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# Performance Analysis of Shear Key in Autoclaved Aerated Concrete (AAC) Slab Subjected to Cyclic Loadings

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**ABSTRACT**

Currently, lightweight slabs made of Autoclaved Aerated Concrete (AAC) have been implemented as an alternative method compared to the conventional slab. This innovation is claimed to make the installation of the slab in buildings faster and more practical. The application of AAC slab for pedestrian bridge infrastructure is quite new and very challenging since the application of AAC slab exists joints between them and needs more careful attention. In the AAC slab method, the system of joints uses only mortar filling between the slabs, which is assumed to have a relatively small shear capacity. According to the requirements in Indonesian Standard (SNI 2847-2013), the behavior of slabs in the structural system must act as a single unit (monolithic system), so the AAC slab system must be able to transfer lateral loads that acts evenly on the vertical elements of the structural system. This research begins with experimental testing on the physical and mechanical properties of AAC slabs in terms of compressive strength, modulus of elasticity, specific gravity, moisture content, and tensile strength of steel reinforcement. These data are used as parameters to perform numerical simulations of the AAC slab as well as parameters for applying AAC slab to the pedestrian bridge structure. The results of numerical analysis using the ANSYS 2019 R3 software obtained the connection strength between AAC slab for a 1% shear target of 86.37 kN, a 2.5% shear target of 237.07 kN, a 5% shear target of 406.63 kN, and a 7.5% shear target of 399.93 kN, where the strength of the connection between the AAC slab has decreased at a shear distortion target of 7,5% or a displacement control of 45 mm. The results of modeling using the SAP2000 v14 software using the AAC slab on the pedestrian bridge structure can reduce the weight of the structure by 49.002% compared to the use of conventional slab.

***Keywords:*** *Shear Key, Slab, AAC, Diaphragm.*

## 1. INTRODUCTION

The development of science and technology in the field of construction continues to increase, this is indicated by the presence of various kinds of building materials. It gives more possibility to choose a variety of materials for the construction of a building. One of the innovations is aerated lightweight concrete (Autoclaved Aerated Concrete) which concrete is made of cement, silica sand, burnt lime, water, and aluminum paste as a chemical air filler. The nature of AAC material is light so that the structure receives a smaller load and automatically reduces the dimensions of other elements which results from a decrease in the total cost of the structure.

The AAC slab is more widely used for residential buildings, shopping centers, factories, hotels, and other buildings [1]. The installation of AAC slabs in buildings can be faster, more practical, does not require scaffolding or formwork, and does not need to wait for the curing process. Currently, the conventional concrete/steel slabs are used for a pedestrian bridge. The application of AAC slabs on the pedestrian bridge is relatively new and very challenging, since in its application always exist joint between slabs and needs more careful consideration.

Analysis of shear key performance has been carried out for Hollow Core Slab (HCS) precast concrete floors [2]. They discussed the effect of different type of shear keys on longitudinal joints which its function as a rigid diaphragm. The objective of this study is to investigate the performance of the shear key on the AAC slab as a structural diaphragm that meets the special requirements for earthquake loading according to SNI 2847-2013 [3]. The results of this study are expected to be used as a reference for product manufacturers and its use for applying and developing AAC slabs.

## 2. LITERATURE REVIEW

Autoclaved Aerated Concrete (AAC) as building materials have been industrially produced since the early 20th century. AAC is lightweight concrete made of raw materials such as cement, silica sand, burnt lime, water, and aluminum paste as a chemical air filler. The nature of AAC materials is light so that the structure receives a smaller load and automatically reduces the dimensions of other elements which results from a decrease in the total cost of the structure.

