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One dimensional static and dynamic compression behaviour of foam glass aggregate

Comportement en compression statique et dynamique unidimensionnel des granulats de verre mousse

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ABSTRACT: Foam Glass Aggregate (FGA) has a wide particle size distribution, in addition to being lightweight and thermally insulating, which extends its potential applications to various infrastructure and construction purposes. For infrastructure projects, it can be used as a lightweight backfill material, allowing the use of soil-improvement methods to be dispensed with in soft subsoils. In buildings, it can be used as thermal insulation under floors, thus helping to improve the energy efficiency of buildings. It acts as a static load for building and earthwork structures, while vehicles or forklift cyclic loads act in case of pavements and industrial floors. It is essential to investigate the effect of different compaction ratios in order to ensure efficient use of materials. In this study, the effects of different compaction ratios (10%, 20%, 30% and 40%) on the elastic modulus (Eoed) and dynamic parameters (Resilient modulus) of the material were investigated. For cyclic loads, elastic and plastic deformations were separated to determine the short and long term behaviour of the material. Different deviator stresses were operated on the FGA for both static and cyclic loads. The results were evaluated by comparing the behaviour of FGA under static and cyclic loads.

RÉSUMÉ: L'agrégat de verre mousse (FGA) a une distribution granulométrique élevée, en plus d'être léger et thermiquement isolant, ce qui étend ses applications potentielles à diverses fins d'infrastructure et de construction. Pour les projets d’infrastructures, il peut être utilisé comme matériau de remblai léger, ce qui permet de renoncer au recours à des méthodes d’amélioration des sols dans les sous-sols mous. Dans les bâtiments, il peut être utilisé comme isolant thermique sous les planchers, contribuant ainsi à améliorer l’efficacité énergétique des bâtiments. Il agit comme une charge statique pour les structures de bâtiments et de terrassement, tandis que les charges cycliques des véhicules ou des chariots élévateurs agissent dans le cas des trottoirs et des sols industriels. Il est essentiel d’étudier l’effet de différents taux de compactage afin de garantir une utilisation efficace des matériaux. Dans cette étude, les effets de différents taux de compactage (10%, 20%, 30% et 40%) sur le module élastique (Eoed) et les paramètres dynamiques (module de résilience) du matériau ont été étudiés. Pour les charges cycliques, les déformations élastiques et plastiques ont été séparées pour déterminer le comportement à court et à long terme du matériau. Différentes contraintes de déviation ont été appliquées sur le FGA pour les charges statiques et cycliques. Les résultats ont été évalués en comparant le comportement du FGA sous charges statiques et cycliques.

Keywords: Foam glass aggregate; thermal insulating material; oedometric modulus; resilient modulus; industrial floor.

1. INTRODUCTION

The foam glass aggregate (FGA) is a new material in Hungary. Foam glass was produced from the 1930s, but it appeared in aggregate form only around the 2000s. The material is popular in the Scandinavian countries, Switzerland and the USA. In the Scandinavian countries, it is used to reduce the depth of frost penetration under road pavements, while in other places it is used as a light material filling in road and railway construction, as well as for the construction of heat-insulating bedding under industrial floors. During the production of FGA, the material is suddenly cooled, so internal stresses arise in it. Due to these internal stresses, it is broken into more or less regular particles of the same size at the end of the manufacturing process.

Its advantageous feature is its durability. Since it does not age, regardless of environmental effects, it behaves in the same way as it did at the time of installation, even years after its installation, in terms of both its physical and chemical properties. Therefore, the material is not collapsing over time, such as polystyrene insulation materials.

Another beneficial feature - it's true that it's only the XXI. became an important aspect in the 19th century - that it is environmentally friendly. It can be produced from waste materials with low energy investment and can be recycled almost endlessly. In addition, it does not react with its environment, so no environmentally harmful substances are released from it.

Having the material's stiffness is essential for construction and infrastructure design purposes. The static and dynamic moduli are used as a design parameter to show the possibility of using the material under the impact of static and dynamic loads. In this regard, many types of recycling and manufacturing aggregates have been studied due to the increasing interest, high cost, and limited supply of high-quality naturally occurring aggregates that satisfy thermal insulation properties and get more sustainable environmental conditions. In recent years the possibility of using various types of recycled construction and demolition materials in road embankments and pavement applications such as recycled concrete (Jitsangiam et al., 2015), recycled crushed glass (Mohajerani et al., 2017) and foam glass aggregate (Arulrajah et al., 2015; Lenarta and Kaynia, 2019; Mustafa et al., 2022; Mustafa and Szendefy, 2023; Swan, Seungcheol Yeom, et al., 2016; Szendefy and Huszák, 2019) has been investigated.

