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THE FLEXURAL PERFORMANCE OF LIGHTWEIGHT FOAMED PRECAST CONCRETE SLABS: EXPERIMENTAL AND ANALYSIS

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ABSTRACT: Building the world need a reliable but light materials. But the development of lightweight concrete by optimizing its constituent limited to material research terms and on the contrary structural research using this material is very limited. In this paper, lightweight concrete slabs and their capacity for flexural loads is proposed and studied. The framework methodology used is performed flexural test experiments of full-scale slabs under 4-point bending, and software modeling will simply verify their results. Based on the deflection results, the maximum deflection of the lightweight concrete slab is found optimum at dimension of 0,5m width and 0.12m depth, which its average is 34.67 mm. The closest element model was solid element that resulted in 37.08 mm which meet the 34.67 mm by test. And more practical run is found for beam element and also plate element as well, which exhibit more appropriate analysis of 31,64 mm deflection for both models, which is also not far from the 34.67 mm by test. Therefore, beam element is accurate enough for sake of simplicity, the solid element more accurate but tends to suffer from time consuming problem or costly both for modeling and running. Finally, the lightweight foamed precast concrete slabs have a good flexural performance and in the future can be a good structural slab for precast construction.

Keywords: Precast slab, Lightweight concrete, Compressive strength, Deflection, Flexural test.

1. INTRODUCTION

In the history of the civil engineering industry, lightweight concrete or foam concrete is a unique concrete that is useful in the civil engineering industry because of its lightweight and solidifies in every self-characteristic. Lightweight Concrete has a relativity low price than normal concrete. The weight of lightweight concrete can be arranged as necessaries. The advancement of concrete technology has been enabled the lightweight structural aggregate concrete to be mass-produced with compressive strength between 17.24 – 41.36 MPa [1]. In the case of lightweight concrete, the concrete specimens were tested starting from the 7th day as anticipated to reach the expected results. The maximum compressive stress occurs is recorded as 17 MPa with a strain of 0.0042. The strain and stress experienced are in line with the predicted results [2].

Increasing interest is nowadays being paid to improving the thermal insulation of buildings in order to save energy and reduce ecological problems. Foamed concrete has unique characteristics and considerable potential as a promising material in construction applications. It is produced with a wide range of dry densities, between 600 and 1600 kg/m^3. However, at a low density below 500 kg/m^3, it tends to be unstable in its fresh state while exhibiting high drying shrinkage in its hardened state [3].

Foamed concrete has unique characteristics that can be exploited in civil engineering works. It requires no compaction but will flow readily from an outlet to fill restricted and irregular cavities, and it can be pumped over significant distances and heights. Thus, it could be thought of as a free-flowing, self-setting fill. This report provides a conspectus of foamed concrete: covering its constituents, production, engineering properties and use [4].

The design of flooring systems is considered as one which has the highest impact on the overall weight of steel buildings, in particular, taller structures, and it is getting more significant with the high demand for increased column spacing (i.e., large spans). Thus, reduced floor slabs have been proposed in the last decade to account for lightweight systems [5].

An accurate modeling and analysis method to obtain the structural behavior of foam concrete panels also can be analyzed in terms of its damage criteria and ultimate load-carrying capacity. A three-dimensional non-linear finite element model of this structure was developed and can be validated with experimental results [6].

Thus in this paper, the authors conducted research on the mixing configuration of the foam agent and fibers content that appropriate for lightweight foamed concrete slab structures, and also determined the appropriate model to meet the flexural testing in laboratory full-scale experiments.

2. LITERATURE REVIEW

2.1 Lightweight Concrete

Usually, it have been distinguished among structural lightweight concrete, concrete used in masonry units, and insulation concrete. This classification of structural lightweight concrete is based on a minimum strength should not be less than 17 Mpa. The density (unit weight) of such concrete (determine in the dry state) should not exceed 1840 kg/m^3 and is usually between 1400 and 1800 kg/m^3. On the other hand, masonry concrete generally has a density between 500 and 800 kg/m^3 and a strength between 7 and 14 Mpa. The essential feature of insulating concrete is its coefficient of thermal conductivity which should be below about 0.3 J/m^2 sec ˚C/m, while density is generally lower than 800 kg/m^3, and strength is between 0.7 and 7 MPa [7]. The classification of lightweight concrete can found in Table 1.

