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DOI
10.1007/978-3-030-49916-7_56

Publication date
2020

Document Version
Final published version

Published in
DC 2020: Second RILEM International Conference on Concrete and Digital Fabrication

Auxetic Behavior of Cementitious Cellular Composites Under Uniaxial Compression and Cyclic Loading

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Abstract. Mechanical behavior of cementitious cellular composites (CCC) with auxetic behavior was investigated under uniaxial compression and cyclic loading. Three cellular structures with different geometrical parameters are designed and prepared by 3D printing technique. Meanwhile, plain mortar and fiber reinforced mortar are used as constituent material, respectively. Ductility of the constituent materials is evaluated by four-point bending tests. Uniaxial compression and cyclic loading tests are performed on the CCCs. Experiments show that with proper structure and constituent material, CCCs can exhibit auxetic behavior. For the tested CCCs (P25 and P50), negative Poisson's ratio is obtained: as a result, strain hardening behavior can be identified in the stress-strain curve under uniaxial compression. In addition, large reversible deformation under cyclic loading is obtained on P25 under cyclic loading. Hysteretic behavior in the stress-strain curve can be identified in a single cycle, which means that CCCs dissipates energy in each cycle. After 3000 cycles, the maximum load and energy dissipation of each cycle increased owing to the slip hardening behavior of the PVA fibers in the constituent material. Owing to the excellent energy dissipation property, these auxetic CCCs may be used for vibration resistance structures in the engineering practice in the future.

Keywords: 3D printing · Negative Poisson's ratio · Cementitious material · Cyclic loading

1 Introduction

Mechanical properties of composite materials are crucially influenced by both mechanical properties of the constituent phases but also the geometrical distribution features of these phases. Cementitious materials are multi-phase materials. Therefore, in the past several decades, numerous efforts have been done to configure, modify or tailor the geometrical distribution, which is more commonly referred as microstructure, for better mechanical performance. For example, modifying the pore structure [1], modifying the air void structure [2, 3] and introducing new phases as reinforcement [4, 5].

F. P. Bos et al. (Eds.): DC 2020, RILEM Bookseries 28, pp. 547–556, 2020.
https://doi.org/10.1007/978-3-030-49916-7_56

Recently, as the rapid development of digital fabrication techniques, materials with tailored geometrical meso-structure have attracted much attention. On one hand, the tailored geometries can give the material excellent mechanical properties such as high fracture toughness [6, 7] and relative strength [8, 9]. On the other hand, tailoring the spatial distribution of constituent phases also enables one more dimension of freedom of materials design: not only design the constituent material property but also the structural response. For cementitious materials, taking advantage of the ability of 3D printing technique to fabricate complex geometries to produce cementitious cellular materials with tailored meso-structure might also be promising. Together with proper constituent material mix design, unprecedented mechanical properties of cementitious materials could be achieved.

Previously, cementitious cellular composites (CCCs) with negative Poisson's ratio were reported by [10, 11], in which cementitious specimens with cellular structure were prepared with the aid of 3D printing technology. However, the influence of structure features and constituent material properties on the compressive behavior of the CCCs were not fully studied. In this work, a similar cellular structure was adopted from [10, 11]. Molds for casting cementitious materials were digitally fabricated by 3D printing. CCCs with different cellular structures were obtained. Meanwhile, different mix proportions were used as constituent materials. Ductility of the constituent material was determined by four-point bending test. Mechanical properties of the CCCs were tested under uniaxial compression and compressive cyclic loading. The influence of constituent material ductility and cellular structural design parameters on the compression and fatigue behavior of the CCCs is analyzed.

2 Materials and Methods

Three types of cellular geometries were used in this study, two were adopted from [10]. Single unit of the cementitious cellular composites (CCCs) and the dimension of a specimen was shown in Fig. 1. The CCCs specimen is consisted of duplicate single cells. Geometrical parameters are listed in Table 1.

