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Fracture energy of foamed concrete based on three-point bending test on notched beams

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Abstract

A series of static loading tests was performed to determine the fracture properties of foamed concrete of varying density. Beams with dimensions of 100×100×840 mm with a central notch were tested in three-point bending. Then, remaining halves of the specimens were tested again as un-notched beams in the same set-up with reduced distance between supports. The tests were performed in a hydraulic displacement controlled testing machine with a load capacity of 5 kN. Apart from measuring the loading and mid-span displacement, a crack mouth opening displacement (CMOD) was monitored. Based on the load – displacement curves of notched beams the values of fracture energy and tensile stress at failure were calculated. Subsequently, the flexural tensile strength was obtained on un-notched beams with dimensions of 100×100×420 mm. Moreover, cube specimens 150×150×150 mm were tested in compression to determine the compressive strength.

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Keywords: fracture energy; foamed concrete; three-point bending; notched beams

1. Introduction

Foamed concrete can be defined as a cementitious material with minimum of 20% (by volume) [1] of mechanically entrained foam in the mortar suspension in which air-pores are entrapped in the matrix by means

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of a suitable foaming agent. Foamed concrete is widely known for its low self-weight and excellent acoustic and thermal properties [2]. For many years, it has been used worldwide for backfill to retaining walls, insulation to foundations and roof tiles, sound insulation, etc. However, in the last years foamed concrete has become a promising material [3] also for structural purposes e.g. for stabilization of weak soils [4] and as a base layer in a sandwich solution for foundation slabs [5].

Due to favourable properties of foamed concrete, many interests and studies were conducted to investigate its strength, mechanical, acoustic and thermal properties. However, these studies do not cover the investigation of fracture energy which is the main parameter governing the damage and fracture mechanisms. Only limited number of studies can be found in literature. Rahman and Jaini [6] performed studies of fracture energy of foamed concrete on notched beams with the density of 1400−1600 kg/m^3. The fracture energy of foamed concrete with compressive strength of 6.4−14 MPa was relatively high around 18−25 N/m. Furthermore, Hengst and Tressler [7] stated that for lightweight concrete, the fracture energy is only a fraction of the normal weight concrete.

The main aim of the research was to determine the fracture energy and mechanical properties of foamed concrete of varying density. The knowledge is required for further numerical simulations of structural behavior and modelling of cracking. This work was supported by the on-going research project “Stabilization of weak soil by application of layer of foamed concrete used in contact with subsoil” (LIDER/022/537/L-4/NCBR/2013) financed by The National Centre for Research and Development within the LIDER Programme.

2. Material and methods

2.1. Materials

An ordinary Portland cement (CEM I 42.5 R) was used in this research. Water used was fresh, clean and drinkable water. Foam was produced by mixing the foaming agent and water in predefined proportions in a foam generator. Subsequently, the foam was mixed with cement in a concrete mixer. After casting in steel molds, the specimens were covered and stored in a curing room at 20±1ºC and 95% humidity for the first 24 hours. Subsequently, the beams were removed from the molds and stored in ambient conditions for 28 days before testing. In this study, four different concrete mixes resulting in varying densities were used, see Table 1. All concrete mixes produced had w_{eff}/c of 0.44.

Table 1. Mix proportions, density and compressive strength of produced specimens.

Specimen type	Cement (c) [kg/m^3]	Water (w) [dm^3/m^3]	Foaming agent [dm^3/m^3]	w_{eff}/c*	Density (ρ) [kg/dm^3]	Compressive strength [MPa]
A	750	300	30	0.44	1024 ± 1.0	5.9 ± 0.2
B	634	241	38		882 ± 0.5	4.4 ± 0.2
C	514	190	36		662 ± 2.0	2.4 ± 0.3
D	386	143	27		488 ± 0.5	0.6 ± 0.2

* – w_{eff}/c includes foaming agent in a liquid state

In total 32 specimens were fabricated, five beam and three cube specimens for the same mix. The beams measured 100×100×840 mm. A 3 mm wide mechanical notch was fabricated with a depth (a) of 42 mm, resulting with a notch to beam depth ratio (a/d) of 0.42. For standardized fracture energy tests [8], the required a/d ratio ranges from 0.45 to 0.55. However, using deep notched beams specimens with foamed concrete may produce undesirable test results, such as large statistical variation and crack initiation under self-weight. The cubes measured 150×150×150 mm. Before testing all manufactured specimens were measured and weighted. Table 1 presents the densities calculated as well as the values of compressive strength determined based on the cube specimens.