Table 1. The classification of lightweight concrete according to usage and requirements [7]

Reference	Lightweight Concrete Type	Density (kg/m^3)	Compressive Strength (MPa)
Dobrowolski (1998)	low density concrete	240 - 800	0,35 - 6,9
	moderate strength lightweight concrete	800 - 1440	6,9 - 17,3
	structural lightwight concrete	1440 - 1900	>17,3
Nevile dan Brooks	structural lightwight concrete	1400 - 1900	>17
	mansory concrete	500 - 800	7,0 - 14
	insulating concrete	<800	0,7 - 7

2.1.1 Lightweight Concrete with Foam Agent

A researched attention to concrete and autoclaved concrete provided by reference [8] conclude a compressive strength of foamed concrete can be developed reach to structural strength compared with autoclaved aerated concrete. Foamed concrete is produced by injecting performed stable foam or by adding a special air-entraining admixture known as a foaming agent into a base mix of cement paste or mortar (cement + water or Cement + sand + water) [8].

2.1.2 Foam Agent

According to [8], the foaming agent used to obtain foamed concrete that was defined as an air-entraining agent the foaming agent is the most essential influence on the foamed concrete. The foam agents when added into the mix water it will produce discrete bubbles cavities that become incorporated in the cement paste. The properties of foamed concrete are critically dependent upon the quality of the foam. Foam agent can be classified according to types of foaming: i) Synthetic-suitable for densities from 1000 kg/m^3 and above. ii) Protein-suitable for densities from 400 kg/m^3 to 1600 kg/m^3.

Fig.1. Liquid foam agent
Source: Structural engineering laboratory

2.2 Concrete Compressive Strength Test

The compressive strength of concrete is one of the most important and useful properties. As a construction material, concrete is employed to resist compressive stresses. While, at locations where tensile strength or shear strength is of primary importance, the compressive strength is used to estimate the required property [9].

The Indonesian code describes the concrete compressive strength testing method clearly. The compressive strength of concrete is the magnitude of the burden of broad unity which causes the concrete specimen to be failure if loaded with a certain compressive force, which is produced by a universal compressive machine [10].

2.3 Wire-mesh Steel

ASTM A 185/A 185M [11] explains that welded wire for concrete reinforcement has been described by various terms: welded wire fabric, WWF, fabric, and mesh. The wire reinforcement industry prefers the term “welded wire reinforcement” (WWR) as being more representative of the range of products being manufactured.

2.4 Precast Slab

Lightweight precast slab is the one type of one-way slab. One way slab is a slab system that has a ratio of long (Ly) to short span (Lx) ratio of more than three[12] such in Figure 2:

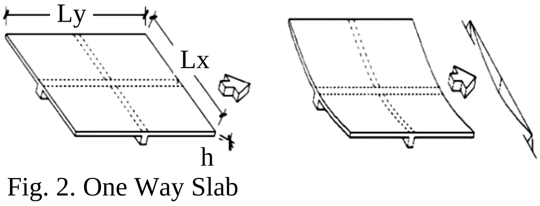


Fig. 2. One Way Slab
Source: [12]

In Fig. 2 a slab that is supported by beams on long sides and across each other is shown. If the bending load penetrates the upper slab, the deflection is shown with a dotted line. The bending moment will be distributed as short ways that span between suffered sides. From the bending moment with the beam grid system, it can be determined that the preparation of tensile reinforcement will span from both. And the installation of upright reinforcement to tensile reinforcement is for solving concrete shrinkage effect. In this thing, the one-way slab can be looked at as a row of beams with a one-width unit [12].

2.5 Slab Design

Reference [13] study on the serviceability constraints and says that the percentage of the longitudinal reinforcement steel, ρ, and the bar spacing, s, in one-way slabs should be between minimum and maximum limits permitted by the design specification that is 0,75 ρ_b.

The width of the one-way concrete slab as in SNI 03-2874-2002 [14] as defining in Table 2.