Table 1. Specimen groups with different design parameters

Specimen groups	Major axis "a" (mm)	Minor axis "b" (mm)	Volume (cm^3)
P0	4	4	63.7
P25	5	3	67.7
P50	6	2	79.8

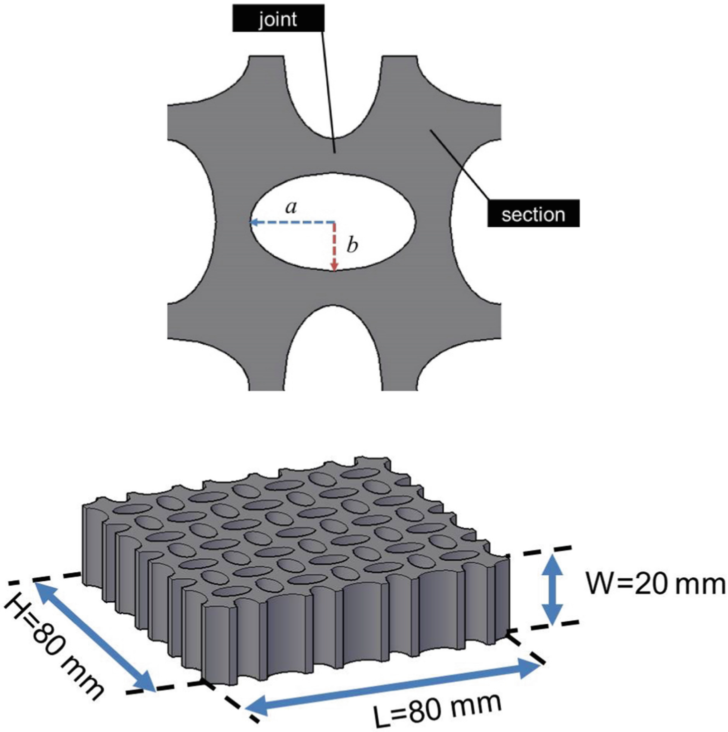


Fig. 1. Design parameters of cementitious cellular composites

2.1 Casting and Curing

The same method described in [10, 11] was adopted to prepare cementitious cellular composite specimens: cellular negative molds were prepared with the aid of 3D printing by a commercial fused deposition modelling (FDM) based 3D printer Ultimaker 2+ and the CCCs were prepared by the negative molds. A same fiber reinforced mortar was used as [11] to be constituent material for the cellular structure. The mix proportion is listed in Table 2.

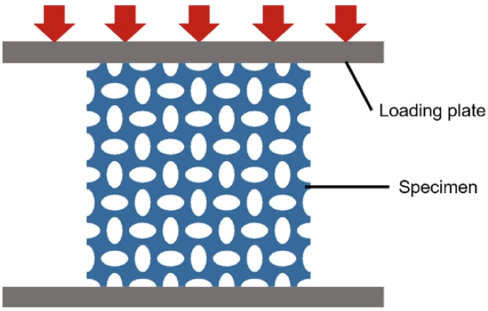
Table 2. Mix proportion of constituent materials (kg/m^3)

CEM I 42.5 N	FA	Sand	Water	SP	VA	PVA fiber
471	556	385	428	0.86	0.3	25.6

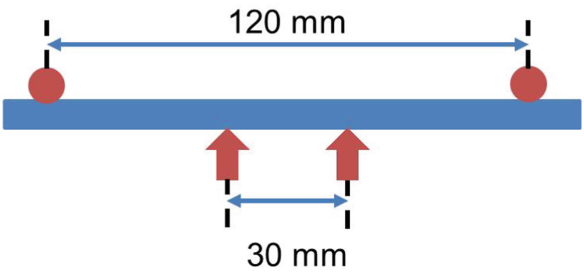
Dry components: CEM I 42.5 N, fly ash (FA), sand (0.125 μm–0.25 μm), VA (methyl-cellulose viscosity modifying agent) were weighed and mixed for four minutes using a Hobart machine. Afterwards, weighted superplasticizer and water were added, followed by 2 min mixing. Then fibers were added and mixed for another 2 min. The mixed fresh mortar was casted into molds and vibrated for 40 s. Covered by plastic film, the specimens were stored in room temperature. After one day, the specimens were demolded and transferred to a curing chamber (20 °C, 96% RH) until 28 days age. Two types of specimens were casted, the CCCs were casted using the negative molds prepared by 3D printing and then tested in uniaxial compression at 28d. Bar specimens were casted using Styrofoam molds and tested in four-point bending at 28d.