Some researchers have conducted several tests on AAC materials, namely as follows:

Genowefa Zapotoczna et. Al [4] investigated the characteristics of AAC (Autoclaved Aerated Concrete) in Poland. Their research includes specific gravity, compressive strength, resistance to cold weather (snow), heat transfer, resistance to fire, and acoustic insulation. The results showed that the specific gravity was 300 to 750 kg/m$^3$ with a compressive strength of about 1.5 up to 5 MPa. Due to cold weather, its strength decreases by 10%, in various cases found to be around 1-12%. The magnitude of the diffusion coefficient showed a value ranging from 5 to 18. Based on the test results at various humidity levels, it showed that the presence of mold has little effect on AAC. The absorption of AAC after 10 minutes was 50-204 g/ (m2s0.5), after 30 minutes was 46-179 g/(m2s0.5) and after 90 minutes was 44-162 g/(m2s0.5). Radioactive resistance depends on each manufacturer, if f1< 1.5 then the resistance is bad, and if f2 ≤ 240 Bq/kg then resistance is good. It has good fire resistance and good sound insulation properties due to its large porosity, so it can be soundproof.

P. Walczak [5] made a comparison about the compressive strength of AAC with samples taken from 9 different factories from various countries. The obtained compressive strength varies between 2.1 MPa to 5.1 MPa at a temperature of 50˚C. In addition, the obtained dry weight varies from 320 kg/m$^3$ to 570 kg/m$^3$.

J. Vengala, S. Mangloor, T. Krishna C. G. [6] studied the effect of AAC material properties on temperature. They obtained the average compressive strength of normal AAC materials with a specific gravity of 777.78 kg/m$^3$ is 4.5 MPa and its strength is reduced by 35% after being heated to a temperature of 1500˚C and then cooled with water.

Faqih Ma'arif, Slamet Widodo [7] conducted an experimental study of bond strength from mortar joint in autoclaved aerated concrete masonry prism. the value of shear bond strength of AAC masonry in SSC and SSB is 0.40 MPa and 0.04 MPa with the porosity and specific gravity of AAC concrete being 69.06% and 0.68 gr/cm$^3$, respectively.

Jennifer Tanner [8] examined the design of the AAC (Autoclaved Aerated Concrete) aerated lightweight structural wall system and the effects of earthquake forces. Tests were carried out on 17 walls of aerated lightweight brick with design specifications of 10 walls for shear damage and 7 for flexural damage. The loading is carried out by a quasi-static method in the lateral direction of the wall. The test results show that from the diaphragm floor to the AAC shear wall it is quite successful in transferring lateral forces with the proposed design. The crack patterns that occur are flexural cracks, shear cracks, a combination of flexural and shear cracks, cracks in the middle of the wall pair, slip cracks (bonding), diagonal cracks, and cracks due to axial forces. The magnitude of the flexural strength obtained is 1.11 to 1.34, with a total average of 1.22 and a coefficient of variation of 6.8%, the shear capacity of the wall is 130 kips with a drift ratio of about 0.7. The magnitude of the displacement ductility factor is between 2.5 and 6.

### *2.1. Compressive Strength*

The calculation of the compressive strength of each test object is based on ASTM C-1693 article 6 [9], as follows:

Compressive strength, $f = \frac{P}{A}$ (1)

Where f is the compressive strength of the test object, psi (Pa), P is the maximum load, lbf (N) and A is the cross-sectional area of the specimen, in$^2$ (mm$^2$).

### *2.2. Specific Gravity and Moisture Content*

The calculation of the moisture content (Moisture Content “MC”) of each test object is based on ATM C-1693 article 7 [9], as follows:

$$MC = \frac{(A-B)}{B} x\ 100\% \quad (2)$$

Where A is the sample mass of the specimen, lb (kg) and B is the dry mass of the specimen, lb (kg).

Calculation of dry specific gravity with the following equation:

$$\gamma = \frac{B}{V} \quad (3)$$

Where B is the dry mass of the specimen, lb (kg) and V is the volume of the specimen, ft$^3$ (m$^3$).

### *2.3. Elasticity Modulus*

Calculate the modulus of elasticity AAC ($E_c$) based on ASTM C-1693 article 9 [9] with the following equation:

$$E_c = \frac{f_b - f_a}{\varepsilon_b - \varepsilon_a} \quad (4)$$

Where $f_a, f_b$ is the stress recorded 0,05 $f'_{AAC}$ and 0,33 $f'_{AAC}$ while $\varepsilon_a, \varepsilon_b$ in the average strain is calculated at 0,05 $f'_{AAC}$ and 0,33 $f'_{AAC}$.