Table 2. The minimum width of the slab on each various slab structure component

Slab structure component	Minimum width (h)
- Two simple support	λ/20
- One cantilever beam point	λ/24
- Both cantilever beam point	λ/28
- Cantilever	λ/10

Source : [14]

On the one-way slab, reinforcement which hold the moment is useful as well for handle and overcome crack distribution that caused by shrinkage and temperature difference. Because the shrinkage of concrete occurs in all directions, it a special reinforcement must be inserted for shrinkage due to construction or temperature and known as distribution rebar. The code sets that distribution rebar must be inserted on the structural slab if the main reinforcement stretched in one-way. Nevertheless, the adjacent reinforcement distance cannot more than 5 times the width of the slab or typically cannot more than 200 mm.

2.5.1 Flexural Strength

Flexural strength is defined as the maximum stress that a material exhibits at failure due to a three or four-points flexural load [15]. Flexural strength is the ability of a material to withstand bending forces perpendicular to its longitudinal axis. The resulting stresses are a combination of compressive and tensile stresses. If a composite component is a beam subject to bending, a flexural test is more appropriate [16]. Flexural strength is an indirect measure of the tensile strength of concrete and can be determined from a third-point loading and center-point loading test [17].

The typical behavior of structural concrete beams under flexural load can be explained in many pieces of literature. Indeed when a structural concrete section is subjected to bending in the cracked state, an internal couple develops with the compression force in the concrete and the tensile force in the steel reinforcement. The forces must remain equal. The compression force in the concrete balances the tensile force, whether it is resisted by reinforcing bars. Since all steel reinforcements are assumed to yield, the initial prestress, if present, does not influence ultimate resistance. Fig.3 illustrates the section forces at nominal resistance [18].

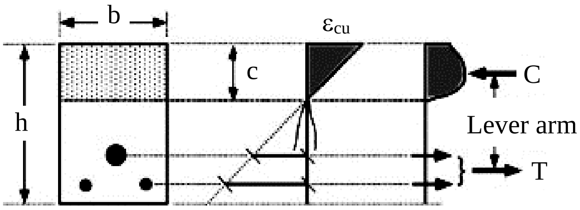


Fig. 3. Typical model of a structural concrete section at nominal bending resistance
Source: [18]

On the under reinforced condition, steel reinforcement has been yielded (f_s=f_y), hence for a slab, that the equilibrium can be stated as Eq. (1):

$$\boldsymbol{T = C = 0.85.fc'.a.1000} \quad (1)$$

Hence, its nominal moment capacity can be calculated as Eq. (2):

$$\boldsymbol{M_n = T_s.\left(d - \frac{a}{2}\right) = A_s\,.f_y.\left(d - \frac{a}{2}\right)} \quad (2)$$

where:

C_c = Concrete compressive force (kNm)
T_s = Steel tensile force (kN)
f'_c = Concrete compressive strength (MPa)
a = Beam length (mm)
b = Beam width (mm)
M_n = Nominal or capacity moment (kNm)
d = rebar effective depth of beam section (mm)

2.5.2 Simple beam structures

Straight longitudinal axis is given lateral forces, it will be deformed to be an arch, that called the deflection curve. The calculation of deflection is an important part of analysis and structural design. As an example, the specifications of slab structure design are set with the deflection limit permitted as the allowable deflection limit [19].

(1) under Distributed Load

A simple beam with a uniform distributed load in Figure 4.

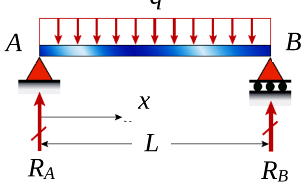


Fig. 4. A simple beam with a uniform load
Source: [19]

(2) under double P Load

The symmetrically loaded simple beam of Fig. 5 is a beam that is partly in pure and partly in nonuniform bending, as seen from Figs. 5b and 5c. The central region of the beam is in pure bending because the shear force is zero and the bending moment is constant. The parts of the beam near the ends are in nonuniform bending because shear forces are present and the bending moments vary in Fig. 5 [19].

