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INTERACTION BETWEEN COLD-FORMED STEEL AND LIGHTWEIGHT FOAMED CONCRETE WITH VARIOUS CEMENT CONTENT

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Abstract: The bonding strength to hold lap slice between concrete and its reinforcing steel is the essential requirement of reinforced concrete and steel-concrete composite structures. In this paper, the compressive strength of lightweight foamed concrete with designated density at 1500 ±50 kg/m^3, by various cement-sand ratio and their respective interaction with cold-formed steel are investigated experimentally. The consistency and stability of lightweight foamed concrete are also examined towards the use of bulk sand. The results show that the compressive strength of lightweight foamed concrete increases with the increment of the cement content. For bonding strength between lightweight foamed concrete and cold-formed steel, specimens with holes in cold-formed steel sheets acting as shear connector exhibit higher pull-out strength. Moreover, the pull-out strength increases in-line with the increment of compressive strength of the lightweight foamed concrete. From the obtained results, lightweight foamed concrete with 5:1 cement-sand ratio exhibits highest compressive strength of 9.387 MPa and pull-out strength of 1.025 MPa with cold-formed steel, where holes exist as shear connector.

Keywords: *Lightweight, foamed concrete, cold-formed steel, compressive strength, pull-out strength*

1.0 Introduction

Concrete is a commonly used construction material for many centuries. It is a compound material that essentially obtained by mixing the binder (cement), aggregate and water with certain designed proportion. Conventional normal weight concrete is dense, hard, strong and durable. The density of normal weight concrete is in the range of 2000 kg/m^3 to 2600 kg/m^3. In certain construction which requires large volume of concrete casting, long span structures, or precast concrete members that need transportation to the construction site, this heavy self-weight of normal weight concrete may be inconvenient.

With the aim towards lighter and sustainable construction, lightweight foamed concrete is introduced as an innovative product, which provides light density ranging from 1000 kg/m^3 to 1600 kg/m^3, together with other advantages e.g. better fire protection, thermal and sound insulation etc. (Lim *et al*., 2013).

Lightweight foamed concrete has been used around world since 1920 with the compressive strength were not critical but limited application (Nayak and Jain,2012). It is referred to a premixed cement paste or mortar with minimum volume of 20% air-voids entrapped in the mortar by using appropriate foaming agent (Awang *et al*., 2012). Lightweight foamed concrete has its advantages in high flowability, low self-weight, minimal consumption of aggregate, controlled strength and excellent thermal insulation properties (Ramamurthy *et al*., 2009). The density of lightweight foamed concrete is governed by the quantity of pre-formed foam. With proper control in amount of stable foam and methods of fabrication, a wide range of densities of lightweight foamed concrete could be formed and hence providing many structural and non-structural application such as floor screed, partition, insulating materials and filling grades. Furthermore, lightweight foamed concrete also facilitates the benefits of self-levelling, where compaction or vibration is not required during the concrete casting work.

Design strength of lightweight foamed concrete normally decreases to the reduction of density. In order to strengthen lightweight foamed concrete for appropriate use in load-bearing structural element e.g. precast slab and wall panels, cold-formed steel section has been introduced to replace the used of reinforcement steel bar inside the concrete. Unprotected reinforcement steel bar embedded inside the lightweight foamed concrete, which the voids are interconnected, would be at risk of carbonation even when the external attack is not very severe. Carbonation is one of the main causes of aging deterioration and corrosion of the reinforcement steel. The reaction of the carbon dioxide at atmosphere and the hydrated cement compounds leads to concrete carbonation (Ramezani *et al*., 2013). Thus, replacement of cold-formed steel section as reinforcement in the reinforced lightweight foamed concrete structures is a good solution as the cold-formed steel section has the corrosion protection by the zinc and zinc alloy coatings (Bellezze *et al*., 2011). For reinforced concrete element, the bonding strength between concrete and reinforcing steel is the fundamental problem that will influence the structural behaviour of the composite material. The bond between interface properties and slip between the concrete and the reinforcing steel is the key element for the ultimate load-carrying capacity of the reinforced concrete structures. It will affect the anchorage of the reinforcing steel and the strength of the lap slices (Ramezani *et al*., 2013). Thus, this study aims to investigate the effect of different cement content of lightweight foamed concrete towards the pull-out test with cold-formed steel strips. The investigation is carried out by two series of experimental studies, where the compressive strength and pull-out strength are determined from each series of test with various cement-sand ratios.

