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STRUCTURAL BEHAVIOUR OF SHORT-SPAN REINFORCED CONCRETE BEAMS WITH FOAMED CONCRETE INFILL

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ABSTRACT

This paper presents the novel application of foamed concrete as infill for reinforced concrete beam. The combination of foamed concrete infill and normal concrete beam produces composite-based-concrete-structure that has an advantage due to the lighter weight. This system of the beam become an ideal situation to reduce the weight and as material saving without having to compromise on its strength and serviceability. In this study, the beam specimens were designed with a dimension of 1100 mm length, 200mm depth and 150mm width. The foamed concrete infill has a size of 1000mm length, 125mm depth and 25mm width. The depth of foamed concrete infill is setup at 100mm, 125mm and 140mm. All beam specimens were tested under four-point bending test to obtain the load-deflection profile and failure modes. Meanwhile, cube samples were also prepared for both normal concrete and foamed concrete. The compressive strength of normal concrete and foamed concrete achieved the target of 21.3MPa and 8.3MPa respectively. The ultimate load of reinforced normal concrete beam, reinforced concrete beam with foamed concrete infill and reinforced foamed concrete beam are 62.07kN, 53.11kN and 27.84kN, while the deflections are 9.6mm, 2.1mm and 1.9mm. Although the strength of reinforced concrete beam with foamed concrete infill is lower than reinforced normal concrete beam, but it poses high serviceability.

Keywords: foamed concrete infill, reinforced concrete beam, ultimate load.

INTRODUCTION

Concrete is one of the important materials in the construction industry. Because of its flexibility in exploitation and sustainability toward the environment as well as can be easily recycled, concrete still a preferable material compared to timber, steel or composite. Moreover, structures that built in from concrete materials can have a long service life. Concrete is reinforced with steel bars to produce composite responses and thus able to sustain all types of actions. Normally, concrete has a density around 2400kg/m^3 that would become weight penalty in larger open floor plans and high-rise buildings. This issue remains a major problem in the construction industry and still become the main interest among researchers and engineers, especially in reducing the weight of concrete by creating a lightweight concrete.

Lightweight concrete structures are desirable particularly when dealing with large open floor plans and high-rise buildings. Lightweight aggregate concrete and foamed concrete have become the recent innovative materials that can potentially be used to reduce the weight of normal concrete. Foamed concrete has low densities around 800kg/m^3 to 1800kg/m^3, high workability and self-compacting that make foamed concrete very attractive for many construction applications. However, the wider use of foamed concrete as structural elements seem to have been inhibited by its technical and engineering unfamiliarity as well as a perceived difficulty of achieving sufficient high strength. Still, foamed concrete has been successfully applied to walls, floor-steel decking systems, precast panels, sandwich panels and hollow core planks.

Moreover, foamed concrete can also be used as infill materials especially for sandwich panels. However, the application of foamed concrete as beam, column or slab that seizes direct actions is still under investigations. This study intends to investigate the behaviour of short-span reinforced concrete beams with foamed concrete infill in term of ultimate load and. The combination of normal concrete and foamed concrete with steel reinforcements produces composite condition on the beam that offer many advantages. This system of the beam not only contributes to the weight saving but also toward green and sustainability. Furthermore, the relation of the ultimate load with infill thickness and failure modes were also discussed. The results of this study will help the extension and manipulation of foamed concrete to another great potential of structural elements.

INFILLED REINFORCED CONCRETE BEAM

In reinforced concrete structures, the material properties, weight and structural geometric are put into the indicator of performance and serviceability. Basically, concrete is highly designed to carry compression while steel reinforcements transfer tension stress and loading. The relationship between tension stress and strain in a normal concrete cross-section is almost linear at small values of stress. However, if the stress higher than about 40% of the compressive strength, the tension stress and strain become increasingly affected by the formation of micro-cracks at the interface between the cement and coarse aggregate (Warner *et al*., 1998).

The micro-cracks also initiate around the bonded region of steel reinforcements and concrete. The inner part of the reinforced concrete structure under the neutral axis only acts as a passive volume that has a small contribution on the crack and failure resistances. However, the deformation of reinforced concrete structure still largely depends on the whole volume of structure that basically can be investigated using flexural or shear capacity tests. The relation of strain and stress, as can be seen in Figure-1, is useful to understand the behaviour of reinforced concrete structure.

