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Effect of Static Loading States on the Compressional Behavior of Foam Glass Aggregate

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Abstract

In this study, two groups of foam glass aggregate (FGA) samples were prepared with four different compaction ratios (10%, 20%, 30%, and 40%) and subjected to a series of static compressional loads from 50kPa to 300kPa with 50kPa interval. In first group of the test (changed load samples, ChLS), for each static load value, a new sample was prepared and tested. In the other group of the test (continuously loaded samples, CLS), all prescribed static compressional loads were sequentially applied over the same sample after satisfying the required strain rate at each load. The results revealed that the overall vertical strain values of CLS were lower than ChLS except for 10%, which shows reverse behavior. For both sample types, the required time to reach the desired vertical strain rate was much higher when the compaction ratio was low, and the compressional load was above 250 kPa. The compaction methodology used in the present study led to more reliable vertical strain values for both short- and long-term loading periods compared to other reported results executed on FGA under the same static compressional load circumstances. The evolution in the particle distribution curve of FGA particles after maximum compaction ratio (40%) was nonsignificant compared to the study works that depended on traditional standard test methods of compaction and led to severe change in particles structural component. The current findings beneficially affect civil engineering applications using FGA by defining the material's final strain values when subjected to static compressional loads at different compaction ratios.

Keywords

compaction ratio, static compressional loads, vertical strain, strain rate

1 Introduction

Last few decades, utilizing waste recycled materials in civil engineering applications has become increasingly important, mostly because of their benefits for producing new materials with acceptable engineering features and more sustainable/greener settings. For this reason, many types of waste materials have been investigated, such as waste rubber tires [1], Aluminum waste [2], construction and demolition waste [3], waste crushed glasses collected from different sources [4] were investigated.

Various research studies have been conducted to explore the advantageous utilization of different types of recycled glass. These studies involved implementing physical and/or chemical procedures, such as producing granular-sized crushed glass [4–6], blending crushed glass with other recycled materials [4, 7, 8], and creating glass powder [9–11]. Ashiq et al. [12] conducted a study to assess the applicability of industrial waste glass powder (IWGP) by incorporating it into air-dried base soil to examine its effects on various properties. Their results indicated that the inclusion of 20% IWGP led to the greatest enhancements in UCS (unconfined compressive strength) by 110%, un-soaked CBR (California Bearing Ratio) by 67%, and soaked CBR by 300%, while also reducing the swelling strain by 26% under 1 kPa effective vertical stresses. In another investigation, Disfani et al. [13] examined three types of recycled glass, namely Fine Recycled Glass (FRG), Medium Recycled Glass (MRG), and Coarse Recycled Glass (CRG), to evaluate their potential as construction materials in geotechnical applications. They found that MRG exhibited superior shear resistance

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in CBR tests compared to FRG, and the internal friction angle of MRG, determined through direct shear tests, was slightly higher than that of FRG. Additionally, the shear strength tests revealed that both the fine and medium glass samples demonstrated shear strength characteristics similar to natural sand and gravel mixtures containing angular particles. Javed and Chakraborty [10] studied the impact of incorporating glass powder into cohesive soil using a range of index and geotechnical engineering tests. Through their experimentation with various ratios of glass powder, they identified that the optimal proportion was 8% relative to the dry weight of the soil. Their findings indicated that the inclusion of glass powder led to a reduction in liquid limit (LL), plastic limit (PL), and plasticity index (PI), as well as an increase in maximum dry density (MDD), California Bearing Ratio (CBR), unconfined compressive strength (UCS), and shear strength parameters. Additionally, they observed a decrease in the optimum moisture content (OMC).

Foam glass aggregate (FGA) is also produced from waste glass materials and has identical physical proportions and forms to natural stone, with excellent thermal insulating capabilities. Some investigations have been conducted on the application of foam glass aggregates in geotechnical contexts [14, 15]. In general, foam glass has a number of technological benefits, including low density, high strength, thermal insulation, frost resistance, fire resistance, rat resistance, acoustic insulation, non-toxicity, minimal water absorption, and short installation times [16]. Compared to other construction materials, foam glass is resistant to bioactivity and bacterial attacks [7, 9] and is simple to handle [10, 11]. FGA can be employed as a lightweight backfilling material for retaining walls, embankments, bridge abutments, and slope stability applications [17–19]. Due to the positive impact of such material, foam glass aggregates can produce lightweight concrete and construct infrastructural foundations and sports fields [9, 13–15].

