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Деформациски карактеристики на материјали со мала тежина и нивна примена во патната инфраструктура
Deformation characteristics of lightweight materials and their application in road infrastructure

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Апстракт

Климатските промени бараат брз и ефективен одговор од инженерската фела во однос на потребите во секојдневниот живот. Во последно време, патната и железничката инфраструктура како значаен дел од современите транспортни системи, е под сериозно влијание на промените во инженерството. Како дел од една поголема истражувачка студија, овој труд дава придонес кон дефиницијата на т.н. „лесни" материјали како можно решение за подобрување на слабоносивата подлога. Употребата на овие материјали носи придобивки при примената во геотехниката. Благодарение на нивната мала густина, може да се користат како „лесен" материјал со цел намалување на тежината во области со слабоносива подлога. Поради нивната добра порозност и следствено добрите својства на топлинска изолација, овие материјали можат да се користат како слоеви за заштита од мраз во студените региони или како термоизолационен слој под конструкциите во нискоградбата. Во механичка смисла, имајќи ги предвид релативно дебелите ѕидови на порите во споредба со дијаметарот на празнините, овој материјал се карактеризира со добра јакост на притисок и крутост. Сепак, доволната јакост на смолкнување и крутоста можеби не се очигледни. Па така, постои недостаток на информации во врска со деформационите својства на овие материјали бидејќи тие би можеле да станат важен градежен материјал за изградба и реконструкција на критичната инфраструктра погодена од климатските промени во Европа во иднина. Попрецизно, трудот ги прикажува резултатите од лабораториските тестови на примероци во голем размер од материјали со мала тежина, имено агрегати од експандирана глина и агрегати од пенесто стакло, при директно смолкнување, за да се дефинираат крутоста и пригушувањето при различни состојби на напрегања. Со цел локално мерење на деформациите на примерокот користени се линеарно променливи диференцијални трансформаторски сензори. Како резултат на тоа, добиени се графици при корелација на напрегањата и деформациите, сè со цел да се пресмета модулот на деформација, како и другите својства на материјалите. Ова истражување е дел од проектот LIWEMAT, добиен во рамките на GEOLAB – Наука за подобрување на критичната инфраструктура во Европа и финансиран од програмата Horizon 2020 од Европската Унија. Сите тестови се извршени во Словенечниот Градежен Институт (ZAG) во Словенија.

Клучни зборови

Климатски промени, патна инфраструктура, „лесен" материјал, агрегати од глина и пенесто стакло.

Abstract

Climate changes require a fast and effective response from the engineering world to everyday needs. In the recent period, the road and railway infrastructure as a significant part of modern transportation systems is seriously affected by the changing engineering conditions. As a part of a larger research study, this paper makes a contribution to the definition of lightweight materials as a possible solution for the improvement of low-bearing subgrade. The use of lightweight materials brings several benefits to geotechnical applications. Due to their low density, one can utilize lightweight material for weight reduction purposes in areas with a low bearing subgrade. Due to their high porosity and consequently good thermal insulation properties, lightweight materials can be used as frost protection layers in cold regions or as a thermal insulation layer under road structures. In a mechanical sense, considering relatively thick pore walls compared to the diameter of the voids, this material can exhibit good compressive strength and stiffness. However, sufficient shear strength and stiffness might not be self-evident. Thus, there exists a lack of information regarding the deformation properties of lightweight materials as they might become an important construction material for the construction and reconstruction of climate change-affected critical infrastructure in future Europe. More precisely, the paper presents results from large-scale laboratory tests of lightweight specimens, namely expanded clay aggregates and foamed glass aggregates, in simple shear mode to define stiffness and damping properties under various stress states. Linear variable differential transformer sensors were used to measure the strains locally. As a result, stress-strain charts are obtained to calculate the deformation modulus and other material properties. This research is part of the LIWEMAT project received under GEOLAB - Science for enhancing Europe's Critical Infrastructure and funded by the European Union's Horizon 2020 program. All the tests are performed at the Slovenian National Building and Civil Engineering Institute (ZAG) in Slovenia.

Keywords Climate change, road infrastructure, lightweight material, clay and foamed glass aggregates.

