Effect of notch position on fracture energy for foamed concrete

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Abstract. Foamed concrete is one of the lightweight concrete used to replace normal concrete. Foamed concrete has potential as a building construction material in Malaysia due to low density range. However, the behavior of fracture energy on foamed concrete still under investigation. Therefore, a study to determine the fracture energy of foamed concrete was conducted. In this study, foamed concrete fracture energy was obtained using the three-point bending test methods develop by RILEM and Hillerborg. A total of 12 beams with different types of notch and positions of notch were tested on the load–deflection condition. In addition, a total of 9 cube samples were cast to support the result of fracture energy by using model from Bazant and Becq-Giraudon and Comite Euro-International du Beton (CEB). Results showed the farther the position of the notch from midpoint, the higher the value of fracture energy. In this study, the value of fracture energy ranges between 15 N/m and 40 N/m.

1. Introduction
In concrete construction, permanent action that included self-weight contributes a very large proportion of the total load of structures. To reduce the dead weight, the use of foamed concrete is one of the solution. Typically the density of foam concrete are range around 1000 kg/m³ to 1800kg/m³ while the compressive strength can be achieved up to 12 MPa [1]. Therefore, using lightweight concrete, such as foamed concrete, can reduce the self-weight of concrete structures. Lightweight concrete has unique benefits in construction to increase productivity such as low density and thermal conductivity.

From previous studies, researchers have focused more on the behavior of foamed concrete in terms of density, permeability, compressive strength, and other factors. The behavior of fracture energy on foamed concrete is still under investigation. Fracture energy can be defined as energy required to open a unit area of crack surface. A current study showed that fracture energy was influenced by the properties of aggregate, with high strength aggregate producing high fracture energy [2-4]. Fracture energy, $G_f$, is the energy required to form a unit area of crack. Fracture energy on concrete is important when concrete fails in tension. This behavior is characterized by the peak stress and the energy required to open the crack fully. Conventional concrete have a fracture energy approximately 75- 100N/m depending on the grade of concrete [5]. Meanwhile fracture energy of foamed concrete is roughly between 15 – 35N/m [6-10].

Three empirical formulas from RILEM and Hillerborg [4], Bazant and Becq-Giraudon [2], and Comite Euro-International du Beton (CEB) [11] is used to determine fracture energy.
The Hillerborg model is assumed that crack bridging stress in the fracture zone is a function of the crack opening displacement of materials [3] and known as a load–deflection method. The fracture energy using Hillerborg model can be obtained from equation 1:

\[ G_f = \frac{(W_o + m_g \delta_f)}{A} \]  

where: \( W_o \) is area under the load-deflection curve, \( m_g \) is mass of the specimens, \( \delta_f \) is maximum deflection and \( A \) is the cross section area of the specimen.

According to Rahman and Jaini [10], the value of fracture energy was influenced by the size of the specimen and the load-deflection curve.

Therefore to support the fracture energy value proposed by RILEM and Hillerborg model’s, Bazant and Becq-Giraudon and Comite Euro-International du Beton (CEB) were used as a comparison for fracture energy determination. Bazant and CEB also known as size effect method where we can see in equation 2 and 3 respectively. From this model, fracture energy will be influenced directly by compressive strength (\( f_c \)), aggregate size (\( D_{\text{max}} \)), and water–cement ratio (\( w/c \)).

\[ G_f = 2.5 \alpha_o \left( \frac{f_c}{0.058} \right)^{0.4} \left( 1 + \frac{D_{\text{max}}}{1.94} \right)^{0.43} \left( \frac{w/c}{c} \right)^{-0.18} \]  

\[ G_f = \left[ 0.0469(D_{\text{max}})^2 - 0.5D_{\text{max}} + 26 \right] \times \left( \frac{f_c}{10} \right)^{0.7} \]

The aim of this study is to obtain the value of fracture energy based on the mortar formulation of fracture energy. Previous studies showed the value of fracture energy for foamed concrete with a density of 1400 kg/m³ to 1,600 kg/m³ ranges between 18 N/m and 25 N/m [11].

2. Materials and method

Materials used in this study are fine aggregate, cement, water, and foaming agent and foamed concrete with a density of 1400 kg/m³. The methodology will be explained in following sub section to achieve the aim of this study. Several tests were conducted to investigate the fracture energy of foamed concrete.

2.1. Specimen

All beams were designed with the dimension of 150 mm \( \times \) 150 mm \( \times \) 700 mm and with different distances of U-notch and V-notch, which are at the midpoint of the beam, 100 mm from the midpoint, and 200 mm from the midpoint. In this study, two beam specimens were prepared for different notch positions. The design of notched beam specimens is based on RILEM [12] and ASTM E1820-13 [13].
2.2. Compression test
Compression test was conducted based on BSEN12390: Part 3 [14] to determine the strength of the material. The results of compressive strength are shown in figure 2. Result showed the compressive strength for this study is 4.3 MPa at 28 days, where the strength is lower than propose strength by British Cement Association [15] due to the selection of formwork made by wood that used in this experiment. Wood formwork absorb more water and caused the composition of foamed concrete disrupted and at a time made the strength of foamed concrete decreased. The compressive strength proposed by British Cement Association for density 1400kg/m³ ranges between 6.0 MPa and 8.0 MPa.

2.3. Experimental test
Three-point bending test (figure 3) was conducted on beam specimens to determine maximum force applied, deflection, and failure behavior after the specimen failed. From the test, the maximum load and maximum deflection at U-notch and V-notch were determined.