Furthermore, employing typical construction materials that produce a lot of vertical loads might make it more difficult to implement many civil engineering applications due to issues like excessive settlement and inadequate subsurface stiffness. To solve such issues, it is seen to be a suitable option to use lightweight materials with appropriate technical qualities [16, 17] which led to more affordable designs of those geo structures use massive amounts of material for be constructed. These materials' lightweight qualities often result from the solid part's low unit weight and a significant number of connected or unconnected pores [14]. Granulated tire rubber [17, 20], extruded polystyrene (XPS) boards [21], lightweight clay aggregate [22, 23], and foam glass aggregate [24] are some examples of the lightweight materials that are used in civil engineering applications such as earthwork construction.

Because foam glass is a manufactured product, many studies have been done to improve the quality of the product with lower cost depending on different glass sources and focusing on those points which influence the final output of the material. In this regard, numerous research has been conducted on components that improve a material's engineering characteristics, such as the type of glass [26–29], sorts and dosages of foaming agents [29, 30], as well as sintering temperature and temperature growth [31, 32]. In order to create foam glass from soda-lime glass using dolomite as the foaming agent, Pokorny et al. [29] evaluated the effects of three heating rates (50, 100, and 150 °C/hr). They found that lower heating rates result in lower volumetric expansion due to the escape of CO_2 from the samples and that higher heating rates result in foams with larger pores. Fernandes et al. [30] found that increasing the content of the foaming agent (eggshell containing 95 wt.% $CaCO_3$) decreases the foam density produced from CRT funnel and panel glass and also concluded that increasing the temperature results in larger pore size.

On the other hand, as seen from the literature, there is still little discussion about the mechanical characteristics of foam glass aggregates while they are in their bulk state. To evaluate the engineering and environmental features of foam glass aggregate, Arulrajah et al. [31] performed experiments on the substance. They demonstrated how foam glass aggregate meets engineering and environmental requirements, making it a perfect lightweight fill material. Swan Jr. et al. [32] investigated the impact of various compaction effects on gradation and compression (short and long loading), and the direct shear behavior of FGA conditions by implementing specific static compressional stresses. They concluded the significant impact of high compaction energy on particle breakage when the material has been subjected to a direct shear test, which led to a change in the material gradation from uniformly graded to very well graded. Additionally, they observed an extra vertical strain after applying the static compressional loads for a longer time on FGA samples, probably due to the material's creep behavior. Furthermore, Ghafari et al. [33] studied the dynamic properties of the material under repeated load in a triaxial apparatus following the standard AASHTO T 307-99 [34].

Due to the availability of high percentages of pores falling between 60% to 96% [14, 35, 36], it was 92.7% for the studded foam glass aggregates, and big particle size distribution nature which led to a high amount of voids foam glass aggregate can be considered a good thermal conductivity material. The study of [37] showed that foam glass could be used for various thermal insulation purposes, including thermal insulation of building foundations and cellar plates, backfilling of cavities or overflows in structural engineering, and cost-effective insulation for large-scale thermal energy storage (TES). The findings of [38] demonstrated the potential of employing foam glass aggregate as a thermal insulation material beneath floor slabs exposed to a highly extended loading period. Many fields and laboratory tests have been done Ghafari et al. [33]. They demonstrated that using foam glass aggregates as a thermal insulation layer in flexible pavement constructions improves pavement durability and lowers maintenance and rehabilitation expenses. According to their investigated method, foam glass aggregates regulate and restrict frost penetration in frost-sensitive subgrade soils, hence reducing the freezing and thawing effects that cause road and highway-bearing capacity degradation. According to the finding of [39], foam glass aggregate can be used in a variety of civil engineering applications to offer thermal insulation and frost protection due to the measured value of the thermal conductivity of compacted foam glass aggregate, which was found to be around 0.085 $Wm^{-1}K^{-1}$.

The previously mentioned introduction showed the importance of foam glass aggregates which can be utilized as lightweight and insulation material for different civil engineering applications. Therefore, to fill this gap the influence of various static compressional loading states, changed load samples and continuously loaded samples, were precisely investigated on compressional behavior of the material. For this reason, different compaction ratios (10%, 20%, 30%, and 40%) and static compressional loads (50 kPa, to 300 kPa with 50 kPa intervals) were applied on FGA samples. Furthermore, the results of the present study have been compared with other studies that used standard compaction methods for such material, which led to more geotechnical problems during its service life.

2 Materials and methods

2.1 Material: foam glass aggregate

The used form glass aggregates developed by a Hungarian company [40] has a grey color and a sharp-grained (angular), broken-edge surface like crushed stone, with a density of around 170 kg/m^3. The particle size distribution curve in Fig. 1 reveals that the material primarily included gravel-sized particles.

The employed foam glass aggregates are poorly graded, with a main grain size range of around 10 to 60 mm, with a coefficient of uniformity and curvature of 1.66 and 1.13, respectively. According to cubic samples, the material's mean uniaxial compressive strength is 1200 kPa [41].

