Quasi-Static Mechanical Characterization of Lightweight Fly Ash-Based Geopolymer Foams

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Abstract. This paper investigates the compressive and flexural behavior of a closed-cell fly ash-based geopolymer foam with a density of 240 kg/m³. The influence of loading speed (0.1, 10, 100, 250 and 500 mm/min) and anisotropy (in-plane and out-of-plane directions) on the compressive mechanical properties at room temperature were investigated. Under compressive loads, the stress-strain curves show a cellular material typical behavior with three different regions: linear-elastic, plateau and densification region. On the other hand, the three-point bending tests were carried out on both un-notched and notched specimens (for fracture toughness determination). In compression, the foam progressively collapsed with a complete destruction of the successive rows of cells, while in the case of bending it exhibited a brittle behavior without plastic deformation, the fracture occurring by the propagation of a single crack.

1. Introduction

Porous materials such as polymeric [1-4] and metallic [5-8] foams have gained a lot of attention in recent years due to their excellent strength properties [9-12], energy absorption capabilities [13-15] and other significant features [16-18]. Many efforts have been made in last three decades in order to characterize experimentally [19-22], analytically [23, 24] ad numerically [25-27] the above mentioned foams. All of these studies have been conducted since cellular materials [28-30] begin to gain more applicability compared to fully dense solid materials [31-34].

In recent years, the interest in geopolymer-based cellular materials has grown significantly. The reduction of geopolymer density through foaming is increasingly being reported in the literature as it has been shown to be effective in improving their properties [35]. Geopolymer foams exhibiting very good physical and mechanical properties, energy absorption and fireproofing [36, 37]. The foamed geopolymers have attracted a lot of attention and are promising alternative to other cellular materials [38], mainly in civil engineering, these may replace in the future conventional concrete based on Portland cement (which is responsible for a significant amount of global CO₂ emissions). Geopolymer foams use high-volume industrial waste with a significant reduction in CO₂ emissions during production [35, 36].

A lot of studies were focused on microstructure [39], different foaming methods [35, 40], thermal properties [36, 37], fire performances [41] of geopolymer foams, while only few papers have been focused on the determination of mechanical properties [39, 42, 43]. This paper investigate the effect of
loading speed and loading direction (effect of anisotropy) on fly ash-based geopolymer foam samples under quasi-static compression tests. Also the three point bending behavior on notched and un-notched samples was investigated.

2. Materials and methods
The presented research are based on geopolymer foams made from the fly ash provided by the local Polish CHP plant (located in city called Skawina) and microspheres. As an activator, an alkaline solution of 14M aqueous solution of NaOH + liquid glass at a ratio of 1:2.5 was used. The cellular structure was achieved thanks to the addition the hydrogen peroxide to manufacturing process.

Large fly-ash based geopolymer foam plates were foamed (Fig. 1a) and subsequently processed as cubic specimens (20 mm × 20 mm × 20 mm) for compression tests (Fig. 1b), while prismatic samples (10 mm × 20 mm × 80 mm) were used for 3PB tests (Fig. 1c). The samples used for the determination of fracture toughness have shown a notch of 10 mm in length and notch thickness of 0.6 mm. Figure 1d presents the macrostructure morphology of the investigated foam. The obtained average foam density was 240 kg/m³.

![Figure 1](image_url)

**Figure 1.** Foamed plate (a), compression sample (b), 3PB samples (c) and foam microstructure (d)

In order to investigate the anisotropy effect, all cubic samples were cut from the same foam plate under three different loading directions, named direction (1), direction (2) and direction (3). Quasi-static compression tests were carried out at room temperature (~23°C) on a 5 kN Zwick Roell 005 testing machine. A constant crosshead speed of 10 mm/min was used for all experimental tests, while 0.1, 10, 100, 250 and 500 mm/min was used for determining the effect of loading speed. Five samples were provided for each test condition.