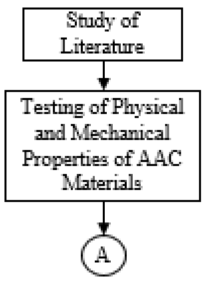
In the AAC slab system, the grouting function is like a bridge diaphragm, which unites all surrounding precast so that they can carry the load together. The presence of grouting causes an effect in the horizontal direction. The floor becomes solid since there is no gap between them. Thus, when there is a horizontal movement, it is expected that every point joined by grouting will have the same movement so it can be considered as a diaphragm effect.

The AAC slab joint system uses only mortar filling between the plates, which is assumed to have a relatively small shear capacity. The Indonesian Standard (SNI 2847-2013) [3] requires the plate must act as a single unit (monolithic system), so the AAC slab system must be able to transfer lateral loads that act evenly on the vertical supporting structural elements. Therefore, it is essential for research on the shear key connection between AAC slabs to quantify the horizontal shear force capacity and fulfill the requirements of a plate as a structural diaphragm which is the monolithic system.

Tianjung Zhang, et. Al [10] concluded that the shear failure pattern of the AAC slab is like the ordinary reinforced concrete. Shear compressive failure occurs when the shear span ratio (λ) is 2.5. This specimen is like the curvature of the tie rods. Aerated concrete forms a curved ring to withstand stress. When the shear span ratio (λ) is greater than 5, the diagonal stress failure occurs and the load when the inclined crack appears is essentially close to the specimen failure load and the shear bearing capacity of the section is generally very low.

## 3. METHODOLOGY

Overall, the flow of research to be carried out in this study is described through a flow chart as follows:



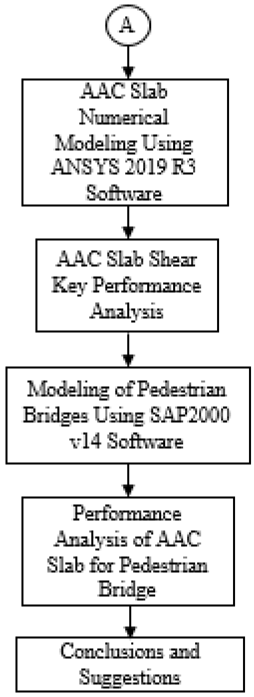




**Figure 1** Research Flowchart

The steps taken in this research are as follows:

1. Research begins by studying previous studies on AAC.

2. Testing the physical and mechanical properties of AAC material experimentally to obtain data in terms of compressive strength, modulus of elasticity, specific gravity, moisture content and tensile strength of steel reinforcement to be used.

a. The compressive strength test refers to ASTM C-1693 article 6 [9] which explains that the requirements for the number of compressive strength test objects should not be less than 3 pieces. The compressive strength test on AAC material is carried out by taking a sample of the test object using a cube-shaped mold with dimensions of 10x10 cm, with condition that the cube sample has a moisture content of 5-15%.

b. The modulus of elasticity test of AAC material is carried out simultaneously with the compressive strength based on ASTM C-39 [11], where the shortening of concrete at a certain load is measured using a dial gauge, then the modulus of elasticity is calculated using data on the shortening of concrete and the strain that occurs at a certain strain where the value of the modulus of elasticity in each specimen refers to ASTM C-1693 article 9 [9].

c. Specific gravity and water content testing refer to ASTM C-1693 article 7 [9], where the bulk weight is obtained from the measurement of the specimen beam 10x10 cm.

d. Three samples of reinforcement were taken with a length of 50 cm. The samples taken were intact reinforcement that had not been given an anti-corrosion coating. Tensile strength testing of reinforcement is carried out in the laboratory to obtain yield stress and ultimate stress.

4. Numerical modeling of AAC slabs is used to obtain shear key performance parameters on AAC slabs subjected to cyclic loading. The AAC slabs are modeled on a pedestrian bridge using finite element software. The physical and mechanical properties of the AAC materials were used as parameters in this modeling to investigate the behavior of the bridge using AAC slabs. The numerical simulations of AAC slabs are difficult to find in the literature compared to concrete materials in general [12-14], so it is very interesting and quite challenging.

