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Natural Frequency of Lightweight Composite Slabs Based on Experimental Study and Numerical Modelling

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Abstract: Recently, lightweight composite slabs have become increasingly popular. Lightweight composite slabs are an innovation that provides a better and more convenient construction method for floor systems. Under dynamic loads, lightweight composite slabs may experience meagre inertia forces due to poor stiffness or low mass. Compared to conventional composite slabs, lightweight composite slabs are 40% lighter and more susceptible to structural resonance. Therefore, the vibration behaviour must be controlled to avoid discomfort issues. This study investigates the natural frequency of lightweight composite slabs through experimental study and numerical modelling. In the experimental study, lightweight composite slabs were prepared for the hammer-impact test. The slab thickness ranges from 100 mm to 200 mm. In numerical modelling, lightweight composite slabs were modelled in SAP2000 using a unique technique called the simplified equivalent plate model. The effective material properties were derived from the rule of mixtures and depend exclusively on elastic properties with strength characteristics. The results of the experimental study and numerical modelling agree positively. The natural frequency decreased with slab thickness, signifying that the natural frequency is dominated by mass rather than stiffness. Overall, the natural frequency of lightweight composite slabs is around 27.23Hz to 31.45Hz.

Keywords: Natural frequency, lightweight composite slabs, hammer-impact test, numerical modelling, SAP2000

1. Introduction

Lightweight composite slabs, specially developed for flooring systems, offer a better alternative to conventional composite slabs. Lightweight composite slabs comprise foamed concrete and steel deck. Foamed concrete is the topping material, while steel deck serves as the permanent formwork and tensile reinforcement. The composition of these materials is environmentally friendly and sustainable, suitable for urban buildings and pedestrian bridges. It is the novel solution to the dead weight disadvantage, a significant concern with conventional composite slabs. Foamed concrete has a lower density, where the density can be designed around 1400 kg/m^3 and 1800 kg/m^3 for structural

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purposes. Similar to conventional composite slabs, using lightweight composite slabs is practical and economical. Foamed concrete has gained wide acceptance as a construction material, although its use in floor systems is still rare. Therefore, the combination of foamed concrete and steel deck is an accepted implementation of lightweight composite slabs in the construction industry. In addition, the development of foamed concrete with high-strength characteristics as performed by Namsone et al. [1], Khan et al. [2], Wei et al. [3] and Xian et al. [4] indicate promising results. Previous investigations by Liu & Tian [5], Abbas et al. [6] and Martinez-Martinez [7] pointed out that the performance of lightweight composite slabs is closely in line with and comparable to that of other types of floor systems.

An experimental study on the structural behaviour of lightweight composite slabs subjected to a four-point bending test by Flores-Johnson & Li [8] revealed that the maximum failure load can reach 38.65 kN with a deflection of 5.50 mm. Foamed concrete with a 1000 kg/m^3 density was used to produce lightweight composite slabs. This foamed concrete has considerably low compressive strength but shows excellent structural performance. It should be emphasised that the minimum compressive strength of foamed concrete in accordance with BS EN 1992-1-1 [9] must not be less than 22 MPa. Meanwhile, ASTM C330 [10] allows the use of foamed concrete with a minimum compressive strength of 17 MPa. Jaini et al. [11] investigated the flexural behaviour of lightweight composite slabs under static loading. The foamed concrete has different densities ranging from 1400 kg/m^3 to 1800 kg/m^3, giving a compressive strength of 25.30 MPa to 32.23 MPa. The ultimate load achieved by lightweight composite slabs was 77.46 kN to 93.17 kN. The ultimate load is far higher than that reported by Hulimka et al. [12] for reinforced foamed concrete slabs. Regarding the failure mode, localised bending of the steel deck, slip-displacement, and fractures of the foamed concrete occurred in lightweight composite slabs. The ductile behaviour of the load-deflection curves shows that the bearing capacity of lightweight composite slabs is mainly controlled by the steel deck, not the foamed concrete.

