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Effect of shearing conditions and initial aggregates' state on the mechanical behavior of cellular glass foam

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Abstract. Cellular glass aggregates made from recycled glass are increasingly being used in civil engineering and infrastructure applications. This contemporary material is relatively new in civil engineering applications. This paper investigates the effect of shearing conditions and initial aggregates' state on the mechanical properties of cellular glass foam. A series of monotonic large-scale triaxial tests (300 mm diameter and 600 mm height) was performed in order to investigate the influence of initial dry density, initial aggregates' state (i.e. flawless, weathered, and compacted), and consolidation stresses on the mechanical behavior of cellular glass foam. The material's behaviour observed under monotonic shear is of contracting type, with significant evolution of the material during shear (grain crushing) and a strongly strain-hardening character. The failure criterion of the studied material is similar to the failure criterion used for granular soils for which a shearing resistance angle and apparent cohesion is perceived.

Introduction

Cellular glass aggregates has many interests, in particular, its lightweight (ten times lighter than the gravel), its self-stability and drainage. Therefore, they are increasingly being used in civil engineering and infrastructure applications such as, lightweight cellular cemented clays, expanded polystyrene, and lightweight concrete [1,2,3,4,5,6].

Foam glass aggregate, is an artificial mixture produced by transferring finely ground glass powder from different glass sources (domestic wastes, industrial wastes, etc.) into glass foam. The condition for the usability of glass is that it should not contain heavy metals or other substances posing a health risk. The glass is grinded to the size of dust where it is spread on a belt conveyor running through high temperature ovens. In the passage through the long furnaces with temperatures of 900°C–1000°C, the glass powder expands about four times upon leaving the furnace, the expanded compound cools down from about 900°C to ambient temperatures. This change in temperature leads to the crack of the product into smaller pieces. The temperature, the thickness of the powder layer and the time spent in the furnaces define the final properties of the material.

In the literature, there are several studies on the properties and mechanical behavior of cellular glass. The NPRA (Norwegian Public road administration) has initiated a program to investigate the possible use of cellular glass material (Hasopor) for road construction applications where this material has been applied on about 25 road projects in Norway. Deformations of about 1-2 % were recorded for a relatively short time. Observations over time (3 years) indicate that further crushing and deformations tend to be negligible [7].

Mechanical characterization of cellular foam has been studied by various authors under different laboratory testing. Mear [8] presented the results of mechanical testing of the material against flexural and compressive strengths. According to the results obtained on the deformation variation of the material, three distinguished deformational zones were observed (zone I: an elastic deformation for low compression values, zone II: a discontinuity in deformation indicating the rupture of the weakest element of the material, and zone III: a local damage which led to total fracture). Arulrajah [9] performed shear box testing on foamed recycled glass. It was observed that the shear resistance at large shear displacement is high leading to an apparent cohesion $c = 23.36$ kPa and an angle of shearing resistance $\varphi = 54.7^{\circ}$. Furthermore, several authors studied the influence of the type of the experimental apparatus on the mechanical characterization of cellular glass foam [10,11]. Seif El Dine [12] studied the effect of the testing set-up on the mechanical characterization of matrix coarse-grained soils. The results obtained indicated that the direct shear box gives higher values of the mechanical properties of the tested material than those obtained by triaxial apparatus (i.e. the direct shear box overestimates the characteristics of the studied material).

As mentioned previously, this material is relatively still considered as new construction material. It is believed that, its mechanical characterization under different state and testing conditions is crucial. The objective of this experimental work is to investigate the effect of shearing conditions and initial aggregates' state on the mechanical properties of cellular glass foam. A series of monotonic large-scale triaxial tests (300 mm diameter and 600 mm height) was performed in order to investigate the influence of initial dry density, initial aggregates' state (i.e. flawless, weathered, and compacted), and consolidation stresses on the mechanical behavior of cellular glass foam.

Experimental Investigation

A large scale triaxial apparatus, which allow the shearing of large soil samples, is adopted in this study to determine the mechanical properties of the cellular glass aggregates. This device is accommodated to perform monotonic tests at different confining pressures, rates of deformation and loading, and saturation conditions which simulate field conditions. The dimensions of the samples used were 300 mm in diameter and 600 mm in height. The setup is composed of a large size triaxial cell incorporated in four columns loading frame, equipped with a 500 kN hydraulic actuator for the application of axial forces. The confining pressure applied to the triaxial cell is also controlled through a second hydraulic actuator. The sample is first prepared outside the frame, and then the cell is positioned under the hydraulic actuator which applies the axial force. A general view of the experimental setup is shown in Figure 1*a*.