The lightweight characteristics of such materials are typically due to the substantial part's low unit weight and large amounts of interconnected or nonconnected pores (Scheffler and Colombo, 2005). Different types of lightweight materials are used in civil engineering applications, including lightweight clay aggregate (Ayati et al., 2018), and foam glass aggregate (Emersleben and Meyer, 2014).

Regarding infrastructure constructions, vertical loads on soft subgrades can be reduced by using lightweight fill materials such as FGA as an alternative and in addition to bearing capacity improvement techniques (Emersleben and Meyer, 2014). FGA, as a lightweight construction material, can be used in many applications such as retaining walls, road embankments, bridge abutments, and slope stability (Szendefy et al., 2020). FGA has several technological benefits, including low density, high strength, thermal insulation, frost resistance, fire resistance, rat resistance, acoustic insulation, non-toxicity, low water absorption, and short constructing time (Hurley, 2003).

Although FGA is considered a beneficial construction material, limited studies are available on the static and dynamic behavior of the material. Therefore, more extensive research is needed to understand the factors influencing the material response under static compressional and cyclic loadings, especially the impact of different compaction ratios due to broad grain size distributions. According to the findings of (Swan, Yeom, et al., 2016), FGA has unbound compressibility behaviour. Regarding FGA, Ghafari et al. (2019) studied the resilient modulus under repeated deviatoric loads in a triaxial apparatus following the standard (AASHTO T 307-99, 2007) for the granular base and subbase materials with some particular adaptations to prepare the samples in a small triaxial scale. They concluded that the FGA resilient modulus was higher for the bigger particle size range of 20-31.5mm (Mr=150MPa) than the smaller one of 0-31.5mm (Mr= 120MPa). Depending on big-scale triaxial tests with monotonic and cyclic loading, Lenarta and Kaynia (2019) studied the properties of FGA, focusing on the stiffness and damping properties of the material. They observed a high initial stiffness, a small elastic threshold strain, and a significant modulus reduction in the first cyclic loading stage compared to other natural materials referring to a brittle structure component.

This study investigated the impact of different compaction ratios (10%, 20%, 30%, and 40%) on static and dynamic stiffness as well as the elastic and plastic strains the cyclic behavior of FGA. To determine the static compressional modulus of FGA series of loads started from 50 kPa to 300 kPa with 50 kPa intervals were applied. A sequence of uniaxial deviatoric stresses (25kPa, 100kPa, and 200kPa) with various cycle numbers were applied to the material samples. Due to the availability of high amounts of internal pored which was 92.7% for the studded FGA, this may lead to severe accumulated strains; therefore, the effect of compaction ratio and cycle numbers on accumulated plastic strains (ε_{acc}) behavior of the material have been evaluated. The resilient modulus at various compaction ratios was calculated to show the impact of elevated compaction ratios. Furthermore, this study presents a comparison between the ε_{acc} values obtained from the dynamic test and the vertical strains obtained from the static compressional test (oedometer test).

2. MATERIAL AND METHODOLOGY

2.1 Material

For the present study, the used FGA material produced by a Hungarian company has a grey color, broken-edge surface like crushed stone, while its bulk density without any compaction is around 170 kg/m3.

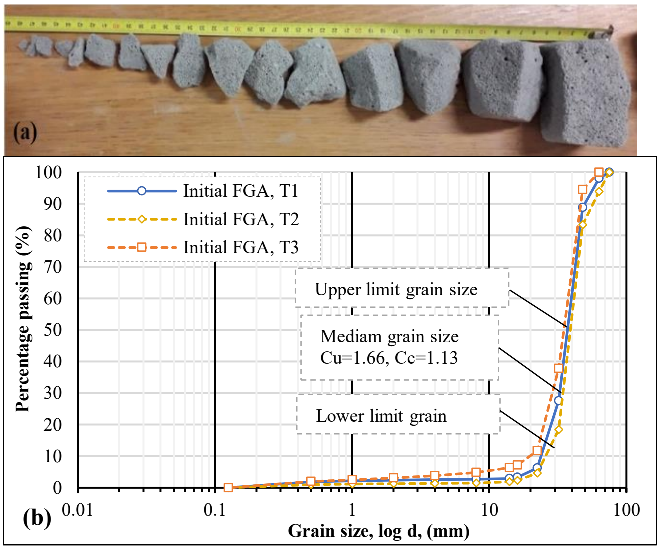

Figure 1. a) Foam glass aggregate, b) grain size distribution curve of FGA.