The dynamic responses of lightweight composite slabs are currently limited to the vibration behaviour such as natural frequency, damping ratio, mode shape and energy dissipation. There is no available literature on accidental loads such as impact and seismic. Rum et al. [13] investigated the vibration behaviour of lightweight composite slabs subjected to the hammer-impact test. Of interest are the effects of the density of foamed concrete. The natural frequency of lightweight composite slabs was 29.70Hz to 33.78Hz. It is well above the vibration limit in BS EN 1992-1-1 [9] and Murray et al. [14]. Meanwhile, the damping ratio lies within 3% to 5%, which is relatively high. Typically, floor systems should have a damping ratio of 1% to 3% [15], [16]. Despite that, a damping ratio of 5% is always taken into account in practical seismic design [17]. A comprehensive evaluation of the vibration behaviour of lightweight composite slabs under human excitation was performed by Nurhalim et al. [18]. The dimension of lightweight composite slabs is 900 mm in width, 2900 mm in span and various thicknesses from 100 mm to 225 mm. The density of foamed concrete is 1600 kg/m^3 and the steel deck is based on ComFlor46. In the transient state, the natural frequency is linearly related to thickness and can be expressed mathematically as:

$$f = 0.1948h - 5.3977 \tag{1}$$

where f is the natural frequency and h is the slab thickness. Lightweight composite slabs with a slab thickness between 100 mm and 225 mm reached the natural frequency of 14.08Hz to 38.43Hz. Although the natural frequency is above the vibration limit, lightweight composite slabs with more than 175 mm thickness exceeded the allowable deflection.

Under dynamic loads, lightweight composite slabs may experience meagre inertia forces due to poor stiffness or low mass. Therefore, understanding the vibration behaviour of lightweight composite slabs is crucial to ensure that its application for urban buildings and pedestrian bridges meets comfort criteria. As lightweight composite slabs become increasingly popular, studying vibration behaviour is paramount to rule out possible damage and uncertainties in structural resonance. In view of this problem, this study presents the investigation of the natural frequency of lightweight composite slabs within the framework of experimental study and numerical modelling. The focus is on the effects of slab thickness on the natural frequency. According to Khan et al. [19], several factors are known to influence the natural frequency and the minimum slab thickness is required to prevent undesirable vibration behaviour. In addition, in many codes and standards, the design of floor systems mainly depends on the slab thickness to control serviceability. Furthermore, Jayaseelan et al. [20] and Johnson [21] found that slab thickness affects the resistance toward longitudinal shear stresses.

2. Experimental Study

2.1 Materials and Specimens Preparation

Two primary materials are needed for casting slab specimens of lightweight composite slabs: foamed concrete and steel deck. Foamed concrete is used as the topping material. It consists of ordinary Portland cement (OPC), sand, water, superplasticiser, foaming agent, rice-husk ash (RHA) and polypropylene mega-mesh (PMM). RHA was used as sand replacement with an optimum content of around 40% fine aggregate, while PMM was added as fibre reinforcement with a total volume of 9 kg/m^3. The mix design of foamed concrete is shown in Table 1. Based on the compression test, foamed concrete offers excellent early strength development with a compressive strength of 26.37 MPa after 7 days, 29.94 MPa after 14 days and 32.40 MPa after 28 days. The compressive strength agrees with that reported by Jaini et al. [22]. As foamed concrete achieves a compressive strength above 22 MPa, it is safe to use in lightweight composite slabs.

The steel deck used in the experimental study is a corrugated cold-formed steel multideck profile, technically known as PEVA45. The steel deck has a width of 840 mm and a span of 1800 mm. According to BS EN 1994-1-1 [23], the nominal bare metal thickness of steel deck should be not less than 0.75 mm. Therefore, PEVA45 with a nominal bare metal thickness of 1.0 mm was selected to meet this requirement. The main benefit of using PEVA45 is ease of laying and assembly. Also, almost 80% of steel reinforcement can be saved and no underside steel reinforcement is needed. According to Roslan et al. [24], in terms of push-out characteristics, PEVA45 has a maximum load of 21.50 kN to 72.02 kN and a stiffness of 2.82 kN/mm to 12.78 kN/mm.