The reconstitution process of the samples consisted of weighing the required quantity of the material according to a preselected dry density value. This quantity is then splitted into six buckets of equal parts for the purpose to prepare the samples in six compacted layers. A neoprene membrane is then inserted into the mold covered by a geotextile film that is used to protect the membrane from any damage that may result during the compaction process. The mold is then filled up with the aggregates which were compacted in layers of 10 cm height each. Finally a porous disk and top end plate are placed on the top of the specimen. Upon preparing the specimen, a 50 kPa vacuum is applied to the specimen in order to remove the mold. This value should always be less than the confining pressure value in order to prevent any over consolidation of the specimen. The triaxial cell is fixed on a movable support that allows its displacement in both translation and rotation. Once the cell is adjusted under the actuator, the test can be launched (Figure 1*b*).

After the preparation of the specimens and the assembly of the apparatus, some preliminary tests were undertaken in order to gain some familiarity with the procedure followed in setting up and carrying out the tests and to ensure the repeatability of the tests. For this purpose, three tests were carefully repeated for consolidation stress values of 25 kPa, 50 kPa and 100 kPa at a dry density of $\rho_d = 212$ kg/m^3. The results obtained showed good consistency between the different tests. %). Consequently, it may be concluded that the test apparatus gives repeatable and reproducible results under the same conditions.

(a) (b)

Figure 1. *General view of the experimental setup*

Test Results and Analysis

In order to evaluate the behavior of cellular glass aggregates under monotonic shear, a series of 14 triaxial tests (M1 to M14) were performed. The main test characteristics are summarized in Table 1. All tests are displacement controlled tests. They were run on dry material at an axial deformation rate of 0.2 %/mn, up to a maximum value of axial deformation of approximately 15%. Most tests were run at a dry specific density of 212 kg/m^3 which was the value originally chosen. In order to evaluate the influence of the dry density (ρ_d) on the behavior of the aggregates, two tests (M12 and M13) were carried out for ρ_d of 230 kg/m^3. Five values of isotropic consolidation stress (25, 50, 100 and 200 kPa) were used in order to evaluate the failure characteristics as well as Mohr-Coulomb failure parameters of the aggregates.

Table 1 – Experimental program carried out for monotonic shear tests.

Test	ρ_d (kg/m^3)	σ'_c (kPa)	$\varepsilon_{a,max}$ (%)	q_{max} (kPa)
Intact material				
M1	142	50	15	214
M2	212	100	15	373
M3	212	100	15	396
M4	212	50	15	259
M5	212	50	15	291
M6	212	100	15	404
M7	212	25	15	243
Aged material				
M8	212	50	15	257
M9	212	25	15	166
M10	212	25	18	194
M11	212	200	16	452
M12	230	50	18	290
M13	230	50	18	296
M14	212	200	16	493

Influence of Consolidation Stress

The influence of the consolidation stress on the mechanical properties of the cellular glass aggregates were considered in the present experimental program. Figure 2 shows the results obtained for a dry density of 212 kg/m^3 and four different consolidation stresses, in this case 25 kPa, 50 kPa, 100 kPa and 200 kPa. This figure indicates that, for all the tests, the deviator stress still keeps increasing after an axial deformation of 15%. However, the higher the consolidation stress and the higher the axial deformation needed to reach a deviator stress plateau. For the highest consolidation stress of 200 kPa, the deviator stress is still strongly increasing after the axial deformation of 15%. As expected, the shear strength of the material increases almost proportionally with the consolidation stress, which is fairly similar to the behavior observed in sands and gravels and should yield a failure criterion of the Mohr-Coulomb type.

Two sieve analyses were performed in order to evaluate the degradation of the material after the shear test for both the lowest and the highest consolidation stresses (i.e. 25 and 200 kPa). The results were compared to the grading curve of the material before shearing and compacted at the same dry density ρ_d = 212 kg/m^3 (Figure 3). The grading curves of the material before and after shear under a consolidation stress of 25 kPa are almost identical, indicating that the shear test has had a very low effect on the degradation of the material. On the other hand, a clear evolution of the grading curve is observed for the 200 kPa consolidation shear test. In this case, all the elements sizes are affected by the degradation, especially the elements of intermediate size (i.e. from 5 mm to 31.5 mm), where the proportion was increased by 30 %.