2.2 Mechanical Tests

Specimens were taken out of the curing chamber before testing. All mechanical tests were done by a hydraulic press INSTRON 8872 at a loading rate of 0.01 mm/s. Load and displacement were measured and recorded during the tests. Images were taken during testing by a camera which was placed in front of the specimen. For the four-point bending test, displacement at the mid span is measured. A schematic of the four-point bending test is shown in Fig. 2.



(a)



(b)

Fig. 2. Schematics of a) uniaxial compression and b) four-point bending test

3 Results and Discussion

3.1 Ductility of Constituent Material

As mentioned before, global mechanical properties of cellular materials are dictated by both its constituent material properties and the structural configuration. Therefore, coupled analyses of the constituent material properties and the structural features of the CCCs helps understanding of the mechanism of the auxetic behavior.

The flexural-deflection curves of plain mortar and fiber reinforced mortar are shown in Fig. 3. As expected, the plain mortar exhibits a rather brittle response: a rapid drop after the peak load can be found, indicating a rapid failure of the loaded specimen. Similarly, as the same cementitious matrix was used, plain mortar and fiber reinforced mortar have similar cracking strength at the first peak. However, after the first peak fiber reinforced mortar shows ductile stress-strain response: instead of rapid failure, due to the crack bridging behavior of the incorporated PVA fibers, load started to increase and a secondary peak can be found. Owing to the secondary peak, the ductility of fiber reinforced constituent material is much higher than plain mortar which enables the cellular structure to exhibit auxetic behavior, which will be discussed in detail in the next part.

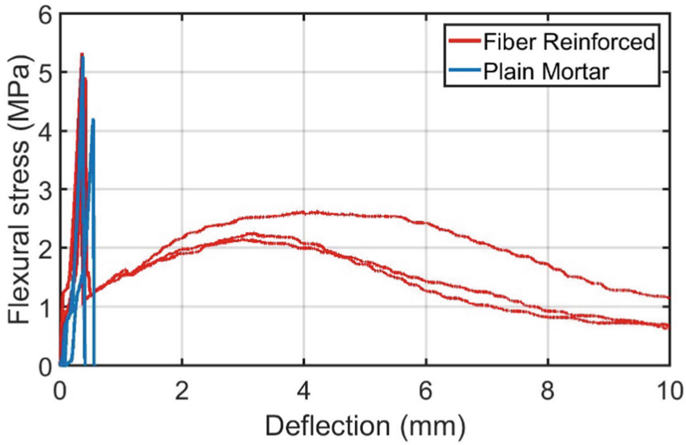


Fig. 3. Flexural-Deflection curves of constituent materials, several results are adopted from [11]

3.2 Compressive Behavior of the CCCs

Figure 4 shows the stress-strain curves of cellular structure P25 with plain mortar as constituent material. Brittle fracture was observed during the compression tests: after the peak load was reached, micro cracks rapidly started to localize and eventually lead to the failure of the compressed specimen, witnessed by a sharp drop in the load-displacement curve. Owing to the cellular structure, in some cases cracks developed through the cellular structure layer by layer so that multiple sharp drops can be found in the load-displacement curves.