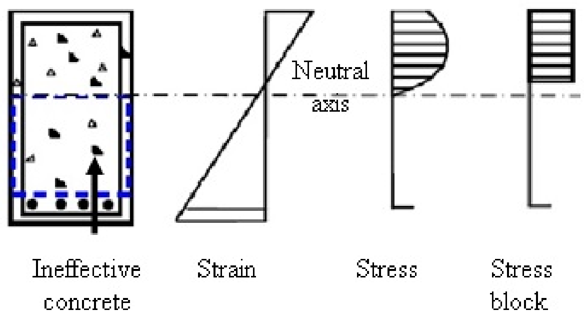


Figure-1. Strain and stress diagrams of reinforced concrete beam (Vimonsatit *et al.,* 2012).

Concrete has low tensile strength, therefore when a reinforced concrete structure is subjected to flexural or shear, the concrete area under the neutral axis of cross-section is considered ineffective when it is in tension at the ultimate limited state. Therefore, the ineffective volume of reinforced concrete structure can be replaced by another material, in many-sided and interest, the foamed concrete block or prefabricated lightweight concrete is highly likely to be used. Consequently, it produces a lighter and compositeness reinforced concrete structure. Although the use of foamed concrete block to replace the ineffective volume of normal concrete structure offer advantageous to the structural system, but the performance of the structure still unclear.

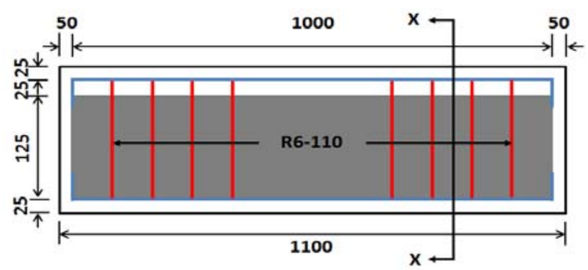
The potential of foamed concrete as beam element was investigated by Jones and McCarthy (2005) where the foamed concrete beam behaves satisfactorily in term of failure load and deflection. Meanwhile, Jumaat *et al.* (2009), Shafigh *et al.* (2011) and Juan (2011) investigated the strength of reinforced foamed concrete beam and found that the strength behaves similar manner or higher than the normal concrete beam. Although foamed concrete has great potential to be utilised as beam element with steel reinforcement, the main drawback is that the foamed concrete has low corrosion resistance due to the presence of air voids.

Therefore, Vimonsatit *et al.* (2012) introduced the lightweight sandwich concrete beam that is a combination of normal concrete with autoclaved aerated concrete as core infill. The failure load of the normal concrete beam and the lightweight sandwich concrete beam was found to be of insignificantly different. Further study conducted by Wahyuni *et al.* (2013) also reveals that the load-deflection profile of lightweight sandwich concrete beam has similar trend as a normal concrete beam. On the other hand, Mokhatar *et al.* (2015) utilized the infilled concrete beam containing lightweight polyethylene concrete block and investigate the dynamic behaviour of the beam. It was observed that the residual displacement of the beam is significantly lower than the normal concrete beam.

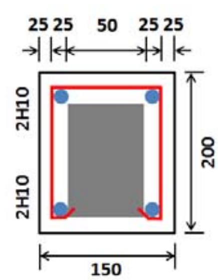
EXPERIMENTAL STUDY

Design of reinforced concrete beam with foamed concrete infill

The design of reinforced concrete beam with foamed concrete infill was based on Eurocode 2 (2004). The beam has a dimension of 1100mm length, 200mm depth and 150mm width. Meanwhile, the foamed concrete infill has a size of 1000mm length, 125mm depth and 50mm width. In order to investigate the thickness effect of foamed concrete infill, the depth was varied at 100mm, 125mm and 140mm. The nominal cover is 25mm. The beam is reinforced by doubly longitudinal bars with diameter of 10mm and stirrups of R6-110. The characteristic strength of steel is 500MPa and 250MPa for the longitudinal bar and stirrups respectively. The details about the design of reinforced concrete beam with foamed concrete infill can be referred in Figure-2.



a) Front view



b) Cross-section X-X

Figure-2. Schematic design of reinforced concrete beam with foamed concrete infill.