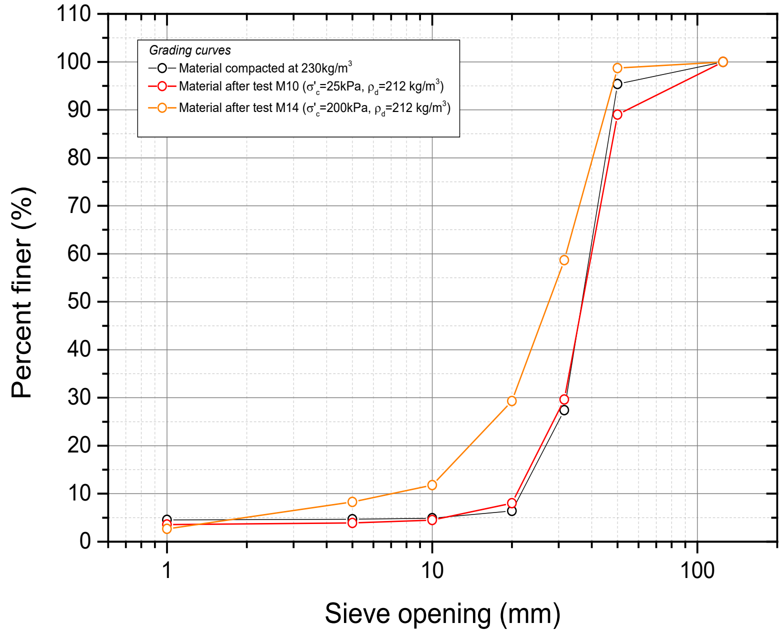

Figure 2. Shear curves obtained on cellular glass for four consolidation stresses: 25kPa, 50kPa, 100 kPa, and 200kPa (for ρ_d =212 kg/m^3))

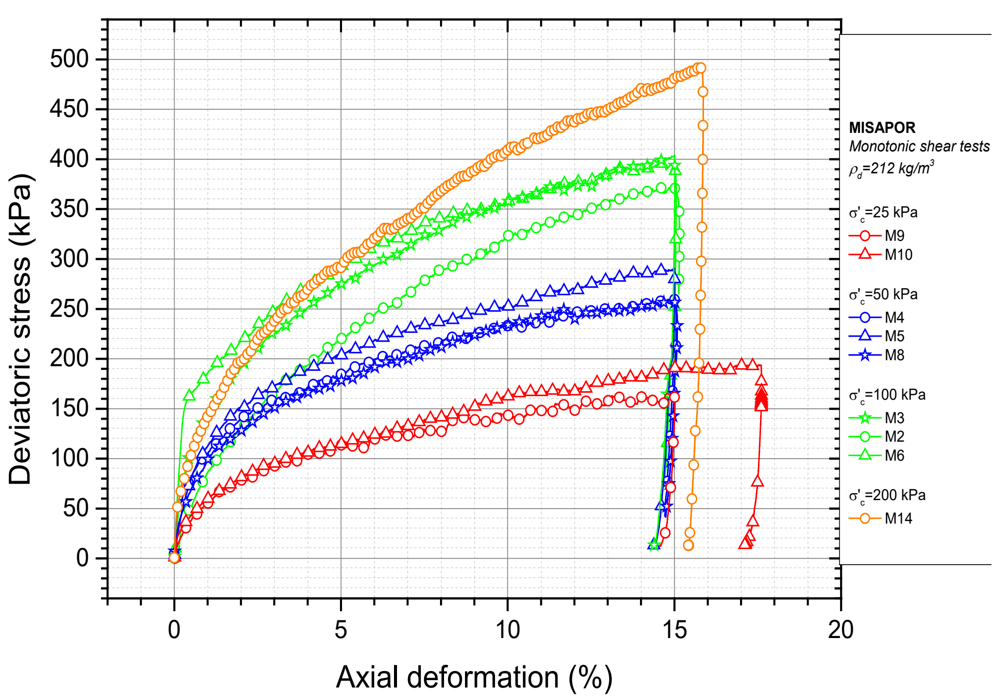

Figure 3. Evolution of the grading curve of cellular glass after shear tests M10 and M14

The Mohr circles at failure were plotted for the different tests as shown in Figure 4. Failure is defined here as the maximum deviator stress reached during shear and therefore corresponds to the maximum axial deformation reached. As indicated on this figure, two different failure regimes were observed. For low values of consolidation stress, it can be noted a relatively high value of angle of shearing resistance (φ') and a rather low apparent cohesion (c'). For higher values of the consolidation stress, the angle of shearing resistance could appear lower with a higher value of apparent cohesion. A nonlinear failure criterion, based on the nonlinear envelope curve of the failure Mohr circles, can be defined. This observation can be attributed to an increase in level of grain crushing for higher values of consolidation stress.