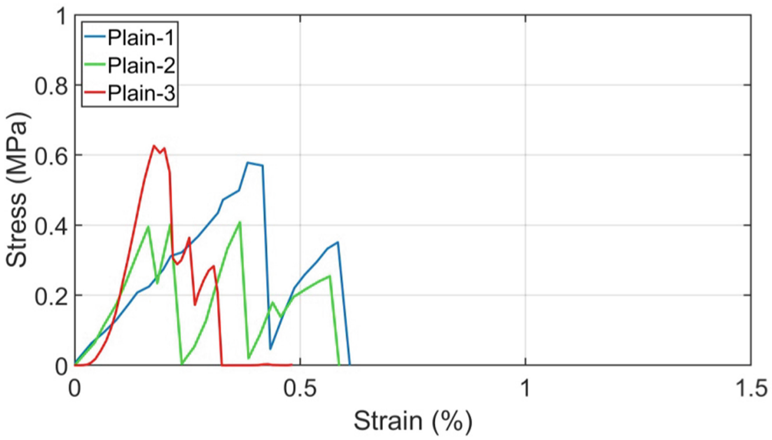


Fig. 4. Stress-strain curves of P25, data is adopted from [11]

On the contrary, when fiber reinforced mortar was used as constituent materials rather ductile damage process can be witnessed from the stress-strain response (see Fig. 5, P25), which can be roughly divided into three stages, marked in the load-displacement curves.

In the first stage (approximately from 0% strain to 11% strain), the mechanical response under compression is similar to that of traditional cementitious materials: an ascending branch can be found when external load imposed. After the elastic regime micro cracks started to initiate, as soon as peak load was reached (around 1 MPa), micro cracks started to localize at the joints of each single cell of the specimen. Because fiber reinforced mortar was used as constituent material, crack bridging allowed those localized small cracks at the joints to open slowly as compression went on instead of a rapid rapture. As a result, the sections of each single cell started to rotate. Meanwhile, lateral contraction could be observed during the test, namely auxetic behavior was achieved in this stage.

In the second stage (from 11% strain to 40% strain), the cellular structure was generally destroyed and compacted to be "solid" constituent material. As can be seen from Fig. 5, the hollow ellipse structure was compressed to deform and shrink, exhibiting more contraction in the lateral direction when the vertical compression continued. Correspondingly, in the stress-strain curves a compressive strain hardening behavior witnessed by a load increase after the first peak in previous stage because the cellular structure was destroyed and generally compacted. Similar strain hardening process can be also found in other auxetic materials [12, 13]. After the second peak (around 3 MPa) cracks started to initiate and localize in the sections of single cells then eventually developed in shear crack planes, witnessed in the stress-strain curves by a descending branch after the secondary peak. In this sense, this secondary peak is quite similar to the typical compression process of a conventional fiber reinforced cementitious material.

The third stage (after 40% strain) is a pure compacting process of the crushed constituent material which leads to rapid stress rise because the materials were compacted denser.

According to the hypothesis in [11], the auxetic behavior of the CCCs can be dominated by both constituent material properties as well as the cellular chirality. In this study, a same mix as [11] was used, the influence of constituent material was eliminated. In this case, obvious impact of cellular geometrical features on overall compression behavior of the CCCs can be identified. As can be seen from, P0 doesn't show auxetic behavior because of the symmetrical geometry of the section, comparatively, P50 shows similar auxetic behavior as P25. Meanwhile, from the stress-strain curves P50 shows similar three-stages response as P25: after the first peak load increased again because the cellular structure was destroyed and compacted. Because the volume of P50 (79.4 cm^3) is higher than P25 (67.8 cm^3), the peak load at the secondary increase is also higher. As for P0, the entire compression process was rather similar to that of conventional fiber reinforced materials, namely one peak can be found and afterwards a long descending branch can be found because of the ductility from constituent material.