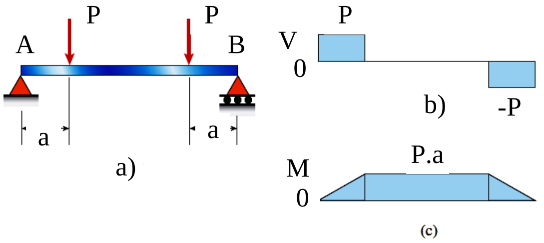


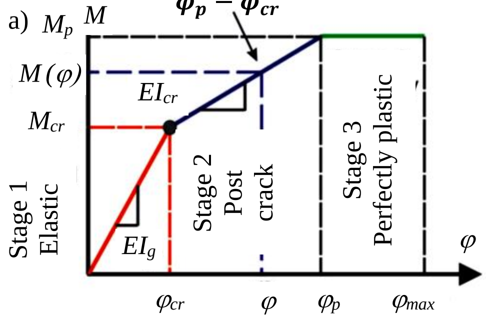
Fig. 5. Simple beam with central region in pure bending and end regions in nonuniform

Source: [19]

2.5.3 Trilinear moment-curvature relationship

Fig. 6 presents the idealized parametric moment-curvature response as a trilinear function that includes elastic, post-crack, and fully plastic range referred to as stages 1, 2, and 3, respectively. The trilinear model is defined by two control points (ϕ_{cr}, M_{cr}) and (ϕ_p, M_p) [20].

$$\boldsymbol{M(\varphi) = \frac{M_p - M_{cr}}{\varphi_p - \varphi_{cr}}(\varphi - \varphi_{cr}) + M_{cr}}$$



$$\boldsymbol{m(\kappa) = \frac{m_p - 1}{\kappa_p - 1}(\kappa - 1) + 1}$$

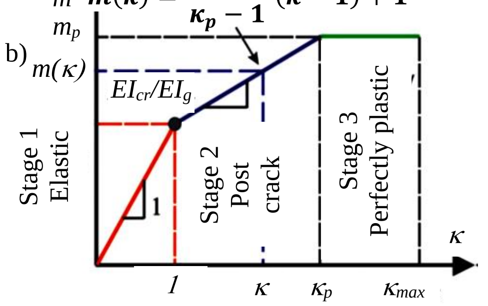


Fig. 6. (a) Simplified parametric moment-curvature relationship: trilinear representation;
(b) dimensionless moment-curvature curve represented as variables (κ, m)

Source: [20]

This relation consists of three area before rupture happens, they are:

Area I : Elastic range or pre-rupture level, where the structural beams are rupture-free.

Area II : Post crack range or post-rupture level, where the structural beams have controlled rupture which can be tolerated its distribution or its width.

Area III : Fully plastic range as post-serviceability, where the stress on reinforcement has reach its yield stress.

2.5.4 Permitted Deflection on Slab

Concrete structure calculation of building explains deflection that permitted on structural system is really depended on the deflection value which can still be held by structural components that interact without losing aesthetic appearance and without damage on deflected element [21].

Therefore, it will be gotten thinner structure elements and, in this case as seen in Table 3, momentary deflection or long-term deflection must be controlled,.

Table 3. Allowable maximum Deflection (Δ) that permitted (L=beam span)

Structural Element Type	Appropriate Deflection	(L/Δ) min
Flat roof which not support and not fixed non-structural element that can be ruptured by high deflection	Momentary deflection caused by live load Δ_L	180
Slabs which not support and not fixed non-structural elements that can be ruptured by high deflection	Momentary deflection caused by live load Δ_L	360
Roof construction or slab that fixed non-structural elements which can be ruptured by high deflection	Half of total deflection happens after installation non-structural elements, total of all sustained load sum half of sustained live load, and momentary load caused additional live load.	480
Roof construction or slab that fixed non-structural elements which can be ruptured by high deflection	Δ_{LT}	240

Source: [21]

2.6 Structural Efficiency

In reference [22], the lightweight concrete or mortars, the compressive strength is firmly connected with their density; compressive strength diminishes with a reduction in density. Particularly when connected in long-span or tall structures, the density and strength of lightweight concrete are pivotal to achieve a high strength while holding low density. This connection is normally researched utilizing the alleged structural efficiency, which is calculated from the proportion of compressive strength at 28 days to density, as Equation 3

$$st_\eta = \frac{f_{ck}}{\rho} \quad (3)$$

Where, st_η is the structural efficiency (Nm/kg), f_{ck} is the compressive strength at 28 days (MPa), and ρ is the actual density of the sample (kg/m^3) [22].