## 4. RESULT

Experimental testing of physical and mechanical properties of AAC material will later be used as the parameters in numerical modeling and application to bridges structures.

### *4.1. Testing the physical and mechanical properties of AAC material*

Testing the physical and mechanical properties of AAC material experimentally to obtain data in terms of compressive strength, modulus of elasticity, specific gravity, moisture content and tensile strength of steel reinforcement to be used.

1. Compressive strength

Compressive testing is carried out in the Laboratory. The results of the compressive strength testing of cube specimens aged 1 day and 28 days, can be seen in the table, as follows:


**Figure 2** Cube Compressive Strength Test

**Table 1.** Cube Compressive Strength Test Day 1

| No. Test Object | Base Area | Max Load | Compressive Strength |
|---|---|---|---|
| | mm$^2$ | N | N/mm$^2$ |
| #1 | 10000 | 30177.42 | 3.02 |
| #2 | 10000 | 24063.83 | 2.41 |
| #3 | 10000 | 31213.95 | 3.12 |

**Table 2.** Cube Compressive Strength Test Day 28

| No. Test Object | Base Area | Max Load | Compressive Strength |
|---|---|---|---|
| | mm$^2$ | N | N/mm$^2$ |
| #1 | 9900 | 37356.48 | 3.77 |
| #2 | 9900 | 46597.50 | 4.71 |
| #3 | 9801 | 44969.04 | 4.59 |

2. Specific gravity and moisture content

The specific gravity test is to find out how many units of weight per m$^3$ are in the AAC material mixture. The results of the dry specific gravity test of the cube test object are shown in the table.


**Figure 3** Cube Specific Gravity Test

**Table 3.** Cube Specific Gravity Test

| No. Test Object | Volume | Weight | Specific Gravity | |
|---|---|---|---|---|
| | mm$^3$ | gr | gr/mm$^3$ | kg/m$^3$ |
| #1 | 990000 | 805 | 0.000813 | 813.13 |
| #2 | 980100 | 819 | 0.000836 | 835.63 |
| #3 | 970299 | 826 | 0.000851 | 851.28 |

Moisture content testing is carried out to find out how much water absorption is received by AAC concrete. The results of testing the moisture content of the cube test object are shown in the table.

**Figure 4** Cube Moisture Content Test

**Table 4.** Cube Moisture Content Test

| No. Test Object | Gross Weight | Dry Weight | Moisture Content |
|---|---|---|---|
| | gr | gr | % |
| #1 | 650 | 493 | 31.85 |
| #2 | 805 | 634 | 26.97 |
| #3 | 818 | 634 | 29.02 |

3. Modulus of elasticity

The modulus of elasticity is the ratio of the normal tensile or compressive stress to strain. From the 15/30-cylinder compression test, the AAC modulus elasticity is calculated regarding ASTM C-1693 [9]. The results of the modulus of elasticity can be seen in the table.

**Figure 5** Cylinder Modulus of Elasticity Test

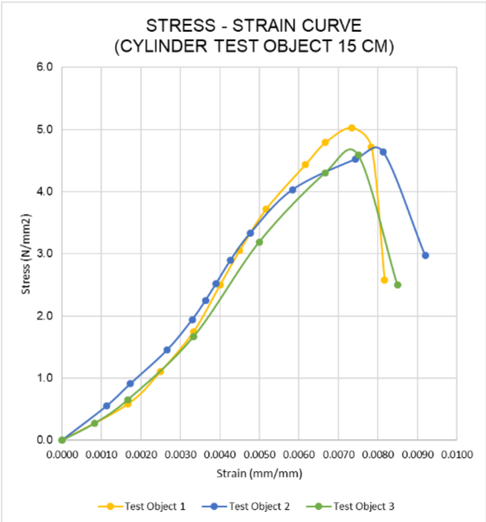



**Figure 6** Stress-Strain Curve (Cylinder Test Object)

**Table 5.** Cylinder Modulus of Elasticity Test

| No. Test Object | Stress Max | Strain Max | Modulus of Elasticity |
|---|---|---|---|
| | N/mm² | mm/mm | N/mm² |
| #1 | 5.0306 | 0.0073 | 586.980 |
| #2 | 4.5228 | 0.0074 | 560.431 |
| #3 | 4.5922 | 0.0075 | 526.850 |

4. Tensile strength of steel reinforcement

The tensile strength test of reinforcing steel is carried out to obtain the actual yield strength and tensile strength values. The results of the tensile strength test of steel are shown in the table.