2.2 Methods

With typical geotechnical instrumentation, it is impossible to conduct a static compression stress test on samples of foam glass aggregate. A single particle may be larger than the usual sample size (grain size ranged between 10 to 60 mm in diameter). To comply with the recommended 5D (most oversized particle diameter) size regulation, a customized test frame (mold) measuring 300 mm in diameter and 250 mm in height was built. To obtain 10% and 20% compaction ratios in the lab, foam glass aggregate (FGA) was compacted into the prepared mold by one layer using a heavy load plate with a smaller diameter of around 5 mm from the mold diameter. While to achieve 30% and 40% compaction ratios, foam glass aggregate was packed into the mold in two layers.

The size of the individual particles prevented the creation of a flat surface. This may lead to drastically changed test findings by causing the load plate to transmit loads to specific locations rather than evenly. Therefore, as a load-distribution layer on top, gravel and sand were utilized to lessen the impact of the rough surface. First, a flatter face was made by closing the big available gaps at the surface of the foam glass aggregate particles with 4/8 mm gravel. After that, it was coated with 0/1 mm of sand to provide a flat surface so that the load plate could transmit loads consistently. Following the static compressional test, grain

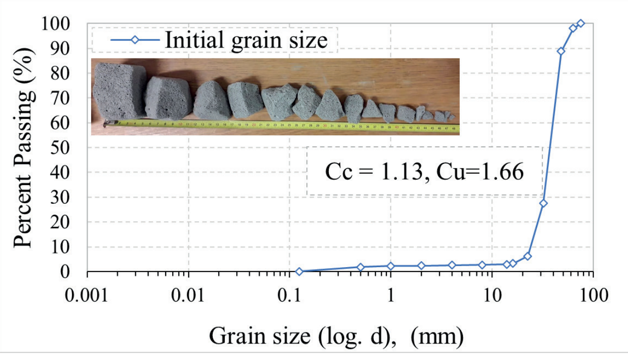


Fig. 1 Foam glass aggregates and foam glass aggregates distribution curves

size distribution analysis was carried out on the samples of foam glass aggregate to determine the effects of various compaction ratios on the development of the particle distribution curves of foam glass aggregate.

The static test has been conducted on two types of foam glass aggregate samples which changed load samples and continuously loaded samples, to evaluate the impact of static compressional loads at different loading states on the material behavior. The result of every single curve of changed load samples and continuously loaded samples was obtained after getting the mean value of (3 to 5) and (5 to 8) trials of the test trials, respectively. The test trials continued until the desired strain rate reached 0.01 mm/min.

3 Results and discussions

3.1 Particle size distribution

To show the minimum and maximum boundary effects of compaction ratios on the evolution nature of particle size distribution curves of foam glass aggregate (FGA), Fig. 2 was drawn. As the figure shows, increasing the compaction ratio increased the smaller particles of FGA. This probably was because of the compaction effect on particle breakages. The material was compacted using a heavy plate load to reach the desired compaction ratio, which led to the crushing of the bigger particles and resulted in smaller ones. Namely, the obtained particle distribution curve at 40% compaction contained smaller particles than the as received once. The impact of compaction energy on the evolution of particle distribution curves of natural and conventional building materials has been shown by various studies in this regard. According to Rammatury et al. [42] the amount of fine content would rise by 1% by compacting the conventional aggregate used in road building. Yaghoubi et al. [43] showed that two kinds of construction and demolition materials utilized in pavement applications tend to have more fine content as compaction energy is increased. Both abrasion and attrition processes contributed to the conventional aggregate's increased fine content, which increased the bulk density and decreased the aggregate's angularity [44, 45]. As a result, increasing the compaction ratio will more obviously and significantly impact the particle distribution nature of lightweight materials such as foam glass aggregate, mainly produced from glass powder. Fig. 2 shows that the growth of the fragmentation process, primarily associated with an increased compaction ratio (compaction energy), was the primary cause of the development of smaller particles. FGA particles were exposed to local compression and shearing failure during the build-in fragmentation process under the influence of impact compaction energy. This influence should be considered at the actual site when foam glass aggregates are proposed for use as a construction material by adapting a proper compaction methodology to reach the desired compaction ratio.

