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BOND STRENGTH OF CONCRETE-FILLED HOLLOW SECTION WITH MODIFIED FIBROUS FOAMED CONCRETE

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The concrete-filled section of columns has been widely in construction used due to its structural elements. As a result, the usage of composite columns has recently increased all over the world. However, using foamed concrete alone does not result in much improvements in strength. Therefore, this paper examines the use of foamed concrete containing fibre to improve the strength of composite columns. Specifically, this study aims to determine the bond strength of concrete-filled hollow section (CFHS) with modified fibrous foamed concrete. Two types of fibre are used in this work, namely, steel fibre and polypropylene fibre, with rice husk ash (RHA) as a sand replacement to improve the compressive strength of foamed concrete. The CFHS with modified fibrous foamed concrete is tested by using the push-out method, and the results show that CFHS with steel fibre has a highest bond strength.

Keywords: bond strength; concrete filled hollow section (CFHS); modified fibrous foamed concrete; rice husk ash (RHA), strength; push-out method

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1. INTRODUCTION

Recent studies on the properties of concrete have only focused on normal, high-strength and lightweight aggregate concrete. Foam concrete has recently emerged as a sustainable material in the construction industry. In addition, the use of concrete-filled hollow section (CFHS) in civil engineering has received increasing interest from researchers and practitioners. CFHS is commonly used in construction projects as primary structural elements, specifically as columns in high-rise buildings, exhibition halls, industrial buildings and conveyor galleries. CFHS comprises a steel tube with a concrete core casted inside, and a CFHS column is governed by stability and failed by column buckling. Vinay et al. [1] argued that unlike hollow steel tubes, core concrete can prevent the buckling of steel tubes, thereby significantly improving their compressive stability. CHFS with circular and square sections has been used in construction due to its earthquake-resistant properties and high strength–weight ratio. CFHS also improve the compressive strength of concrete and use steel tubes as ductile materials. When subjected to compression load (e.g. steel yielding or concrete crushing), the CFHS stub column reaches its ultimate capacity, at which point both the concrete core and steel section reach their strength limits. Hafiz [2] examined the experimental and numerical simulation results and found that a CFHS column under axial compression load is not affected by a change in length. The experimental results may be primarily influenced by the confinement effect and the contribution of the steel section [3].

2. BOND STRENGTH OF CFHS

In CFHS columns, load transfer can sometimes take place between the steel tube and concrete. A load transfer needs to be ensured by maintaining a sufficient level of bond strength between the steel tube and concrete [4]. Over the past few decades, many studies have investigated the bond strength between the steel tube and concrete in concrete-filled carbon steel tubes [4-9]. However, the previous push-out tests mainly involve specimens whose cross-sectional dimensions are smaller than 200 mm and which measured bond strengths are not representative of that of real structures. Previous researches have examined the influence of concrete strength on bond behaviour, and a series of push-out tests have been conducted on CFHS specimens to investigate the effect of modified foamed concrete on bond behaviour. According to Mouli and Khelafi [10] bond strength is not influenced by the tube section of the steel specimen but by the type of concrete used. Meanwhile, Khodaie [11] reported that the bond strength increases along with the decreasing water–cement ratio (w/c) of concrete mixes. The interface adhesive force completely disappears when the interface elements between the inner concrete and outer stainless-steel tube slide along the entire height of the specimens [12]. The bond strength of a normal concrete-filled specimen is about 50% of the strength of a lightweight concrete-filled specimen due to the different shrinkage strains exhibited by these concretes at the same age [10]. The bond strength at the interface can be computed as

$$F_b = \frac{N}{P_o L}. \tag{1}$$

3. MATERIAL DEVELOPMENT OF MODIFIED FIBROUS FOAMED CONCRETE

Several materials were developed and used in this work to determine the optimum usage of fibre in foam concrete. One must ensure that the foamed concrete used has the optimum strength in order to achieve the maximum ultimate strength of CFHS. To determine the optimum strength of fibrous foam concrete, 108 cube specimens and 108 cylinder specimens were prepared. These specimens were cast with 0%, 0.2%, 0.4%, 0.6% and 1.0% volume fractions of fibre with 40% rice husk ash (RHA) as a cement replacement in foam concrete. These specimens had a target density of 1600 kg/m^3. A 1:2 cement–sand ratio, 0.55 water content and 1:20 foam agent–water ratio were selected for FC. The mix design proportions are listed in Table 1. Given that foamed concrete is self-flowing, no compaction was required. All specimens were air cured for 7, 14 and 28 days before being subjected to compression and tensile tests (Fig.1).