Materials preparation

Normal concrete was designed to achieve a compressive strength of 20MPa at 28 days of curing process. Meanwhile, foamed concrete has targeted density of 1400kg/m^3. Thus, the ratio of mix proportion is according to 0.5:1:2 for water, cement and sand. The details of the mixture for both normal concrete and foamed concrete can be referred in Table-2.

Table-1. Mix design of normal concrete and foamed concrete.

W/C ratio	Cement (kg)	Coarse aggregate (kg)	Sand (kg)	Foam agent (L)
Normal concrete				
0.65	25	97	79	-
Foamed Concrete				
0.50	50	-	100	0.25

Note: Maximum size of coarse aggregate is 20mm while sand is 2mm. The total amount of water is 16.30 litres for normal concrete and 31.25 litres for foamed concrete.

Specimen preparation

A total ten (10) beam specimens were cast that involving six (6) reinforced concrete beams with foamed concrete infill, two (2) reinforced normal concrete beams and two (2) reinforced foamed concrete beams. In addition, cube samples of normal concrete and foamed concrete were also prepared for the compression test. The cube samples were cast using the mould of $150\text{mm} \times 150\text{mm} \times 150\text{mm}$ for normal concrete and $100\text{mm} \times 100\text{mm} \times 100\text{mm}$ for foamed concrete. The cube samples of normal concrete were undergoing water curing process at 7, 14 and 28 days while cube samples of foamed concrete were placed at the ambient atmosphere.

Laboratory testings

The tests that were conducted include a slump test for fresh normal concrete, compression test for cube samples and four-point bending test for beam specimens. The slump test was carried out immediately after the mixing of normal concrete. The value of slum is $70 \pm 10\text{mm}$ and the obtained failure is a true slump. The compression test was conducted to cube samples of normal concrete and foamed concrete at 7, 14 and 28 days of curing age. Figure-3 shows the compression test that was conducted for the cube samples of normal concrete and foamed concrete.

On the other hand, the beam specimens were tested using the four-point bending test to determine the ultimate load, deflection and failure modes. The test requires a load cell to impose load on the beam specimen and deflectometer to accurately measure the deflection at the few points on the beam specimen. In this experimental study, three (3) linear variable displacement transducers (LVDT) were used to measure the deflection at the mid-span and point load (left and right) of beam specimens. Figure-4 shows the arrangement of beam specimen for four-point bending test.

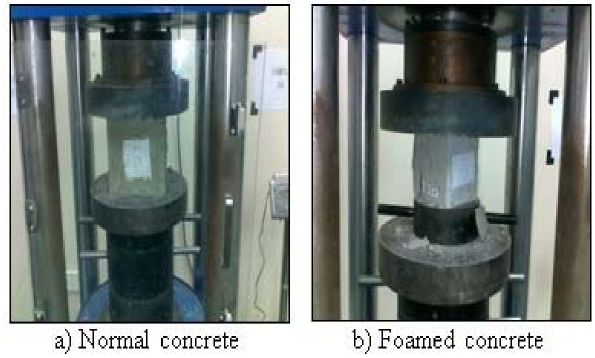


Figure-3. Compression test for cube samples.

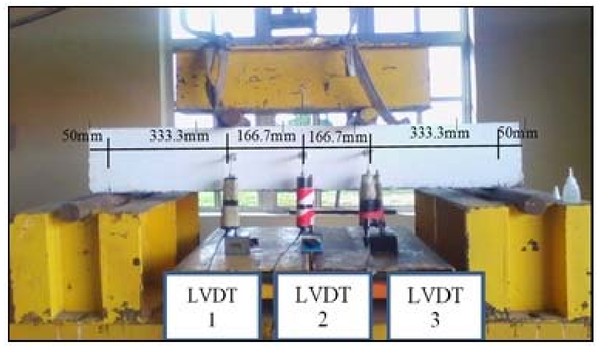


Figure-4. The four-point bending test.

EXPERIMENTAL RESULTS

Compressive strength

The results of compressive strength for normal concrete and foamed concrete at 7, 14 and 28 days is shown in Figure-5. It can be observed that the strength development for both normal concrete and foamed concrete is similar by exhibiting the significant increase in the strength with respect to curing age. However, the compressive strength of normal concrete is higher than foamed concrete approximately by 65.60%, 72.82% and 61.03% at7, 14 and 28 days respectively. At the age of 28 days, normal concrete achieved the compressive strength of 21.30MPa that is the targeted characteristic strength. Meanwhile, the compressive strength of foamed concrete at the age of 28 days is 8.30MPa.