In addition to the results of particle size distribution curves obtained from present study, the results of the previous study conducted by Swan Jr. et al. [32] on foam glass aggregates (FGA) is also presented in Fig. 3. Swan Jr. et al. [32] investigated the impact of higher compaction energy on the particle distribution behavior of FGA following ASTM [46] standard. Two different compaction efforts, 2,700 kN-m/m^3 and 1,200 kN-m/m^3, were utilized in their experiments. From both studies appeared that by applying higher compaction energy to the samples of FGA, an increase in the quantity of smaller particles observed but with different extensions depending on used compaction methodology, as depicted in the particle distribution curves. Based on that, the final distribution curves of the study of Swan Jr. et al. [32] changed from poorly graded FGA into a well-graded material under the

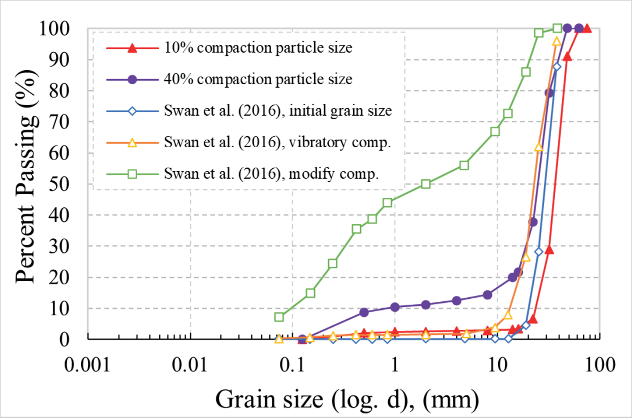


Fig. 2 Particle distribution curves of foam glass aggregate of the present work and the study of Swan Jr. et al. [32]

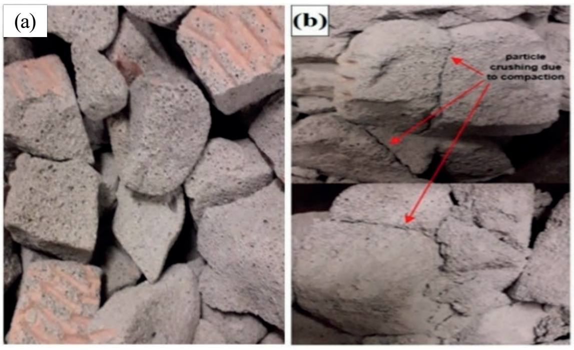


Fig. 3 Foam glass aggregates at different compaction states, a) before compaction, b) after compaction

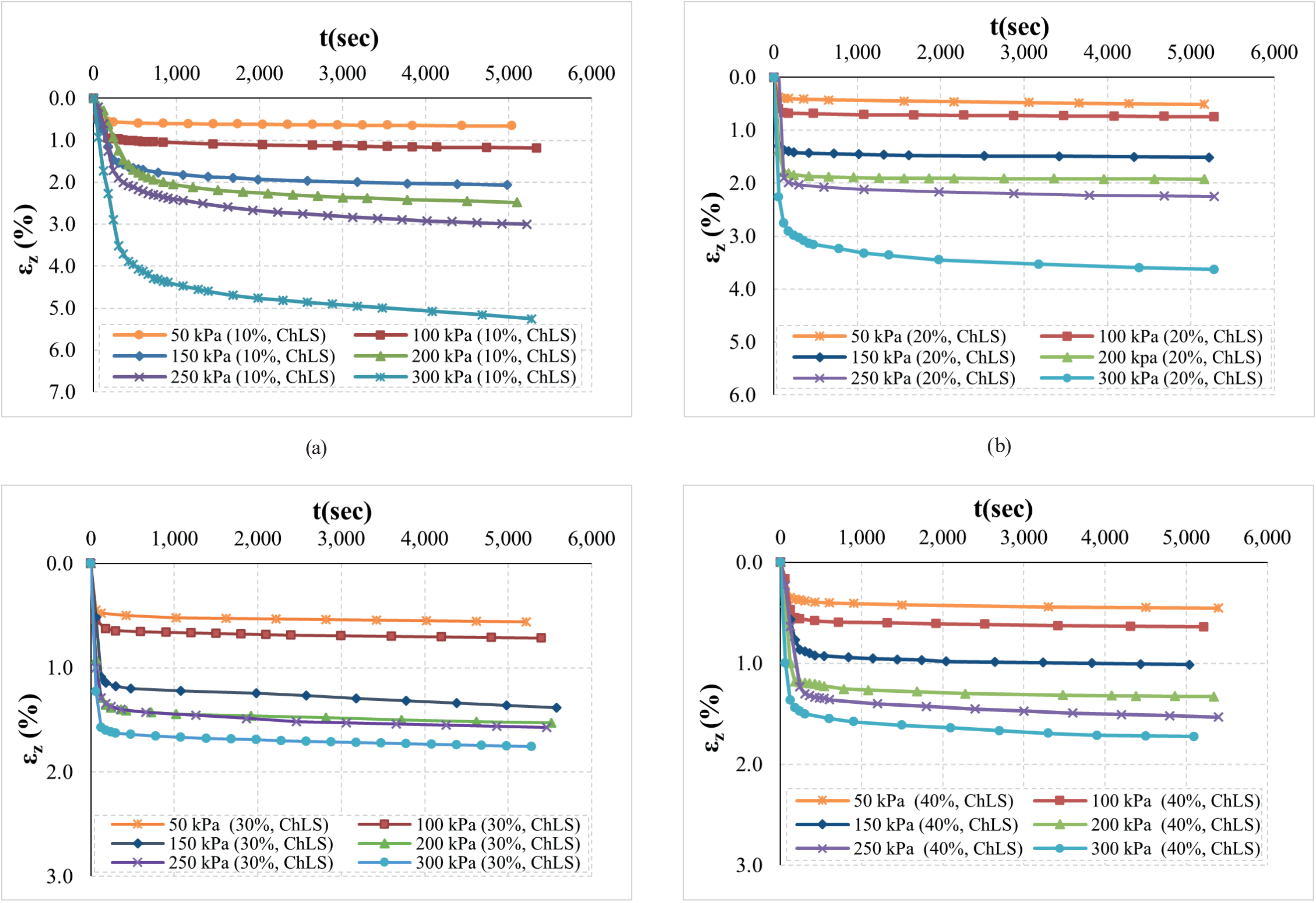
influence of increased compa (b) n energy. While, in case of the present study, comparatively small change happened in the distribution curves resulted in an increase in the amount of smaller particles. Especially, comparing the evolution that happened for the particle size distribution curve of the present study after 40% compaction with the results obtained by Swan Jr. et al. [32] revealed that using traditional standard compaction methods to compact a lightweight material such as FGA led to getting more smaller particles which finally cause more geotechnical problems due the composition nature of the material. Therefore, avoiding a significant change in the physical composition of the material is recommended to be a way from crushing the grains, which increases the smaller particles and fine contents, eventually increasing the material's compressibility.