**Table 6.** Tensile Strength of Steel Reinforcement

| No. Test Object | Diameter (mm) | *fy* (MPa) | *fu* (MPa) |
|---|---|---|---|
| #1 | 5.0 | 309.990 | 462.061 |
| #2 | 4.8 | 383.432 | 540.913 |
| #3 | 5.0 | 312.915 | 450.364 |
| Average | | 335.446 | 484.446 |

### *4.2. Finite element models*

The method used in this research is a numerical simulation using the ANSYS 2019 R3 program. The numerical simulation uses the AAC slab specimen model with dimensions of 1470x600x125 mm, with concrete quality and average density from laboratory test results, namely 4,36 MPa and 833,35 kg/m$^3$. For yield stress and tensile strengths, laboratory test results were taken as fy = 335.446 MPA and fu = 484.446 MPa.

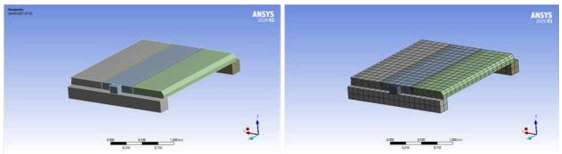


**Figure 7** Numerical Modeling and Meshing of AAC Plate

Numerical modeling of AAC slabs using software is used to obtain shear key performance parameters on AAC slabs with cyclic loading. To accurately represent the boundary conditions of the subdiaphragmatic region used in this study, displacement control is carried out.

**Table 7.** Cyclic Test Protocol: Target Shear Distortions and Displacements

| Shear Distortion (%) | Target Displacement (mm) |
|---|---|
| 0.010 | 6 |
| 0.025 | 15 |
| 0.050 | 30 |
| 0.075 | 45 |