According to Aldrige (2000), the compressive strength of foamed concrete for the water-cement ratio of 0.5 is around 6.0MPa to 8.0MPa. Similarly, the British Cement Association (1994) suggested that the compressive strength of foamed concrete with density 1400kg/m^3 is around 6.0MPa to 8.0MPa. In addition, Brady *et al*. (2001) specified that foamed concrete with density 1400kg/m^3 should has compressive strength at the range of 5MPa to 10MPa regardless the water-cement ratio. Therefore, the compressive strength of both normal concrete and foamed concrete have achieved the standard requirement for the beam specimens.

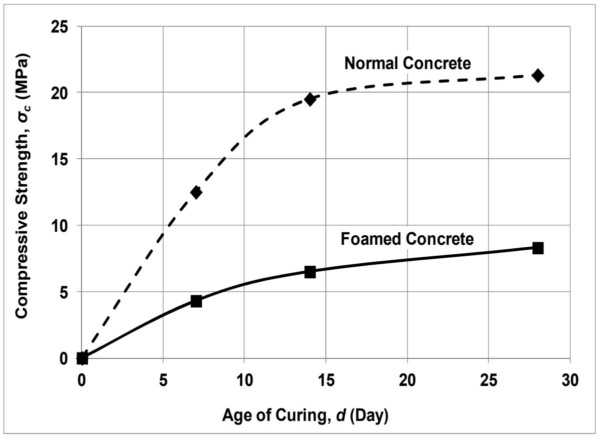


Figure-5. Compressive strength of normal concrete and foamed concrete.

Load-deflection profile

The relation of ultimate load and mid-span deflection of the beam specimens is depicted in Figure-6. It is should be noted here that NFCR refers to the reinforced concrete beam with foamed concrete infill, while NCR and FCR are reinforced normal concrete beam and reinforced foamed concrete beam respectively. The results showed that the NCR beam experiences highest ultimate load at 62.07kN. The ultimate load of NFCR beam is 53.11kN which indicates 14% lower than the NCR beam, while FCR beam only achieves 27.84kN. Although the ultimate load of NFCR beam is lower that NCR beam, but the mid-span deflection is within the serviceability limit. The maximum allowable deflection based on the standard design of L/250 is 4.4mm. Therefore, only NFCR and FCR beams pass the serviceability requirement while NCR beam is noticeably exceeding the maximum allowable deflection.

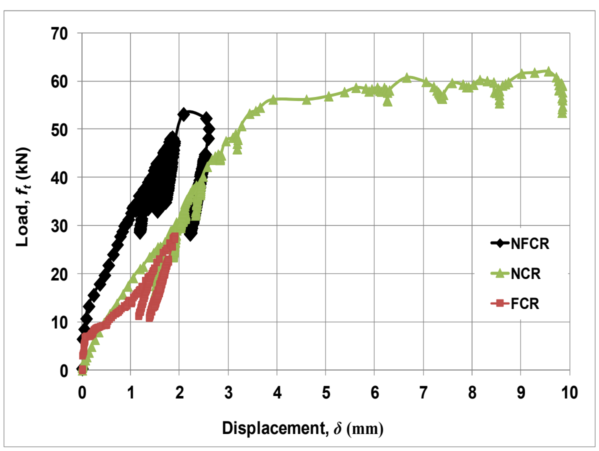


Figure-6. Load-deflection profile of beam specimens.

Besides that, the first crack load of NFCR beam is slightly higher than NCR beam. This happens due to the compositeness condition between normal concrete and foamed concrete. In addition, foamed concrete is well known as good absorbing energy, and thus the crack initiation occurs in very low rate. However, it is also observed that the NFCR beam exhibits high stiffness in the range of elastic phase. This situation shows that the NFCR beam behave more brittle than NCR and FRC beams. The high stiffness that experienced by the NFCR beam probably due to the weak interface interaction and bond between normal concrete and foamed concrete. The summary of ultimate load and deflection of the beam specimens can be seen in Table-2. Based on these results, the NFCR beam has potential to be applied as a structural element without compromise with its strength and serviceability.

Table-2. Summary of ultimate load, first crack load and deflection.