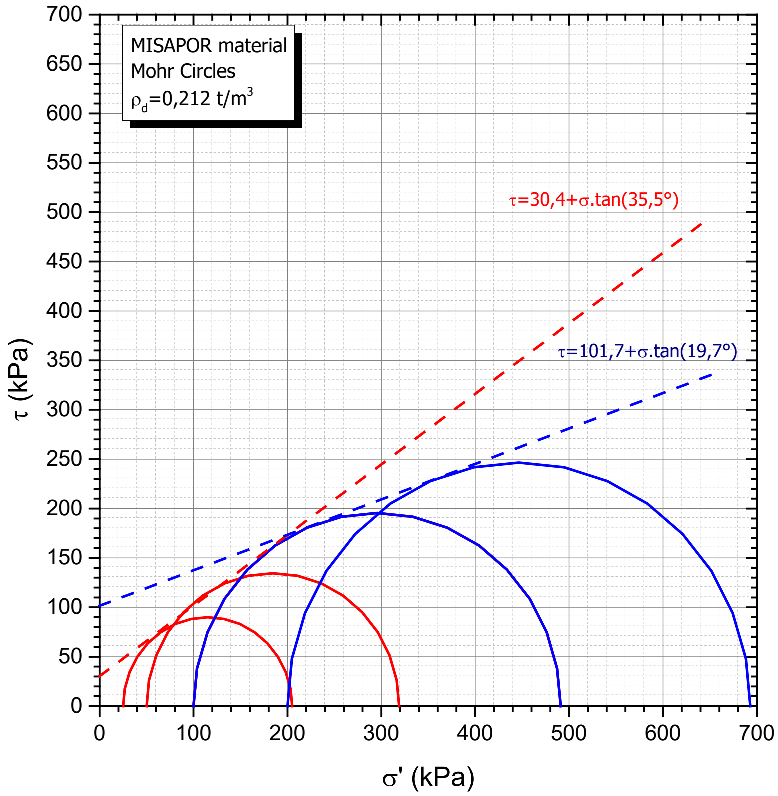

Figure 4. Evaluation of Mohr-Coulomb failure parameters

Influence of dry density

In order to investigate the influence of the initial dry density on the mechanical properties of the cellular glass aggregates; two different values of dry density were considered (ρ_d = 212 kg/m^3 and ρ_d = 230 kg/m^3). These two densities correspond respectively to a compression ratio, with respect to the loose state, of 1.18 and 1.28. Figure 5 shows the results obtained at a consolidation stress of 50 kPa. The differences observed between the results corresponding to the two densities are not very significant, where a discrepancy of about 7% was noted.

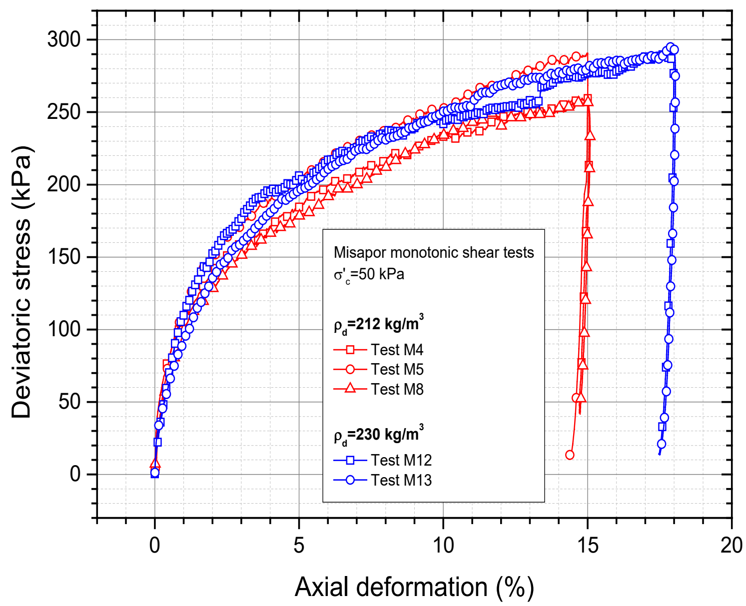

Figure 5. Shear curves obtained at σ'_c = 50 kPa for two different dry densities, in this case ρ_d = 212 kg/m^3 (M4, M5 and M8) and ρ_d = 230 kg/m^3 (M12 and M14)