2.0 Experimental Programme

2.1 Material Preparation

Ordinary portland cement (OPC) conforming to BS EN 197-1:2011 (Bristish Standard Institution, 2011) manufactured by Tasek Corporation Berhad was used for all the lightweight foamed concrete specimens. River sand was used as fine aggregate. The sand was taken directly from the bulk condition, which was exposed to natural weathering. Figure 1 shows the particle size distribution grading of sand used in this study. Normal tap water and a locally manufactured synthetic-based foaming agent were used to produce premixed foam for the lightweight foamed concrete.

Cold-formed steel strips were cut from cold-formed steel channel section with the strip length of 600 mm, 50 mm width and 1.6 mm thickness. The cold-formed steel section was manufactured by Kemuning Structures Sdn Bhd with steel grade S450, i.e. design strength of 450 MPa.

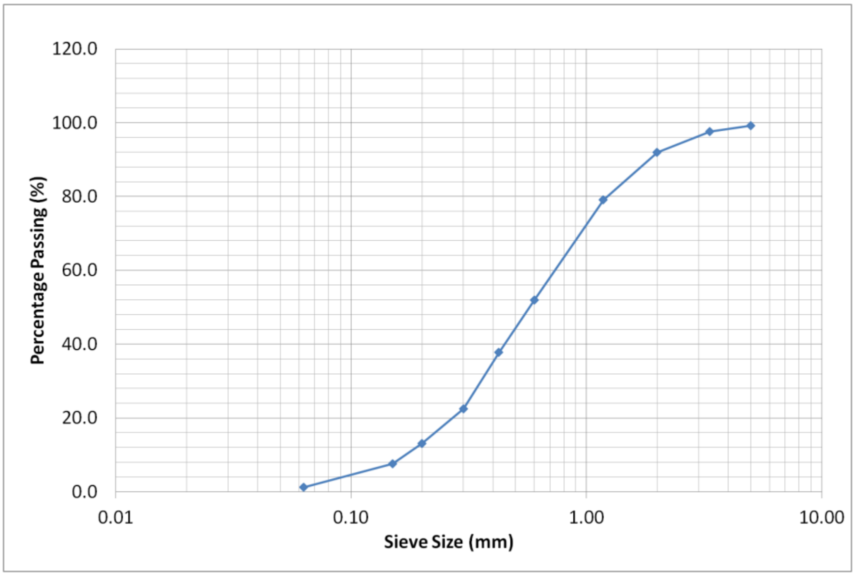

Figure 1: Particle size distribution grading of river sand used

2.2 Test Specimens

Two series of test specimens were investigated. For the first series, three different cement-sand ratio for lightweight foamed concrete, i.e. 3:1, 4:1 and 5:1 (designated as C31, C41 and C51 respectively) were prepared. The base mix proportion detail was based on 1 m^3 of each designed cement-sand ratio of lightweight foamed concrete specimens as shown in Table 1. Moreover, the designated density has been fixed at 1500 kg/m^3 with ± 50 kg/m^3 as it is acceptable in accordance to typical industrial practice in the manufacture of foamed concrete (Jones & McCarthy, 2005). Stable foam with density of 45 kg/m^3 was produced by using dry pre-foamed method (Aldridge, 2005). The foaming agent was diluted with water in a ratio by weight of 1:30. The amount of added foam in the mortar mix is depended on the designated density of foamed concrete.

For series 2 specimens, pull-out tests for cold-formed steel strips embedded in lightweight foamed concrete are carried out. The study covered the effect of two parameters, i.e. pull-out strength for cold-formed steel strips with holes of 12.5 mm diameter as shear connector and plain strips without holes (as shown in Figure 2), and the effect of the pull-out strength for lightweight foamed concrete with different design mix.

