 and 4 mm, as shown in figure 1. The type of steel used is square hollow section steel.
2.3. Material properties
Cube tests were conducted to determine the strength of modified foam concrete at 28 days [20]. A tensile coupon test was performed to determine the strength of steel hollow sections in accordance with BS EN ISO 6892-1:2016 standard [21]. The strengths of modified foam concrete and FCFHS-FA are presented in table 2. The strength of the steel hollow section is presented in table 3.

| Material Properties | Average compressive strength (MPa) | Average load value (kN) |
|---------------------|-----------------------------------|------------------------|
| FC-FA               | 22.10                             | 220.76                 |

Table 3. Tensile strength of steel hollow section.

| Type                        | Thickness (mm) | Yield strength, $f_{yk}$ (MPa) |
|-----------------------------|----------------|--------------------------------|
| Steel hollow section I      | 2              | 323                            |
| Steel hollow section II     | 4              | 376                            |

2.4. Experimental work
Six specimens of FCFHS-FA were prepared, with 3 specimens with 2 mm thicknesses and 3 specimens with 4 mm thicknesses. The steel hollow sections have the same dimension and outer diameter (figure 2).

The bottom of steel hollow sections is covered with plastics to avoid the concrete water flowing out from the bottom of steel hollow sections. The FCFHS-FA specimens were placed on the steel plate followed by concrete casting for the 6 specimens. The specimens were tested under compression load (figure 3).
3. Result and discussion

3.1. Strength Index (SI)
Table 4 shows the result of the axial strength and SI of FCFHS-FA. SI is measured by using Equations (1) and (2). The experimental result and SI are compared with the FCFHS without RA from a previous study [23]. The strength of FCFHS-FA is lower compared with the result of previous study under the same thickness. However, the 4 mm specimen has higher strength compared with the 2 mm specimen. The strength of the FCFHS increases when the $b/t$ is increased. According to Guler et al. [23], the specimens with thick steel hollow section walls exhibit increased strength improvement due to the strong confinement.

The strength of modified FCFHS using FA as sand replacement slightly decreases compared with the strength of modified FCFHS although the strength of the concrete is higher compared with the strength of FCFHS without FA. However, the SI is similar between the modified FCFHS-FA and FCFHS. The SI value of more than 1.00 indicates that the concrete prevents the local buckling of the steel tube [17].

Table 4. Strength of FCFHS.

| Specimen    | Thickness (mm) | $B/t$ ratio | Compressive strength, Fc (MPa) | Theoretical value (kN) | Experimental value (kN) | SI |
|-------------|----------------|-------------|--------------------------------|------------------------|-------------------------|----|
| FCFHS-FA 21 | 2              | 50          | 22.10                          | 313.08                 | 366.07                  | 1.00 |
| FCFHS-FA 22 | 2              | 50          | 22.10                          | 313.08                 | 414.24                  | 1.45 |
| FCFHS-FA 23 | 4              | 25          | 22.10                          | 313.08                 | 418.85                  | 1.50 |
| FCFHS-FA 41 | 4              | 25          | 22.10                          | 560.51                 | 706.00                  | 1.53 |
| FCFHS-FA 42 | 4              | 25          | 22.10                          | 560.51                 | 697.73                  | 1.49 |
| FCFHS-FA 43 | 4              | 25          | 22.10                          | 560.51                 | 701.97                  | 1.51 |
| FCFHS 21[22]| 2              | 50          | 14.50                          | 323                    | 495.00                  | 1.53 |
| FCFS 22[22] | 2              | 50          | 14.50                          | 323                    | 520.00                  | 1.61 |
| FCFHS 41[22]| 4              | 25          | 14.50                          | 608                    | 870.00                  | 1.44 |
| FCFHS 42[22]| 4              | 25          | 14.50                          | 608                    | 910.00                  | 1.50 |

Note: ‘21’, where 2 refers to ‘thicknesses in mm’, and 1 refers to ‘Sample 1’.

3.2. Buckling
Figure 4 shows the local buckling failure appearance of the test specimens. In figure (a), FCFHS-FA 21 and (d), FCFHS-FA 41, the buckling mode appears at the top part of the steel hollow section structures. For specimens FCFHS-FA 22, FCFHS-FA 22, FCFHS-FA 42 and FCFHS-FA 43 in figures (b), (c), (e) and (f), the buckling mode appears at the bottom part of steel hollow section structures. Figures (b) and

Figure 3. Compression test on FCFHS-FA.
(c) have the same specimen. For FCFHS-FA 22, buckling mode appears on two sides at the bottom part. Specimen FCFHS-FA 23 has no buckling mode. In this experiment, local buckling always occurs at the top part and bottom part. Figure 4 indicates that the buckling mode on steel hollow section structures with 2 mm thickness is more significant than that with 4 mm thickness. The buckling mode on these specimens is inconsistent. This appearance can be related to the bonding strength between the steel and the concrete. According to Abd Rahman [5], surface irregularities, such as roughness of steel section or surface of a concrete cross section along with specimen size, affect the bond strength.

![Figure 4. Typical local buckling failure of the test specimens. Figures (a), (b) and (c) are the test specimens with 2 mm thickness. Figures (d), (e) and (f) are the test specimens with 4 mm thickness.](image)

4. Conclusion
The use of FA as sand replacement to foam concrete shows a similar strength although the strength of foam concrete using FA as sand replacement shows higher strength compared with normal foam concrete. Therefore, further study needs to be conducted by adding the fibre to improve the strength debonding of modified FCFHS using FA as sand replacement and by increasing the percentage of FA
to 70% [16]. The concrete and steel debonding will be explored to reduce the debonding issues and delay the local buckling mode.

5. References

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