3. METHODOLOGY

3.1 Foamed Concrete Slab Structural Modeling

The lightweight foamed concrete slab structure analyzed using plate/shell elements and solid elements to meet closest slab specimen geometry. The modeling is shown in Fig. 7. The other model was a combination of plate + beam elements and also solid + beam elements were another model. The wire-mesh reinforcement modeled as beam element using a 6mm diameter circle rebar section.

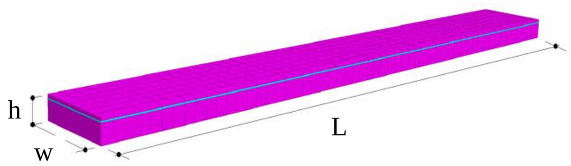


Fig. 7. Finite modeling of lightweight slab: plate element for slab; beam element for rebar

4. RESULTS AND DISCUSSIONS

4.1 Mix Design

The foam agent variation mix design for lightweight concrete can be seen in Table 4.

Table 4. Foam agent concentration

Water / Cement	Water (kg)	Cement (kg)	Fine Agg. (kg)	Foam Agent (lt/m^3)
0.50	1.25	2.5	5.0	0.0
0.50	1.25	2.5	5.0	0.4
0.50	1.25	2.5	5.0	0.6
0.50	1.25	2.5	5.0	0.8

Foam agent and fiberglass content for single cylinder and concrete slab specimen can be seen in Table 5 and Table 6 respectively.

Table 5. Foam agent and fiberglass variation mix design for one cylinder specimen

Water / Cement	Water (kg)	Cement (kg)	Fine Agg. (kg)	Foam Agent (lt/m^3)	Fiber glass
0.50	1.25	2.5	5.0	0.6	1%
0.50	1.25	2.5	5.0	0.6	3%

Table 6. Concrete mix design for single slab

Water / Cement	Water (kg)	Cement (kg)	Fine Agg. (kg)	Foam Agent (lt/m^3)	Fiber glass
0.50	70	140	135	0.6	1%
0.50	70	140	135	0.6	3%

4.2 Compressive Strength of Lightweight Foamed Concrete

In this research, the relation between compressive strength and the weight of lightweight concrete with foam agent variation 0.0 lt/m^3; 0.4 lt/m^3; 0.6 lt/m^3 and 0.8 lt/m^3, on 28th days have been tested. The resulting graph of the concrete compressive strength test is shown in Fig 8.

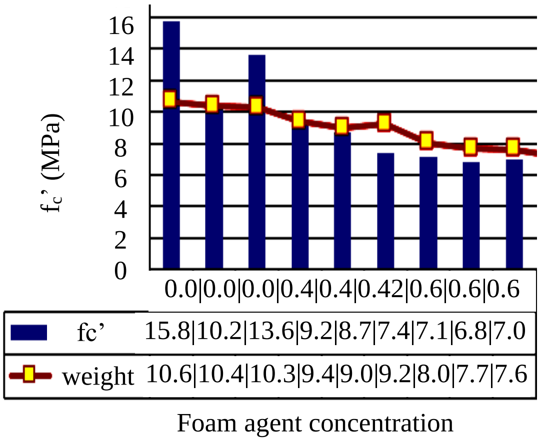


Fig. 8. Compressive strength versus weight at the various of foam agent concentration

The result of foam agent variation 0.6 lt/m^3 has a quite consistent compressive strength and weight is represented in Fig. 8. Hence, foam agent variation 0.6 lt/m^3 is determined as a mix design for lightweight concrete slab.

4.3 Compressive Strength of Lightweight Foamed Concrete with Fiberglass Variation

The relationship between lightweight concrete compressive strength with the percentage of addition fiberglass 1% and 3% on 28th days have been carried out. The concrete compressive strength test using 1% and 3% foam agent content is depicted in Fig. 9.

