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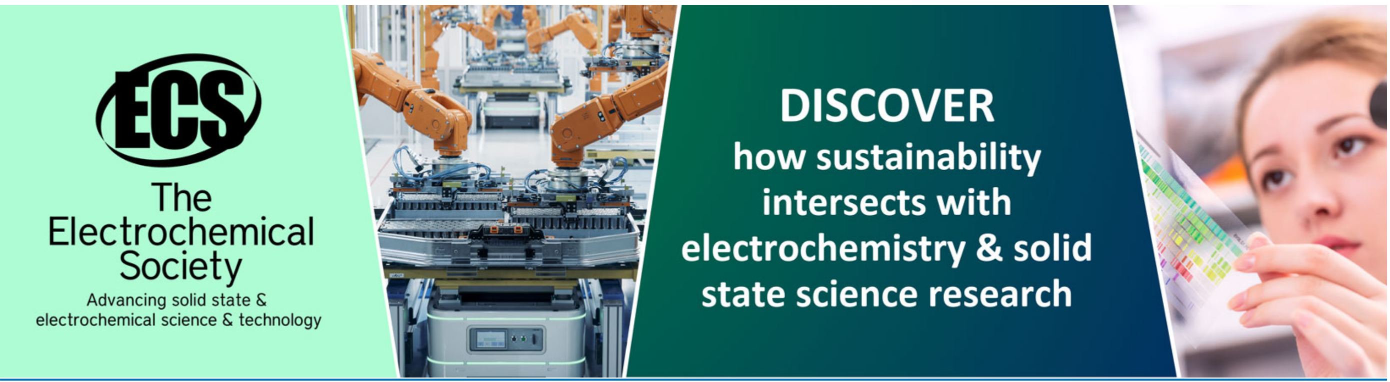

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Combined Experimental and Numerical Study on Fracture Behaviour of Low–Density Foamed Concrete

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Abstract. The paper presents results of a combined experimental and numerical study on the fracture behaviour of low–density foamed concrete (< 1100 kg/m^3). A series of static tests was carried out on notched beams tested in three-point bending to determine the fracture properties of foamed concrete. Based on the load–displacement responses fracture energy and maximal tensile stress were evaluated. The paper also presents the results of numerical investigation of the fracture behaviour of notched beams using Extended Finite Element Method (XFEM). The numerical studies involve a simulation of fracture initiation and crack evolution in the notched beams subjected to three–point bending.

1. Introduction

Foamed concrete is a broadly recognised material in the building industry, mainly due to of its low self–weight and superb thermal and acoustic properties [1, 2]. It has been commonly used primarily as a thermal insulation of roofs and foundations, as backfill material for retaining walls and sound insulation of building partitions. In the last years, however, it has become a promising material for structural purposes [3]. This includes stabilization of poor soil conditions [4], sub–base layer in sandwich solutions for foundation slabs and industrial floors [5–9] and road–pavement systems [10].

Cracks of various shapes and forms may develop during construction phase and throughout the lifetime of concrete structures. Engineering practice shows that cracking of concrete is almost unavoidable, however, current technology can minimize the risk. Moreover, computation software used for simulations of fracture behaviour of concrete elements may also contribute to predict these risks. Numerical studies allows to reduce the costs of experiments and time to estimate the safety level of engineering structures and perform extensive simulations including various options to identify the optimal solution for a specific case.

Fracture behaviour of foamed concrete, especially of low–density (< 1800 kg/m^3), is still unknown phenomenon. Relatively limited number of studies report that the fracture energy of lightweight foamed concrete is below 25 N/m [10–16], which is only a fraction of what ordinary concrete shows [17].

2. Materials and Methods

An ordinary Portland cement CEM I 42.5R was used in current research. Water used was clean and drinkable. The procedure of preparation of foamed concrete samples and proportions of produced mixes are described in [18]. In total 20 specimens were fabricated with dimensions of 100×100×840 mm, five beams for the same mix resulting in varying density from approximately 500 to 1000 kg/m^3, see Table 1. A 3 mm wide notch was mechanically fabricated with a depth of 42 mm.

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In this study three-point flexural tests were performed. The tests were performed on initially notched beams to obtain the fracture energy G_F and the maximal tensile stress at failure, according to [19, 20]. Further details regarding the test procedure were reported in previous studies [18].
Extended Finite Element Method (XFEM) is a development of the classical Finite Element Method, it allows for simulation of propagating cracks [21]. This approach does not require identification of preliminary cracks nor definition of crack paths. In addition, the crack domain does not require re-meshing during the crack propagation. A simple measure is used to detect the crack initiation. A crack starts forming when the maximal principal tensile stress exceeds the tensile strength of the material. The post–cracking behaviour (material softening) is based on the predefined value of fracture energy.
Three–point bending of foamed concrete beams with a notch were simulated using XFEM method [22]. Figure 1 shows a 2D model of the beams which represents the geometry and boundary conditions of the experiments. The loading was introduced in a displacement controlled manner through a steel roller on the upper surface of the beam at its mid-span. The loading allowed the crack to penetrate through the entire beam height. Contact properties between the steel roller and the beam were applied to represent the boundary conditions from experiments. Material parameters were set according to the experimental results, see Table 1. Rectangular mesh with the element size of 2×2 mm was applied in the model. The size of the elements in the vicinity of the notch were reduced to 1×1 mm.