The material mainly contained gravel-sized particles, as shown from the particle size distribution curve of the received FGA. The initial FGA has a coefficient of uniformity Cu=1.66 and a coefficient of curvature Cc=1.13, which makes the material classified as poorly graded based on the USCS classification system, with one primary grain size range of 10-60 mm. The initial FGA material underwent over ten tests to determine its grain size distribution. However, for the purpose of clarity, only three key trials displaying significant differences in their distribution curves are included in Figure 1 (a, and b).

2.2 Methodology

A customized testing setup specifically designed for conducting static compression tests on foam glass aggregate (FGA). Since utilizing a conventional geotechnical apparatus for static compression tests on FGA samples is not feasible due to the impracticality of accommodating the individual particle size, which may exceed the conventional sample size range of 10 to 60 mm in diameter (Mustafa et al., 2022). Therefore, a cylindrical steel frame was constructed adheres to the 5D (largest particle diameter) size criterion. FGA was compacted into the mold by one layer at both 10% and 20% compaction ratios, while to reach the 30% and 40% compaction ratios the material was compacted into the mold in two layers using a heavy load plate. During the static compression test different series of static loads was tested starts at 50 kPa to 300 kPa with 50 kPa intervals were applied on samples To reach each compaction ratio, the initial FGA has been compacted into the mold till the desired mass per volume has been obtained. The 10% ration means the density is 10% higher as the origin bulk, while the weight is 20% more in case of 20% and etc.. Each loading stage was performed to the vertical strain reached the 0.01 mm/min strain value. During the tests, five trials were conducted on FGA samples to show the diversity.

To do the uniaxial dynamic compression test on the material in oedometric condition (fully side restrained) two load types of vertical stresses have been applied to FGA samples. First, a sustained conditioning load (25 kPa) was applied to the samples to represent the self-weigh of the pavement and capping layers. Then, depending on the stress distribution profile of road application sections under the pavement where FGA can be used as filling material, three different values of cyclic deviatoric vertical stresses (25 kPa, 100 kPa, 200 kPa) were selected to generate the effect of the repeated moving traffic loads. Where, the 200 kPa represent the stress at the top of the base layer, 100 kPa is at bottom of the base layer, while 25kPa is a general load in the embankment. Besides the selected deviatoric stresses, various cycle numbers have also been selected. For all compaction ratios and under the impact of 25 kPa and 100 kPa the samples were loaded for 40,000 cycles while under the impact of 200kPa the samples were loaded for 100,000 cycles. The selected cyclic stresses have been applied to the samples sequentially after the desired number of cycles has been reached.

Furthermore, because FGA contains a high amount of pores according to the nature of the structural composition of the material, in the case of the used FGA, it was 92.7%; also, there were a high amount of void ratios between the particles in their bulk condition due to the big particle size nature of the material. Therefore, the impact of long-term cycle stresses on the dynamic behavior of the material has been investigated in this study. An electro-hydraulic actuator with a 100 kN capacity was used in the axial loading condition. To measure the vertical strain (ε), a pair of linear variable displacement transducers (LVDTs) were placed on both sides at the top of FGA samples. The applied cyclic load frequency in the one-way dynamic compressional test was set to be 1.0 Hz simulating traffic loads on the roads.

3. RESULTS AND DISCUSSION

3.1. Static compressional modulus

Based on the stress-strain curves obtained from the static compressional tests conducted on five to eight FGA test samples, the compressional modulus (E_{oed}) values have been calculated. The mean values the E_{oed} under varying compaction ratios and static compressional loads ranging from 50 kPa to 300 kPa with 50 kPa intervals are presented in Table 1.