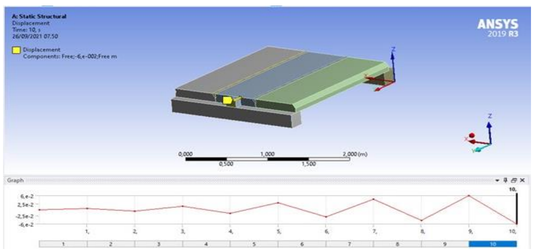



**Figure 8** Cyclic Test Protocol: Target Shear Distortions and Displacements

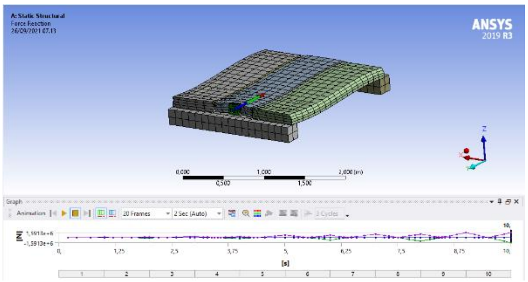



**Figure 9** Force Reaction

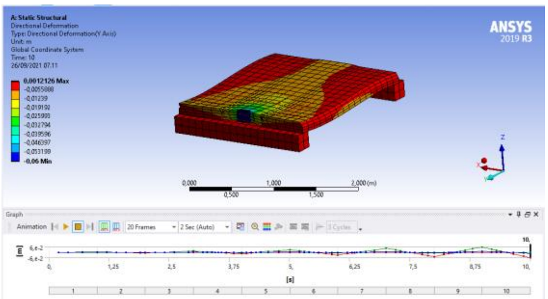
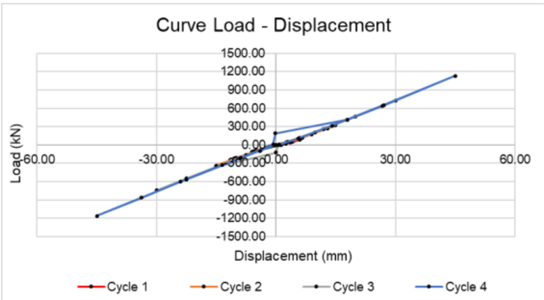
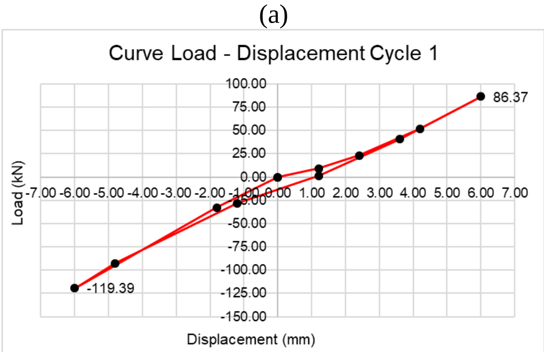



**Figure 10** Directional Deformation




(a)

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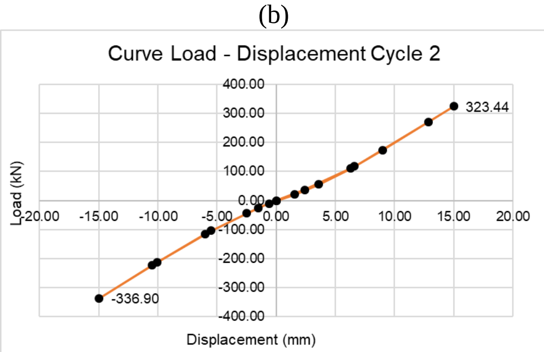


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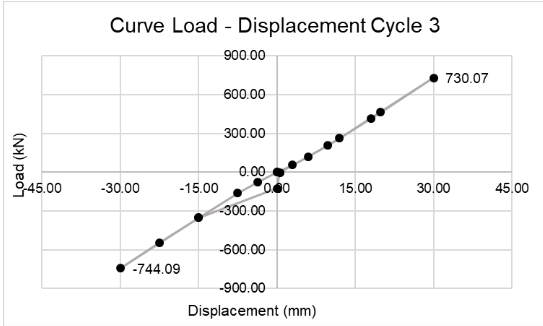
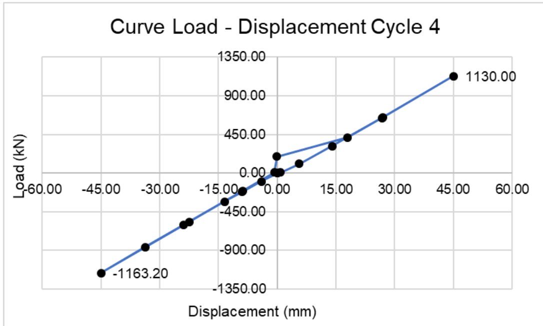



(d)




(f)

**Figure 11** Curve Load – Displacement (Cycle 1 to Cycle 4)

**Table 8.** Load Difference Accepted Connection Between AAC Slab

| Shear Distortion (%) | Load (kN) | The Difference in Charges Received (kN) |
|---|---|---|
| 1.0% | 86.37 | 86.37 |
| 2.5% | 323.44 | 237.07 |
| 5.0% | 730.07 | 406.63 |
| 7.5% | 1130 | 399.93 |

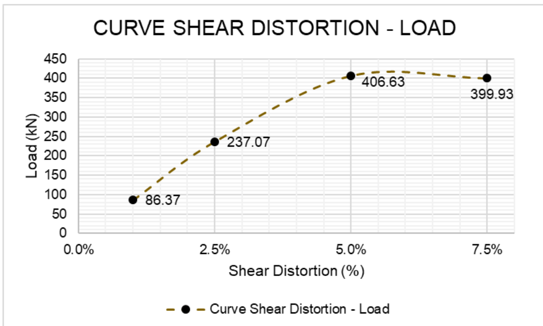



**Figure 12** Curve Shear Distortion - Load

## *4.3. Applications of AAC slabs for the pedestrian bridge*

The structural analysis of the pedestrian bridge modeling aims to compare the bridge using conventional concrete slabs with bridges using Autoclaved Aerated