2.2. Methods

In this study two testing procedures were performed. In the test I a three-point bending test was performed on notched beams to determine the fracture energy (G_F) and maximal tensile stress (σ_c), according to [8, 9]. Then, in the test II, two halves of the specimens left after test I (after breakage) were tested in a three-point bending to determine the flexural tensile stress (f_t) on un-notched beams with respect to [10].

The test set-up I was a three-point bending test on notched beams with dimensions of 100×100×840 mm, see Figure 1. The nominal distance between the supports (l) was 800 mm, while the loading was introduced at mid-span of the beam. The rollers allowed for free horizontal movement. The specimens were loaded at constant displacement rate of 0.1 mm/min. The tests were performed in a displacement controlled hydraulic testing machine with a capacity of 5 kN. Apart from measuring the loading and mid-span displacement, a crack mouth opening displacement (CMOD) was also monitored. To measure the CMOD an extensometer with a gauge length of 5 mm was mounted across the notch.

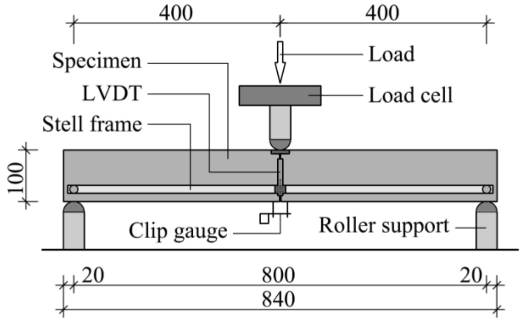

Fig. 1. Test set-up I.

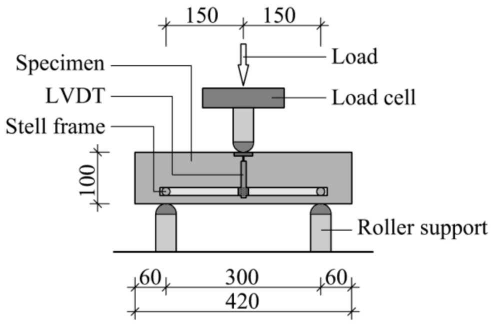

Fig. 2. Test set-up II.

Test set-up II was a three-point bending test on un-notched beams with dimensions of 100×100×420 mm, see Figure 2. Two halves of broken beams after test I were used in this test. The nominal distance between the supports was 300 mm and the loading was introduced at mid-span of the beam. The rollers allowed for free horizontal movement. The specimens were loaded at constant displacement rate of 0.1 mm/min. The tests were performed in a displacement controlled hydraulic testing machine with a capacity of 5 kN. In the test the loading and mid-span displacement was measured.

3. Results and discussion

The main objective of this study was to investigate the influence of density of foamed concrete on the fracture energy and mechanical properties based on three-point bending tests on notched and un-notched beams.

3.1. Notched beams

Figure 3 presents typical load vs. CMOD/deflection plots for selected specimens of group A, B, C and D, see Table 1. Typical load-deflection plot (e.g. Figure 3A) comprises three stages of behavior. In the first phase (1) the deflection increases linearly with the load while the notch is opened but does not extend. A fracture process develops during the second phase (2) where microcracks form and slow crack growth is noticeable. In the third phase (3), known as strain softening, rapid crack growth is apparent.