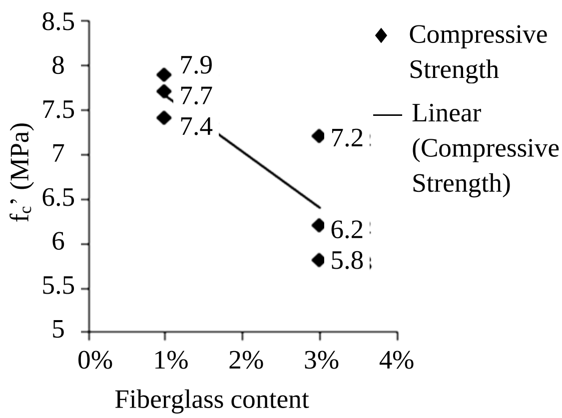


Fig.9. The relationship between fiberglass content and its compressive strength.

While the relation between concrete sample weight and fiberglass percentage variation of 1% and 3% is shown in Fig. 10.

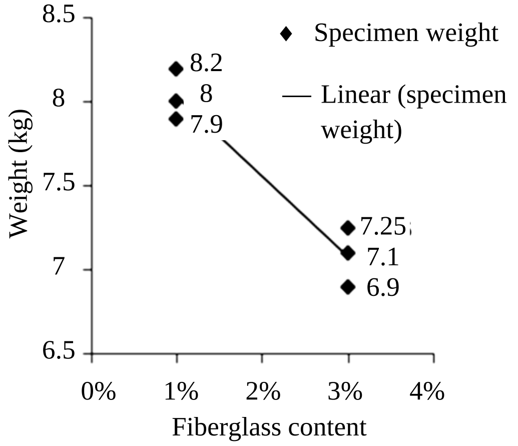


Fig. 10. The relationship between fiberglass content to the weight versus its weight

Based on Fig. 9 and Fig. 10, fiberglass content of 1% has both compressive strength and weight higher over 3% content. These were due to the fibers is blocking the foam concrete entrance hence the more pores decrease their compressive strength.

4.4 Structural Analysis

4.4.1 Structural Loading on Slab Modeling

All dead loads were applied automatically including wire-mesh beam elements. Self-weight factor value was inputted as 1.05 due to bulge pouring such shown in Fig. 11.

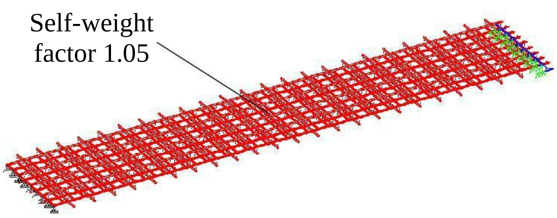


Fig. 11. All dead loads were applied automatically

The flexural loading used in this model was 4 points bending in the form of nodal line load on the certain area such as conceived in Fig. 12.

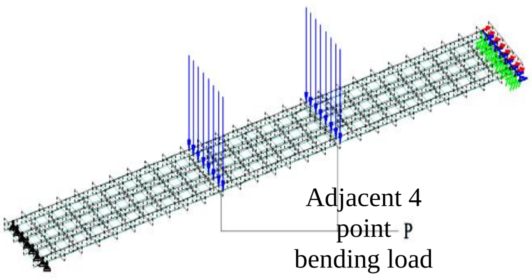


Fig. 12. Four-points bending load act on model

The P loads were begun from P = 0 kN in the quasi-static load of 200 kN until its failure. The distance of adjacent load ±0,5 m is from the center of slab length. Hence the total distance between adjacent load was 1m length.

4.4.2 Solid Element Stress Contours

The contour stress results can be drawn as Fig. 13, where the stress S_{xx} is the normal stress on X axis is a longitudinal slab axis, while the-Y axis and the-Z axis are vertical and lateral slab axis.

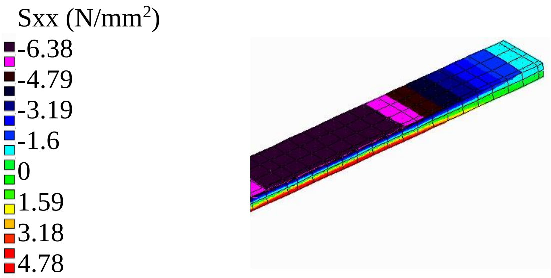


Fig. 13. Stress contour S_{xx} as -6.38 MPa which is compressive valued at the mid-span.