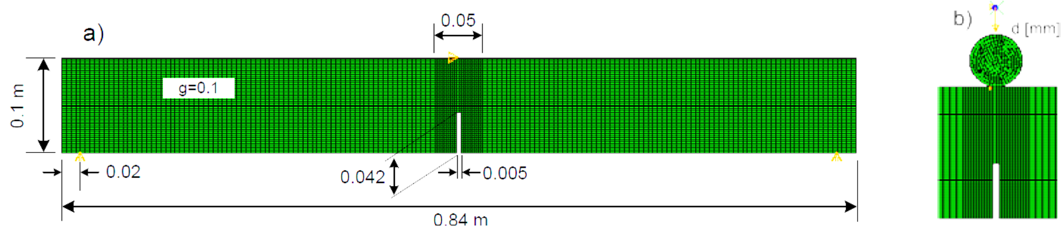

Figure 1. Geometry and boundary conditions of specimen (left), loading introduced as kinematic displacement of steel roller (right) [22].

3. Results and discussion

3.1. Experiments

The main objectives of the experiments were to investigate the influence of the density on the fracture energy and mechanical properties of foamed concrete. This includes Young’s modulus and maximal tensile stress at initial cracking.

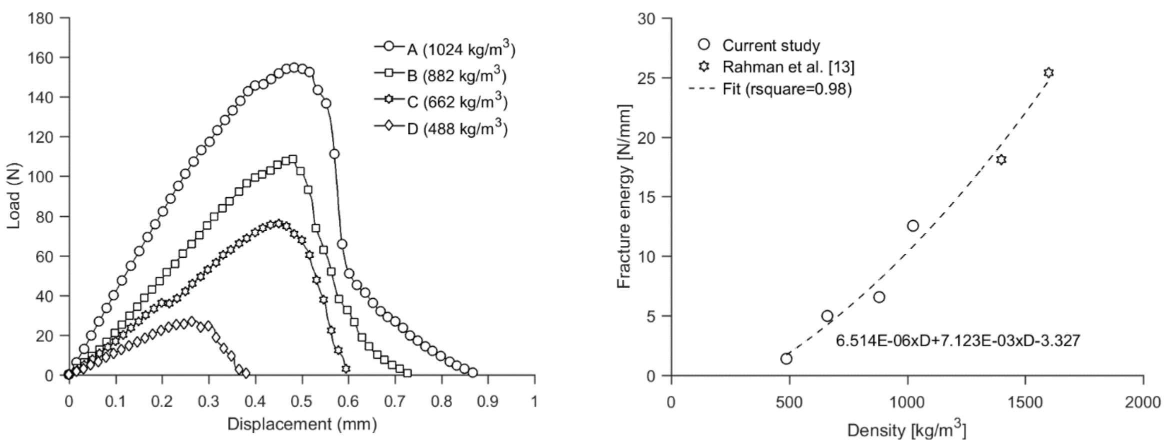

Figure 2. Load–displacement curves for beams with varying density (left), corresponding variation of fracture energy with density (right) [18].

Figure 2 (left) presents load–deflection curves for selected specimens of group A, B, C and D with different densities obtained from experimental study [18]. Structural responses, shown in Figure 2 (left), can be characterized by three particular phases which are common for all density groups. During the first phase the deflection increases linearly with the load, the notch is opening but no crack forms. A fracture process starts during the second phase where micro-cracks start forming and slow crack growth can be observed. During this phase a slight decrease of stiffness can be noticed. In the final phase (strain softening) rapid crack growth is noticed and corresponding vertical deflection increases. It can be noticed that specimens with higher density show faster increase of deformation during material softening phase thus present more brittle behaviour. It is clear from Figure 2 (left) that density affects stiffness, the value of maximal stress and ultimate displacement at failure. The specimens with higher density allow for greater displacement before failure.

Table 1. Test results from notched beams. The mean values of density, Young's modulus, tensile strength and fracture energy [18].