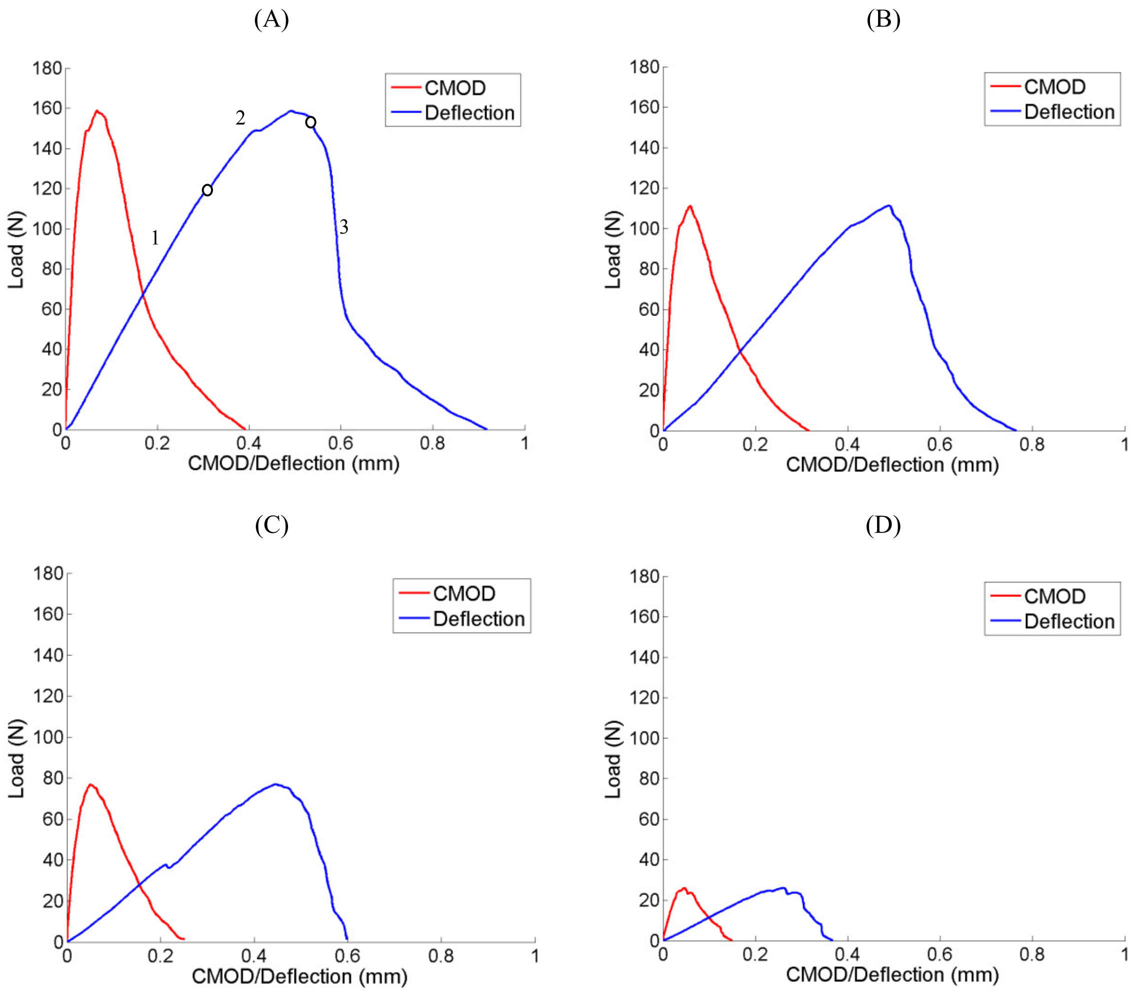

Fig. 3. Load vs. CMOD/deflection plots for specimens A, B, C, D.

The fracture energy (G_F) was calculated as the total energy consumption divided by the cross-sectional area of the ligament over the notch. The total energy was calculated as a sum of the area of the complete load-deflection curve and work done by the deadweight of the specimen, according to formula:

$$G_F = \frac{W_0 + mg\delta}{(d-a)b} \tag{1}$$

where W_0 is the area of the complete load-deflection curve, *m* is the weight of the beam between the supports, calculated as the beam weight multiplied by *l/L, g* is the acceleration due to gravity, δ is the deformation at the final failure of the beam, *d* is the beam height, *b* is the beam width, *a* is the notch depth. Additionally, G_F was calculated based on load-CMOD curve.

The maximal tensile stress (σ_c) was obtained on notched beams after other researchers [11]. In the present work it was calculated using the following equation:

$$f_t = \frac{3P_{max}l}{2b(d-a)^2} \tag{2}$$

where P_{max} is the maximal load, *l* is the span of the beam, *b* is the beam width, *d* is the beam height, *a* is the notch depth.