Table 1: Mix proportion and summary work details with density unity at 1500 kg/m^3

MIX PROPORTION					
Mix Designation	w/c	Cement (kg)	Sand (kg)	Water (kg)	*% Foam
C31	0.34	896	298.7	304.6	2.1
C41	0.35	938	234.5	328.3	2.7
C51	0.35	968	193.6	338.8	1.9

Note:
1. *All the specimens were cure by totally immersed in water after 24 hours of casting, at the room temperature.*
2. *w/c = Water-cement ratio based on the optimum 7-day strength for trial mix of each mix designation.*
3. **% Foam used was based on the total weight of solids(cement and sand).*

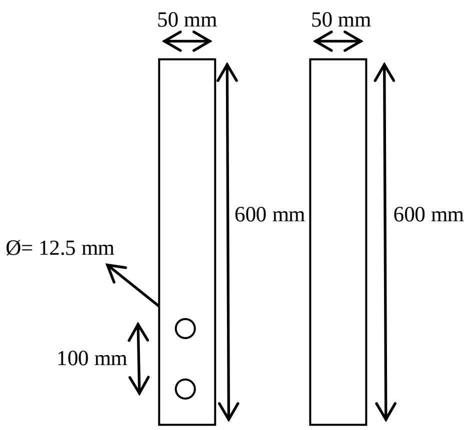

Figure 2: Configuration of Cold-formed steel strips

2.3 Preparation and Casting Work of Foamed Concrete Specimens

Lightweight foamed concrete was obtained initially with the preparation of mortar as base mix, followed by foam preparation and finally mixing the foam with the mortar base mix. The foam was prepared by diluting the foaming agent with water and poured into the chamber of a locally fabricated foam generator. Stable foam as shown in Figure 3 was produced through the nozzle of the foam generator with compressed air pressure of 0.5 MPa consistently supplied to the foam generator. Prior to the introduction of foam, the density of mortar was determined to ensure accurate amount of foamed that need to be added. Flow table test was performed to check the workability of the base mix mortar. Base mix with low water content will be too dry, causing the burst out of the bubble in foamed concrete and hence affect the density and strength of the lightweight foamed concrete (Ramamurthy, *et al*., 2009).

Figure 3 : Produced stable foam

The required amount of foam was then measured by weight and added into the base mix mortar. Afterwards the mix were blended uniformly, and the foamed concrete was measured for its bulk density by pouring the foamed concrete into a known volume container and weighed. When the lightweight foamed concrete has reached to the designated density, it was poured into mould with cube size of 70.7 × 70.7 × 70.7 mm for compressive test specimens; and mould with size 200 × 200 × 200 mm together with embedded cold-formed steel strips stand vertically in the middle of the mould for pull-out test specimens. The casting work for each set of different cement-sand ratio was carried out in the same batch to ensure the homogeneity for both compressive test and pull-out test. The fresh lightweight foamed concrete was then left to set for 24 hours before de-moulding, and all specimens proceed to water curing process until the respective testing ages of 7 days and 28 days.

2.4 Testing Method

2.4.1 Fresh Properties

The inverted slump test as shown in Figure 4, was conducted to determine the consistency of the foamed concrete in accordance with BS EN 12350-8:2010 (Bristish Standard Institution, 2010). After mixing of the mortar with stable foam, the produced lightweight foamed concrete was filled into the inverted slump flow cone without compaction and vibration. The cone is raised and allowed the foamed concrete to spread freely. The spread diameter values were measured with a measuring tape in orthogonal direction. Average value was taken to control the fluidity consistency of the fresh mixed lightweight foamed concrete.

Figure 4:Inverted slump test for lightweight foamed concrete

2.4.2 Compressive Strength

The compressive strength test was performed in accordance to BS EN 12390-3 (Bristish Standard Institution, 2009) by using a universal compression test machine with constant loading rate of 0.1 kN/s. Cube specimens with 70.7 × 70.7 × 70.7 mm dimension were tested. The compressive strength was obtained based on the average of three crush cubic specimens. Figure 5 shows the setup of compressive strength test.

Figure 5: Compressive strength test setup

2.4.3 Pull-Out Test

Pull-out tests was used to evaluate the shear bonding strength between the steel and the lightweight foamed concrete. It was performed for the lightweight foamed concrete mixtures with 1500 kg/m^3 density by using stable foam concrete compositions. The specimens dimension 200 × 200 × 200 mm for steel strip 50 mm in width was prepared. The steel strips were standing in the middle of the specimens and embedded 200 mm into the lightweight foamed concrete.