3. Results and discussion

3.1. Compression tests
Figure 2 present a typical stress-strain curve obtained from compression tests carried out on a cubic fly-ash based geopolymer foam. The obtained curve is similar to those studied by other researchers on different cellular materials [44-47], highlighting three regions of deformation: a linear-elastic region followed by a large plateau region and ends with the onset strain of densification. The serrated character of the stress-strain curves is mostly due to the brittleness of the matrix material used for the foam production.
The following compressive mechanical properties were investigated in this paper: compressive modulus ($E$), yield stress ($\sigma_y$), strain corresponding to yield stress ($\varepsilon_y$), stresses at 20% ($\sigma_{20\%}$) and 40% ($\sigma_{40\%}$), plateau stress ($\sigma_p$), densification stress ($\sigma_d$) and densification stress ($\varepsilon_d$).

Figure 3 presents the stress-strain curves of investigated foams under three different loading directions. As it can be seen, all curves highlights the same compressive behavior with above mentioned regions. No large differences were observed between directions (1) and (2), while a decrease of compressive modulus and strength properties was obtained for direction (3) of loading. Therefore, the investigated foam does not have a strong anisotropic behavior, like other types of cellular materials [47].

The main mechanical properties of investigated geopolymer foams samples depending on the loading directions are presented in Table 1, while Table 2 shows the same properties according to different loading speeds.

On the other hand, the loading speed (Fig. 4 and Table 2) present significantly higher elastic properties (about 50%) only at 500 mm/min, while for the other loading rates, approximately the same values are obtained (except for 22.63 MPa value at 100 mm/min).
Table 1. The mechanical properties of geopolymer foams. Influence of loading direction

| Loading direction | Linear-elastic region | Plateau region | Densification region |
|-------------------|-----------------------|----------------|----------------------|
|                   | E [MPa] | σ_y [MPa] | ε_y [%] | σ_20% [MPa] | σ_40% [MPa] | σ_pl [MPa] | σ_D [MPa] | ε_D [%] |
| 1                 | 33.92   | 0.60      | 3.15    | 0.41         | 0.24        | 0.325      | 0.15      | 64.99   |
| 2                 | 34.73   | 0.54      | 2.96    | 0.57         | 0.24        | 0.405      | 0.18      | 67.24   |
| 3                 | 19.19   | 0.35      | 2.75    | 0.26         | 0.37        | 0.315      | 0.38      | 66.64   |

Table 2. The mechanical properties of geopolymer foams. Influence of loading speed

| Loading speed [mm/min] | Linear-elastic region | Plateau region | Densification region |
|------------------------|-----------------------|----------------|----------------------|
|                        | E [MPa] | σ_y [MPa] | ε_y [%] | σ_20% [MPa] | σ_40% [MPa] | σ_pl [MPa] | σ_D [MPa] | ε_D [%] |
| 0.1                    | 30.21   | 0.50      | 1.92    | 0.40         | 0.31        | 0.355      | 0.24      | 62.96   |
| 10                     | 33.92   | 0.60      | 3.15    | 0.41         | 0.24        | 0.325      | 0.15      | 64.99   |
| 100                    | 22.63   | 0.55      | 3.53    | 0.49         | 0.30        | 0.395      | 0.36      | 64.92   |
| 250                    | 42.53   | 0.69      | 2.74    | 0.48         | 0.35        | 0.415      | 0.48      | 63.35   |
| 500                    | 68.91   | 0.55      | 3.14    | 0.47         | 0.35        | 0.410      | 0.34      | 66.21   |

The main strength properties (σ_y and σ_pl) are not influenced by the loading speed, only densification stress (σ_D) is slightly different. Also, the onset strain of densification show a deviation of ±1.5% between all investigated loading speeds.

3.2. Three point bending tests

Figure 5 presents the stress-strain curve of foam loaded under three point bending fixture on samples without notch. The flexural modulus was calculated from the initial slope of the curve, while the maximum stress at failure represents the flexural strength of foam. Table 3 lists the obtained bending mechanical properties.

![Figure 5.](image1.png)  
**Figure 5.** 3PB stress-strain curve of un-notched sample.