Table 1. Calculated values of Eoed (MPa) for all loading steps and compaction ratios.

Comp. ratio (%)	**E_{oed} (MPa) Applied loads (kPa)**					
	50	100	150	200	250	300
10	7.5	8.5	8.0	6.0	5.0	4.0
20	9.5	12.5	14.0	15.0	15.5	13.0
30	8.5	11.0	13.5	15.5	17.5	19.0
40	10.0	14.5	17.5	19.5	21.5	23.0

According to the Table 1, it is strange that the oedometric modulus was decreasing in 10% and 20% compaction ratios, while in 30% and 40% compaction ratios, the oedometric modulus continued to increase under all tested compressional loads. These findings indicate that the material at lower compaction ratios (10% and 20%) became progressively softer with higher compressional loads. Conversely, the consistently elevated oedometric modulus values suggest that the material exhibited stiffness and stability similar to conventional soils like sandy soil, which hardens. This implies that the material could be considered for geotechnical applications under similar loading conditions by providing the valuable insights for geotechnical engineers in selecting suitable compressional modulus for specific projects or applications.

As appears from the results of Table 1, the oedometric modulus of the examined FGA at 10% compaction and under the impact of 50kPa was about 7.5 MPa then it raised up to 23 MPa when compacted by 40% under the impact of 300 kPa. In this regards, the present study results is in harmony with the study of Steurer Steurer (2012) conducted a comprehensive study involving large-scaled and oedometric laboratory compression tests to investigate the load-deformation behavior of foam glass aggregates. According to his study finding, by rising the compaction ratio from 10% to 25% an increase in the stiffness modulus was also appeared. Additionally, Steurer (Steurer, 2012) observed a higher stiffness modulus compared from the long-term confined compression test ranging from 30 MPa to 43 MPa under the same compressional stress impact compared to the of the present study ranging from 100 kPa to 300 kPa. According to the authors' perspective, the higher compressional modulus observed in the mentioned study can be attributed to the greater compressive strength of the foam glass aggregate grains, which was measured at 2100 kPa. In our case, the compressional strength was approximately 1200 kPa.

3.2 Resilient modulus

The Mr values of FGA samples at different compaction ratios and under various deviatoric stresses are shown in Figure 2.

As it can be seemed from Figure 2 the decrease in Mr value was appeared parallel with an increase in the amount of compaction ratios from 10% to 40%. This considered a reverse behavior compared to other geomaterials. According to the study of Liu et al. (2019) which has been executed on dynamic and static resilient modulus of six types of sub-grade soils. They observed that dynamic and static resilient modulus was positively related to increasing the compaction degree and increased the amount of dynamic, resilient modulus by about 21%-26% when the compaction degree elevated from 90% to 93%. This behavior of FGA may be related to the impact of extra applied compaction energy to get the desired compaction ratio, which affects the material's dynamic response. FGA is considered a fragile material; this reality was practically observed by previous scholars (Lenart and Kaynia, 2019), making the material particles behave in a brittle condition under the effect of impact actions that happened during the sample preparation process. At a low compaction ratio, the material subjected to a lower amount of compaction energy saves the manufacturing properties of the particles connected at small connection areas. While to reach a high compaction ratio, a much higher amount of impact compaction energy was applied over the samples of FGA, leading to an increase in the connection area between the particles. Although, the overall skeleton of the material became stiffer to resist the applied external stresses due to better interlocking. But on the other hand, under the impact of high compaction energy, the walls, and the struts of the pores at the connection areas of FGA particles locally (completely or partially) failed and led to collect microfine deposits between the connection areas of the particles. This reality was observed clearly during the experimental work when the material was taken out from the molds. Therefore, the particles of the material were only crushed under the effect of applied impact compaction at the connection areas when the maximum strength was generated. In this regard Mustafa et al. (2022) observed from the density and porosity analysis of foam glass material and foam glass aggregates that the total voids decreased by 4.8% compared to the material density and by 3% compared with as received bulk density after compacting FGA by 40% compaction. These were because of a decrease in the void ratios and the micro- or macropores crushing under the impact of the elevated impact compaction process. As a result, due to the material's lightweight properties, the particles' connected area behaved like a micro spring when subjected to cyclic loads and made the material gain some extra elastic recoverable strain. Since the same equation (2) was used during the calculation process for all compaction ratios, a less resilient modulus was obtained when the compaction ratio elevated due to a bigger amount of recoverable elastic strain.