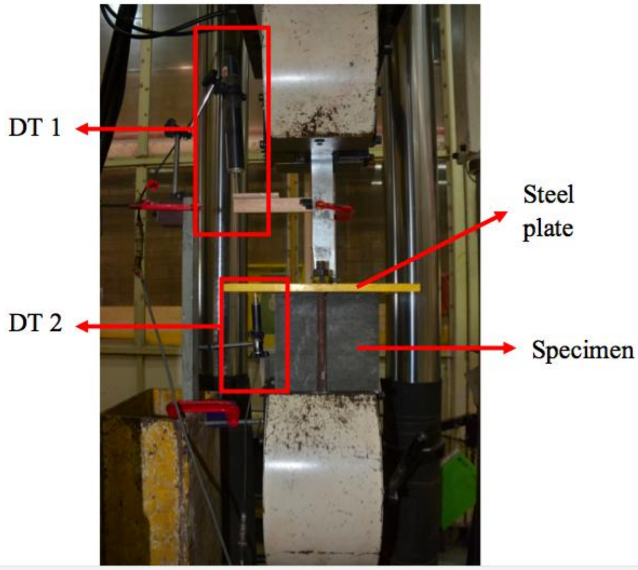

Figure 6: The test setup of the pull-out test.

A typical pull-out test setup is shown in Figure 6 in accordance to previous research (Fava *et al.*, 2013). Universal testing machine with maximum load capacity of 300 kN was used with the ram velocity for all tests was set at 0.01 mm/s to allow slow deformation of steel strips and concrete. Two displacement transducers namely DT1 and DT2 are placed to measure the relative displacement between steel strip and lightweight foamed concrete, and to ensure the static of concrete block during the test. The different of the two relative displacements recorded from the two DTs provides the slip between the steel strip and the lightweight foamed concrete block.

3.0 Results and Discussion

3.1 Consistency, Stability and Compressive Strength

Since the lightweight foamed concrete mix intended for large-volume casting, bulk production of lightweight foamed concrete may be needed. The raw material for lightweight foamed concrete such as sand is directly taken from the bulk that was exposed to natural weathering and without dry or sieve process. Therefore the consistency and stability check are needed to make sure the mixed was considered stable, where the density ratio was kept nearly to unity (Nambiar & Ramamurthy, 2008). Table 2 shows the result of consistency and stability based on 28-day concrete cube.

Table 2: Results of consistency and stability

Specimen	W/C	Consistency	Stability	Inverted slump cone spread value (mm)	Performance index
C31	0.34	0.94	0.96	510	4.44
C41	0.35	0.97	0.86	438	4.71
C51	0.35	0.96	0.89	475	5.80

Note:

1. *w/c = Water-cement ratio based on the optimum 7-day strength for trial mix of each mix designation.*
2. *Consistency = proportion of measured fresh density to designated density (1500 kg/m^3)*
3. *Stability = proportion of measured fresh density to measured hardened density.*
4. *Inverted slump cone spread value = average diameter measured from four different angle.*
5. *Performance index = proportion of 28-day compressive strength to the unit density (1000 kg/m^3)*

For consistence mix, the produced fresh density of foamed concrete are suppose to be ± 50 kg/m^3 difference corresponding to designated density, which the consistency is in the range of 0.97 to 1.03 (Jones & McCarthy, 2005). From the result shown in Table 2, the consistency was at the low margin, especially for sample C31 as the additional of foam was too much during mix into the mortar. However, sample C31 exhibit the stability nearest to unity among the samples. The low stability of sample C41 and C51 may due to the mixture is a bit dry as compared to C31, as the inverted slump cone spread value is much lower than C31. C41 had the lowest value for inverted slump cone spread value.