Table 1 - The mix design of foamed concrete

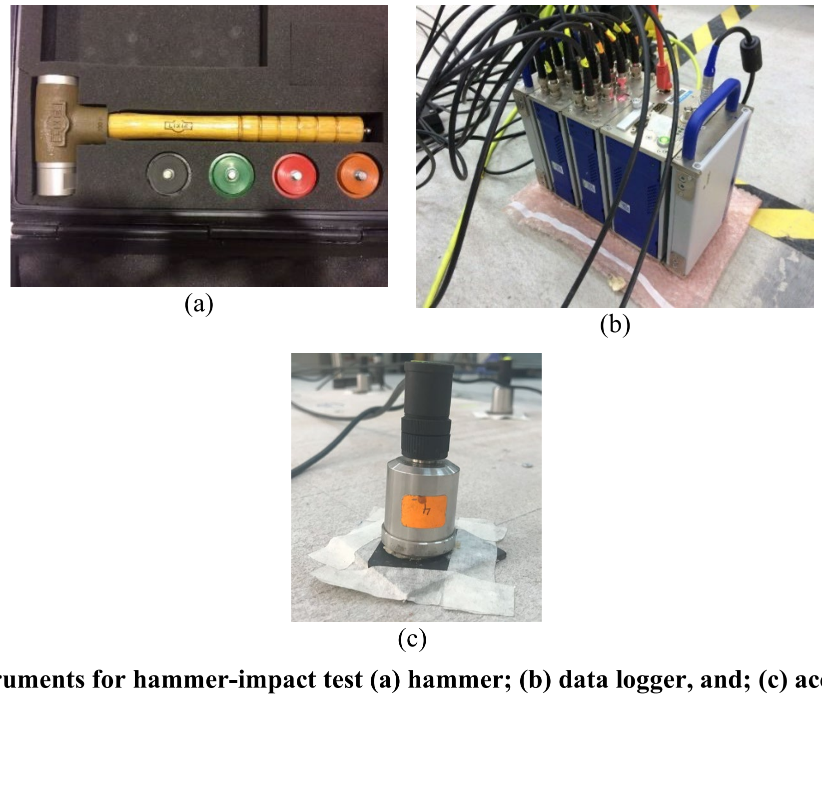
W/OPC Ratio	OPC/S Ratio	FA/OPC Ratio	FA/W Ratio	SP (%)	S:RHA (%)	PMM (kg/m^3)
0.55	0.50	0.70	0.05	0.55	60:40	9

Note: OPC = Ordinary Portland cement, S = Sand, W = Water, FA = Foaming agent, SP = Superplasticizer, RHA = Rice husk ash, PMM = polypropylene mega-mesh.

A total of 15 slab specimens were prepared for the hammer-impact test. The slab specimens were produced with different thicknesses ranging from 100 mm to 200 mm. The density of foamed concrete is 1800 kg/m^3. The slab specimens were prepared to the specifications of BS EN 1994-1-1 [23]. The deflection calculation can be omitted since the length-to-thickness ratio of lightweight composite slabs is less than 18. The span can be designed using an elastic analysis that accounts for deflection and neglects the effects of shrinkage. The width (b) should not be less than three times the overall thickness (h) or 600 mm, whichever is greater. At the same time, h must be at least 90 mm to ensure adequate fire resistance. The thickness of topping material above the main flat surface of the steel deck (h_c) shall be not less than 50 mm, and the profile depth (h_s) should be at least 40 mm. Because PEVA45 has h_s = 45 mm, h_c should be around 55 mm to 155 mm.

2.2 Hammer-Impact Test

A hammer-impact test is carried out to investigate the vibration behaviour concerning natural frequency. Meruane et al. [25] and Shahnewaz et al. [26] previously implemented this non-destructive method for composite slabs. As shown in Fig. 1, the hammer-impact test requires instruments such as a hammer, data logger and accelerometers. A hammer weighing 5 kg is used to impose an external loading on the top surface of slab specimens. The force transducer on the hammer measures the magnitude of external loading. Meanwhile, accelerometers were used to detect the wave propagation induced by the hammer. The wave propagation is recorded by the data logger as acceleration-time history. The measured data can then be digitally recorded using the QuickDAQ program.



(a) (b) (c)

Fig. 1 - Instruments for hammer-impact test (a) hammer; (b) data logger, and; (c) accelerometers

After 28 days of air curing, the slab specimens were painted white on the top and edge surfaces. Then, the grid lines are drawn on the top of slab specimens, where the intersections become the accelerometer location points. There are 15 location points, labelled A1 through A15. On the other hand, the external loading location points are marked as H1 and H2. The details of location points can be referred in Fig. 2. For the hammer-impact test, the slab specimens are placed on the I-steel beams at both ends.