Comparing the evolution that happened for the particle size distribution curve of the present study after 40% compaction with the results obtained by Swan Jr. et al. [32] revealed that using traditional standard compaction methods to compact a lightweight material such as FGA led to getting more smaller particles which finally cause more geotechnical problems due the composition nature of the material.

Therefore, avoiding a significant change in the physical composition of the material is recommended to be a way from crushing the grains, which increases the smaller particles and fine contents, eventually increasing the material's compressibility.

3.2 Time vertical strain of foam glass aggregates

Time-vertical strain results of both sample types, changed load samples (ChLS) and continuously loaded samples (CLS), are presented in both Fig. 4 and Fig. 5. As can be seen from the parts of Fig. 4, increasing the compaction ratio from 10% to 40% significantly affected decreasing the vertical strain values of FGA. The maximum vertical strain obtained at 10% after applying 300 kPa was about 5.26%. In comparison, it decreased to about 1.73% at 40% at the same loading-time circumstances showing about



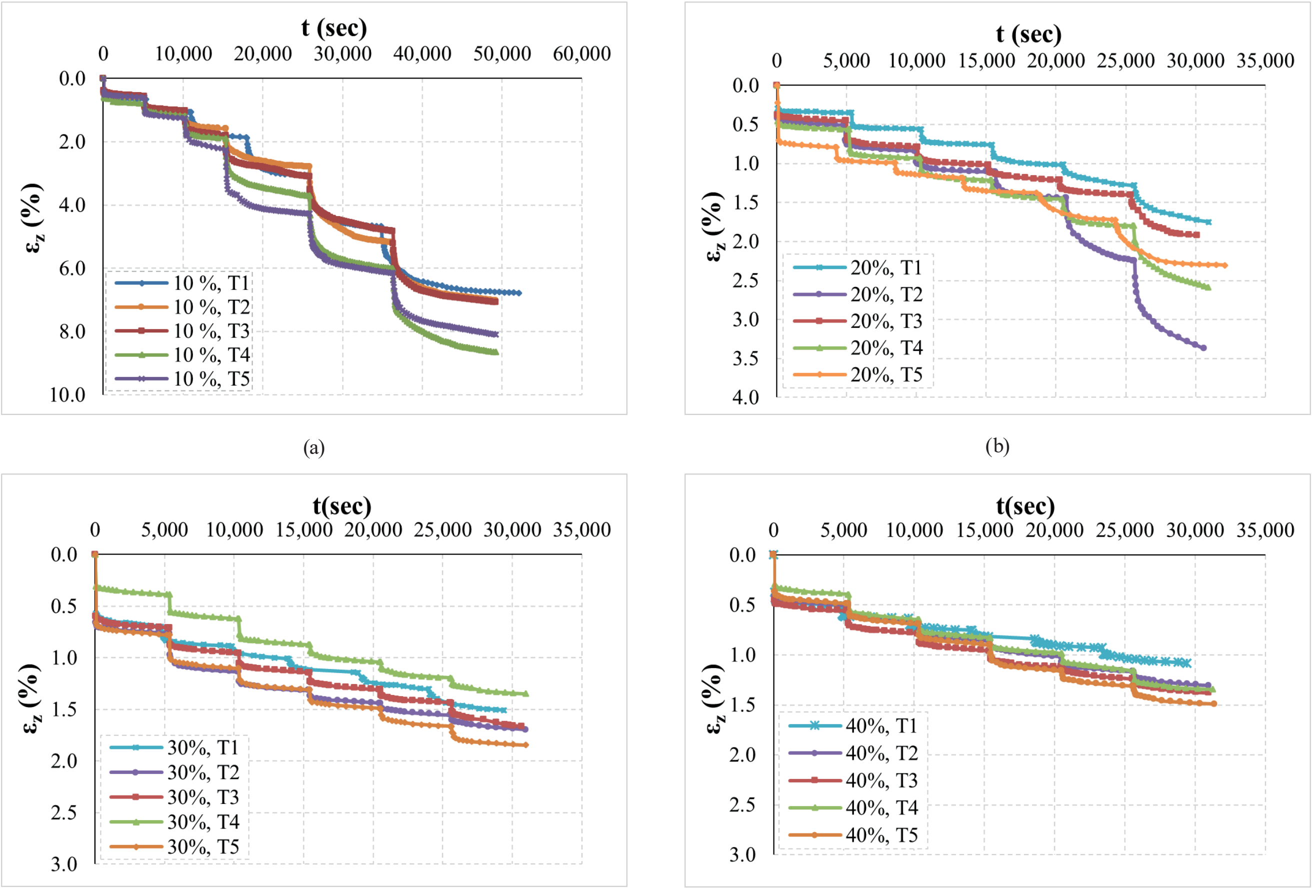
(a)