Dry mixture caused burst out of the bubble inside the lightweight foamed concrete during the hardenend process. It also caused the highest amount of foam added into the mix as shown in Table 1, in order to control the consistency in the range of 0.97 to 1.03. The burst out made the concrete denser after hardening and hence influece its stability. Besides that, the sand taken from bulk without sieve may leads to large variation size of sand. Large size variation of fine aggregate as shown in Figure 7, could cause burst out of the bubble of stable foam. Furthermore, non-uniform size of aggregate would entrap large amount of foam bubble, which later create larger void in the lightweight foamed concrete. These factors lead to the inconsistancy and fluctuation of the 7-day compressive strength as shown in Figure 8. Morever from Figure 8, it is shown that the 28-day compressive strength of lightweight foamed concrete is more consistent, and is increasing with the increment of cement content. Higher cement content in foamed concrete, resulted production of more C-S-H gel that can imposed to additional load bearing.

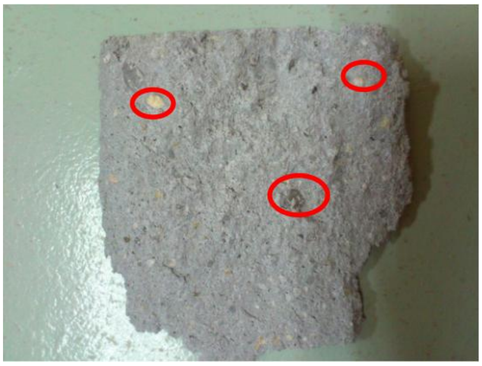

Figure 7: Coarser sand inside the lightweight foamed concrete specimens

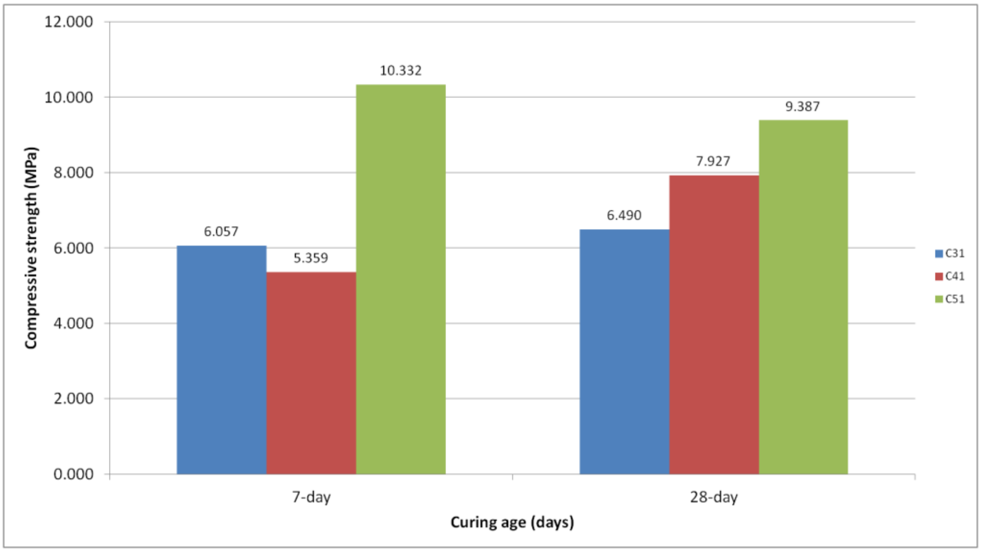

Figure 8: Result of compressive strength with respective different cement content

3.2 Pull-Out Test

The main purpose of carrying out the pull-out test was to find the interaction between the steel strips with holes, which act as shear connector, and lightweight foamed concrete. Steel strips without hole were used as control samples to find out the bonding effectiveness of the shear connector to the lightweight foamed concrete. Six specimens for each single set of strip design were prepared and tested to determine the bonding strength during pull-out tests. The total hole area was 245.44 mm^2 with two holes of 12.5 mm diameter. Table 3 shows the result of average maximum load and pull-out strength with respective cement content of lightweight foamed concrete. The specimens were tested after 28-day curing and the concrete strength is based on 28-day compressive strength as shown in Figure 8. From the result in Table 3, the pull-out strength increased as the increment of the strength of lightweight foamed concrete. This has shows that the higher compressive strength of the lightweight foamed concrete contribute to higher bonding between the steel strips with and without holes.