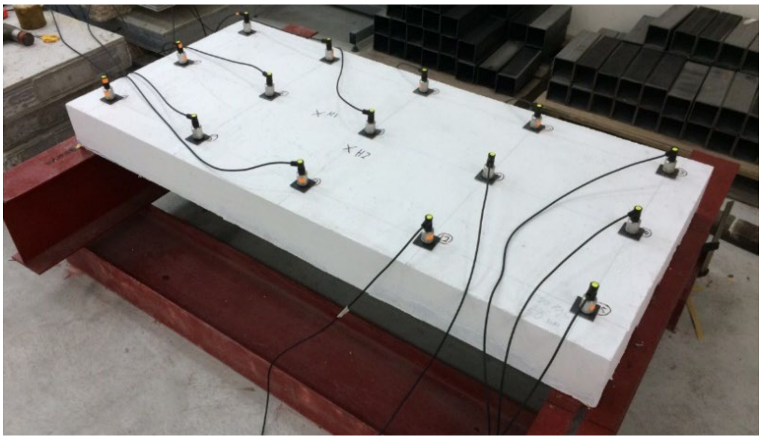


Fig. 2 - Location points for accelerometer and external loading

In order to ensure that the acceleration-time history is measured accurately and errors are minimised, essential parameters must be entered into the data logger. Table 2 gives the parameters used in the hammer-impact test. Once the instrument setup is complete, the hammer-impact test can be performed using the designed procedure. The hammer is struck ten times at H1 with a constant magnitude of external loading. Fig. 3 shows the typical force-time history generated from the hammer-impact test. The data logger can measure the acceleration-time history simultaneously at 15 location points. Then, a similar step is repeated at H2. Once the hammer-impact test is done, the acceleration-time history can be converted from hpf to txt format. This will allow the acceleration-time history to be plotted in xlsx format.

Table 2 - Parameters used in the hammer-impact test

Parameters	Value
Sample rate (Hz)	1000.115
Sample interval (sec)	0.001
Number of scans	100000
Sensitivity of impact hammer	1.030
Sensitivity of accelerometer	103.100

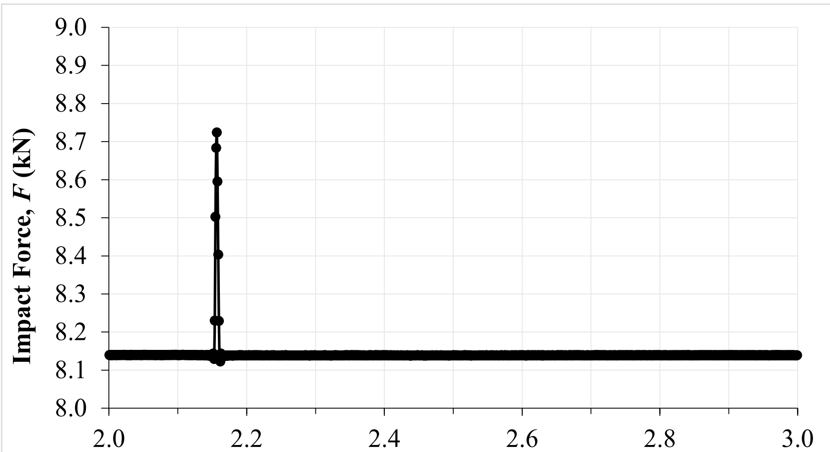


Fig. 3 - Force-time history

3. Numerical Modelling

The numerical modelling of lightweight composite slabs was carried out with SAP2000. This commercial software can perform complex solid mechanics assessments through an easy-to-use graphical user interface. Earlier works by Junges et al. [27], Mushina et al. [28] and Yu et al. [29] used SAP2000 to investigate the vibration behaviour of various structural components. It turns out that the vibration behaviour in the linear-elastic range can be precisely simulated with SAP2000. However, the regular numerical modelling for composite slabs is somewhat complicated and requires special geometry and material properties treatment.

3.1 Geometry Properties

The physical properties of lightweight composite slabs were constructed three-dimensionally using shell elements. Since lightweight composite slabs have an irregular cross-section (corrugated shape) due to the nature of PEVA45, direct modelling is almost impossible. In addition, SAP2000 prohibits joining two different materials, as in the case of composite slabs. Therefore, a special technique called the simplified equivalent plate model proposed by El-Dardiry & Ji [30] was employed in numerical modelling. Norhalim et al. [18] proved that the simplified equivalent plate model is suitable for determining the vibration behaviour of composite slabs. The orthotopic manner of foamed concrete and steel deck in the simplified equivalent plate model is converted to an isotropic system. Fig. 4 shows the conversion process from the original cross-section to the simplified equivalent plate model.