Concrete (AAC) slabs. The result of the structural analysis are as follows:

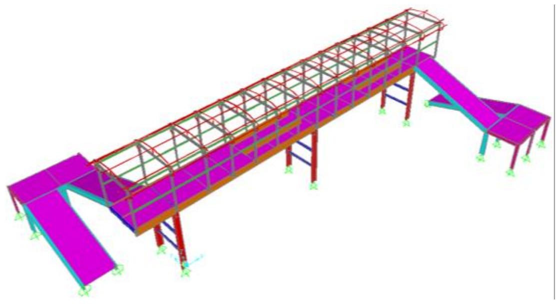


**Figure 13** Pedestrian Bridge Structure Modeling

1. Mode shape structure

The mode shape of the bridge structure for the use of AAC slab and conventional slab can be seen in the table.

**Table 9.** Modal Periods and Frequencies Pedestrian Bridge of Slab Conventional

| StepType | StepNum | Period | Frequency |
|---|---|---|---|
| Text | Unitless | Sec | Cyc/sec |
| Mode | 1 | 0.401 | 2.495 |
| Mode | 2 | 0.239 | 4.180 |
| Mode | 3 | 0.206 | 4.852 |
| Mode | 4 | 0.200 | 4.999 |

**Table 10.** Modal Periods and Frequencies Pedestrian Bridge of Slab AAC

| StepType | StepNum | Period | Frequency |
|---|---|---|---|
| Text | Unitless | Sec | Cyc/sec |
| Mode | 1 | 0.375 | 2.667 |
| Mode | 2 | 0.269 | 3.722 |
| Mode | 3 | 0.252 | 3.971 |
| Mode | 4 | 0.204 | 4.897 |

2. Self-Weight structure

The self-weight of the bridge structure for the use of AAC slab and conventional slab can be seen in the table.

**Table 11.** Masses and Weights

| GroupName | SelfWeight | Application |
|---|---|---|
| Text | Tonf | Text |
| All | 35.160 | AAC Slab |
| All | 52.389 | Conventional Slab |

3. Displacement structure

The displacement of the bridge structure for the use of AAC slab and conventional slab can be seen in the table.

**Table 12** Joint Displacements Pedestrian Bridge of Slab Conventional

| Joint | OutputCase | CaseType | U3 |
|---|---|---|---|
| Text | Text | Text | mm |
| 99 | Envelope | Combination | -12.989 |

**Table 13.** Joint Displacements Pedestrian Bridge of Slab AAC

| Joint | OutputCase | CaseType | U3 |
|---|---|---|---|
| Text | Text | Text | mm |
| 99 | Envelope | Combination | -15.517 |

## 5. CONCLUSION

The results of this study can be concluded as follows:

1. The result of the cube compressive strength test experienced a significant increase from the age of 1 day to 28 days by 52.93%. with an average modulus of elasticity of 558.087 N/mm$^2$, an average specific gravity value of 833.350 kg/m$^3$, and an average moisture content value of 29.28%. For yield stress and tensile strengths, laboratory test results were taken as fy = 335.446 MPA and fu = 484.446 MPa.
2. The results of numerical analysis using the ANSYS 2019 R3 software obtained the connection strength between AAC slab for a 1% shear target of 86.37 kN, a 2.5% shear target of 237.07 kN, a 5% shear target of 406.63 kN, and a 7.5% shear target of 399.93 kN, where the strength of the connection between the AAC slab has decreased at a shear distortion target of 7,5% or a displacement control of 45 mm.
3. The results of modeling using the SAP2000 v14 software using the AAC slab on the pedestrian bridge structure can reduce the weight of the structure by 49.002% compared to the use of conventional slab. In addition, the use of AAC slab is not significant in increasing the bridge structure, where the frequency results of AAC slab are not much different from a conventional slab. The deformation of the bridge structure with the use of an AAC slab is greater than that of a conventional slab which is influenced by the very low modulus of elasticity of the AAC slab.