(b)

(c)

(d)

Fig. 4 Time-vertical strain behavior of changed load samples of FGA at different compaction ratios: a) 10% compaction, b) 20% compaction, c) 30% compaction, and d) 40% compaction



(a) (b)

(c) (d)

Fig. 5 Time vertical strains of the continuously loaded sample of FGA at different compaction ratios: a) 10% compaction, b) 20% compaction, c) 30% compaction, d) 40% compaction

a 00% decrease in the vertical strain. The improvement rate indicates the significant impact of elevated compaction ratios on improving the oedometric stiffness of the material, which can beneficially affect the degree of stability of such material in geotechnical applications.

As apparent from the time-vertical strain curves of Fig. 4 (a and b), the available difference between the consequence compressional loads increased by showing a wider gap after applying more than 250 kPa. This behavior of FGA refers to the material's weakness in resisting such applied static compressional loads, which should be avoided at the actual site to prevent the dramatic increase in the vertical strain's values.

Furthermore, applying higher compressional loads increased the required time to reach a stable vertical strain value from the beginning of the loading process, especially when the compaction ratio was low (10%), and the applied load was high. For example, after devoting more than 150kPa, the required time to reach a stable vertical strain value at 10% compaction increased compared to lower loading values. Although, the loading process stopped only after getting the required strain rate of 0.01 mm/min.

The time needed to reach a stable vertical strain value significantly decreased when the compaction ratio was increased to 30% and 40%. This resulted from the elevated compaction ratio's positive effects on the material's stability under static compressional loads and showed a shorter loading time to reach the same vertical strain rate (0.01 mm/min).

In the same regard, as shown in Fig. 5, the impact of increasing compaction ratios appears on the compressibility behavior of FGA. Increasing the compaction ratio led to a significant decrease in the vertical strain of the individual loading steps, which decreased the final vertical strain values obtained after applying the final compressional load (300 kPa). At a low compaction ratio (10%), five trials' mean vertical strain value after applying 300 kPa on FGA was about 7.46%. In comparison, at the same loading circumstances and 40% compaction, the final mean vertical strain value was only 1.32%. The obtained results appeared that the percentage decrease in the vertical strain value after compacting the material by 40% was about 465%, meaning a significant decrease in the amount of compression and apparent improvement in the material's stiffness. Moreover, the final vertical strain values of FGA material in many civil engineering applications as a filling material compared to other geomaterials such as dense sand and stiff clay.

As appeared from both the above-mentioned compressional states ChLS and CLS, increasing the compaction ratio caused a significant decrease in vertical strain values. This behavior of FGA could be related to the internal connection conditions of the particles, which primarily depended on the compaction ratio of the material. Mustafa et al. [47] did a series of compressional static tests on FGA. They explained the main reason behind the significant impact of elevating compaction ratios on decreasing the compressional strain of the material. They observed that at low compaction conditions, the particles of the material connected with smaller connection areas, leading to weak load transition paths between the particles. While at high compaction ratios, the particles associated with much broader connection areas result in providing strong primary load transfer machines with the availability of lower void ratios between grains of the material. As a result, the material can transfer the same amount of applied compressional load with much lower vertical strain values.