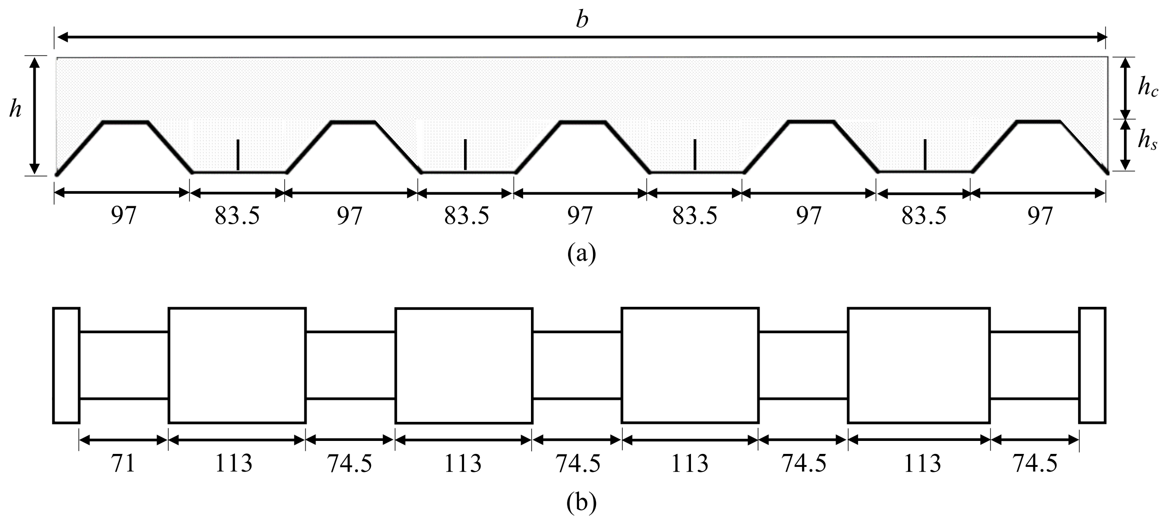


Fig. 4 - Conversation process (a) original cross-section, and; (b) simplified equivalent plate model

For numerical modelling, lightweight composite slabs must consist of two parts, namely the frame segment and the cross-sectional properties. The frame segment can be modelled separately as either a beam or girder. A new frame segment must be defined if more than one beam or girder exits. For each frame segment, the cross-sectional properties are assigned by a flat shape section. The torsional and the weak axis of moment of inertia are set constant at 1.0. When the frame segment is entirely constructed, the actual dimension of lightweight composite slabs is entered into the cross-sectional properties in SAP2000. The cross-sectional properties are defined as the section area and the section moment of inertia, which can be calculated using Eq. (2) to Eq. (7). A complete set of cross-sectional properties can be referred in Table 3.

$$A_i = b_i h_i + n b_i t \tag{2}$$

where A_i is the section area, h_i is the section thickness, b_i is the section width, t is the nominal bare metal thickness of steel deck, and n is the modular ratio of steel-to-concrete. Eq. (3) can be used to determine the modular ratio of steel-to-concrete:

$$n = \frac{E_s}{E_c} \tag{3}$$

where E_s is Young's modulus of steel and E_c is Young's modulus of concrete. In the case of lightweight composite slabs, the modular ratio of steel-to-concrete can be taken as 10.57. On the other hand, the section moment of inertia (I_i) can be calculated using the following formula:

$$I_i = I_{i,s} + I_{i,c} \tag{4}$$

$$I_{i,s} = \frac{nb_i t^3}{12} + nb_i t\left(h_i + \frac{t}{2} - \overline{z}_i\right)^2 \tag{5}$$

$$I_{i,c} = \frac{b_i h_i^3}{12} + b_i h_i\left(\frac{h_i}{2} - \overline{z}_i\right)^2 \tag{6}$$

where $I_{i,s}$ and $I_{i,c}$ are the section moment of inertia for steel and concrete, respectively. Meanwhile, $\overline{z}_i$ is the section neutral axis and can be determined using the following formula:

$$\overline{z}_i = \frac{\left[b_i h_i\left(\frac{h_i}{2}\right)\right] + n\left[b_i t + \left(\frac{t}{2} + h_i\right)\right]}{A_i} \tag{7}$$