## 6. SUGGESTION

Some of the suggestions made are as follows:

1. Testing of physical and mechanical properties of AAC material in this study has not been able to

present the quality of AAC material in Indonesia, so it is necessary to test other factory products with more samples and new variants.

2. Analysis of the shear key performance on the AAC slab needs to be done experimentally to present the failure pattern or the failure mechanism that occurs at the AAC slab connection due to the horizontal directional force that occurs.
3. The result of this study is good if the modeling shows the expected results.

## AUTHORS' CONTRIBUTIONS

This work was led by Luthfi, providing direction on research in general, providing recommendations on research stages, and numerical analysis. Fachmi conducted experimental tests (physical and mechanical properties of AAC), processed test data, reported the progress of experimental test results. Heri helps the process of experimental tests and reviewed them.

## ACKNOWLEDGMENTS

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## REFERENCES

[1] PT Beton Elemen Persada, Catalogue Leibel (Leicht Beton Element), Bandung, 2016.

[2] G. Soeprapto, M. Sunarso, S. F. Murdono, W. Agustin dan R. Siahaan, "Effect of longitudinal joint on the shear-key of hollow core slab which function as an rigid diaphragm," MATEC Web of Conferences 101, pp. 1-7, 2017.

[3] Badan Standardisasi Nasional, "SNI 2847-2013 About Structural Concrete Requirements for Buildings", Jakarta,2013

[4] G. Zapotoczna, "Autoclaved Aerated Concrete Properties on the basis current research result conducted by ICiMB - Research and Development Center for Cellular Concrete Industry CEBET and Building Research Institute," Handbook for AAC producers and users. Magazine of Concrete Producers Association. 5 International Conference of Autoclaved Aerated Concrete, 2011.

[5] P. Walczak, "Compressive Strength of Autoclaved Aerated Concrete : Test Methods Comparison," Brzesc Kujawski : Ernst & Sohn Verlag fur Architektur und Technische Wissenschaften GmbH & Co. KG, Berlin.

[6] J. Vengala, S. Mangloor dan T. Krishna, "Performance of Autoclaved Aerated Concrete Blocks Under Varying Temperatures," International Journal of Recent Technology and Engineering (IJRTE), pp. 615-619, 2019.

[7] F. Ma'arif dan S. Widodo, "Experimental Study of Mortar Joint Bond Strength of Autoclaved Aerated Concrete Masonry Prism," Proceeding of Annual South East Asian International Seminar (ASAIS), pp. 61-66, 2013.

[8] J. Tanner, J. Varela, M. Brightman, U. Cancino, J. Argudo dan R. Klingner, "Seismic Performace and Design Of Autoclaved Aerated Concrete (AAC) Structural Systems," dalam *13th World Conference on Earhquake Engineering*, Vancouver, B.C., Canada, 2004

[9] ASTM International, ASTM C1693-09 Standard Specification for Autoclaved Aerated Concrete (AAC), United States, December 2009.

[10] T. Zhang, J. Dai dan S. Qin, "Experimental Study on Shear Behavior of Reinforced Autoclaved Aerated Concrete Slab," International Conference on Electrical Automation and Mechanical Engineering, 2020.

[11] ASTM International, ASTM C39/C39M-14 Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, United States, March 2014.

[12] Mauludin, Luthfi M., Xiaoying Zhuang, and Timon Rabczuk. "Computational modeling of fracture in encapsulation-based self-healing concrete using cohesive elements." Composite Structures 196, pp. 63-75, 2018.

[13] Mauludin, Luthfi Muhammad, Chahmi Oucif, and Timon Rabczuk. "The effects of mismatch fracture properties in encapsulation-based self-healing concrete using cohesive-zone model." Frontiers of Structural and Civil Engineering 14 (3), pp. 792-801, 2020.

[14] Mauludin, Luthfi Muhammad, et al. "Numerical modeling of microcrack behavior in encapsulation-based self-healing concrete under uniaxial tension." Journal of Mechanical Science & Technology 34 (5), 2020.