1. INTRODUCTION

Some of the most commonly used lightweight materials in earthworks are expanded polystyrene (EPS) [1], [2], [3], [4], extruded polystyrene (XPS) boards [5] granulated tire rubber [6], [7], and various natural and artificial lightweight aggregates, e.g. lightweight clay aggregate [5], [8], lightweight aggregates from sand sludge, and foam glass aggregate [9], [10].

Lightweight aggregates are obtained either from natural or artificial resources, yet using artificial lightweight aggregates but generally, those made from waste materials are environment-friendly and economical solutions [11]. They are preferred due to their low density, which brings the advantage of their use in infrastructure in case of compressible and low-strength subgrade. Lightweight materials are aggregates with a particle density not exceeding 2000 kg/m^3 or a bulk density not exceeding 1200 kg/m^3. Their properties come from their porous structure with a uniform pore distribution, closed cells, and a hard, densely sintered outer surface. Due to low density, the use of lightweight material is an added advantage when used as subgrade bed filler in road pavements or railway tracks. The primary reason for the use of lightweight materials is weight reduction with respect to their strength [12]. With relatively low water absorption, high mechanical strength, and high frost resistance, expanded glass aggregates are the perfect material for such a task.

This research aims to determine the characteristics of expanded clay and foamed glass aggregates through laboratory testing, performing cyclic loading for the stiffness and damping evaluation, which would be beneficial parameters for numerical simulations.

1.1 Material

According to data published by the European Container Glass Federation (FEVE), the recycling of glass has reached record levels across all countries of the European Union in 2014 with a volume of 11.6 million, or a rise of 3.5% compared to 2013 [13]. In 2018, 18.7 million tons of container glass waste was produced [6]: 26% recycled, 13% destined for combustion with energy recovery, and the remaining 61% ended in a landfill. In 2020, production reached a volume of 35.9 million tons [14]. The worldwide production is approximately 195 million annually, out of which 46% is container glass [15].

Fig. 1: Lightweight foamed glass aggregate

Generally, foam glass is composed of 98% recycled glass. The production of expanded glass aggregate involves mixing fine-grained ground waste glass with appropriate expansive agents and heating it at high temperatures up to the softening point of glass to achieve a viscosity of less than 10E6.6 Pa (Ducman et al., 2002) [16]. The foam glass aggregate has a homogeneous microstructure with approximate uniform shapes and sizes. Foam glass aggregate is considered to be one of the best insulation materials with several unique properties (Fig. 1). Thus, it can be widely used in many applications such as basement walls, foundations, floors, terrace and garden covers, rooftops, and parking lots [17].

Fig. 2: a) Expanded clay aggregate; b) Interconnected different sizes of air-filled cavities

Another type of lightweight material family is expanded clay aggregate (Fig. 2.a). The lightweight expanded clay aggregate is produced from special plastic clay with no or very little content of lime. The clay is dried, heated and burned at very high temperatures (1100-1130° C) in a rotary kiln. The aggregate has a round shape with different sizes with small air-filled cavities (Fig. 2.b), with dark brown, reddish, brown-red or gray colors, which depends on its chemical composition. The lightweight expanded clay aggregate has a bulk density from 250kg/m^3 to 710kg/m^3 [18], mostly dependent on the size of the aggregate (Fig. 3).

Fig. 3: Different grain sizes of lightweight expanded clay aggregate

The lack of data for specification in the literature makes these lightweight aggregates a research worth material. Therefore, in this paper results from large-scale laboratory tests of the expanded clay aggregate are presented. Both expanded clay aggregates and foamed glass aggregates were exposed to simultaneous vertical and horizontal loads simulating the traffic action. The very small and large strains were measured during the cyclic shear loading. The goal of the testing was to define the stiffness and damping characteristics of these materials, determine the impact of the traffic actions, as well as the long-term damage and fatigue of the material.

2. TESTING PROGRAM

All of the investigations were conducted at the Slovenian National Building and Civil Engineering Institute in Ljubljana, Slovenia. In this period, both materials were tested, however, in this paper we focus our attention only on the expanded clay aggregate.

2.1 Large-scale Triaxial Apparatus

A Large-scale Triaxial Apparatus was used to perform the loading tests, which enables the characterization of materials at very small strain ranges with a very high accuracy level of load-displacement control (Fig. 4). The apparatus has rigid confining aluminum frames with a height of 3 cm and cross-section of 40 x 40 cm, enabling prismatic specimens with a height of up to 80 cm to be tested.