Table 3 - Cross-sectional properties of lightweight composite slabs

Slab Thickness, h (mm)	Section Width, b_i (mm)	Section Depth, h_i (mm)	Section Area, A_i (mm^2)	Section Neutral Axis, $\overline{z}$ (mm)	Section Moment of Inertia, I_i (10^6 mm^4)
100	11.25	100	1243.945	54.829	1.2118
	71.00	55	4655.677	32.015	1.4781
	113.00	100	12494.74	54.829	12.172
	74.50	55	4885.182	32.015	1.5509
125	11.25	125	1525.195	67.413	2.2663
	71.00	80	6430.677	44.728	4.1170
	113.00	125	15319.74	67.413	22.764
	74.50	80	6747.682	44.728	4.3199
150	11.25	150	1806.445	79.971	3.7974
	71.00	105	8205.677	57.349	8.7651
	113.00	150	18144.74	79.971	38.143
	74.50	105	8610.182	57.349	9.1972
175	11.25	175	2087.695	92.514	5.8931
	71.00	130	9980.677	69.926	15.977
	113.00	175	20969.74	92.514	59.193
	74.50	130	10472.68	69.926	16.765
200	11.25	200	2368.945	105.05	8.6411
	71.00	155	11755.68	82.481	26.309
	113.00	200	23794.74	105.05	86.795
	74.50	155	12335.18	82.481	27.605

3.2 Material Properties

Lightweight composite slabs consist of foamed concrete and steel deck that bond together compositely. Since the numerical modelling has adopted the simplified equivalent plate model for lightweight composite slabs, the material properties must be converted into a homogeneous criterion. This will merge the definition of material properties as a single value instead of having a distinct value. The material properties for foamed concrete and steel deck can be found in Table 4. In numerical modelling, the observation of the natural frequency must be performed in a nonlinear-elastic range where lightweight composite slabs are still intact. Therefore, numerical modelling only incorporates elastic properties with strength characteristics.

In general, the homogenous criterion can be established using the rule of mixtures, where the volume fraction plays an important role in altering the material properties. The rule of mixtures is simple and straightforward. The stiffness of the contact surface can be ignored by assuming that foamed concrete and steel deck have perfect surface contact interaction. Adopting the simplified equivalent plate model changes the material properties to the effective material properties. The effective material properties depend on the thickness of foamed concrete rather than the thickness of the steel deck. Table 5 shows the effective material properties of lightweight composite slabs.

The rule of mixtures allows the calculation of effective material properties based on the separated material properties. As an example, the effective Young's modulus can be calculated using the following formula:

$$E_{eff} = VE_c + \left(1 - V\right) E_s \tag{8}$$

where E_{eff} is the effective Young's modulus, E_c is Young's modulus of foamed concrete, E_s is Young's modulus of steel deck, and V is the volume fraction.

$$V = \frac{V_c}{V_c + V_s} \tag{9}$$

where V_c is the volume fraction of foamed concrete and V_s is the volume fraction of steel deck. While the volume fraction of the steel deck remains constant, the volume fraction of foamed concrete changes due to increasing slab thickness. Replacing Young's modulus in Eq. (8) can determine effective material properties. For example, the effective tensile strength can be determined by:

$$f_{t,eff} = Vf_{t,c} + \left(1 - V\right) f_{t,s} \tag{10}$$

where $f_{t,eff}$ is the effective tensile strength, $f_{t,c}$ is the tensile strength of foamed concrete and $f_{t,s}$ is the tensile strength of steel deck.

Table 4 - Material properties of foamed concrete and steel deck

Material Properties	Foamed Concrete	Steel Deck
Young modulus, E (MPa)	19.20	203
Poisson's ratio, v	0.3	0.3
Density, ρ (kg/m^3)	1800	7800
Shear modulus, G (GPa)	8	81
Compressive strength, f_{cu} (MPa)	32.40	-
Yield strength, f_y (MPa)	-	280
Tensile strength, f_t (MPa)	2.87	410
Yield strength ratio, R_y	-	1.5
Tensile strength ratio, R_t	-	1.2