The compressive strength of concrete with different percentages of steel and polypropylene fibres are presented in Fig. 2. The maximum compressive strength of concrete increases up to 22.20 MPa with 0.8% steel fibre but reduces to 21.45 MPa with 1.0% steel fibre. This increment in compressive strength can be ascribed to the confinement of fibre reinforcement, more than that it has damage effect [13]. Meanwhile, the compressive strength of concrete with 0.4% polypropylene fibre is 20.60 MPa, which decreases to 20.40 MPa when the percentage of polypropylene fibre increases to 0.6%. However, when the amount of the percentage increase fibres up to 1.0%, the compressive strength was reduces. Adding a larger amount of polypropylene fibres does not improve the cracking control [14]. Therefore, the optimum percentages of polypropylene and steel fibres are 0.4% and 0.8%, respectively.

Table 1. Mix Design of Modified Fibrous Foamed Concrete

Mixture	**Foamed Concrete**	**SF Foamed Concrete**	**PF Foamed Concrete**
Cement–Sand Ratio (C/S)	0.5	0.5	0.5
Foamed–Cement Ratio (F/C)	0.7	0.7	0.7
Water–Cement Ratio (W/C)	0.55	0.55	0.55
RHA (%)	40	40	40
Steel Fibre (%)	-	0.8	-
Polypropylene Fibre (Mega Mesh Type) (%)	-	-	0.4

a) Compression Test b) Splitting Tensile test

Fig. 1. Test set up for the cube specimens and cylinder specimens

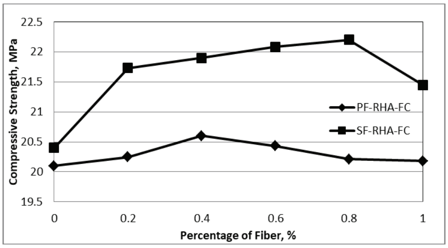


Fig. 2. Compressive Strength of the Modified Fibrous Foamed Concrete

The modified foamed concrete with different fibre percentages shows an acceptable tensile strength (Fig. 3). Jaini et al. [15] stated that the tensile strength of foamed concrete is directly proportional to its compressive strength and is approximately 10 times lower than its compressive strength. Despite that the compressive strength for 1.0% steel fibre reduces, the tensile strength increase by 2% than

0.8% of steel fibre. Polypropylene enhances the tensile strength of foamed concrete but not at a significant level. However, the split tensile strength test results do not yield perfect estimates for the tensile strength of concrete because of the mixed stress field and fibre orientation [16]. Meanwhile, the steel fibres improve the splitting tensile strength through the action of fibre across the cracks in the concrete matrix [17].

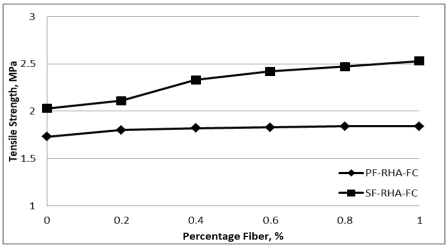


Fig. 3. Tensile Strength of the Modified Fibrous Foamed Concrete

4. EXPERIMENTAL PROGRAMME OF CFHS

4.1. SPECIMEN PREPARATION

A total of 18 CFHS specimens were casted to examine the bond strength of CFHS. A mild steel hollow section was selected for the experimental work. The dimensions of short column is 100 mm (h)×100 mm (b)×350 mm (L) with a thickness (t) of 2 mm and 4 mm as shown in Fig. 4.

The material preparation involved a mixed design to produce high-strength foamed concrete with w/c, cement-sand ratios and foam–cement ratios of 0.55, 0.05 and 0.07, respectively. The amount of fibrous foamed concrete for 1 m^3 of ordinary Portland cement was 500 kg and sand with particles size of 3 mm is 765 kg. Concrete cubes with sizes of 100 mm×100 mm× 100 mm were prepared and subjected under compression test.