The normal stress contour S_{yy} in lateral local direction can be seen in Fig. 14.

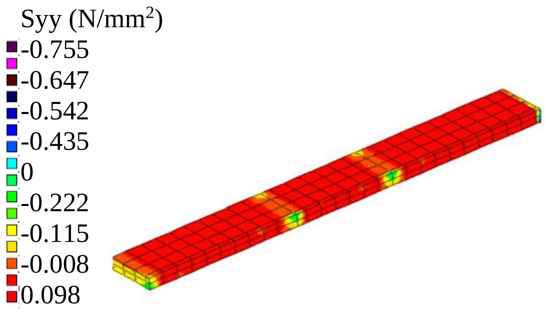


Fig. 14. Stress contour S_{yy} as -0.755 MPa which is compressive valued at the support

4.5 The four-point bending results of lightweight foamed concrete slab flexural test

The above analysis is then needed to be verified with 4-points bending test from 4 pieces of 3m span between support of 4.1m length and 0.5m width foamed concrete slab specimen geometry such as depicted in Fig.15.

Fig. 15. Slab flexure under 4 points bending load

The cracks propagated parallel with line load occurs in the bottom slab as seen in Fig. 16.

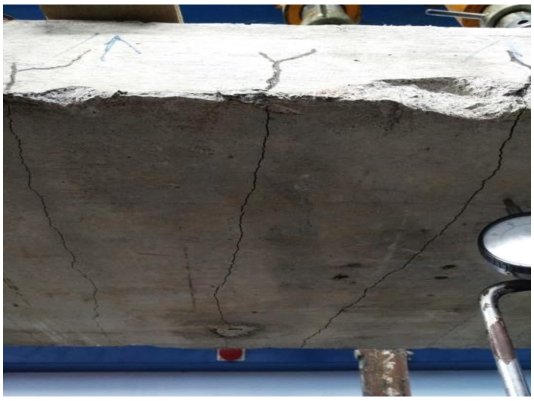


Fig. 16. Cracks on the specimen during loading test

Four dynamic strain amplifier NEC AS-1803 equipment were used to measure the strains of 1, 2, 3, and 4 channel data results are shown in Fig. 17.

Fig. 17. Dynamic strain amplifier AS-1803

The deflection results of specimen-1 compared among experimental tests (3m span of 4.1m length), and analysis model of beam, plate and solid elements idealization can be seen in Fig. 18.

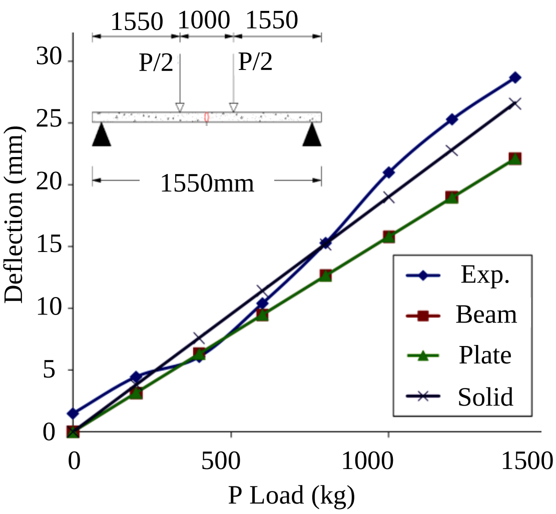


Fig. 18. Load-deflection curves of specimen-1.

The deflection comparison results from a comparison among experimental test, beam, plate and solid elements idealization of specimen-2 and specimen-3 can be seen in Fig.19 and Fig. 20 respectively.