3.3 Stress-strain behavior of foam glass aggregates

To compare the values of vertical strains obtained from both types of FGA samples, changed load samples (ChLS) and continuous loaded samples (CLS), Fig. 6 has been drawn. As seen from the figure, generally, the samples with compaction ratios (20%, 30%, and 40%) had smaller vertical strain when continuously loaded except for 10%, in which the condition was reversed. The reason behind getting more vertical strain in the case of ChLS could be related to the initial strain values obtained at the beginning of each newly loaded sample. For the ChLS, approximately an extra amount of vertical strain was exhibited due to the virginity of the loaded surface, which led to more instability against external loads. While for the CLS, the material passed the initial surface stability condition, and the only major impact was related to the load's effect on the material's compressional behavior. This behavior of foam glass aggregates indicates the sensitivity of the material for the initial loading stage, which led to extra vertical strain as in the case of the present study when the load was above 250 kPa and the compaction ratios was lower than (10% and 20%).

Furthermore, Swan Jr. et al. [32] conducted a compressional test on samples of FGA after compacting the material depending on ASTM D1557 [46], using two types of compaction effort of 2,700 kN-m/m^3 and 1,200 kN-m/m^3. To compare the result of static compression with the one which has been done by Swan Jr. et al. [32] Fig. 7 has been drawn. According to their results, as seen from the figure, a much higher amount of vertical strain was obtained compared to the one got from the present study, probably due to the method they followed to prepare the sample in the lab. By depending on the ASTM standard method, they applied a substantial amount of impact energy, leading to significant particle breakage. Due to the particle breakage under the effect of impact compaction, the amount of fine contents collected at the external contact area between the material particles have been deposited. As the figure shows, the material's compressibility increased incredibility with the availability of the smaller size and fine contents.

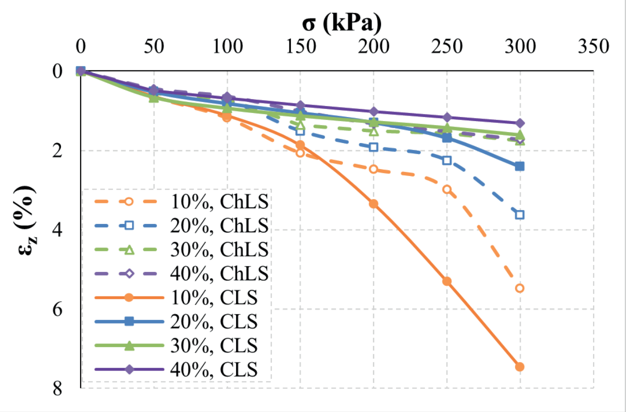


Fig. 6 Compressional behavior of foam glass aggregate of both continuously loaded samples and changed load samples

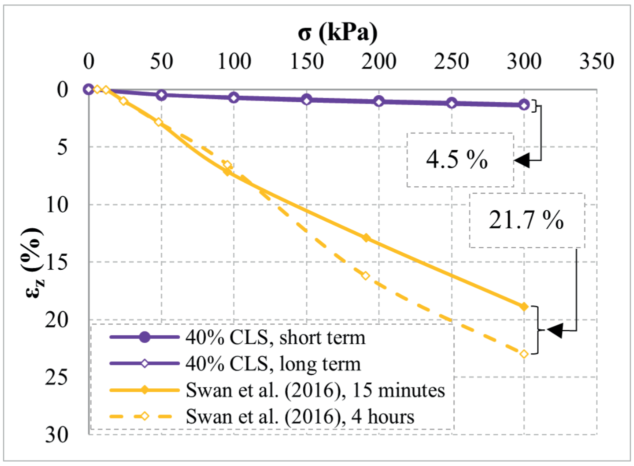


Fig. 7 Short and long-term compressional behavior of foam glass aggregate of the present study compared with the study of Swan Jr. et al. [32]

Moreover, Fig. 7 shows the short- and long-term behavior of FGA of the present study with the one available in the literature. According to the figure, a nonsignificant amount of vertical strain of the studded FGA was obtained (4.5%) compared with the results obtained by [32] which was around 21.7%.