Fig. 4: Large-scale Triaxial Apparatus (ZAG Laboratory, Ljubljana, Slovenia)

Proper installation of the specimen is the first and most important step of the examination. The second step is adjusting and calibrating of sensors which is one of the crucial tasks for accurate results. After each examination, the specimen was removed from the Apparatus's box and the membrane was cleaned up entirely to install the next one.

2.2 Specimen preparation

For both materials, three consecutive direct shear tests were performed. Each of the samples was embedded into a rubber membrane within the rigid aluminum frames of the large triaxial apparatus to avoid material loss between the frames. Prismatic samples with a cross-section of 40 x 40 cm, and a height of up to 40 cm, were prepared with light compaction in a dry state. The weight of the specimens for the expanded clay aggregate was around 18.5-20 kg per single test (Fig. 5). For the specimen loaded with a 100 kPa vertical load, the weight amounts to 19.05 kg.

Three tests were performed for each material, meaning three samples per material are taken into consideration. The test begins with carefully lowering the plate for the vertical load. Thus, constant vertical stress is applied, equal to 50kPa, 100kPa, and 200kPa. After that, cyclic loading is applied with a gradually increasing strain with a range between 10^{-5} and 10^{-1} mm, depending on the material behavior, but usually 10-^{4} (starting at 0.002 mm) The cycles were performed according to the testing program (Table 1).

Table 1. Cyclic deformation for a vertical load of 100 kPa in steps

Step	Load amplitude Horizontal displ. u [mm]
1	0.002
2	0.008
3	0.015
4	0.022
5	0.033
6	0.053
7	0.070

8	0.140
9	0.210
10	0.270
11	0.410
12	0.620
13	0.920
14	1.390
15	2.300

After the experiment, it was noticed that the aggregate grains were cracked and split (Fig. 6) which confirms that the shear strength is reached.

a) b)

Fig. 5: Expanded clay aggregate material a) before installation, b) after testing, exposed to damage

2.3 Stress-strain measurements

Strains measurement data was collected by six LVDT sensors installed on the frame of the Apparatus (Fig. 6). Four of them were measuring the large strains, two of which were horizontal and vertical strains. The other two were measuring small strains. The Linear variable differential transformer is an electromechanical device that converts mechanical motions to electric signals. When it comes to precision, these devices were quite sensitive. They are hollow metallic cylinders with a smaller diameter rod that moves freely back and forth, sending electrical signals to the data acquisition system.

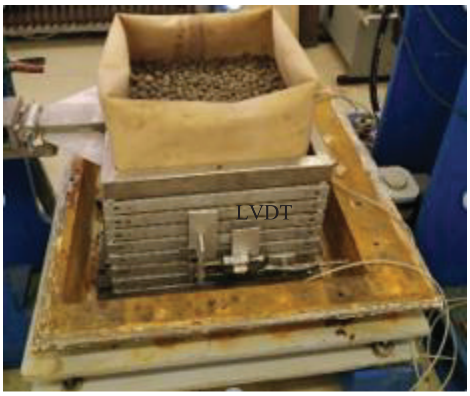

Fig. 6: LVDT sensors for strain measurements

3. RESULTS

The measurements from the LVDT sensors were recorded using adequate software connected to the system. After lowering the plate to apply vertical loading and perform consolidation settlements, horizontal loading is applied. The software graphs diagram between the load and strain, hence cyclic loading is being continuously recorded. The software output gives tables of values of time, load and displacement. Using these values charts are made to determine the deformation characteristics. The results in terms of shear stress versus horizontal displacement are given in Fig. 7

