Application of precast foamed concrete panels for the structural deck of green roof system

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Abstract. Rapid development in urban areas has caused many environmental problems, one of which is the phenomenon of urban heat island (UHI) which results in excessive energy usage. The building sector is the most responsible for energy use, which accounts for 40% of total energy consumption. A green roof is a sustainable solution to solve the problems related to urban heat islands. To reduce more structural self-weight, lightweight foamed concrete could be applied as a roof construction material. This paper presents experimental results on the structural behavior of a U-shape precast panel made of lightweight foamed. Three foamed concrete panels in the U-shaped form having different width dimensions of 200mm, 400mm and 600mm with a clear span of 1800 mm were cast and tested until failure under a double mid-span concentrated load. The panels were considered as a simple U-shaped beam filled with a growing medium for a green roof system. This result shows a potential use of foamed concrete for roof deck structure integrated with a green roof system. The U-shaped panel with a width of 400mm is the optimal form of the three tested specimens for the structural roof deck of the green roof system.

1. Introduction
Building construction in urban areas causes many environmental problems, including the urban heat island phenomenon. The temperature of cities continues to increase because of the heat island phenomenon and the climatic change. Using green roofs is an enormous potential for the urban environment in urban heat island mitigation [1,2] and shows an increase in the thermal performance of buildings in tropical regions [3,4,5].

The existence of plants on the building roof provides many ecological and economic benefits, including stormwater management, energy conservation, mitigating the effects of urban heat islands and extending the life of roofing materials, and providing aesthetically better environment [6]. More than an aesthetic function, green roofs give a greater advantage to buildings by reducing heat flow through evapotranspiration, shading the roof, and increasing roof insulation and thermal mass, thereby reducing energy requirements for cooling systems [7].

Construction and maintenance costs are the reasons green roofs have not been widely applied. The main disadvantages of the green roof are cost and weight. The green roofs add more weight to the structural load, which leads to changes in the structural design of columns, beams, and slabs, resulting in a more expensive structural cost [8,9]. Green roofs add 60 - 150 kg/m² (extensive) and 180 – 500
kg/m² (intensive) for the roof construction load with the green roof medium of 60-200 mm for extensive and 150 – 400mm for intensive [10]. This is a major disadvantage when applied to earthquake-prone areas like Indonesia. Using extensive types of green roofs is more likely to be applied in Indonesia given the lighter structural load and simpler application. Reducing the self-weight of the roof by using lightweight foamed concrete is an alternative to reduce the risk of building damage due to earthquake disasters.

Lightweight concrete has been used widely today because it has many advantages, including low density, low thermal conductivity, high flowability, and self-compacting. The density of foamed concrete ranges from 300 to 1800 kg/m³, which is significantly lower than that of normal concrete (2400 kg/m³). Cement, water, and foam compose foamed concrete [11,12,13]. With the density ranges that can be made, foamed concrete can be applied for both structural and non-structural construction. Due to distinctive properties of foamed concrete including density reduction, low thermal conductivity, high flowability, and self-compacting concrete, and given the ease to produce and its relative cost-effectiveness, foamed concrete has found applications in many civil and structural engineering areas [14].

One example application of lightweight concrete is as a structural panel wall in the form of precast. Many researches have focused on the use of lightweight foamed concrete for structural elements because it has the advantage of being lighter than conventional concrete. Using foam concrete panels for walls of buildings is commonly applied, but for the roof is still limited. This research initiates the use of precast foamed concrete panels for roofs by maximizing its benefits of being lightweight material with high heat resistance and the ability to reduce the heat flow to the room beneath by absorbing solar thermal radiation by the green roofs system. This combination is expected to reduce energy usage in buildings to mitigate the effects of urban heat islands in urban areas.

This study focuses on the structural behavior of foamed concrete panels when applied to a green roof system. The aim of this research is to investigate the flexural behaviors of a U-shaped lightweight foamed concrete panel. Three shapes of concrete panels were cast with a foamed concrete density of 1400 kg/m³ and reinforced by 8mm rebars and 1mm galvanized wire mesh. The behavior of the test object against loading is also analyzed based on crack patterns and failure modes. This paper discusses structural aspects in terms of the ability of foamed concrete panels to carry roof loads by adding green roof systems.

2. Experimental Program
2.1. Material
Materials used for the concrete mix are Portland cement (PC) Type-I, foam agent, and water. The physical and chemical properties of PC were not examined in this study since the material has been certified for Indonesian Standard (SNI) 03-2847-2002. However, we checked the physical condition of the packaging and the cement grains, which are still in good condition. The drinking water from the city supply was used in the experiments. The foam controls the density of concrete by incorporating pre-formed foam into a fresh concrete mix to obtain a target density of 1400 kg/m³ of fresh concrete. The ratio of a foaming agent to water is 1:30 by volume.