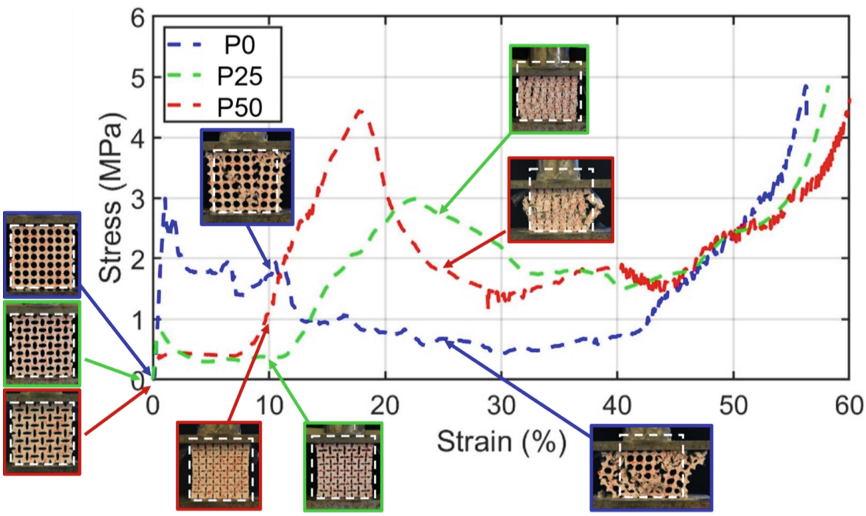


Fig. 5. Stress-strain curves of the CCCs and corresponding compressed specimens, several curves and pictures are adopted from [11, 14]

A stress-strain curve of P25 under one cyclic loading (the 3000th cycle) is shown in Fig. 6. Typical hysteresis behavior can be found from the curves (from 11.25% to 13.75% of strain): the loading and unloading branch do not completely overlap in one cycle. After 3000 cycles, the maximum load increased slowly with the cycle number increasing (from 0.1 MPa to 0.14 MPa, see Fig. 7). Similar trend can be also observed from the specific dissipated energy in one cycle (calculated by the area surrounded by the loading and unloading branch in each cycle divided by the specimen volume, see Fig. 8). According to previous studies [15, 16], the crack bridging ability of PVA fibers comes from slip-hardening behavior when fibers are pulled out from cementitious matrix. The slip-hardening behavior can be explained by fibrillation phenomenon of PVA fiber, which means that under external load molecules of PVA polymer stretch out from a single PVA fiber increasing surface roughness of the PVA fiber, increased the friction between PVA fiber and cementitious matrix. Similarly, under cyclic loading fibrillation may be much more severe [17] and more jamming friction may be the reason of load and energy dissipation increase after 3000 cycles. In general, the developed CCC possessed pseudo-elasticity of 2.5% reversible strain even until 20000 cycles, which means that the CCC is a promising energy dissipating material.

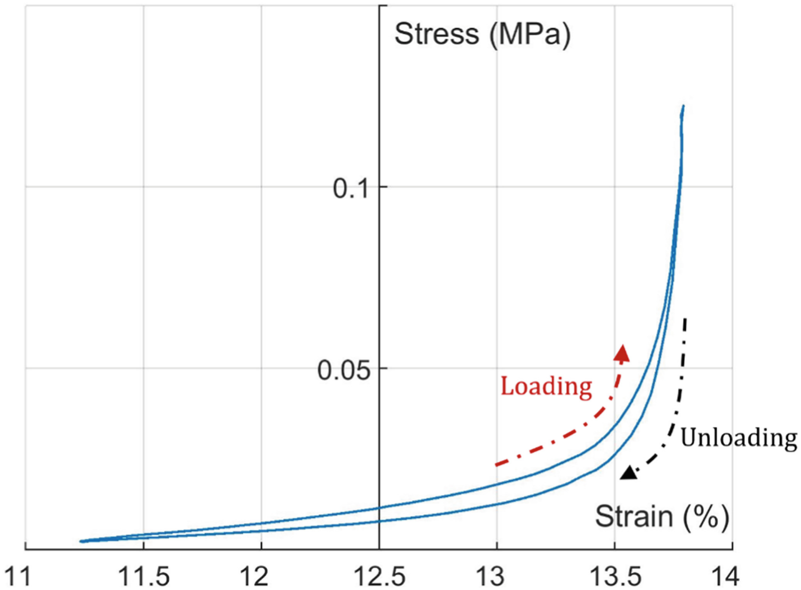


Fig. 6. Stress-strain response of the P25 at the 3000th cycle, data is adopted from [11]