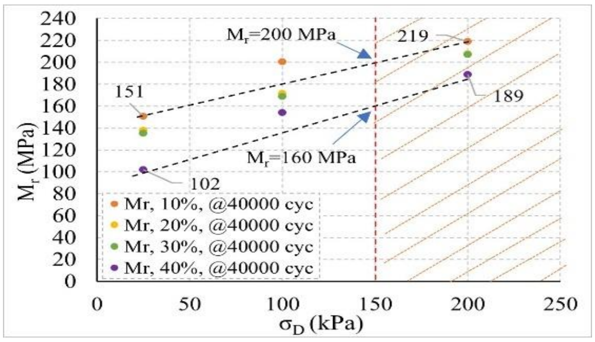

Figure 2. Boundary limits of the resilient modulus of FGA at different compaction ratios.

3.3 Elastic and plastic vertical strains

The results which obtained from both of static and uniaxial cyclic test that applied at the same boundary conditions (oedometric test) and compaction ratios (10%, 20%, 30%, and 40%) on FGA samples are presented in Figure 3. Since all samples were subjected to the same amount of loads starting from 50kPa to 300kPa with 50 kPa. Therefore, the evaluations have been made between amounts of total vertical strains obtained from both of static and dynamic tests.

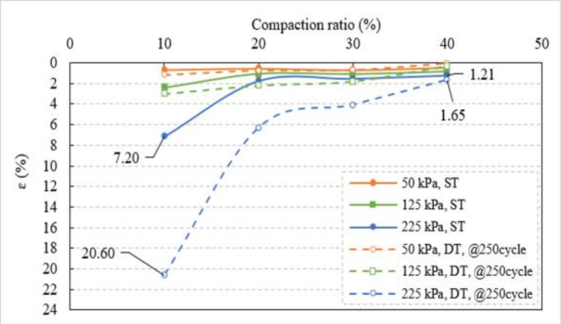

Figure 3. Effect of static and one-dimensional dynamic compression loads at various compaction ratios after 250cycles at 40,000cycle.

As appeared from Figure 3, the vertical strain exhibited by FGA in both static and uniaxial dynamic tests displayed a similar pattern of improvement. The dynamic test showed a greater disparity in strain values at lower compaction ratios of 10% and 20%, with an increase of around 15%. However, this disparity was reduced at higher compaction ratios of 30% and 40%, resulting in a difference of approximately lower than 3% at the same applied load. This condition was observed after deducting the amount of settlement obtained at the beginning 250cycles for both 30%, and 40%. This condition obtained in site under the impact of construction machine and before starting the real service life of the material as a construction material. This result considered very valuable for the practical purposes since it is more convenient to rely on static tests rather than dynamic tests to determine the final vertical strains, because static tests are easier to execute and analyse.

4. CONCLUSIONS

FGA is an extremely innovative material made from recycled glass waste. The material is durable and resistant to environmental effects, so it can be used in structures under the ground. Due to environmental protection requirements, it is a good technical solution for the thermal insulation of the underground parts of buildings, and it is also possible to reduce the amount of primary aggregate used in these places. As a light filling material, in the case of roads passing through soft, organic soils, it can be used as a filling material to avoid costly embankment foundations, which is also more beneficial from an environmental point of view. In contrast, retaining structures have advantages, where the reduction of lateral earth pressure can reduce the cross-section of structures.

When designing these structures, it is essential to know the strength characteristics of FGA. The oedometric modulus of the FGA was determined with laboratory measurements.

The compression modulus of the FGA was determined with laboratory measurements under different compaction conditions. The test results (elastic modulus) illustrated that at 10% and 20% compaction ratios, the material shows behavior similar to compressible soils, while at 30% and 40% compaction ratios, it can already provide the properties of good soils, such as sand and gravely sand soils. Based on the cyclic load tests, the material is also sufficiently resistant to dynamic loads, so it can also be designed for cyclic loads caused by vehicles using the Mr value determined by our measurements.

By comparing the settlements caused by static and dynamic loads, it was seen that the FGA is not sensitive to cyclic loading. It does not develop a larger settlement under cyclic loading in the long term than if it were statically loaded with the same pressure.

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