Material	Density (kg/m^3)	Young's modulus (GPa)	Poisson's ratio (-)	Maximal tensile stress (MPa)	Fracture energy (N/m)
A	1024	1.0	0.2	0.555	12.54
B	882	0.9		0.350	6.55
C	662	0.6		0.278	4.95
D	488	0.5		0.112	1.39

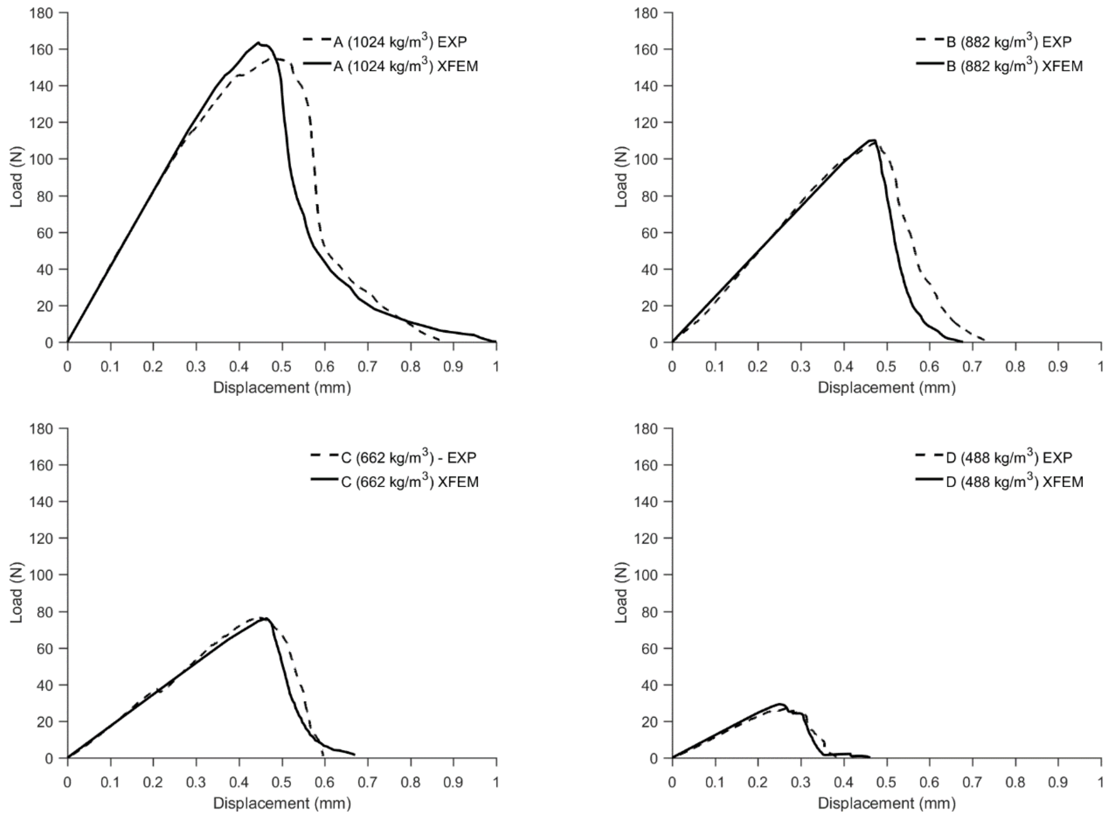

Figure 3. Comparison of experimental and numerical results for notched beams [22].

Figure 3 presents a comparison of load–deflection plots obtained from experiments and numerical simulations using XFEM method. The results present very good agreement regarding initial stiffness, maximal load and post–peak softening behaviour.

Based on the load–displacement behaviour, shown in Figure 2 (left), the value of fracture energy G_F was calculated for each specimen, according to [19, 20]. Figure 2 (right) shows a variation of the fracture energy with the density. It includes results of the current study and work by Rahman et. al [13]. The relation can be approximated with polynomial function shown in Figure 2 (right).

4. Conclusions and further study

Experiments and numerical study on notched foamed concrete beams in three-point bending were performed and simulated using the Extended Finite Element Method. The following conclusions have been drawn from the findings of the studies:

- an increase of the density of foamed concrete results in an increase of its stiffness, maximal tensile stress and fracture energy. For the notched beams with the density of 488-1024 kg/m^3 the mean values of fracture energy and maximal tensile stress obtained from experiments were 1.39-12.54 N/m and 0.112-0.555 MPa, respectively;
- XFEM method is suitable to represent fracture behaviour of notched foamed concrete beams tested in three–point bending. A comparison of the results from numerical models and experiments presents good correlation in terms of initial stiffness, peak load and post–cracking behaviour.

Based on the experimental studies and numerical simulations performed a number of topics is recommended to investigate in further studies:

- an investigation of fracture energy of foamed concrete with higher densities (>1000 kg/m^3);
- an experimental campaign involving the influence of addition of polypropylene fibres on the stiffness, strength and fracture characteristics of foamed concrete;
- numerical simulations of real application of foamed concrete as stabilization of poor soil conditions by an application of layer of foamed concrete as a subbase used in contact with subsoil.

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