The foam generator produced foam from the foaming agent and a certain quantity of foam was poured to the concrete mix shortly after preparation to obtain the target density. To improve workability, we added a small amount of super-plasticizer to the concrete mix, which does not influence the characteristics of foamed concrete. The composition of foamed concrete mix calculated on the basis of specific gravity (SG 1.4) and water to cement ratio (w/c 0.4) comprises 1000 kg/m³ of PC, 400 kg/m³ of water, and 282.5 liter/m³ of foam. Six cylindrical specimens (Ø15-30) were cast to analyze the concrete characteristics in terms of their specific gravity and compressive strength. The samples were cured by wet covering (moist curing) method in a shaded area for 28 days before the test.
2.2. Precast panel specimens
Specimens for precast foamed concrete roof panels are U-shaped beams prepared with 3 different widths, namely 200mm, 400mm and 600mm with 40mm of thickness. The depth space for the green roof medium is 150mm and the total length of the beam is 2000mm. The panels use Ø8 mm steel and galvanized welded wire mesh (wire diameter 1.0 mm, opening square 1 inch) for reinforcement. Figure 1 shows the details of the panels with reinforcement bars and dimensions of the beams.

The specimens were cast based on the proportion of the mix design. The PC and water were weighed and mixed in a concrete mixer until it was mixed uniformly, then added the foam into the wet mix and controlled for the target density of 1400 kg/m³. The fresh concrete mix is then poured into the mold that has been prepared by the dimensions specified. We open the mold after 7 days of the concrete age and then cured by wet covering fabric (moist covering method) exposed to shaded open air before the flexural testing schedules.

![Figure 1. Cross-sections of precast foamed concrete panels with different width (unit in mm).](image)

2.3. Compression Test
The compressive strength test was conducted using a universal compression test machine with a constant load rate of 0.1 kN/s after 28 days of age. The test was performed under ASTM Standard C234. An axial compressive load with a specified rate of loading was applied to Ø15cm-50 cm until failure occurred. The compressive strength was obtained based on the average crushing strength of three crushed cylindrical specimens.

![Figure 2. Test specimen set-up.](image)
2.4. Full-Scale Flexural Test
All beams were tested to investigate the flexural capacity under pure bending by using four-point loading tests. Four-point symmetrical loading tests were adopted for the beam specimens under ASTM D6272-17. The dimension and the details of the specimens are shown in Figure 2. All beams were loaded constantly with a loading speed of 0.1 kN/s using a hydraulic press with an automatic recording of the applied force until failure.

To determine deflections, linear displacement transducers (LDT) set at five points along the specimen length (at supports, at loading points and in the middle of the span). Two LDTs at the loading positions and two LDTs at support positions were installed to ensure that both loading and support points were balanced during the test and one LDT was placed under the mid-span of the beams. The strain gauge and five LDTs that attached to the tested beam were connected to a data logger to obtain concrete strains as well as deflection at distinct levels of loading respectively throughout the testing period. During the test, photos were taken to observe cracking behavior and failure mode for the beams for visual analysis of strains and displacements, especially crack pattern and propagation.

3. Result and Discussion
3.1. Compressive strength
Consistency and stability checks are necessary to ensure that the mix is considerably stable. The stable mixture is achieved when the ratio of fresh density to chosen density and the ratio of fresh density to hardened density are kept to unity [15]. Table 1 shows the test result of cylindrical samples for the compressive strength and stability of the lightweight foamed concrete at 28 days of age. The average density of all samples is 1392 kg/m$^3$, only 0.5% less than the designated density of 1400 kg/m$^3$. This result shows a stable condition of foam with a ratio of 1.01 on average compared to the density of fresh foamed concrete. The average compressive strength is about 12 MPa, which is right for its density to density 1400 kg/m$^3$ as summarized from various literature [16]. The mixtures got a compressive strength lower than 17 MPa, which is the minimum requirement compressive strength for structural used concrete. However, the roof panels can be considered as a simple beam structure that mostly works on flexural load only.

| Cylindrical specimen | Specific gravity a (Kg/m$^3$) | Maximum load (Ton) | Compressive strength (MPa) | Stability b |
|-----------------------|-------------------------------|--------------------|---------------------------|-------------|
| Sample-1              | 1373.21                       | 20.00              | 11.10                     | 1.02        |
| Sample-2              | 1361.89                       | 22.00              | 12.21                     | 1.03        |
| Sample-3              | 1384.53                       | 21.00              | 11.65                     | 1.01        |
| Sample-4              | 1450.55                       | 24.00              | 13.32                     | 0.97        |
| Sample-5              | 1384.53                       | 22.00              | 12.21                     | 1.01        |
| Sample-6              | 1399.62                       | 21.00              | 11.65                     | 1.00        |
| Average               | 1392.39                       | 21.67              | 12.02                     | 1.01        |
| SD                    | 31.16                         | 1.37               | 0.76                      | 0.02        |

a based on the dry weight of cylinder samples at age 28 days
b ratio of fresh to harden foamed concrete

3.2. Deflections
Figure 3 illustrates the relationship between the load given to the deflection that occurs in the U-shaped beam specimen. The evaluation of the flexural behavior was made by recording failure load
and analysis of deformations during the test. Table 2 shows a summary of the achieved results for all beams. The Table includes the ultimate load, mid-span deflection at the ultimate load, experimental ultimate moment, and predicted moment for the green roof load on the day the experiment.