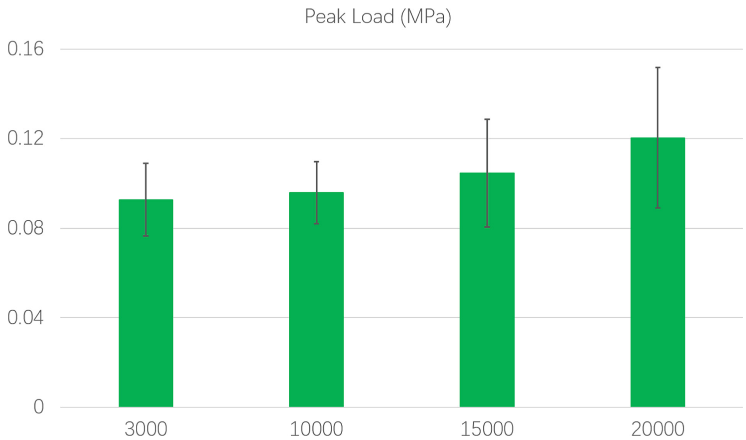


Fig. 7. Development of peak load in one cycle with number of cycles, standard deviation is indicated, several data is adopted from [11]

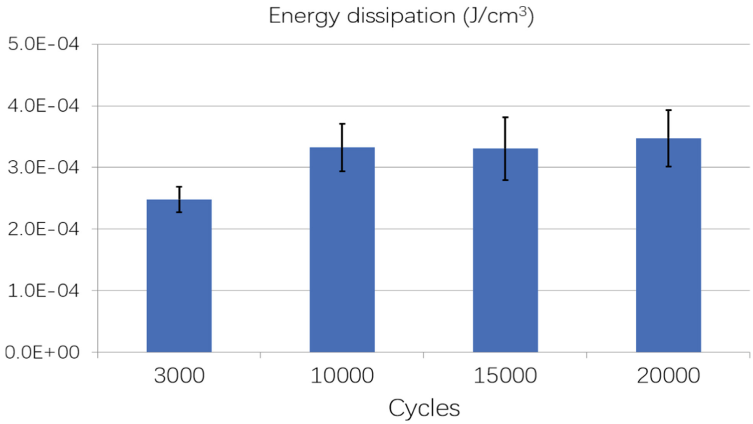


Fig. 8. Development of energy dissipated in one cycle with number of cycles, standard deviation is indicated, several data is adopted from [11]

4 Conclusions

In the present work, cementitious cellular composites (CCCs) with auxetic behavior are developed using 3D printing. The mechanical properties of CCCs are evaluated under uniaxial compression and cyclic loading. Influence of constituent materials and structure design parameters on the mechanical behavior of the CCCs are studied. Characteristics of auxetic CCCs under cyclic loading were measured. Based on the obtained experimental results several conclusions can be drawn:

- Both constituent material property and geometrical structure determine the overall compressive behavior of the CCCs. On one hand, the crack bridging ability of constituent material (fiber reinforced mortar) enables the CCCs exhibiting auxetic behavior; On the other hand, chirality of the sections in each single cell is required for cellular structures to show auxetic behavior.
- Under uniaxial compression, auxetic behavior was witness in P25 and P50 specimens. Owing to the auxetic behavior, P25 and P50 shows strain hardening behavior under compression: a secondary peak exists after the first peak.
- For the developed CCC (P25), a pseudo-elastic regime is found between 11.25% ~13.75% strain (in total 2.5% compressive deformation) under 20000 cycles, within this regime P25 shows flexible behavior and excellent energy dissipation property.
- The fatigue process of P25 under cyclic loading exhibit recoverable damage: after 3000 cycles, owing to the fibrillation of PVA fibers the maximum load increases leading to an increase in energy dissipation in each cycle until 20000 cycles. The increase of maximum load and energy dissipation implies that CCC is possible to be used as promising vibration resistant material.

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