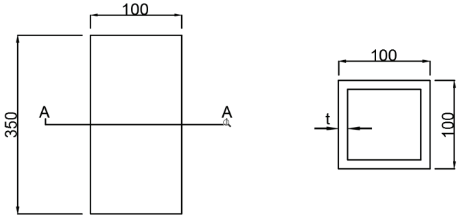


Fig. 4. Cross Section of the Specimen

4.2. MATERIAL PROPERTIES

The strength of the modified foamed concrete (FC) increased along with the addition of fibre. The compressive strength of cube specimens is shown in Fig. 5. The result shows that FC with incorporating RHA as sand replacement and additional fiber improved the compressive strength. However, the highest compressive strength of the modified steel fibre (SF) foamed concrete (FC) (21.7 MPa) was obtained at a density of 1600 kg/m^3. Compared with that in Rahman et al. [18], the modified polypropylene fibre (PF) and steel fibre (SF) used in this study had 12% and 19% higher strengths, respectively. Jaini, Rum and Boon [19] stated that the improvements in compressive strength can be ascribed to the confinement provided by fibre, which increases the bonding of FC.

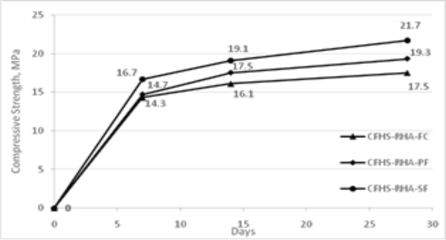


Fig. 5. Compressive Strength of Modified Fibrous Concrete

A coupon test was performed following the BS EN ISO 6892-1 [20] guidelines (Fig. 6). The three (3) specimen for each thickness was subjected to a constant tensile ultimate failure test by using a universal tensile testing machine. The properties of steel were determined through the stress–strain curve. The results are presented in Table 2.

Fig. 6. Tensile Test

Table 2. Tensile Strength of the Steel Hollow Section

Dimensions (h×b×t) (mm)	Length (L) (mm)	f_{yk} (MPa)
100×100×2	350	323
100×100×4	350	376

4.3. PUSH-OUT TEST

A push-out test was conducted to investigate the bond strength of CFHS. The specimen was prepared with a gap of 50 mm at the bottom as shown in Fig. 7. Afterwards, load was applied on the inner concrete, and then the bond–slip failure between the inner concrete and outer steel section was measured. Fig. 8 illustrates the arrangement of the test specimens. A universal testing machine was operated at a minimum speed of 1 mm/min to provide sufficient time for the specimens to fail. The loading rate was maintained, and strain and displacement readings were recorded at each load increment.

Fig. 7. 50 mm Gap at the Bottom of the Specimen

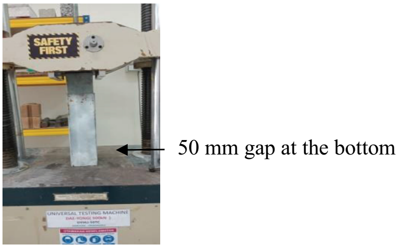


Fig. 8. Axial Compression Test Set Up

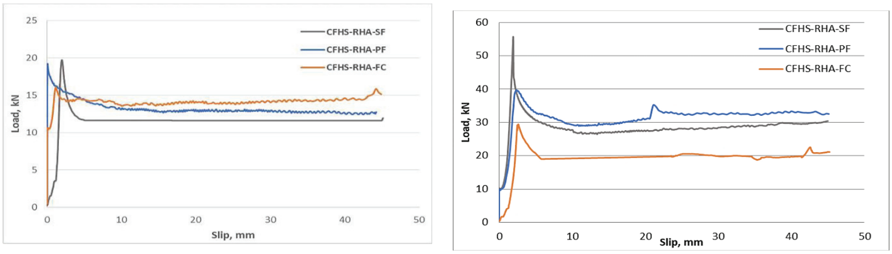
5. EXPERIMENTAL RESULTS

5.1. LOAD–SLIP CURVE

At the initial stage of loading (Fig. 9), the slip of the interface between the steel tube and core concrete was very small. When the load reached the ultimate level, the interface of the CFHS began to slip. When the ultimate bond load (P) was reached, the load–slip curves demonstrated two trends. Firstly, when the ultimate bond load was reached, the curves showed a steady upward trend. Secondly, these curves showed a downward trend after reaching their peaks. When slip occurred between the steel tube and core concrete throughout the whole length of the interface, the chemical bonding action of the whole interface stopped working. When the chemical bonding action, mechanical interlocking action and frictional resistance along the entire interface prior to bond failure were greater than the sum of the mechanical interlocking action and frictional resistance after the bond failure of the entire interface, the load–slip curve exhibited a clear peak point followed by a downward trend [21]

The influence of the specimen cross-section, concrete type and concrete strength may contribute to the enhanced interaction between the steel tube and concrete [22]. The shape of the curve is sensitive to the quality of concrete and depends on several factors, including the casting and hardening conditions, shrinkage and internal reinforcement. When fibre is added in the concrete, the concrete demonstrates a lateral expansion that is restrained by the steel tube [22].