Although the long-term loading period (4 hours) has been adopted in their study which is considered very short compared to the present study in which the long-term (creeping) loading periods were (5, 7, 10, 10, 15, and 15) days, respectively, to the applied corresponding static compressional loads (50, 100, 150, 200, 250, and 300) kPa. According to creeping test specifically at both 30% and 40% compactions the material did not exhibit any creep behavior which can be very valuable for the practical use of the material. Therefore, it is recommended to use the material under such compaction condition in geotechnical and civil engineering applications which subject to long term loading. For the same reason, Swan Jr. et al. [32] applied static compressional long-term loads (creep test) on FGA following ASTM test standard methods to analyze the material's creep behavior. After applying a steady load of 24 kPa for 10,025 minutes (about seven days), they noticed from the time-deformation curve that the specimens of FGA had a creep strain rate of 6.56×10^{-6}%/min with bulk unit densities ranging from 400 to 460 kg/m^3. Destructive issues, including collapse, landslides, and residual settlement, were caused by creeping material behavior [48]. Further detailed research is needed to assess the creep behavior of the FGA under various compressional loading states and for different long-term loading durations. Furthermore, Fig. 8 indicates that the structural condition of FGA of the present study reached 40% compaction was much better than the one obtained by Swan Jr. et al. [32] after applying modified compaction effort. This result appeared more apparent through the availability of more damage in the structural component of their particle distribution curves, which led to a significant difference in the vertical strain values obtained at long-term loading conditions.

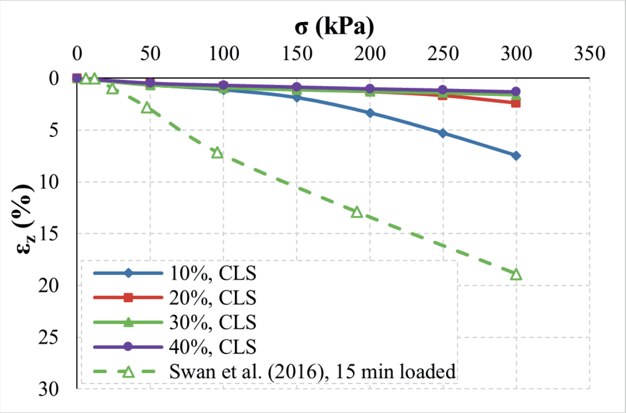


Fig. 8 Compressional behavior of foam glass aggregate of the present study compared with the study of Swan Jr. et al. [32]

4 Conclusions

The present study focused on showing the impact of different static compressional loading states (changes load samples and continuously loaded samples) on the compressibility behavior of FGA samples prepared with different compaction ratios (10%, 20%, 30%, and 40%). The impact of the compaction ratio on particle gradation evolution was presented by comparing the particle distribution curves of the (40%) compaction ratio with the received material. In the same regard, the results of the particle distribution curves compared with other studies depended on different methodologies to compact the material. The compressibility behavior of FGA through both sample states changed load samples (ChLS), and continuously loaded samples (CLS) was illustrated. A comparison was made between the compressibility behavior of FGA using the unique methodology of the present work with the one that used traditional standard test methods to compact FGA. All the categories mentioned above led to the following conclusion:

The required time to reach the desired vertical strain rate (0.01 mm/min) at 10% compaction was much higher than the one that was needed at 40% compaction. Therefore, the compressional time-vertical strain curves showed leveled trend in a shorter time when the compaction ratio was more than 30% and 40% compared with the one at low compaction ratios (10%, and 20%), especially when the amount of compressional load was above 250 kPa.

The vertical strain of continuously loaded samples showed less values than changed load samples except for the 10% compaction. This was due to the impact of the initial stability of the samples reached at the beginning of the first continuous compressional loads making the samples able to tolerate the same amount of compressional loads showing stiffer conditions. This behavior of FGA should be considered at the site during the loading process to be away from extra vertical strains, especially when the compaction ratio is lower than 20% and the applied load is above 250 kPa. Moreover, the material did not exhibited any creep behavior under long-term loading state when it was compacted by both (30%, and 40%) which is considered very valuable for the practical purposes.

The maximum vertical strain observed in ChLS was approximately 5.26% at 10% compaction with a 300 kPa load. However, this strain decreased to around 1.73% at 40% compaction under the same loading and time conditions, indicating a reduction of about 200% in vertical strain. In contrast, for CLS with a low compaction ratio of 10%, the vertical strain measured approximately 7.46%, whereas at 40% compaction, the vertical strain decreased significantly to only 1.32%. This indicates a percentage decrease of approximately 465% in the vertical strain of CLS after compaction by 40%.

Vertical strain values significantly increased when the samples were prepared using traditional standard compaction methods due to getting more fine contents and smaller particles due to the nature of the grains in which the material was made. This finding illustrates the significant rule of compaction methodology used to reach the desired compaction ratios, especially for lightweight materials due to having special structural composition.

The difference between long- and short-term loading of foam glass aggregates prepared using traditional standard test methods for compaction was much higher than the one obtained through using the individual compaction method followed in the present study, although the loading period of the present study was by much higher than the one adopted in compared research.

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