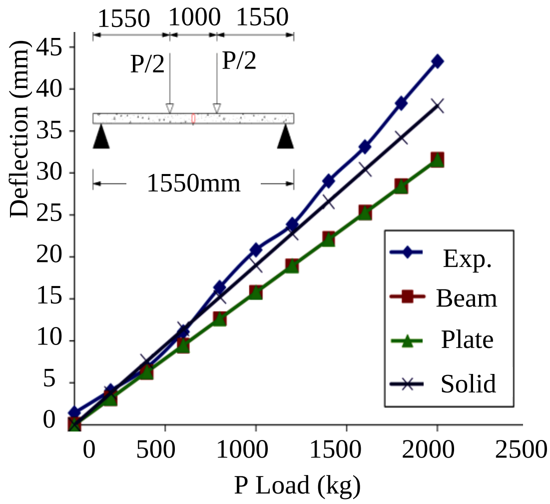


Fig. 19. Load-deflection curves of specimen-2

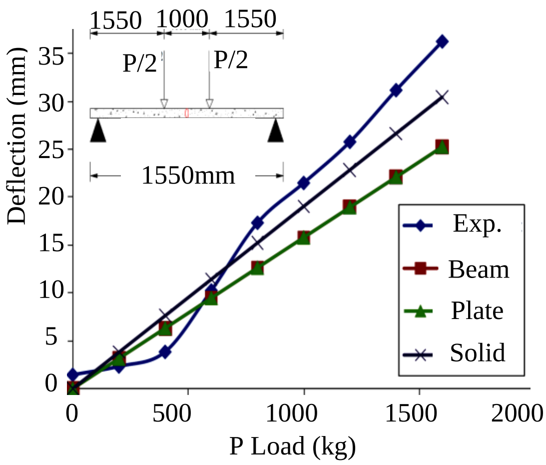


Fig.20. Load-deflection curves of specimen-3

From the discussion above, can be concluded deflection of experimental and analysis results in solid modeling has more closed results compared to the flexural test. Hence, solid element modeling can be used to estimate the deflection closely but suffer from time costly. Both beam and plate also not too far from the precise results, and for the sake of simplicity also can be used for initial analysis and design.

4.6 The structural efficiency values

The structural efficiencies, as well as the densities of these mixes and their appropriate compressive strength at 28 days, are listed in Table 8 and Table 9.

Table 8. Calculated structural efficiency using different fiberglass content

Fiberglass content (%)	Compressive Strength (MPa)	Dry Density (kg/m^3)	Structural Efficiency (Nm/kg)
1	7,67	1508,42	5,085
3	6,4	1335,58	4,792

Table 9. Calculated structural efficiency using different foam agent content

Foam Agent content (lt/m^3)	Compressive Strength (MPa)	Dry Density (kg/m^3)	Structural Efficiency (Nm/kg)
0	13,2	1960,94	6,731
0,4	8,43	1696,97	4,968
0,6	6,43	1433	4,487
0,8	2,8	1319,87	2,121

From the results above, lightweight foamed concrete with a variation of 0 lt/m^3 has the highest structural efficiency value of 6,731 Nm/kg and concrete with fiberglass variation of 1% the structural efficiency value is 5,085 Nm/kg.

5. CONCLUSION

Based on overall of lightweight foamed concrete test result, it can be concluded that

(1) The compressive strength was summarized as:
   a) variation of foam agent 0,6 lt/m^3 can be used for lightweight foamed concrete slab mixing because it has the best matched between specific gravity and compressive strength value which is closest to the specific gravity design of 1440 kg/m^3 and compressive strength design 10 MPa.
   b) The optimum result for compressive strength of lightweight concrete slab occurs at 1% in fiberglass content which is 7,67 MPa. The fiberglass increasing above 1% exhibits in no significant results, on the contrary their compressive strength tends to decrease.

(2) Based on the deflection results, the maximum deflection of the lightweight concrete slab is found optimum at dimension of 0,5m width and 0.12m depth, which its average is 34.67 mm.

(3) The closest element model was solid element that resulted in 37.08 mm which meet the 34.67 mm by test. And more practical run is found for beam element and also plate element as well, which exhibit more appropriate analysis of 31,64 mm deflection for both models, which is also not far from the 34.67 mm by test. Therefore, beam element is accurate enough for sake of simplicity, the solid element more accurate but tends to suffer from time consuming problem or costly both for modeling and running.

(4) From the structural efficiency results, it was found that the higher dry density specimens produced, the higher the value of its structural efficiency.

As an recommendation for future woks, as another research mainly studied the materials, a further investigation regarding the vibration response, its performance to the impact load, connection with adjacent beam is interesting topics to further examined basically.

6. ACKNOWLEDGMENTS

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