The cross-section of the steel hollow section affects the ultimate strength of CFHS. Fig. 9 shows that the CFHS with SF has a higher bond strength compared with the CFHS with PF and FC because of its concrete area, which contributes to bond strength. When the B/t ratio of the specimen increases, the contact area between the steel tube and core concrete increased whereas the average and ultimate bond strengths of the specimen gradually increased. Roeder et al. [6] attributed this phenomenon to the gap induced by the concrete shrinkage. A larger steel tube indicates the possible formation of a larger gap between the steel tube and concrete. Concrete shrinkage is affected by many factors, especially by the sealing of concrete in a steel tube [21].



2 mm Thickness of Steel Section 4 mm Thickness Steel Section

Fig. 9. Load vs. Slip

5.2. BOND STRENGTH OF CFHS WITH FIBROUS FOAMED CONCRETE

The bond strength between the steel section and concrete was evaluated based on the formula of bond strength, which were computed by dividing the maximum load (kN) by the area of the contact interface. After reaching the ultimate bond strength, the difference became negligible. This result is consistent with the observation of Tao et al. [4] which shows a good bond strength between steel section and concrete core. Table 3 shows that when the concrete strength increases, the bond strength of CFHS also increases due to the shrinkage of the concrete setting and the hardening of the fibrous foamed concrete. At this time, the shrinkage of the core concrete plays a dominant role in the interfacial bond force [21]. The interfacial bond force between the concrete and steel tube was unable to resist the influence of the shrinkage of the concrete setting and hardening.

Meanwhile, the bond strength decreased along with an increasing b/t ratio. Specifically, along with an increasing b/t ratio, the contact area between the steel tube and core concrete increased whereas the average and ultimate bond strengths of the specimen slowly increased. When the specimen thickness was relatively small, a greater restraint force was applied on the transverse deformation of the core concrete at the loading ends under vertical pressure [21].

Table 3. Bond Strength of CFHS with Fibrous Foamed Concrete

Specimens	Thickness (mm)	b/t ratio	Load (kN)	Bond Strength (MPa)
CFHS-RHA-PF	2	50	19.22	0.040
CFHS-RHA-PF	2	50	17.65	0.037
CFHS-RHA-PF	2	50	16.71	0.035
CFHS-RHA-PF	4	25	39.73	0.084
CFHS-RHA-PF	4	25	34.60	0.074
CFHS-RHA-PF	4	25	32.03	0.068
CFHS-RHA-SF	2	50	19.74	0.041
CFHS-RHA-SF	2	50	17.83	0.038
CFHS-RHA-SF	2	50	17.52	0.037
CFHS-RHA-SF	4	25	55.52	0.118
CFHS-RHA-SF	4	25	54.57	0.116
CFHS-RHA-SF	4	25	48.32	0.103
CFHS-RHA-FC	2	50	16.02	0.034
CFHS-RHA-FC	2	50	15.14	0.032
CFHS-RHA-FC	2	50	14.71	0.031
CFHS-RHA-FC	4	25	29.13	0.062
CFHS-RHA-FC	4	25	25.34	0.054
CFHS-RHA-FC	4	25	24.17	0.051

5.3. FAILURE MECHANISM

The core concrete was clearly pushed out with traces of the steel tubes, and then an interface bond force failure occurred as shown in Fig. 10. A careful observation of the specimens after the tests revealed that all core concrete did not show obvious cracking. A small amount of concrete debris was produced at the loading ends of the specimens.

a) Front view b) Top view

Fig. 10. Specimens Failure

6. CONCLUSIONS

An experiment was conducted on CFHS with modified foamed concrete to determine their bond strength. Two types of fibres were used as additional materials to enhance the compressive strength of the modified foamed concrete. The experimental results show that amongst the tested specimens, the CFHS-RHA-SF obtains the highest bond strength due to the mechanical interlocking between the concrete core and steel tube. The failure mechanism of all specimens also leaves a small amount of concrete debris at their top end. The factors that influence bond strength include core concrete strength and width–thickness ratio.

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