![Figure 6.](image2.png)  
**Figure 6.** 3PB stress-strain curve of notched sample.
Table 3. The main 3PB mechanical properties of un-notched geopolymer foam

| Geometrical parameters | Mechanical properties |
|------------------------|-----------------------|
| Sample Sample Span     | Flexural Flexural     |
| h [mm] b [mm] l [mm]   | modulus strength     |
| 10 20 64               | E [MPa] \( \sigma_f \) [MPa] | \( \varepsilon_f \) [%] |
|                        | 14.96±1.76 0.042±0.004 0.3±0.02 |

On the other hand, Fig. 6 presents the stress-strain curve of investigated foam under 3PB test on notched samples. For all tested samples plan strain condition was fulfilled [48]. Brittle fracture was observed and the linear-elastic behavior was confirmed during the test when no cushioning occurs and no plastic deformation remain after the test [49-52]. It has been found a fracture toughness value of 0.17±0.02 MPa m^{0.5}. The fracture occurs by the initiation and propagation of a single crack.

4. Conclusions

Quasi-static compressive and 3PB mechanical properties (compressive and flexural modulus, compressive and flexural strength, fracture toughness and densification strain) of closed-cell fly ash-based geopolymer foams are experimentally investigated.

The following conclusions can be drawn:

- The research results confirm that the investigated geopolymer foams have good mechanical properties for their specific weight;
- Investigated foam emphasize slightly anisotropic compressive behavior;
- Loading speed does not significantly affect the main mechanical properties;
- All 3PB notched and un-notched samples showed brittle failure without plastic deformation.

References

[1] Gibson, L.J. and Ashby, M.F., Cellular Solids-Structures and properties-Second edition. Published by the Press Syndicate of the University of Cambridge, UK, 1997.

[2] Linul E and Marsavina L 2015 P. Romanian Acad. A 16(4) 522-530

[3] Şerban DA, Weissenborn O, Geller S, Marşavina L, Gude M 2016 Polym. Test. 49 121-127

[4] Aliha MRM, Linul E, Bahmani A, Marsavina L 2018 Polym. Test. 67 75-83

[5] Ashby MF, Evans A, Fleck NA, Gibson LJ, Hutchinson JW, Wadley HNG, Delale F 2000 Metal Foams: A Design Guide. Butterworth-Heinemann, USA

[6] Linul E, Marsavina L, Kováčik J 2017 Mat. Sci. Eng.-A Struct. 690 214-224

[7] Kováčik J, Jerz J, Mináriková N et al. 2016 Frattura ed Integrita Strutturale 36 55-62

[8] Taherishargh M, Linul E, Broxtermann S, Fiedler T 2018 J. Alloy. Compd. 737 590-596

[9] Movahedi N, Linul E, Marsavina L 2018 J. Mater. Eng. Perform. 27(1) 99-108

[10] Linul E, Movahedi N, Marsavina L 2018 J. Alloy. Compd. 740 1172-1179

[11] Voiconi T, Linul E, Marsavina L, Sadowski T, Kne M 2014 Solid State Phenomena 216 116-121

[12] Marsavina L, Linul E, Voiconi T, Constantinescu DM, Apostol DA 2015 Frattura ed Integrita Strutturale 34 444-453

[13] Linul E, Şerban DA, Marsavina L, Kovacik J 2017 Fatig. Fract. Eng. Mater. Struct. 40(4) 597-604

[14] Movahedi N and Linul E 2017 Mater. Lett. 206 182-184

[15] Linul E, Movahedi N, Marsavina L 2017 Compos. Struct. 180 709-722

[16] Apostol DA, Stuparu F, Constantinescu DM et al. 2016 Materiale Plastice 53(4) 685-688

[17] Marsavina L, Constantinescu DM, Linul E et al. 2015 Eng. Fail. Anal. 58 465-476

[18] Marsavina L, Kovacik J, Linul E 2016 Theor. Appl. Fract. Mech. 83 11-18

[19] Şerban DA, Voiconi T, Linul E, Marsavina L, Modler N 2015 Materiale Plastice 52(4) 537-541

[20] Negru R, Şerban DA, Pop C, Marşavina L 2018 Theor. Appl. Fract. Mech. DOI:10.1016/j.tafmec.2018.01.016
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