3. Result and discussion
3.1. Load–Displacement
Table 1 shows the results of the maximum load of beam with maximum deflection. The graph of load against deflection is plotted and shown in figure 4.
Table 1. Results of maximum load and maximum deflection

| Beam specimen | Notch type | Notch position from midpoint (mm) | Maximum load (N) | Maximum deflection (mm) |
|---------------|------------|----------------------------------|-----------------|------------------------|
| FCB-U0        | U          | 0                                | 2,087.50        | 0.688                  |
| FCB-V0        | V          | 0                                | 1,081.00        | 0.640                  |
| FCB-U100      | U          | 100                              | 3,518.75        | 0.789                  |
| FCB-V100      | V          | 100                              | 1,894.00        | 0.870                  |
| FCB-U200      | U          | 200                              | 3,844.00        | 1.298                  |
| FCB-V200      | V          | 200                              | 2,237.50        | 0.925                  |

Figure 4 shows the variations of load against deflection for two types of notch which are U-notch (U) and V-notch (V) at different distances. Figure 4 and table 1 showed that the further the position of the notch from the midpoint, the higher the values of load and deflection. The high value of load of 4.3 kN occurred on the sample with U-notch for all the distance of notch from the midpoint. In addition, the load of the sample with V-notch is lower than that of the sample with U-notch at the distance of 200 mm from the midpoint. Thus, the load that occurred on the sample with U-notch is higher than that on the sample with V-notch because the specimen needs to develop a crack between two edges before the crack appeared on either edge and resulted in failure. By contrast, for V-notch, the crack directly occurred on the edge of the notch, resulting in the lower value of load. Thus, the development of deflection can also be observed when the position of the notch is far from the midpoint, which will increase the value of deflection itself.

3.2. Fracture Energy
Fracture energy, $G_f$, is determined using data collected from the three-point bending test. The value of fracture energy is computed using three empirical equations derived from three reference equations, as follows:

i. Hillerborg [4] model;
ii. Bazant and Becq-Giraudon [2] model;
iii. CEB [11] model.
Figure 4. Graph of load versus deflection $G_f$, a) U-notch beam b) V-notch beam

Table 2. Analysis of fracture energy, $G_f$, by Hillerborg [4] model

| Notch position | $W_0$ (Nm) | Mass (kg) | $g$ (N) | $\delta_f$ (mm) | $A$ ($m^2$) | $G_f$ (N/m) |
|----------------|------------|-----------|---------|-----------------|-------------|--------------|
| FCB-U0         | 0.17       | 21.83     | 9.81    | 0.69            | 0.0158      | 20.280       |
| FCB-V0         | 0.07       | 22.34     | 9.81    | 0.71            | 0.0158      | 14.170       |
| FCB-U100       | 0.22       | 22.00     | 9.81    | 0.79            | 0.0158      | 24.800       |
| FCB-V100       | 0.20       | 21.71     | 9.81    | 1.26            | 0.0158      | 29.270       |
| FCB-U200       | 0.22       | 21.91     | 9.81    | 1.16            | 0.0158      | 30.360       |
| FCB-V200       | 0.28       | 21.90     | 9.81    | 1.10            | 0.0158      | 32.300       |

Results in table 2 shows that the value of fracture energy varies with different equations, where the value of fracture energy for foamed concrete ranges between 15 N/m and 40 N/m [8]. The values obtained from the equations derived from Hillerborg [4] model (table 2) and from Bazant and Becq-Giraudon model (table 3) are 15 N/m to 35 N/m and 15.595 N/m, respectively. Using Hillerborg model, the lowest value of $G_f$ is on the midpoint with V-notch (14.170 N/m), whereas the highest value
of $G_f$ is on 200 mm from the midpoint with V-notch (32.300 N/m). The calculation of $G_f$ from Hillerborg model depends on the area under the graph, which will result in a high value of fracture energy when the area is large. The notch shape does not significantly affect the fracture energy where the percentage is 10% in average. The test done by Rahman [7] was shown that there are 15% of average for different notch shape and different density.

The formula proposed by Bazant and Becq-Giraudon model and CEB model was used to support the calculation of fracture energy using the formula derived from Hillerborg model. Table 3 and Figure 5 shows that fracture energy, $G_f$, from Bazant and Becq-Giraudon model is 15.595 N/m, whereas that from CEB model is slightly lower at 14.400 N/m. This is due to the model proposed by CEB does not take into account the w/c ratio meanwhile the Bazant and Becq-Giraudan model does take into account the w/c ratio. Fracture energy obtained using this formula is slightly lower because of the lower compressive strength. Thus, it still supports the value of fracture energy and can be accepted when the value lies in the range previously stated.

Table 3. Analysis of fracture energy, $G_f$, using model Bazant and Becq-Giraudon and CEB

| Equation | $D_{max}$ (m) | w/c | Compressive strength, $f_c$ (MPa) | $G_f$ (N/m) |
|----------|---------------|-----|----------------------------------|------------|
| (2)      | 0.003         | 0.55| 4.3                             | 15.595     |
| (3)      | 0.003         | Nil | 4.3                             | 14.400     |

4. Conclusion
The study was conducted to determine the effect of distance on notch position under the three-point test. The Results using the Hillerborg model shows that different positions of the notch will directly affect the value of fracture energy. Meanwhile fracture energy using model Bazant and Becq-Giraudon and CEB does not show an effect to the fracture energy. This is due to the both of model only affected by the diameter of aggregate and the compressive strength.

Figure 5. Overall fracture energy, $G_f$
Overall, study shows that, the further the position of the notch from the midpoint, the higher the value of fracture energy. The overall fracture energy for U-notch and V-notch ranges between 15 N/m and 35 N/m.
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