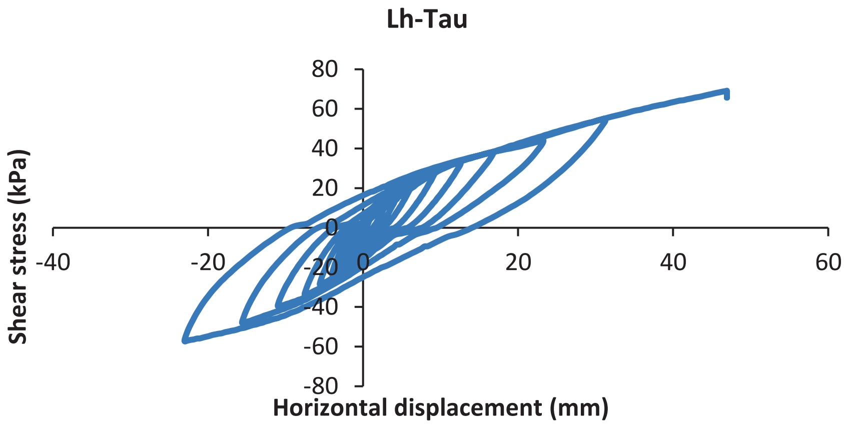

Fig. 7 Shear stress versus horizontal displacement

In the graph 15 cycles of stress-strain measures are presented, all of them before the failure of the material had occurred at around 30 mm, with the maximum value of the horizontal displacement at the end of the experiment is 46.935 mm, giving maximum shear stress of 69.194 kPa. The area of the stress-strain loops is the dissipated energy used to calculate the system's damping. The diagram is asymmetric, hence the deformation is not equal in both directions and the same goes for the shear stresses. After the tenth cycle, we observe a significant increase in the stress-strain loops.

In Fig. 8 the envelope of the hysteresis loops is presented depicting the progress of deformation and equivalent stresses per cycle with there and minimum values from each hysteresis loop.

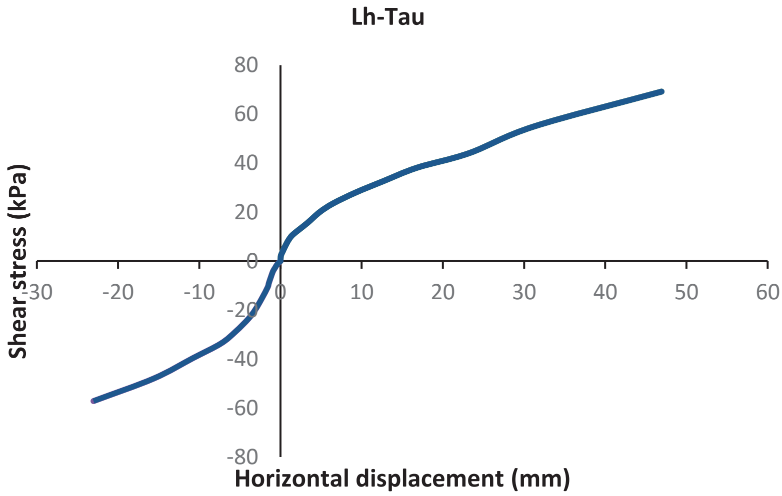

Fig. 8 Envelope curve of hysteresis loops

The envelope has a different gradual increase in both directions but in general, it can be assumed that the material with every cycle is experiencing softening flattening the Lh-Tau curve. Two different behavior of the material can be observed, the initial part with dominantly elastic behavior with G= 3,200 kPa, and the later one, after cycle number nine with larger deformation and viscous behavior with G= 1,151 kPa. This effect is due to the elastoplastic nature of the material and the cyclic loading which reduces the modulus by 64 %.

4. CONCLUSION

Lightweight materials are used for infrastructure construction purposes (roads, railroads, airports, buildings and industrial plants, etc.) in areas with low-bearing capacity subgrade soils for settlement mitigation and load reduction measures as well as thermal insulation in cases sensitive to temperature gradients. Critical infrastructure of Europe, particularly in the urban and transport sectors is facing challenges related to the low-bearing capacity of sub-grade, which requires a reduction of infrastructure weight, and on the other hand, climate change challenges with extreme temperatures bring requirements for additional thermal insulation of infrastructure. Due to those reasons, lightweight materials become an important construction material for the construction and reconstruction of critical infrastructure in Europe in near future.

In this research, we were able to study the behavior of expanded clay aggregate material exposed to cycling loading using large-scale triaxial apparatus which eventually was used to define the deformation characteristic of the material. If the future more testing is going to be performed on other lightweight materials such as foamed glass aggregate, hence contributing to the material definition of lightweight materials.

5. ACKNOWLEDGEMENTS

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