As illustrate in Table 3, it also can be seen that specimens with steel strip with hole exhibit higher pull-out strength than steel strips without hole. There are about 4.89%, 25.15% and 5.67% increase for each respectively specimens C31, C41 and C51. The existing of shear connector create a uneven of steel strip surface that create friction force during the pull-out force applied and hence additional force needed to pull-off the steel strip with hole from the lightweight foamed concrete. However, specimens without hole had the displacement at maximum load, which can be consider as slip value for steel strip, lower than that of the specimen with holes. This shows that even though the steel strip with hole at maximum load had higher displacement, but with the existing of hole in the steel strip it gives the later strength toward the specimens as the holes create the friction to hold the extra loading before it totally failed to resists any additional loading. Figure 9 shows the failure mode of the specimens. At failure, the steel strip that embedded inside the lightweight foamed concrete will be pulling-off as the hole at the steel strip can be seen as shown in Figure 9(a). Figure 9(b) and Figure 9(c) show the side of the lightweight foamed concrete specimens after failure occur with the foamed concrete block crack or split into half.

Table 3: Result of average maximum load and strength for pull-out test with respective cement content

Specimen	Cold-formed steel strip without holes			Cold-formed steel strip with holes		
	Maximum load (kN)	Displacement at maximum load (mm)	Pull-out strength (MPa)	Maximum load (kN)	Displacement at maximum load (mm)	Pull-out strength (MPa)
C31	18.4	1.06	0.920	18.8	0.42	0.965
C41	16.3	0.75	0.815	19.9	3.01	1.020
C51	19.4	0.66	0.970	20.0	1.28	1.025

Note:
The contact area for cold-formed steel strip without holes is 20000 mm^2 whereas the contact area for steel strip with holes is 19509.12 mm^2.
The values performed in the table are the average value from the six samples for each single set of variation cement-sand ratio specimen

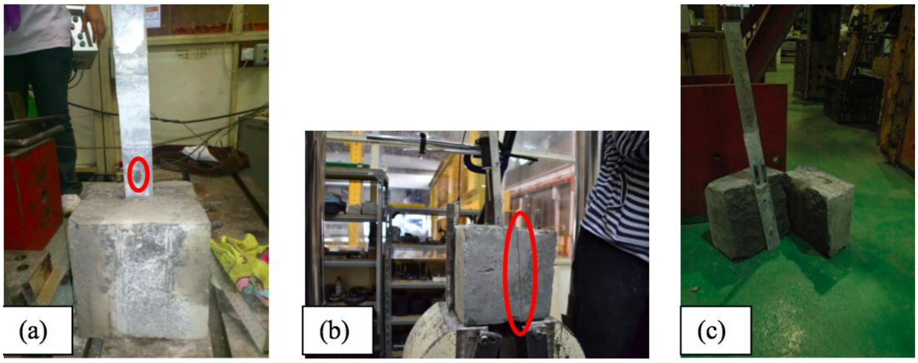

Figure 9: The failure mode of the specimen

4.0 Conclusions

The compressive strength of lightweight foamed concrete with various cement-sand ratio and its effect towards the shear bond strength with cold-formed steel strips are investigated. Several conclusions can be drawn from the laboratory study:

1. Lightweight foamed concrete with density of 1500 kg/m^3 achieve design strength between 6.495 MPa to 9.387 MPa.

2. Unsieved sand as filler for lightweight foamed concrete gives low stability to the designated density as larger sand size or coarse aggregate could affect the forming of stable foam in lightweight foamed concrete.

3. Lightweight foamed concrete with cement-sand ratio of 3:1, 4:1 and 5:1 are investigated. The 28-day compressive strength increases in-line with the cement-sand ratio. Highest compressive strength occurred at samples with cement-sand ratio of 5:1, and thus it is taken as the optimum design within the scope of study.

4. Provision of holes act as shear connector on cold-formed steel strips give better pull-out strength as compared to plain steel strip without holes. The strength increment range from 4.89% to 25.15%.

5. There is a trend of pull-out strength increment in-line with the increment of compressive strength. The highest pull-out strength is 1.025 MPa with the cement-sand ratio of lightweight foamed concrete at 5:1.

5.0 Acknowledgements

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