Specimen	f_s (kN)	f_{lc} (kN)	δ_{ms} (mm)	δ_{cp} (mm)
NFCR	53.11	29.22	2.10	1.85
NCR	62.07	21.53	9.56	7.88
FCR	27.84	7.69	1.90	1.43

Note: f_s is the ultimate load, f_{lc} is the first crack load, δ_{ms} is the deflection at the mid-span of the beam, and δ_{cp} is the deflection at the point load.

Effect of infill thickness

The relation between the thickness of foamed concrete infill and the ultimate load is depicted in Figure-7. The relation is linear through the infill thickness. The results showed that the ultimate load of NFCR beam with infill thickness of 100mm and located below than neutral axis is higher at 56.78kN. It is proved that the concrete volume under the neutral axis can be considered ineffective and only acts as passive volume. Meanwhile, the infill thickness of 125mm and 140mm that located above the neutral axis of beam contribute the ultimate load of 53.11kN and 48.18kN. It is found that when the depth of infill increases, the ultimate load decreases. Ironically, the deflection also decreases and gave high serviceability limit.

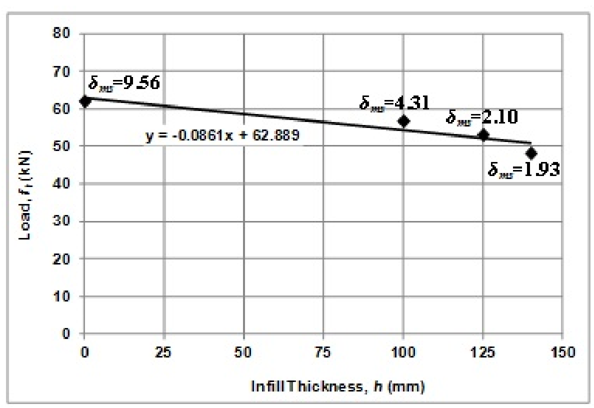
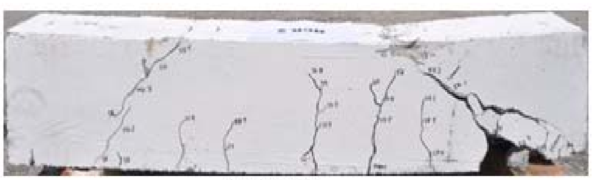


Figure-7. Relation of ultimate load with infill thickness.

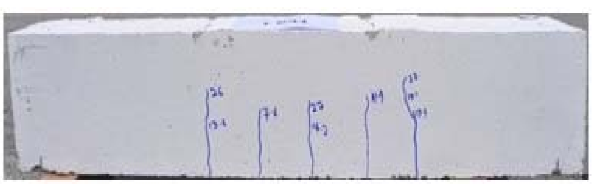
Failure modes

The beam specimens under four-point bending test predominantly experience flexural-tension and shear cracks. The failure modes for NFCR, NCR and FCR beams can be seen in Figure-8. The cracks in NFCR beam propagate as tension crack from the bottom zone that led to the flexural-shear cracks at the ultimate load. At the end of the test, the cracks appear only as hairy cracks at the surface of the normal concrete. There is no observation whether the foamed concrete infill experiences any failure. The failure mode of NCR beam started in the form of flexural-tension cracks. The cracks then propagate vertically from the tension zone to compression zone, followed by diagonal-tension cracks. Suddenly, the dowel cracks happen due to the shear cracks and the beam experiences total failure. For the FCR beam, the failure mode is dominant by the hairy cracks in the form of flexure-tension cracks and without total rupture. The hairy cracks only occur at the mid-span of the beam which is similar as observed by Jones and McCarthy (2005).

a) NFCR beam



b) NCR beam



c) FCR beam

Figure-8. Failure modes of beam specimens under four-point bending test.

CONCLUSIONS

An experimental study was conducted on the structural behaviour of reinforced concrete beams with foamed concrete infill. A comparison with reinforced normal concrete and reinforced foamed concrete was also performed. It is found that for normal concrete and foamed concrete that have compression strengths of 21.4MPa and 8.3MPa, the reinforced concrete beam with foamed concrete infill achived the ultimate load 53.11kN. However, this ultimate load is slightly lower than reinforced normal concrete. Moreover, the deflection of the beam is within the serviceability limit. Since the structural behaviour of the beam involves phenomena that not yet well understood, thus extensive investigations are required in both experimental and numerical studies.

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