Table 5 - Effective material properties of lightweight composite slabs

Material Properties	Slab Thickness, *h* (mm)				
	100	125	150	175	200
Young modulus, E (MPa)	22.11	21.43	21.01	20.72	20.51
Poisson's ratio, v	0.17	0.17	0.17	0.17	0.17
Density, ρ (kg/m^3)	1895	1872	1859	1849	1842
Shear modulus, G (GPa)	9.16	8.89	8.72	8.60	8.52
Compressive strength, f_{cu} (MPa)	30.50	30.62	30.70	30.74	30.78
Yield strength, f_y (MPa)	4.44	3.40	2.75	2.31	2.00
Tensile strength, f_t (MPa)	9.32	7.81	6.87	6.23	5.77
Yield strength ratio, R_y	0.02	0.02	0.02	0.01	0.01
Tensile strength ratio, R_t	0.02	0.02	0.02	0.01	0.01

4. Results and Discussion

Fig. **5** shows the acceleration-time history obtained from the experimental study. Lightweight composite slabs were observed to associate with a large magnitude of acceleration within 0.35 sec before returning to a steady state. This acceleration-time history provides key information for calculating the natural frequency. In this experimental study, the natural frequency was analysed using Mescope.

Fig. 6 shows the natural frequency of lightweight composite slabs from the experimental study, which was also compared with numerical modelling. The discrepancy in results between the experimental study and numerical modelling is less than 3.5%. This is apparent evidence that numerical modelling with SAP2000 gives reasonably good agreement despite the lack of conventional modelling techniques for composite slabs. For slab thickness of less than 150 mm, the natural frequency obtained from numerical modelling is the lower bound of the experimental study. For slab thickness of more than 175 mm, the trend is contradictory. The most anticipated reason is that the grooved anchor rail is not considered in numerical modelling, causing lightweight composite slabs to lose stiffness.