Influence Initial Aggregates' State

It is believed that the initial aggregates' state plays an important role in the shearing characteristics of cellular glass foam. For this reason, it was decided to investigate the influence of the aggregates' state on the initial dry density and the particle size distributions of this material. Three different aggregates' states were considered and studied, in this respect flawless or intact, weathered, and compacted state. For testing, the material was divided into six packs; where each pack was poured into the mold from a constant drop height. This procedure is repeated three times. The average dry density ρ_d was found to be 178 kg/m^3, which corresponds to a loose state. Knowing that, the lowest dry density that can be reached for a standard Fontainebleau sand (e_{max} = 0.87, ρ_s = 2650 kg/m^3) is ρ_d = 1417 kg/m^3, it can be confirms that this material is lightweight (i.e. eight times lighter than Fontainebleau sand).

It is well known that using cellular glass in the field involves several phases of handling and transportation that may damage the material. In order to take this aspect into account, a weathering process has been used, based on mixing or shaking the material in a cement mixer.

The cement mixer was filled at 45 % of its maximum capacity with the intact material. The mixer was inclined at 45° with respect to the horizontal and the material was mixed or shacked for 2 minutes. The weathered material is then collected and sieved in order to determine the impact of the weathering protocol on the material. Figure 6 shows a comparison of grading curves obtained for the intact and the weathered materials, showing a moderate decrease of the large elements proportion, decreasing from 21 % to 15 % and an increase by 4 points of the proportion of the particles smaller than 31.5 mm. The grading parameters needed to classify the weathered material are reported in Table 2. They differ slightly from those of the intact material, showing a low impact of the weathering process on the material, which is still classified as a poorly graded gravel (GP).

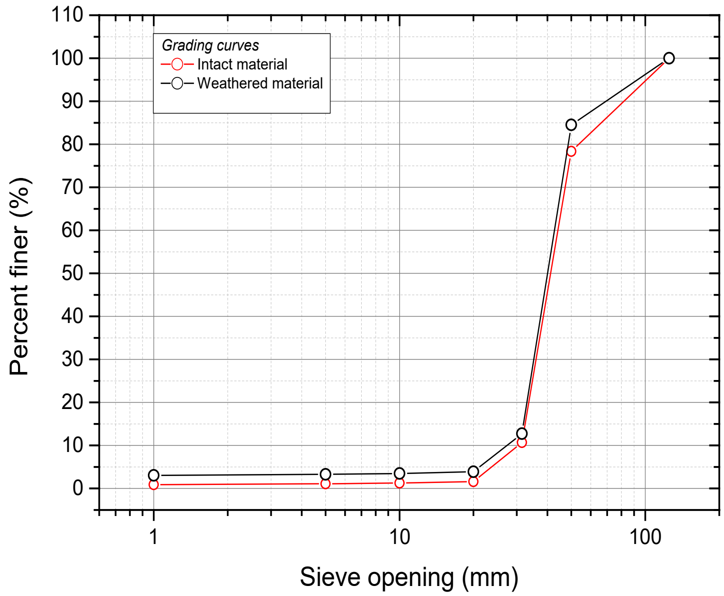

Figure 6. Comparison between the grading curves obtained for the intact and weathered material

Table 2. Values of d_{10}, d_{50}, d_{60} and C_u for cellular glass after the weathering process

Type of material	Dry density ρ_d (kg/m^3)	d_{10} (mm)	d_{50} (mm)	d_{60} (mm)	$c_u = d_{60}/d_{10}$
Loose material	179	30	41	45	1.50
Aged Material	179	27	40	43	1.59