The results obtained on the notched beams are presented in Table 2. As expected, the increase of density results in an increase of fracture energy and maximal tensile stress of tested beams. The fracture energy was calculated based on the area under load-deflection and load-CMOD curves, resulting in $G_{F(u)}$ and $G_{F(CMOD)}$. The $G_{F(CMOD)}$ to $G_{F(u)}$ ratio for all tested beams was constant and equals 0.37 ± 0.01, see Table 2 and Figure 4a. This confirms the finding made by others [12] that the factor representing the ratio between deflection *u* and CMOD can be calculated as $\alpha_{u,CMOD}=l/4(D-(d-a)/2)$. For the tested beams the factor was 0.36.

Table 2. Test results of notched beams. The mean values of fracture energy and maximal tensile stress.

Specimen type	$G_{F(u)}$ [N/m]	$G_{F(CMOD)}$ [N/m]	$G_{F(CMOD)}/G_{F(u)}$	σ_c [MPa]
A	12.54 ± 0.21	4.94 ± 0.09	0.39	0.555 ± 0.01
B	6.55 ± 0.42	2.53 ± 0.12	0.38	0.350 ± 0.01
C	4.95 ± 0.08	1.81 ± 0.10	0.36	0.278 ± 0.01
D	1.39 ± 0.12	0.48 ± 0.03	0.34	0.112 ± 0.01

3.2. Un-notched beams

Results of flexural strength of the un-notched beams are presented in Table 3. As expected, the increase of density causes the increase of flexural strength of foamed concrete, see Figure 4b.

Table 3. Test results of un-notched beams: mean values of flexural strength.

Specimen type	f_t [MPa]
A	0.585 ± 0.37
B	0.550 ± 0.22
C	0.362 ± 0.24
D	0.163 ± 0.09

4. Conclusions

Experiments were conducted to determine the fracture and mechanical properties of foamed concrete of varying density in three-point bending on notched and un-notched beams. The main conclusions that can be drawn from this study are the following:

- An increase of the density of foamed concrete results in an increase of fracture energy (G_F) and maximal tensile stress (σ_c). For the notched beams of density of 488–1024 kg/m^3 the mean values (based on five specimens per mix) of G_F (based on the load-deflection relationship) and σ_c obtained were of 1.39–12.54 N/m and 0.112–0.555 MPa, respectively. The $G_{F(CMOD)}$ to $G_{F(u)}$ ratio for all tested beams was constant and equals 0.37± 0.01;

- The mean value of flexural tensile strength (based on ten specimens per mix) obtained for the un-notched beams of density of 488–1024 kg/m^3 was 0.163–0.585 MPa.

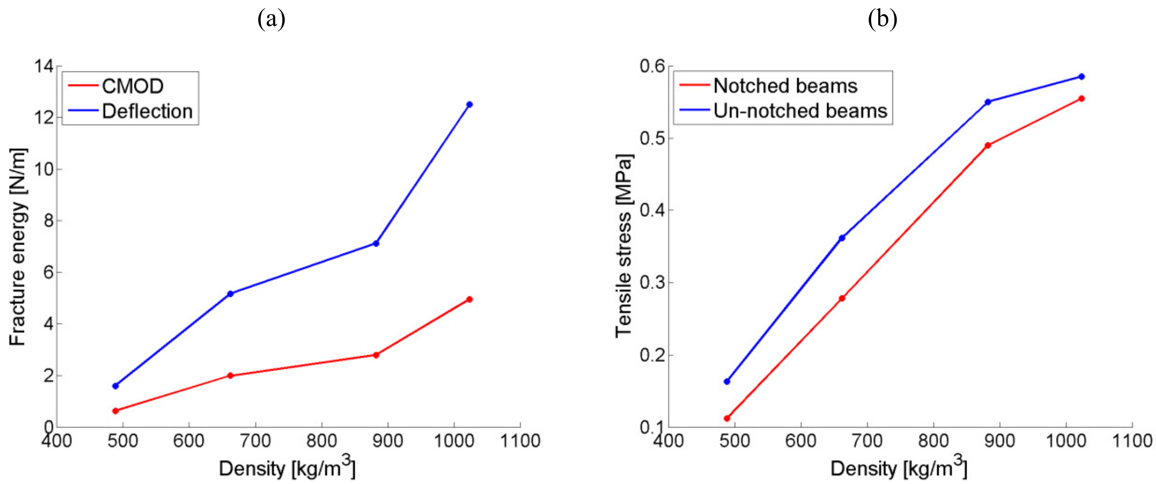

Fig. 4. Density versus fracture energy (a) and tensile stress (b) plots for tested specimens.

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