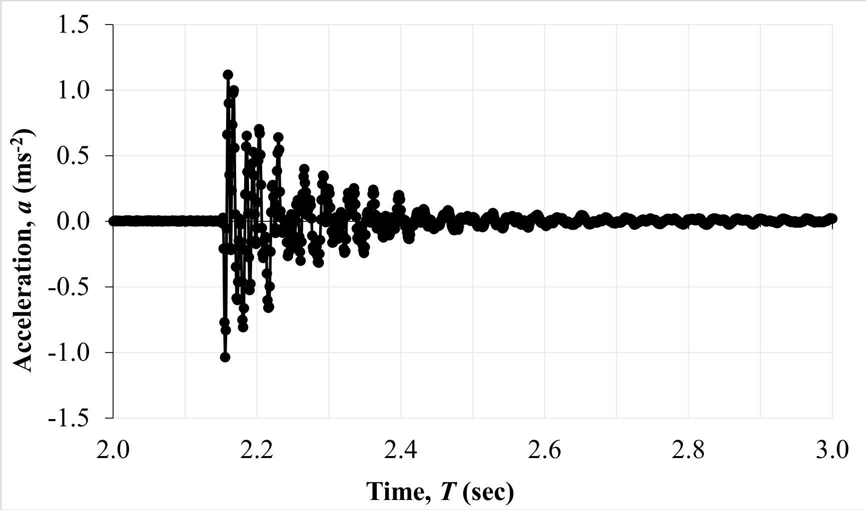


Fig. 5 - Acceleration-time history

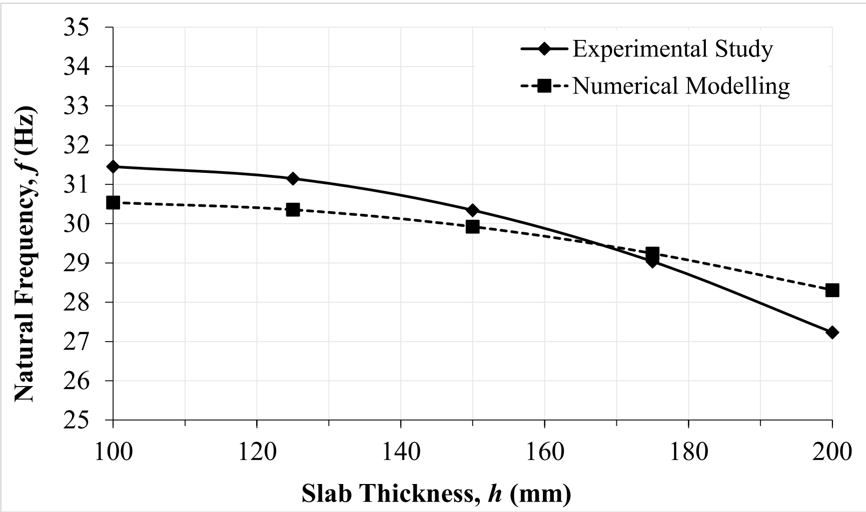


Fig. 6 - The natural frequency corresponds to the slab thickness

The experimental study and numerical modelling results depicted that the natural frequency decreases with slab thickness. This means that the vibration behaviour of lightweight composite slabs is dominated by mass, not stiffness. This finding is similar to that observed by Rahimi et al. [31] for the precast hollowcore slabs. In most cases, as reported by Khan et al. [19] and Abd Ghafar & Sahban [32], the natural frequency is increased when the structural components are dominated by stiffness. Adding foamed concrete increases the mass of lightweight composite slabs; therefore, the natural frequency is inversely proportional to mass. Despite the downward trend, the natural frequency of lightweight composite slabs with a slab thickness of 200 mm is still above the vibration limit. It is predicted that as the slab thickness increases, lightweight composite slabs will experience greater discomfort issues.

The plot of natural frequency versus length-to-thickness ratio, as in Fig. 7, provides a clear picture of the vibration behaviour of lightweight composite slabs regarding preliminary design aspects. Usually, the deflection of composite slabs can be controlled by limiting the length-to-thickness ratio. Ideally, since the length-to-thickness ratio accounts for both length and slab thickness, it becomes a quick way to access the vibration behaviour since lightweight composite slabs can have different geometry properties. A trendline based on a polynomial function was established from the mean data of the results. The following formula can best represent this trendline:

$$f = -\alpha_p \left[0.0617 \left(\frac{L}{h} \right)^2 - 2.0024 \left(\frac{L}{h} \right) - 14.892 \right] \tag{11}$$

where L is the length, h is the slab thickness and α_ρ is the multiplying factor related to the density of foamed concrete. For foamed concrete with a density of 1800 kg/m^3, the multiplying factor can be taken as 1.0.

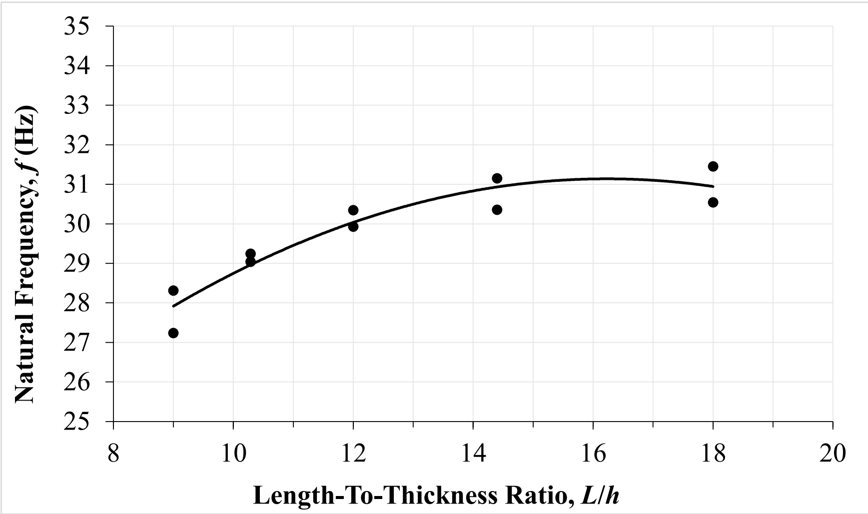


Fig. 7 - The natural frequency corresponds to the length-to-thickness ratio

5. Conclusion

The natural frequency of lightweight composite slabs has been studied through experimental study and numerical modelling. From the evaluation of methodology and results, the following conclusion can be drawn:

- Different slab specimens of lightweight composite slabs were subjected to hammer-impact test, producing different natural frequency values. The natural frequency decreases with slab thickness, showing that the natural frequency is dominated by mass rather than stiffness.
- The numerical modelling of lightweight composite slabs was established on the basis of the simplified equivalent plate model in SAP2000. The material properties were defined as effective material properties derived from the rule of mixtures. The results of numerical modelling showed similar tendencies as the experimental study.
- The simplified equivalent plate model in three-dimensional produces convincing results despite the lack of conventional modelling techniques for composite slabs. The simplified equivalent plate model is more straightforward than the orthotropic system.
- An empirical formula that relates the natural frequency with the length-to-thickness ratio was established using the mean results data. The multiplying factor associated with the density of foamed concrete is included to account for the fact that lightweight composite slabs can be made from different densities of foamed concrete. However, this empirical formula requires further validation.

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