For industrial applications of cellular glass, compaction is usually necessary for the implementation of the material. It is therefore important to characterize and quantify the compaction process. Different compaction tests have been performed on the material in order to set up a well-defined protocol and evaluate the impact of this protocol on the evolution (damaging) of the material. The tests have been carried out for two specific dry densities, $\rho_d = 212$ kg/m^3 and $\rho_d = 230$ kg/m^3, which correspond, respectively, to a compaction ratio (with respect to natural state) of 1.19 and 1.29. In order to ensure a good homogeneity of the material density within the mold, the specimens were fabricated by successively compacting six layers of 10 cm thickness each. A PVC disc was used to level each layer and homogenize the compaction energy within the layer. The compaction tool was dropped on the plastic plate from a constant drop height and the thickness of the layer was measured after each drop. This process was repeated until a layer thickness of 10 cm was reached. Figure 7 shows the state of the material after compaction. Clearer zones are visible, corresponding to contact surfaces with the compacting plate, where the material was locally crushed. Also, some big size elements were broken down into smaller elements. In order to better quantify the material damage induced by compaction, the grading curves of the material after compaction, for both densities, are shown in Figure 6 and compared with the grading curve of the intact material. The evolution of the grading curve appears mainly on the elements bigger than 20 mm and it may be seen that the compacting process mainly breaks the biggest elements down to intermediate ones, while creating a small amount of fines. A synthesis of the effects of the compaction on the material is given in the Table 3.

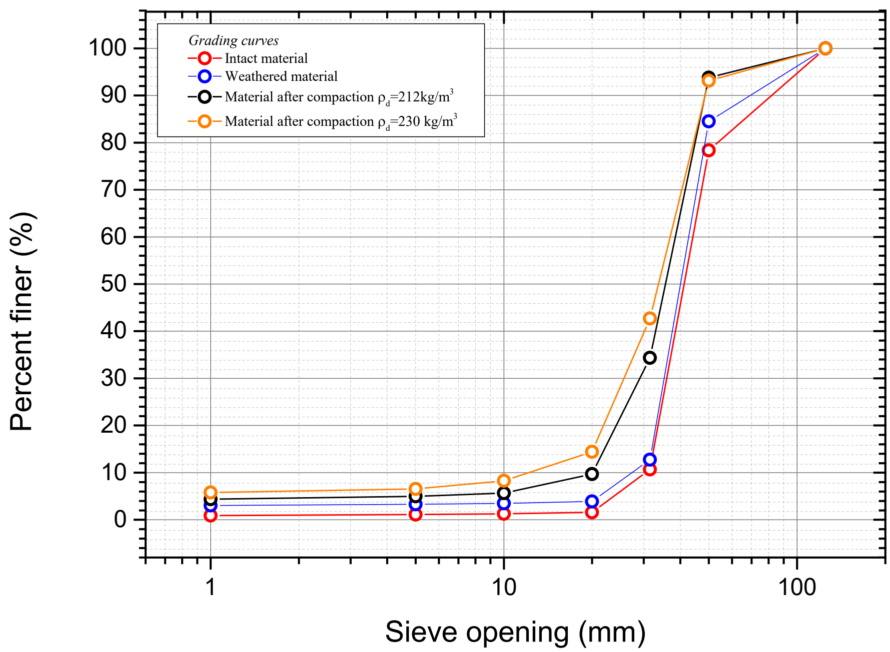

Figure 7. Comparison of grading curves obtained for cellular glass: intact, weathered and compacted material

Table 3. Values of d_{10}, d_{50}, d_{60} and c_u for cellular glass in a loose and compacted state

Type of material	Dry density ρ_d (kg/m^3)	d_{10} (mm)	d_{50} (mm)	d_{60} (mm)	$c_u = d_{60}/d_{10}$
Bulk material	179	30	41	45	1.50
Compacted material	212	21	36	39	1.87
Compacted material	230	20	35	38	1.90

Conclusion

Cellular glass material is considered as relatively new and innovative material. It is therefore important and essential to obtain mechanical characterization of this material under different testing conditions. In this experimental program, the influence of initial dry density, initial aggregates' state (i.e. flawless, weathered, and compacted), and consolidation stresses on the mechanical behavior of cellular glass foam were investigated. It can be conclude that the material's behaviour observed under monotonic shear is of contracting type, with significant evolution of the material during shear (grain crushing) and a strongly strain-hardening character. The failure criterion of the studied material is similar to the failure criterion used for granular soils for which a shearing resistance angle and apparent cohesion is perceived.

It is important to mention that; cellular glass waste recycling can also reduce costs associated with obtaining natural aggregates and reduce the environmental impact associated with solid waste disposal. Recycling of wastes glasses could reduce the demand for virgin natural resources and help to dispose of them effectively. The innovation in the circular economy is crucial to the transition to more sustainable infrastructure development.

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