Table 2. Flexural test results for maximum load capacity, deflection, and estimated moment value for the extensive green roof.

| Specimen | Pmax (tf) | Defection (mm) | Mmax a (tf.m) | Mmax, green roof b (t.m) |
|----------|-----------|----------------|---------------|-------------------------|
| U20      | 2.89      | 21.14          | 0.87          | 0.053                   |
| U40      | 4.2       | 22.25          | 1.26          | 0.066                   |
| U60      | 3.49      | 14.63          | 1.05          | 0.079                   |

a Maximum bending moment calculated based on Pmax test results
b Maximum bending moment estimated based on maximum green roof load (60 - 150 kg/m²) for extensive green roof [10] and 100 kg at mid-span for live-load for a worker.

3.3. Ultimate moment capacity and cracking pattern

Based on the test results on all precast specimens, it shows that there are different behaviors for each test object. This result concludes that all beams fail in bending during the loading process. Figure 4 illustrates the load-deflection relationship of the specimens. The highest ultimate load and the ultimate moment is obtained for the U-40 specimen, namely 4.2 tf and 1.26 tf.m, respectively. Increasing the width of the panel cross-section does not increase the ultimate moment, thus reducing the ultimate load. This weakening can be explained based on the cracking and failure patterns that occurred during the test.

The failure of U-60 is different from that for U-20 and U-40, as shown in Figure 4. The initial cracking and failure of the specimens U-20 and U40 occurred at the bottom part of the specimens (tension zone) at the loading points. As for the U-60, the bending failure occurs at the top side of the specimen (compression zone). It can be explained that the failure occurred due to the increase of the cross-section area and reinforcement in the tension zone, while in the compressive zone there was no difference with the U-20 and U-40. This causes an increase in the moment of resistance in the tension zone, resulting in weakening in the compressive zone. From these results, it can be concluded that
increasing the size of the precast panel does not improve moment capacity. Based on this test, the optimum panel width is 400mm.

Figure 4. Deflection at the mid-span recorded during the test for each specimen.

3.4. Green roof application
The test results of precast foamed concrete panel specimens have shown the performance of foamed concrete for roof construction, which also functions as a green roof system. In this study, the roof panel is treated as a simple beam on two supports with a 1800mm of span. Based on the loading scheme provided, the strength of the beam can be seen from the value of the ultimate moment for U-40 is equal to 1.26 tm when the panel failure due to maximum loading. Table 2 shows the comparison of the ultimate moments and maximum moment for all panel specimens with the green roof load assumed to be 60 - 150 kg/m² for an extensive green roof system [10]. The panels also add the live load that works on the roof at 100 kg (the maximum moment at mid-span). The maximum moment with a green roof load that occurs in each panel (Table 2) is still much smaller than the ultimate moment. The U-40 panel that has the best performance shows that the maximum moment of the green roof load is only 5% of the ultimate moment. With this assumption, using a 4000mm span still produces a maximum moment of 0.22 tm (10% ultimate moment) for the U-40 panels. However, this assumption is still general, which requires further study of the behavior of U-shaped panels from various dimensions and other aspects.

Another application form of the panel as a green roof is by treating the panel as a roof cover that is placed on top of the girder with a shorter span (for example 1000mm), as on conventional roof construction. The panels only function as a container for the green roof and transfer the load to the girder construction underneath. Thus, the thickness of the panel can be reduced so that its weight also decreases, which then makes the installation process easier.

This research has shown the prospect of using integrated precast foamed concrete panels as a green roof system as an initiation of the use of green roofs for areas prone to earthquake hazards. However, further investigation is still needed about the behavior of foam concrete to loading for various combinations of dimensions of the U-shaped precast panel. The use of panels as a roof also still
requires practical applications for the systems such as inter-panel connection systems, waterproofing systems, green roof drainage systems, and various other technical aspects.

4. Conclusions
Applications of lightweight foamed concrete as green roof construction to reduce structural self-weight have been discussed in this paper. This paper presents experimental results on the structural behavior of a U-shape precast panel made of lightweight foamed. Three foamed concrete panels in the U-shaped form having different width dimensions of 200mm, 400mm and 600mm were tested until failure under a double mid-span concentrated load. The panels were considered as a simple U-shaped beam filled with a growing medium for a green roof system. The U-shaped panel with a width of 400mm is the best form of the three tested specimens for the structural roof deck of the green roof system. The maximum moment calculated based on a green roof load is lower than the ultimate moment based on test results. This result shows a potential use of foamed concrete for roof deck structure integrated with a green roof system. Further study requires practical applications of systems such as inter-panel connection systems, waterproofing systems, green roof drainage systems, and various other technical aspects.

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